1 Introduction

The results of more than 150 crater-producing events have been identified on the Earth's land mass. These range from recent craters, formed before our eyes, as at Sikhote Alin, to ancient craters, eroded almost away and a billion years old, as at Acraman. Some are nicely preserved and spectacular places to visit, as at the Barringer Crater, and others are completely invisible, buried beneath hundreds of meters of sediments, as at Des Plaines. They range in diameter from a few meters, as at Henbury, to over 100 km, as at Vredefort. Whether large or small, young or old, clear or obscure, all of the structures are important records of how astronomical objects have continued to have an effect on the events that made up the history of the Earth.

How this book is organized

The following chapters of this book provide descriptions of the craters and impact structures, organized with a separate chapter for each continent. Within each chapter, the individual objects are described in alphabetical order.

Some difficulty of separation arises for objects that lie near the ill-defined boundary between Europe and Asia. This was not so serious a problem in the past, when the Soviet Union, which hosted most Asian impact structures, could be used as a delineating unit. However, with the dissolution of the Union, the craters lie in various political divisions, and so I have adopted the continental dividing line to separate them. Following tradition, I have used the Ural Mountains as the primary boundary between Europe and Asia, with the Ural River, the Caspian Sea and the Turkish and Iranian northern borders as the southern extension of the line.

For each crater and impact structure there is an initial summary table that lists its location, including its latitude and longitude, its size, its age (or known limits on its age) and its present condition. Positions and diameters were adopted (except for very newly recognized objects and for a few cases where there were some typographical errors) from the authoritative list compiled in 1991 by R. A. F. Grieve (*Meteoritics*, **26**, 175–194). In some cases, different sources give different values for the sizes of craters. This is usually the result of different choices having been made regarding the definition of the outer boundaries of structure, a particularly awkward problem for very large, complex, eroded cases. I have chosen to follow Grieve's decisions about sizes.

The descriptions of the craters and impact structures are based on both published accounts and personal experience. I have visited many of the objects, photographed

them, and in some cases have done some scientific research, in particular on the meteoritic and related microscopic objects that are found in the soil surrounding the younger craters. But much of the description has been based on the accounts of those scientists who have most thoroughly explored the objects and most completely described them in print.

Because many meteorite craters are fascinating places to visit, providing the only chance for most of us to see and study and walk on real astronomical phenomena, I also provide some guidance about access. Where possible, this is based on personal experience, but for many I have had to rely on published accounts and detailed maps. As times change, many of the more remote sites are becoming increasingly accessible and so a prospective visitor would be wise to make up-to-date and local inquiries before planning an expedition to a crater locale. I have not visited any of the Asian and East European structures and therefore refrain from giving advice on how to reach most of them.

At the end of each description one or two references to published papers are given. This is a selected sample for the better-studied craters. More complete reference lists are given, for example, by M. J. Grolier (*NASA Technical Memorandum 87567*, 1985). For some craters, such as the Snelling Crater in Australia, no published account is yet available. For many objects formerly located in the Soviet Union easily-accessible publications are also unavailable, explaining why many of them receive very limited coverage in this book.

How complete is this book?

The objects described in this book include all certain and probable impact structures known to me in 1992. I have used Grieve's list, cited above, as my criterion, with only eight objects added from the more recent literature. Many other objects around the world have been proposed by various scientists, and some of these will probably be admitted to 'probable' or 'certain' status with further study.

Many, however, will not. The meteorite-crater literature is rife with false alarms. Because really good criteria for an impact origin have only recently been developed, the subject has seen wild swings back and forth in the past, between claims that obvious volcanic features are meteorite craters to claims that obvious meteorite craters, such as the Barringer and Wolfe Creek craters (where fragments of the responsible meteorite are abundant), are not. As explained below, evidence for the production of high pressure shock effects now provides a reasonably reliable method for recognizing the real thing.

Meteorite craters versus impact structures

Readers of the above paragraphs and those who paid attention to the title of this book many wonder why 'meteorite craters' and 'impact structures' are mentioned and discussed as if they were different kinds of object. They really are not different in origin, but workers in this field usually distinguish them in this way in order to separate the relatively fresh, uneroded 'meteorite craters' that still have their complete craterform anatomy from the older, eroded and nearly-unrecognizable 'impact structures', of which we only see the skeletons. In some cases, as for Gosses Bluff, a casual glance might suggest that what we see is a complete crater, but a careful field study shows that the 'rim' of the apparent crater is really a ridge of rock hardened by the original impact, but located inside and deep below the original crater, which was far larger and has long since been eroded away.

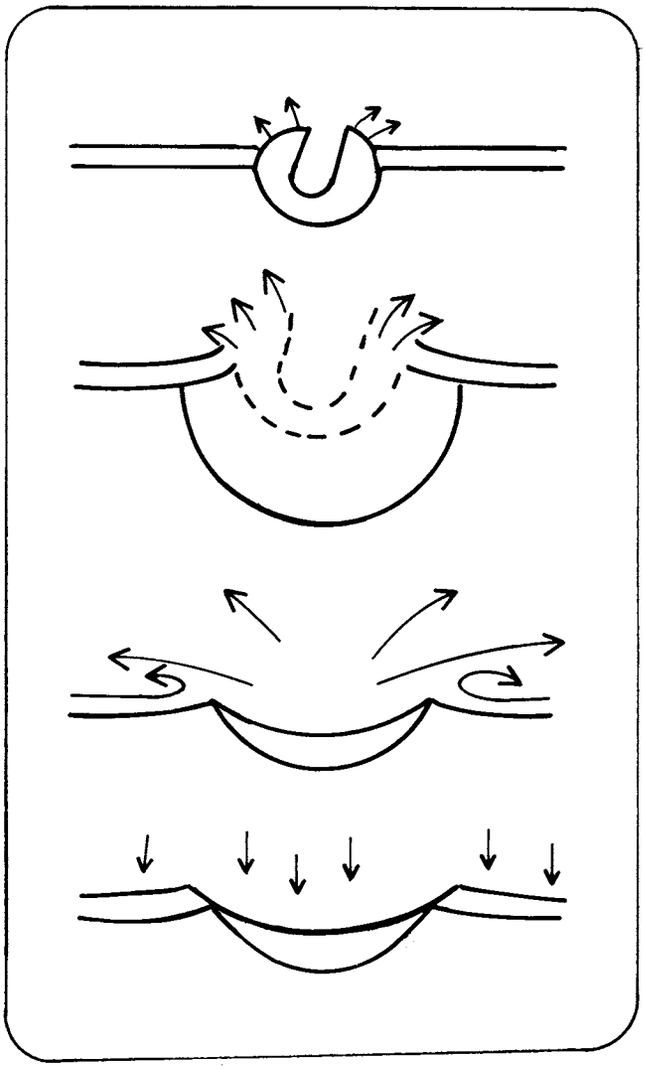
The cratering mechanism

Impact cratering is a primary means for forming the surface characteristics of many objects in the solar system – the Moon, Mercury, much of Mars and its satellites, most of the moons of the major planets, the asteroids, and even interplanetary spacecraft. Study of the cratering mechanism thus has widespread relevance and much progress in understanding it has been made in recent years. There are several excellent books on the subject, of which I mention here only a sample:

Roddy, D. J., Pepin, R. O. and Merrill, R. B., 1977, *Impact and Explosion Cratering*. Pergamon Press, New York.

French, B. M. and Short, N. M., 1968, *Shock Metamorphism of Natural Materials*. Mono Book Corp., Baltimore.

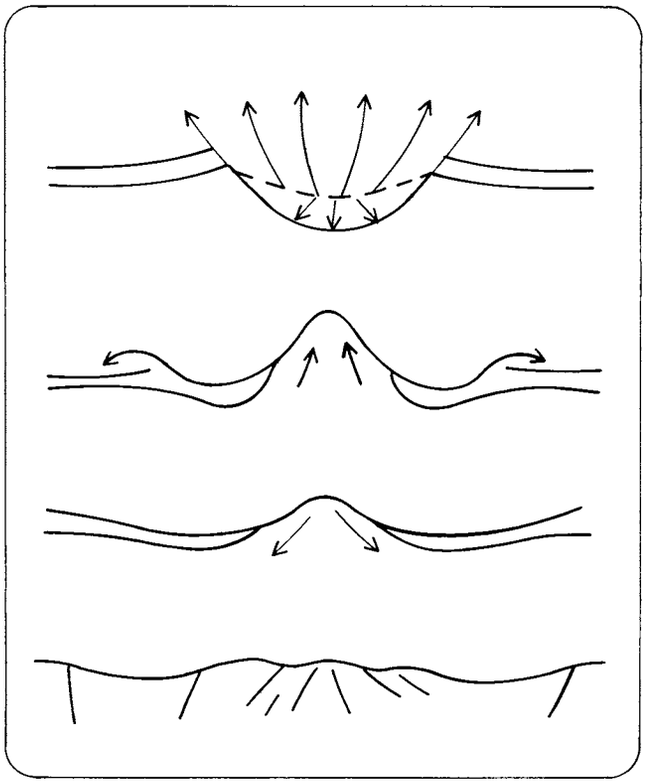
Rim of the Barringer crater in Arizona, showing the characteristic upturned layers at the top of the steep crater walls.



For a relatively small crater like the Barringer crater, the formation can be represented by this sequence of events. Almost all of the meteorite and the rocks at the point of contact are explosively destroyed. A shock wave radiates out through the rocks and debris is thrown out into the atmosphere. The rock layers are upturned and overturned at the rim and the fragments of shattered rocks form a lens below the depression, which then fills in with the material that was ejected.

A very brief summary of the events involved in meteoritic impact on the Earth is given here:

1. When a large meteorite encounters the Earth its passage through the atmosphere is very brief (unless the angle of incidence is shallow), only taking a few seconds. Sometimes the collision with the atmosphere breaks the projectile into several fragments.
2. A shock wave is formed at the prow of the meteorite, where there is a layer of highly-compressed air together with a small amount of melted and evaporated meteorite material.



Large impact structures are more complex. A central uplift results from the rebounding rocks, which undergo compression and ejection. In addition to the large amount of rock fragments, vapor and liquid, material flows out along the surface in waves. The final form results from the collapse of the central peak and downfaulting in the outer parts, forming a ring or rings.

Small craters, like this one at Henbury in Australia, sometimes still retain some of the impacting meteorite. Meteorites were excavated from this crater in 1932.

3. For very large impactors, the frontal layer of compressed gas is capable of melting and ejecting blobs of rock before the solid object touches the Earth's surface. These blobs are the tektites and are often found hun-

dreds of kilometers away from the crater, as in the case of the Moldavites and their parent, the Ries crater.

4. Upon hitting the ground the meteorite and the rock below it are pulverized and vaporized by the explosive energy of the impact. Except for objects smaller than a few meters, the meteorite is completely destroyed by the explosion and its material is dispersed as vapor, melt, and fragments, much of it mixed with material from the target.
5. The explosion causes shock waves to pass through the rock below the point of impact. Rocks are shattered, forming impact breccia. Often there is a layer of liquid rock, which cools to form an impact melt, superficially resembling lava. Even far below the impact, rocks develop minerals that are distorted on a microscopic scale. Large amounts of rock fragments and fine-scale debris are thrown from the site, leaving a crater surrounded by a blanket of ejecta. Rock layers at the edges of the cavity are pushed up and turned over, leaving a raised rim that is overlain with beds of rock that are now up side-down. The diameter of the crater is approximately ten times the diameter of the incoming meteorite.
6. For very large impacts, forming craters several kilometers across, the final form of the crater is more complex, with a raised central object (analogous to the central peaks of lunar and Martian impact craters) and a series of concentric rings in the outer regions, made up of alternating uplift areas and depressions. Because such large cratering events occur very rarely (fortunately), terrestrial examples are all highly eroded. Often all that remains is the central uplift and the circular zone of shocked and shattered basement rock.

Types of crater

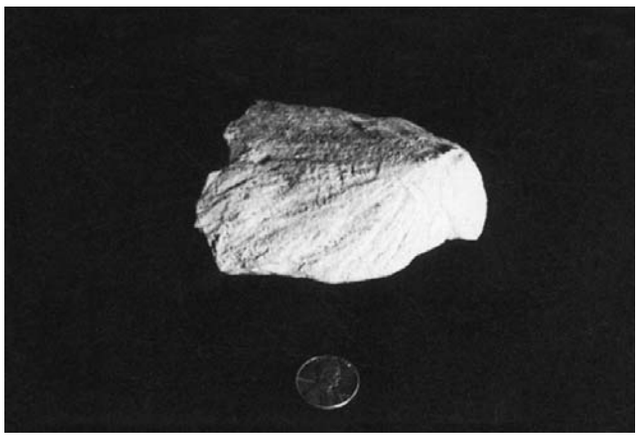
Meteoriticists often divide impact craters on the Earth into three types, according to the size of the impact. For small meteorites, up to sizes of a few meters, the energy of the impact is usually insufficient to produce a true explosion, and the meteorite plows into the ground, making what can be called a **'dug crater'**. This is usually several times the size of the meteorite, but for small meteorites hitting soil rather than rock, it can be only as large as the meteorite.

Larger impacting bodies produce an explosion, with shock waves passing through the target, leaving the many features described above. For craters that are tens of meters up to a few kilometers in diameter, the result can be called a **'simple crater'**. It is symmetrical and perfectly bowl-shaped.

Impacts that result in cavities larger than a few kilometers in diameter produce what are called **'complex craters'**. These have central uplifts and two or more concentric rings making up a series of ridges and valleys.

Evidence of shock

For fresh craters the best proof of an impact origin is the presence of meteorites around or in the crater or meteoritic material in the surrounding soil. Older craters, however, are usually too eroded; the meteoritic material has long since been carried away or has been chemically altered beyond easy recognition. In such cases, the evidence of impact must rely on the morphology of the structure (a central uplift, a lens of impact breccia, symmetry, a raised rim, pools of impact melt, etc.), together with evidence of shock waves, which are not usually produced by terrestrial events, even by violent volcanic activity. Common forms of shock effects include:

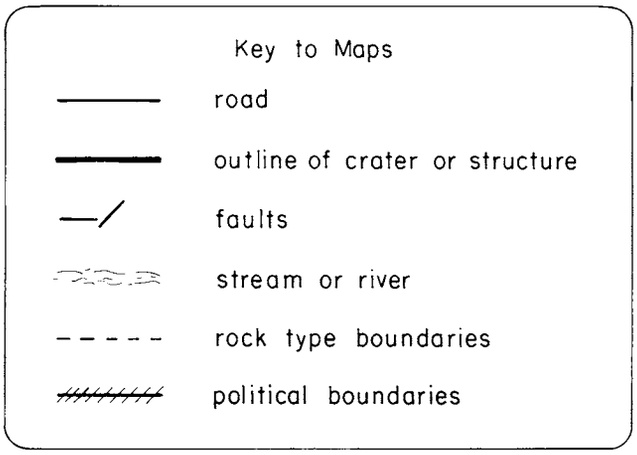


A large crater is formed with such high pressures that shatter-coning can occur in the target rocks. This shatter cone was retrieved from the Sierra Madera structure in Texas.

1. Shatter cones. When strong shock waves pass through appropriate types of rock, they produce weakened zones radiating out from the direction of shock, resulting in ridged cone-shaped rock fragments when the shocked layers are bared by erosion. Much of the large spurt of progress in recognizing impact structures that occurred in the 1960s was the result of the discovery of shatter cones at many previously dubious sites.
2. Shock lamellae and linear features in quartz. When subjected to strong shocks, crystals of quartz and other minerals show microscopic parallel linear patterns, called shock lamallae. Sometimes there are several systems at different angles. These kinds of features are

common in lunar rocks, for which impacts have been the primary geological process.

3. Shock-induced minerals. Certain minerals, such as coesite (a high-pressure phase of silica that is formed at 450–800 °C and 38 000 atmospheres) and stishovite (a high-density form of silica formed at 130 000 atmospheres), are strong confirmation of an impact origin for a feature.



2

Impact structures of the United States

Barringer

Arizona

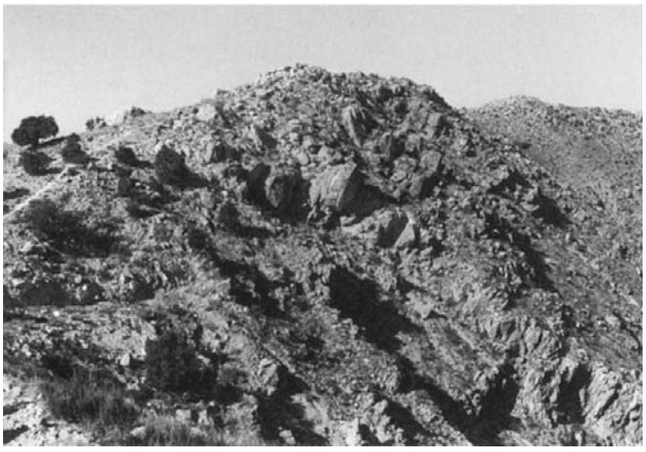
Lat/Long: N35° 2′, W111° 1′
Diameter: 1.2 km
Age: 0.049 Ma
Condition: Fresh

The Barringer Crater, also known as the Arizona Crater or Meteor Crater, is the best known impact structure in North America. At least two excellent books have been written about it (see below) and it played an important role in the development of the history of the field, being the first universally-recognized example of a meteorite crater. The story of this history, in the first three decades of the twentieth century, is fascinating, involving an 'outsider' with a radical theory and a powerful establishment figure who held tenaciously to his conservative views in the face of what (to us now, at least) seem to be unarguable facts. Daniel Moreau Barringer, a mining entrepreneur, spent much of his life and fortune attempting to convince the scientific community that the crater (locally known as 'Coon Butte') must have had an impact origin. The geology community, led by the chief geologist of the US Geological Survey, Grove Karl Gilbert, insisted that the crater was a volcanic explosive feature and that the existence of meteoritic fragments around it was merely a coincidence. The issue was not really resolved until about 1930, when enough studies had finally convinced enough scientists that a meteoritic origin was the most likely explanation of the facts. Much of the resistance to the acceptance of this idea had been caused by Barringer's conviction that a huge mass of iron–nickel lay beneath the crater floor. When such an object was not found, the entire hypothesis was faulted, even when the astronomer F. R. Moulton showed the such an object couldn't withstand an impact whole and would be destroyed and dispersed.

The Barringer Crater has the outline of an imperfect circle, nearly polygonal. Its rim rises 45 m above the surrounding, very flat, high Arizona desert, and is nearly uniformly high around the entire perimeter. The flat floor of the crater (which at some time or times, according to sediments, was lake-filled) lies 100 m below the surroundings. Its inner slopes are steep and rugged, while the outer slopes are gentle, marked by large and small deposits of debris from the cratering process. The nearly flat-lying beds of sedimentary rock are upturned radially in the rim, and in some areas it is possible to see that they have

BARRINGER: The east rim of the Barringer crater. Edges of uptilted strata are visible in the upper half of the inner wall.

BARRINGER: The floor of the Barringer crater is 145 m below the rim. It is filled with Recent and Pleistocene sediments.



BARRINGER: The south rim of the Barringer crater. Blocks of ejecta and upturned beds are visible. The rim trail is at left.

been overturned near the edge, with the normal vertical sequence reversed. Although made up of fragments and somewhat mixed, these beds form a nicely overturned flap surrounding the crater.

Thousands of meteorite fragments have been recovered from the Barringer Crater, mostly from the outer rim, but also from as far as 7 km from the crater. Over 10 000 ponderable meteorites have been recovered and many more micrometeorite-sized specimens have been found. One study of the soil surrounding the crater showed that meteoritic dust pervades the soil out to distances of nearly 10 km from the crater and that the total mass in this form is on the order of 12 000 metric tons. Compared to the 30 or so tons in the form of large meteorites, this is by far the largest form for the meteoritic matter, and it corresponds fairly closely to estimates of the total mass necessary to produce a crater of this size.

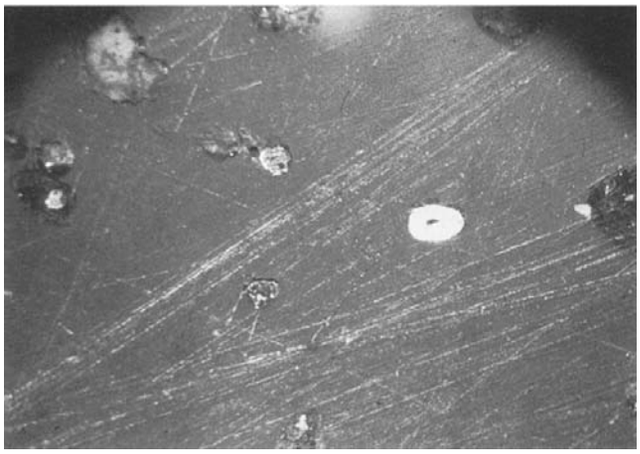
Other forms of impact materials include large numbers of shale balls, some meteoritic-laced impact glass and various forms of shock-induced minerals, including small diamonds, coesite and stishovite.

Anyone interested in impact craters should visit the Barringer Crater (the other essential visit is to the Ries and its remarkable museum in Nordlingen). It is easy to visit (see below) and is so well preserved that many of the features of moderate-sized impact structures are displayed well. At the time of writing, visitors are generally not permitted to climb down into the crater, but a good trail exists around the rim, from which many important features are visible. A clockwise itinerary follows. But first it is useful to identify the various rock formations that exist in the region. Before the meteorite landed, the geology of the area was relatively simple. Basically, there were nearly horizontal layers of Mesozoic and Paleozoic sedimentary rock. Leaving out detail, the following table lists the principle layers and their approximate thicknesses near the present position of the crater:

Formation	Age	Thickness (m)
Alluvium	Recent and Pleistocene	Thin, variable
Moenkopi (sandstone)	Triassic	Thin, variable
Kaibab (limestone and dolomite)	Permian	90
Coconino (sandstone)	Permian	270

The main outcrops near and at the crater rim are of the Kaibab and Moenkopi formations, while the Coconino sandstone is exposed in the inner crater walls.

BARRINGER: Beds of sandstone on the western rim of the Barringer crater, lying vertically (foreground) and at an intermediate angle (background).



BARRINGER: Microscopic meteoritic and iron oxide particles from the soil, collected 10 km from the crater.

The following is an itinerary for a walk around the crater rim on the Rim Trail, proceeding clockwise:

Distance from museum (km)	Features to note
0	There is a path to the left from the museum. A few meters from the building, just before a branching path leads to the left up the ridge to a lookout platform, there is an exposure of upturned bedrock. The uppermost beds are of red Moenkopi sandstone and they are sharply tilted and, in some places, overturned.
0.1	An excellent view of the rim and floor of the crater is provided from the lookout platform at the top of the path. The yellowish blocks surrounding the platform are Kaibab limestone, forming a blanket of debris that occupies much of the outer flanks of the crater. The stratification of the Kaibab formation is found to be inverted here, compared to the undisturbed strata, demonstrating that the cratering process overturned the layers of rock as it lay down the debris. The rim trail proceeds eastward from the lookout.
0.4	The rim trail passes through a field of blocks of Kaibab limestone and dolomite. Note the immense size of those on the outer flanks of the rim, which were thrown out of the crater cavity whole.
0.9	Small exposures of Moenkopi sandstone are found on the inside of the rim, related to small nearly radial faults.
1.2	The trail passes near debris of Coconino sandstone, which lies along much of the southern outer rim. Trees, absent elsewhere in the crater area, grow here.
1.5	Here is the site of the drilling carried out at the rim in 1920–22, when it was hoped that a large meteoritic mass might exist beneath the south rim, assuming that the meteorite entered from the north. Timbers and excavations remain. The cut in the rim shows exposures of breccia related to the faulting that formed this cut.
1.6	The trail divides beyond the drilling site, with one section proceeding along the inner rim and the other on the outer. The inner branch descends a few meters and passes through outcrops of red sandstone.
2.0	Several derelict buildings are encountered on the southern flank of the crater.
2.2	The highest point on the rim is reached.
2.8	The trail descends onto the western outer slope, where it threads its way through huge blocks of Kaibab formation.
3.1	The picturesque ruins of Barringer's

Distance from museum (km)	Features to note
	original museum are passed. From here the old mule trail descends into the crater. A spur trail leads out onto flat shelves of red sandstone, providing a superlative view down into the crater.
3.4	Trail passes above outcrops of uptilted Moenkopi sandstone.
3.7	Return to the museum.

Access: One of the easiest meteorite craters in North America to visit, the Barringer Crater is located about 7 km south of US 66 in northern Arizona, east of Flagstaff. A paved access road leads to an excellent museum, a shop, and a snack bar at the rim of the crater. The crater is privately owned and an admission fee is charged.

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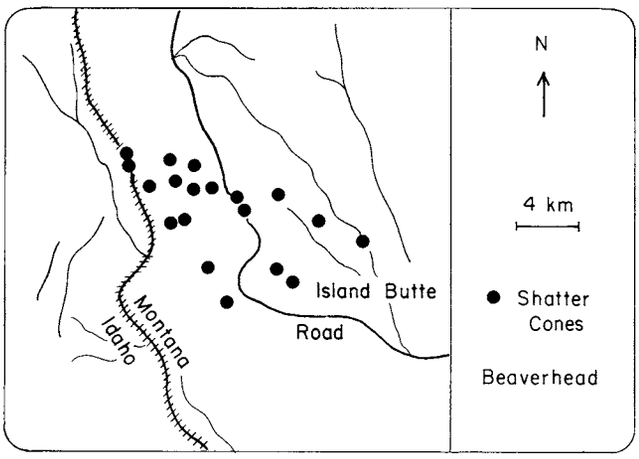
Beaverhead

Montana

Lat/Long: N45° 0′, W113° 0′
Diameter: 15 km
Age: ~600 Ma
Condition: Eroded, partly exposed

The Beaverhead impact structure was only recognized in 1990, having been identified on the basis of the presence of shatter cones in outcrops of a geologically complex area. The shatter cones were found at Island Butte, a mountainous structure at the Montana–Idaho border next to the Continental Divide. The area is marked by many fault zones and includes rocks from the Precambrian to the Cenozoic. The shatter cones are found over an area of approximately 17 km radius, but they all show an identical orientation (with apexes at 90°), and thus it is inferred that the original crater may have been as large as 60 km in diameter. The cones are found in outcrops of Proterozoic sandstones and are absent in adjacent Mississippian rocks, indicating that the impact must have occurred during the late Precambrian or early Paleozoic. Some samples of the sandstones show veins that may be melt flows from impact melting.



BEAVERHEAD: Sketch map of the Island Butte area, showing locations of Beaverhead shatter cones (after Hargraves *et al.*).

Access: The shatter cones are spread out over an area of ~100 km^2 in southwest Montana approximately 50 km west of Interstate 15 and 125 km southwest of Butte, Montana. A mountain road passes through the center of the shattercone field.

References

Hargraves, R. B., Cullicott, C. E., Deffeyes, K. S., Hougen, S., Christiansen, P. P. and Fiske, P. S., 1990, Shatter cones and shocked rocks in Southwestern Montana: the Beaverhead impact structure. *Geology*, *18*, 832–834.

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Bee Bluff

Texas

Lat/Long: N29° 2′, W 99° 51′
Diameter: 2.4 km
Age: <40 Ma
Condition: Partly exposed

This entry is included in the book as an example of the numerous cases of proposed impact structures that have been considered doubtful and that have recently been omitted from authoritative lists of impact structures. The Bee Bluff structure (also called Uvalde) was first proposed as a possible impact site in 1979, when its unusual geology was found to have no other reasonable explanation. Large allocthonous blocks of sandstone and an arcuate rim of possible ejecta, combined with numerous thrust faults were the primary evidence. The suggestion was that the deformed rocks and faulting indicated a crater approximately 2.4 km in diameter. Lamellae found in the sandstone fragments and breccias at the site seemed to indicate formation by impact shock, though they are characteristic of a fairly low pressure shock.

More recent studies have cast considerable doubt on the impact hypothesis for these features. Similar lamellae are present in rocks collected far (135 km) from the site, suggesting that they were not caused by a local event.

Access: The proposed impact feature is located 20 km south of Uvalde, Texas. US highway 83 passes straight through it, bisecting the arc of proposed ejecta material. The east side of the proposed impact rim nearly coincides with a bank of the Nueces River.

References

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Wilson, W. F. and Wilson, D. H., 1979, Remnants of a probable Tertiary impact crater in South Texas. *Geology*, *7*, 144–146.

Calvin

Michigan

Lat/Long: N42°, W86°
Diameter: 7 km
Age: 460 Ma
Condition: Buried

The Calvin Structure was delineated by cores from 107 wells drilled in Cass County, southwestern Michigan. The surface expression of the structure is minimal; a slightly higher topography at the center of the feature shows up because of its influence on the drainage in the area. The entire structure is deep below the present surface, which is underlain by ~100 m of glacial drift that sits on top of 1300 m of Paleozoic strata.

The drilling shows the presence of a central uplift about 400 m high, surrounded by an annular depression about 1 km wide. An anticlinal rim zone, consisting of an annulus 1.5 km wide and several meters high, surrounds this depression. Microbreccia exists in the rocks below the supposed surface of the crater-shaped structure and the fact that it is found in layers of widely differing ages indicates that it was probably formed by an impact.

Shock-metamorphosed quartz grains were identified in 1992 and possible iron-melt spherules were found in the outside walls of the structure.

Access: There is nothing to see at the surface of the Calvin Structure. It is located beneath a portion of Michigan that is easy to reach, however. Adamsville is near one edge of the structure and Calvin Center (12 km by road northeast of Adamsville) is near its center. A chain of six lakes, from Chain Lake to Curtis Lake, lies partly above the north portion of the structure.

References

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