THE METEOR CRATER, ARIZONA: A CENTURY OF EXPLORATION AND DEBATES

V. L. Masaitis
Karpinsky Russian Geological Research Institute, Sredny prospect 74
St-Petersburg, 199106, Russia
<*victor_masaitis@vsegei.ru*>

ABSTRACT

The scientific research of the Meteor (Barringer) Crater (also known as the Coon Butte) started more than a hundred years ago, but the ideas of its origin were contradictory. At the beginning of the XX century, mining engineer Mr. Daniel Moreau Barringer become interested in the search in this crater for a large mass of meteorite iron suitable for an economic extraction. For twenty-seven years he carried out prospecting works persisting in the idea that the crater was formed due to the collision of the Earth with a large meteorite, though some scientists attempted to explain its origin by the ordinary geological processes. The mining accompanied by exploration provided certain data on the crater's interior and on its impact origin; however, no iron body was ever found beneath the crater's floor.

The Meteor Crater was the first on the Earth that was studied purposefully over a long period. This study allowed to elaborate some criterions of impact origin of the geological objects, to reveal the mechanisms of their origin, and to compare them with the circular structures on the other planets. All these investigations are of great importance for the development of the generally recognized theory of impact cratering.

On December 5, 1905, at a session of the Academy of Natural Sciences, Philadelphia, USA, its president Mr. S. G. Dixon has announced that two members of the Academy, D. M. Barringer and B. C. Tilghman made a "...discovery that the crater of Coon Mountain or Coon Butte… is an impact crater and not a crater produced by a steam explosion, as has been supposed since the examination made of it by members of the United States Geological Survey. They have proved, " he continued, " that the large crater and elevation known as Coon Mountain is the result of a collision with the Earth of a very large meteorite or possibly of a small asteroid, fragments of which are well known to the scientific world by name of the Canyon Diablo siderites… Mr. Barringer and Mr. Tilghman have presented to the Academy for publication two comprehensive papers in which they set forth in full their reasons for the above statements " [1].

The peculiar depression surrounded by a rim (Coon Butte, or Coon Mountain) as well as numerous fragments of iron, which were scattered on the surface in its vicinity, were well known to the Native Americans long before the arrival of the Europeans. Some naturalists who had visited this area at the end of the XIX century mentioned it too. However, only the reports, which were published at the beginning of the 1906 [2, 3] gave strong impulse to the investigation of this unusual site and to the debates regarding its origin, which continued for several decades.

The data regarding the findings of numerous iron meteorites in Arizona dispersed around deep depression have attracted the attention of G. K. Gilbert, Chief Geologist of the USA Geological Survey. A. E. Foot, who had found some tiny diamonds in the meteorite sample [4], provided this information to him. Some years earlier G. K. Gilbert had studied the Moon's surface and had an idea of meteoritic origin of lunar craters [5]. At first, G. K. Gilbert supposed that Coon Butte was of impact origin too, and this scar could be the result of a collision with the Earth of a large iron meteorite, which is buried under the crater's floor, and if that is the case, it can produce a strong magnetic anomaly. The subsequent examination of this suggestion did not prove it right and later Gilbert renounced his point of view and concluded that the crater originated due to some volcanic activity. For a long time this opinion remained an official position of the US Geological Survey. It is no wonder that Barringer's and Tilghman's statements provoked a sharp discussion on the origin of the Coon Butte.

According to the modern data [6], the Meteor Crater (35° 03' N, 111° 02' W) was formed about 50,000 years ago. The diameter of a round-shaped depression is 1,220 m, its depth – 180 m. The surrounding rim is made of ejected rock fragments. The target consists of the sedimentary Permian (Coconino, Toroweap, and Kaibab formations), and Triassic (Moenkopi formation) rocks. The layers of these formations are uplifted, and dissected by faults at the crater's wall. The depression is filled with breccia, which is made up of blocks and fragments of the target rocks, and is about 200 m thick. The breccia lens is covered with lacustrine deposits of Pleistocene age. Iron fragments of the Canyon Diablo meteorite are scattered on surface around the crater and occur inside the breccia. Tiny diamonds, which are present in this octahedrite (IAB), originated after the graphite, which was transformed into high-pressure phase due to the shock compression.

Because numerous fragments of iron were found around the crater, D. M. Barringer, mining engineer and entrepreneur from Philadelphia, became interested in the prospecting for a large mass of meteoritic iron suitable for an economic mining. He first learned about the Coon Butte on the Colorado plateau and the observations and first suggestions of

G. K. Gilbert in 1902. D. M. Barringer took into account Gilbert's idea that a large iron mass may be found under the crater's floor and had founded the Standard Iron Company even before he visited the site. The purpose of this enterprise was a commercial use of a large iron body presumably lying under the crater's bottom that also contained nickel, platinum, iridium, and diamonds. D. M. Barringer was sure that a huge meteorite, which produced the crater, penetrated deep into the country rocks and has remained there under their fragments. The mining company has soon started to drive prospecting shafts, holes, and mines. This was the first case in the history of mining, when the purpose of prospecting was the search for a cosmic body.

Observations carried out by D. M. Barringer driven by the desire to confirm his assumptions, have allowed to reveal various features of morphology and internal structure of the crater, and to make a number of important finds. For example, he has found the sandstones transformed into a rock flour, particles of the oxidized iron embedded into breccia, established the inverted stratigraphic sequence in rock fragments on the crater's rim etc. Once D. M. Barringer and B. C. Tilghman obtained all these data, they have found it fitting and necessary in the autumn of 1905 to declare about the impact origin of the Coon Butte crater that they had established. However, although the reasons in favor of the impact origin of the Coon Butte were rather serious (many of them still keep the value as criteria of impact origin of circular geological structures) the United States Geological Survey chose to ignore them.

After Barringer's and Tilghman's publications there appeared a number of articles in which the idea about the meteoric nature of the crater has undergone doubts and criticism. The history of a long discussion about the crater's origin and the opportunity of detection of the meteoric iron under its bottom have been described in detail by W. G. Hoyt [7]. Following G. K. Gilbert's opinion, a significant number of the American geologists rejected the idea about the extraterrestrial origin of the Coon Butte, though some of them carrying out personal observations recognized its validity and the absence of any attributes of the volcanic phenomena within the limits of the crater.

One of the first geologists who have visited the Coon Butte was H. L. Fairchaild who supported Barringer's opinion and suggested to rename the area into the "Meteor Crater" in the name of the nearest postal station [8]. One of the employees of the United States Geological Survey G. P. Merrill has also visited this place following Barringer's invitation. Merrill has shown that the varieties of the altered sandstone found by D. M. Barringer mark the successive phases of progressive transformations caused by a powerful impulse of pressure that acted over a very short time-interval and was accompanied by sharp heating. Merrill recognized that there is no alternative explanation of the crater's formation other than the one suggested by Barringer and Tilghman. In addition, he has pointed out the possibility of evaporation of a great volume of the collided body that would explain the absence of a large iron mass at the crater's depth [9, 10]. Merrill's conclusions concerning shock metamorphism have played an important role in further discussions of the nature of the Meteor Crater; in essence they begun the development of ideas about the transformations of rocks that underwent the impact of the cosmic body. The conclusions made by Merrill compelled Barringer to get into dispute not only with the opponents of the idea of the impact origin, but also with those supporters that agreed with the impact origin idea, but objected to the idea that a significant part of the cosmic substance remains preserved inside the crater.

After several years of prospecting and observations, D. M. Barringer has presented a detailed report that contained his objections against the volcanic theory of crater's formation [11]. He categorically declared "…the further discussion about formation of the crater is a waste of time" (p.17). Yet, various hypotheses connecting the crater's origin with a karst sinkhole, magmatic stoping, or even volcanic explosion initiated with the impact of a meteorite continued to appear in the press. D. M. Barringer sharply objected to such theories. His correspondence shows that he was not indulgent to his opponents and did not show tolerance to the persisting supporters of the idea of the volcanic origin of the crater.

On the other hand, a number of geologists and especially astronomers supported D. M. Barringer's arguments and some of them pointed out to the similarity between the Meteor Crater and the craters on the Moon. At the beginning of the XX century, the statements about the meteoritic nature of the craters on its surface have been expressed repeatedly. The idea that the impact is a fundamental process in the formation and the evolution of the Solar system and that not only the Moon, but also other planets as well undergone such impacts was expressed by an astronomer T. See [12], however, outside of any link with the Meteor Crater discussion. Many other astronomers and geologists at that time took part in the discussion about the origin of the lunar craters as well.

While continuing to drill and to sink mines in the search of an iron deposit, D. M. Barringer actively corresponded with many scientists. When at the depth of 419 m the drill hole came across something very hard, he explained the breakage, which occurred by suggesting that the bit had entered into the iron mass. D. M. Barringer insisted that the impact crater could form without any explosion and that a huge meteorite still exists somewhere underneath its bottom [13].

In mid 20th, somewhat transformed mining company began to experience significant difficulties in attracting investors and finding the means to carry out further work. There were mining related problems as well. At this time, many astronomers emphasized a high probability that the main part of the iron meteorite has been evaporated at the time of explosion, which caused the formation of the crater. Based on calculations that dealt with energies necessary to eject shattered bedrocks the astronomer F. R. Moulton estimated the possible size of the meteorite, which formed the crater. He pointed out that the initial mass of the collided body did not exceed 500,000 tons and that its significant portion must have been dispersed during the impact and the explosion. These estimates (they have not been published) finally destroyed hopes for the detection of large iron bodies inside the crater. F. R. Moulton has sent his conclusions to the president of the mining company at the end of November 1929. D. M. Barringer died of a heart attack on November 30, 1929, shortly after.

In spite of a variety of additional arguments in favor of an extraterrestrial origin of the Meteor Crater, which were published in different editions, only a small number of researchers have recognized the impact theory up until the end of the 1940th. During this period, only astronomers almost unconditionally recognized the meteoric nature of the crater, especially in connection with further development of the theory of the formation of the lunar craters and the publication of the book by R. Baldwin [14], where this theory was substantiated in detail.

A serious blow to some attempts to explain the crater's origin by essentially terrestrial processes that continued to appear in the press was delivered by a long-term work of H. H. Nininger [15]. In the vicinity of the crater and on its rim he discovered numerous particles of slag formed by fusion of various local rocks that contained magnetite spheroids enriched with cobalt and nickel. The latter could occur only from fusion or condensation and oxidation of the material of the collided body. Particles of glass slag were named impactites, in accordance with the meaning of this term offered by G. B. Schtenzel and for the first time applied to products of impact fusion by V. Barns [16].

The renewal of interest to further research of the Meteor Crater in the middle of the last century has been indirectly connected with the study of sites of the underground nuclear tests made in the USA, and also with the beginning of the epoch of the space exploration. This interest has been realized by G. M. Shoemaker, who has seen in the simultaneous geological study of the Meteor Crater and the hollows of the underground explosions an opportunity to explore in greater detail the nature of the lunar craters. He sent several samples of shocked sandstones from the Meteor Crater for research to the mineralogist E. Chao, and very soon, the coesite has been found [17]. A short time previously this mineral was synthesized by the compression of quartz at over 15 thousand atmospheres. The other high–pressure phase of SiO_2 – stishovite, has been found in these samples as well [18]. These two finds have finished long discussions about the origin of the Meteor Crater and about the formation of the other similar terrestrial objects.

The detailed analysis of the mechanism of the Meteor Crater formation undertaken by G. M. Shoemaker showed that its formation (as well as other impact craters, including lunar) is connected, mainly, with the effect of a shock wave, instead of being a direct result of the "explosion" of the collided body [19, 20]. A little bit earlier G. M. Shoemaker took part in one of the projects on remote studying of the Moon and then begun to organize the Department of Astrogeology of the USA Geological Survey in Flagstaff, Arizona. Actually, this meant the recognition of an impact origin of the Meteor Crater by Geological Survey. G. M. Shoemaker was the participant in the Apollo program in the beginning and the middle of the 1960th at which time he together with other astronaut candidates repeatedly visited the Meteor Crater that was chosen as a training ground by the NASA. Among G. M. Shoemaker's geology students were the first astronauts who have landed on the Moon [21, 22].

Special geological and other research proceeded in the Meteor Crater in the next decades; the intentions of these studies were specification of its morphology and structure, comparison with other impact objects on the Earth and with craters of the underground nuclear explosions [23, 24], the in-depth study of the transformations of the shocked rocks [25, 26], and also modeling of the cratering processes [27, 28]. G. K. Gilbert's idea about the extraterrestrial nature of the Coon Butte, which he had prematurely rejected, has born plentiful fruits many decades later.

Strange as it may seem, but D. M. Barringer who devoted the better part of his life to the exploration of the Coon Butte inadvertently worked on his scientific opponent who was one of the first to suggest the impact origin of the lunar craters. Paradoxical as it may also seem, but it was the elaboration and the substantiation of the hypothesis of the meteoric impact defended by D. M. Barringer that was further developed and worked out in detail by scientists specializing in the field of astronomy that at the end lead his mining company to its financial demise. At the same time, various works carried out in the Meteor Crater by D. M. Barringer and later by many other researchers revealed numerous important facts regarding its interior structure and shed light on the conditions of its formation.

The value of D. M. Barringer's contribution to the creation of the basis for the geological exploration of the impact structures may have even exceeded the supposed profits, which he hoped to achieve by mining the iron mass that was never found. In recognition of Mr. D. M. Barringer's contribution to the exploration of the Meteor Crater, in 1946 the crater itself was renamed in his honor [29].

The results acquired during the research of the Meteor Crater exerted great influence on the evolution of ideas regarding mechanisms of the impact cratering, and on the elaboration of various criteria of impact origin of structures similar to this crater, including structures modified by some other geological processes. One of the main results was the identification of various mineralogical and petrographical features of shock metamorphism, which received comprehensive theoretical and experimental substantiation. In many respects due to the use of such mineralogical and petrographical criteria, the nature of a number of so-called «cryptovolcanic» or «cryptoexplosive» structures that were long a subject of debates was finally reliably determined. In the middle of the 1960th, because of the specialized research in a number of regions of the world, mainly in Europe and the Northern America, it has been shown, that some circular geological structures are in fact eroded impact craters. At the suggestion of R. Dietz, they were named «astroblemes» [30]. Further development of the geological research in this field in combination with the analysis of the remote sensing and the geophysical surveys data led to the discovery of numerous ancient impact structures on the Earth's surface, the combined number of which is now approaching two hundred. The Meteor Crater was in essence the first impact structure where the purposeful geological works accompanied by geophysical observations, drilling, and prospecting for economic minerals took place. In the second half of the last century, this arsenal of various methods of exploration of such objects, though further improved, was widely used in different regions of the world.

The first partially systematized results of such studies were widely presented at a special conference in 1966 [31]. The study of the Meteor Crater and the accompanying discussion appreciably promoted the development of separate branches of the doctrine about the impact cratering and also contributed to its formation into a new field of natural science that combined data from astronomy, meteoritics, physics of solid bodies, comparative planetology, and from various other branches of geology. The study of the Canyon Diablo meteorite also had great value; it allowed to establish abundance of some elements in space, and to develop standards of parities of isotopes of sulfur in cosmic bodies. In the middle of the 1950th, fragments of this meteorite were used to achieve first reliable estimates of the ages for the Solar System and the planet Earth.

Research carried out at the end of the last century have shown that economic mineral deposits, which were found within some impact structures, are connected with processes that had occurred in the target rocks either before the shock event, during the cratering, or at some point in a long period after formation of the impact structure [32, 33]. In a number of impact structures various ores (copper, nickel, iron, uranium, gold, basic metals), nonmetallic raw materials (technical diamonds, evaporites, combustible slates), and liquid and gaseous hydrocarbons are now found. Therefore, almost eighty years later D. M. Barringer's dreams about a possibility of discovery of economic mineral resources inside impact craters have come to fruition, although mineral deposits found in such structures have nothing to do with the remains of the meteoric substance that are found in small size craters and only as small fragments.

Widespread exploration executed during the last several decades showed that round-shaped depressions bordered with rims (they reflect the changes of morphology of their solid surfaces in the exact sense of the term "impact cratering") that form at the sites of the high-speed collisions of cosmic bodies are only one of the results of such interactions. In addition, they are also accompanied by considerable changes of the geological structure at the impact site, and by appearance of a wide spectrum of newly formed and transformed rocks – impactites and impact breccias. If the colliding body falls into the gaseous or liquid environment it produces only a short-term disturbance of these environments as was seen for example during the collision of the comet Shoemaker-Levi fragments with the outer shell of the planet Jupiter in 1994 [22]. In connection with this, in terms of etymology an earlier suggested term "coptogenesis" more precisely corresponds to the general character of the transformations that occur at such collisions [34, 35].

The ideas about the character and the consequences of cosmic collisions during the evolution of the system of bodies rotating around the Sun are now universally recognized. Impact interactions are considered a major factor of transformation of surfaces of the solid cosmic bodies (especially devoid of outer gaseous shell), and with reference to the Earth as a fundamental geological process [36], which played an essential role at an early stages of the formation of the Earth's crust and which during the subsequent epochs sporadically influenced external shells of our planet, and the evolution of biota [37, 38, 39].

Over a hundred years long history of the Meteor Crater exploration and the accompanying debates may serve as an example of the vicissitudes of scientific hypothesis that little by little was converted into the well-grounded and generally recognized theory, which became the basis of one of the fundamental lines of investigation of the Earth's and space science [40]. This history confirms once again that only firmly established and concordant observation results may reject some hypothesis, or confirm and transform it into the finalized theory. Exactly such approach allowed, on the one hand, to reject the assumptions regarding the possibility of discovery of an iron mass beneath the crater's floor, and on the other to prove the crater's extraterrestrial origin.

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