Impact Structures in the United States

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The following is a catalog of geologic structures in the continental United States that have been attributed to impact by a meteorite, comet, or asteroid. Two notable impact structures outside the U.S. are included: Sudbury in Canada and Chicxulub in Mexico. Published lists of impact features served as a starting point, but literature search turned up several probable impact sites overlooked by most listers. For comparison, I've also described several features that resemble impact structures but have terrestrial origin.

Types of Impact Structures. Two types of impact structures are recognized. *Simple craters* are bowl-shaped, having an upturned or flipped-back rim. Barringer (Meteor Crater) in Arizona is the classic example. Simple craters form by collision with relatively small objects and range in diameter from a few feet to one mile or more. Known simple craters in the United States are geologically young. There are three confirmed examples (Barringer, Haviland, and Odessa) and two possible or probable simple craters (Big Basin and Merna). The only ancient structure that may be a simple crater is Howell in Tennessee. Old simple craters easily escape detection because of relatively small size and rapid burial in sediments.

Complex craters possess (1) a central peak or uplift of intensely shattered rock, surrounded in turn by (2) a ring-graben or depression and (3) an outer raised rim. Complex craters require catastrophic impacts and range in diameter from a few miles to tens of miles. Many of the larger craters on the Moon exhibit complex structure. Chesapeake Bay, at least 50 miles across, is the largest known in the continental United States. The Sudbury structure in Ontario was originally 30 miles across and the Chicxulub structure in Yucatan, Mexico possibly 190 miles. The latter is widely believed to be the site of impact that caused mass extinctions at the end of the Cretaceous Period, 65 million years ago.

A glance at the map shows that impact structures are concentrated in the Midwestern and Great Plains region. This does not mean that meteorites avoided the East and West Coasts, but that their geologic effects there are much harder to recognize. Circular areas of intensely deformed rock stand out in the flat land and (generally) geologically simple Plains. Also many buried impact structures have been discovered during oil exploration in the central United States. Eastern and Western areas are mountainous, rocks more strongly deformed, in many cases obliterating evidence for possible old impacts. The West Coast, in particular, consists of a series of tectonic plates added to the continent in relatively recent geologic time.

Criteria for Impact Recognition. The most conclusive evidence that a structure formed by impact is finding at least part of the impacting body. This requirement has been met only in the cases of the Barringer, Haviland, and Odessa structures, all young simple craters. Old craters rarely yield meteorite fragments because (1) in large collisions, the object commonly vaporized upon impact, and (2) the iron/nickel alloy and iron-rich minerals of stony meteorites rapidly weather away in Earth's atmosphere. Nevertheless, large bolides may leave their signature in such form as the famous world-wide iridium layer associated with Chicxulub and, possibly, the enormous nickel deposits being mined from the Sudbury structure.

Barring meteoritic material, most geologists recognize the following features as convincing evidence of impact:

- Shatter cones
- Coesite and stishovite, the high-pressure forms of quartz
- Planar deformation features, distinctive patterns of fractures microscopically visible in quartz, feldspar, and other minerals
- Suevite and impact-melt breccia; that is, rocks that were not only blasted apart but partially or completely melted by the energy of impact.

Lacking these definitive criteria, the following features strongly favor impact origin:

- Circular area of intense deformation out of place in local geology.
- Evidence for a crater, especially one containing breccia.
- Upturned or overturned rim surrounding ring-shaped depression or crater.
- Central uplift of highly shattered rock, in structures larger than 1-2 miles
- Pervasive shattering, down to the scale of individual mineral grains. "Rock flour" commonly occurs.
- Evidence that the structure is rootless; that is, it dies out with depth and is underlain by undisturbed rock.
- Absence of volcanic rock and mineralization. Although some confirmed impact structures have these features, their absence rules against volcanic or tectonic origin.

Among many publications that discuss criteria for impact structures, French (1996) and Koeberl and Anderson (1996) are particularly thorough and well illustrated. Two of the best websites are those of the Lunar and Planetary Institute, www.lpi.usra.edu; and the Earth Impact Database maintained by the University of New Brunswick, www.unb.ca/passc/ImpactDatabase.

Catalog of Impact Structures

Alamo

Location: southern Nye County, Nevada
Type: complex crater
Diameter: unknown; many miles

Age: Early Late Devonian (about 370 million years ago)
Description: Most catalogues of American impact structures omit this monster. A chaotic breccia of sedimentary rocks, as thick as 500 feet, has been traced through at least 14 mountain ranges covering a roughly circular area 180 miles across. Quartz recovered from the breccia exhibits abundant shock metamorphic features, attesting to impact origin. Dimensions of the actual impact site are poorly known. Nevada has been subjected to three major mountain-building episodes since the Devonian; the actual crater is likely either eroded or deeply buried. Evidently, a bolide excavated a crater at least a mile deep in a shallow sea floor, hurling rocks and sediments across a vast area.
References: Leroux et al., 1995; Morrow and Sandberg, 2002.

Ames

Location: Major County, Oklahoma (about 60 miles northwest of Oklahoma City)
Type: buried complex crater
Diameter: 10 miles
Age: Early to early Middle Ordovician (460 to 475 million years ago)
Description: Discovered during petroleum exploration, the Ames structure has a central uplift, ring syncline, and raised rim. Within the central core, rocks of the Arkbuckle Group (Lower Ordovician), Reagan Sandstone (Cambrian), and Precambrian crystalline rocks are intensely brecciated. Lithic breccias, impact-melt breccias, and planar deformation features demonstrate impact origin. Rock units overlying the crater are thicker than normal and sag into the structure, suggesting compaction and collapse of the breccia. Oil and gas are produced out of brecciated rock in the central uplift.
References: Johnson and Campbell (editors), 1997.

Barringer (Meteor Crater)

Location: 20 miles west of Winslow, northern Arizona
Type: simple crater
Diameter: 0.9 mile
Age: estimated 50,000 years
Description: Probably the world's most famous and frequently visited meteorite impact site is a few miles south of Interstate 40 east of Flagstaff. Originally called Coon Butte, the present name honors Daniel M. Barringer (1860-1929), who attempted to mine iron here and first published evidence of impact origin. The bowl-shaped crater is 570 feet deep and has an upturned rim of shattered sedimentary rocks 150 high. More than 30 tons of nickel/iron meteorites have been collected from a surrounding area 8 to 10 miles across. The colliding object, estimated to have been 150 feet across weighing 300,000 tons, fragmented on impact. This was the first site where coesite and stishovite, the high-pressure varieties of quartz, were found in nature. These occur only in large craters formed by meteors or nuclear bombs. Also present at Barringer are the usual shatter cones and planar

shock lamellae in quartz.
References: Barringer, 1915; Fahey, 1964; Krinov, 1966.

Beaverhead

Location: near the southwestern corner of Montana
Type: complex crater
Diameter: estimated 60 km (37 miles)
Age: Late Precambrian to Devonian (360 million years or older)
Description: Complex geology in mountains often hides impact features that are "sore thumbs" in flat-lying rocks of the plains. Shatter cones occur in outcrops of Precambrian gneiss and sandstone through an area about 5 X 10 miles. Lower Mississippian limestone in the same area lacks shatter cones, constraining age of the impact. Island Butte, a hill where intensely brecciated and fluidized sandstone yields shocked quartz, may mark ground zero.
Reference: Hargraves et al., 1990

Belton

Location: Cass County, Missouri (about 20 miles south of Kansas City)
Type: possible complex crater
Diameter: about 3 miles
Age: post-Late Pennsylvanian (300 million years or less)
Description: First described in 1922, the "Belton ring-fault complex" has some aspects of complex impact structures. Gentile (1984a, 2018) mapped a ring of faults surrounding a down-dropped area in otherwise flat-lying Upper Pennsylvanian rocks. Numerous small anticlines and domes mark the periphery. No central uplift is identified, but the central area lacks outcrops and drill-hole information is meager. Gentile (1984a, 2018) attributed the Belton structure to collapsing caverns in Mississippian limestone and did not address other possible modes of origin. Evidence for collapse includes boreholes that encountered features indicative of large-scale solution in Mississippian limestone and similarity of the Belton structure to other solution-collapse features in the Kansas City area (Gentile, 2018b). McCracken (1971) listed Belton among 20 "anomalous structures in Pennsylvanian rocks" in Missouri, attributed mostly (with considerable uncertainty) to solution-collapse. She also stated that a high magnetic anomaly of 850 gammas is associated with the Belton structure; such an anomaly suggests uplift of the basement rocks beneath the structure. Beauford and Evans (2014) are the only authors to directly suggest impact origin of the Belton structure. Their evidence includes indications of a raised rim and central uplift together with strong mechanical twinning of calcite from well samples obtained from the central area.
References: McCracken, 1971; Gentile, 1984a, 1984b, 2018; Beauford and Evans, 2014.

Big Basin

Location: Clark County, southwestern Kansas, about 35 miles south of Dodge City

Type: possible simple crater

Diameter: about 0.9 mile

Age: Quaternary, probably less than 10,000 years

Description: About 20 miles north of the Oklahoma border, U.S. Rt. 283 passes through this roughly circular, enclosed basin about 115 feet deep. The Kansas state geologic map shows Late Tertiary Ogallala Formation on the rim, Permian bedrock in the walls, and Quaternary alluvium on the floor. Two small satellite craters are nearby. Big Basin has been interpreted as a sinkhole; but upturned and intensely fractured strata around the rim suggest impact origin.

Reference: Cannon, 1997

Brushy Creek

Location: southwestern St. Helena Parish, Louisiana (about 35 miles northeast of Baton Rouge)

Type: simple crater

Diameter: 1.2 miles

Age: Pleistocene, likely less than 30,000 years

Description: Geologic mapping revealed a roughly circular depression surrounded by a dissected rim about 50 feet high in the hill country of eastern Louisiana. The feature is developed in the Citronelle Formation, which comprises sand, gravel, silt, and clay of Pliocene age. Outcrops are few, but intensely fractured and shocked quartz is a large component of sediment samples within and near the depression. Origin by non-impact processes, such as solution collapse, volcanism, and salt doming, can be dismissed. Given apparent topographic expression of a backfilled simple crater and its rim, this feature is likely less than 30,000 years old.

References: Heinrich, 2003a and 2003b.

Calvin

Location: Cass County, southwestern Michigan (about 30 miles southwest of Kalamazoo)

Type: buried complex crater

Diameter: about 5 miles

Age: Late Ordovician (445 million years ago)

Description: Drilling revealed a brecciated central uplift surrounded by a ring graben and outer raised rim. Shock metamorphism in quartz and black metallic spherules (apparently meteorite fragments) in well samples confirm impact origin. Richmondian (Upper Ordovician) and older rocks are deformed; Silurian and younger overlying strata are gently domed. Oil is produced from Devonian rocks above the central uplift, which is marked by a gravity high.

Reference: Milstein, 1997

Chesapeake Bay

Location: centered near western shore of Virginia's Delmarva Peninsula about 25 miles northeast of Norfolk
Type: buried complex crater
Diameter: 50 to 55 miles
Age: Late Eocene, 35.5 million years ago
Description: The largest impact structure in the United States escaped discovery until geophysical surveys were run in the early 1990s. Drilling and seismic surveys reveal a gigantic, multi-ring basin having a small central peak. The impact shattered Precambrian metamorphic rocks and left a basin as deep as 1,350 feet filled with fall-back breccia. Drill cores have recovered a variety of melt-breccias along with quartz and feldspar bearing intense shock metamorphism. The ejecta blanket and tsunami disturbances extend through Upper Eocene sediments well beyond the crater rim, precisely dating the event. In fact, the Chesapeake impact likely produced a vast field of tektites (glassy ejecta that returned to earth) strewn across the southeastern United States and many Carribean islands. Miocene and younger sediments that buried the crater are folded, probably in response to structural adjustments and slumping within the shattered basin.
References: Poag et al., 1994; Koeberl et al., 1996; Johnson et al., 1998.

Chicxulub

Location: centered near Merida in northern Yucatan, Mexico
Type: buried complex crater
Diameter: nearly 300 km (190 miles)
Age: End of Cretaceous Period, 65 million years ago
Description: The landmark scientific paper by Alvarez et al. (1980) proposed that collision with an asteroid wiped out the dinosaurs and many other life forms at the end of the Cretaceous. This theory was based on concentrations of iridium 20 to 160 times greater than normal in sediments at precisely the end-of-Cretaceous in Italy, Denmark, and New Zealand. Iridium, a platinum-group metal, is extremely rare in the earth's crust but a significant constituent of many meteorites. Subsequent investigators have confirmed the end-of-Cretaceous iridium concentration at many other sites around the world. Alvarez et al. postulated an impacting body 6 to 14 km (about 4 to 9 miles) in diameter, casting an immense dust cloud into the atmosphere, blocking sunlight and killing nearly all land and marine plants and the animals that depended on them. In 1980 no impact structure of the requisite age was known.

Gravity surveys in 1948 by Pemex, the Mexican national oil company, showed a huge concentric structure in northern Yucatan and prompted exploratory drilling. Test holes revealed highly deformed Cretaceous and older rocks underlying normal Tertiary-age sediments. New core drilling during the 1980s and 1990s confirmed that Chicxulub is among the largest impact structures on the globe. It has a multiple ring structure surrounding a central uplift of intensely brecciated and melted basement rocks. The crater is filled with Tertiary sediments. Microfossils date origin essentially at the Cretaceous-Tertiary boundary. Secondary disturbances attributed to tsunamis along with ejected material are mixed with end-of-Cretaceous sediments all around the Gulf of Mexico (Ryder et al., 1996). DePalma et al. (2019) described what appears to be an actual death assemblage from the Chicxulub impact, including fish with impact ejecta in their gills at the iridium-rich layer.

Chimney Prospect

Location: Garfield County, central Montana (about 90 miles northeast of Billings)
Type: possible buried complex crater
Diameter: about 2 ½ miles
Age: Late Jurassic or Early Cretaceous (about 120 to 160 million years ago)
Description: Plawman and Hagar (1983) reported a possible buried impact feature based on seismic reflection profiles acquired for oil exploration. The seismic data suggest a central uplift, ring syncline, and outer raised rim. Well records confirm a roughly circular area of jumbled Jurassic and older rocks overlain by gently domed Cretaceous strata. An impact origin appears plausible, but shock-related features have not been reported.
References: Plawman and Hagar, 1983; Nelson, 1993.

Cloud Creek

Location: about 15 miles northwest of Casper, Wyoming
Type: buried complex crater
Diameter: 4 ½ miles
Age: Late Triassic to Middle Jurassic (160 to 220 million years ago)
Description: Gravity, magnetic, seismic-reflection, and well data indicate a buried complex crater in central Wyoming. The central uplift is nearly a mile across and contains rocks as much as 1,700 feet above normal elevation. Surrounding the central peak are an annular trough and a rim anticline. Marginal faults, as imaged on seismic profiles, dip inward. A gravity high coincides with the central peak. Triassic and older rocks are deformed and overlain unconformably by Middle Jurassic strata that are domed slightly. The circular structure was slightly deformed by the Laramide orogeny (early Tertiary), which produced the Rocky Mountains. Shocked quartz grains with planar deformation features, found in drill cuttings, add Cloud Creek to the list of confirmed impact structures (Stone and Therriault, 2003).
References: Stone, 1999; Stone and Therriault, 2003.

Crooked Creek

Location: southern Crawford County, Missouri (about 20 miles east of Rolla and 80

miles southwest of St. Louis)
Type: complex crater
Diameter: about 4 miles
Age: Early Ordovician (470 million years) or younger
Description: The Crooked Creek structure lies in an area of nearly flat-lying Lower Ordovician rocks on the Ozark Plateau. The central uplift, about 1 ½ mile in diameter, contains intensely deformed Cambrian rocks as much as 1,000 feet above their normal position. The surrounding ring basin contains Ordovician rocks and a few small outliers of Pennsylvanian coal-bearing strata, filling ancient sinkholes. The Palmer fault, apparently unrelated, runs eastward from the structure. Hendriks (1954) described and illustrated shatter cones from Crooked Creek and, with reference to similar features world-wide, proposed origin by either subterranean explosion or meteorite impact. Shatter cones are presently accepted as conclusive evidence for the latter. Crooked Creek is one of eight features comprising a dubious "impact chain" (Rampino and Volk, 1996) and the equally dubious alignment of volcanic structures (Snyder and Gerdemann, 1965; Luczag, 1998).
Reference: Hendriks, 1954

Decorah

Location: near Decorah, northeast Iowa
Type: complex crater
Diameter: 3.6 miles (5.5 km)
Age: early Middle Ordovician
Description: Well logs, well samples, two cores, and two outcrops indicate an anomalous structure centered just east of the city of Decorah. Cambrian and Lower Ordovician rocks are brecciated and overlain by a deposit named the Winneshiek Shale, apparently filling a crater. The shale contains a *Lagerstatte* of soft-bodied fossils, along with abundant conodonts that precisely bracket its age. Undeformed St. Peter Sandstone overlies the Winneshiek Shale. Shocked quartz grains and planar deformation features from core smaples of the breccia confirm impact origin. The Decorah structure is the same age as the nearby Rock Elm structure in Wisconsin and may be a product of the same event involving two or more projectiles.
References: McKay et al., 2010 and 2011; French et al., 2018

Decaturville

Location: about 15 miles north of Lebanon, Missouri
Type: complex crater
Diameter: 3 ½ miles
Age: between Silurian and Early Mississippian
Description: Bulls-eye topography and radial drainage mark this intensely deformed circular feature on the Ozark Plateau. The central uplift contains Cambrian rocks

raised more than 1,000 feet and Precambrian granite and schist uplifted at least 1,800 feet. Shatter cones, planar fractures in quartz, intensely granulated rock, and a variety of breccias verify impact origin. The annular graben contains Middle and Upper Ordovician and Silurian rocks otherwise eroded from the region. Also in the ring are large blocks of Cambrian and Precambrian rock, apparently ejected upon impact. Offield and Pohn (1979) deduced that the structure is not deeply eroded and the initial crater was immediately destroyed by rebound and fall-back. Evans and Miller reported Middle and Late Ordovician conodonts in breccia from Decaturville. Because Lower Mississippian rocks unconformably overlies Lower Ordovician in the surrounding area, these fossils indicate that impact took place prior to Early Mississippian erosion.

Reference: Offield and Pohn, 1979; Evans and Miller, 2010

Des Plaines

Location: Northwestern suburbs of Chicago, Illinois

Type: buried complex crater

Diameter: 5 ½ miles

Age: Mississippian (340 million years) or younger, but pre-Quaternary

Description: Located partly beneath O'Hare Airport, the Des Plaines structure is concealed by glacial drift and is known from borehole data. The surrounding bedrock is flat-lying Silurian dolomite. In the central uplift, pulverized St. Peter Sandstone (Ordovician) is 600 feet above its normal elevation. Surrounding the central peak is a complex ring structure partially filled with Mississippian rocks elsewhere eroded from the region. One well encountered Pennsylvanian coal and black shale. Core drilling for a deep tunnel project in the 1970s revealed rocks at Des Plaines are intensively fractured and brecciated. McHone et al. (1986) identified strain lamellae and planar deformation fabrics in quartz along with shatter cones in limestone and dolomite, confirming impact origin.

References: Emrich and Bergstrom, 1962; McHone et al., 1986.

Dycus

Location: about one mile northwest of Highland in Jackson County, north-central Tennessee, approximately 36° 22' 30" N, 85° 47' W

Type: unknown; existence uncertain

Diameter: unknown

Age: post-Ordovician

Description: The only reference to the "Dycus disturbance" is the unpublished Master's thesis of Mitchum (1951), who mapped a small area of deformed Ordovician limestone. The location is not precisely specified and Dycus is not shown on current maps; this may be a former name for Milltown. The most prominent feature is a narrow, upright anticline trending north-northeast and having the western limb overturned. Mitchum described rocks in this area as tightly crumpled, faulted, and locally brecciated. The Dycus structure lies nine miles northwest of the Flynn Creek structure (see next entry) and possibly represents (1) peripheral deformation from Flynn Creek, (2) impact by a smaller body that accompanied the Flynn Creek meteorite, or (3) impact by material ejected from the Flynn Creek crater. A troubling fact is that C.W. Wilson, who suggested that Mitchum study the Dycus area and signed off on his thesis, showed no deformation on his own geologic maps that encompass the Dycus area (Wilson, 1980 and 1988).

Edgerton

Location: just south of Edgerton in Miami County, Kansas, about 17 miles southeast of Lawrence and 35 miles southwest of downtown Kansas City

Type: possible buried complex crater

Diameter: slightly elliptical, 5.5 X 6.5 km (3½ to 4 miles)

Age: pre-Pennsylvanian

Description: A nearly circular surface feature with radial drainage drew attention to the site. Pennsylvanian rocks at the surface are not deformed, and no deep drill-hole information is available. For investigation, ground-based magnetometer surveys were run north-south and east-west across the circular feature. These revealed a magnetic high near the center and highs around the perimeter, suggesting an impact structure having a central uplift, ring graben, and raised rim. Depth of the anomalies are estimated at 1 km, near the Precambrian surface, with relief in the range of 90 m (300 feet)(Merriam et al., 2009).

Flynn Creek

Location: Jackson County, north-central Tennessee (about 70 miles east of Nashville)

Type: complex crater

Diameter: 2.8 miles

Age: Middle to Late Devonian (360 to 380 million years ago)

Description: Although definitive shock features have not been reported, non-impact origin of this structure is scarcely possible. A central uplift contains Lower and Middle Ordovician limestone and dolomite intensely deformed and uplifted more than 1,000 feet. The surrounding ring depression 12,000 feet in diameter contains from bottom upward: non-bedded breccia with clasts as large as 1 foot, bedded breccia with clasts smaller than 4 inches, coarse dolomitic sandstone with small breccia clasts, and bedded dolomite. This in turn is overlain by Upper Devonian Chattanooga Shale 200 feet thick, compared to 15-25 feet thick outside of the structure. Drilling shows that intensity of deformation decreases downward, an earmark of impact structures.

References: Roddy, 1966 and 1968; Wilson and Roddy, 1990; Evenich and Hatcher, 2007

Glasford

Location: About 10 miles southwest of Peoria, Illinois

Type: buried complex crater
Diameter: At least 2 ½ miles
Age: Late Middle or early Late Ordovician (450 to 460 million years ago)
Description: A dome mapped on shallow Pennsylvanian strata prompted development of an underground gas-storage facility. Core drilling revealed abnormally thick Maquoketa Shale (Upper Ordovician) overlying intensely brecciated older rocks. A gravity high coincides with the structure, confirming uplift of dense older rocks. Shatter cones identified in drill cores (McHone et al., 1986) verified the impact hypothesis initially advanced by Buschbach and Ryan (1963). Over-thickened Maquoketa Shale represents crater filling, while subsequent rebound or compaction over the central uplift created the dome.
References: Buschbach and Ryan, 1963; McHone et al., 1986.

Glover Bluff

Location: Marquette County, Wisconsin, about 75 miles north of Madison
Type: complex crater
Diameter: poorly known; at least 5 miles
Age: apparently Middle Ordovician, about 465 million years ago
Description: Not much is published on this site, although definitive impact features have been reported. Ekern and Thwaites (1930) mapped highly deformed Upper Cambrian and Lower Ordovician sandstone and dolomite in a region of otherwise undisturbed strata. Writing before impact structures were widely accepted, they suggested origin by glacial ice shove, volcanic activity, or tectonic faulting. Read reported shatter cones (1983) and “impact bombs” in St. Peter Sandstone (Middle Ordovician) from the surrounding area (1985). Photographs of possible suevite or impact-melt breccia have been posted on the Internet, but not described scientifically. Outcrops showing impact features apparently are limited to quarries in a small area of the central uplift.
References: Ekern and Thwaites, 1930; Read, 1983 and 1985

Haviland

Location: Kiowa County, south-central Kansas (about 90 miles west of Wichita)
Type: simple crater
Diameter: 50 feet
Age: Probably less than 1,000 years
Description: As early as 1885 local residents collected meteorites on farms outside of Haviland. In 1925 the dedicated meteorite hunter Harvey Nininger discovered a shallow crater with a raised rim in the midst of the meteorite field. Digging turned up as many as 100 meteorite fragments per cubic foot; total weight of recovered fragments is more than a ton. Decades of farming virtually obliterated the feature; little trace remains today.
Reference: Nininger and Figgins, 1934

Howell

Location: Lincoln County, south-central Tennessee (about 6 miles north-northwest of Fayetteville and 65 miles south of Nashville)
Type: possible simple crater
Diameter: 1.5 miles
Age: Late Middle Ordovician to early Late Ordovician (about 450 million years ago)
Description: A circular area contains angular blocks of Middle Ordovician limestone, some more than 20 feet across, jumbled in a matrix of smaller blocks and powdered limestone. The disturbance is shot through with dikes that contain pulverized limestone. Limestone blocks are as much as 100 feet above their normal elevations. Overlying the breccia is mostly flat-lying Upper Ordovician shale, which thickens from its usual 15 feet to as much as 115 feet. Born and Wilson (1939) deduced that a crater was formed and filled during the Ordovician Period - close to the age of the Calvin structure in Michigan and the Glasford structure in Illinois. There are unconfirmed reports of shatter cones and a borehole that penetrated breccia into undeformed rock below. Petrographic study by Deane et al. (2004) confirmed widespread micro-breccia but failed to find conclusive evidence (such as impact melt or planar deformation) for an impact origin.
References: Born and Wilson, 1939; Wilson and Barnes, 1973; Deane et al., 2004.

Jeptha Knob

Location: Shelby County, Kentucky, about midway between Lexington and Louisville
Type: complex crater?
Diameter: about 3 miles
Age: latest Ordovician or Early Silurian
Description: The circular Jeptha Knob structure disrupts flat-lying Ordovician shale and limestone in Kentucky's Outer Bluegrass region. Its central uplift, poorly exposed, contains a plug of Middle Ordovician limestone about 700 feet above its normal elevation. Surrounding this is a series of tilted, downdropped blocks outlined by steeply dipping radial and concentric faults. There is no clear-cut raised rim. Horizontal, undisturbed Lower Silurian dolomite truncates the deformed Ordovician rock. Breccias are common; most are composed of fragments of a single type of limestone, rather than being a mixture of diverse rock types as seen in many impact structures. Origin of Jeptha Knob remains controversial. Although it bears many earmarks of impact structures, definitive evidence such as shatter cones or shock metamorphism has not come to light. Also, deformation is less intense and chaotic than in most bona fide astroblemes of similar dimensions. An origin by explosive vulcanism, as at Hicks Dome in Illinois, appears plausible. Pending further information, the label "crypto-explosive" seems appropriate.
References: Bucher, 1925; Seeger, 1968; Cressman, 1981; Pope et al., 1997.

Kentland

Location: Newton County, Indiana (about 40 miles northwest of Lafayette)
Type: Complex crater
Diameter: about 8 miles
Age: Pennsylvanian (300 million years ago) or younger, pre-Quaternary
Description: Limestone outcrops jutting through flat, glaciated farmland became the site of a quarry in what proved to be the central uplift of an 8-mile wide impact structure. Drilling and geophysical surveys further delineated the Kentland feature. Shattered Ordovician rocks in the quarry have been thrust upward as much as 2,000 feet. Shocked quartz and shatter cones occur in abundance. Surrounding the central peak is a ring-shaped depression that contains coal-bearing Pennsylvanian strata otherwise eroded from the area. The Newton County Stone Quarry hosts tours for groups interested in their unique geology.
References: Laney and Van Schmus, 1978

Kilmichael

Location: About 10 miles east of Winona, north-central Mississippi
Type: probable complex crater
Diameter: 5 ½ miles
Age: likely Middle Eocene (40 to 45 million years ago)
Description: A roughly circular area of intensely deformed Cretaceous, Paleocene, and Eocene sediments interrupts flat-lying strata of the inner Coastal Plain (Priddy, 1943). A ring graben downdropped about 600 feet surrounds a central core uplifted nearly 1,500 feet. Gravity and seismic surveys mimic the geologic structure (high in center, low in surrounding ring). In 1996 the Mississippi Geological Survey drilled cores into the central uplift, recovering brecciated Cretaceous and early Tertiary formations. A search for shock metamorphic features came up blank; however, Koeberl et al. suggested a “wet” impact (into loosely compacted sediments under water) may explain their absence. Considering its setting, the Kilmichael structure is difficult to explain by any mechanism other than impact.
References: Priddy, 1943; Koeberl et al., 2000, King and Petruny, 2002.

Manson

Location: centered in southeastern Pocahontas County, Iowa, about 16 miles west of Fort Dodge
Type: complex crater
Diameter: about 24 miles
Age: Late Campanian Stage, upper Cretaceous, about 74 million years ago
Description: Largely buried in glacial drift, the gigantic Manson structure has no surface expression. A central peak of shattered Precambrian rocks is surrounded by a broad ring graben, which contains a succession of Cretaceous marine rocks

otherwise eroded from western Iowa. Outside of this is a “megablock zone” of inward-dipping fault blocks. A magnetic high corresponds with the central uplift; gravity lows mark the surrounding graben. Core drilling into the central uplift by the Iowa Geological Survey during the early 1990s yielded abundant shock-metamorphic features in quartz and feldspar. Also present is impact melt-breccia, dated by means of argon isotopes at 74 million years before present. This age is confirmed by microfossils from Cretaceous rocks at Manson and, intriguingly, in Cretaceous shale containing splashed-out fragments as far west as central South Dakota. Disturbed bedding features in the same rocks suggest that the impact produced tsunamis in the shallow Cretaceous sea. Dating the Manson structure about 9 million years before the end of the Cretaceous, laid to rest speculation that this was the site of the impact that drove the dinosaurs to extinction. For that story, *see* Chicxulub.

Reference: Koeberl and Anderson, 1996

Marquez

Location: About 12 miles southwest of Uvalde, Texas and 90 miles west of San Antonio
Type: buried complex crater
Diameter: about 9 miles
Age: Probably Eocene; 50 to 55 million years ago.
Description: Highly deformed sedimentary rocks occupy the central uplift of this partially buried structure, associated with a strong gravity high. This was previously interpreted as a salt dome, but drilling revealed no salt and seismic reflection surveys show that deformation dies out with depth (*see* Sierra Madera). Shatter cones have been reported from the central part of the structure. Upper Cretaceous rocks are deformed, whereas the Wilcox Formation (Eocene) appears to have filled the crater. At the time of impact, this area probably lay under shallow water.

Reference: Gibson and Sharpton, 1989

Merna

Location: Custer County, central Nebraska
Type: Possible simple crater
Diameter: 1 mile
Age: approximately 2,860 years ago
Description: The Merna crater is a flat-floored circular depression about 65 feet deep in Peoria loess, which is wind-blown silt. Although “blow-out” depressions made by the wind are numerous in this part of Nebraska, the Merna crater is much larger and more symmetrical than its neighbors. Black magnetic spherules and glass fragments, not normal constituents of loess, support impact origin. The crater apparently was deeper initially, having been partially filled by washed-in sediment. Nearby ravines reveal a white layer, possibly an impact-ejecta blanket, radiocarbon dated at 2,860 years before present. Test drilling is needed

to confirm origin of this feature.
Reference: Dort et al., 1997.

Middlesboro

Location: southeastern corner of Kentucky, near Cumberland Gap
Type: complex crater
Diameter: about 4 miles
Age: Middle Pennsylvanian (300 million years ago) or younger
Description: The city of Middlesboro occupies a circular topographic basin that contrasts with the highly linear ridges and valleys of the Appalachian Mountains. Outcrops are few, but brecciated sandstone of the central uplift (at Middlesboro Golf Course) has yielded shocked quartz and shatter cones. Surrounding the uplift is a depressed ring of folded and faulted coal-bearing rocks. Deformed rocks are Lower and Middle Pennsylvanian; timing of the impact is poorly constrained.
References: Englund, 1964; Englund et al., 1964; Englund and Roen, 1962; Dietz, 1966.

Muldraugh Dome

Location: Meade County, Kentucky, about 25 miles southwest of Louisville.
Type: Possible buried complex crater
Diameter: Dome at surface is 1.8 miles wide
Age: Early to Middle Silurian (430 to 440 million years ago)
Description: Absent from many lists of possible impact structures, Muldraugh Dome has received little study, partly because it lies within the confines of Fort Knox. A geologic map (Withington and Sable, 1969) depicts an unfaulted, circular dome having 360 feet of relief in Mississippian rocks at the surface. A gas storage field has been developed. Deep wells reportedly encountered abnormally thin Silurian strata overlying brecciated dolomite of the Knox Group (Upper Cambrian and Lower Ordovician), at least 1,560 feet above its expected elevation (Cressman, 1981). Although Cressman discounted an impact origin on account of the doming, several well-accepted subsurface impact structures, including Glasford and Red Wing Creek, exhibit doming above the central uplift. If Muldraugh is in fact an astrobleme, its total diameter could exceed 10 miles.
References: Withington and Sable, 1969; Cressman, 1981.

Newporte

Location: Renville County, North Dakota (near Canadian border northwest of Minot).
Type: Buried simple crater
Diameter: about 3 miles
Age: Late Cambrian or Early Ordovician (about 490 to 500 million years ago)
Description: Drilling and seismic reflection surveys outline a bowl-shaped depression

with a raised rim; there is no central uplift. Planar deformation features in quartz and feldspar demonstrate impact origin, during deposition of the Deadwood Formation near the end of the Cambrian Period. Brecciated Deadwood rocks and Precambrian granite on the rim serve as reservoirs for oil production.
References: Gerlach et al., 1995; Forsman et al., 1996.

Odessa

Location: about 10 miles southwest of Odessa, west Texas
Type: simple crater
Diameter: average 530 feet
Age: Late Pleistocene
Description: In the 1890s a local rancher discovered meteorites near a shallow crater on the wind-swept High Plains. Beginning in 1939 the site was thoroughly investigated by drilling, trenching, and geophysical surveys. The main crater is about 100 feet deep, but largely back-filled with debris from the impact plus washed-in and blown-in sediment. Fossils of Pleistocene horses and elephants in the crater are at least 10,000 years old. The floor is currently 5 to 10 feet below the surrounding plains, surrounded by a low rim of shattered Cretaceous limestone. Several much smaller craters are nearby. Meteorite finds lie within an egg-shaped area extending northwest from the main crater, indicating the object was traveling northwest when it struck the ground. Excavation has revealed shatter cones and a large quantity of rock flour. The meteorite exploded below ground level, flipping the crater rim backward. Open to the public are a museum, visitors' center, and self-guided tour.
Reference: Evans and Mear, 2000

Red Wing Creek

Location: McKenzie County, western North Dakota (about 40 miles south of Williston)
Type: buried complex crater
Diameter: 6 miles
Age: Triassic (205 to 250 million years ago)
Description: This structure has been delineated by geophysical surveys and drilling for oil and gas, which are produced from shattered Mississippian rocks in the central uplift, 3,000 feet above original elevation. The surrounding ring-valley is filled with greatly thickened sandstone of the Spearfish Formation, indicating the crater was formed and filled during the Triassic Period. Younger rocks sag into the ring graben and are arched above the central peak. Shatter cones and shocked quartz have been identified from drill cores.
Reference: Brenan et al., 1975

Rock Elm

Location: Pierce County, northwestern Wisconsin (about 45 miles west of Eau Claire)

Type: complex crater
Diameter: 4 miles
Age: Middle Ordovician (450 to 460 million years ago)
Description: This structure is mantled in glacial drift and incompletely exposed. Surrounding bedrock is flat-lying Lower Ordovician dolomite and sandstone. These rocks are folded and fractured along the ring-shaped boundary fault. Within the boundary is an annular basin, apparently a crater filled with shale and sandstone that yields Middle Ordovician fossils. The central uplift contains basal Cambrian Mt. Simon Sandstone along with breccia of diverse rock types. Gravity and magnetic surveys revealed no anomalies. No shatter cones have been found, but quartz from the central uplift displays planar microfractures strongly indicative of impact.
Reference: French et al., 2004

Santa Fe

Location: about 12 km northeast of Fanta Fe, New Mexico
Type: unknown
Diameter: unknown
Age: between 1.4 billion years (Precambrian) and 300 million years (Pennsylvanian).
Description: Shatter cones as large as 1 meter along with “pervasive brecciation” occur through an area of at least 3 square kilometers in Precambrian granite, schist, and gneiss. A mantle of breccia may represent an ejecta blanket. No shatter cones have been found in Pennsylvanian sedimentary rocks, although multiple episodes of tectonic deformation obscure the nature and extent of the impact structure.
References: Fackelman et al., 2007; Tegtmeier et al., 2008; Newsom et al., 2011.

Serpent Mound

Location: southwestern Ohio, about 60 miles east of Cincinnati
Type: complex crater
Diameter: about 5 miles
Age: Mississippian (about 340 million years ago) or younger, pre-Quaternary
Description: This structure, located partly in a state park, takes its name from a nearby serpent-shaped prehistoric effigy mound. A series of faulted anticlines radiate from the central uplift into the surrounding ring graben. Ordovician through Mississippian rocks are deformed and partially overlain by glacial drift. Evidence for more than one episode of fault movement has led some authors, such as Reidel et al. (1982), to favor igneous or tectonic origin. However, Serpent Mound has yielded coesite, shatter cones, shock-metamorphic features, and high iridium counts - conclusive evidence for impact. Baranoski et al. (2003) suggested that faults beneath the structure moved again after the impact in response to rebound or regional tectonic forces.
References: Reidel et al. (1982), Baranoski et al. (2003).

Sierra Madera

Location: Pecos County, west Texas, about 20 miles south of Fort Stockton.
Type: complex crater
Diameter: 8 miles
Age: Early Cretaceous (100 million years ago) or younger, pre-Quaternary.
Description: Madera Mountain, on the east side of U.S. Rt. 385, contains the 5-mile-wide central uplift, where Permian sedimentary rocks have been heaved upward as much as 4,000 feet and intensely brecciated. The surrounding ring valley is mantled in alluvium; Cretaceous rocks form a range of low hills along the raised outer rim. The axes of shatter cones around the central uplift point inward and upward, indicating that the focus of shock waves lay above the present mountain peak. Shocked quartz with planar fabric and both mono-lithologic and mixed breccia also are widely present. The subsurface has been thoroughly explored by oil and gas test holes to depths greater than 17,000 feet. These demonstrate that the deformation dies out with depth, rocks below 6,000 to 8,000 feet being unfractured and horizontal or nearly so. Together, this information virtually demands that the causal force came from above.
Reference: Wilshire et al., 1972.

Sudbury

Location: Sudbury, Ontario; northeast of Lake Huron
Type: Complex crater
Size: 20 miles wide and 40 miles long (originally 30 miles in diameter)
Age: Precambrian, variously estimated at 1.7 to 1.84 billion years
Description: World-class deposits of nickel, copper, iron, and platinum-group metals have been mined at Sudbury for more than a century. Metals occur in unusual layered igneous rocks within a syncline whose long axis runs northeast. The ore-bearing rocks are overlain in turn by impact-melt breccia and metamorphosed sedimentary rocks. Early geologists ascribed the Sudbury basin to ordinary magmatic processes, but prolific shatter cones and diverse examples of shock metamorphism indicate this is one of the largest impact structures on Earth. French (1998) estimated an asteroid 10 km (6 miles) in diameter releasing nearly 100 million megatons of energy. Such an impact may have penetrated the Earth's crust, causing or triggering massive melting of rock and mobilizing ore minerals. Nickel, iron, and platinum-group metals being mined at Sudbury may have actually originated in the impacting body. Following impact, two mountain-building episodes deformed the original circular structure to its present elliptical form.
References: French, 1967 and 1969; Milkereit et al., 1992

Toms Canyon

Location: Offshore 90 miles east-southeast of Atlantic City, New Jersey
Type: buried, undersea complex crater
Diameter: about 13 miles
Age: Late Eocene, about 35 million years ago
Description: Deep-sea drilling turned up a layer of apparent crater ejecta in Eocene sediments near the edge of the continental shelf. Seismic reflection profiles from offshore oil exploration revealed a buried crater having a flat floor and a raised rim. Drilling into the crater showed that the filling consists of breccia. Lack of a central peak and the irregular outline of the feature led Poag and Poppe (1998) to conclude that a cluster of relatively small meteorites might have struck the sea floor obliquely. Age of the Toms Canyon structure is closely similar, if not identical to that of the larger Chesapeake Bay structure.
References: Poag et al., 1992; Poag and Poppe, 1998

Upheaval Dome

Location: 30 miles west-southwest of Moab, Utah in Canyonlands National Park
Type: possible complex crater
Diameter: 3 miles
Age: Middle Jurassic or younger (about 170 million years ago)
Description: The origin of this spectacular circular feature of the Canyonlands remains controversial. Brightly colored Triassic and Jurassic rocks define a faulted central uplift, a rim syncline, and an outer monocline. Faults radiate from the core and partially surround the rim. Shatter cones and shock metamorphism have been reported but are poorly documented. Overall, the intensity of deformation is less than observed at most undoubted impact structures of similar size. Jackson et al. (1998) interpreted the structure as a pinched-off salt dome, a plausible hypothesis considering presence of thick beds of salt in subsurface Pennsylvanian rocks. Alvarez et al. (1998), however, interpreted unusual deformation of Middle Jurassic rocks surrounding Upheaval Dome as evidence for impact shaking.
References: Alvarez et al., 1998; Jackson et al., 1998.

Versailles

Location: Woodford County, Kentucky, about 10 miles northwest of Lexington
Type: complex crater?
Diameter: 1 mile
Age: Late Ordovician (450 million years) or younger
Description: This structure in the heart of the Bluegrass country was discovered by Black (1964) during geologic mapping. Intensely brecciated Middle Ordovician limestone is at the center, surrounded by a ring of synclines and concentric faults. An outer rim of arcuate, gentle anticlines is on the east side only. Breccia consists of angular blocks of several types of limestone, to several feet across, in a matrix of smaller fragments. Gravity and magnetic surveys revealed no

anomaly, suggesting that the structure dies out with depth and supporting the impact hypothesis (Seeger, 1972). If this is an astrobleme, it is probably eroded nearly to its roots.

References: Black, 1964; Seeger, 1972.

Weaubleau (also called Weaubleau-Osceola)

Location: southern St. Clair County, Missouri (about 55 miles north-northwest of Springfield)

Type: complex crater

Diameter: 12 miles (?)

Age: Middle Mississippian(about 340 million years ago)

Description: Beveridge (1951) mapped geology of the Weaubleau (locally pronounced wob-low) Creek area after new highway cuts revealed faulting. He discovered widespread low-angle and horizontal thrust faulting, a style of deformation foreign to the Ozark Dome. Remarkably, slices of Lower Ordovician dolomite are thrust through overlying, less competent Mississippian rocks. Beveridge also documented unusual Mississippian conglomerate or breccia of angular rock fragments in a dolomite matrix. Pennsylvanian rocks are undisturbed, constraining the age of deformation. Beveridge postulated tectonic compressive forces from the southwest. Evans et al. (2003) stated that the faulted area mapped by Beveridge is part of a larger circular structure approximately 19 km in diameter. New mapping, core-drilling, magnetic and gravity surveys outline a central uplift raised nearly 1,300 feet surrounded by a ring moat and raised outer rim (Stockdell et al., 2004). These authors further reported “planar fractures and decorated shock lamellae” in quartz as evidence of impact origin. Miller and Evans (2007) narrowed down the time of impact to near the Osagean-Meramecian boundary (Mississippian, about 340 million years ago) on the basis of conodonts and crinoids recovered from the breccia. Remarkably intact crinoid fossils found within the breccia are interpreted as remains of animals that were living at the time of impact and washed into the crater by tsunamis.

References: Beveridge, 1951; Evans et al., 2003; Stockdell et al., 2004; Miller and Evans 2007, Evans and Miller 2010.

Wells Creek

Location: Stewart County, Tennessee (about 20 miles southwest of Clarksville and 50 miles WNW of Nashville)

Type: Complex crater at surface

Diameter: 8 miles

Age: Late Mississippian to Late Cretaceous (about 80 to 330 million years ago)

Description: An anomalous area of highly deformed rocks was discovered during railroad construction around 1860. Named Wells Creek basin, the topography reflects the geologic structure: a central hill surrounded by a ring valley. In the central uplift, pervasively brecciated dolomite of the Knox Group is more than

2,500 feet above its normal position. Shatter cones are locally abundant; their apices point inward. The ring graben contains Ordovician through Mississippian rocks; faults converge with depth. A gravity survey produced a central high surrounded by an annular low, reflecting topography and geology. The Upper Cretaceous Tuscaloosa Formation is not deformed, putting an upper limit on the time of impact.

References: Stearns et al. 1968, Tiedemann et al., 1968; Wilson and Stearns, 1968; Tiedemann, 1997

Wetumpka

Location: near Wetumpka, Alabama; 10 miles northeast of Montgomery
Type: complex crater
Diameter: 4 miles
Age: Late Cretaceous (80 million years ago) or younger; pre-Pleistocene
Description: The Wetumpka structure lies on the boundary between the Piedmont and Gulf Coastal Plain in southern Alabama. Metamorphic rocks of the Piedmont, largely schists and gneiss, form a broken, arcuate rim. Within are folded and faulted, weakly lithified Cretaceous sediments. At the center is a mega-breccia of angular schist and gneiss boulders in a matrix of Cretaceous sediment. Pleistocene(?) river terraces are undeformed, setting an upper limit on the time of formation. Planar fractures in quartz and deformed twinning lamellae in feldspar indicate impact origin. Neathery et al. (1976) suggested a submarine impact during or shortly after deposition of the Upper Cretaceous Mooresville Chalk.

Reference: Neathery et al., 1976.

Non-impact structures

A number of geologic processes can produce structures that superficially resemble impact craters and have been mistaken for such:

- Volcanism, especially explosive volcanism
- Doming and subsequent collapse by igneous intrusion (calderas)
- Karst or solution-collapse features
- Blow-out depressions formed by the wind

Following are several examples of structures (all of which I have visited) that have been misidentified as impact structures.

Hicks Dome

Location: southern Illinois, 15 miles southeast of Harrisburg
Type: faulted dome formed by intrusive and explosive igneous activity
Diameter: 8 miles

Age: Early Permian (about 270 million years ago)

Description: Rampino and Volk (1996) listed this as one of eight aligned impact craters, but geologists who have looked closely at Hicks Dome agree on its igneous origin. Although complexly faulted, the structure is basically a dome lacking the ring depression and raised rim of a complex impact crater. No shock indicators exist. Ultramafic dikes, sills, and plugs along with intrusive breccias radiate from the apex along a NW-SE axis. There is no gravity anomaly; a magnetic high is centered 6 miles northeast. Seismic reflection profiles indicate that doming extends into Precambrian crystalline rocks at a depth of greater than 2 miles. Potassium-argon dating of biotite and hornblende from intrusive rocks yields Early Permian age. Hicks Dome lies at the center of a mineralized region, the Illinois-Kentucky fluorspar district. Potter et al. (1995) interpreted origin by a combination of magma intrusion and explosive brecciation within Precambrian basement.

References: Bradbury and Baxter, 1992; Potter et al., 1995.

Kilbourne Hole

Location: southern New Mexico, about 23 miles southwest of Las Cruces

Type: maar, a type of volcanic crater

Size: 1.1 by 1.7 miles

Age: Quaternary (less than 2 million years ago)

Description: Kilbourne Hole is an unusual type of volcanic crater. Its flat floor lies 250 to 300 feet below and its rim rises up to 150 feet above the surrounding plateau. Crater walls expose stratified, undeformed Pleistocene silt, clay, and caliche; overlain in turn by a basalt flow, layered volcanic tuff, and wind-blown sand. The crater floor is filled with dry lake sediment. Fragments of rock from deep in the crust and upper mantle were blasted from the now-buried vent and litter the crater walls. Despite the fact that Kilbourne Hole lies in the midst of the Potrillo volcanic field, some early investigators interpreted origin by solution-collapse. Volcanic tuff on the rim superficially resembles water-laid sediment. The most obvious differences between Kilbourne Hole and simple impact craters such as Barringer are (1) irregular, elliptical outline, (2) rim is raised but not upturned, and (3) Kilbourne has clear volcanic associations.

References: Hoffer, 1976; Seager, 1987

The Solitario

Location: southern Presidio County, west Texas

Type: partially collapsed volcanic dome

Diameter: 10 miles

Age: Eocene, 35 to 38 million years ago

Description: The raised rim, intensely deformed central area, and gigantic breccia blocks suggest a complex impact crater; yet despite disagreement on details, investigators concur on volcanic origin. Noted for spectacular scenery, the

Solitario is in Big Bend Ranch State Park and accessible on foot, horseback, or via four-wheel-drive vehicles. Sheer cliffs of Cretaceous limestone comprise the rim. Paleozoic rocks of the interior were deformed during the Ouachita orogeny, as seen also in the Marathon region of Texas. These are intruded and overlain by a wide variety of Eocene volcanic and igneous rocks. In the southern part of the central area, huge angular blocks of Paleozoic and Mesozoic sedimentary rocks are in a matrix of volcanic material. In a nutshell, magma formed a dome, which collapsed partially during a series of eruptions. Like Hicks Dome, the Solitario formed in a region of crustal rifting.

References: Corry et al., 1990; Henry, 1998; Henry et al., 1997.

Wilbarger Dome

Location: southern Wilbarger County, Texas; about 45 miles west of Wichita Falls
Type: faulted anticline of probable tectonic origin
Diameter: less than 1 mile
Age: Permian (about 260 million years ago) or younger
Description: Hughes (1932) interpreted this sharply localized uplift as a shale diapir; Monnig (1963) suggested impact origin without presenting much supportive evidence. In October 2002 geologists David Hale, Todd Thomas and I mapped the Wilbarger structure, using global positioning equipment (GPS). The structure is poorly exposed in rolling rangeland dotted with mesquite. Steeply dipping dolomite beds poke through the soil through an area about 1,000 by 1,200 feet. These rocks are uplifted at least 200 feet through surrounding flat-lying, unfractured Permian redbeds. Although folded and faulted, the dolomite is only lightly fractured and displays no brecciation. The outcrops appear to outline a faulted anticline running west-northwest. Absence of shattering, brecciation, and a ring structure render an impact hypothesis untenable. Igneous and volcanic rocks are absent from the region. Salt or shale doming, as suggested by Hughes (1932) appears unlikely, as sufficiently thick shale or salt is absent at depth and Wilbarger Dome lies isolated from other such features. I conclude Wilbarger Dome is most likely a tectonic “pop-up” structure produced by strike-slip faulting along the Matador-Red River uplift, a regional structure whose axis lies a few miles north.

References: Hughes, 1932; Monnig, 1963; Freeburg, 1966.

The “chain of impacts”

In 1996 Michael R. Rampino and Tyler Volk stirred up controversy with a paper proposing that eight structures in the Midwestern U.S. resulted from impact by a chain of comets or asteroids. The eight structures lie along a straight line running due west from southern Illinois across Missouri to eastern Kansas. From east to west, the structures are Hicks Dome, Avon, Furnace Creek, Crooked Creek, Hazel Green, Decaturville, Weaubleau Creek, and Rose Dome.

Rampino and Volk's theory was inspired by the spectacular breakup of Comet Shoemaker-Levy 9 on the planet Jupiter. Crater chains resulting from near-simultaneous impacts by swarms of meteors are known on the Moon and elsewhere in the solar system. Might not similar events have taken place here?

The impact chain hypothesis falls apart when the details are examined. The eight structures vary widely in origin and age. Only Crooked Creek and Decaturville are confirmed astroblemes. Weaubleau Creek may be an impact structure or the product of intense, recurrent fault movement. The other five features are of igneous or volcanic origin. Furnace Creek and Hazel Green are of Cambrian age, the Avon diatremes are Devonian, Hicks Dome is Permian, and Rose Dome is Cretaceous.

It is noteworthy that Luczag (1998), in dismissing the impact chain theory, continued the error by asserting that eight aligned structures must have the same origin. He attributed them all to explosive igneous activity, a hypothesis first advanced by Snyder and Gerdemann (1965). These authors speculated that the structures lay along a great linear fault zone, which provided pathways for magma. Although some of the eight features lie on or near fault zones, no through-going east-west fracture exists. In fact, the prevalent trend of faults in the region is northwest. The occurrence of so many diverse igneous, volcanic, and impact structures nearly in a straight line is apparently just a coincidence.

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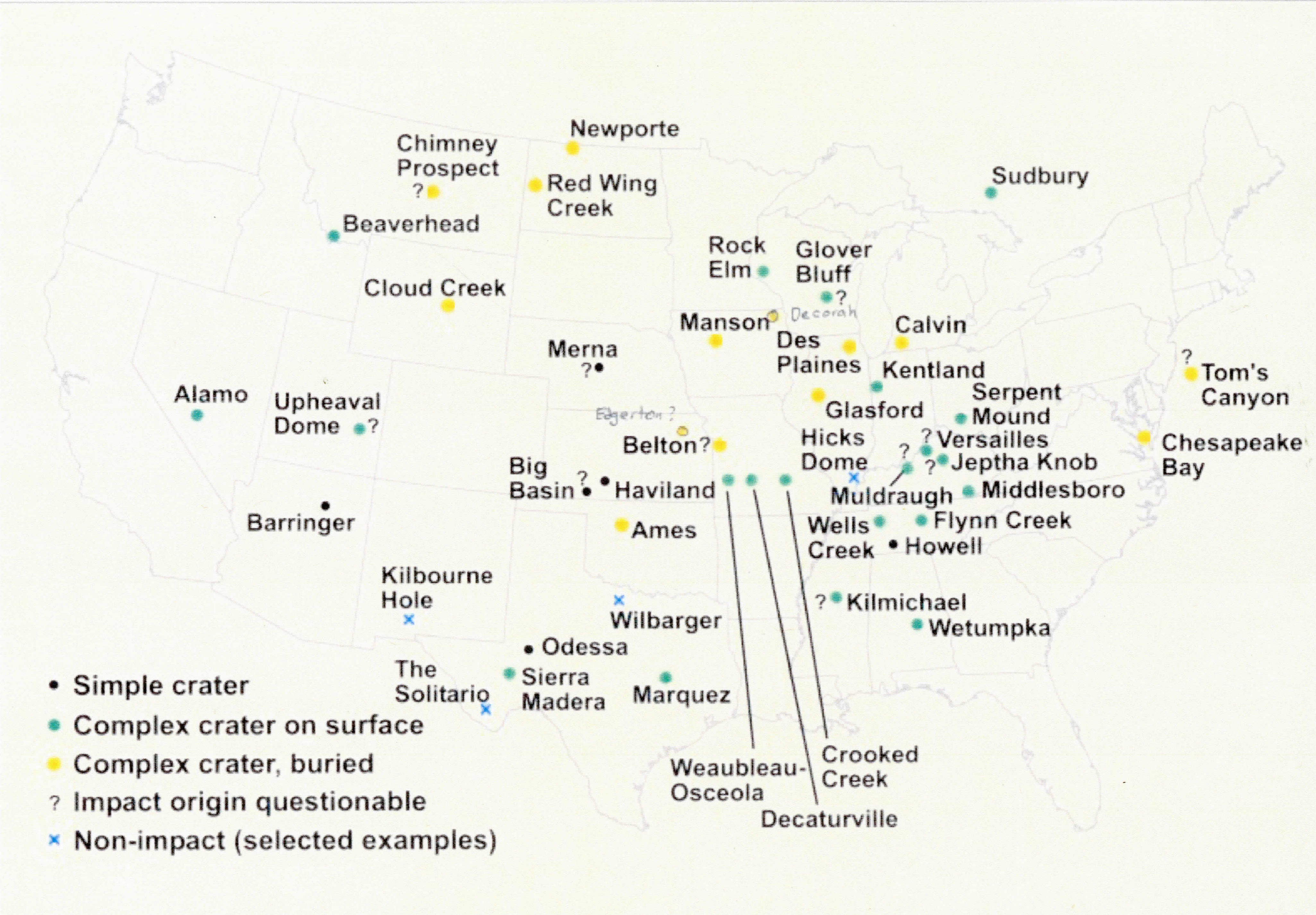

Newporte
Chimney Prospect ?
Red Wing Creek
Sudbury
Beaverhead
Rock Elm
Glover Bluff ?
Cloud Creek
Manson
Decorah
Des Plaines
Calvin
Merna ?
Kentland
Tom's Canyon ?
Alamo
Upheaval Dome ?
Edgerton ?
Glasford
Serpent Mound
Belton?
Hicks Dome
? Versailles
Chesapeake Bay
Big Basin ?
Haviland
? Jeptha Knob
?
Muldraugh
Middlesboro
Barringer
Ames
Wells Creek
Flynn Creek
Howell
Kilbourne Hole
Wilbarger
? Kilmichael
Wetumpka
Odessa
The Solitario
Sierra Madera
Marquez
Weaubleau-Osceola
Crooked Creek
Decaturville
Simple crater
Complex crater on surface
Complex crater, buried
? Impact origin questionable
Non-impact (selected examples)