

1. Introduction



Science does not always move forward in a straight line and rarely at a constant cadence. The study of Barringer Meteorite Crater (*a k a* Meteor Crater) is a classic example. Although an immense collection of meteorites of undisputable extraterrestrial origin was gathered at northern Arizona's crater (Foote, 1891), the association was considered coincidental by many (*e.g.*, Gilbert, 1896) and nearly fifteen years passed before a serious case linking the meteorites to the impact origin of the crater was presented (Barringer 1905; Tilghman 1905). That latter effort was part of an intense mining operation at the crater to recover the suspected projectile. The works were extensive, including a reservoir in the distant Canyon Diablo, a pipeline to the crater, and camps on both the crater rim and crater floor. Sadly for investors, economically viable deposits of metal were never recovered. Sadly for science, decades passed before the implications of Barringer's work were appreciated.

There are many ways to trace the path of this story, but perhaps the best place to begin is with the mineralogist A. E. Foote, who published the first scientific report about the crater and meteorites found there. Foote's interest was piqued by a railroad executive who sent him a sample of native iron and requested an analysis. Foote deduced the sample was a fragment of a meteorite and, having been told more material existed in northern Arizona ("185 miles due north from Tucson"), promptly traveled to the site from Philadelphia. Foote and his team collected several large masses (201, 154, and 40 lbs), 131 smaller masses (ranging from 1/16 oz to 6 lbs 10 oz), and 200 lbs of oxidized meteorite fragments. After returning to Philadelphia, he received three additional large masses (632, 506, and 145 lbs). Several of the larger samples were perforated with cavities similar to the one in the spectacular Tucson ring meteorite ("Signet Iron"). The iron meteorites also contained troilite, daubréelite, carbon, and diamonds (up to 1/8 inch diameter), the latter of which were described as being mostly black and of little commercial value.

The purpose of Foote's paper was to describe the diamond-bearing iron meteorites, but he was clearly impressed with the "Crater Mountain," where the samples were found and provided the scientific community with its first geologic description. He noted an uplifted rim of sandstone and limestone dipping 35 to 40° that stood 432 ft above the surrounding plain. The crater floor appeared to be 50 to 100 ft below the surrounding plain. He further noted that he could not locate any "lava, obsidian or other volcanic products," and, thus, concluded that he was "unable to explain the cause of this remarkable geological phenomenon." He did not recognize any genetic association between the crater and meteorite irons. Nor did he add any remarks about the unusual quantity of iron meteorites. With regard to the iron oxide fragments, however, he concluded that a large iron meteorite of 500 to 600 pounds "had become oxidized while passing through the atmosphere and was so weakened in its internal structure that it had burst into pieces not long before reaching the earth."

Foote presented his paper at a meeting of the American Association for the Advancement of Science (AAAS) in Washington DC. Sitting in the audience was the chief geologist of the United States Geological Survey, Grove Karl Gilbert. Gilbert developed an immediate interest in the crater and its association with meteoritic iron. Having also recently heard T. C. Chamberlin's (1890) proposal for a new scientific method of "multiple working hypotheses," Gilbert decided to apply the principle to the origin of the crater. He posited two origins: (1) that the crater was produced by the impact of a large iron mass from space and (2) that the crater was produced by a volcanically-driven steam explosion, in which case the fall of meteoritic irons at that locality was coincidental and had nothing to do with the formation of the crater. He reasoned that if the impact of a "stellar body" occurred, it must still lay beneath the crater floor, but would be absent if the crater was produced by a volcanic steam explosion. To determine if a meteoritic mass lay beneath the crater floor and, thus, test the hypotheses, he devised several measurements that were conducted during a two week stay at the crater in November, 1891. He measured the volume of the crater

and ejected material contained in the rim: if the volumes are equal, he reasoned, then a mass did not lie buried beneath the crater floor. He also measured the magnetic field in the vicinity of the crater, assuming that a buried mass of iron would deflect magnetic instruments. While making those measurements, he also made notes about uplifted strata in the upper crater walls and the distribution of ejected sedimentary blocks and iron masses around the crater.

To compare the volume of the crater cavity and crater rim, Gilbert's team generated a topographic map with a contour interval of 10 feet, which is a remarkable achievement. It is a higher resolution topographical result than that currently available on the USGS Meteor Crater 7.5 minute quadrangle, which has a 20 ft contour interval. Unfortunately, Gilbert's map has not resurfaced and is only available in a small reproduction in his 1896 paper. (About 100 years later, David Roddy developed another 10 ft contour map of the crater that he informally distributed to some investigators. The map is available from the present author.) Using the 1891 map, Gilbert calculated that the crater cavity and the ejected rim material had the same volume, from which he concluded a buried mass could not be partially filling the crater volume. Interestingly, Gilbert did not recognize the lake sediments that partially filled the crater or discuss the change in density between the original target strata and the rim deposits, both of which affect this type of calculation. Nor does he describe the red Moenkopi Formation in the walls of the crater. His team's measurements of magnetism at the crater were negative: they did not reveal any variations in direction or intensity inside or outside the crater, leading Gilbert to conclude that a mass did not exist beneath the crater floor.

Thus, the tests of the meteoritic impact theory as envisioned by Gilbert failed. Consequently, he turned to the other hypothesis and observed that Arizona's crater "is in the midst of a great volcanic district." (See Fig. 1.1 for a modern view of the volcanic district.) He then drew comparisons between Arizona's crater and several volcanic vents around the world, including the maars in Germany that would again draw attention during the Apollo era. Interestingly, he also referred to Lonar Crater of India, which, because it occurs within the Deccan Traps, he concluded also had a volcanic origin. As we now know, Lonar Crater has an impact origin. Based on these comparisons, Gilbert erroneously concluded that of the two hypotheses the steam explosion origin for northern Arizona's crater was the correct solution. Having applied Chamberlin's principle of multiple working hypotheses, Gilbert concluded his report with a principle of his own, one that remains a benchmark of comparative planetology today (although it has an echo of uniformitarianism): "tentative explanations are always founded on accepted explanations of similar phenomena," in this case referring to the similarities he believed existed between Arizona's crater and the volcanic ones to which he alluded.

Gilbert's (1896) conclusion that the crater was produced by a steam explosion greatly influenced the geologic community, because he was one of the nation's most eminent geologists. He had already been the chief geologist at the USGS for eight years and would continue in that post for many more years. At the time of his report, he was also President of the Geological Society of Washington. Indeed, he presented his report in the form of the annual presidential address to the society, which was then published in *Science*.

Quite unaware of Gilbert's work (at least initially), Daniel Moreau Barringer independently heard about the crater and its meteoritic irons from S. J. Holsinger on the veranda of the San Xavier Hotel in Tucson (Fig. 1.2). Barringer was entranced, particularly with the potential wealth associated with a source of metallic iron and nickel. He was well-schooled in the mining industry, having already made a fortune with silver. He quickly obtained the crater property and began a series of investigations of the structure with his business partner, Benjamin Chew Tilghman. Barringer was soon in a position to challenge the conclusions of Gilbert and he produced a series of reports over a 25 year period, beginning with his first report to The Academy of Natural Sciences of Philadelphia in 1905.

Barringer obtained the property in 1903, formed the Standard Iron Company to extract the metal, and immediately began a survey and drilling operation (Fig. 1.3 and 1.4). By the time Barringer prepared his 1905 report, he had made more than ten trips to the crater.

In comparison to Gilbert's report, Barringer's paper provides a much better description of the stratigraphic units and their regional context. He also provides a series of observations that are relevant to the structure's formation. He points out that meteoritic irons are concentrically distributed around the crater, suggesting the occurrence is not coincidental, but rather tied directly to the formation of the crater. (In a later paper (1910), he also observes that the concentration of irons increases towards the rim of the crater.) He describes uplifted strata in the crater walls, which he argues were "turned out bodily by the force which produced this enormous hole." He describes a mix of underlying strata in a breccia at the crater surface and, in one location, correctly notes the inverted stratigraphy of ejected material. Barringer found that some of the meteoritic irons are buried within the ejecta and, thus, both must have formed at the same time. He notes that the largest ejected blocks are distributed east and west, indicating a plane of symmetry that he would later map to the trajectory of an impacting object. Barringer focused a lot of attention on pulverized silica that he found beneath lake sediments and in ejected material. He noted that individual grains are sharply fractured, which is inconsistent with a sedimentary origin, and inferred the silica is crushed target sandstone. In some cases, he wrote, the silica was powdered so completely that no silt or sand grittiness was detectable with one's teeth. In a companion paper, his partner, Tilghman (1905), makes similar arguments. Importantly, Tilghman also describes three boreholes that encountered iron masses buried 300, 400, and 480 ft below the crater floor, which, like irons buried within the ejecta blanket, illustrated the simultaneous fall of the irons and production of the crater.

In counterpoint to Gilbert's findings, Barringer also wrote that he was unable to find any eruptive rock or any other evidence of volcanic-related activity. He organized eight arguments against a volcanic steam explosion hypothesis and three additional arguments against any other type of volcanic action. Barringer bluntly criticized Gilbert and his conclusion of a volcanic steam explosion, writing that if Gilbert "examined the surface carefully, it does not seem possible to me that any experienced geologist could have arrived at such a conclusion." Barringer's geologic and petrologic methods trumped Gilbert's geophysical techniques and he wanted it well known. Tilghman (1905), in his companion paper, emphasized that the drilling did not encounter any volcanic material beneath the crater to a depth of 1400 ft relative to the surrounding plane, thus demonstrating there is no magmatic conduit that could have fed a volcanic steam explosion.

For Barringer and his heirs, the issue was settled: Arizona's crater was produced by a meteoritic impact. The geologic community was less receptive. In general, processes that could be described as catastrophic were ignored or abandoned in favor of uniformitarian concepts. The problem continues to plague geology, although progress is being made (Marvin, 1990).

One of the most significant series of events to affect the scientific community's perception of Barringer's thesis was a re-examination of the problem by Gene Shoemaker (1960) and the Apollo exploration of the heavily cratered lunar surface. Shoemaker drew upon new observations of crater excavation associated with nuclear explosions and developed an analytical model for the penetration mechanics of hypervelocity impact events. One of the strengths of his work was the superb geologic description he provided of diagnostic features at Meteor Crater and nearly identical features that he found at the nuclear Teapot Ess Crater: crater rims overturned in synclinal folds, upper fold limbs composed of debris that preserves an inverted stratigraphic sequence, glass in the uppermost components of the debris, and crater floors covered with breccia lenses. With Ed Chao, he later discovered evidence of the shock-metamorphic transformation of quartz in target sediments to coesite and stishovite (Chao *et al.*, 1960, 1962).

Collectively, the work of Barringer, Tilghman, Shoemaker, and Chao demonstrated the impact origin of Barringer's crater and also provided the diagnostic geologic and petrologic tools needed to recognize structures formed by similar processes elsewhere on Earth and in the Solar System. We now understand that impact cratering is one of (if not the) dominant geologic process affecting planetary surfaces.

For students interested in additional details about the early exploration of the crater, I recommend the following primary references: Barringer (1910, 1914, 1924), Fairchild (1907), and Merrill (1908). I also recommend a very nice and pleasantly concise review written by Brandon Barringer (1964) and a longer, book-length review written by William Hoyt (1987). Both of the latter reviews include details of the mining operations associated with studies of the crater's origin. For an intimate portrait of Barringer and his enterprise, the best source is a small book written by Nancy Southgate and Felicity Barringer (2002).



Fig. 1.1. Three views of the volcanic terrains in the vicinity of Barringer Meteorite Crater (a.k.a. Meteor Crater) that influenced G. K. Gilbert when interpreting the origin of the crater. The eastern portion of the San Francisco Volcanic Field is visible northwest of the crater (top panel). The stratovolcano in the midst of the field, near Flagstaff, is visible from the crater rim (lower left). Also visible from the crater rim are the basalts of East and West Sunset Mountains south of the crater (lower right).



Fig. 1.2. View of the San Xavier Hotel, Tucson, where S. J. Holsinger told D. M. Barringer about northern Arizona's crater and its meteoritic irons. This photograph (c. 1893) was taken approximately a decade before that conversation in 1902. Arizona was a territory at the time, not receiving statehood until 1912. The photograph appears courtesy of the George Mason University and should not be reproduced further without permission.

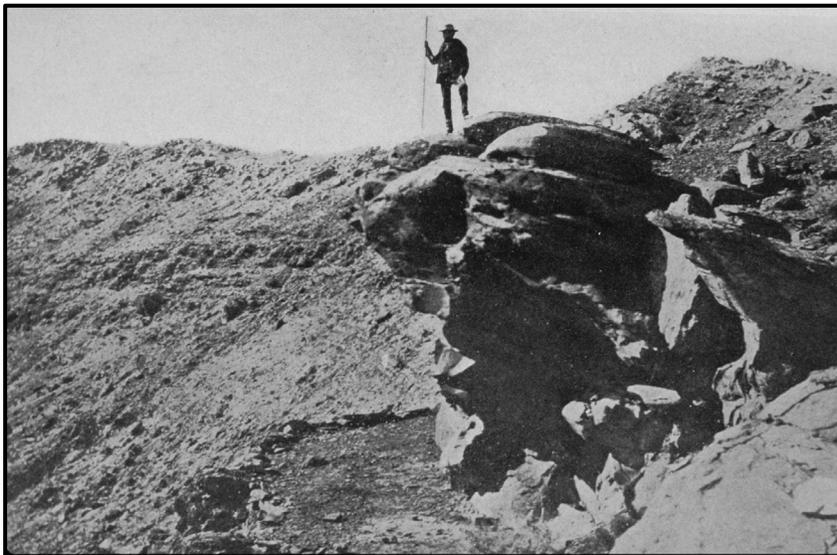


Fig. 1.3. View of the upper crater wall and crater rim, with uplifted (tilted) red Moenkopi in foreground. (Bottom panel of Plate VIII in Barringer, 1910.)

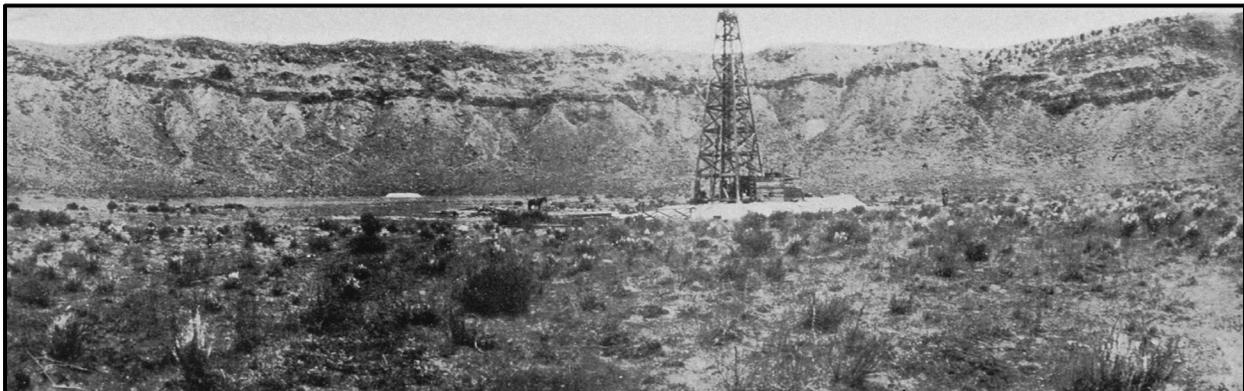


Fig. 1.4. (below) View of crater floor and a drilling unit near crater center. (Bottom panel of Plate IV in Barringer, 1910.)