Kentland Impact Crater, Indiana, USA - State of the Science (2018)

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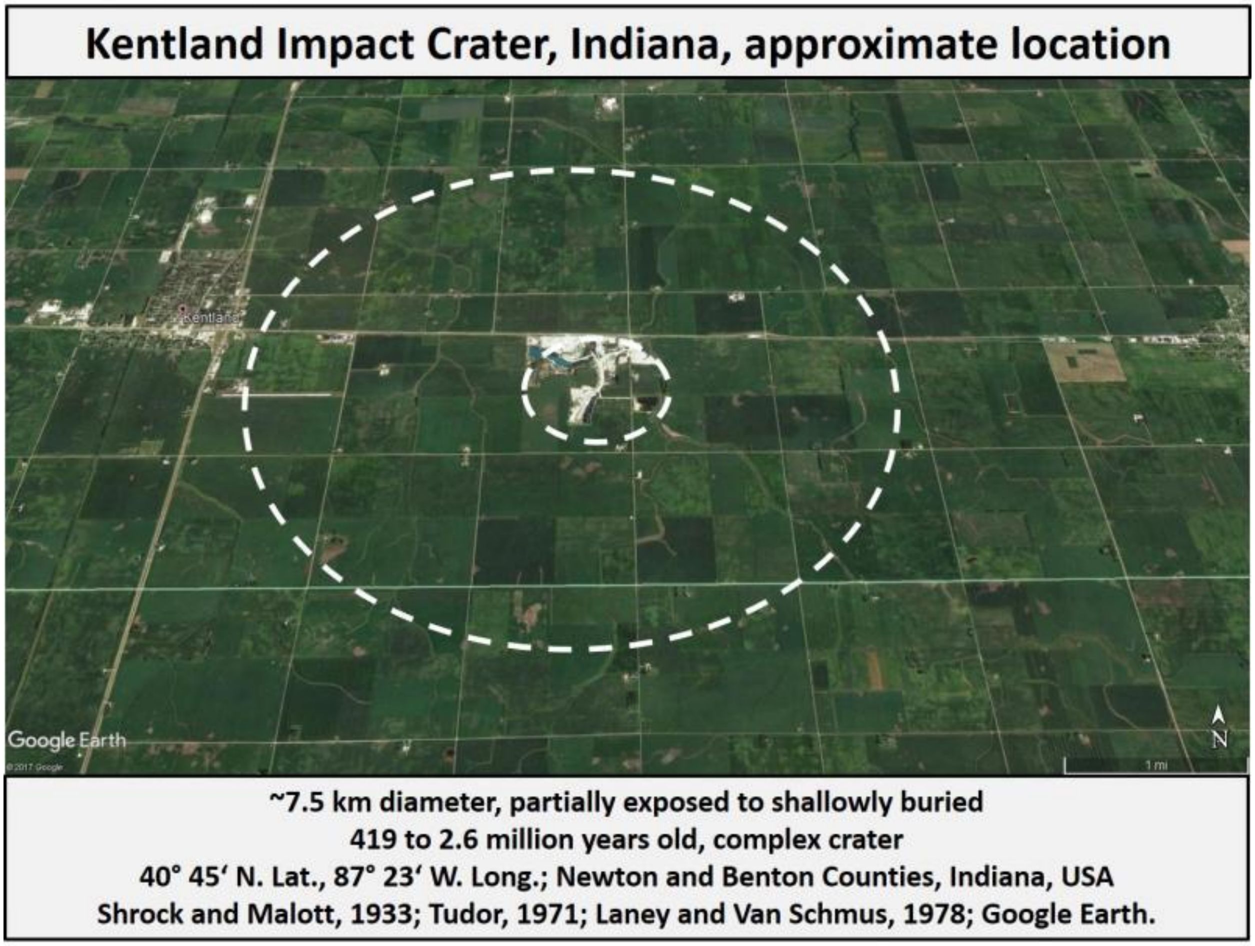


Kentland Crater (Impact Structure) is an approximately 7.5 km impact structure centered 4 to 5 km (about 3 miles) east of the town of Kentland, Indiana, at approximately (N 40° 45' W 87° 24') (Laney and Van Schmus, 1978 and others). Evidence suggests the structure underlies a portion of southern Newton and northwestern Benton counties. It is exposed only in an area of about 1/2 square kilometer or less, where a portion of the central uplift is quarried. The annular basin and rim of the crater are shallowly but completely buried by Pleistocene glacial drift, to a depth of typically 15 to 40 meters, and produce no known topographical expression (Tudor, 1971; Laney and Van Schmus, 1978). The impact is preserved in disturbed Paleozoic Middle Ordovician to Silurian carbonate, shale, and sandstone units, and may include younger Mississippian and Pennsylvanian units as well (Shrock and Malott, 1933; Boyer, 1953; Gutschick, 1987; Laney and Van Schmus, 1978; Tudor, 1971).

Kentland is a key site in the global history of impact crater research. It produced the earliest known description of shatter cones, contributed to the recognition of shatter cones as a distinct class of small scale geologic structures, and contributed to the recognition of shatter cones as a criterion for the recognition of impact craters. It was also one of the first two complex impact craters at which coesite was reported, leading to the recognition of coesite as a means for recognizing complex impact structures, and it played a large part in the emergence of the concept of complex impact craters as a sub-class of impact craters distinct from the simple craters.

Evidence of Impact Origin

Unambiguous diagnostic evidence of shock metamorphism associated with hypervelocity impact supports the meteorite impact origin of Kentland Impact Crater. The following list is not exhaustive: Shrock and Malott, 1933; Dietz, R. S., 1947, 1959, 1960; Laney and Van Schmus, 1978; and others (shatter cones) (see Figure 2); Cohen et al., 1961 (coesite in St. Peter sandstone in the central uplift, report of coesite has been challenged); Morrow and Weber, 2009; Laney, 1976; Laney and Van Schmus, 1978 (PDFs in quartz grains, basal orientation). Dietz (1959, 1960) reported that shatter cones at Kentland can reach up to 2 meters in length in limestone and up to 12 meters in shale.

Other significant but non-diagnostic evidence: breccia, megabreccia, central uplift, complex structural deformation, comminuted quartz 'rock flour' (Shrock and Malott, 1933; Shrock, 1937; Boyer, 1953; Dietz, 1959; and other authors); multiple sets of planar fractures - PFs, indexed (Laney, 1976; Laney and Van Schmus, 1978); mosaicism in quartz (Huss, 1996). Gutschick (1987) and Huss (1996) both mention lamellae in quartz. Morphology, core drilling, detailed geologic mapping, and cross-sectional modeling are described in Laney and Van Schmus (1978) and Tudor (1971).

Figure 2. Shatter cone from the Kentland Impact Crater.

Kentland is listed as a confirmed impact crater in the Earth Impact Database maintained by the University of New Brunswick, and the Kentland Impact Crater name is recognized as standard for publications concerning this crater in the Meteoritical Society Database.

Dimensions

The central rebound covers an area of approximately 4 to 7 square km, with the strongest dislocation confined to an area about 1 km in diameter (Tudor, 1971; Laney and Van Schmus, 1978), and reveals exposed middle Ordovician strata uplifted at least 600 to 610 meters (1968 feet) above their original position (Tudor, 1971; Laney and Van Schmus, 1978; Gutschick, 1987). Geophysical modeling from a detailed gravity and seismic survey reported in Tudor (1971) suggests 600 to 900 meters of uplift of the crystalline basement below the quarry exposures, suggesting subsidence or other factors may have reduced the uplift apparent at the surface relative to the true original displacement.

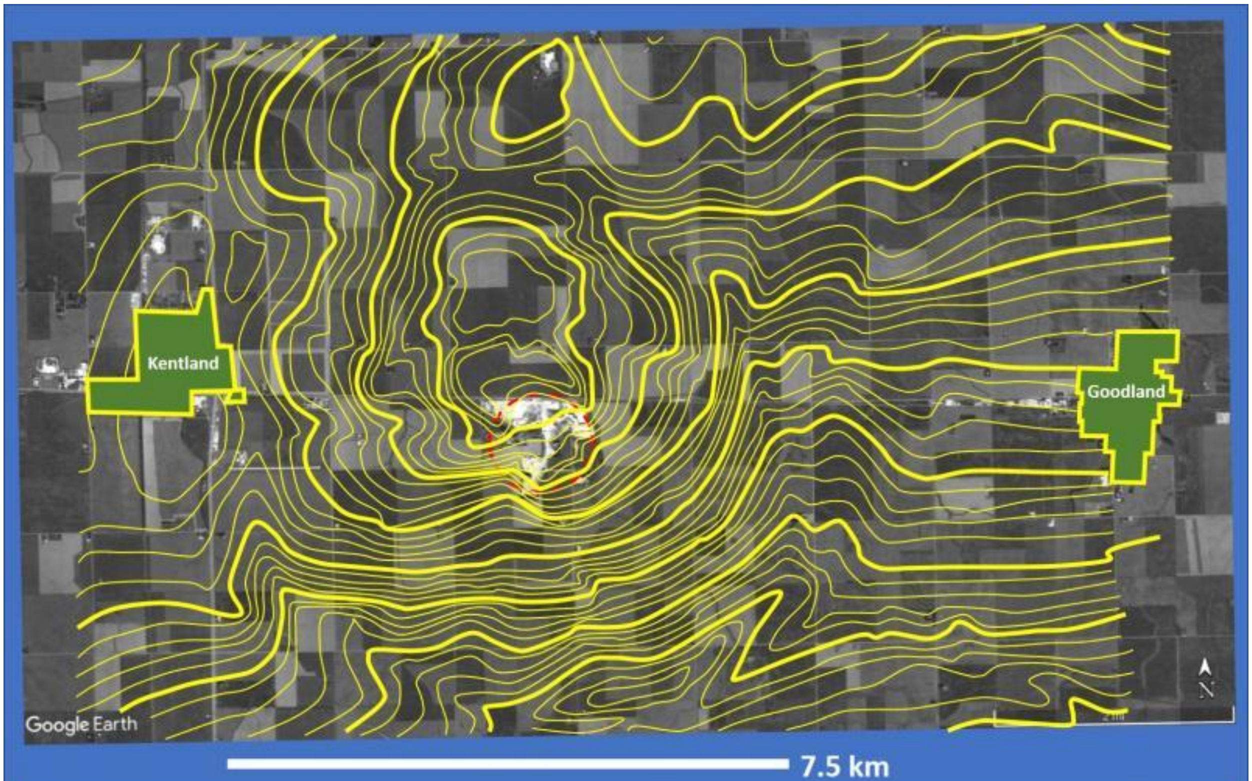
An early geophysical radio field intensity survey (Pullen, 1953), using radio signal strength from existing regional transmitters as a source of signal, reported a generally circular high centered roughly at the quarry and measuring about 4 miles (6.4 km) across. A detailed gravity survey, series of seismic refraction and reflection profiles, and study of drilling reported in Tudor (1971) produced the most frequently cited recent dimension of 12 to 13 km. The work revealed a complex circular structure comprised of a central sub-circular disturbed area of uplift with a maximum radius of about 2 miles (about 3.2 km), surrounded by an annular basin (a circular depression) with a radius of about 2 miles (3.2 km), surrounded by a broad ring anticline (rise) that extended beyond the basin to a radius of about 4 miles (6.2 km) from the center.

Working from sparse data, Laney and Van Schmus (1978) also tentatively identify an annular basin 1.5 to 2 km in width surrounding the central uplift, and similarly interpret a subdued structural high (crater rim) at a distance of about 6.2 km from the center of the structure, suggesting a probable diameter of 12 to 13 km. Most recent authors report a diameter of 12, 12.5, or 13 km, citing Laney and Van Schmus (1978) and Tudor (1971).

Tudor approached his interpretation from a volcanic paradigm. Laney worked on the site several years later, in the mid-1970s, and understood it to be of impact origin, but described the overall limit of disturbance, not the radius to the edge of the transient cavity and beginning of the rim - what would conventionally be considered the crater diameter today. Reconsidered the original maps in terms of modern publication conventions and understandings of the crater-forming process at complex structures, both the work of Tudor (1971) and Laney and Van Schmus (1978) are consistent with a crater diameter of about 7.5 km, with a well preserved central uplift, annular basin, and rim. (see Figure 3) A central gravity high is surrounded by a negative anomaly consistent with an annular impact basin, surrounded by an inconsistent gravity positive extending for some distance beyond a radius of about 3.5 to 4 km. Tudor's original gravity data were supported by geophysical seismic and drilling studies.

Weber et al. (2005) and the Weber (2013, field guide) challenge the 12 to 13 km diameter of the structure based on inconsistency between the observed uplift of 600 meters and predictions of 1.0 to 1.3 km of central uplift for a 13 km crater per models given by Melosh and Ivanov, 1999. Weber suggests 600 meters of uplift is consistent with a diameter of 6 to 7 km, somewhat closer to what is suggested by a 7.5 km reinterpretation of Tudor's original (1971) results. Weber's observation supports a smaller diameter, and the original (1971, 1976, 1978) work agrees with this prediction if considered in light of modern understanding.

Multiple studies have found no regional magnetic anomaly associated with the Kentland structure (Shrock and Malott, 1933; Shrock, 1937; Joesting and Henderson, 1948; Lucas, 1952; Tudor, 1971).



Bouguer gravity map of the Kentland crater region. Daniel Tudor (1971) interpreted his results to suggest a diameter of 12.8 km or greater. The map appears to better reflect a diameter of about 7.5 km, and reveals a well preserved central uplift, annular basin, and rim. Tudor's gravity data was supported by geophysical seismic and drilling studies. This map was modified from Laney (1976) and Tudor (1971), using landmarks visible in Google Earth imagery. The dashed red circle in the center represents the central uplift. The diameter of the transient crater appears to be at about 7.5 km. Beauford, R. E. (2018).

Figure 3. A reconsideration of the work of Laney (1976) and Tudor (1971) suggests a 7.5 km crater diameter.

How Much Has Been Removed by Erosion?

The central uplift has been at least modestly eroded. Laney and Van Schmus (1978) loosely infer less than 300 meters of erosion of the central uplift after the impact, and Jackson and Van Der Voo (1986) reach a similar conclusion in a paleomagnetic study of rocks in the Kentland quarry. Laney (1976) and Laney and Van Schmus (1978) report only modest levels of peak shock (5-6 GPa, not exceeding 8 GPa) recorded in rocks exposed in the quarries, based on petrographic evidence, while both Nasser and Howe (1995) and Votaw (1980) found evidence of only low-level heating of conodonts from dolostone in the quarries (specifically <90 C in Votaw). Modest impact generated temperatures (~150 C) at the depth of the quarry exposures are supported in the paleomagnetic work of Jackson and Van Der Voo (1986). These low temperatures and modest shock levels support the idea of erosional removal of a minimum of about 300 meters of more heavily shock-altered overburden. Weber (2013) speculates that erosion may be up to a kilometer. The actual extent of preservation or erosion of the rim and annular basin is largely unknown, but combined evidence suggests the structure may be largely intact below the glacial drift.

Timing of the Impact

It is broadly agreed that impact altered rock units exposed at the Kentland quarry range from the Lower Ordovician Shakopee Dolomite to the Silurian Salamonie Dolomite (Shrock and Malott, 1933; Shrock, 1937; Gutschick, 1983, 1987; Tudor, 1971; Laney, 1976). The ages of the Ordovician and Silurian units have been confirmed by detailed analysis of the faunal assemblage. (Shrock and Malott, 1933; Shrock and Raasch, 1937). This establishes that the impact occurred during or after the Silurian, meaning less than about 419 million years ago.

Undisturbed Wisconsin stage Pleistocene glacial units cover much of the structure, placing the event firmly prior to the Pleistocene glaciation (Shrock and Malott, 1933; Tudor, 1971, and others). Gutschick (1987) more specifically identifies the Pleistocene glacial till as the Cartersburg Till Member of the Trafalgar Formation drift sheet.

Tudor (1971) delineates a localized Pennsylvanian coal, incompetent shale, and sand unit, up to 300 feet thick (Tudor, p. 78), that is present only in the lowest paleotopographical zones (p. 92) in the annular basin. This is named the Schluttenhofen coal basin and was first described in Ashley (1898). Tudor seems to suggest that this unit of relatively fragile Pennsylvanian shales and sands sits undisturbed in the annular basin, except where tilted by a known fault. He further notes that where the Pennsylvanian was drilled through, his team encountered a normal regional sequence of the Borden Group (Early to Middle Mississippian - roughly Osagean). Though Tudor was aware of the impact hypothesis for Kentland, he interpreted the site as originating from subsurface igneous intrusion (cryptovolcanism) and interpreted the annular basin as a down-warped region, rather than part of an original transient cavity. Lacking a modern understanding of formation of the annular basin, he did not perceive relatively undisturbed Pennsylvanian and Mississippian sediments in this context as a constraint on timing, and thus was unfortunately sparse in related descriptions. The presence of an in-situ unit of friable Pennsylvanian and undisturbed Mississippian sediments in the annular basin, partially encircling the central uplift, suggests an additional stratigraphic constraint on the most recent possible date of the structure's formation (prior to the Middle Mississippian or Pennsylvanian). But the literature does not explicitly resolve this, as these cores are not described in detail. On the assumption that the coal-bearing units are pre-impact in origin, both Tudor (1971) and Laney and Van Schmus (1978) date the structure to between the Pennsylvanian and Pleistocene. If the units are in fact undisturbed in the annular basin, they may alternatively be interpreted to date the structure between the Silurian and Osagean Mississippian, about 419 to 340 million years old. Neither possibility is well constrained.

An apatite fission-track study by Weber et al. (2005) found that St. Peter Sandstone that was broken and uplifted 600 meters in the central uplift recorded post depositional heating (≥135°C) followed by a rapid cooling event at 184±13 Ma. (Jurassic) identical with unexcavated regional St. Peter strata well beyond the perimeter of the crater. The authors concluded that their results provided no new constraint on timing of crater formation, but it could be argued that their results suggest that the St. Peter remnants found in the Kentland Quarry were shattered and uplifted after uniform regional cooling at their original depth, providing a tentative impact timing constraint of later than 184±13 Ma.

Jackson and Van Der Voo (1986) provide a tentative Late Cretaceous (97±10 Ma.) age estimate, based on a paleomagnetic study of samples of Middle Ordovician Quimby's Mill Limestone from the Kentland quarry.

Bjørnerud (1998) provides a significant potential constraint on timing, observing that clasts of sphalerite that resulted from a regional sulfide mineralization event, which is best understood to have occurred in the late Pennsylvanian or Permian, are entrained in impact breccia. Gutschick (1987 and others) places a potential similar constraint, observing that what he interpreted as a Pennsylvanian fluvial channel is bisected by the uplift.

Taken cumulatively, these reported data provide a solid constraint of late or post-Silurian to pre-Wisconsin Stage Pleistocene, about 419 million to 2.6 million years old, though refinement seems likely.

Quarries Referenced in Literature

A series of quarries have been operating on the northwest flank of the central uplift since the late 19th century, taking advantage of the exposures of rock produced by the central uplift within the surrounding plain of glacial drift. At the time quarrying began, these were the only rocks in a flat glacial plain "unbroken by bedrock exposures for many miles" (Shrock, 1937). From history recorded on the Newton County Stone company website (2017), Shrock (1933, 1937), Gutschick (1983), and several earlier descriptions, quarrying at Kentland originally started under several different owners. The land was purchased in February of 1865, by Samuel Means and John McKee, and was divided into two farms. The small Means Quarry and McKee's Quarry were both opened around 1881 for personal and local construction needs. Sources disagree concerning which opened first. Both were abandoned prior to 1904, but were later subsumed by the larger quarry between them (see Figure 4).

The larger central Vanetta and Evans quarry, located between these two, was added in 1900. By 1904 (see: Blatchley, 1905), it was being operated as the U.S.F.&G. quarry under the United States Fidelity and Guarantee Co. In 1905 it was called the Goff Quarry (under W. F. Goff Stone Co.). It operated under the Goff name until at least the early 1920s (see cited volume for Cummings, 1922). It was renamed the McCray quarry in 1928, under the ownership of Warren T. McCray, an Indiana Governor, who later sold it to George Hart. It is later generally referred to as the Kentland Quarry. The final name, Kentland Quarry, has persisted in the literature from at least the 1930s to the present.

More formally, the Kentland Quarry has been operated by/as Newton County Stone Company, later Newton County Stone, since at least 1937 (Shrock, 1937 and others). It was acquired by Ralph Rogers in 1946. Under the current lineage of ownership and name, the operation has subsequently grown to encompass all 3 original quarries. Quarry owners have, at this writing, kindly facilitated 136 years of research at the site (since 1881). The quarry is currently operated as Newton County Stone, owned by Rogers Group, Inc., headquartered in Nashville, Tennessee. The quarry is located in the northern half of Sec. 25, T.27N., R.9W, centered at about 40° 45' 52" N. by 87° 23' 17" W., and is shown on the USGS Kentland, Indiana, 7.5 minute quadrangle.

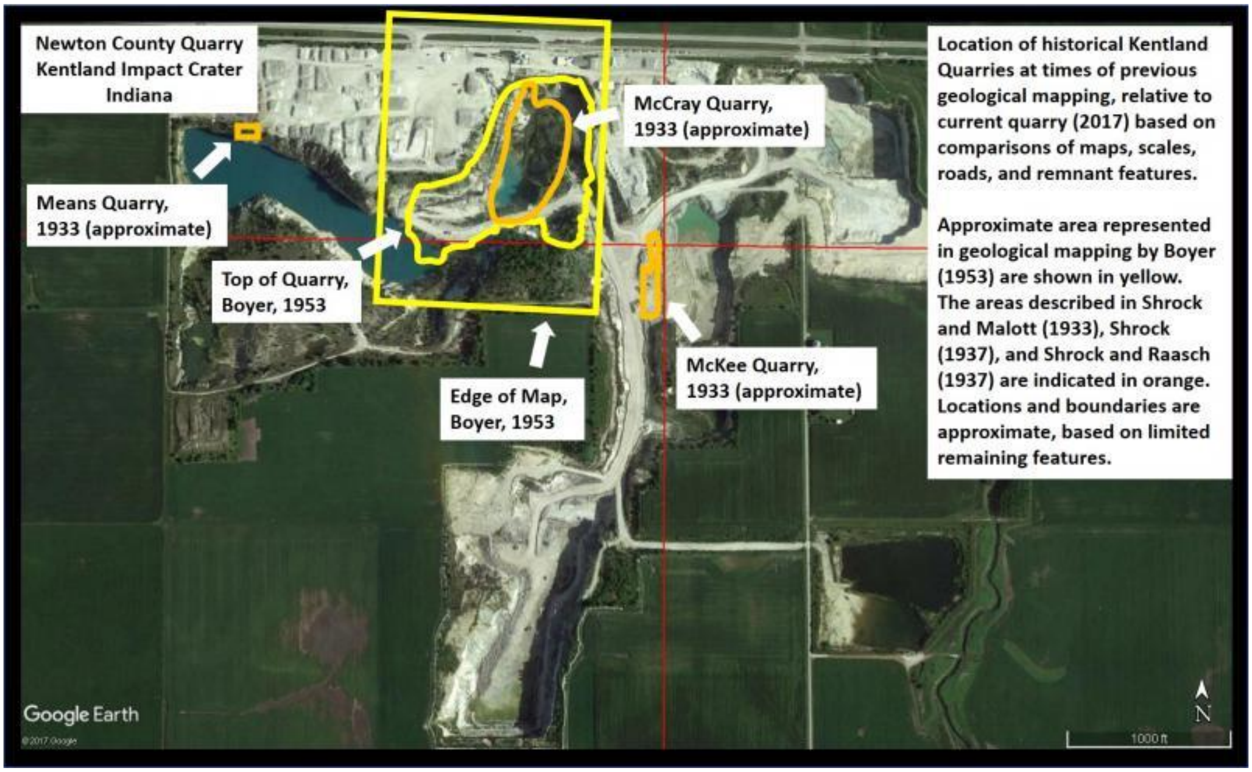


Figure 4. Excavation at the Kentland Quarry has penetrated as deep as 100 meters (Gutschick, 1983), and though discontinuous, stretches up to 1 km north to south and east to west.

Early Literature

The existence of an unusual structural anomaly in the Kentland area was first described at least as early as Collet, 1883:

"But three and a half miles southeast of Kentland the rocky beds come to the surface, or nearly approach it, over an area of more than 100 acres. At one of these exposures the bedding is nearly horizontal - at the other, in close proximity, the rocks were in nearly a vertical position, with a north-south trend, showing either serious dislocations or deposition under circumstances which gave origin to the most pronounced false bedding."

See Figure 5 for a sense of how the original exposures appeared to the first people to visit and surface quarry the site. Collet continues with what may be the very first description of shatter cones in the geological literature:

"At the latter station the stone was a slightly crystalline, bluish-gray limestone, with great nodules of cone-in-cone one to two feet in diameter, indicating pressure of superimposed material while it was in a plastic condition."

And later concludes:

"This quarry is a mystery. Its investigation invites and will reward the future geologist, who may be enriched with better light than is now available."

Figure 5. Unknown person, possibly Edward Kindle, in a 1903 photograph of exposed rocks in the central uplift of the Kentland Impact Crater, published in Kindle (1903) and Blatchley (1905), Indiana. Dept. of Geology and Natural Resources.

Discussion and reasoned guesses concerning the location's shattered, faulted, and uplifted rocks ranged from a narrow regional arch or synclinal fold, to a carbonate reef structure, to a dome, diastrophism, and to a cryptoexplosive or cryptovolcanic structure. These explanations competed through the late 19th and earliest 20th century literature (e.g.: Gorby, 1886; Thompson, 1889, 1892; Ashley, 1899; Kindle, 1903, 1904; Ward, 1906; Shrock and Mallot, 1933, etc.). Early interpretations are most thoroughly summarized in Shrock (1937) and Gutschick (1983).

Along with the account of changing quarry names, above, the following notes may be of particular use to the reader if an attempt is made to engage this early literature: The existence of 'The Wabash Arch', mentioned in several early works (e.g.: Gorby, 1886; Thompson, 1889; Kindle, 1903, 1904), has been refuted. There is no such structure, though there are unrelated structures in the region that are still known as Wabash domes. These are sometimes called 'cones,' which can be confusing. Mentions of other shatter-cone-like structures (distinct from and unrelated to the 'cone' domes) in the region are not supported by evidence. And while carbonate reef structures (same references) do exist in the region, producing mounds and hummocks in the stratigraphy, these do not come into play at Kentland. There is no fossil reef at Kentland. That it is a dome or uplift is of course true - in a sense - and descriptions of this and cryptovolcanic/cryptoexplosive features (e.g.: Cumings, 1922; Cumings and Shrock, 1927;

Bucher, 1928, 1935; etc.), can be readily re-framed in terms of a modern, impact-based model of structural displacement and distortion.

A great deal of very good descriptive work was accomplished at the site before the impact paradigm emerged in geology in the early-mid 20th century. The impact paradigm allowed the evidence to be more meaningfully contextualized. Research at Kentland contributed significantly to this change in perspective, and particularly to the early understanding of impact astrogeology at 'complex structures' (meaning those with a central rebound, like Kentland, rather than simple bowl structure, like Barringer).

The site was first described in significant detail in a series of 3 papers published in the 1930s (Shrock and Malott, 1933; Shrock, 1937; Shrock and Raasch, 1937). Shrock and Malott (1933) and Shrock (1937) both contain detailed summaries and reviews of literature concerning the structure prior to that date and record the shifting perspectives on the site that lead to its recognition as an explosive structure. These two publications then go on to describe the Middle Ordovician strata exposed in an active McCray's Quarry (also known at that time as the Kentland Quarry) and in two earlier abandoned quarries (McKee and Means) in significant detail. The authors describe typical impact features that are now familiar from a wider set of locations, including shatter cones, 'rock flour' from crushed sandstone, megabreccia (though not so named), abundant slickensides, and dikes of intruding breccia and powdered stone between larger blocks. This work thoroughly replaced earlier explanations of the site as an arch, dome, or reef with an explanation as a cryptovolcanic structure. The third of this trio of papers, Shrock and Raasch (1937), covers the entire fossil record known at the site through that time.

The Emergence of the Impact Paradigm

In 1936, Boon and Albritton published an article suggesting that some 'cryptovolcanic' structures may have actually originated from meteorite impacts and provided a hypothetical mechanism for the formation of the central uplift found at complex impact structures. They were later proven remarkably correct on both counts. Shrock (1937) listed Boon and Albritton's suggestion as the 5th of 7 possibilities for the origin of the structure, very rationally arguing against it. Boone and Albritton more directly suggested an impact origin specifically for the Kentland structure in a catalog of proven and questionable sites published in 1938. Acceptance of the notion was slow, as evidence emerged from this and other locations.

Robert S. Dietz (1946, 1947) further supported an impact origin for the structure in a foundational study of shatter cones from the location, and expanded upon the subject in a series of later publications. He observed that the apices of shatter cones pointed upward, not downward (this is actually harder to distinguish at first glance than one might think), which indicated formation by a force from above. Dietz also coined the term 'crypto-explosive,' in 1946, providing a linguistic framework within which to discuss explosive structures independent of cause.

Work shifted back from the interpretive to the descriptive in two papers from the first years of the 1950s. The first of these, a published doctoral dissertation by William Pullen (1953), measured radio signal strength, using existing regional transmitters as a source of signal for geophysical survey. The radio field intensity survey found a roughly circular high centered in the region of the Kentland (McCray at the time) quarry, measuring about 6.4 km across. This work provided the first sense of the scale of the structure beyond the exposed fraction of the central uplift.

The second 1953 article, an Indiana University geology master's thesis by Robert E. Boyer (1953), set out to map the exposed portion of the structure in greater detail, with an aim of correlating structure, petrology, mineralogy, and stratigraphy. Boyer resisted the impact interpretation, but produced a detailed map of the quarry and a measured stratigraphic column with detailed petrologic and petrographic descriptions of the lithologic units, which refined upon the stratigraphic column of Shrock and Malott (1933) and Shrock (1937).

Drawing heavily on work at Kentland, Robert Dietz published a pair of pivotal articles in 1959 and 1960. The first (Dietz, 1959) drew out Kentland, Flynn Creek, Well's Creek, and Steinheim as probable impact sites that presented shatter cones, and predicted that shatter cones might be present and usable as a criterion for recognition at other impact sites. After a flurry of travel and fieldwork, he did exactly that, increasing the catalog of known impact craters to seven (Dietz, 1960), based on the presence of shatter cones as an indicator of shock force from above. Boone and Albritton's class of hypothetically distinct structures, presented in 1936, had emerged as a distinct geological grouping - the complex impact craters.

In the same year, 1960, naturally occurring coesite was discovered at Meteor Crater, Arizona (Barringer crater). Coesite is a polymorph of quartz that can only be produced at extremely high pressures, such as those produced by a large meteorite impacts. This discovery provided a new possible tool for confirming an impact origin for cryptoexplosive structures like Kentland. The next year, investigations found the same mineral polymorph at both Kentland and Serpent Mound, offering a second unequivocal line of evidence indicating impact origin (Cohen et al., 1961). The discovery of coesite at these two locations also lent significant inertia to Robert Dietz work on shatter cones, and to the emerging reinterpretation of cryptoexplosive structures as impact craters.

Though the location's impact origin is no longer seriously questioned, the 1961 finding of coesite at Kentland has somewhat ironically not been reproduced, and has been challenged (e.g. Henderson and Milam, 2014, 2015; Bjørnerud, 1998). Laney (1976) and Laney and Van Schmus (1978) report results from indexing of planar deformation features (PDFs) and planar fractures (PFs) in quartz in thin section, using a universal stage. They report shock petrographic indicators consistent with 5 to 6 GPa (50 to 60 kbars), and not exceeding 8 GPa, and Henderson and Milam (2014, 2015) report XRD results in dolostone from the quarry consistent with 4.6 to 17 GPa. Morrow and Weber (2009) reports PFs, PDFs, and mosaicism consistent with 10 GPa or lower peak shock pressure from petrographic examination of St. Peter Sandstone quartz grains. Coesite is expected at around 5.5 to 10 GPa, the upper range of the indicated pressure for these units.

Further support for an impact origin at Kentland arrived in 1968, with analysis of shock deformation of quartz (Bunch, 1968; Carter, 1968; Dachille et al., 1968).

Between 1961 and 1987, Raymond Gutschick, a professor from Notre Dame, continued mapping and describing quarry exposures in a series of field guides to the site. Though difficult to find, these are frequently cited. (note: Gutschick mentions a substantial body of field maps and notes of his own production on several occasions, as well as being heir to the entire body of Dr.

Shrock's early field notes, "which has much information that is no longer available in the quarry." If these still exist, it would be good to know the location of these resources.)

Both Raymond Gutschick and Robert Shrock, who was still a professor at M.I.T. at the time, were in communication with Daniel Tudor when he began doctoral work at Kentland in 1966. The result of Daniel Tudor's work, a 1971 doctoral dissertation, provided a synthesis of geophysical data and marked a milestone in the understanding of the crater. Tudor reported a geophysical survey and drilling program, providing new information about the age, dimensions, and subsurface structure of the crater based on gravity survey, seismic refraction profiles, and data from over 140 shallow drill holes (Tudor, 1971). Tudor's team expanded the understanding of the Kentland impact structure beyond the quarry walls. Since the entirety of the regional bedrock beyond the quarry is covered by glacial drift, nobody was really sure that anything else remained from the impact beyond the quarried central uplift until this time, nearly 90 years after the disturbance was first described! Tudor provided the first good sense of the structure's geometry - concentric rings - an uplift surrounded by an annular depressed basin, surrounded by a raised rim marking the probable edge of the structure, and of the crater's overall diameter (Tudor, 1971). (see Figure 3)

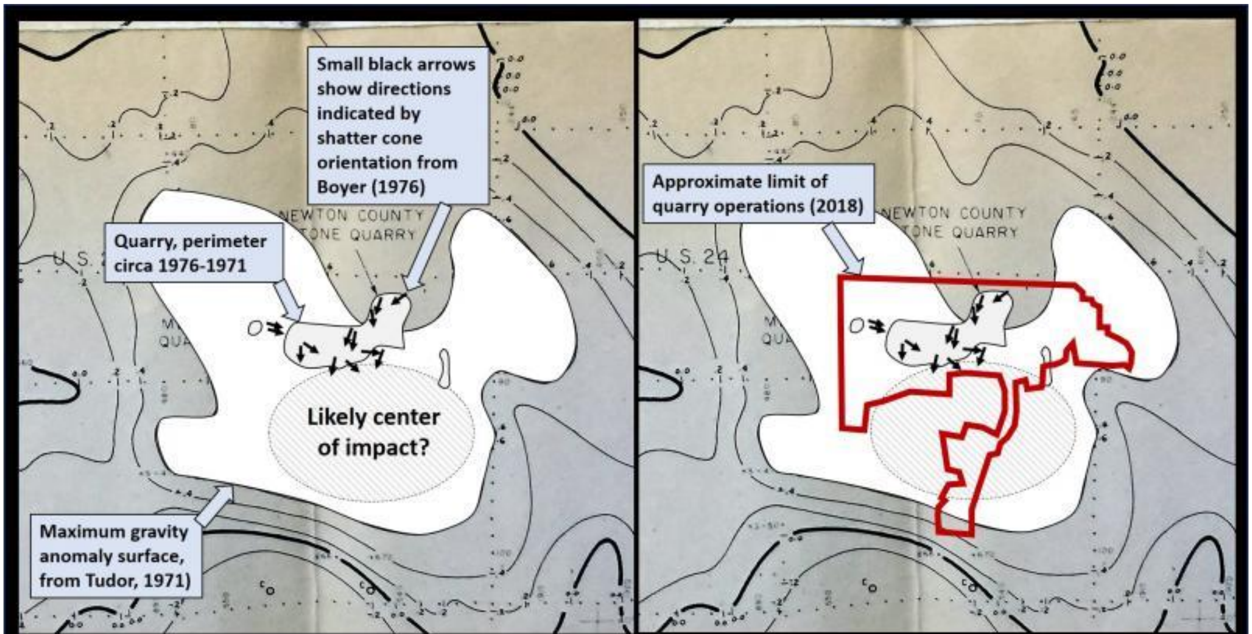
Randy Laney expanded upon and refined Tudor's work 7 years later, in a 1978 Master's thesis.

Nasser and Howe (1995) looked at thermal alteration of conodonts in Silurian and Ordovician units in the Kentland quarry, and found alteration to be modest (not indicative of strong heating) and highly variable.

A 1998 paper by M.G. Bjørnerud quantitatively characterized breccias at the Kentland quarry, with an aim of determining order and process of formation and emplacement. Analysis of grain/clast size distributions and cross-cutting relationships among 3 different types of breccia units suggested that all three units formed during excavation and modification stages of crater formation, after initial contact and compression, and established that fault breccias and breccia lenses were cross-cut by dikes of injection breccia, but that that the characteristics of all 3 were consistent with a single disruptive event. The paper also reported evidence of possible devolatilization (removal of a portion converted to gas) of carbonates.

Gaps in Knowledge

At the times Shrock, Malott, Boyer, Gutschick, and others mapped the exposure of the central uplift, the quarry was a small fraction of its current size. It now extends about 1.3 km north to south, and about 1.5 km east to west, meaning it may well reach the flank of the central uplift and into the presumed fallback breccia and basin-filling breccia and megabreccia, or that it might have exposed younger sections of the uplifted material, removed in previously mapped areas, or may have exposed a contact between the uplifted rock and minor units that post-date the impact but underlie the glacial drift. Renewed work at the quarry perimeter may illuminate impact timing. Note, also, that Laney's 1976 work on shatter cone orientation suggested that the point of impact was south and east of the quarry, meaning that subsequent quarry expansion, which has been substantial in this direction, may have uncovered this zone. (see Figure 7)



Background map is Tudor (1971), Plate 8, *Gravity Contours from the Residuals From the 6th Degree Surface*, showing gravity anomaly maximum encompassing and just south of the quarry. Depending upon the residual surface used, Tudor showed the maximum anomaly just north or just south of the quarry. This is overlain with data from Laney (1976), figure 23, summarizing orientation of shatter cone axes as an indicator of location of source of shock. Fit is based on comparing the sketches of quarry outlines by Boyer (1953), Tudor (1971), Laney (1976), and aerial photos of modern quarry outlines from Google Earth. This is a best effort based on very limited points of common reference between the maps. (The authors only roughly sketch the changing quarry outlines.) I've interpreted a possible region that may encompass the center of impact. The results appear to suggest that the quarry sits on the northern flank of the uplift, and that subsequent quarry expansion may have cross-cut the center of the impact.

Figure 6. Ground cover and surface soil removal after earlier published works may have exposed additional structures of interest, including the center of the central uplift.

Tudor (1971) and others have reported no topographical expression of the structure beyond the central uplift, but more recent higher resolution digital elevation data may not have been employed to search for a subtle topographical expression of the basin or rim.

Age is also only moderately constrained. Tudor (1971) and Laney and Van Schmus (1978) are not completely clear whether coal units of presumed Pennsylvanian age and underlying Mississippian carbonate units in the annular basin were disrupted by the impact or not. Tudor leaned towards their emplacement prior to disruption, but he perceived the annular basin as a down-warped area, or syncline, rather than an impact excavated transient cavity, and thus would not have found a relatively undisturbed coal unit to be inconsistent with emplacement prior to the formation of the central uplift. One would expect breccia/mega-breccia in the annular basin. Erosion of only about 300 meters from the central uplift (see discussion above) is not consistent with complete removal of disturbed materials from the region. And even if excavated by erosion, the drilled floor of the inner annular basin should reveal older rock than is typical for the location not younger. The age of the unit also needs to be confirmed. If it is established that the coal unit is Pennsylvanian in age, and that it postdates the impact, this would tightly constrain the impact timing to between the Pennsylvanian or Mississippian and Silurian. The opposite is also true - If it were established that the unit pre-dated the impact, it would push the earliest possible impact date forward to the age of the coal. Tudor (1971, page 37) notes that the cores from his work were given to the Indiana Geological Survey for identification and storage. They could still be in storage.

Coesite in the St. Peter Sandstone in Kentland was reported at very low concentration of about 100 parts per million (Cohen et al., 1961), compared for instance to about 1% in shocked specimens at Wabar. The result was not reproduced in an attempt by Bell and Sharpton (1996), and was challenged in Henderson and Milam (2014, 2015); Bjørnerud (1998), and others. Though the presence of coesite has been questioned, subsequent reported indicators of shock (Laney and Van Schmus, 1978; Henderson and Milam, 2014) are consistent with both shatter cone formation (~3-10 GPa) and with coesite formation (5.5-10 GPa).

Koeberl and Sharpton (1993) report initial work on impactor characterization, finding only a possible trace of the impactor at low concentration (~0.02%) in a breccia unit, but nothing else is known yet about the classification of the impacting meteoroid.

A lot of the work on this structure is in abstracts, theses, and field guides. Little is reported in a peer reviewed context.

Maps

Small portions of the central uplift exposed in the Kentland Quarry have been mapped very well, notably in Boyer, 1953, though the quarry has expanded significantly in subsequent decades, and portions of the mapped surface have changed. The central uplift of the Kentland impact structure is captured on the USGS 7.5 Minute Kentland, IN., topographical map. Tudor (1971) produced gravity maps, as well as maps of the bedrock geology and bedrock topography of the overall structure, using drill holes and seismic refraction data. Though they still exist (2017), it does not appear that these critical contributions have been digitized or reproduced in any durable publication. Gutschick (1987) contains several small maps and a good stratigraphic column.

Annotated Bibliography and References

(If your research leads you to additional scientific references related to this crater, please help improve this resource by sending a note with the new citation(s) to: robert@impactcraters.us)

Ashley G. H., Siebenthal C. E. (1899) The Coal Deposits of Indiana. Indiana Department of Geology and Natural Resources, 23rd Annual Report, page 190.

https://scholarworks.iu.edu/dspace/handle/2022/6728

[Attributes the structure to cryptovolcanism - "it would almost seem as though volcanic or other agencies had produced an upheaval of a kind seldom found in nature." Siebenthal (contributor and illustrator) is omitted from some citations.]

Bell M. S., Sharpton V. L. (1996) High-pressure shock effects in silica in St. Peter sandstone from the Kentland impact structure, Indiana, USA (abstract). Meteoritics & Planetary Science, volume 31, p. A13.

http://adsabs.harvard.edu/full/1996M%26PSA..31R..13B

[Preliminary report of attempt to identify coesite or stishovite in St. Peter sandstone from Kentland. None found.]

Beukema S., Weber J., Donelick R. (1998) Apatite fission-track dating of uplift, Kentland dome, Indiana (abstract). Michigan Space Grant Annual Meeting, Ann Arbor, Michigan.

no link found

Bjørnerud M. G. (1998) Superimposed deformation in seconds: breccias from the impact structure at Kentland, Indiana (USA). Tectonophysics, Volume 290, Issue 3-4, pages 259-269.

http://www.sciencedirect.com/science/article/pii/S0040195198000237

[Distinguished 3 different types of breccia units in the central uplift, quantitatively characterized them through grain/clast size distributions and cross-cutting relationships, and determined timing and process of emplacement.]

Blatchley W. S. (1905) The Roads and Road Materials of Indiana, in Department of Geology and Natural Resources 30th Annual Report, Indiana. Department of Geology and Natural History, Volume 30, pages 214-219.

[Early photos are shown on page 215. This work describes quarries at Kentland. It also clarifies name and ownership of active quarry at that time.]

https://books.google.com/books?id=eBk0AQAAMAAJ

Bliss K. M., Morrow J. R., Weber J. C., Vice M. (2009) Evaluation of XRD and Raman peak broadening in shock-metamorphosed carbonates from carbonate-target bolide structures (abstract #2211). Abstracts of the 40th Lunar and Planetary Science Conference, Lunar and Planetary Institute, Houston, Texas.

http://www.lpi.usra.edu/meetings/lpsc2009/pdf/2211.pdf

[Samples from Kentland and 7 other confirmed impact sites were used to evaluate changes in XRD and MRS results from shocked carbonates versus carbonates from other high temperature-pressure settings.]

Boon J. D., Albritton C. C. (1936) Meteorite craters and their possible relationship to "cryptovolcanic structures". Field and Laboratory, Volume 5, No. 1, pages 1-9.

https://sites.smu.edu/shulermuseum/publication_pdfs/field_lab/BoonAlbritton1936.pdf

[Suggests that some cryptoexplosive or cryptovolcanic structures may be meteorite impact craters.]

Boon J. D., Albritton C. C. (1938) Established and supposed examples of meteoritic craters and structures. Field and Laboratory, Volume 6, No. 2, pages 44-56.

https://sites.smu.edu/shulermuseum/publication_pdfs/field_lab/BoonAlbritton1938a.pdf

[Early catalog of possible, questionable, and proven impact craters. Offers a tentative suggestion that Kentland could be of impact origin.]

Boyer R. E. (1953) The geology of the structural anomaly near Kentland, Indiana. Master's Thesis, Indiana University, Bloomington.

no link found

[Boyer describes and maps the structure of the Kentland quarry, correlating stratigraphy, petrology, and petrographic and mineralogical analysis. Though arguing against an impact or cryptoexplosive origin, he produced a detailed map and an improved measured stratigraphic section for the quarry, providing an excellent physical record of the site.]

Brusnahan H., Weber J., Reynolds R. (2007) Shock metamorphic effects in lattice structure of sphalerite (ZnS) from polymict impact breccia dikes, Kentland crater, Indiana (abstract). Geological Society of America, Abstracts with Programs, Volume 39, No. 6, page 373.

https://gsa.confex.com/gsa/2007AM/finalprogram/abstract_128918.htm

[Brief abstract examines shock induced changes in XRD results from sphalerite. Some of the results are illustrated in Figures 9-10 in Weber (2013).]

Bucher W. H. (1936) Cryptovolcanic structures in the United States (with discussion) Report XVI. 16th International Geological Congress (Washington), 1933, Proceedings, Volume 2, pages 1055-1084.

no link found

[Also cited as 1935.]

Bunch T. E. (1968) Some characteristics of selected minerals from craters, in Shock metamorphism of natural materials, Bunch T. E. and Short N. M. (editors): Baltimore, Maryland, Mono Book Corp., pages 413-432.

[shock deformation of quartz, incl. at Kentland]

Carter N. L. (1968) Dynamic deformation of quartz, in Shock metamorphism of natural materials, Bunch T. E. and Short N. M. (editors): Baltimore, Maryland, Mono Book Corp., pages 693-696.

[shock deformation of quartz, in Shock Metamorphism of Natural Materials]

Chamberlin R. T. (1923) On the crustal shortening of the Colorado Rockies. American Journal of Science, Series 5, Volume 6, pages 215-221 (217). doi: 10.2475/ajs.s5-6.33.215

http://www.ajsonline.org/content/s5-6/33/215.extract

Cohen A. J., Bunch T. E., Reid A. M. (1961) Coesite discoveries establish cryptovolcanics as fossil meteorite craters. Science, Volume 134, pages 1624-1625.

http://www.sciencemag.org/content/134/3490/1624

[Report of coesite in St, Peter sandstone at Kentland in extremely low concentrations of about 100 parts per million.]

Cohen A. J., Reid A. M., Bunch T. E. (1962) Central uplifts of terrestrial and lunar craters - Pt. 1, Kentland and Serpent Mound structures (abstract). Journal of Geophysical Research, Volume 67, No. 4, pages 1632-1633. doi/10.1029/JZ067i004p01627

https://agupubs.onlinelibrary.wiley.com/doi/10.1029/JZ067i004p01627

Collett J. (1883) Geological survey of Newton County. Indiana Department of Geology and Natural History, 12th Annual Report, pages 58-59.

https://scholarworks.iu.edu/dspace/handle/2022/5321

[The earliest description of the disturbed rocks at the Kentland structure, and possibly the first description of shatter cones (as cone-in-cone structures) in any literature.]

Collins H., Brown L. A. (1973) Fracture analysis of the Kentland, Indiana, disturbance (abstract). Jackson M. T. (editor) Proceedings of the Indiana Academy of Science, Volume 83, page 243.

https://journals.iupui.edu/index.php/ias/article/view/7902

Cumings E. R. (1922) Nomenclature and Description of Geological Formations of Indiana, in Handbook of Indiana Geology by W. N. Logan, E. R. Cummings, C. A. Malott, S. S. Visher, W. M. Tucker, and J. R. Reeves, Indiana Department of Conservation, Part 4, pages 420-449.

https://books.google.com/books?id=H0E5AQAAMAAJ

[Cumings and other authors in this volume provide useful insights on facets of the early history of the site within the context of a broad review of the geology of the entire state. A more specific understanding of the early work relevant to Kentland can be gained from the literature reviews in Shrock and Malott (1933) and in Shrock (1937).]

Cumings E. R., Shrock R. R. (1927) The Silurian Coral Reefs of Northern Indiana and Their Associated Strata. Indiana Academy of Science Proceedings for 1926, Volume 36, pages 71-85.

https://journals.iupui.edu/index.php/ias/article/viewFile/4248/4192

[Attributes domes elsewhere in the region of Kentland to reef structures, and distinguished the origin of Kentland from these other structures. Also, briefly reviews previous work. See Shrock and Malott (1933) and Shrock (1937) for a more complete review of early work at Kentland.]

Cumings E. R., Shrock R. R. (1928) Niagaran Coral Reefs of Indiana and Adjacent States and Their Stratigraphic Relations. Bulletin of the Geological Society of America, Volume 39, pages 579-620.

https://pubs.geoscienceworld.org/gsa/gsabulletin/article/39/2/579/3152

Cumings E. R., Shrock R. R. (1928) The Geology of the Silurian Rocks of Northern Indiana. Indiana Department of Conservation, Division of Geology, Publication No. 75. page 137.

no link found.

Dachille F., Gigl P., Simons P. Y. (1968) Experimental and analytical studies of crystalline damage useful for the recognition of impact structures, in Shock metamorphism of natural materials, Bunch T. E. and Short N. M. (editors): Baltimore, Maryland, Mono Book Corp., pages 555-569.

[shock deformation in quartz]

Dietz R. S. (1946) Geological structures possibly related to lunar craters. Popular Astronomy, Volume 54, pages 465-467

http://adsabs.harvard.edu/full/1946PA.....54..465D

[Earliest brief mention of orientation of shatter cones as evidence of impact origin. the idea is expanded in Dietz (1947).]

Dietz R. S. (1947) Meteorite impact suggested by the orientation of shatter-cones at the Kentland, Indiana disturbance. Science, Volume 105, pages 42-43. DOI: 10.1126/science.105.2715.42

http://www.sciencemag.org/content/105/2715/42.extract

[Proposes an impact origin for shatter cones based on studies at Kentland.]

Dietz R. S. (1959) Shatter cones in cryptoexplosion structures (Meteorite Impact?). The Journal of Geology, Volume 67, No. 5, pages 496-505.

https://www.jstor.org/stable/30056104?seq=1#page_scan_tab_contents

Dietz R. S. (1960) Meteorite impact suggested by shatter cones in rock. Science, Volume 131, No. 3416, pages 1781-1784. doi: 10.1126/science.131.3416.1781

http://www.sciencemag.org/content/131/3416/1781.extract?

[Establishes shatter cones as evidence of impact, drawing partly on work at Kentland.]

Dietz R. S. (1972) Shatter cones (shock fractures) in astroblemes. Proceedings of the 24th International Geological Congress, Section 15, pages 112-118.

http://adsabs.harvard.edu/full/1971Metic...6R.258D

[A brief abstract indicating that shatter cones are a definitive criterion for impact crater identification, and that the orientation of shatter cones may be used to identify the location of impact.]

Foerste A. F. (1921) Notes on Arctic Ordovician and Silurian Cephalopods. Denison University Bulletin, Volume 19, pages 277-278.

https://books.google.com/books?id=cKEWAQAAIAAJ

Gorby S. S. (1886) The Wabash Arch. Geological Survey of Newton County, Indiana Department of Geology and Natural History, 15th Annual Report, pages 228-241.

https://scholarworks.iu.edu/dspace/bitstream/handle/2022/3620/15th_Pt16.pdf?sequence=1

[Early description of exposure and disruption of rock units at the Kentland quarries. Also contains one of the earliest published descriptions of shatter cones (as 'cone-in-cone' structures).]

Greene G. K. (1906) On the age of the rocks near Kentland, Indiana. Contributions to Indiana Paleontology, Volume 2, Part 1, pages 11-17.

no link found

[Shrock (1937), Shrock and Raasch (1937), and others cite this 1906 work as having firmly established the exposed rocks at the Kentland Quarry as Ordovician in age, based upon fossil genera.]

Gutschick R. C. (1961) The Kentland Structural Anomaly, Indiana, in Geology from Chicago to Cincinnati: Geological Society of America, Guidebook for Field Trips, 1961 Cincinnati Meeting of the Geological Society of America, No. 2, pages 12–17.

no link found

Gutschick R. C. (1969) Geology of a quarry in the Kentland anomaly, Indiana (abstract), in Abstracts with Programs for 1969, part 6, North Central Section: Geological Society of America, page 19.

no link found

Gutschick R. C. (1970) The stratigraphy and structure of the Kentland impact anomaly, Indiana (abstract). Abstracts with Programs, Geological Society of America meeting, Milwaukee, Wisconsin, Volume 2, no. 7, page 564.

no link found

Gutschick R. C. (1971) Geology of the Kentland impact structural anomaly, northwestern Indiana. Field Guide for the National Association of Geology Teachers, East-central Section, April 17, 1971, Annual Meeting. 20 pages.

no link found

Gutschick R. C. (1972) Geology of the Kentland impact structural anomaly, Guidebook for the 35th Annual Meeting of the Meteoritical Society Field Trip. November 15th, 1972, Chicago, Illinois.

no link found

Gutschick R. C. (1976) Geology of the Kentland structural anomaly, Northwestern Indiana. Guidebook for the 10th Annual Meeting, North Central Section, Geological Society of America, April 28th, 1976, Western Michigan University, Kalamazoo. 59 pages.

[This is a hands-on field guide, providing both the geological context and a practical description of the location and character of the rock units, with an aim to allowing a visitor or researcher to orient themselves and locate the various rock units. It contains many photographs, maps, and summary diagrams, many of which are the product of Gutschick's own mapping efforts.]

Gutschick R. C. (1982) Geology of the Kentland structural anomaly, northwestern Indiana -- update. Purdue University, Department of Geosciences, and Geological Society of America, North-Central Section, Guidebook 4, 38 pages.

no link found

Gutschick R. C. (1983) Geology of the Kentland Dome structurally complex anomaly, northwest Indiana (Field Trip 5). In: Shaver R. H., Sunderman J. A. (editors) Field trips in midwestern geology: Bloomington, Indiana, Geological Society of America, Indiana Geological Survey and Indiana University Department of Geology Guidebook 1, 105–138.

no link found

[This guide provides an excellent history of investigations, contextualizes the structure geologically, and gives a detailed summary of the stratigraphic succession exposed within the quarry. Gutschick's 1983 work provides a concise, practical summary of exposures and rock units in the quarry at the time, with plain-English physical descriptions of the rock units and their locations to aid with identification. It would be an invaluable tool for anyone attempting to gain the hands-on familiarity necessary to continue research at the site.]

Gutschick R. C. (1987) The Kentland Dome, Indiana: A structural anomaly, in Geological Society of America Centennial Field Guide Volume 3, North-Central Section of the Geological Society of America, Biggs D. L. (editor), pages 337–342.

http://geoscienceworld.org/content/north-central-section-of-the-geological-society-of-america

[A good brief summary of stratigraphy, regional geologic context, and rock exposures at the Kentland Quarry from the unit scale to hand specimens. Gutschick did not go into a literature review, and remained skeptical of impact origin.]

Heller N. A., Weber J. C., Sivron R., Pope M. (1998) Testing theoretical shatter cone models using data from the Kentland, Indiana, dome and Sudbury, Ontario, structure (abstract), in Michigan Academy Annual Meeting, Ann Arbor, Michigan Academy.

no link found

Henderson T., Milam K. A. (2014) Initial XRD analysis of Silurian carbonates from the central peak of the Kentland impact structure, Newton County, Indiana, USA (abstract). Abstracts of the 2014 GSA Annual Meeting, Geological Society of America, Abstracts with Programs, Volume 46, No. 6, p. 760.

https://gsa.confex.com/gsa/2014AM/webprogram/Paper249499.html

[Reports XRD results in dolostone consistent with 4.6 to 17 GPa shock pressure, and challenges coesite report in Cohen, 1961.]

Henderson T., Milam K. A. (2015) XRD Analyses of Silurian Dolostones from the Central Uplift of the Kentland Impact Structure, Newton County, Indiana, USA (abstract). 46th Lunar and Planetary Science Conference.

http://www.hou.usra.edu/meetings/lpsc2015/pdf/2989.pdf

[Reports XRD results in dolostone from the Kentland quarry consistent with less than 17 GPa shock pressure, and describes ongoing work.]

Hoholick D. J. (1980) Porosity, grain fabric, water chemistry, cement, and depth of the St. Peter Sandstone in the Illinois Basin (Master's Thesis), Cincinnati, Ohio, University of Cincinnati, 72 pages.

no link found

Huss Q. S. (1996) Shocked quartz of the St. Peter Sandstone from the Kentland structural anomaly, Indiana, USA (Abstract No. 7476). Geological Society of America Abstracts with Programs, North-Central Section, Volume 28, No. 6, page 46.

no link found

[Very short abstract. Reports "uneven extinction (mosaicism), cataclasis, contact features, and lamellae" in St Peter sandstone.]

Jackson M., van der Voo R. (1986) A paleomagnetic estimate of the age and thermal history of the Kentland, Indiana, cryptoexplosion structure. Journal of Geology, Volume 94, pages 713–723.

http://www.jstor.org/stable/30078335

[Provides a review of stratigraphic age constraints and reports on a new paleomagnetic study, offering a tentative age of Late Cretaceous. Demonstrates evidence of heating of the materials exposed in the quarry to about 150 C, and models a minimum depth of erosion of about 300 meters.]

Joesting H. R., Henderson J. R. (1948) Preliminary report on an experimental aeromagnetic survey in northwestern Indiana: U.S. Geological Survey.

[Tudor (1971) describes this earlier vertical magnetic intensity survey as having shown no anomaly in the Kentland area.]

Kindle E. M. (1903) The Niagara Domes of Northern Indiana. American Journal of Science, 4th Series, Volume 15, pages 459-468.

http://www.ajsonline.org/content/s4-15/90/459.extract

Kindle E. M. (1903) The Stratigraphy and Paleontology of the Niagara of Northern Indiana, in Indiana Department of Geology and Natural Resources, 28th Annual Report, pages 399-486.

https://cmis.dnr.in.gov/annualreports/Annual_Report_1903.pdf

or

https://scholarworks.iu.edu/dspace/handle/2022/9945

[This contains an early sparse description of the Kentland structure, interestingly including an early photograph at McKee quarry (page 404). If you are researching this work, note that this is cited by Shrock (1933, 1937) and others as 1904, instead of 1903, and pages 428-486 are listed as a second publication, "Kindle E. M. and C. L. Breger (1904) Paleontology of the Niagara[...]". This earlier citation may be more appropriate, but these pages are simply headed as 'Part II' in the document. The co-authorship of Part II by Mr. C. L. Breger is mentioned in a footnote on page 428.]

Koeberl C., Sharpton V. L. (1993) Geochemical study of rocks from the Kentland, Indiana, impact structure: Progress report (abstract). Meteoritics, Volume 28, No. 3, page 382.

http://adsabs.harvard.edu/full/1993Metic..28..382K

[Reports preliminary work on identifying the impactor through geochemical and petrographic study of breccias. Slightly elevated Ir levels were reported in one sample.]

Laney R. T. (1978) A structural and petrographic study of the Kentland, Indiana impact site. Master's Thesis, University of Kansas.

no link found

[A substantive study. Laney provides a brief literature review, and then refines results from Tudor's 1971 gravity work, using measured densities for rock units. Laney also indexed PDFs and PFs in quartz grains from the St. Peter sandstone found in the quarry, placing limits on peak shock pressure. He also measures corrected orientation of shatter cones exposed in the quarry, finding that the point of impact was probably south of the quarry (see p. 66.).]

Laney R. T., Van Schmus W. R. (1978) A Structural Study of the Kentland, Indiana Impact Site (abstract). Abstracts of the 9th Lunar and Planetary Science Conference, pages 627-629.

http://adsabs.harvard.edu/full/1978LPI.....9..627L

[Brief description of the general dimensions, exposure, structural expressions, and impactite lithologies of the Kentland site.]

Laney R. T., Van Schmus W. R. (1978) A structural study of the Kentland, Indiana impact site (abstract). Proceedings of the 9th Lunar and Planetary Science Conference, Volume 2, pages 2609-2632.

http://www.lpi.usra.edu/meetings/lpsc1978/pdf/1218.pdf

or

http://adsabs.harvard.edu/full/1978LPSC....9.2609L

[Integrates well logs, cores, and earlier maps from the quarries, and Tudor's (1971) gravity survey and modelling to infer tentative dimensions and subsurface structure of the crater. Reviews shock evidence and delivers some new petrographic work.]

Laney R. T., Van Schmus W. R. (1978) The Kentland impact site: A structural study of a partially dissected central uplift (abstract). Abstracts of the American Geophysical Union, Midwest Meeting, EOS, Volume 59, page 223. DOI: 10.1029/EO059i004p00221

http://onlinelibrary.wiley.com/doi/10.1029/EO059i004p00221/full

Lindsey A. A., Schmelz D. V., Nichols S. A. (1969) Natural areas in Indiana and their preservation, in The Report of the Indiana Natural Areas Survey: West Lafayette, Indiana, Purdue University Department of Biological Sciences, pages 488-490.

no link found

[This is cited in Gutschick '87 as concerning the importance and preservation of Kentland.]

Lloyd H. L. (1931) Middle Ordovician fauna from the disturbed area three miles southeast of Kentland, Indiana. Unpublished Master's Thesis, University of Wisconsin.

no link found

[Shrock and Malott, 1933, attributes identification of fossils from fieldwork at Means Quarry to this unnamed volume. Gutschick (1976) later cites Lloyd's initials as C. H.]

Lucas D. R. (1952 or 1953) Unpublished geophysical maps of Kentland area. Indiana University Master's Thesis, incomplete.

[Unpublished magnetic survey of Kentland, referenced in text of Boyer (1953), Tudor (1971), and Laney and Van Schmus (1978) - all describe it as showing no magnetic anomaly. Tudor (page 37-38) describes the unpublished work, reporting that Lucas found a distinct circular Bouguer gravity anomaly, inspiring a portion of Tudor's 1971 fieldwork and dissertation.]

Melosh H. J., Ivanov B. A. (1999) Impact Crater Collapse. Annual Review of Earth and Planetary Sciences, Volume 27, pages 385-415.

http://www.lpl.arizona.edu/~jmelosh/impact_crater_collapse.pdf

[Referenced by Weber (2005, 2013) to support a possible smaller crater diameter for Kentland.]

Milam K. A. (2007) Petrographic observations of central uplift formation in complex craters (abstract #8053). Workshop on Impact Cratering II, Bridging the Gap II: Effect of Target Properties on the Impact Cratering Process

http://www.lpi.usra.edu/meetings/gap2007/pdf/8053.pdf

Morrow J. R., Weber J. C. (2009) Comparison of low-pressure shock-metamorphic effects in quartz from Barringer Crater, Arizona, and Kentland Dome, Indiana (abstract). Abstracts of the 40th Lunar and Planetary Science Conference.

http://www.lpi.usra.edu/meetings/lpsc2009/pdf/1913.pdf

[Petrographic examination of St. Peter Sandstone quartz grains finds PFs, PDFs, and mosaicism consistent with 10 GPa or lower peak shock pressure.]

Nasser M. N. III, and Howe R. C. (1995) Bedrock paleotemperature study of the Kentland impact site, Kentland, Indiana. Proceedings of the Indiana Academy of Science, Volume 104, No 3-4, pages 207-211.

https://journals.iupui.edu/index.php/ias/article/view/7395

[Records isolated and varied zones of low level thermal alteration of conodonts in the Ordovician and Silurian rock units within the quarry.]

Nasser M. N. III, Howe R. C. (1993) Lack of Silurian conodont alteration, Kentland anomaly, Indiana (abstract). Indiana Academy of Science, Abstracts with Program, page 70.

no link found

Pavlis G. (1983) Seismic refraction results for the Kentland dome, in Field Guidebook for the 23rd Annual Meeting of the North-Central Section of the Geological Society of America. the University of Notre Dame, Notre Dame, Indiana. Pages 35-39.

no link found

Poulos C., Weber J., Donelick R. (2001) Determining the age for the Kentland, Indiana, meteorite impact event using apatite fission-track data (abstract), in Michigan Space Grant Annual Meeting Abstracts, Ann Arbor, Michigan.

no link found

Pullen M. W. Jr. (1950) Geologic aspects of radio wave transmission. University of Illinois, Doctoral Dissertation, 257 pages plus maps.

[This is generally cited as 1953, when it was published as Illinois State Geological Survey Report of Investigations No. 162. see following.]

https://iucat.iu.edu/iusb/7905586

Pullen M. W. (1953) Geologic aspects of radio wave transmission: Illinois State Geological Survey Report of Investigations No. 162. pages 47-53.

https://www.ideals.illinois.edu/bitstream/handle/2142/44572/geologicaspectso162pull.pdf?sequence=2

[Radio field intensity survey that measured radio signal strength from existing regional transmitters as a potential geophysical proxy. The study reported a regional high at and surrounding the structure's central uplift.]

Sagy A., Reches Z., Fineberg J. (2001) Fracturing analysis of shatter cones from Kentland, Indiana impact site (abstract). Annual Meeting of the Israel Geological Society, Israel Geological Society; 1998, 2001.

no link found

Sagy A., Reches Z., Fineberg J. (2002) Dynamic fracture by large extraterrestrial impacts as the origin of shatter cones. Nature, Volume 418, Number 6895, pages 310-313. doi:10.1038/nature00903

http://www.nature.com/nature/journal/v418/n6895/abs/nature00903.html

Schmieder M., Buchner E., Reimold W. U. (2011) Impact-related deformation features in cherts from terrestrial impact structures (abstract). Abstracts of the 42nd Lunar and Planetary Science Conference.

http://www.lpi.usra.edu/meetings/lpsc2011/pdf/2274.pdf

Shrock R. R. (1937) Stratigraphy and structure of the area of disturbed Ordovician rocks near Kentland, Indiana. American Midland Naturalist, Volume 18, No. 4 (July, 1937), pages 471-531.

http://www.jstor.org/stable/2420651?seq=1#page_scan_tab_contents

[Contains an excellent literature review of the work leading up to the publication date. The author describes the strata exposed at the Kentland quarry (3 quarries at that time) in significant detail, correlates stratigraphic sections between the quarries, and discusses large- and small-scale structural evidence of origin.]

Shrock R. R, (1940) Note on "Paleontology of the disturbed Ordovician rocks near Kentland, Indiana." American Midland Naturalist, Volume 23, page 493.

Shrock R. R., Malott C. A. (1929 or 1930) Notes on some Northwestern Indiana rock exposures. Proceedings of the Indiana Academy of Sciences, Volume 39, page 221-227.

https://journals.iupui.edu/index.php/ias/issue/view/387

[Briefly describes the age of the Kentland structure exposures, and distinguishes its origin from others in the region. This work mentions ('in preparation'), and is subordinate to, the more thorough treatment in Shrock and Malott (1933). This article is cited several places as Shrock and Malott, 1930.]

Shrock R. R., Malott C. A. (1933) The Kentland area of disturbed Ordovician rocks in northwestern Indiana. Journal of Geology, Volume 41, pages 337-370.

http://www.jstor.org/stable/30058967?seq=1#page_scan_tab_contents

[Earliest major description. Presents a thorough review of literature prior to 1933, and a detailed description of stratigraphy in the quarries in the central uplift. (Cryptovolcanic paradigm.) The work also presents a fossil faunal assemblage from the quarries.]

Shrock R. R., Raasch G. O. (1935) Correlation of Ordovician sequence at Kentland, Indiana. Proceedings of the Geological Society of America for 1934. Pages. 355-356.

no link found

[Described in Shrock (1937) as correlating the Ordovician exposures at Kentland with sequences in Tennessee and the upper Mississippi valley.]

Shrock R. R. and Raasch G. O. (1937) Paleontology of the disturbed Ordovician rocks near Kentland, Indiana. American Midland Naturalist. Volume 18, No. 4, pages 532-607.

http://www.jstor.org/stable/2420652?seq=1#page_scan_tab_contents

[Provides a thorough review of earlier literature on the fossil assemblage at the Kentland Quarries, along with a catalog of the entire faunal assemblage known through the date of publication, with plates.]

Templeton J. S., Willman H. B. (1963) Champlainian Series (Middle Ordovician) in Illinois: Illinois Geological Survey Bulletin, Volume 89, 260 pages.

https://www.ideals.illinois.edu/handle/2142/91524

[Clarified and contextualized Shrock's 1937 discussion of stratigraphy at Kentland, in the context of broadly correlating regional stratigraphy. The Kentland quarry is used as a point of reference throughout, but is discussed specifically from page 164-167.]

Thompson M. (1889) The Wabash Arch. Geological survey of Newton County, Indiana Department of Geology and Natural History, 16th Annual Report, pages 41-53.

https://scholarworks.iu.edu/dspace/bitstream/handle/2022/13882/16_03The+Wabash+Arch.pdf?sequence=1

[Though attempting to contextualize the Kentland structure within the now defunct 'Wabash Arch' paradigm, Thompson attributes the structure to abrupt, catastrophic forces of uplift, presciently contextualizing the comment within the broader uniformitarianism versus catastrophism debate of the era. As a description of Kentland, the work is marginal, but as a self-aware time capsule of science history, it is wonderful. note: This is sometimes cited as 1888.]

Thompson M. (1891) Geological and Natural History Report of Carroll County. Indiana Department of Geology and Natural Resources, 17th Annual Report, pages 171-191 (182-185).

https://igws.indiana.edu/CMIS/library/Annual_Report_1891.pdf

[Consistent with and similar to Thompson's 1889 work. (See above.) note: This is sometimes cited as 1892. It is not a separate work. 1891 is the publication date. It was printed in 1892.]

Tudor D. S. (1971) A geophysical study of the Kentland disturbed area. Ph.D. Thesis, Indiana University, Bloomington. 111 pages and plates.

no link found

[A key resource among the studies at this crater. Tudor reports a detailed gravity survey, seismic refraction and reflection profiles, and a shallow drilling program performed at Kentland from

1966 to 1967. The work also provides an excellent literature review of both the Kentland site and of the emerging field of impact crater studies through the 1960s. Note that the digital copy that is delivered if this is purchased or borrowed does NOT include the appendix or the 8 plates that actually constitute the results of the work. The plates from this work need to be preserved!]

Tudor D. S., Mead J., Rudman A. J., Blakely R. F. (1972) A geophysical study of the Kentland disturbed area (abstract). Geological Society of America, North-Central Section Meeting, DeKalb, Illinois. Volume 4, page 353.

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[Gutschick (1976) describes this as an abstract of Tudor's 1971 work. A substantial section of the abstract is quoted in Gutschick (1976), on page 30.]

Votaw R. B. (1980) Middle Ordovician conodonts from the Kentland structure, Indiana (abstract). Geological Society of America, North-Central Section, Abstracts with Programs, Volume 12, No. 5, page 259.

[Brief abstract reporting discoloration of conodonts consistent with heating to 50-90 degrees C.]

Ward L. C. (1906) Roads and road materials of the northern third of Indiana. In Indiana Department of Geology and Natural Resources 30th Annual Report (1905), W. S. Blatchley, editor, Indiana Department of Geology and Natural Resources, Volume 30, Section VI, pages 214 to 219.

https://books.google.com/books?id=XAe8AAAAIAAJ

[Brief early description of the quarry with photos and sketch.]

Weber J. C., Poulos C., Donelick R. A., Pope M. C., Heller N. (2005) The Kentland Impact Crater, Indiana (USA): An apatite fission-track age determination attempt, in Impact Tectonics, Koeberl C. and Henkel H., editors, Springer Berlin Heidelberg. Pages 447-466. DOI 10.1007/3-540-27548-7_18

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[An apatite fission-track study of the St. Peter Sandstone, reporting post depositional heating (≥135°C) followed by a rapid cooling event at 184±13 Ma. (Jurassic) that was found to be identically preserved within the central uplift and throughout the surrounding region.]

Weber J. C., Poulos C., Donelick R. A., Pope M. C., Heller N. (2005) An apatite fission track age-determination attempt at the Kentland Impact Crater, Indiana (USA) (abstract), in Evans K. R., Horton J. W. Jr., Thompson M. F., Warme J. E., editors, SEPM Research Conference: The Sedimentary Record of Meteorite Impacts, Springfield, Missouri, 2005, Abstracts with Program, 35 pages. (see page 32)

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[Brief summary of work reported in the longer 2005 work by the same authors.]

Weber J. C. (2013) Impact geology: Central uplift, Kentland impact structure, Newton County Stone (Kentland) Quarry, Indiana, USA, in Insights into the Michigan Basin: Salt Deposits, Impact Structure, Youngest Basin Bedrock, Glacial Geomorphology, Dune Complexes, and Coastal Bluff Stability, Gillespie R., editor, Geological Society of America Field Guide, Volume 31, pages 1-7.

http://geoscienceworld.org/content/insights-into-the-michigan-basin

[Brief field guide.]

Winkler E., Gutschick R. C. (1983) Ultraviolet luminescence, a simple important tool illustrated by study of breccias in the Kentland, Indiana, disturbed area (abstract). Geological Society of America, Abstracts with Programs, volume 15.

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Ziemba E. A. (1955) Microfacies studies of the Platteville Group (Iowa-Illinois-Indiana). Master's Thesis, University of Illinois. 69 pages

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[Gutschick (1976) lists this thesis in a chronologic resume of significant developments at Kentland. I have not seen it cited elsewhere and have not obtained it to review.]