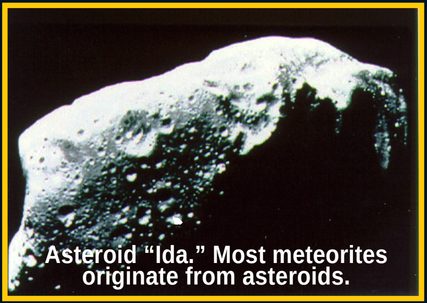
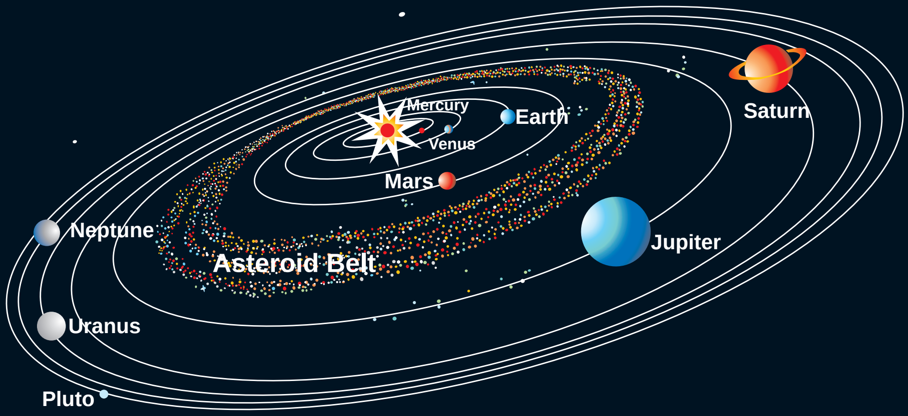


Asteroid "Ida." Most meteorites originate from asteroids.

Meteorite from Clark County, Ky.



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Space Visitors in Kentucky:
Meteorites and Meteorite Impact Sites in Kentucky

William D. Ehmann
with contributions by
Warren H. Anderson

Kentucky Geological Survey
James C. Cobb, State Geologist and Director
University of Kentucky, Lexington

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Special Publication 1 Series XII, 2000

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The Kentucky Geological Survey at the University of Kentucky is a State-mandated organization whose mission is the collection, preservation, and dissemination of information about mineral and water resources and the geology of the Commonwealth. KGS has conducted research on the geology and mineral resources of Kentucky for more than 150 years, and has developed extensive public databases for oil and natural gas, coal, water, and industrial minerals that are used by thousands of citizens each year. The Survey's efforts have resulted in topographic and geologic map coverage for Kentucky that has not been matched by any other state in the Nation.

One of the major goals of the Kentucky Geological Survey is to make the results of basic and applied research easily accessible to the public. This is accomplished through the publication of both technical and nontechnical reports and maps, as well as providing information through open-file reports and public databases.

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FOREWORD

In 1999, Dr. William Ehmann donated part of his meteorite collection to the Kentucky Geological Survey (KGS). The meteorites are housed in the foyer of the Mining and Mineral Resources Building on the University of Kentucky campus. The Kentucky Geological Survey then asked him to write a popular publication on meteorites, and we are grateful for his willingness to write this book and for his contribution to our meteorite display. His generosity will benefit the public for years to come.

Dr. Ehmann, Professor Emeritus in the Department of Chemistry at the University of Kentucky, is highly qualified to write about meteorites, as evidenced by his many publications on the chemical composition of meteorites. His research included studies of the chemical composition of the Apollo Mission lunar samples for NASA.

Twenty-seven documented meteorites have been found in Kentucky, and this book provides photographs and technical descriptions of them. This book, together with the KGS meteorite display, gives the citizens of the Commonwealth a tremendous opportunity to understand these fascinating rocks from space.

Warren H. Anderson
Mineral Curator, Kentucky Geological Survey

ACKNOWLEDGMENTS

The author wishes to acknowledge the assistance of Warren H. Anderson, Kentucky Geological Survey, for his efforts in helping to establish the display of meteorites in the Mining and Mineral Resources Building at the University of Kentucky and for his help with this manuscript. The assistance of Maggie Johnson in literature searches and Carleton B. Moore, Center for Meteorite Studies, Arizona State University, in providing photographs is also appreciated.

The cover illustrations are a NASA artist's conception of our solar system (NASA Johnson Space Center, S79-29468); a photograph of asteroid Ida taken by the Galileo spacecraft (NASA Jet Propulsion Laboratory); and a NASA artist's conception of a meteor streaking through space (NASA Johnson Space Center, S79-29471).

Space Visitors in Kentucky:

Meteorites and Meteorite Impact Sites in Kentucky

William D. Ehmann[1]

WHAT ARE METEORITES?

Meteorites are natural objects from space that survive their passage through the atmosphere to land on the Earth. The term "meteor," often confused with "meteorite," refers only to the visual phenomena in the sky when showers of small particles, principally from comets, intersect the atmosphere. An object becomes a meteorite when at least part of it reaches the Earth's surface, where it can be collected. Most meteorites are solid rock material and are believed to originate from collisions between objects in the asteroid belt between Mars and Jupiter in our solar system. Recently, a few meteorites have been identified that appear to have originated from the Moon and Mars.

Comets are composed of solid particles and frozen gases such as water, ammonia, and methane. They are common in the outer solar system and periodically orbit the Sun, meaning that they have semi-regular periods where they can be observed as they fly close to the Earth. The volatilization of the frozen gases as comets approach the Sun results in spectacular celestial sights as they pass by the Earth. Sometimes comets intersect the atmosphere or collide with the Earth. Because comets are largely gaseous, evidence of their earthly impact is not easy to find or substantiate.

Early Greek philosophers suggested that meteorites were "gifts from God" or "iron from Heaven" (Bagnall, 1991). Diogenes of Apollonia in the 4th century B.C. described meteorites as "invis-

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[1] Professor Emeritus, Department of Chemistry, University of Kentucky

ible stars that fell to Earth" (Bagnall, 1991, p. 1), but his views were not widely accepted. Thomas Jefferson stated, "I could more easily believe two Yankee professors would lie, than that stones fell from the sky" (Cerf and Navasky, 1998, p. 320). Not until the L'Aigle meteorite was observed to fall in France in 1803 did an important scientific body, the French Academy of Sciences, accept that "cosmic bodies" had actually fallen from space (Biot, 1806).


Artist's rendering of meteorite fall in France in 1883. Original by Poyet. Reproduced in *The Arizonian* newspaper, April 17, 1969, p. 18–19.

Prior to 1969, only about 5,000 meteorites had been collected. In 1969 a group of Japanese scientists discovered concentrations of meteorites in blue glacial ice in Antarctica. Scientists from the United States and Europe quickly joined the ongoing recovery effort. At this writing, more than 16,000 pieces of meteorite have been collected in Antarctica, although not all the pieces represent individual falls. A list of the largest meteorite collections has been recently published by Sears (1996). The five largest collections of meteorites are in the National Institute of Polar Research, Tokyo; the Johnson Space Center, Houston; the U.S. National Museum, Washington, D.C.; the Naturhistorisches Museum, Vienna; and the Natural History Museum, London. Other large collections in the United States are in the Arizona State University Center for Meteorite Studies, Tempe; the American Museum of Natural History, New York; and the Field Museum of Natural History, Chicago. The U.S. National Museum, the Field Museum of Natural History, and the Center for Meteorite Studies contain many Kentucky meteorites. The Kentucky Geological Survey has a small collection in the foyer of the Mining and Mineral Resources Building on the University of Kentucky campus.

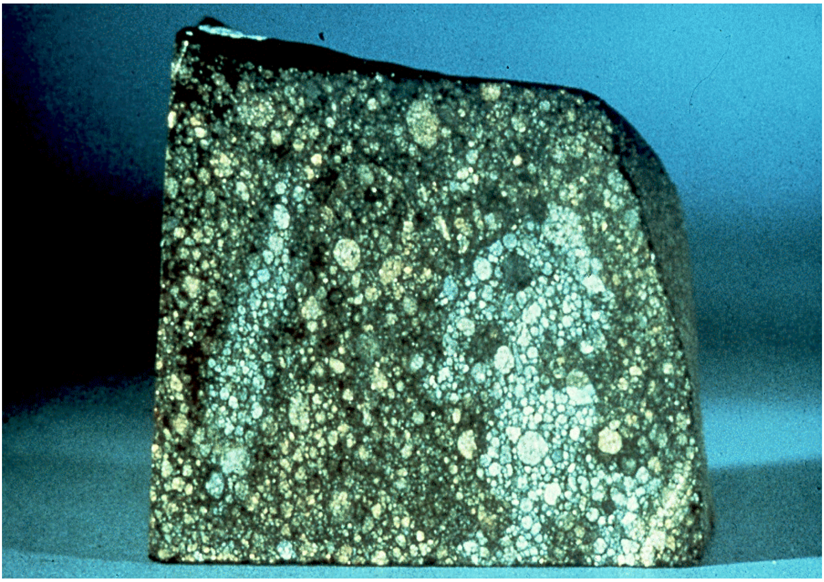
HOW ARE METEORITES CLASSIFIED?

Most meteorites may simply be described as either stony or metallic in appearance, although some are nearly equally stony or metallic. The three major categories are *stones, stony-irons,* and *irons* *(siderites).* Meteorites can be further classified on the basis of their mineralogy, chemical composition, texture, and volatile contents. More than 100 minerals have been identified in meteorites.

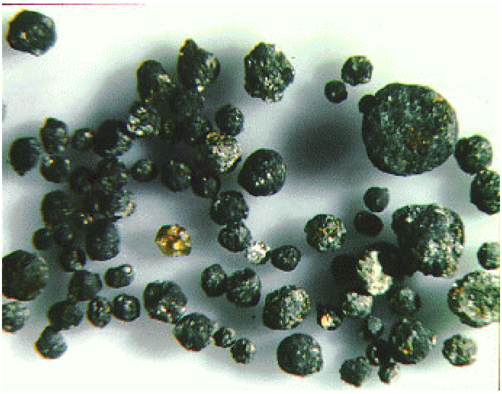
A detailed description of all meteorite classes is beyond the scope of this publication, so only brief descriptions of the most common types are presented here. The list of Kentucky meteorites in the next section will denote the classification type for each meteorite.

Stones

Chondrites. These meteorites are composed mainly of silicate minerals (for example, orthopyroxene, olivine, and plagioclase). They often contain metallic inclusions of iron-nickel alloys, and minor amounts of many other minerals (sulfides, graphite, phosphorus minerals, microscopic diamonds, etc.). Chondrites constitute approximately 85 percent of observed meteorite falls. Most chondrites are characterized by rounded silicate mineral or glassy inclusions, called *chondrules,* within a stony matrix. Chondrules typically range in size from a fraction of a millimeter up to a centimeter in



Mezö-Madaras L-group chondrite that fell in Romania in 1852. Photo courtesy of the Center for Meteorite Studies, Arizona State University.



Chondrules. The largest is about 1 centimeter in diameter. NASA Johnson Space Center photo S93-33279 by A. Treiman.

diameter. They show evidence of having been partially or completely melted and often have a droplet shape.

Chondrites are divided into different subgroups based on their chemical composition and mineralogy. The subgroups may be further divided into petrologic types based on degree of reheating.

Enstatite (E-group) chondrites are those in which most of the iron occurs in the metallic inclusions as an iron-nickel alloy. The meteorite may be up to 28 percent metallic. The major silicate mineral present is enstatite ($(Mg,Fe)SiO_3$), a member of the orthopyroxene silicate mineral family. The iron content of the silicates is variable and relatively low. Although classified as chondrites on the basis of their bulk chemical composition, not all E-group meteorites have chondrules. Enstatite chondrites are rare and make up only about 1.5 percent of all observed meteorite falls.

Olivine-bronzite (H-group) chondrites generally consist of approximately equal amounts of bronzite, an orthopyroxene with a higher iron content than enstatite, and olivine ($(Mg,Fe)_2SiO_4$), a mineral that in meteorites is richer in magnesium than in iron. They are made up of approximately 16 to 21 percent iron-nickel alloy and many accessory minerals. H-group chondrites constitute about 32 percent of observed falls.

Olivine-hypersthene (L-group) chondrites are the most common subtype. They are mineralogically similar to H-group chondrites, but typically are less than 10 percent metallic. Iron content is greater for L-group silicate minerals than for H-group silicate minerals. L-group chondrites constitute about 39 percent of observed falls.

Amphoterite (LL-group) chondrites are the most oxidized members of the chondrite group and have both a low bulk iron content and a low metallic content (typically less than 3 percent). The principal minerals are bronzite and olivine. They were originally grouped with the L-group chondrites. LL-group chondrites make up about 7 percent of observed falls.

Carbonaceous (C-group) chondrites are rich in carbon (up to approximately 4 percent as organic compounds) and hydrated minerals. Complex molecules such as amino acids have been identified in these meteorites, which are relatively rare, friable, and constitute less than 4 percent of observed falls. They are typically black, have a relatively low density, and have almost a total absence of metal. Carbonaceous chondrites may exhibit relatively high contents of rare gases, such as xenon.

The C-group chondrites differ in their total carbon content and the degree of heating to which they have been exposed. They are regarded as the most primitive category of meteorites. C-group chondrites are further divided into the subgroups CI, CM, CO, and CV; the second letter designates a specific meteorite that is characteristic of the subgroup (Ivuna, Mighei, Ornans, and Vigarano). CI chondrites are high in complex organic compounds and mixtures of low-temperature mineral assemblages, but do not contain chondrules. Both CI and CM chondrites contain clay-like minerals and sulfates, which suggests they may have been deposited from aqueous solutions. CM chondrites differ from CI chondrites because they contain chondrules and refractory (high-temperature origin) mineral inclusions. CI and CM meteorites may have originated in the nucleus of a comet. CO chondrites are noted for their abundant, close-packed, small chondrules, and they also contain calcium- and aluminum-rich inclusions (CAI's). CAI's are composed of highly refractory minerals and may be relicts of the first material to condense from the original cooling solar nebula during the formation of the solar system. CV chondrites contain millimeter-size CAI's and may have large chondrules that contain sulfur and metal dispersed in an olivine matrix.

Achondrites. These meteorites are predominantly silicate and are without chondrules. They have little or no metallic content (typically less than 1 percent). Some of these meteorites are believed to have originated on the Moon and Mars. Shergottites, nakhlites, and chassignites (known as SNC meteorites) are grouped together as being most probably from a relatively large planet such as Mars, rather than from the asteroid belt. Some achondrites closely resemble remelted or recrystallized chondrites. Others appear to be breccias (stones composed of compacted fragments of materials from one or

Sioux County, Nebr., achondrite. Note the black glassy fusion crust (caused by friction melting its outer layer) and lighter interior. Photo courtesy of the Center for Meteorite Studies, Arizona State University.

a variety of sources). Some of the brecciated achondrites are believed to come from the Moon. Achondrites are often hard to identify as meteorites because they resemble terrestrial rocks, especially basalts and dolerites. They constitute only 7 to 9 percent of observed falls.

Achondrites are divided into two major subgroups based on their calcium content and their relative proportions of iron and magnesium oxides, although there may not be any direct relationship between the meteorites in a given subgroup. The major subgroups are further divided based on their mineralogy, texture, and bulk chemistry.

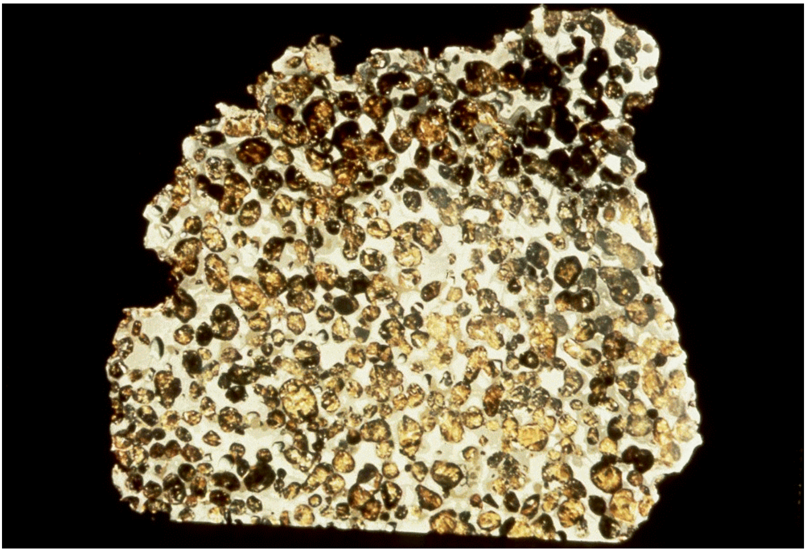
Calcium-poor achondrites typically contain 0 to less than 3 percent calcium. Their silicates are magnesium-rich. Minor amounts of iron-nickel alloys and troilite (FeS) may be present. This subgroup includes the aubrites, diogenites, chassignites, and ureilites. Aubrites are composed of enstatite that is nearly pure $MgSiO_3$. Ureilites contain minor amounts of very fine-grained carbon in the forms of graphite and diamond. They also contain more metal than other achondrites.

Calcium-rich achondrites contain up to 18 percent calcium. This subgroup includes the angrites, nakhlites, eucrites, shergottites, and howardites. Eucrites are the most common type of achondrite. They are often breccias and may contain a small amount of metal. They are chemically similar to basalts from the Moon. Howardites are the second most common achondrites. They are usually breccias made up of components that may originate both from other achondrites and from chondrites. Angrites, nakhlites, and shergottites are quite rare and may be represented by only one or a few meteorites.

Stony-Irons

These are meteorites containing approximately equal amounts of metals and silicates. Only about a dozen falls have been recorded in the world, and one of these was in Kentucky. Subtypes include:

Pallasites. These meteorites consist of an iron-nickel matrix in which are imbedded large (up to 1 centimeter in diameter) inclusions of olivine. Metals and silicates are often present in nearly equal amounts. They are regarded as the most attractive type of meteorite and are prized by collectors, but they constitute less than 1 percent of falls. A subtype of pallasite is based on the Eagle Station meteorite, found in Carroll County, Ky.



Springwater, Canada, stony-iron meteorite. Note yellow crystals of olivine dispersed in the iron-nickel matrix. Photo courtesy of the Center for Meteorite Studies, Arizona State University.

Siderophyres. This subtype is represented by only one meteorite, the Steinbach meteorite. It resembles a pallasite, but its silicate inclusions are aggregates of orthopyroxene (bronzite) and tridymite (SiO_2).

Lodranites. This subtype is also represented by only one meteorite, the Lodran meteorite. Its silicates consist of olivine and bronzite.

Mesosiderites. These stony-irons contain various pyroxenes and plagioclase ($(Na,Ca)(Al,Si)_4O_8$) as the major silicates. These meteorites have approximately equal amounts of metals and silicates. The metals are irregularly distributed in granular inclusions, not as a solid matrix, as in the pallasites. They represent less than 1 percent of observed falls.

Irons (Siderites)

Siderites are metallic meteorites made up of a matrix of iron-nickel alloys. They commonly have inclusions of graphite and troilite. These meteorites are easily identified and are heavily represented in collections. They occur in about 5 percent of observed falls.

Subtypes are based on chemical composition, especially the nickel, gallium, germanium, and iridium contents. The crystalline structure is also a factor in their classification.

Hexahedrites. These siderites consist of large body-centered, cubic (hexahedron) crystals of kamacite, an iron-nickel alloy. They have a typical bulk composition of 93 percent iron, 5 percent nickel, and 0.5 percent cobalt. The remainder consists of small amounts of many other minerals (such as phosphorus minerals, carbon, and sulfur).

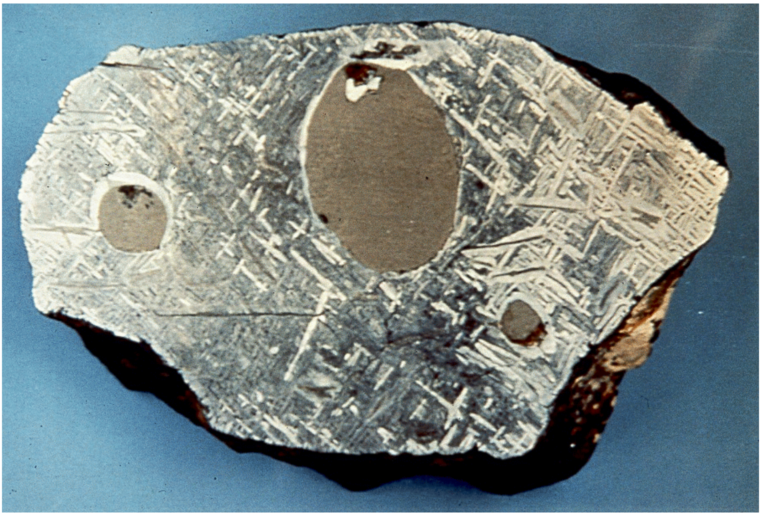
Octahedrites. The most common type of iron meteorite, they are further classified according to the width of the kamacite bands, as coarsest, coarse, medium, fine, or finest. They exhibit a pattern of bands of kamacite and taenite (another iron-nickel alloy that is 27 to 65 percent nickel); this pattern is called Widmanstatten structure. The bands intersect each other at different angles in three dimensions. The bulk nickel contents of octahedrites range from 6 to 14 percent. The highest nickel content is found in the finest-width kamacite bands.

Nickel-Rich Ataxites. These iron meteorites have narrower bands of kamacite than octahedrites do and no Widmanstatten structure. The nickel content is greater than 14 percent and may reach 25 percent. These meteorites are very rare, and no one has ever seen a nickel-rich ataxite fall.

How Do I Identify a Meteorite?

If someone sees a meteorite fall and promptly collects it, identification is normally obvious. Some meteorites have actually fallen through roofs and on cars! When they hit the ground, meteorites can form impact craters. Associating a suspected meteorite with an impact crater significantly aids in its identification. Meteorites whose falls are observed are described as "falls." They are the most desirable for scientific study because they are usually quickly collected and have not been subjected to weathering.

Many more meteorites are collected that no one saw fall. These are called "finds." Finds can often be identified simply by their physical appearance and bulk properties. Many meteorites are quite dense and will feel heavy compared to terrestrial rocks or pieces of slag of similar size. Iron meteorites and many stony meteorites have abun-



Sanderson, Tex., iron meteorite (octahedrite). Note the Widmanstatten pattern and the large inclusions of troilite. Photo courtesy of the Center for Meteorite Studies, Arizona State University.

dant inclusions of metal, so they will be attracted to a magnet. Of course, some man-made materials are also magnetic, so this test is not definitive. Pieces of blast-furnace slag may be slightly magnetic and are commonly mistaken for meteorites. Slag may be found many miles from the original furnace site. Many small furnaces operated throughout Kentucky during the Civil War, and pieces of slag are still turned up in plowed fields.

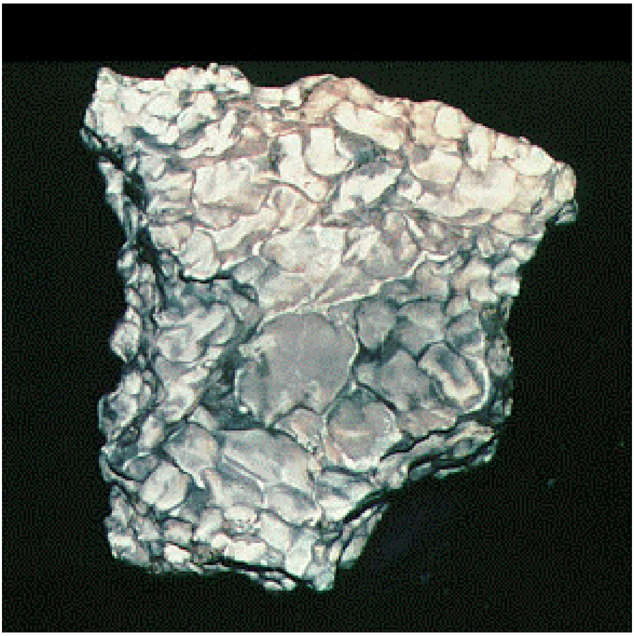
Because nickel is present in the metallic portion of all meteorites, its absence is strong evidence that the object is not a meteorite. If a small bit of metal can be filed or cut from the suspected meteorite, or extracted with a magnet from powdered stone, a simple chemical test can be used to detect nickel. A bit of the metal is carefully dissolved in nitric acid, and the solution is then neutralized with ammonium hydroxide solution until it is alkaline (turns litmus paper blue). A few drops of a solution of dimethylglyoxime in alcohol are added, and if nickel is present, a red precipitate will form. The presence of nickel, however, is still not absolute proof that an object is a meteorite, because some man-made alloys also contain nickel.

Most stone meteorites (as opposed to iron meteorites) become coated with a smooth crust a few millimeters thick when they pass through the Earth's atmosphere; the crust is caused by friction melting the outer layer of the stone. The presence of a fusion crust is strong evidence that a stony object is a meteorite. Fusion crusts may be fragile and can flake off on exposure to the weather. Even badly weathered stony meteorites that have lost their fusion crusts may still retain a cone-like shape caused by ablation (loss of material caused by friction) as the meteor passes through the atmosphere in a straight line. Other meteorites may tumble during entry and take on a rounded shape.

Archie, Mo., stony meteorite with black fusion crust (at left) and lighter-color interior (right). Photo courtesy of the Center for Meteorite Studies, Arizona State University.

Slices of the interior of a weathered stony meteorite can be examined for the presence of chondrules and iron-nickel inclusions to confirm identification. Because they resemble terrestrial rocks, achondrites that have lost their fusion crusts are the hardest meteorites to identify. In difficult cases, only detailed chemical and mineralogical analyses will firmly identify a stony object as a meteorite. Geologists at Kentucky universities and the Kentucky Geological Survey can help you identify meteorites.

Iron meteorites have no obvious fusion crusts, but may have striations that look like trails or color streaks on their surface. These marks are caused by the flow of melt from the leading edge toward the rear of the meteorite during entries in which the meteorite does not rotate appreciably. Many iron meteorites also have depressions on their surfaces that resemble thumbprints. These depressions, called regmaglypts, are usually caused by selective ablation of lower-melting minerals (such as troilite) from the surface of the meteorite when it enters the atmosphere. Sometimes Widmanstatten patterns can even be discerned on the weathered surfaces of iron meteorites. Stony-iron meteorites have an appearance that is unique in nature and are the easiest of all meteorites to identify.



Iron meteorite exhibiting regmaglypts. NASA Johnson Space Center photo S94-43472 by C. Allen.

HAVE METEORITES BEEN COLLECTED IN KENTUCKY?

At least 27 meteorites have been independently collected, named, and properly identified in Kentucky. They are listed below in alphabetical order. Two of these, however, the Hustonville and Williamstown meteorites, are now believed to be identical to other nearby falls. Many others were probably collected, but are still undocumented. They may be currently thought of as unusual rocks or pieces of iron and may be used as doorstops or boot scrapers. Names, descriptions, locations, coordinates, and masses listed in this publication are in most cases those given in the fourth edition of "Catalogue of Meteorites" (Graham and others, 1985). This edition of the catalogue updates, with some corrections and additions, earlier editions. Classifications in parentheses are from the "Catalogue of Meteorites" or "Meteorites: Classification and Properties" (Wasson, 1974). Geographical coordinates given here may vary slightly from those given in the earliest publications. None of the Kentucky meteorites have been confirmed to be from the Moon or Mars.

"The Geology of Kentucky," by A.M. Miller (1919a) describes many of the falls that occurred in Kentucky during the mid-1800's, including his personal witnessing of the fall of the Bath Furnace meteorite in Bath County. Additional details of many of the early Kentucky finds and falls may be found in the "Catalogue of Meteorites of North America" (Farrington, 1915). This publication has excerpts from many early publications that may now be hard to locate. Included are descriptions of fireballs associated with the falls, specific locations of collection, analyses, and the distribution of the specimens.

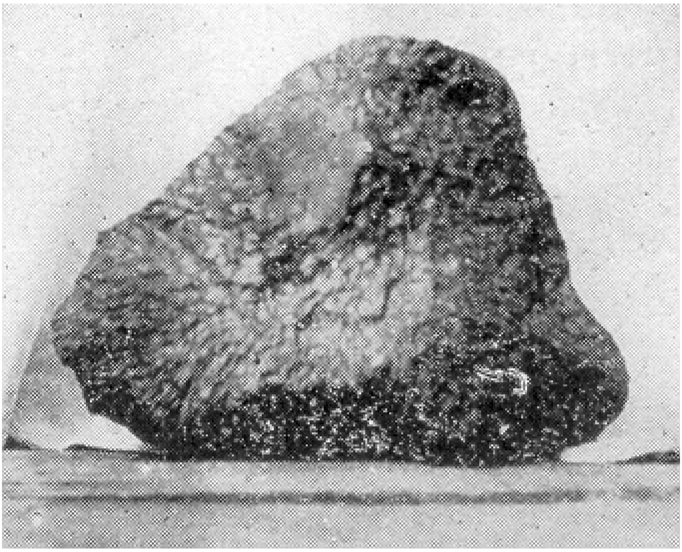
At least one original reference for each Kentucky meteorite is listed below. More recent publications mentioning each meteorite may be found in the "Catalogue of Meteorites."

1. Bath Furnace (Stone), Bath County (38°15'N, 83°45'W)

This spectacular meteorite fell November 15, 1902, at 6:45 P.M. The brilliant fireball was observed by people in seven states, including A.M. Miller of the Kentucky Geological Survey, who described the fall and subsequent recovery of this meteorite (Miller, 1903a, b). The largest mass was not found until the following spring. The first stone was collected by a man who saw it fall on a road 5 miles south of Salt Lick. It is classified as an olivine-hypersthene chondrite (petrologic type L6). Stones of 0.5, 13, and 178 pounds were eventually recovered, the largest about ¾ mile south of the original recovery. See Ward (1903).

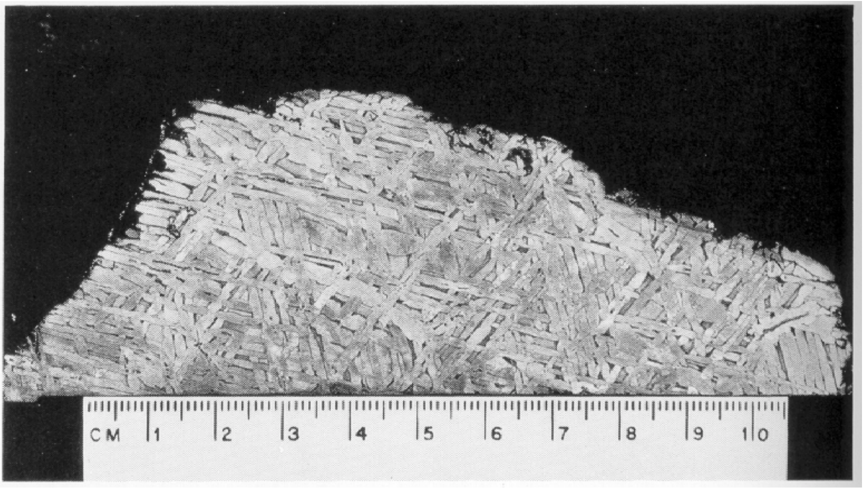
2. Burnwell (Stone), Pike County (37°37'19"N, 82°14'14"W)

On September 4, 1990, at 3:45 P.M., this stone fell through the roof and porch of the home of Arthur and Frances Pegg, near the town of Burnwell. It is most similar to an olivine-bronzite chondrite (petrologic type H4), although it is somewhat anomalous in mineralogy and has a higher iron-nickel content than ordinary H-group chondrites. A stone of approximately 3.3 pounds was collected and is currently on display at the Smithsonian Institution in Washington, D.C. See Russell and others (1998).



Bath Furnace meteorite. Photo by A.M. Miller (1919a).

3. Campbellsville (Iron), Taylor County (37°22'N, 85°22'W)



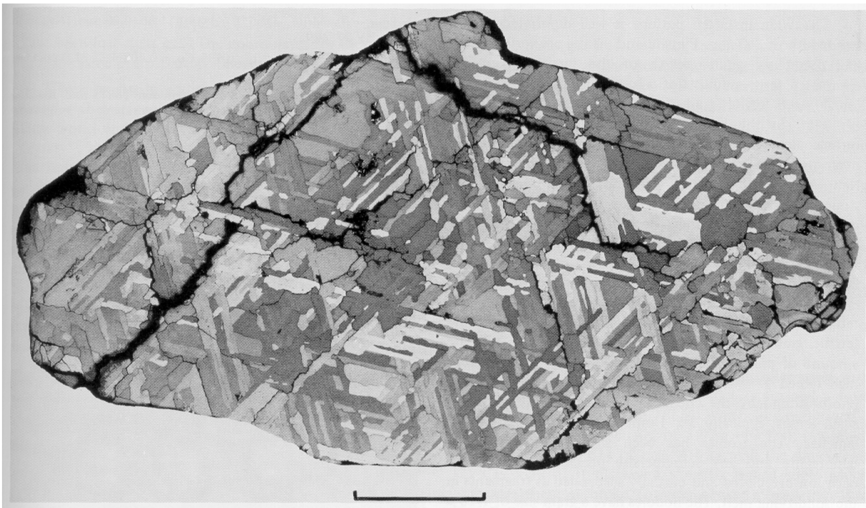
Campbellsville meteorite. Specimen courtesy of C.B. Moore. Photo by Buchwald (1975), courtesy of the Center for Meteorite Studies, Arizona State University.

This find collected in a plowed field on Stoner Creek in June 1929 was acquired by the University of Kentucky in 1939 and permanently loaned to the U.S. National Museum in 1968. It is classified as a medium octahedrite (subtype IIIB) and has a good Widmanstatten pattern. One corroded iron mass of 34 pounds was recovered. See Young (1939) and Buchwald (1975).

4. Casey County (Iron) (37°15'N, 85°0'W)

A find known before 1877, acquired by J.L. Smith, it is classified as a coarse octahedrite (subtype IA); it is very corroded with a limonite crust. Some specimens may have been artificially heated. This iron meteorite may be identical to the Hustonville meteorite. The original mass is unknown, but approximately 732 grams was originally reported to be in collections. Harvard University has a chisel made from this mass. See Smith (1877b) and Buchwald (1975).

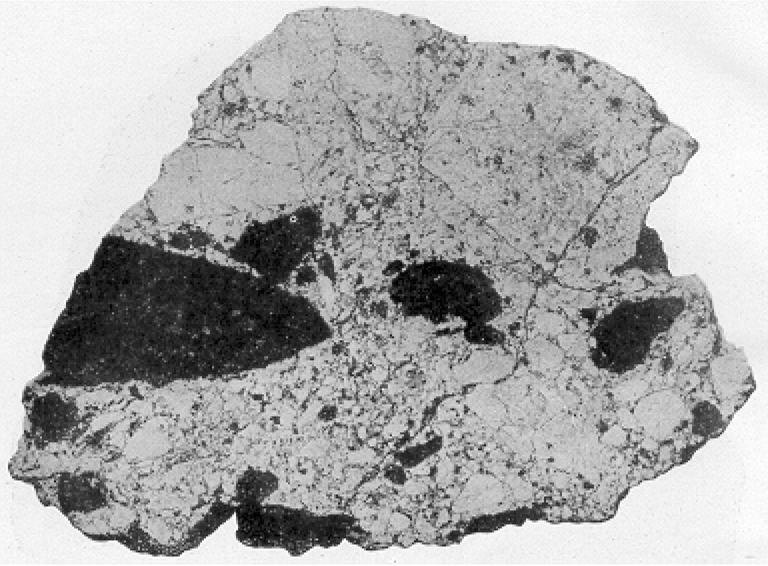
5. Clark County (Iron) (38°0'N, 84°10'W)



Clark County meteorite. Photo by V.F. Buchwald (1975, Fig. 632), courtesy of the Center for Meteorite Studies, Arizona State University.

A find known many years before 1937, its exact location is not known, but it did come from southern Clark County. This mass is shaped like a flattened ellipsoid, it is heavily corroded, and has a good Widmanstatten pattern. It is high in chromium and has uniform Neumann bands, which are fine straight lines etched on the surface (not visible in this photo). It is chemically and structurally similar to the Nelson County find (number 21, below), and is classified as a medium octahedrite (subtype IIIF). One iron mass of 25 pounds was recovered. See Nininger (1939) and Buchwald (1975).

6. Cumberland Falls (Stone), Whitley County (36°50'N, 84°21'W)



Cumberland Falls meteorite. Photo by G.P. Merrill (1920).

The meteor that produced this fall was one of the more prolific to streak through the Kentucky skies and was observed by numerous persons in eastern Tennessee and southern Kentucky. This mass fell April 9, 1919, at noon near Sawyer in Whitley County. The fireball left a trail of smoke and sonic booms that were heard by several people. One witness was the postmaster of Sawyer, W.H. Morgan, who stated that one of the four fragments "whizzed past his head" (Miller, 1919a, p. 111). He later recovered the fragment. At one time these specimens were in the possession of W.R. Jillson, former State Geologist of Kentucky. A.M. Miller, a geologist with the Kentucky Geological Survey, asked the press and other observers to help him try to determine the direction and fall location when he heard about the fall. He determined it to be in the vicinity of Cumberland Falls and found that 45 pieces had been recovered. Apparently, a large piece hit the conglomerate at Cumberland Falls and shattered. It is classified as a breccia of a white aubrite achondrite and black enstatite chondrite. Several stones totaling 31 pounds were recovered. See Miller (1919a, b) and Merrill (1920).

7. Cynthiana (Stone), Harrison County (38°24'N, 84°15'W)

On January 23, 1877, at 4:00 P.M., a brilliant meteor display was observed in Monroe County, Ind., and Harrison County, Ky. This stone is classified as an olivine-hypersthene chondrite (petrologic type L4). A farmer heard the meteorite strike the ground approximately 9 miles from Cynthiana and recovered a stone of approximately 13 pounds. See Smith (1877a).

8. Eagle Station (Stony-Iron), Carroll County (38°37'N, 84°58'W)

Found in 1880 about ¾ mile from the town of Eagle Station, this specimen is the only known example of the pallasite subclassification called the Eagle Station Group. Although it looks similar to other pallasites, oxygen isotope data indicate it is different (McSween, 1987). A mass of approximately 80 pounds was recovered. Fragments believed to be from this meteorite were also found in the Turner Mounds in the Little Miami Valley, Ohio. See Kunz (1887) and McSween (1987).

9. Edmonton, Kentucky (Iron), Metcalfe County (37°2'N, 85°38'W)

Found in 1942 and acquired by the U.S. National Museum in 1943, this mass has an irregular and distorted shape caused by atmospheric sculpturing. It is classified as an anomalous fine octahedrite (subtype IIICD). This mass has a high nickel content, kamacite and taenite banding, and contains schreibersite ($(\mathrm{Fe,Ni})_3\mathrm{P}$). A rusted mass of approximately 22 pounds was recovered, parts of which were artificially heated and sliced to show the well-developed Widmanstatten pattern. See Henderson and Perry (1947) and Buchwald (1975).

10. Frankfort (Iron), Franklin County (38°12'N, 84°50'W)

Found in 1866 on a hill 8 miles southwest of Frankfort, it is classified as a medium octahedrite (subtype IIIA). One mass of 24 pounds was identified in a Frankfort blacksmith shop. See Smith (1870) and Buchwald (1975).

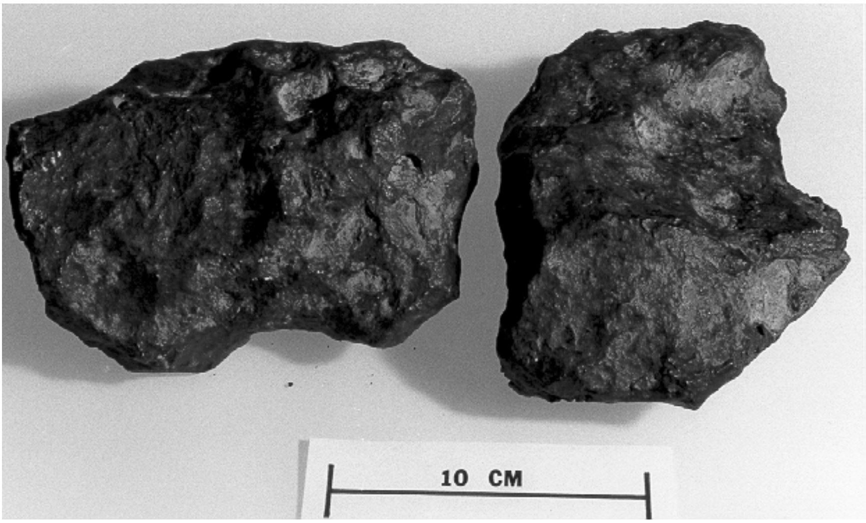
11. Franklin (Stone), Simpson County (36°43'N, 86°34'W)

Found in 1921 but not recognized until 1956, it is classified as an olivine-bronzite chondrite (petrologic type H-5). A stone of approximately 20 pounds was recovered. See Leonard (1957).

12. Glasgow (Iron), Barren County (37°1'N, 85°55'W)

This mass was found in a plowed field in 1922, and was sent to the U.S. National Museum. It was very corroded, and by 1975 had disintegrated into a pile of small pieces. It was photographed and classified as a medium octahedrite (subtype IIIA). It has shock-hardened kamacite with troilite nodules. Two masses of 20 and 25 pounds were recovered. See Merrill (1922, 1923) and Buchwald (1975).

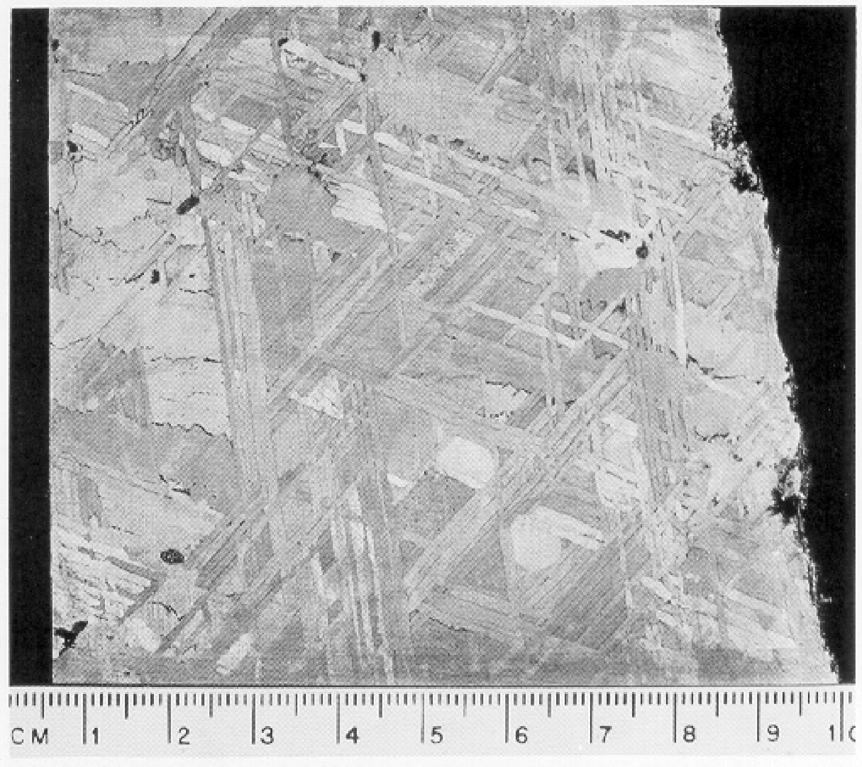
13. Hustonville (Iron), Lincoln County (37°28'N, 84°49'W)



Hustonville meteorite. Photo by W.D. Ehmann.

The date it was found is unknown. It was purchased from a shopkeeper by a Mr. Goins. His wife, Dorothy Estes Goins, later of Lexington, Ky., entrusted a piece to Lon Clay Hill at the University of Texas, who sent it to Arizona State University for cutting and identification. Mrs. Goins retained some of the meteorite, and small amounts were distributed for research. It is classified as a coarse octahedrite. The site is close to the Casey County find of around 1877, and these two meteorites are probably from the same event. Individual pieces of 9 and 10 pounds were known. Referenced in a letter from Lon Clay Hill to W.D. Ehmann in 1979.

14. Kenton County (Iron) (38°49'N, 84°36'W)



Kenton County meteorite. Photo courtesy of C.B. Moore. Photo by Buchwald (1975), courtesy of the Center for Meteorite Studies, Arizona State University.

Found in 1889, buried 3 to 4 feet below ground level, about 8 miles south of Independence, it was purchased by Wards Natural Science Establishment and sold by the slice. It is classified as a medium octahedrite (subtype IIIA), and the kamacite bands show "hatching": evidence of shock deformation. Carlsbergite (CrN), a rare mineral, is well formed in this meteorite. A mass of approximately 359 pounds was recovered. The Williamstown meteorite collected nearby in 1892 is believed to be identical in structure, chemical composition, and state of corrosion, and is most likely derived from the same parent meteorite that broke apart upon entrance into the atmosphere. See Preston (1892) and Buchwald (1975).

15. La Grange (Iron), Oldham County (38°24'N, 85°22'W)

Found in October 1860 near La Grange, this flattened, elongate mass is turtle-shaped and smooth. It was acquired by J.L. Smith in 1861, who distributed one-third of it to various museums. It is classified as a fine to finest octahedrite (subtype IVA), contains troilite, and has interesting zigzag features, which may represent fissuring of the mass and injection of troilite melts. The Widmanstatten structure is distorted, and has minute faulting and folding structures, implying that the meteorite underwent some form of cold deformation. A mass of 112 pounds was recovered. See Smith (1861).

16. Louisville (Stone), Jefferson County (38°15'N, 85°45'W)

On January 31, 1977, at 3:30 P.M., several persons witnessed this fall as it traveled east to west (S87°W) near Louisville. The meteor was visible for several kilometers and fragmented into four distinct pieces, some of which struck homes and cars. The bolide (exploding meteor) was described as reddish- or bluish-white with an orange tail, and detonations sounded like firecrackers or rockets exploding. It was observed as far away as the Kentucky-Tennessee border. It has a fusion crust, some shock metamorphic banding, and is classified as an olivine-hypersthene chondrite (petrologic type L6). Stones totaling approximately 3 pounds were recovered. See Hunt and Boone (1978).

17. Marshall County (Iron) (37°0'N, 88°15'W)

A find first described in 1860, its exact location is unknown. It was collected by J.L. Smith and is classified as a medium octahedrite (subtype IIIA). A mass of 15 pounds was reported, which was corroded; some of the kamacite bands had been distorted by being heated in a forge and manipulated with a sledgehammer. See Smith (1860) and Buchwald (1975).

18. Monticello (Stone), Wayne County (37°57'N, 84°54'W)

Found on May 29, 1982, on the shore of Lake Cumberland, it is classified as a howardite achondrite. A single gray and unweathered specimen weighing 210 grams was recovered. A fusion crust was absent. See Olsen and others (1987).

19. Mount Vernon (Stony-Iron), Christian County (36°56'N, 87°24'W)

A find known by 1868 and described in 1903 by E.O. Ulrich (Merrill, 1903, p. 157) of the U.S. Geological Survey, it is classified as a pallasite, primarily olivine with a cementing of iron, the exterior of which was oxidized. A mass of 351 pounds was recovered approximately 7 miles northeast of Hopkinsville. It is now on exhibit at the U.S. National Museum. See Merrill (1903).

20. Murray (Stone), Calloway County (36°36'N, 88°6'W)

This meteorite fell on September 20, 1950, at 1:35 A.M. Stones totaling approximately 28 pounds were eventually recovered near Wildcat Creek, 9 miles east of Murray. The Murray meteorite is unusual because it is very organic and gas rich and one of the largest classified as a carbonaceous chondrite (subtype CM2).

Amino acids found in carbonaceous chondrites may be evidence of microbial biogenic activity. Analysis of this meteorite has identified 17 amino acids, seven of which contain D and L isomers (D and L isomers have the same chemical composition, but different molecular structure). Eleven of these amino acids are not found in terrestrial protein, which implies that they are extraterrestrial. The Murchison meteorite, another carbonaceous chondrite (CM2), which fell in Australia in 1969, also contains amino acids.

Gases in this meteorite are divided into two categories: “solar” or light rare gases (helium and neon) and “primordial” or heavier gases (argon and xenon). Gases in the Murray meteorite are primarily solar and are similar in composition to the solar wind.

Water in the Murray meteorite has a very high deuterium to protium ratio, a ratio dissimilar to that of terrestrial water. This suggests that the water in the meteorite must be extraterrestrial.

Analysis of silicon carbide from isotopically anomalous acid residues of the meteorite suggests that the silicon carbide in the Murray meteorite is of interstellar pre-solar system origin. Additional analysis of the residues indicates that an amorphous oxide alteration also occurred in the meteorite. Isotopic anomalies for silicon, nitrogen, and carbon indicate that these mineral grains may be circumstellar grains from carbon-rich stars.

Mass spectrometry isotopic analysis of rhenium and osmium indicates that the Murray meteorite may have been formed from different, earlier precursor materials than iron meteorites formed from. These data also suggest that aqueous leaching may have occurred during the meteorite's preterrestrial history.

Evidence indicates that the Murray meteorite is a very early cosmic body, formed in a primordial interstellar nebula of the solar system, before the planets were formed. Thus, the Murray meteorite predates the solar system, and some of its silicon carbide grains are being used to date the Milky Way galaxy. See Boata (1954), Wiik (1956), Mazor and others (1970), Lawless and others (1971), Bernatowicz and others (1987), Zinner and others (1987), and Walker and Morgan (1989).

21. Nelson County (Iron) (37°45'N, 85°30'W)

The exact location is not known, but it was found in a plowed field in 1856 and first described in 1860. It is classified as a coarsest octahedrite (subclass IIIF). This meteorite underwent some plastic deformation prior to its impact. The kamacite bands were deformed, the troilite showed twinning, and the taenite bands were sheared, all indicative of plastic deformation. Fractures and the partial plastic flow indicate a violent deformation of this meteorite. The plastic deformation and low phosphorus content make this meteorite unique. A mass of 161 pounds was collected, and parts of this meteorite are in over 25 major collections around the world. See Smith (1860) and Buchwald (1975).

22. Providence (Iron), Trimble County (38°34'N, 85°14'W)

Found in 1903 and described in 1939, it is classified as a medium octahedrite (subtype IIIA) and was extensively weathered when found. A mass of approximately 15 pounds was recovered; it has a large troilite nodule on the surface. See Young (1939) and Buchwald (1975).

23. Salt River (Iron), Bullitt County (37°57'N, 85°47'W)

Found about 1850, approximately 20 miles south of Louisville, the meteorite was later heated in a forge, which caused some alteration, melting, and resolidification of the original mineral material. It is classified as a finest octahedrite (subtype IIC). A mass of approximately 8 pounds was recovered. Several Salt River specimens were mislaid around 1900 and were mislabeled Tocavita, Columbia, material. See Silliman (1851) and Buchwald (1975).

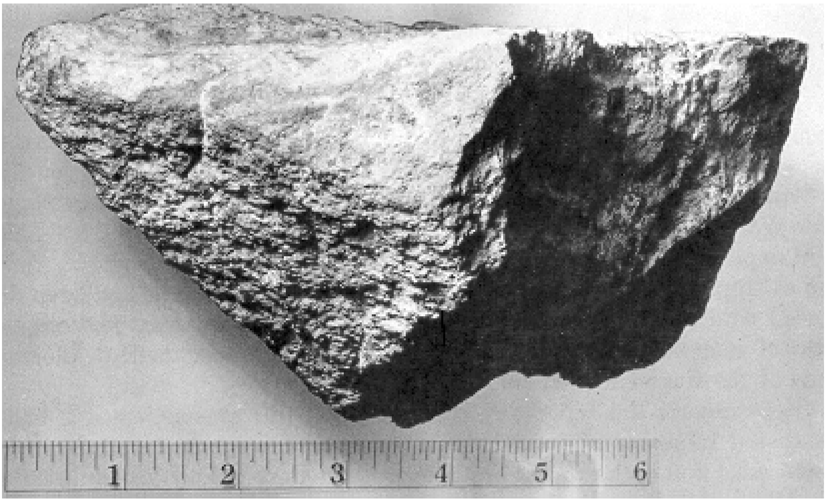
24. Scottsville (Iron), Allen County (36°46'N, 86°10'W)

This wedge-shaped meteorite was found in a tobacco field near Scottsville in June 1867 and first described in 1887. It is classified as a hexahedrite (subtype IIA) with extensive Neumann bands. Parts of it were artificially reheated and manipulated with a sledgehammer. It has troilite nodules, and is a low-phosphorus, high-iridium meteorite. A mass of approximately 22 pounds was recovered. See Whitfield (1887) and Buchwald (1975).

25. Smithland (Iron), Livingston County (37°8'N, 88°24'W)

Found around 1839 or 1840 and first described in 1846, the original large mass (weight unknown) was cut up and heated in a forge by a blacksmith, who made a chisel out of part of it. The original mineralogy was altered during the artificial reheating, which damaged the specimen and makes an accurate classification difficult. It is classified as a nickel-rich ataxite (subtype IVA), and contains shock-melted troilite nodules. All but about 10 pounds of the original mass was smelted. Parts of it were acquired by Gerard Troost in about 1840 and are on display in the Troost Collection at the Louisville Science Center. See Troost (1846).

26. Walltown (Stone), Casey County (37°19'30"N, 84°43'0"W)



Walltown meteorite. Photo by W.D. Ehmann.

Found in 1956 and 1957 and recognized in 1963, it is classified as an olivine-hypersthene chondrite (petrologic type L-6). A large mass of unknown weight was reported to be used as fill in a sinkhole. Approximately 3.5 pounds of badly weathered stones was recovered. See Ehmann and Busche (1968).

27. Williamstown (Iron), Grant County (38°38'N, 84°32'W)

Found in April 1892 on a farm in Grant County, this iron meteorite has Widmanstatten structure and the shape of a large double-edged ax. A mass of approximately 68 pounds was recovered from a farm 3 miles north of Williamstown. It is classified as a medium octahedrite (subtype IIIA). This meteorite is now believed to be identical to the Kenton County meteorite that was found nearby, so the Williamstown meteorite is no longer listed separately in the "Catalogue of Meteorites." See Howell (1908).

The Williamstown meteorite. Photo by E.E. Howell (1908).

ARE THERE METEORITE CRATERS IN KENTUCKY?

Prior to 1928, the Barringer Crater in Arizona was the only widely recognized meteorite crater on Earth. Some scientists held to the theory that the crater was volcanic, but the collection of large numbers of meteorites near the crater confirmed its identification. The crater is now known as Meteor Crater and is open to the public. Hundreds of suspected meteorite craters have now been identified on Earth with the help of satellite photography. Meteor Crater is in a desert where there is little or no vegetation to obscure it, and thus it is easily seen on satellite photography, whereas impact craters in highly vegetated areas or areas of intense weathering would be more difficult to see. The criteria for the identification of a meteorite crater, classified in Dence (1972) and Shoemaker and Eggleton (1961), are:

Meteor Crater, Arizona. The crater is approximately 50,000 years old and 3,900 feet in diameter. Photo courtesy of the Center for Meteorite Studies, Arizona State University.

- *Certain:* Sites where meteorites or their weathered products have been collected in the crater, or are clearly associated with the crater.
- *Probable:* Sites with definite evidence of shock metamorphism, such as the presence of high-pressure polymorphs of silica and submicroscopic shock damage to crystals.
- *Possible:* Other evidence—for example, sites where the crater is approximately circular, and breccia, shatter cones, impactites, or finely pulverized rock known as "rock flour" are present.
- *Doubtful:* Sites with other uncertain indications of meteoritic origin.

Coesite and stishovite are high-pressure polymorphs of silica; their presence provides strong evidence of a violent impact or explosion. Shatter cones are cone-shaped structures formed by high-pressure shock waves passing through the local rock. If undisturbed, the cones will point toward the center of the impact crater. Impactites are typically glassy impact melt products that may have droplet shapes. They result from melting of the local rock or soil by the impact of a large meteorite. They may also contain traces of nickel from the meteorite.

Three structures in Kentucky, the Middlesboro Structure, Jeptha Knob, and the Versailles Structure, exhibit some evidence of being formed by meteorite impact. These structures are bounded by a series of ring faults; this is not a normal geologic process, but can be associated with volcanic eruptions and subsurface solution collapse. The three Kentucky impact structures occur in middle to late Paleozoic rocks along the Cincinnati Arch in central Kentucky.

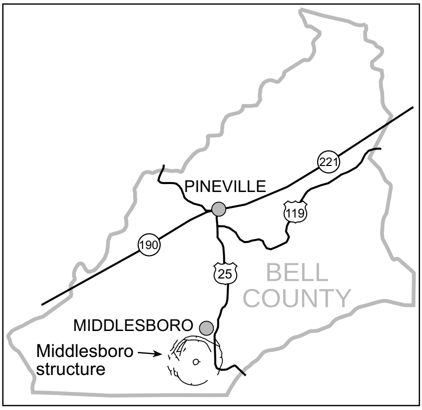
These structures are the shattered and deformed rocks beneath the craters created by the initial impact. Any crater that was formed in central Kentucky was eroded millions of years ago, and all that remains are the root fractures and faults beneath the original crater.

Shatter cones (approximately 5 centimeters long) from the Charlevoix Structure, Quebec, Canada. Photo by W.D. Ehmann.

Large (13 to 15 centimeters) shatter cone from the Kentland Structure, Indiana. Photo by W.D. Ehmann.

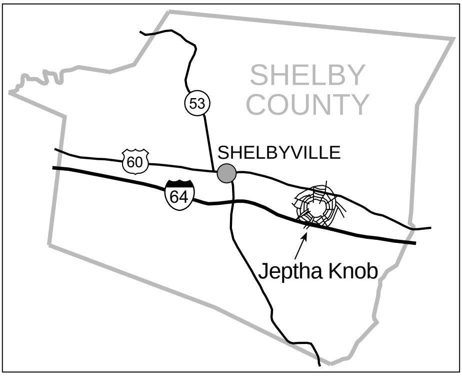
Determining the possible age of impact is difficult because of the amount of weathering and erosion that has occurred since the impact. Other geologic events such as orogenic or tectonic events, basement faulting, or dolomitization can influence or mask the true age and origin of geologic features.

Middlesboro Structure, Bell County (36°37'N, 83°44'W)



This disturbance consists of a circular depression approximately 7,000 meters in diameter, in which the entire city of Middlesboro is located. This crater and subsequent erosion created flatlands in the midst of Cumberland Gap, which is probably why a settlement was established at Middlesboro. This feature was first mapped by Englund and Roen (1963), and consists of a central uplift region approximately 400 meters in diameter surrounded by ring faults. The age of the structure is Late to post-Pennsylvanian to Early Tertiary (approximately 286 million years ago). Shatter cones have been found near the edge of the central uplift (Dietz, 1966), and intense brecciation was noted by Rice and Ping (1989). Shock-induced damage has been observed in quartz grains in the local rock. No meteorites have been found. This site is regarded as a probable meteorite crater.

Jeptha Knob, Shelby County (38°06'N, 85°06'W)

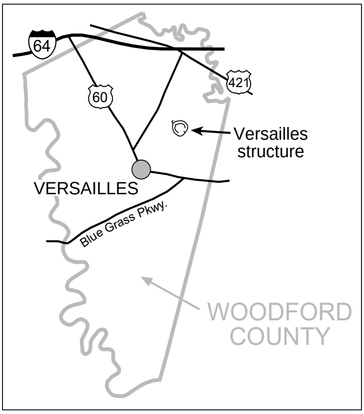


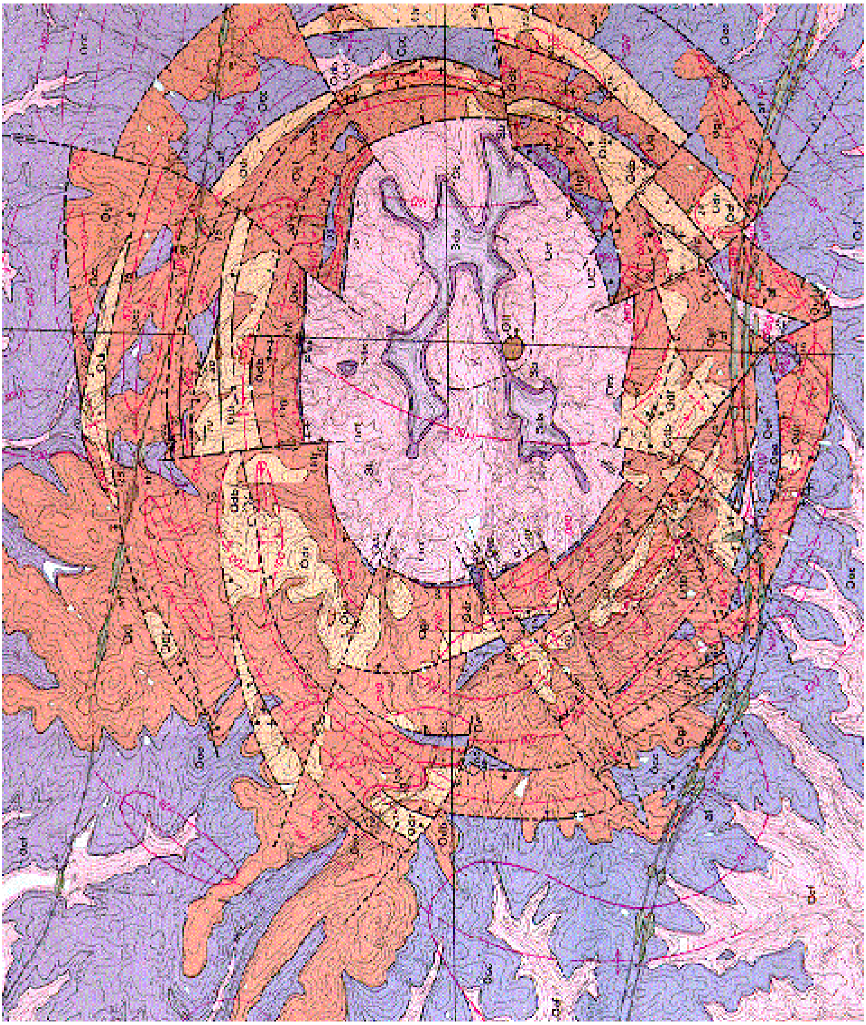
This structure is visible to the north of Interstate Highway 64, approximately 7 miles east of Shelbyville. It was mapped by Cressman (1975) as an elevated circular structure approximately 3,200 meters in diameter. Cressman noted that subsurface core data indicate extensive dolomitization and brecciation. The age of the structure is Late Ordovician to Early Silurian (approximately 408 to 438 million years ago). Breccia is abundant, but no shatter cones or meteorites have been found. Jeptha Knob has also been described as a cryptovolcanic structure, but geophysical investigations by Seeger (1968) indicate no basement or deep-seated connection with this feature, implying that it is an impact feature.

Based on current evidence, it is probably best categorized as possible to doubtful.

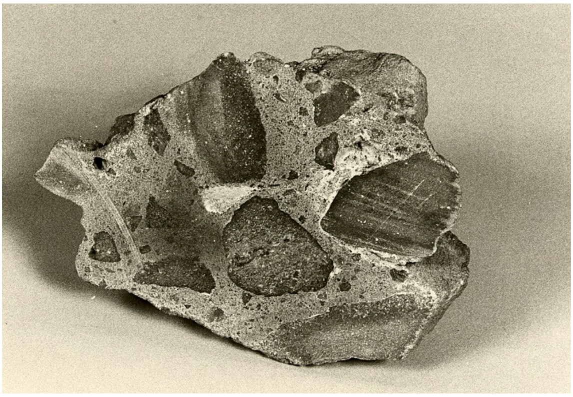
Versailles Structure, Woodford County (38°02'N, 84°42'W)

The structure is located on the west side of Big Sink Road, approximately 3 miles northeast of Versailles. It is now a slightly raised circular structure approximately 1,500 meters in diameter, and was first mapped by Black (1964). Abundant breccia is present, but no shock effects are seen in the rocks and no meteorites have been found. The age of the structure is post–Middle Ordovician (approximately 438 to 505 million years ago). Evidence supporting its impact origin is not strong, and Black (1986) stated that possible tectonic-related diapiric events could be responsible for "point source explosions," which





Jeptha Knob impact structure, in the Waddy quadrangle (Cressman, 1975).



Breccia from the Versailles Structure (approximately 20-centimeter section). Photo by W.D. Ehmann.

could be the cause of the structure. The disturbance is shallow, which is characteristic of impact structures. Geophysical investigations by Harris and others (1991) indicate there are no deep-seated or basement fractures associated with this structure. They suggested that it is an eroded remnant of an impact crater. It is best regarded as a possible meteorite impact crater.

WHAT ARE TEKTITES?

Originally, many scientists believed tektites to be splash objects ejected from the Moon by large meteorite or asteroid impacts. After the lunar visits of the Apollo Program, this theory quickly lost support. Few, if any, lunar materials collected to date would be suitable as parent material for tektites. Most scientists now believe that tektites are a form of impact glass resulting from large meteorites or asteroid-size bodies striking the Earth and splashing out molten droplets of the surface rock or soil.

If the impacting body is very large, the impact glass formed may be heated to a very high temperature, so that it becomes a nearly homogeneous liquid with no identifiable residual mineral crystals. This liquid may be sprayed high up in the Earth's atmosphere, and in passage it may take the form of splash droplets (spheres, teardrops, dumbbells, etc.). These droplets, called tektites, cool and solidify quickly in the upper atmosphere, and as solids may retain the original liquid droplet shapes. As the now-solid droplets reenter the lower denser atmosphere, their outer surfaces are reheated to melting again by friction with the Earth's atmosphere (as occurs in space vehicle reentries). This second heating may form a thin winglike ring or rim around the primary splash droplet, which will solidify and may survive impact with the Earth. Tektites with this fragile flange intact are rare and are highly prized by collectors.

A perfect flanged Australian tektite, approximately 2 centimeters in diameter. Photo by W.D. Ehmann.

No tektites have been found in Kentucky, probably because they generally occur near the surface of the Earth immediately after an impact, and Kentucky's impact sites have had millions of years of exposure to the elements and extensive erosion, so any tektites would have also been eroded long ago.

Tektites are found in strewn fields that can be hundreds or even thousands of miles across. In many cases, giant meteorite craters have been found that are associated with specific tektite strewn fields. Tektites have been found in several locations around the world, and each occurrence has a characteristic name. The major localities and most common names are given below.

North America

These tektites have been associated with both the subsurface Chicxulub Crater, which overlaps the northwest coastline of the Yucatán Peninsula in Mexico, and the Chesapeake Bay Impact Structure off the coast of Maryland. Microtektites of similar composition have also been found in coastal oceanic sediments. The age of these tektites is approximately 35 million years, and color ranges from black to green. These tektites are located in southeastern Texas (where they are called bediasites), Georgia (chiefly Dodge County), and Martha's Vineyard, Mass.

Australasia

The Australasian tektites are black. They may be associated with the ancient Lake Tonle Sap Crater in central Cambodia, although numerous other impact sites have been proposed. Their age is approximately 0.7 million years. They are found in Australia, chiefly the southern half (australites); Billiton Island, Indonesia (billitonites); the Sangiran area of Java, Indonesia (javanites); and the Philippines (philippinites or rizalites). Various Southeastern tektites are grouped together as indomalaysianites.

Various droplet shapes of Thailand tektites. The largest is about 7 centimeters long. Photo by W.D. Ehmann.

Central Europe

The central European tektites are typically olive green and may be translucent. They appear to be associated with the Ries Impact Structure near Nördlingen in southern Germany. Their age is approximately 14 million years. They are located mainly in the Czech Republic (moldavites), in Bohemia around Ceské Budejovice, and in Moravia west of Brno.

West Africa

The West African tektites have been related to the Lake Bosumtwi Crater in Ghana. The Lake Bosumtwi Crater is a massive impact structure measuring 7 to 8 kilometers in diameter. Concentric hills that formed during the impact surround the crater and have a relief of about 1,000 feet above the lake surface. This structure has evidence of shattering, shock deformation and brecciation, tektites, impact glasses, and nickel anomalies. The tektites are black, and their age is approximately 1.1 million years. They are located along the Ivory and Gold Coasts of West Africa (Ivory Coast tektites).

Lake Bosumtwi Crater, Ghana, West Africa. Photo by W.H. Anderson.

Libyan Desert

Libyan Desert glass is typically yellow green and partly translucent. The glass normally does not exhibit the droplet or flight shapes of other tektites, probably because it has been eroded by blowing sand. Some specimens are layered. As a result, some scientists class them only as impact glasses, not tektites. These tektites are located in Egypt and the Libyan Desert in North Africa.

Other meteorite impact glasses are known, but they are not usually characterized as tektites because they generally result from the impact of small meteorites. As a result, they often contain unmelted minerals and do not exhibit the characteristic droplet shapes, or the secondary reentry flanges associated with many tektites. Well-known impact glasses include Darwin glass from Tasmania, Zhamanshin glass from Russia, and Aouelloul glass from Mauretania. The Henbury Meteorite Craters in central Australia are surrounded by large pieces (several inches in diameter) of slaggy impact glass that contain many inclusions. Smaller bits of impact glass have been collected around Meteor Crater in Arizona and many other crater sites.

Henbury Meteorite Craters in central Australia. A cluster of objects fell here, producing 13 craters. The largest is 360 by 660 feet. The dark areas around the craters contain impact glass. Multiple craters like this are rare. Photo by W.D. Ehmann.

COLLECTING METEORITES AND TEKTITES

Meteorites and tektites are widely collected. Numerous suppliers may be found on the Internet. Iron meteorites (siderites) are most easily found and identified. Hence, some may be purchased for less than $1 per gram. Carbonaceous chondrites and meteorites that may have originated on Mars or the Moon can bring prices as high as $1,000 per gram. Some tektites can be purchased for only 10 to 25¢ per gram.

Many collectors have had success searching sites of earlier falls, but the extensive ground cover in Kentucky makes searching difficult. New finds are reported regularly in the western United States and in the Central Plains, where deserts or open fields allow a meteorite to clearly stand out. Tektites can still be collected in Georgia and southeastern Texas.

Reference to the published literature can serve to identify good collecting sites. You should always get permission from landowners in order to collect on private property. Collection on public lands may also be controlled. If you do observe a fall, or recover a new find in Kentucky, you are encouraged to confirm its identity and record the details of the occurrence and report them to the Kentucky Geological Survey. Collecting these “space visitors,” impact melts (tektites), and examples of impact shock in crater rock can be a fascinating hobby.

REFERENCES AND SELECTED ANNOTATIONS

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