

THE ORIGIN OF LUNAR CRATERS*

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Translator's Preface

This important paper of Wegener's has virtually not been cited or recognized in the current literature, both American and German. It contains many interesting and early ideas on the origin of lunar craters, structure of the lunar surface, accretion of the Moon and Earth, origin of tektites, importance of impacts in early terrestrial history and the comparative tectonics of the Earth and Moon, as well as other topics. As with all translations, considerable freedom has been taken with the actual English words used, but it is hoped that the ideas and technical details are unchanged. In places where the translator was concerned about retaining the specific content, many rather cumbersome sentence structures are preserved. If there are passages of particular importance to the reader, it is recommended that the original text be consulted. Only three of the nine figures of the original text are reproduced in this translation, as the other six are unfortunately very poor quality photographic reproductions which cannot be reproduced any further. The reader who wish to see these figures need to refer to the original text also.

1. Introduction

In the professional literature there exists a striking difference of opinion concerning the origin of lunar craters. There are at least four different hypotheses: 'bubble hypothesis', 'tide hypothesis', 'volcanic hypothesis' and 'impact hypothesis'. Also, a number of hypotheses that are combinations of the above, especially the combination of the 'volcanic hypothesis' with the others, have existed contemporaneously for decades, but a widely accepted view has not yet been reached.

The problem does not seem to be insoluble. If we could know the succession of origin of the lunar seas, crater seas, ring mountains, craters with and without central peaks, crater chains, grooves, valleys, trenches, ray systems, etc., with the accuracy that would enable us to see the laws that govern the formation of these features, which have always seemed to be totally irregular and chaotic, it would then be possible at

* *Die Entstehung der Mondkrater* von Dr Alfred Wegener, Sammlung Vieweg, Heft 55, Braunschweig, Druck und Verlag von Friedr. Vieweg & Sohn, 1921; 48 Seiten, mit 9 Abbildungen im Text und auf 3 Tafeln.

least to decide which hypothesis is the most probable answer to the question. Thanks to the clear shadows that are cast on the atmosphereless Moon, that accuracy has long been available. Under favorable conditions we can recognize objects that have a diameter of as small as 50 m as little points. Through higher magnification we would be able to discover a host of small features; however, for the understanding of the prominent gross features, whose explanation will be our main concern, this would not be a great contribution. Probably the casual irregularities would only become more striking. As the works of Ebert, Mainka, Franz and others show, we know the gross features of the near side of the Moon much better than those of our Earth. Through the work of Landerer on the polarization angle of lunar rocks, which was clearly supported by Ebert's demonstration with the glass block, we gained substantial views about the nature of the rocks which make up the crust of the Moon and the material that produced these surface forms.

The purpose of the following paragraphs is an examination of the above mentioned four hypotheses in the light of new criteria provided by geophysics. In this treatment, the experiments on impact craters performed by the author during the winter of 1918/19 will play a decisive role. To orient the reader, it seems useful to say beforehand, that the 'bubble hypothesis' and the 'tide hypothesis' appear to be obvious fallacies and the 'volcanic hypothesis' does not seem to be plausible either. The 'impact hypothesis', on the other hand, is supported by a large amount of evidence.

2. Review of the 'Bubble Hypothesis'

Recently the 'bubble hypothesis' has been defended, particularly by F. Sacco [1]. Among the older supporters are Secchi, R. Hooke, T. Bergeron, A. St. Claire, Humphreys and Puiseux. Paul Lehman, G. Dahmer and others may also be mentioned. Among these authors it would be possible to find some differences of opinion, but the important common idea is that the ring mountains originated as the remains of large, exploded bubbles that had formed in hot viscous magma. R. Hooke, Poulette, Scrope, Bergeron, Stewart Harrison, De Beaumont, Gorini, St. Mennier, F. Sacco, G. Dahmer and others, tried to explain and support this idea through experiments. These investigators used different paste-like substances such as gypsum, lime, sulfur, wax and clay. They cooled these substances and let the bubbles rise through the cooling mass. Bubbles sometimes were produced simply by aeration of the material, but generally they were formed by boiling the material. A test of these experiments undertaken by me demonstrated that the resemblance between the experimental ring walls and those of the Moon is only superficial. The bubble craters fail to show the characteristic proportions of crater profiles as compiled by Ebert. This result also is confirmed by the photographs published by Dahmer [2].

It is easy to show that the 'bubble hypothesis' is based on a fallacy. In order to do that we need to collect some more information. When we go from experiments to cosmic dimensions we must be very careful as to whether we are dealing with molecular forces or with mass forces [3]. In the transition from experiments to cosmic dimen-

sions the proportions between the two forces become reversed. In the laboratory we work only with the molecular forces – with the exception of weight which almost always appears as a problem. In order to detect the force of gravity even only qualitatively, we must use very sensitive instruments. In the Cosmos it is totally different, because as bodies become larger the molecular forces do not become larger, but the mass forces grow. Therefore, in astronomy the molecular forces of magnetism, electricity, and tenacity are overshadowed by the force of gravity to such a degree that before the introduction of spectral analysis, physics of the Cosmos was essentially composed of the Newtonian gravitational law. An example should make this clear: quartz crystallizes as hexagonal prisms. The shape is controlled by the molecular forces and the crystal's own gravity does not affect the process conspicuously. Now let us imagine a quartz crystal of the size of the Earth in space. Because of the immense deviation from spherical shape, the crystal's own gravity would cause such pressure differences and tensions in the different parts of the crystal that the crystal's strength would be overcome. The crystal would be distorted, projecting parts would slide along slickensides to locations closer to the center of gravity; or, through continuous flow the whole mass will approach the form of a sphere. The spherical forms of the heavenly bodies show the dominance of mass forces over molecular forces. Meteorites, the smallest moons of the planets and the asteroids are small enough to resist this leveling force of gravity. The Moon and Earth mostly are overcome by the force but the mountains show to what a degree the molecular forces remain effective here. The mountains on the Moon are steeper and higher than ones on Earth [4] not only because of the lack of erosion, but especially because the gravity of the Moon is only one-sixth of that of the Earth [5].

It follows from these observations that we can carry over to the cosmic dimensions only those laboratory experiments that are based on the mass forces and not on molecular forces. Bubble building, however, is totally based on the molecular force of surface tension. It is possible to form bubbles of different sizes according to the strength of surface tension but they always fall within finite limits. Also, on the Moon there cannot be, nor could there have been, larger bubbles. It is sufficient to discard the 'bubble hypothesis' totally. Anyone who wants to explain the origin of giant lunar features hundreds of kilometers in diameter with broken bubbles will be making a fallacy comparable to one who wants to explain the flotation of transatlantic ships with surface tension.

3. Review of the 'Tide Hypothesis'

The 'tide hypothesis' has been defended by, among others, Faye, H. Ebert and Hannay, and accepted by Scheiner as the most probable in his *Populäre Astrophysik*, (page 493, Leipzig and Berlin 1908). Ebert formulates it as follows: [6]

"Let us imagine a shining-hot viscous planetary body that cools by radiation from all sides. Thus, on its surface, rigid 'frozen' flakes would form that float in the still liquid magma. In the case of the Moon there exists the attraction of the Earth which

caused a great tidal wave of the liquid parts. The Moon rotates under this tidal wave and therefore in every part of its surface the liquid magma is alternately raised and lowered. It welled up during every tide, flooded these flakes and retreated with the coming of the ebb, and the play is repeated during the next tide.”

During an interesting lecture experiment Ebert showed that, through such periodic wellings-up of the molten liquid in holes through a superficial crust, the crater forms really can be created that resemble the lunar craters. The same experiment also demonstrated the origin of mud volcanoes. He used Wood’s metal alloy (melting point 68°) that was kept liquid in an open, steam heated container. The surface of the alloy cooled and ‘froze’. The position of the liquid could be changed by means of a piston pump. The floors of the resultant craters, generally were lower than the level of the surrounding area. In a few cases, which correspond to that of the filled Moon crater Wargentín, the ‘freezing’ occurred at the highest level of the molten liquid. The angle of the interior slope of the ring wall was 34° and of the exterior slope 5° . Concerning the accidental formation of a central peak, which actually was one of the various deformations of the crater floor produced during the experiment, Ebert stated: “When the whole floor is frozen and there is only a little free passageway left, the magma wells up and forms a central cone sometimes steep, sometimes smooth, but never exceeding the height of the surrounding walls.” Thus, the experiments show that through the periodic rise and fall of magma in holes (which by no means have to be circular), features can be obtained that have many common characteristics with lunar craters.

It does not seem possible to have tide and ebb of liquid magma that would be observed in the holes of the outermost solid lunar crust, because such a case would require a firm, solid crust that maintains its form in spite of the tidal waves of its foundation. This is impossible. On Earth, flotation or isostasy of the firm crust has been known for a long time. If the crust, for example, is loaded by an ice cap, then, although with some delay, it sinks in order to preserve the pressure balance, the isostasy. In a similar manner the ice cover on water sinks when it is loaded. After the melting of the ice, the strand terraces, that were formed when the land mass was in its lower position are again raised and they show, for example, in Canada and Scandinavia, that these areas were depressed 500 or 200 m. Also in the case of the Moon we must assume that the crust floats on its foundation, or at least it floated at one time when the foundation was still liquid. Ebert’s experiment is successful when we use containers, in which the superficial crust sticks to the walls of the container, but it would fail if we would try to repeat it with a lake of a diameter of 500 m. Following from this we see that the crust of the Moon must have followed the movements of the foundation. The above mentioned hypothesis of Ebert is as impossible as to try to measure the tide and ebb from the floating icebergs in the North Sea.

People tried to use Ebert’s experiment to explain the origin of lunar craters, but they tried to ascribe the rise of magma to causes other than tides, such as repeated gas explosions within the fluid foundation, or other volcanic manifestations. But then, the cause becomes volcanic, and in the next chapter we will come to that.

4. Review of the 'Volcanic Hypothesis'

A somewhat more comprehensive review than the previous two hypotheses is deserved by the 'volcanic hypothesis' which has been defended by many geologists such as Alexander von Humboldt, Leopold von Buch, Dana, Eduard Suess, Branca, G. Tschermak, S. Günther, Stübel, v. Wolff, and also by many astronomers such as Mädler, Schröter, Nasmyth and Carpenter, Pickering and others. According to this group, the lunar craters are volcanoes. The ones with a central peak correspond to the form of Vesuvius whose younger central cone is surrounded by the older Mount Somma. The flat ring plains usually are thought to be features similar to the lava lakes like that of Kilauea or the crater lakes of Italy or the maars of Eifel. Von Wolff, for example, compared the lunar seas, with the terrestrial areal or fissure eruptions like those of Iceland: "The floors of the lunar seas are the results of the areal or linear eruptions whose lava flows covered an older topography." [7] This explanation does not give any reason for the existence of the wreath of mountains partially surrounding the lunar seas. In his interpretation of the surface of the Moon being the result of the volcanic activities, Eduard Suess considers the lunar seas and through this method he comes to an interpretation of lunar craters which differs considerably from that of the terrestrial volcanoes. He describes the evolution of the surface of the Moon with the following words: [8]

"The temperature of the great mass is by no means a homogeneous one. At some point it rises, eats up the scoriaceous cover and from that spot the melt is spread out equally in every direction, for hundreds of kilometers. The form of the hearth is that of a cross-section of a sphere and its perimeter is a circle. Finally the event approaches an end; the temperature of the surface of the hearth is lower at its periphery; the scoria is not consumed any more but just pushed outward like moraines. Then the hole gets clogged. A vast flat surface, surrounded by a circular edifice which has wild outlines: a scoriaceous wall with a steep slope inward toward the newly solidified surface. Its height may reach many thousands of feet. Such scoriaceous walls, which are known under the names of Apennines, Alps, etc., surround Mare Imbrium."

As already pointed out, Suess wants to explain the craters, seas, and larger ring plains by means of the explanation quoted above. But this leads him to the dilemma that in order to explain the smaller forms one must go back to the classical volcanic hypothesis. One can object to his explanation, as his description is so clear, because the great basaltic floods on Earth never pushed such scoriaceous walls like moraines and deposited them at the periphery. Such a process would be hard to understand because the necessary factor for moraine formation, namely the melting of the glacier, is completely absent in this case.

It must be pointed out, however, that it is possible to modify the volcano hypothesis and to give it many forms. It actually did experience such modifications. We have already seen that the above mentioned experiment of Ebert caused such a modification. But as we go away from the comparison with the typical terrestrial volcanic forms, we then enter the field of sheer speculations which can neither be proved nor disproved

because we have no experience with any actual representative of the assumed processes. In the following study, we will avoid such speculative explanations because, as will be shown, the ‘impact hypothesis’ provides a completely satisfactory explanation whose foundation is composed of testable premises. Therefore, we will confine ourselves to the comparison of lunar craters with typical terrestrial volcanoes.

A more detailed comparison of the forms leads us to very serious doubts about the volcano hypothesis. The similarity of the forms are totally superficial. The normal

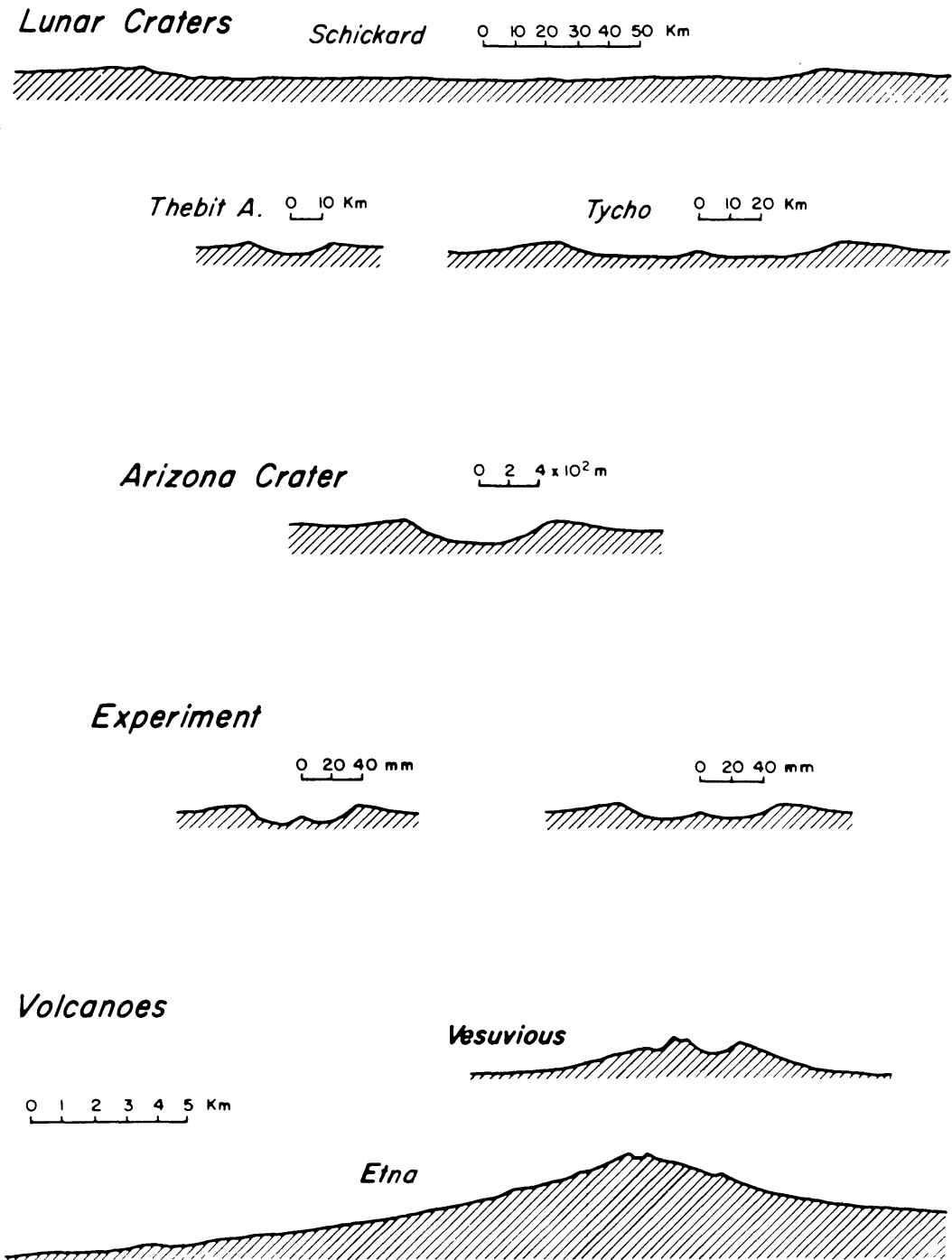


Fig. 1. Profiles of different craters (true to scale).

shape of a terrestrial volcano (here some rare deviations do not matter) is a steep cone-shaped mountain with a crater opening on the top; and the bottom of the crater is always higher than the surrounding terrain. One should read, for example, the informative summaries by J. Schmidt (*Der Mond*, p. 103, Leipzig 1856) or by von Wolff (*Der Vulkanismus I*, page 450, Stuttgart 1914). According to Schmidt, for instance, Mt. Etna has a height of 3274 m, a crater opening of 485 m and a crater depth of 105 m. This is the most common form. But there are a host of other forms that are called shield volcanoes, collapse calderas, dikes, domes, etc. These display better forms with which to compare lunar craters. The forms that provide the best comparisons, such as the maars of Eifel or the crater lakes of Italy, are the products of lasting erosion, and this we do not have on the Moon. On the Moon, the normal shape of a crater, especially the fresh ones, is that of a plate whose floor lies kilometers lower than the surrounding terrain. As a whole, a lunar crater is not a mountain at all, because the walls that are thrown up are just enough to compensate for the depression of the floor. If we would pour the material of the walls into the crater we would just fill it. These differences are not only interesting in themselves but also appear to be in contrast with the normal nature and activity of the familiar volcanoes. The place of eruption of terrestrial magmas must naturally be a mountain as new material from the depths (liquid lava, foam-like pumice or dust-like volcanic ash) wells up and is deposited. Violent eruptions occur only in rare cases such that the older deposits are blown away and the volcano itself attains a hole-like shape until a normal eruption. The typical forms of lunar craters force us to assume that the volcanism on the Moon is of another kind. But here again we lose the safe foundation of our experiences.

When we consider the central peak, the difficulties accumulate. Among the terrestrial volcanoes a few have a central peak also, like Vesuvius. It shows the awakening of the activity and the continuation of the quiescence during which the older crater was considerably eroded and enlarged. Therefore, the central peak is the highest point of the volcano; on top is the active crater which has the size and shape that is normal for volcanoes. On the Moon there are relatively more central peaks on the sunken plains' surfaces that tend to reach diameters of hundreds of kilometers. They never reach the height of the surrounding, supposedly older, ring walls and generally not even the level of the surrounding terrain. A normal crater opening which is supposed to be there, has never been seen on top of these central peaks. When the ones that are in the limits of our optical instruments are present, their diameters rarely exceeds 50 m. Therefore on one side we have to form an additional hypothesis saying that the volcanic forces on the Moon create not mountains but flat, plate-shaped depressions of huge dimensions. On the other side, we must now make another additional hypothesis which states that in the case of central peaks only such craters form which are smaller than the terrestrial ones. Thus, here again we have to abandon our comparisons with terrestrial volcanoes and go over to processes about which we have no experience. But that means that the volcanic hypothesis is not a sound one.

If we compare the sizes, this would be even clearer. Here we compare exactly identi-

cal features on two terrestrial bodies of which the Moon is the smaller one. Here we do not carry over a laboratory experiment to other dimensions. Therefore, we would expect a far reaching agreement not only of forms but also of sizes. If we agree that there must be a systematic size difference between the volcanic features of the Earth and of the Moon, the ones that are on the Moon must be smaller.

If their mountain-like forms are considered the Earth volcanoes are of considerable dimensions, but the Moon lacks these. The terrestrial volcanic craters, on the other hand, rarely reach a diameter of one or more kilometers. It is extremely rare to encounter volcanic craters with diameters of 10 km or more like Askja in Iceland [9]. When we compare the sizes of the lunar craters, we come to absurdities, because here we see an uninterrupted series of features ranging in size from the limit of resolution to the size of many kilometers. The typical and most striking features have diameters ranging between 50 and 200 km. We give the large diameter end of this long series after Franz: [10]

	λ	β	Diameter (km)
Funerius	+60°	-36°	124
Phocylides	-54	-52	124
Maurolycus	+14	-42	124
Posidonius	+29	+32	124
Pythagoras	-63	-63	140
Alphonsus	- 3	-13	143
Endymion	+53	+54	146
Vendelinus	+61	-16	149
Cleomedes	+57	+17	149
Boussignault	+69	-50	155
Stoffler	+ 7	-42	158
Maginus	- 6	-50	158
Langrenus	+61	- 8	158
Ptolemaeus	- 2	- 9	161
Petavius	+59	-25	174
Gauss	+79	+36	183
W. Humboldt	+81	-27	189
Schiller	-38	-52	192
Riccioli	-76	- 3	192
Schickard	-54	-44	273
Clavius	-15	-58	248
Grimaldi	-67	- 6	254

But these are indeed inseparable from the following ones:

	λ	β	Diameter (km)
Mare Humboldtianum	+80°	+60°	300
Otto Struve	-75	+23	310
Bailly	-70	-68	310

With those figures we have already reached the dimensions of Mare Crisium with a diameter of 450 to 550 km. It is impossible to separate this feature with almost circular peripheral mountains having steep interior slopes and gentle exterior slopes from the above mentioned crater seas and ring mountains. And with this step, we reach the greatest insurmountable difficulty of the volcano hypothesis. Also, those seas other than Mare Crisium, like Mare Serenitatis with a diameter of 700 km, and Mare Imbrium with a diameter of a little more than 1000 km, which are surrounded by almost circular peripheral mountains, cannot be excluded from the series. Basically they are also lunar craters and therefore must have originated in the same way. The supporters of the volcanic hypothesis naturally object to this conclusion, but their arguments are not satisfactory. The absence of a central peak in the seas, a fact that was put forward by von Wolff, cannot separate those from the real lunar craters because a great number of the latter do not possess a central peak either. Another objection, made by Franz, states that the ring mountains of Mare Imbrium and Mare Serenitatis are not complete. This objection also is unsound because there are pear-shaped objects among the lunar craters. In these pyriform craters, generally only one side of the crater is developed (in the impact hypothesis this is explained by oblique impacts). In the case of the smaller Sinus Iridum, only that part of the ring wall is preserved which was on the firm crust; whereas, the rest of the ring wall which was in the then liquid magma of Mare Imbrium either did not form at all or not preserved

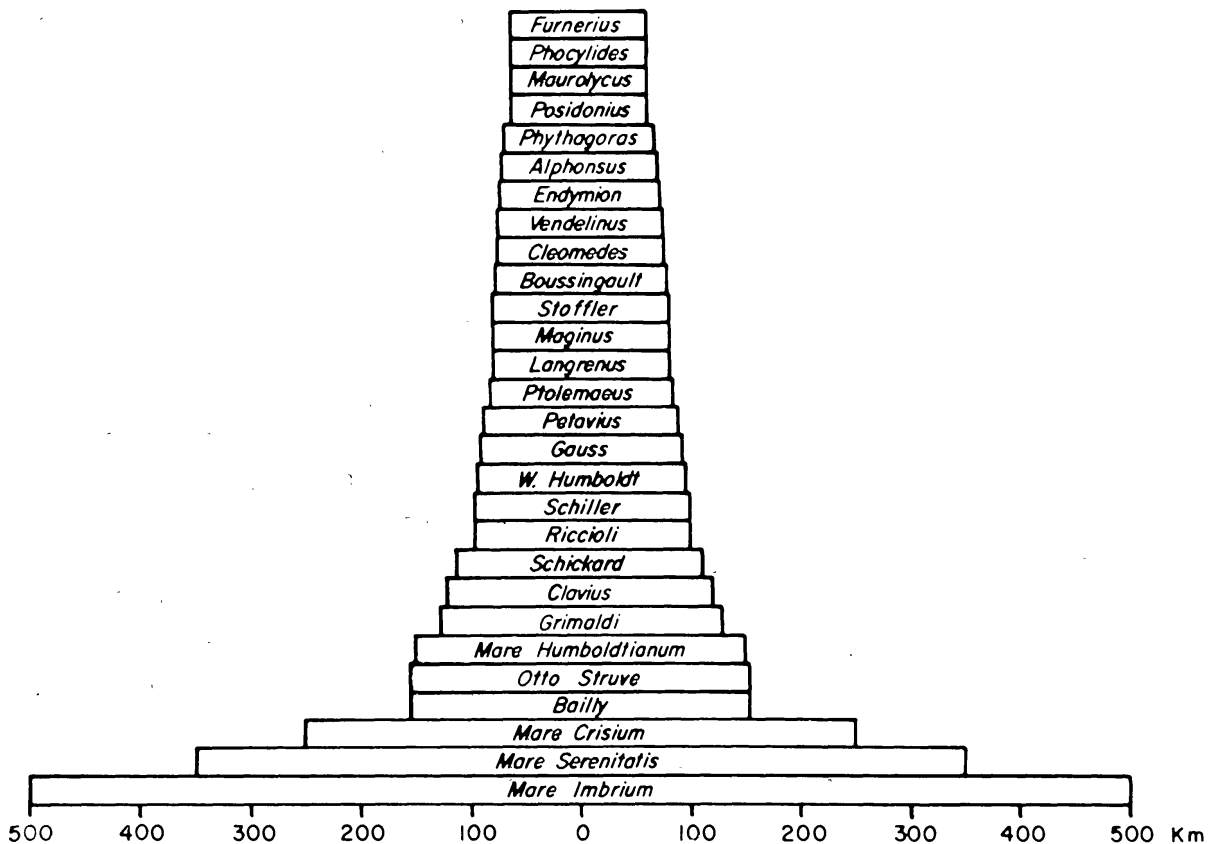


Fig. 2. Diameters of the largest craters.

and melted back. In order to show the gradual change in size all of the above mentioned craters are schematically drawn from largest to smallest. It would be ridiculous if we try to separate the lowermost steps of this ladder and try to explain their origins in a different way from the upper ones. As we said above, even E. Suess, although himself a vulcanist, did not attempt this. He did not realize, however, that the lowermost members of the series cannot be explained by the same volcanic hypothesis of his that explains the uppermost ones.

In my opinion, the above reasoning is positively convincing, for the volcano hypothesis cannot possibly explain these facts unless it makes the already rejected supposition that the volcanic processes on the Moon cause totally different activities.

Here we can end the review of the volcano hypothesis as what we have said is more than enough to reject it. But for the sake of completeness let us take a look at the distribution and frequency of craters and terrestrial volcanoes.

On the Moon a grandiose arrangement of craters is recognizable. As first pointed out by Franz the large seas, especially the Mare Fecunditatis, Tranquillitatis, Serenitatis, Imbrium, Oceanus, Procellarum, Grimaldi and Mare Crisium are all on a belt which intersects the present equator of the Moon at angle of approximately 21° and which probably corresponds to the old equator. At the poles on the other hand, as suggested by the high albedo and the general appearance of these terrains, the melting processes, which are so common in the zone of the seas, are lacking. The arrangement of the individual craters, however, shows an irregularity which was emphasized by many authors. The younger craters seem to be scattered without any apparent rule on the old ones, and the pre-existing old craters do not seem to have affected the location of the younger craters.

On the Earth, there is no known dependence of the volcanoes on geographical latitude. The volcanoes of Alaska (60°) and of Antarctica (77°) are constructed just like the tropical volcanoes of Indochina, South America and Africa. Even the large basalt sheets of Iceland are not different from those of the east of Abyssinia, under the latitude of 10° . On the other hand the arrangement of terrestrial volcanoes does not present an irregular picture. Here a new volcano's place will be determined by the present volcanic areas; therefore, there is no chance to form a Chaos of craters on Earth like on the Moon. The volcanoes on Earth mainly relate to the areas of tectonic movements. This is, of course, easy to explain, as in these areas such pressures are created as to push the magma inclusions of the lithosphere to the surface. So the volcanoes, on one hand, accompany the zones of young fold-mountains of the Cordilleras and the Alp-Himalaya system; on the other hand, they follow the fracture zones of the central seas of the West Indies up to Indochina and the continental margin of East Asia. Through growing geologic knowledge concerning the enormous horizontal pressures that created the mountains, and which are expressed in the form of large thrust sheets, and through new geophysical studies revealing the horizontal movements of the continents, new views on the system of those tectonic movements are being developed [11]. According to these ideas the continental plates are the compressed remnants of a lithosphere that once covered the whole Earth. The deep

sea floor represents the Sima-sphere on which the continental plates are floating. They are sunk into the Sima 95%. This long process of continual compression of the remnants of the lithosphere causes the eruption of the baryspheric inclusions which accompany the process. As the size of the Moon is much smaller, it is doubtful whether the crust of the Moon also has experienced such processes or if it is still undergoing them. In fact, on the Moon there are no such features which we can compare with the continental areas and the fold mountains of the Earth. Though the lunar seas resemble the deep sea basins of the Earth and we can even recognize a small continental drift of the northwest peripheral area of Mare Imbrium towards the interior of the sea, such events play a very insignificant role on the Moon. Therefore, according to our present knowledge on the nature of the volcanoes, it is at least doubtful whether we can expect to see them on the Moon. There is no way, however, that we can explain the incredible abundance of the lunar craters with our knowledge of terrestrial volcanoes. Inasmuch as the face of the Moon is covered with craters to such a degree that it seems doubtful to be able to find a single point which at least once has not been a part of the floor of a crater. The volcanoes on the Earth cover a negligible area of the Earth's crust and with the present size of volcanic craters it would be either extremely difficult or simply impossible for an astronomer on the Moon to detect those even with the largest telescope. Who knows if such Moon astronomers would know anything about the existence of the terrestrial volcanoes? On the Moon, on the other hand, the craters represented in every size up to the giant dimensions of the seas are not only the most typical and most common surface forms, they are, as a first look would reveal, almost the only forms!

I do not understand how one cannot come to the following conclusion when one compares the Moon with the Earth: The forms are fundamentally different; therefore, the origins also should be different. The contradiction is so flagrant that the next generation will only laugh at our desperate experiments with which we try to establish an equality between the Moon and the Earth.

5. The Previous Presentations of the 'Impact Hypothesis'

There is a comprehensive but less systematic literature on the impact hypothesis.

It was presented in 1828 by the astronomer Gruithuisen [12] of Munich (see the quotation on page 215). However, there are other fanciful explanations in the writings of this author.

The privy councillor of the mining board, Althans, observed that artillery projectiles create crater-like holes on armour and concluded that the crust of the Moon was able to produce similar impact craters after it had cooled [13]. He is said to have produced an artificial impact crater with a central peak through impacting with shrapnel a variety of plaster composed of slaked lime, cement and gypsum [14]. The formation of the central peak seemed to Althans to be caused by the rebound wave. This idea is encountered in the works of the later supporters of the impact hypothesis but rejected by the present author based on his experiments. In 1839, Althans published

a paper in which he tried to explain the origin of terrestrial ring mountains, like that of Bohemia, through impacting [15] – an endeavor accepted by some supporters of the impact hypothesis.

In 1873, Proctor explained the numerous small lunar craters through impacts of meteoritic masses which hit the then still hot and plastic surface [16].

The architect Meydenbauer explained the impact hypothesis in 1877 and produced small impact craters by scattering a knife's tipfull of dextrin on powder of the same material. Although these craters also had central peaks Meydenbauer did not make any effort to explain them. He thought that the surface of the Moon is covered with dust – or sandlike material and concretions of the same material had fallen on it. The seas he peculiarly views as masses of molten sulphur and phosphorus. During a later meeting (1906) he made the daring proposal to utilize the impact hypothesis for terrestrial geology [17]. Meydenbauer's experiment was later modified by Ahlsdorf [18]. He used *Lycopodium* powder on which he bounced elastic caoutchouc or wool projectiles at various angles.

Contemporaneously with Meydenbauer, and like him without any knowledge of his predecessors, the architect August Thiersch also supported the impact hypothesis in a paper that he wrote together with his father, Heinrich Thiersch, professor of Theology, first in 1879 under the pseudonym 'Asterios' but later in 1883 under his own full name [19]. Thiersch believed also that Mare Imbrium was formed by impact: "Through the impact of a falling body of considerable dimensions, a flood wave was created which broke the crust of the moon for great distances and threw the debris to the standing periphery of the depression." About the nature of the impacting body he writes the following:

"Like Saturn, the Earth could also have had a ring of moons around it; on a smaller scale, however. Through aeons the largest of these, our own Moon, might have attracted and assimilated those." Like Gruithuisen, Althaus and Meydenbauer, also Thiersch tried to explain terrestrial mountain formation with the impact hypothesis.

In 1892, the geologist Gilbert gave a presentation of the impact hypothesis which is worth reading. In this paper the volcano hypothesis is very carefully examined and rejected. The melt features of the seas were produced by the evolution of heat caused by the impact, and furrows by the radial forces; the rays are erroneously viewed as scattered liquids. Likewise, the explanation of the central peak through rebound is not sound. Grooves are interpreted as the result of the blasting of the crust through neighboring impacts. Also, Gilbert believes that the Moon formed from a ring of solid particles that surrounded the Earth and resembled the ring of Saturn. When meteorites are considered as the causes of the craters, then the craters should have an elliptical form rather than a circular one. Here we will give the result of the calculations of Woodward and compare them with Gilbert's own measurements on the ellipticity of 120 lunar craters [20].

E. H. L. Schwarz believes that the Earth also was heavily bombarded but the impact places are not recognizable anymore. He got this idea from the observation of a body of lava (almond stone-melaphyr) in South Africa which is completely sur-

rounded by sedimentary rocks so that any fissure or pipe does not seem to exist to feed the lava. Schwarz concludes from this that the metaphyr body and similar occurrences formed through impacts from space during geologic time. This supposition, in regard to the impact experiment about which we will talk shortly, at least seems untenable [21].

In 1903 N. S. Shaler extended Gilbert's views. He believes there must be a tremendous evolution of heat following the impact. The melting features that are recognizable in many places must be observed at least as consequences of the impact. Especially the melting of the interior part of the seas can thus be explained [22].

Nearly at the same time, Romanes ascertained the fact that heating through impact does take place. He shot a lead plate with bullets and showed that the periphery of the bullet hole became red hot for a short time. Romanes reached the erroneous conclusions that the atmosphere protects the Earth, in opposition to the objection that similar features that should form in the Earth's surface if the impact hypothesis were true. But this shield is only effective for the small objects. The objects with dimensions that are necessary to form the lunar craters would not be stopped by the atmosphere. It becomes easier to understand this when we think that the atmosphere forms only a very thin layer on the Earth's surface. Additionally, the meteorite crater of Arizona is a striking proof of the mistake in Romanes' observation. He considers the ray systems as dust, but in regard to high albedo he makes the unnecessary supposition that they must be crystalline [23].

In 1907 H. Martus, the famous author of *Astronomische Geographie* gave a new presentation of the 'impact hypothesis' [24]. Following reasoning similar to Gilbert's, he states that if the craters are of impact origin then all of them cannot be circular. Here he makes an undoubtedly incorrect assumption that the diameters of lunar craters correspond exactly to that of the falling object. He examines this problem by measuring numerous craters on Neison's map of the Moon, and he reaches the surprising conclusion that lunar craters are circular only in the middle part of the near side of the Moon and as we proceed from the center towards the sides they assume an egg shape and the long axis always points to the center! This conclusion seems very likely to be the result of the fact that on Neison's map the peripheral craters are not drawn with enough perspective shortening. For the features which are at the outermost side, Martus himself admits the mistake and therefore concludes from his observation: "They are drawn at a favorable libration. When they were drawn on the map, though, the western-most and the eastern-most ones are not shortened enough to show how they would look if they were at the center of the map. So the length measurements on the map are considerably erroneous." In my opinion, however, the explanations of Martus, that the same systematic mistake is not similarly made on Nielson's map are not convincing. This gives a much simpler explanation than the one Martus is trying to give.

Like Gilbert, Martus interprets the ray systems as material that was molten and spread by the impact. This material was later crystallized and the crystal faces are now reflecting the sunlight. This is, however, highly improbable because lapilli and

lava streams do not show any such crystal faces and, in contrast to the ray systems, they have a very low albedo.

In 1913, the volcanologist Johnston-Lavis came to the conclusion that the closer we compare terrestrial volcanoes with lunar craters the more impossible becomes the volcano hypothesis, and he supported the impact hypothesis. He considered the ray systems as cracks, an opinion which we cannot share [25].

With the above mentioned works we have not exhausted the literature on the impact hypothesis in any way [26]. A complete summary would be difficult because of the scattered literature and would require historical studies which are more comprehensive than what I have intended to do.

6. My Own Experiments on the Impact Hypothesis

From the literature reviewed above, the great uncertainty which makes it more difficult to better conceptualize details of the impact process, and which is the source of many errors and objections, is evident. This uncertainty is due to our lack of experience with the processes caused by impact and with the features that are associated with it. The few experiments made in this field are very unsystematic and cannot be used to support the hypothesis. In order to help the situation, I performed a series of experiments on impact craters in the Physical Institute at Marburg in the winter of 1918/19. The results will be reviewed briefly as follows: [27]

As material, I used cement powder both for the target surface and the impacting object. The reason I used such a weakly coherent powder is because the impacts were created by hand power, that is the force of the impacting object was reduced considerably compared to the lunar processes. If one wants to obtain similar forms in spite of this small force then one must also diminish the molecular force of the rock resistance that is overcome by the impact force up to the crater limits, on the same scale. Hence, such a powder with a small degree of cohesion. Therefore it cannot be concluded from my experiments that the surface of the Moon is covered by powder-like material. The powder in the experiment corresponds to the solid rocks on the Moon which are similar to the ones on Earth. Cement was especially advantageous as it is possible to harden the resulting craters without causing any change in the forms. In order to do that, water is very carefully sprayed onto the surface. The next day when the surface is hardened the whole is saturated with water. An eating-spoon was always used to throw the powder. Most of the craters were formed by a half-spoonful of powder. The largest with a diameter of 12 cm was created by an overfilled spoon. When the target was too tightly packed no craters formed. When it was loose enough, then crater-like depressions formed. In the beginning, I obtained craters without any central peaks with this method. Finally, however, good central peaks were obtained. When the central peaks formed the target was, by chance, in very shallow paper-boxes, that is, the thickness was only about $\frac{1}{2}$ to 1 cm. This led to the important observation that when the thickness of the ground was not exceeding $\frac{1}{10}$ of the diameter of the crater, a central peak always was formed. As these thin cement pieces were

broken when they hardened, a layer of cement powder a few centimeters in thickness was laid under them and pressed by means of a piece of paper; it behaved like a firm underlayer. Upon this layer, was spread a loose layer of cement powder of a $\frac{1}{2}$ cm thickness. With such targets, a series of craters were obtained that obviously resemble the lunar craters as seen in Figures 3 and 4 on Plate I.

In order to establish this similarity quantitatively, the profiles of 18 craters having a central peak were measured very carefully. These measurements led to the following figures. d stands for the diameter, w is the height of the ringwall, the level of the crater floor is b , and the height of the central peak is z . The heights are relative to the surrounding level. (See Table I. All figures are in millimeters.)

TABLE I

	d	w	b	z	$w-b=T$	$z-b=h$	T/w	d/T	T/h
	41	4.5	-3.0	1.0	7.5	4.0	1.7	5.5	1.9
	50	4.0	-3.0	0.5	7.0	3.5	1.8	7.1	2.0
	52	2.0	-9.0	-6.8	11.0	2.2	5.5	4.7	5.0
	53	4.5	-3.5	-0.5	8.0	3.0	1.8	6.6	2.7
	53	5.8	-5.2	-2.7	11.0	2.5	1.9	4.8	4.4
	55	3.9	-8.9	-6.9	12.8	2.0*	3.3	4.3	6.4
	56	1.3*	-5.3	-2.3	6.6*	3.0	5.1	8.5	2.2
	58	4.0	-12.0	-9.5*	16.0	2.5	4.0	3.6*	6.4
	58	7.0	-4.0	-1.0	11.0	3.0	1.6*	5.3	3.7
Average of the 1st Part	53	4.1	-6.0	-3.1	10.1	2.9	3.0	5.6	3.9
	61	2.2	-6.3	-2.8	8.5	3.5	3.9	7.2	2.4
	62	3.5	-5.0	-3.0	8.5	2.0*	2.4	7.3	4.2
	65	3.0	-5.0	-0.5	8.0	4.5	2.7	8.1	1.8*
	68	3.6	-5.9	-1.9	9.5	4.0	2.6	7.2	2.4
	80	9.5	-6.0	-2.2	15.5	3.8	1.6*	5.2	4.1
	84	9.5	-9.5	-2.5	19.0	7.0	2.0	4.4	2.7
	97	5.8	-12.2*	-3.7	18.0	8.5	3.1	5.4	2.1
	98	6.0	-3.5	0.5	9.5	4.0	1.6*	10.3	2.4
	122	9.0	-9.5	-4.0	18.5	5.5	2.1	6.6	3.4
Average of the 2nd Part	82	5.8	-7.0	-2.2	12.8	4.8	2.4	6.9	2.8
General Average	67	5.0	-6.5	-2.7	11.4	3.8	2.7	6.2	3.3

The depth of the crater, $T=w-b$, the height of the central peak $h=z-b$, also the ratio of the crater depth L to the height of the ring wall T/w , of the diameter to the crater depth d/T and the depth of the crater to the height of the central peak T/h are given in the left columns. The whole series is divided into two groups according to the size of the craters. In every column the largest value is printed in bold face type, the smallest is indicated by an asterisk.

The average values and the values of s specific crater (one before the last, the same one that is shown in Figures 3 and 4) are drawn on profiles in Figure 1, page 216.

Now we can compare these figures with the ones that are compiled by H. Ebert for 92 lunar craters [28]. Of these 33 will have no central peak, 40 with central peak but central peak not measured, and 19 with measured central peaks.

In our experiments, the average value of the ratio of the diameter to the crater depth d/T is 6.2, in the case of smaller craters having an average diameter of 53 mm. it is somewhat smaller, namely 5.6, in the case of larger ones with a diameter of 82 mm it is a little larger, 6.9. The value 7 was exceeded seven times and the maximum was 10.3. In the case of lunar craters, 7 is the smallest value of these ratios, in nine cases it stays under 10. The most common value is 17, and the maximum reaches 70. Such high values only are encountered in crater seas or similar ring mountains, whose crater depths were considerably diminished by the lava floods. These forms with melting features cannot be compared directly with our experimental craters. This special situation of the large lunar craters is marked by the regularity discovered by Ebert: the crater depths adjust themselves to a constant of 3.5 km which is not dependent on the size of the crater any more and which apparently corresponds to the isostatic height difference between the solid Moon crust and the (then) liquid lava body. This is similar to the level differences between the continental areas and the deep sea floor on the Earth. Our experiments agree satisfactorily with the smaller lunar craters, which are not filled by lava. On the Moon d/T grows with the size of the craters [29].

The agreement between the other values is even better. For the ratio of the depth of the crater to the height of the walls, T/w , which is always 1 in the case of terrestrial volcanoes, we obtained the average value of 2.7. Ebert gives it as ranging between 2 and 3 for lunar craters. Our experimental values vary between 1.6 and 5.5, on the Moon the range is from 1.1 to 4.4.

Furthermore the ratio of the depth of the crater to the height of the central peak, T/h , is 3.3 in our experiments. That is, the central peak rises only to the height of $\frac{1}{3}$ of the crater depth. For the Moon Ebert found this ratio to be 2.9. In our experiments the individual values vary between 1.8 and 6.4, on the Moon between 1.5 and 9.4. In both cases the central peak never reaches the height of the ring walls and it exceeds the level of the surrounding terrain in 6 cases (among 19) on the Moon and in 3 cases in our experiments (among 18). On the average, the top of the peak always remains under the level of the surrounding terrain. Ebert's statement, "therefore the central peak does not always remain under the mean level of the Moon surface" (see Schmidt, *der Mond*, p. 60) also is valid for the experimental craters.

In order to appreciate these almost total quantitative accordances fully it is necessary to point out that the experiments were performed without having any knowledge of Ebert's figures. Those were considered only after the final results of the experiments had been obtained. Under these conditions, the experiments constitute a strong support for the view, that lunar craters formed by impact.

A series of special experiments were performed to get a clear picture of the terminal

locations of the falling mass and of the structure of the central peak. For that purpose I used gypsum powder as the impacting body because it contrasts strongly with the gray cement powder of the target. In the craters that are produced by gypsum powder impacts, the gypsum formed a closed, thin layer that covered the whole interior of the crater up to the tip of the ring mountains. The ring wall itself formed from the cement which was radially pushed outwards. The gypsum powder covered only the interior slope thereof and ended at a structural break which showed that the ring wall was originally higher when it first formed, but the uppermost part slid toward the outside. That explains the existence of many individual gypsum particles that are found attached to larger cement particles far outside of the crater. These conditions show that the extra mass of the ring mountains is equal to the mass removed from the crater, a fact which has already been reported from lunar craters by Schröter. The impacting body plays an unimportant role because of its spreading as a thin sheet and the mass of this addition is nearly compensated by the material which is thrown out. Resulting surplus of matter or deficiency of matter is determined by, among other things, the velocity of the impact. Ebert's idea of the more frequent occurrence of such mass deficiencies being an argument against the impact hypothesis is therefore unsound. He found that in 28 of the 92 lunar craters, there is a surplus of mass, in 64 of them there is a deficiency. I would doubt whether it is possible to draw a conclusion other than that such surpluses and deficiencies would cancel each other, as expected from the impact hypothesis.

The experiments also can give us information on the structure of the central peak. When a few craters with central peaks were cut to show the profile it was observed that the gypsum layer had a uniform thickness throughout the whole area of the interior. On the central peak, it was only a little thicker. The central peak was, therefore, composed not only of the impacting material but mainly of the material of the target which was only covered by a thin layer of gypsum. A tin layer put between the tightly packed lower layer and the thin, loose upper layer showed that only the upper layer contributed to the formation of the central peak (see Plate II cross section in Figure 5). The tin layer runs undisturbed under the central peak. In the ring-shaped deepest part of the crater the loose upper layer of cement disappears and the gypsum lies directly on the tin layer. From this we can draw a clear picture of the formation of the central peak. The vertically falling object loses its coherence as it hits the target. Its small parts gain radial acceleration and hollow out the circular crater depression by pushing out the target material. The cone-shaped central peak, on the other hand, is composed of that part of the target material which, due to its central position, gained no radial acceleration but on the contrary was compressed. Thus, it is easy to see why the central peak never rises about the level of the mean surface altitude and usually stays below it. It was not heaped up but reformed. Therefore, an important characteristic of lunar craters, which we also found in our experiments, is explained.

The reason for the formation of the central peak, that the existence of a firmer underlayer is reached by the deepest parts of the crater, can now be understood. If it

is absent from the center, then the center of the target can be pushed downwards. On the Moon the craters with no central peaks, especially the ones in the seas, tell us that here there is no firmer underlayer. The craters that are formed after the complete cooling of the lava of the seas should show such central peaks.

The experiments also produced other features that may be viewed as support for the impact hypothesis. Sometimes, apparently through the partition of the impacting body, a central chain formed, instead of a central peak. In such cases the ejection of the target material was more pronounced in perpendicular directions to the central chain, so the whole structure gained a bipolar appearance as shown in Figure 8.

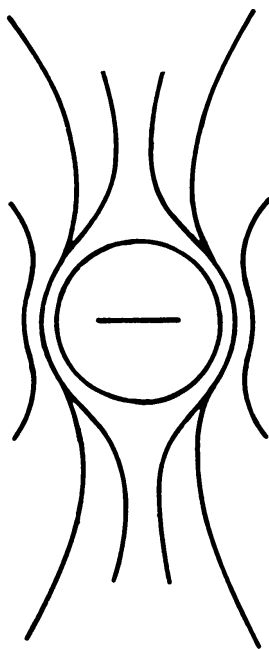


Fig. 8. Schematic diagram of an impact structure showing a bipolar structure and a central chain.

In the direction of the central chain, the concentric ring wall structure was dominant. Perpendicular to the central chain, radial structure of the ejected material was observed. One of these craters is shown in Figure 6. Only during the experiments I became aware of the possibility of forming such craters. As we know the same structure is observed in the lunar crater Copernicus. In the E-W direction is the concentric structure, in the N-S direction radial structure prevails. The direction of the central chain is, as expected, E-W.

Another series of experiments were performed with viscous cement pulp. Here again the material was used both for the target and for the impacting body. Among the resultant craters, some had a striking similarity to the lunar crater Archimedes. The ring wall was double, like that of Archimedes, and in the interior ring it was composed of the material of the impacting body. This material covered the entire floor of the crater as a thin sheet and terminated in the form of the interior ring. The exterior ring, on the other hand, was composed of the material that had been pushed

outwards. Here nothing was ejected. These experiments seem to confirm the obvious conclusion that the crater Archimedes formed when the lava of Mare Imbrium had not yet cooled completely.

Furthermore, pear-shaped craters were obtained by oblique impact. Also crater rows and furrows were produced, which resembled the corresponding features of the Moon, by spraying the contents of the spoon.

In order to imitate the dust rays of the ray systems, I threw a half a spoonful of gypsum powder onto a black pulp. Then the rays of gypsum dust, which commonly reached a length of more than 2 m, were deposited in a very similar form to the lunar features. Here no crater was formed but the other experiments had already shown that such ejection of material does happen when craters form.

7. The Meteorite Crater of Arizona

Our knowledge concerning impact craters was increased recently from another direction, namely by the studies on the crater-shaped feature, the so-called Coon Butte, in the northern part of central Arizona. Since the first detailed description of A. E. Foote [30] which appeared in 1891, American geology developed a comprehensive literature on the subject and the facts concerning the crater were well-presented especially by Barringer [31] and G. P. Merrill [32].

The diameter of the crater is 1150 m, the wall height is 40 to 50 m above the surrounding terrain, the depth of the crater is 170 m. Thus the bottom of the crater is 125 m below the level of the surrounding terrain. The approximate profile is given in Figure 1 on page 216. The nearly vertical interior slope of portions of the ring wall and the borings, which we shall talk about later, revealed that the surrounding terrain is composed of a 50 m thick red sandstone, an 80 m thick bed of limestone underlying the red sandstone and under the limestone an at least 300 m thick white sandstone. All of these are undisturbed, horizontal layers. In the crater walls, on the other hand, the beds are upturned and pressed outwards from the center. Numerous broken pieces of sandstone and limestone were thrown as far as $6\frac{1}{2}$ km away from the crater. The sizes of these pieces generally decrease with increasing distance from the crater. Within a diameter of 1 km, blocks with diameters 20 to 30 m were found. Among the ejected material, as well as within the crater, powdered sandstone was found. This 'rock flour' comprises 15 to 20% of the ejected material. Within the crater there are insignificant traces of melting of the rock.

Naturally, geologists hesitated to explain this crater as an impact feature rather than a volcanic one. But it happened that far and wide no trace of a volcanic rock had been encountered. The borings within the crater did not reveal such rock either. Furthermore, a boring through a debris zone here revealed only undisturbed horizontally layered sandstone. Additionally, since 1866, meteoritic iron discoveries had been made within the crater and in the surrounding area. Some of the individual pieces weigh more than 500 kg. With the irregular pieces, which are the most common, there are found also iron spheres with crusts up to a weight of 20 kg. Their

structure seems to indicate that they are melted iron drops similar to lapilli. Also in the bored debris zone, meteoritic iron pieces were found down to 200 meters. The total weight of the collected iron pieces amounts up to 15000 kg.

Under these conditions the assumption of the volcanic origin was abandoned, and today there is general agreement that the feature is an impact crater that was formed by a big iron meteorite or a group of such meteorites. The diameter of the meteorite is thought to be 150 to 200 meters.

Because it was hoped to find an even larger, economically useful iron mass, 28 borings were undertaken in the central part of the crater. One of these went down to 300 m. The result has already been mentioned. The hoped for iron mass was never found. The idea, put forth by several authors, that the impact was an oblique one and therefore the iron mass must be under the southern ring wall seems to be highly improbable, as our experiments show that the impacting body has the tendency to spread itself superficially. The magnetic observations do not give any indication of such an iron body.

Although it is not possible to give a certain age, the lack of well-developed erosion features suggests that the crater cannot be older than several thousand years. As reported, there is supposed to be a legendary description of the event among the Indians of the surrounding area.

The significance of this natural phenomenon, which is the only known example of its kind, for the problem of lunar craters cannot be overestimated. The ease with which the impacting meteorite overcame the molecular forces of the limestone and a little looser sandstone confirms our previous observations and our selection of powder-like material for the experiments. That no central peak formed in that case is in agreement with our experimental results. The firmer limestone was broken evenly but it is underlain by soft sandstone. Therefore the firm underlayer, necessary for the formation of a central peak, was lacking.

It is highly improbable that this is the only meteorite crater on Earth. Especially the abundance of some volcanic glasses like the moldavites in certain tertiary formations of Bohemia and Moravia, australite in Australia and others seem to suggest that similar magnificent meteorite impacts occurred repeatedly, at least in the later geologic history. It should remain uncertain if geology will ever be able to find such old impact craters, probably altered by erosion. The daring assumptions in this direction made by some of the supporters of the impact hypothesis appear to be premature in the light of our present knowledge of mountain building. But based on the facts, we can say that such impacts have played an incomparably smaller role on the Earth than on the Moon where they are practically the only factor in mountain building.

8. Summary

In the above paragraphs, from a purely morphologic-empirical method we came to the conclusion that the typical lunar craters can best be interpreted as impact craters. Now we would like to consider the question – what is the nature of the impacting

bodies and why our Earth has so few traces of such things? Therefore, we have to resummarize the impact hypothesis as it appears to us.

According to Landerers' measurements [33] the polarization angle of the dark sea surfaces is $33^{\circ}17' \pm 7'$ and this is closest to that of volcanic glasses, Obsidian ($33^{\circ}46'$) and vitrophyr ($33^{\circ}18'$) and also to that of the meteoritic moldavite ($33^{\circ}43'$). We must therefore conclude, that the surface of the Moon essentially is composed of dark volcanic glass, into which light can penetrate down to a small depth. The places with higher albedo are explained by pulverization. Either the debris particles lie upon each other or they have been lithified to clastic sediments. It is known how much the albedo of a glass-like rock increases when it is fragmented or powdered. H. Ebert performed an experiment [34] with a glass block on which he spread glass powder partially and illuminated it with a light whose angle of incidence could be changed. The experiment gave the result, already known from the Moon, that when the light comes at an angle of incidence of 90° the albedo differences are extremely high, and when the angle is decreased the differences also decrease. Therefore, the ray systems appear to be of dusty material which was spread over the lunar surface during the impact. As the movement of these dust rays is composed of falling and radial advance, they tend to accumulate substantially on the near flank of an obstacle and only slightly on the other side. This can be seen clearly on the long ray that goes out from the crater Tycho and crosses Mare Serenitatis. Before going into the sea it has to cross the mountain chain of Haemus and here we actually see a considerable thickening of the ray, whereas on the far side of the crater Menelaus, which is on the northern side first it is totally absent and reappears at a little distance from Haemus on the dark surface of the sea. For the astonishingly long range of these dust rays we should take the Moon's strongly curved surface into consideration. The tangents to any point on the Moon gain altitude very rapidly and also the gravity is only $\frac{1}{6}$ that of the Earth.

The craters with dark interior surfaces, especially the crater seas and the seas that are surrounded by walls, show that in these places the solid crust is broken and the interior of the craters was filled with lava that cooled later. The crater depth of such gross features is found to be constant, 3.5 km by Ebert. The 'streaks' (Adern) seem to be the boundaries of younger lava flows. The non-walled seas are lava floods. Although their connection with the impacts is apparent, it is not directly recognizable anymore. In any event here lava covered a surface spotted by older impacts. The 'sunken' craters, discovered by Loewy and Puiseux seem to suggest that Sinus Iridum formed by an impact that occurred at a time when the surface of Mare Imbrium was still liquid. At the time of the formation of Archimedes it was still viscous, hence no dusting occurred. When the Aristillus was formed it was totally cool as in that case a central peak formed and dust rays were thrown out. The absence of the eastern walls of Mare Imbrium can be explained either by oblique impact or the extremely low viscosity of the masses that were present there. In the northwest of this sea, a part of the ring wall with attached exterior terrain broke loose and slid toward the interior of the sea, as already has been recognized by E. Suess. Here these melting processes

can be designated as volcanic and thus the formation of lunar craters can be explained as being of impact-volcanic origin. But we should not forget that the high temperatures – as will be explained below – are most probably caused by the impact itself.

In the polar regions down to the seas no trace of melting is recognizable. Here the rocks have been continuously disintegrated by new impacts of moderate size and may have a sedimentary structure. Therefore the albedo is very high (see Figure 9 on Plate III). Thus, we can assume a zonal distribution of heat also on the Moon. The highest temperatures were on the former equator of the seas (which intersects today's equator at an angle of 21°) and the lowest at the corresponding poles. The radiation of the Sun, which alone governs the heat distribution on Earth today, might have supported that heat distribution on the Moon. But the giant impacts of Mare Crisium, Mare Serenitatis, and Mare Imbrium seem to suggest that the great magnitude of heat in that region was produced by impact.

Pear-shaped craters, like Censorinus north of Theophilus are explained in the impact hypothesis by oblique impacts, furrows are explained by tangential collisions, crater rows are formed by the fall of a group of discrete bodies which were given a chain order by the gravitational attraction of the Moon. The same is valid for the twin craters. The NE–SW alignment of crater rows and furrows between Tycho and the Mare Tranquillitatis, which I emphasized elsewhere [35], can be explained by the contemporaneous impacting of a widely distributed group of smaller bodies, and not by the material thrown out of Mare Imbrium as Gilbert suggested [36]. There is no reason to discard totally the existence of real volcanoes on the Moon. The evidence of their existence, however, has not yet been found. It can be assumed that they are rarer and relatively smaller than the terrestrial volcanoes. The lunar trenches are breaks in the solid crust of the Moon and are comparable to the graben on Earth, although the graben on Earth are very rarely not attacked by erosion, whereas on the Moon that is the rule. Whether they form through the increase in volume caused by the impacts or through rapid cooling due to radiation remains uncertain.

Now we come to the question what can the nature of the impacting bodies be? The answer to this question should give information about the other question, why the Earth has such an incomparably small number of traces of impact.

It should be made clear that with these questions we surpass the boundaries of the narrower impact hypothesis. Even if we cannot say anything about the nature of the impacting bodies today we should still accept the impact hypothesis because of purely morphologic reasons. And, we must emphasize one thing: even if the speculation concerning the nature of the impacting bodies would turn out to be wrong, that would affect the validity of the hypothesis only slightly, because the evidence of the impacting is not speculative but based on empirical morphology.

The surface of the Moon itself gives us some definite clues concerning the nature of these bodies.

The confining of the largest impact features to the possible former equatorial zone of the seas, seems to suggest that the paths of the impacting bodies were not irregular but were generally within a main plane. It is reasonable to assume that this main

plane was identical with the ecliptic and, therefore, the impacting bodies belonged to our solar system. Thus, the meteorite hypothesis becomes invalid because according to our present knowledge meteorites have hyperbolic paths; therefore, they do not belong to the solar system but to the fixed star streams. This leads us to an important conclusion for the impact hypothesis; the impacting objects could not have velocities greater than a few kilometers per second, because we cannot assume too high an eccentricity for the paths of these bodies. This relatively low velocity makes it easier to explain the crater form, as already emphasized by Gilbert. The smaller the velocity the larger becomes the effect of the acceleration caused by the gravitational attraction of the Moon, and; hence, the angle of the impact becomes closer to vertical. Thus, we obtain an explanation of the prevalence of the circular craters.

It also is evident that in the zone of largest impacts the heat was greatest and then later, during the last crater building time, it radiated into the space. These observations are closer to Gilbert's assumption that the heat evolved through impacting. Before the formation of the present craters there was a much denser rain of craters, probably of larger size, and this almost continuous impacting created the Moon's own high temperature, which rapidly declined in the epoch of new crater building. What we see on the Moon today, then, is the decline of a once much more intensive and rapid process. But even the traces of the last impacts are so large, that we should admit the overall mass of the Moon has been increased considerably by these impacting bodies. Therefore, we are forced to accept the explanation that the Moon itself was built through the same process, that it is an accretion of a large number of firm bodies whose paths were going around the Sun and were close to each other [37]. This accretion process must have begun slowly at first, later reaching a culmination point. This was because the mass of the Moon and, therefore, its gravitational attraction grew and attracted the bodies more rapidly. After some time, all of the available large objects were consumed and the rate of the process slowly declined. During the culmination point, impacting was so rapid that the amount of heat evolved surpassed the amount radiated away to that the temperature of the bulk of the Moon rose – at least in the main zone of impacting probably everywhere – over the melting point of the rocks. But in the last phase of the process radiation again prevailed and the new impacts found the seas totally solidified.

Therefore, we can deduce from the facts that the impacting bodies belonged to the solar system and the Moon-building was a process of accretion. For further conclusions I cannot find any other reference point. It could have been the case that the small parts formed a sort of ring around the Earth like that of Saturn. Then the question would naturally arise: why we do not see similar features on the Earth? It is further possible that these particles had their own paths which were parallel to that of the Earth around the Sun. Then the Earth can be thought as having formed in the same way. The material of the Earth and the Moon comprised a single ring around the Sun, which was similar to that of the small planets but had a higher density. Instead of one planet, two planets were formed as a result of accretion, the smaller of which was

later captured by the larger one. Therefore, the ideas of some astronomers are confirmed that the Moon of the Earth also was captured like the moons of other planets. In the case of the much larger Earth, which was also covered by an atmosphere, impacts caused much higher temperatures and hence the decline phase fell into the high-temperature epoch. Therefore, the impacts did not leave any traces. Reaching these conclusions now, however, is too premature. The important thing is that the absence of large impact craters on the Earth can in no way be used against the hypothesis of lunar impacts.

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Notes and References

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2. G. Dahmer, 'Die Gebilde der Mondoberfläche', *Neues Jahrb. Min., Geol. u. Paläont.*, 1911, I. pp. 89–113. Also see same journal 1912, II pp. 42–44.
3. Translator's note: In the original text Wegener uses the word *Massenkraft* which I translated as 'mass force'. I believe, however, this is identical with 'gravitational force'.
4. Among 1095 altitude measurements Mädler found six peaks between 6000 and 7000 meters, 21 between 5000 and 6000 m; 82 between 4000 and 5000 m. above the surrounding terrain.
5. It is interesting to note that these ideas, among many absurdities, were clearly stated by Gruithuisen in his *Analekten für Erd- und Himmelskunde* (vol. 2, p. 48, Munich 1928). "Here we deal with totally rigid masses. The effects of gravity overcome their strength more easily as the masses become larger. The large masses would like to sink into the Moon, so its total rigidity (Kohärenz) would be like that of other heavenly bodies. Figuratively speaking, the heavenly bodies behave more like dough or soft lime as they become larger. So, even if the Moon were always as rigid as it is today it would still have a spheric shape."
6. H. Ebert, 'Ein Vorlesungsversuch aus dem Gebiete der physikalischen Geographie' (Bildung der Schlammvulkane und der Mondringgebirge) *Ann. d. Phys. u. Chem. N. F.* **41** (277), 351–363 (1890).
7. J. v. Wolff, *Der Vulkanismus*, I, Stuttgart 1914.
8. E. Suess, 'Einige Bemerkungen Über den Mond', *Sitzungsber. d. k. Akad. d. Wissensch. zu Wien* (1) **104**, 21–54 (1895). See also in the same place (1) 116, 1355, 1561 (1907) also in *Das Antlitz der Erde* III (2), s. 627. Translator's note: An English edition of *Das Antlitz der Erde* exists: *The Face of the Earth*, 5 vols. Oxford, Clarendon Press 1904–1924, translated under the direction of Prof. Sollas.
9. In his paper which will be quoted later, Gilbert gives an average diameter of 18 km (maximum 24 km.) for the terrestrial volcanic craters. Most of these, however, have been enlarged by erosion.
10. J. Franz, *Der Mond*. (From *Natur und Geisteswelt*, 90, 2nd Edition, p. 75 Leipzig 1912).
11. A. Wegener, 'Die Entstehung der Kontinente and Ozeane', 2nd Edition, *Die Wissenschaft* **66**, Braunschweig 1920.
Translator's note: The first English translation of this important work is that of the 3rd German edition (1922) and was published by Methuen, London in 1924 under the title: *The Origin of Continents and Oceans*. The translation of the 4th edition is more easily accessible: *The Origin of Continents and Oceans*, Dover, New York, 1966. Also under the same title, the same edition was published by Methuen, London 1967.

12. H. von P. Gruithuisen, *Analekten für Erd. u. Himmelskunde*, vol. 2 München, 1828 – On the other hand I do not agree that Kant's *Allgemeine Naturgeschichte und Theorie des Himmels*, which has often been quoted in this connection, is in accordance with the impact hypothesis. Also see S. Günther 'Die Entstehung der Lehre von der meteoritischen Bildung des Erdkörpers', *Sitzungsber. d. Bayer. Akad. d. Wissensch., math.-phys. Kl.*, p. 21ff, 1908.
13. K. L. Althans, 'Über Versuche, die eigentümliche Gestalt der Mondoberfläche zu erklären', *Gaea* 27, 7, 87 (quoted after S. Günther).
14. H. Archenhold, 'Zur Entstehung der Mondkrater', *Das Weltall* 18, 166–171 (1918).
15. K. L. Althans, *Grundzüge zur ganzlichen Umgestaltung der bisherigen Geologie oder kurze Darstellung der Weltkörper und Erdrindenbildung*, 1839.
16. R. Proctor, *The Moon*, London 1873.
17. A. Meydenbauer, 'Über die Bildung der Mondoberfläche', *Sirius* 10 (N.F. 5), 180 (1877) (contains only the description of the experiment with no illustrations) – 'Die Gebilde der Mondoberfläche', same place 15 (N.F. 10), 59–64 (1882), with plates – Kant oder Laplace? *Kosmologische Studie*, Marburg (Elwert) 1880 – *Kohle, Kali und Petroleum, Himmel und Erde*, pp. 390–401 (1906) (also contains plates of his experiment).
18. H. Ahlsdorf, 'Experimentelle Darstellungen von Gebilden der Mondoberfläche, mit besonderer Berücksichtigung der Details', *Gaea* 1898, p. 35ff.
19. Heinrich W. J. Thiersch and August Thiersch, *Die Physiognomie des Mondes*, An attempt to interpret the surface of the Moon in connection with the works of Mädler, Nasmyth und Carpenter, 42 pp., Augsburg 1883.
20. G. K. Gilbert, The Moon's Face; a study of the Origin of its Features, *Bulletin of the Phil. Soc. of Washington* 12, 241–292 (1892–1894); see also H. J. Klein, *Jahrb. d. Astron. u. Geophys.* 5, 33ff. Leipzig 1894.
21. E. H. L. Schwarz, 'The Probability of large Meteorites having fallen upon the Earth', *Journ. of Geology* 17, 124ff (after S. Günther).
22. N. S. Shaler, 'A Comparison of the Features of the Earth and the Moon', *Smiths. Contributions to Knowledge* 34, No. 1438 Washington 1903 (after S. Günther).
23. After a reference in *Tägl. Rundschau* of 29th of December, 1904. Unfortunately. I could not see the original work.
24. H. Martus, 'Die Gestalten der Ringgebirge des Mondes sind Zeichen seiner Entstehungsweise', *Das Weltall* 8, 73 (1907/08) – *Die Entstehungsweise der Monde der Planeten*, Dresden 1909. (Reviewed by C. Schoy in *Gaea* 45, 555ff.).
25. H. J. Johnston-Lavis, 'Systems of Rays on the Moon's Surface', *Nature* 92, 631 (1913/14).
26. Also T. J. J. See is supposed to have discussed the same problem. Unfortunately, I could not get a hold of his work on this matter.
27. A. Wegener, Versuche zur Aufsturztheorie der Mondkrater. *Nova Acta. Abh. d. Leop. – Carol. Deutsch. Akad. d. Naturf.* 106, Nr. 2, 107–117, Halle 1920– 'Die Aufsturzhypothese der Mondkrater', *Sirius* 53, 189–194 (1920).
28. H. Ebert, 'Über die Ringgebirge des Mondes', *Sitzungsber. d. Physik – med. Soc. Erlangen* 1890, pp. 171–191.
29. Ebert found this value to be equal to 10 in the craters having a diameter smaller than 28 km, 20 in the ones having diameters between 28 and 90, 32 for the ones between 90 and 120 and 40 for craters larger than 120 km diameters.
30. *Am. Journ. of Sci.* 1891, p. 413.
31. D. M. Barringer, 'Meteor Crater in Northern Central Arizona' (Reference *Am. Journ. of Sci.* 1910, p. 427).
32. *Quarterly Issue of the Smithsonian Miscellaneous Contributions*, Vol. I, January 1908, p. 265; 1911, pp. 461–498. See also *Am. Journ. of Sci.* 1908, p. 265; 1911, p. 335; 1915, p. 482 – A short German description with numerous photographs can be found in L. Waagen, *Unsere Erde*, München o.J., p. 5577.
33. J. J. Landerer, 'Sur l'angle de polarisation de la lune', *Compt. Rend.* 109, 360–362 (1889), II – 'Sur l'angle de polarisation des roches ignées et sur les premières déductions sélénologiques qui s'y rapportent', *ibid.* 111, 210–212 (1890), II.
34. H. Ebert, 'Beitrag zur Physik der Mondoberfläche', *Sitzungsber. d. Bayer. Akad. d. Wissensch., math.-phys. Kl.* 38, 150–180 (1908).

35. A. Wegener, 'Versuche zur Aufsturztheorie der Mondkrater', *Nova Acta. Abhandl. d. Leop.-Carol. Deutsch. Akad. d. Naturf.* **106**, No. 2, p. 111, Ammerung, Halle 1920.
36. According to Gilbert, the Mare Imbrium is surrounded by a radial furrow structure which covers the half of the Moon disk. The parts of the same have already been described by Beer and Mädler and also by Neison.
37. Also the present orbit of the Moon can be viewed as being around the Sun. It is never convex to the latter.