ESTABLISHED AND SUPPOSED EXAMPLES OF METEORITIC CRATERS AND STRUCTURES

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Meteor Crater of Arizona, three-quarters of a mile across and six hundred feet deep, with its walls of tilted and faulted strata and its encircling high rim of pulverized and brecciated rock, is a spectacle for the student of land forms, of geologic structures, and of katamorphic processes. Standing on its rim, one is impressed by the fact that crater-forming meteorites are extraterrestrial agents that are truly catastrophic in their geological effects. However, the relative importance of giant meteorites among the agents that shape the landscape and deform or break rocks depends upon the distribution of meteorite scars in space and time. At present no one can say how many meteorite craters are to be found on the face of the earth; nor can one say how many scars recording geologically ancient falls exist in the rock layers of the crust. But it is significant that the number of recognized craters is rapidly increasing.

Craters With Associated Meteoritic Material

In 1933 L. J. Spencer summarized the available information on meteorite craters.[1] At that time he was able to cite five craters or crater clusters with associated meteoritic material: the Arizona crater, Odessa Crater of Texas, the Henbury craters of Australia, the Wabar craters of Arabia, and the Campo del Cielo craters of Argentina.

In addition to these five, Spencer listed four craters or crater groups for which a meteoritic origin had at one time or another been postulated without conclusive evidence in the form of meteoritic material. These were: the Kaali craters of Estonia, the Siberian craters, the Ashanti crater of the Gold Coast, and an extremely doubtful example in Persian Baluchistan.

It appears that the Siberian and Estonian examples may now be added to the list of established meteorite craters.

In 1937 Reinvald discovered meteoritic irons associated with two of the Estonian craters.[2] The same year Kulik reported silica glass and fused quartz aggregates containing globules of nickeliferous iron from two of the Siberian craters.[3]

Nininger and Figgins have described a depression near Haviland, Kiowa County, Kansas, which they believe to be of meteoritic origin.[4] Recently, Spencer has pointed out certain objections to this interpretation.[5] Until more information on the Haviland depression is available, it seems best to regard it as a questionable crater.

In the following table, craters with associated meteoritic material are listed along with available data on their shapes and dimensions.[6] It should be emphasized that the table does not give an adequate notion of the number of individual examples in the crater clusters. Alderman believes that a more detailed survey of the Henbury area will lead to the discovery of additional craters.[7] Philby has suggested that there may be others at Wabar in addition to the two listed.[8] The number of Siberian craters is unknown; at least ten have been reported by Kulik.[9] Likewise the number in the Campo del Cielo remains to be determined.[10]

Questionable Meteorite Craters

Today no one would question the proposition that meteorite craters have been formed by explosions—this despite the existing uncertainty regarding the way explosive forces are derived from the kinetic energy of meteorites.[11] It is not surprizing, therefore, that some investigators have championed the meteoritic hypothesis for certain explosion craters whose origin has been and still remains a subject for debate. Since 1931 various authors have appealed to the impact and explosion of meteorites to account for the Ries and Steinheim basins of Germany, the Ashanti Crater of the African Gold Coast, the Köfels Crater of the Tyrolian Alps, and the Pretoria Salt-Pan of South Africa.

Rohleder,[12] Kaljuvee,[13] and Stutzer[14] have argued independently for the meteoritic origin of the Ries and Steinheim basins.[15] The circular forms of these great depressions, the brecciated rocks lying in or scattered to great dis-

Name	Plan	Width (feet)	Depth (feet)
Meteor Crater (Arizona)	Roughly circular	3,800 to 4,000	600
Odessa Crater (Texas)	Roughly circular	500 to 650	14
Haviland Crater (?) (Kansas)	Elliptical	35x55	5
Henbury Craters (Australia)			
Crater No. 1	Circular? (eroded)	75	?
Crater No. 2	Circular	90	?
Crater No. 3	Circular	135	18
Crater No. 4	Circular	135	20
Crater No. 5	Circular	75	?
Crater No. 6	Roughly circular	240	25
Crater No. 7	Elliptical	360x660	40 to 50
Crater No. 8	Circular	180	15
Crater No. 9	Indefnite	45 ?	?
Crater No. 10	Circular	60	?
Crater No. 11	Circular	45	?
Crater No. 12	Circular	60	12
Crater No. 13	Indefinite	30	3
Wabar Craters (Arabia)			
Crater A	Elliptical	130x180	?
Crater B	Circular	328	40
Kaali Craters (Estonia)			
Kaali Jarv	Circular	300	50
Crater No. 1	Circular	120	13
Crater No. 2	Elliptical	120x175	12
Crater No. 3	Circular	100	12
Crater No. 4	Circular	65	4
Crater No. 5	Circular	35	?
Campo del Cielo Craters (Argentina) "Rubin de Celis" hoyo	Circular	183	16
Siberian Craters (number unknown)	Circular	33 to 165	13 to 19

Table I. Craters with associated meteoritic material.

tances around them, and the strong but localized deformation about the rims, are features strongly reminiscent of Meteor Crater of Arizona. Tuff-like materials associated with the broken and ejected rocks of the Ries Basin have been compared with the "silica glass" found at Wabar, the Arizona crater, and elsewhere.[16] No meteorites have been reported from either of the German craters, but, as Stutzer has emphasized, even if meteoritic irons were originally present at these localities, it seems unlikely that they would have escaped decomposition or burial for the hundreds of thousands of years that have elapsed since Miocene time when the craters were formed.[17] Or, on the other hand, it has been suggested that the hypothetical meteorites may have been stony, and exploded to dust when they struck.[18] Finally, meteorite fragments may be buried beneath Miocene lake beds that partly fill the basins.[19]

This interpretation has met with strong opposition.[20] It is generally conceded that both basins have been formed by explosions. The explosion that produced the Ries Basin must have been exceedingly violent; boulders were hurled more than 35 miles from the crater.[21] Most theorists, however, have favored some form of cryptovolcanic hypothesis, maintaining that the explosions were due to expansion of gases associated with ascending magmas.[22] Yet there are no volcanic materials at Steinheim, where the term "cryptovolcanic" was first applied. Nor at the Ries Basin are there any rocks whose extrusive origin is unquestioned.[23] Thus with regard to the origin of the Ries and Steinheim basins, one hardly knows which is better: a meteoritic hypothesis without meteorites, or a volcanic hypothesis without volcanics. For the present, these greatest known explosion craters may head the list of supposed but unestablished examples of meteorite craters.

The Ashanti Crater of the Gold Coast of Africa, like the Ries and Steinheim basins, has been interpreted by some as the result of a cryptovolcanic explosion,[24] by others as the result of a meteoritic explosion.[25] The crater is roughly circular, with a diameter of about six and a half miles and a depth of some 1,300 feet. The rim, which is highest on the south side, stands as much as 600 feet above the surrounding upland. The structure of the crater itself is largely concealed by the waters of Lake Bosumtwi. Rohleder has detected in adjacent quartzites, phyllites, and gneisses evidences of strong but localized deformation said to resemble that around the Ries and Steinheim basins.[26] At present the origin of the Ashanti Crater remains unsettled; no meteoritic or volcanic materials have been discovered in the area.

Rohleder has suggested a meteoritic origin for the Pretoria Salt Pan, located 4 kilometers northwest of the town of the same name in South Africa.[27] The salt pan has been described as a circular basin with a flat bottom covered with salt and brine. It has a diameter around 3,275 feet and a depth approximating 330 feet. A rim of uncemented granite breccia encircling the depression rises 100 feet above the level of the surrounding country. No volcanic material is associated with the crater, and there are no signs of recent volcanism in the surrounding country. On the other hand, no meteorites have been reported from the area, so that the origin of the salt pan remains uncertain.

In 1936 F. E. Suess proposed a meteoritic origin for the Köfels "crater," a curious widening in the Oetz valley of the Tyrolian Alps.[28] No meteorites have been found, but "pumice," associated with and apparently derived by fusion from the gneissic country rock, is believed to be similar in origin to silica-glass of meteorite craters.[29] The gneiss is locally fractured and brecciated, and the depression seems to show evidence of having been formed by violent explosive forces. There are no volcanic rocks at Köfels, and no signs of recent volcanism in the surrounding region.[30] The form of the Köfels crater is somewhat irregular, as one would expect of an explosion crater superposed on a mountainous region of great relief.

The five examples cited above constitute a group of explosion craters of debated origin. Apparently they are due either to explosions following the impact of giant meteorites, or to gas explosions caused by ascending magmas. Their dimensions are compared in Table II.[31]

A. Explosion craters.

Name	Plan	Diameter
Ries Basin (Germany)	Roughly circular	13 to 15 mi.
Steinheim Basin (Germany)	Roughly circular	1.5 mi.
Ashanti crater (Gold Coast of Africa)	Roughly circular	6.5 mi.
Köfels crater (Austria)	Irregular	2.5 mi. approx.
Pretoria salt pan (South Africa)	Roughly circular	3,275 ft.

B. Depressions which show no convincing evidence of having been formed by explosions.

Persian "crater"	Elliptical	70x95 ft.
Carolina Bays	Elliptical	Up to 5 mi.

Table II. Questionable meteoritic craters; circular or elliptical depressions without associated meteorites.

A second group of supposed meteorite craters includes depressions of debated origin which lack associated meteorites, and which show no convincing evidence of having been formed by explosions. The Persian "crater" and the Carolina Bays are examples.

A supposed meteorite crater near Gwarkuh, Persian Baluchistan, has been discredited by Spencer.[32] The depression has been described as a vertical hole in horizontal strata. According to Skrine's figures, it is 95 by 70 feet across, with a depth of 35 feet.[33] It is evident from descriptions that the pit, whatever its origin, possesses none of the features peculiar to the known meteorite craters.

Considerable difference of opinion has been expressed concerning the origin of the Carolina Bays. Within an area of some 10,000 square miles in the Carolinas, there are more than 1,500 shallow, elliptical depressions or "bays,"[34] ranging from a few hundred feet to about five miles across.[35] Their longer axes are remarkably parallel, the average alignment being around S 45° E. Low rims of sand border these depressions. At many of the bays the rims are present only at the southeastern ends; here the rims may be single, double, or triple. In 1933 Melton and Schriever suggested, with due caution, that the Carolina Bays have been formed by a shower of meteorites.[36] More recently MacCarthy has suggested that they were formed by shock waves accompanying the meteorites, rather than by the direct impact of the meteorites themselves.[37]

Those who deny that the Carolina Bays have been formed by meteorites emphasize that hardly any feature seems to relate them with established meteorite craters. No meteoritic material or silica glass is found in the sandy rims. There is no convincing evidence to show that the bays have been formed by explosions; the rims, according to Melton and Schriever, contain no rock fragments larger than sand grains.[38] The bays are strongly elliptical, while typical meteorite craters are nearly circular. Sand rims of the bays are best developed around, and often limited to the southeastern sides. Conversely, rims of ejected material commonly encircle meteorite craters. Rims of the bays may be double or triple; meteorite craters do not show multiple rims.

Magnetic "highs" occurring southeast of the southeastern rims of bays, at distances approximating the shorter diameters of the depressions, may be due to buried meteoritic material.[39] On the other hand, as MacCarthy has noted, it has not yet been demonstrated that these anomalies are always associated with bays.[40] Hence the association may be coincidental. Moreover, the eccentricity of "highs" with respect to some of the bays implies that bodies causing the anomalies lie several miles below the surface.[41] In view of the tremendous inertia-resistance giant meteorites must encounter when they strike, it seems unlikely that they could penetrate to depths so great.[42] Finally, accumulating evidence seems to indicate that giant meteorites are backfired from the craters they form; only rarely have even small irons been found in meteorite craters.[43] As the matter stands, one would conclude that the meteoritic hypothesis does not offer a satisfactory explanation for the Carolina Bays.[44]

Questionable Meteoritic Structures

In a sense, the intense deformation of rock layers outcropping along the walls of Meteor Crater is of greater geological significance than the crater itself. The crater must in time be filled with sediment, or destroyed by erosion. On the other hand, the deformation of rocks beneath it is a more enduring token of the catastrophe that occurred in the area. Even after a crater has been erased by erosion, the underlying structures might remain and, under favorable conditions, be preserved.[45] Whether or not meteorite scars can be identified beneath unconformities in ancient rocks depends, however, on the types of structures that exploding meteorites produce. If such structures are sufficiently distinctive to be distinguished from those produced in other ways, it may yet be possible to discover evidence of geologically ancient falls.

Examples which at the present time contribute most to our ideas on the nature of meteoritic structures are: Meteor Crater, the Estonian craters and the Siberian craters. Limestone and sandstone layers around the Arizona and some of the Estonian craters are tilted radially away from the centers, suggesting that underlying strata are domed.[46] At Meteor Crater the structures exposed in the walls show a pronounced bilateral symmetry about a line trending roughly north-south.[47] A section through the encircling rim of one of the Siberian craters showed "great folds (up to 1.5 m.) in the peat mosses and in the underlying blue clay."[48] In all certain examples of meteorite craters the rocks are locally fractured and pulverized. Putting these characteristics together we may formulate an idea of the typical meteorite structure.

A meteorite structure should be characterized by a central dome with one or more ring folds surrounding it. The deformation should be intense, but localized within a roughly circular area. The central dome and peripheral folds might be broken by radial faults, while brecciation and pulverization of the rocks would attest the violence of the deforming forces. The deformation should grow less intense both outward and downward from the central uplift. The majority of such structures would be expected to show a bilaterally symmetrical pattern.[49]

Structures which various authors have cited as giving evidence of violent deformation, apparently due to explosion or shock, are listed in Table III.[50] Only one of these—the Flynn Creek disturbance—preserves evidence of an explosion crater; the others are more deeply eroded. Where the structures are unconcealed by younger rocks, they show certain common characteristics. These are: (1) nearly circular peripheries within which the structural elements may show a bilaterally symmetrical arrangement (Wells Creek, Jeptha Knob, Serpent Mound, Flynn Creek, and Sierra Madera structures have well defined bilateral structural symmetry[51]), (2) a central uplift, sometimes succeeded outward by ring folds of diminishing amplitude, (3) evidence, in extreme brecciation and pulverization of associated rocks, indicating operation of explosively violent forces, and (4) absence of volcanic materials of the same age as the structures themselves.[52]

Granting that these are explosion structures, the nature of the explosions which formed them still remains doubtful. The explosions may have been cryptovolcanic,[53] or they may have been produced by giant meteorites striking the earth.[54] However, as the writers have pointed out,[55] the meteoritic hypothesis accounts for the bilateral symmetry of some of the structures, and for the absence of volcanic materials, better than does the alternate hypothesis. For the present, one seems justified in regarding these ancient explosion structures as questionable meteorite scars.

This paper will have achieved its purpose if it has demonstrated the variety of geomorphic and structural features which have been assigned either surely or tentatively to the impact and explosion of giant meteorites. At present there is only one criterion by which the meteoritic origin of a crater may be established. This is the occurrence of meteoritic material in association with the crater itself. For explosion craters without meteoritic material, the cryptovolcanic hypothesis is an alternate explanation. Likewise

Name and location of structure	Approximate plan of disturbed area	Approx. diam. in miles	Date of deformation
Jeptha Knob (Kentucky)	Circular	2	Mid-Silurian
Serpent Mound (Ohio)	Circular	4	post-Lower Mississippian; pre-Illinoian
Wells Creek (Tennessee)	Circular	6	post-Middle Mississippian
Decaturville (Missouri)	? (Concealed)	?	late Cambrian or early Ordovician
Kentland (Indiana)	? (Concealed)	?	post-Middle Ordovician; pre-Pleistocene
Flynn Creek (Tennessee)	Circular	2	late Devonian or early Mississippian
Upheaval dome (Utah)	Circular	3	post-Navajo (Jurassic)
Sierra Madera (Texas)	Circular	3	post-Permian pre-Comanchean
Vredefort dome (Orange Free State, Africa)	Circular	75	pre-Carboniferous

Table III. Questionable meteoritic structures:—Ancient and deeply-eroded domical structures showing strong, localized deformation presumably produced by explosion or shock.

in the case of deeply eroded explosion structures both meteoritic and volcanic hypotheses must be considered. Neither hypothesis, on the other hand, can well account for large depressions or crater-like features which show no evidence of having been formed by explosion.

More information is needed regarding the nature of structures underlying meteorite craters. If such structures are found to differ significantly from those formed by other types of explosions, then we may hope to identify meteorite scars produced in past geological eras.

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