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METEORITE CRATERS AND THEIR POSSIBLE RELATIONSHIP TO "CRYPTOVOLCANIC STRUCTURES"

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Abstract

The increasing number of recognized meteorite craters indicates that these features are not so rare as formerly believed. It is probable, moreover, that meteorite craters of the geologic past were larger and more abundant than the relatively recent examples. Evidence for the fall of ancient meteorites must be sought, however, in geologic structures produced by impacts.

The history of a large falling meteorite of the order of 100 feet or more in diameter may be divided into three intervals: (1) interval of passage through air, (2) interval during which meteorite is brought to rest, (3) interval of explosion. During the first interval, the meteorite possesses kinetic energy several hundred times that of an equal weight of nitroglycerin. Upon impact, this energy is immediately transformed into heat and pressure potential energy. Beds immediately beneath the locus of impact would be momentarily subjected to pressures of several million atmospheres. The next instant, the highly compressed rocks, by virtue of their high elasticity of volume, would expand with explosive violence, backfiring the meteorite and forming a crater. A more lasting result of impact and explosion would be the formation of elastic waves of large amplitude. These would be strongly damped and fixed to form a central dome surrounded by ring folds of diminishing amplitude outward. Long after the surficial evidence for impact had been destroyed, the subjacent structures might be preserved.

The type of structure to be expected beneath large meteorite craters is strikingly similar to certain "cryptovolcanic structures," currently believed to have been formed by explosive release of subterranean gases. It is suggested, therefore, that some of these structures may record the fall of meteorites in the geologic past.

Introduction

Prior to 1927 the great Meteor Crater of Arizona was the only known feature of its kind. Within the last decade, however, four similar craters or groups of craters have been discovered in Arabia, Australia, Argentina, and Texas. In addition to these established examples of meteorite craters, Spencer (1933)[1] has listed crater-like depressions in Estonia,

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[1] Numbers in parentheses refer to articles in bibliography at end of paper.

Siberia, the Gold Coast of Africa, and Persia, for which a meteoritic origin has at one time or another been maintained without conclusive evidence. No doubt other meteorite craters will be discovered, since it is now evident that such features are widely distributed over the earth, and are not nearly so rare as has been generally supposed.[2]

It seems probable that meteorite craters were larger and more abundant in the geologic past than at present. Meteorites may be considered as scraps left over after the formation of the larger elements of our solar and galactic systems. Since the beginning of its career as a planet, the earth has been garnering these scraps, and it is likely that the larger portion was drawn in during the early stages of its existence. Granting the meteoritic origin of craters on the moon, it is interesting to note in this connection that Shaler believed that the larger lunar craters are, as a rule, older than the smaller ones.

> So far as I have been able to determine, the largest were, at least in a general way, first produced, and the smaller, approximately, in the order of diminishing size, the smallest in most instances being formed last (Shaler, 1903, p. 14).

But where is the evidence for the falling of meteorites on the earth during geologic antiquity? Oliver (1925, p. 251) has pondered the question, and wondered why the rocks of the earth do not preserve the record of meteorite impacts. If relatively shallow craters were the only results of such impacts, we should be obliged to limit our search to the present landscape. But we know that in addition to creating ephemeral depressions, meteorites deform surficial rock layers when they strike the earth. Rim rocks of meteorite craters dip radially outward. Meteorite impacts are, therefore, capable of producing geologic structures, and long after superficial evidence of the impacts has been destroyed, these structures may be preserved.

Knowing the mechanics of meteorite impact, and the physical nature of the medium encountered, it is possible to predict what *general types* of structures should underlie a large meteorite crater. The writers believe that certain

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[2] For descriptions of established and supposed examples of meteorite craters, with references to original papers, see Spencer (1933).

structures previously described by geologists as "cryptovolcanic" may be old meteorite scars. Before considering these structures, however, it is necessary to describe the mechanics of meteorite impacts.

Evidences of Explosive Nature of Large Meteorite Impacts

Large iron meteorites of the order of 100 feet in diameter (vastly larger than those commonly displayed in museums) and weighing several million tons, would be many times heavier than the column of air they would displace during fall.[3] Hence their velocities of impact would be very near the velocities at which the bodies had been previously traveling through outer space. Direct measurements of meteor velocities have given figures as high as 50 miles per second (Fath, 1928, p. 201).

Wylie (1933, p. 213) has calculated that a meteorite traveling at the rate of 40 miles per second would possess energy approximating 306 times that of an equal weight of nitroglycerin. A rifle bullet traveling at a velocity of only 0.66 miles per second explodes and is shattered to bits when it strikes its target (Wylie, 1934, p. 470). We must conclude with Spencer (1933, pp. 322, 325) and Wylie (1933, 1934) that large meteorites, traveling at velocities 75 times that of the rifle bullet, must *explode* when they strike the earth.

Evidence for this is found in the association of *craters* with abundant meteorite fragments in at least five widely separated localities. The radial distribution of ejectamenta (both country rock and meteorite fragments) around the craters, the intense local brecciation and powdering of the country rock, the occasional manifestations of intense but localized thermal metamorphism, and the radially-outward dip of rim rocks lead to the same conclusions; tremendous explosions have occurred at these localities, and these ex-

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[3] Small meteorites, like those found in museums, lose most of their high initial velocities due to friction with the atmosphere during fall. Hence relatively large and relatively small meteorites cause radically different effects when they strike the earth. Obviously it is to the former class that we owe meteorite craters, and unless specifically qualified to the contrary, it is to meteorites of the order of 100 or more feet in diameter that the writers are referring in the following discussion. For an illuminating discussion of the variation in velocities of impact for meteorites of various sizes, the reader is referred to Wylie (1933), p. 213.

plosions have been caused by the impacts of meteorites.[4]

Mechanics of Meteorite Impacts

It is evident that falling meteorites possess great energy. Let us now consider how this energy is dissipated. For convenience in analysis, the history of a large falling meteorite is divided into three intervals.

1. *Interval of passage through the air.* Throughout this interval, which may last for several seconds, the meteorite possesses great kinetic energy, which for bodies of the magnitude considered would be equivalent to several hundred times the potential energy in an equal weight of nitroglycerin.

A relatively small amount of this energy is dissipated as heat resulting from friction with the atmosphere. But since the interval is short this frictional heat never penetrates beyond a thin outer rind of the falling body. A small meteorite which fell in India in 1860 was found, shortly after its fall, coated with ice (Fath, 1928, p. 206). The inside of a large meteorite would probably have a temperature near absolute zero at time of impact.

2. *Interval during which meteorite is brought to rest.* When the meteorite first strikes the earth it would deal the superficial rocks a terrific blow. In a fraction of a second the body would penetrate the earth a short distance and be brought to rest. It would appear that, during this brief interval, the energy of the bolide is stored in two places. (a) *In a thin, intensely hot, gaseous layer surrounding the bottom of the meteorite.* It is likely that a falling meteorite of the magnitude assumed would possess sufficient energy to melt and vaporize the entire body, if all the kinetic energy could be transformed into heat. But it would be impossible for more than a small part of the kinetic energy to be so transformed in the fraction of a second between impact and explosion.

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[4] As Spencer (1933, p. 235, Pl.'s I, II.) has observed, meteorite craters find their closest artificial analogies in craters formed by high-explosive shells and military mines. The mine crater on Hill 60, near Ypres, formed by the explosion of 70,000 pounds of ammonal, is 340 feet wide and 67 feet deep. The form of this crater is essentially that of the Arizona meteorite crater, which, however, is approximately eleven times wider and nine times deeper than its artificial analogue.

This part would probably result in the vaporization of a thin rind of material beneath the meteorite. This intensely hot zone would be the locus for thermal metamorphism, and is adequate to account for silica glass occasionally associated with meteorite craters. Due to the comparative slowness with which heat travels by convection and conduction, however, this zone of vaporization could accommodate only a small portion of the transformed kinetic energy, the greater portion of which, it would appear, is momentarily stored in (b) *a zone of highly compressed rock beneath the locus of impact.* As the meteorite is being brought to rest, it would drive down and compress the rocks beneath it. By the time the body had been brought to a standstill it would have stored the greater part of its energy in this zone of compression as *pressure potential energy.*

An example will make clear the tremendous compression to which rocks beneath an impinging meteorite would be subjected. Let us assume that a cubical meteorite, 300 feet on a side, with a density of 200 pounds per cubic foot, strikes the earth at a velocity of 80,000 feet (about 16 miles) per second, and penetrates 200 feet into the earth before it is brought to rest. The following equations are used to find the pressure in atmospheres to which the rocks beneath the bolide would be momentarily subjected.

$$(1)\quad F = M \times A$$
$$(2)\quad A = V/T$$
$$(3)\quad T = D/Va$$

F is the total force of the impact, M is the mass of the meteorite, V is the velocity at the instant of impact, T is the time required to bring the body to rest, D is the distance the body penetrates into the earth, and Va is the average velocity during the time T. G is introduced to obtain the answer in pounds. Substituting, we obtain:

$$F = M \times V \times Va/D \times G = 27 \times 10^{14} \text{ pounds}$$

Dividing by the area in square inches (13×10^6), the pressure per square inch is found to be 21×10^7 pounds, or 14×10^6 atmospheres. This is about five times the calculated pressure at the center of the earth (Gutenberg, 1929, pp. 450-451).

3. *Interval of explosion.* Bridgman (1935) has shown that many substances when subjected to hydrostatic pressures of forty or fifty thousand atmospheres, explode violently upon application of shearing stresses. Impacts of large meteorites, as shown above, produce pressures that run into millions of atmospheres. It would appear, moreover, that impinging meteorites would supply the shearing stresses apparently necessary to cause explosion of materials subjected to high pressures.

The instant a large meteorite is brought to rest, the highly compressed materials beneath it would expand with explosive violence. The energy thus released would be dissipated in forming a crater, backfiring the meteorite and shattering it, brecciating and pulverizing the country rock, forming elastic waves, and deforming rock strata. Considering all of the explosive forces brought into play by meteorite impacts, it would seem that a body sufficiently large to reach the earth with virtually undiminished velocity would be backfired and shattered upon impact.

Deformation of Rock Strata Resulting from Meteorite Impacts

The strata composing rims of meteorite craters commonly dip radially away from the center, suggesting that the subjacent beds are domed. At the present time, however, details of structure beneath meteorite craters are not well known. Nevertheless, it is possible to predict what general types of structures should occur beneath large craters.

When a large meteorite strikes the earth, it deals a terrific blow to a medium which has a limited degree of freedom, and a high degree of elasticity of volume. It should be remembered that while some of the materials (such as clay) composing the crust of the earth, have little or no elasticity of shape, they all have great elasticity of volume. Brittle substances are not shattered by pressure, if pressure be applied to all sides, but by tension. Hence after compression they all rebound.

Therefore, as a result of impact and explosion, a series of concentric waves would go out in all directions, forming ring anticlines and synclines. These waves would be strongly damped by the overburden and by friction along joint, bedding, and fault planes. *The central zone, completely damped by tension fractures produced by rebound, would become fixed as a structural dome.*

The general and simplest type of structure to be expected beneath large meteorite craters would, therefore, be a central dome surrounded by a ring syncline and possibly other ring folds, the whole resembling a group of damped waves.

These structures should not be radially symmetrical, unless the falling meteorites struck the surface of the earth at right angles. Rims of meteorite craters commonly show opposed points of minimum and maximum uplift, suggesting that impacts were oblique rather than vertical. An oblique blow would be expected to impart bilateral rather than radial symmetry to resulting *structures,* although the *craters,* which result from up- and outwardly-directed explosions should exhibit radial symmetry. Long after these craters had been destroyed by erosion, the underlying structures might be preserved.

Possible Relationship Between Meteorite Craters and "Cryptovolcanic Structures"

Cryptovolcanic structures are subcircular, complex, domical structures characterized by intense deformation and brecciation within an area of a few square miles. Recently Bucher (1936, p. 1074) has cited the following characteristics common to six American structures he believes to be cryptovolcanic.

1. They show a tendency toward a circular outline.
2. A central uplift is surrounded by a ring-shaped depression, with or without well-developed marginal folds beyond it.
3. In the larger disturbances the area of the uplifted central part is small compared to the areas that sank.
4. Where the nature of the rock materials permits any judgment, evidence is found of violent action, such as seems explicable only as the result of sudden release of pressure—that is of explosive force.
5. Except in the Decaturville structure, no volcanic materials or any signs of thermal action have been observed.[5]

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[5] Tarr (in Bucher, 1936, p. 1084) has maintained that the igneous rock in the Decaturville structure is much older than the explosion which formed the structure.

Cryptovolcanic structures are currently believed to have been formed by "disturbances produced by the explosive release of gases under high tension, without the extrusion of any magmatic material, at points where there had previously been no volcanic activity" (Bucher, 1936, p. 1075). Structures which have been assigned to this origin range in age from early Paleozoic to late Tertiary.

It is apparent from the foregoing account that certain cryptovolcanic structures are strikingly similar to those which would be expected to underlie large meteorite craters. It is significant that Bucher (1936, p. 1068) has written of the Wells Creek Basin structure of Tennessee:

> Aside from the normal faulting, the pattern resembles that of damped waves, a central uplift surrounded by two pairs of down-and-up folds, with diminishing amplitude. It is the sort of pattern that results from a sudden impulse such as that of an explosion.

Moreover, it appears significant that several of the structures described by Bucher have a distinctly bilateral rather than radial symmetry. This is particularly true of the Wells Creek, Jeptha Knob, and Serpent Mound structures. This symmetry would be in accordance with the writers' predictions relating to an obliquely-impinging meteorite. On the other hand, it appears that if these structures had been formed by a single upward- and outwardly-directed explosion, as postulated by the cryptovolcanic hypothesis, they would possess radial rather than bilateral symmetry.

Bucher (1936, pp. 1080-1081) has noted that the American examples of cryptovolcanic structures may have a causal relationship to regional domes and anticlines, such as the Cincinnati anticline and Nashville dome, "since all of them seem to lie on the flanks of large swells." It would be difficult, however, to find an area in the interior of the United States which would not bear a similar spatial relationship to regional uplifts. On the other hand, there appears to be a close relationship between the location of the six supposed examples of cryptovolcanic structures and areas in which bedrock structures are well exposed, which are unaffected by intense folding, and which have been subjected to close geologic scrutiny.

In conclusion, it appears that some of the structures which have been assigned to volcanic origin are equally as well interpreted as meteorite structures. Certainly it can no longer be maintained that all explosion structures are necessarily volcanic. The meteorite hypothesis explains the occurrence of folds resembling damped waves, and evidences of violent explosion (breccias, shatter-cones, etc.) as well as does the cryptovolcanic hypothesis. It offers a better explanation for the bilateral symmetry of many of the structures than does the volcanic hypothesis. It removes the embarrassing question as to reason for lack of associated volcanic materials. Finally, it gives a tentative answer to astronomers who have long reasoned that large meteorites must have fallen in the geologic past.

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