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# THE FLYNN CREEK METEORITE IMPACT SITE AND CHANGING VIEWS ON IMPACT CRATERING

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**Abstract:** Flynn Creek is one of two confirmed meteorite impact sites in Tennessee, USA. The first published mention of the Flynn Creek Structure was by J.M. Safford, Tennessee's State Geologist, in his *Geology of Tennessee* (1869). Subsequently, the site was investigated briefly in the 1920s and 1930s, but it was only in the 1960s following the founding of the United States Geological Survey's Astrogeological Studies Group as a lead-up to manned lunar exploration that Flynn Creek assumed international importance. This was because it was seen as the best terrestrial analog of a 'typical lunar crater'. As a result, CALTECH graduate student D.J. Roddy used Flynn Creek as the focus of his Ph.D. research, under the supervision of the Group's leader, Gene Shoemaker. After graduating, Roddy continued to conduct on-going investigations at this site up until the time of his death in 2002. Roddy's research has provided a wealth of information regarding the formation and structural features of the Flynn Creek site and shown that the crater was formed during Middle to Late Devonian times as a result of a shallow marine impact. Impact folding and faulting and subsequent uplift and erosion led to the formation of a system of caves at Flynn Creek that is unique among US impact sites.

**Keywords:** Flynn Creek, Tennessee, impact structure, shatter cones, extreme brecciation, marine impact events, faulting, cave-formation, D.J. Roddy

## 1 INTRODUCTION

The state of Tennessee in the USA boasts two undisputed impact sites, Wells Creek and Flynn Creek, and two possible impact craters, the Dycus Structure and the Howell Structure (e.g. see Berwind, 2006; 2007; Born and Wilson, 1939; Deane et al., 2004; 2006; Ford et al., 2012; Mitchum, 1951; Price, 1991; Schedl et al., 2010; Stearns, 1988; Wilson, 1953; Wilson and Stearns, 1966; 1968; and Woodruff, 1968), and these are shown in Figure 1. Of these, the Wells Creek crater has played a major role in increasing our awareness of the nature of terrestrial impact cratering (see Ford et al., 2012), but the Flynn Creek Structure[1] has also made a valuable contribution to our knowledge of marine impact events and the subsequent formation of cave systems associated with such impact sites. In addition, from the 1940s the Flynn Creek site was regarded as more closely resembling a typical lunar crater than any other known terrestrial crater, and this would later prompt its intense investigation in the era leading up to the first American Moon landing. In this paper we review the accumulating evidence that has been provided by the Flynn Creek impact site.

According to Dietz (1959: 498), "An event, if there is any possibility of its happening, becomes a commonplace occurrence within the enormous span of geologic time …" We see a myriad of craters on our nearby neighbor, the Moon, so similar impacts should have occurred and be evident on the surface of our own Earth. In late Devonian or early Mississippian times, a nearly circular crater, about 3.6 km in diameter, formed at the location that is known today as Flynn Creek in Jackson County, Tennessee, and was soon after filled with and preserved by sediments from the Chattanooga Sea (Baldwin, 1963; Schieber and Over, 2005). Today the Highland Rim entirely surrounds the Nashville Basin in central Tennessee, and the Flynn Creek Structure is located on the northern section of the Eastern Highland Rim escarpment (Roddy, 1966c) where the strata are essentially horizontal and dips >5° are rare (Roddy, 1963, Wilson

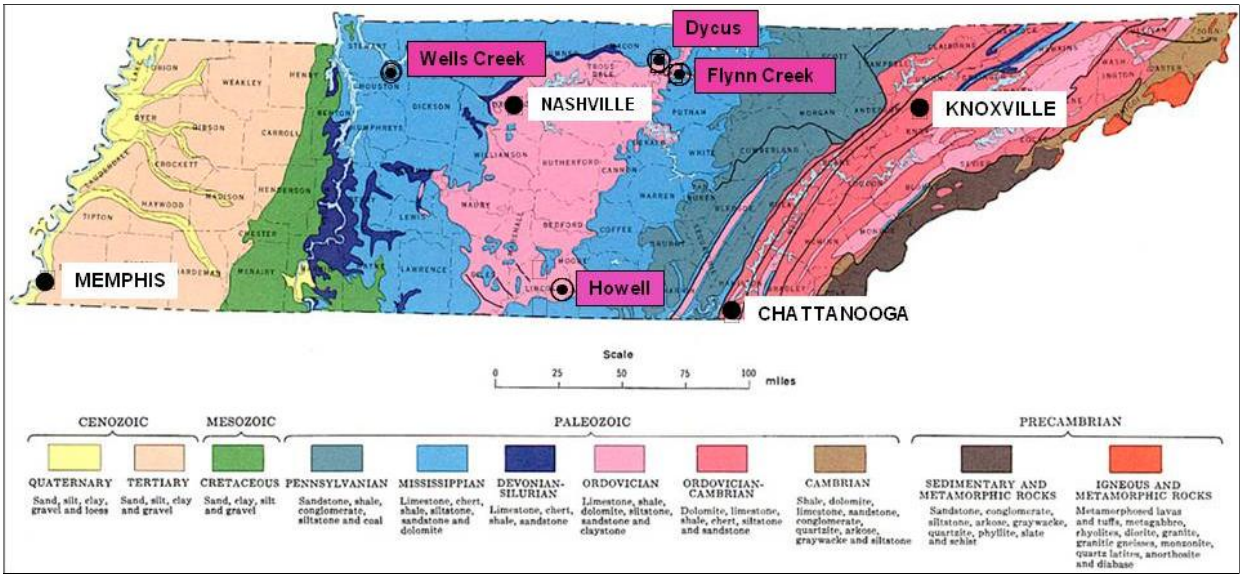


Figure 1: Generalized geological map of Tennessee showing the locations of the four largest cities (black dots) and the two confirmed and two suspected meteorite impact sites (small black dots with circles). These sites are located on the Highland Rim (Wells Creek), a Highland Rim outlier remnant (Howell), or on the Highland Rim escarpment (Dycus and Flynn Creek). The Highland Rim is the sky blue region on the map (base map after Tennessee Department Conservation, Division of Geology, 1966).

Figure 2: View of the Flynn Creek area on Safford's 1869 geological map of Tennessee (adapted from: http://alabamamaps.ua.edu/historicalmaps/us_states/tennessee/index2_1851-1900.html), showing no indication whatsoever of the Flynn Creek Structure.

and Born, 1936). In fact,

> The average regional dip is about 0.25 degrees … [and] In such a region, characterized by relatively underformed strata, the presence of a small area of highly disturbed, contorted and brecciated strata, locally vertical and overturned, is of more than passing interest … (Roddy, 1966c: 96).

This is especially true since faults and fault zones are rare in central Tennessee, and faulting has not been observed in the several hundred square miles surrounding the Flynn Creek area (Roddy, 1966c). However, at Flynn Creek itself,

> … fault zones are present in the region of the innermost rim, crater wall, and outermost crater floor region, and are continuous around at least the western, northern, and eastern sides

> of the crater … (Roddy, 1980: 941).

The Highland Rim of Tennessee is included in the Central Forest Region of eastern North America, and the area in which Flynn Creek is located is heavily wooded and dense undergrowth makes field work rather difficult. Ridge tops in the area lie at a nearly uniform level of 300 meters above sea level with the valleys, including parts of the Flynn Creek Valley, on average some 160 meters above sea level.

The Flynn Creek Structure was named after the largest stream that flows through the area. This stream is fed by a large spring located at the eastern edge of the crater rim, and it drains directly into the Cumberland River some 8.0 km northwest of the crater (Roddy, 1966c). This feature is not prominent on photographs taken by the United States Department of Agriculture, Production and Marketing Administration (Baldwin, 1963: 89), due, in part, to the fact that it "… does not greatly affect the present topography except along the northwest rim …" (Roddy, 1966c: 25). In this particular section, one of Flynn Creek's larger tributaries follows the outline of the crater rim as "… it erodes into the less resistant, overthickened Chattanooga Shale …" (ibid.). It was here at Flynn Creek, during an early mapping expedition by James M. Safford (1822–1907), a Professor of Natural Science and the State Geologist for Tennessee, that this unusual geological structure was first noticed.

## 2 HISTORICAL CONTEXT

The first mention of a disturbance at Flynn Creek was made in Safford's report, *Geology of Tennessee*, which was published in 1869:

> Another area of disturbance is in the upper part of the valley of Flynn's Creek, in Jackson County. This area is limited in extent, and has comparatively little importance, yet the formations are greatly disturbed. The rocks are seen to dip at high angles, and are occasionally almost vertical. The valley is narrow, and the hills on each side high. In their normal position the *siliceous* is at the top of the series of formations, and the *Black Shale* next below. In several places both are brought down, by great folds and faults, to the bottom of the valley, and, at one point, may be seen abutting against the Nashville Formation. One fault shows a displacement of a thousand feet [300 meters]. The lines of disturbance run nearly north and south. (Safford, 1869: 148).

Although Safford considered the Wells Creek Basin of sufficient importance to be included on his map of the State of Tennessee which accompanied the geology report (see Ford et al., 2012), the Flynn Creek structure was not even noted on the map. For example, see Figure 2, which is a close up view of the Flynn Creek area as depicted on Safford's 1869 map.

The area was mapped again in 1925 by the Topographical Branch of the United States Geological Survey, with no mention or indication of the disturbance, and then again in 1926 by R.G. Lusk for the State Geological Survey of Tennessee. Lusk wrote that "An interesting result of the summer's work was the discovery of an extraordinary local thickness of the Chattanooga Shale …" which was generally 3-15 meters thick in the Nashville Central Basin and adjacent areas and "According to general observation, the thickness does not vary more than five or ten feet [1.5 to 3 meters] in many miles …" (Lusk, 1927: 579). However, Lusk (ibid.) found the thickness in Flynn Creek to be greater than 45 meters along the creek where the Shale is exposed in several places with up to 23 to 27 meters of strata visible in a continuous outcrop. He wrote (ibid.) that the Shale "… lies in an irregular closed depression … [and] in a limestone conglomerate-breccia …" Lusk did not observe actual contact of the breccia with formations other than the Chattanooga Shale, but he did note that the breccia was greater than 30 meters thick in some locations. Lusk concluded (1927: 579-580) that the structure was a "… pre-Chattanooga Sink Hole …", with a depth of almost 60 meters.

Wilson and Born (1936: 815) visited the structure in 1935 and concluded that Flynn Creek was not a sink hole, but that "All the data accumulated indicates a crypto-volcanic origin of the structure." Dietz (1946: 466; our italics) disagreed, and also explained why Flynn Creek was important in the study of astrogeology:[2]

> A resemblance between these crypto-explosion structures and lunar craters is most clearly apparent in the Paleozoic-aged Flynn Creek structure which, although filled and covered with later marine sediments, uplifted, and subaerially eroded in the few hundreds of millions of years that have elapsed since its formation, contains a nearly two-mile-wide [3.2 km] explosion crater with a central uplift. Here, then, is an example of a terrestrial explosion crater with a central hill as well as other shape aspects such as a circular outline, radial symmetry, a rim of rock detritus, and a crater depressed below the surrounding terrain all of which are characteristic of lunar craters. As reconstructed by Wilson and Born, *the Flynn Creek crater probably bears a closer resemblance to a typical lunar crater than any present-day terrestrial feature*.

Roddy (1965: 50) notes as a result that the Flynn Creek structure "… has been under study as part of a larger program of crater investigations by the Branch of Astrogeology … " It was one of two impact structures located in the United States selected for this study (*Astrogeologic Studies*, 1967), and a series of *Astrogeologic Studies Annual Progress Reports* from the

1960s and 1970s describe research conducted by the United States Geological Survey on behalf of the National Aeronautics and Space Administration. The long-range objectives of this project were

> … to determine and map the stratigraphy and structure of the crust of the Moon and other planets, to determine the sequence of events that led to the present condition of the surfaces of the planets, and to describe how these events took place. (*Astrogeologic Studies*, 1967: 1).

Denson (2008: 13) describes the result of the Flynn Creek investigation undertaken by the Astrogeologic Studies Group:

> It was not until the 1960s and 1970s that the true nature of the site came to light under the careful scrutiny of one of the great planetary scientists of the twentieth century, Eugene Shoemaker [who founded the Group], when one of his graduate students chose to do his dissertation on the site. That individual … [was] Dave Roddy ...

Figure 3: Dave Roddy, 1932–2002, who spent about forty years researching the Flynn Creek Structure (adapted from Chapman, 2002).

We have to thank the late Dave Roddy (Figure 3) for much of what we now know about the Flynn Creek Structure. David John Roddy

> … was born in Springville, Ohio, in 1932 to Jack and Nellie Roddy. He attended the U.S. Air Force School in Harlington, Texas, from 1957 to 1958. Dave got his A.B. and M.S. degrees from Miami University in Ohio in 1955 and 1957, respectively. He was a distinguished graduate of the U.S. Air Force ROTC program at Miami University. From 1957-1960, he was in active service as an Air Force navigator. He attended California Institute of Technology in southern California from 1960 to 1966, receiving a Ph.D. on the dissertation topic of "Impact-cratering mechanics of Flynn Creek, Tennessee" working under Dr. Gene Shoemaker. In 1962, he was induced by Gene to work in an interim capacity at the USGS in the newly-formed Branch of Astrogeology. He joined the Astro Team full time in 1965. Dave was Associate Branch Chief of the Astrogeology Team from 1983-1984. He retired from the USGS in 1992, but remained with the Team as an Emeritus and was extremely active in Science to the very end. David was a member of Sigma Gamma Epsilon, the Geological Society of America, the Mineralogical Society of America, Sigma Xi, American Geophysical Union, and the American Society of Industrial Security …
>
> The prestigious Barringer Award was presented to David Roddy at the International Meteoritic Society Meeting in Prague, Czechoslovakia, on August 3, 1994, in recognition of his outstanding scientific contributions and lifetime work in the field of impact crater mechanics …
>
> Throughout the 1980s and early 1990s his constant companion was a small white terrier named Michelle. Clad in sunglasses and leather pilot jacket with Michelle trotting at his side, Dave was a driven scientist with a Colonel Flag persona, who aspired to the highest of standards, but usually had time for lunch with friends …
>
> Most of his life Dave was a vital man with a passion for running and staying fit. Although the last ten years of his life were marked by a battle with Parkinson's disease, he fought it every inch of the way ...
>
> U.S. Geological Survey, Astrogeology Team Emeritus David John Roddy passed away at 9:40 in the morning, March 21 [2002] at St. Louis hospital while on a short trip. He had gone into the hospital complaining of chest pains and ruptured an aorta while undergoing a heart scan. He died immediately. (Chapman, 2002).

Roddy was a graduate student at CALTECH when he first investigated the Flynn Creek site and began publishing papers about it in the *Astrogeologic Studies Annual Progress Reports* for the U.S. Geological Survey. These early reports were followed by many more papers on Flynn Creek that Roddy wrote throughout the rest of his career. Roddy's research and field work associated with his Ph.D. thesis was supported by the U.S. Geological Survey's Branch of Astrogeology, as well as by a National Aeronautics and Space Administration (NASA) grant from 1963 to 1965 (Roddy, 1966c: 33). His thesis involved a comprehensive study of the Flynn Creek Structure, and he noted that "Since 1961 increased interest in the lunar craters has been stimulated by the efforts directed toward manned lunar exploration. This interest in lunar craters in turn revived an interest in terrestrial crater studies …" (Roddy, 1966c, 10).

Unfortunately this interest did not spread very far, as noted by Denson (2008: 15), a native of the area:

> During the days of Apollo, some of the astronauts visited this site while Dr. Shoemaker was giving them their "crash course" in the geosciences. I find it very frustrating in retrospect that I cannot remember this ever being the topic of discussion during my elementary school years, which were spent just a few miles away.

Roddy (1966c: 14) states that "The Flynn Creek crater was chosen for the current study because the local and regional exposures are among the best of all the 'cryptoexplosion' structures in the United States." He concluded that the Flynn Creek crater "… appears to have been formed during the impact of either a comet or a meteorite …" (Roddy, 1966c: 217).

Not all agreed, however, that such structures were the result of meteorite impacts. As late as 1964, in the Introduction to Volume 2 of the *Developments in Sedimentology*, Amstutz (1964: 1, 3, 5) expressed his skepticism:

> We tend to approach the outcrop and set up an experiment on the basis of preconceived hypotheses – consciously or, more often, subconsciously – and in interpreting these observations, we are prone to use only those assumptions which are indigenous with us …
>
> These figures also illustrate how, actually, ore genesis theories at present go through exactly the same crisis and change as did paleontology one hundred years ago, when Darwin and others proposed to look for factors "from within", and rejected the exogenous creationistic theories.
>
> This process of evolution of thought from epi-exo-patterns to syn-endo-patterns is one which takes place all the time in all fields of human culture, including the sciences. It suffers relapses of course as recently seen when the myth of flying saucers and of meteor impact structures swept around the world and even affected the scientists …
>
> It is interesting to note that the hidden sources for the emanating solutions are almost always at "unknown depth". The movement away from the myth of the "unknown depths" and the myth of replacement is most interesting and valuable historically because it parallels the general integration of a sound knowledge and acceptance of the realm of the subconscious in the human mind. This acceptance eliminates the need for a mythological compensation in form of a "scientific" theory on emanations from unknown depth or impact from unknown outer space sources.

Progress in understanding the formation of crypto-explosive structures was being made in both the astronomical and geological communities, however (McCall, 1979; Mark, 1987; Shoemaker, 1977). In 1963, another luminary of impact cratering, Robert Dietz (1914–1995) wrote:

> In view of the growing literature on impact structures and the topical interest in lunar craters … it has been satisfying to witness the changing view of geologists toward the impact rationale from virtually non-acceptance, and even ridicule, to its present position as the favored hypothesis. (Dietz, 1963: 650).

Koeberl (2009) points out, however, that opposition to the meteorite impact hypothesis remained right up until the time of the first manned landing on the Moon. He states that "Planetary exploration and extensive lunar research eventually led to the conclusion that essentially all craters visible on the moon (and many on Mercury, Venus, and Mars) were of impact origin …" (Koeberl, 2009, 12). These observations led to an understanding that the Earth has also experienced significant meteorite impacts (Hoyt, 1987; Melosh, 1989), and "Today, astronomers and geologists recognize that impact processes are among the most common mechanisms to have shaped the Earth …" (Koeberl, 2009: 12-13).

## 3 STRUCTURAL FEATURES AND AGE

Miller (1974: 56) states that in contrast to the Wells Creek Structure, the event that formed the Flynn Creek crater can be dated with a fair amount of accuracy:

> This crater presumably formed in Middle to Late Devonian time (350-375 million years ago), for it is filled with Chattanooga Shale. This indicates that erosional alteration of the crater itself had been occurring for only a geologically brief time prior to deposition of the Chattanooga Shale in Late Devonian time.

When formed, the crater was most likely around 100 to 120 meters deep relative to the surrounding surface and "Since the rim was completely removed by erosion and yet the pit was not filled with air-borne sediments, the explosion is dated as shortly before the deposition of the Chattanooga shale, or in late Devonian time." (Baldwin, 1963: 89).

Figure 4 shows a composite stratigraphic section for Middle Tennessee by Miller (1974: 59) as a reference for discussing the Flynn Creek crater. Referring to Upper Devonian units, Roddy (1966c: 59) writes that "Until the present work on the Flynn Creek structure, Richmond strata had not been recognized in the area." According to the United States Geological Survey, the Upper Ordovician units in Tennessee include the Richmond Group (name not shown in Figure 4), which is composed of the Mannie Shale, Fernvale Limestone, Sequatchie Formation, and the Arnheim Formation; the Maysville Group, which includes the Leipers Formation; the Eden Group, which includes the Inman Formation; the Middle Ordovician with the Nashville Group, which includes the Catheys Formation, Cannon Limestone, and Hermitage Formation; and then the Stones River Group, which includes the Pond Spring Formation. In Tennes-

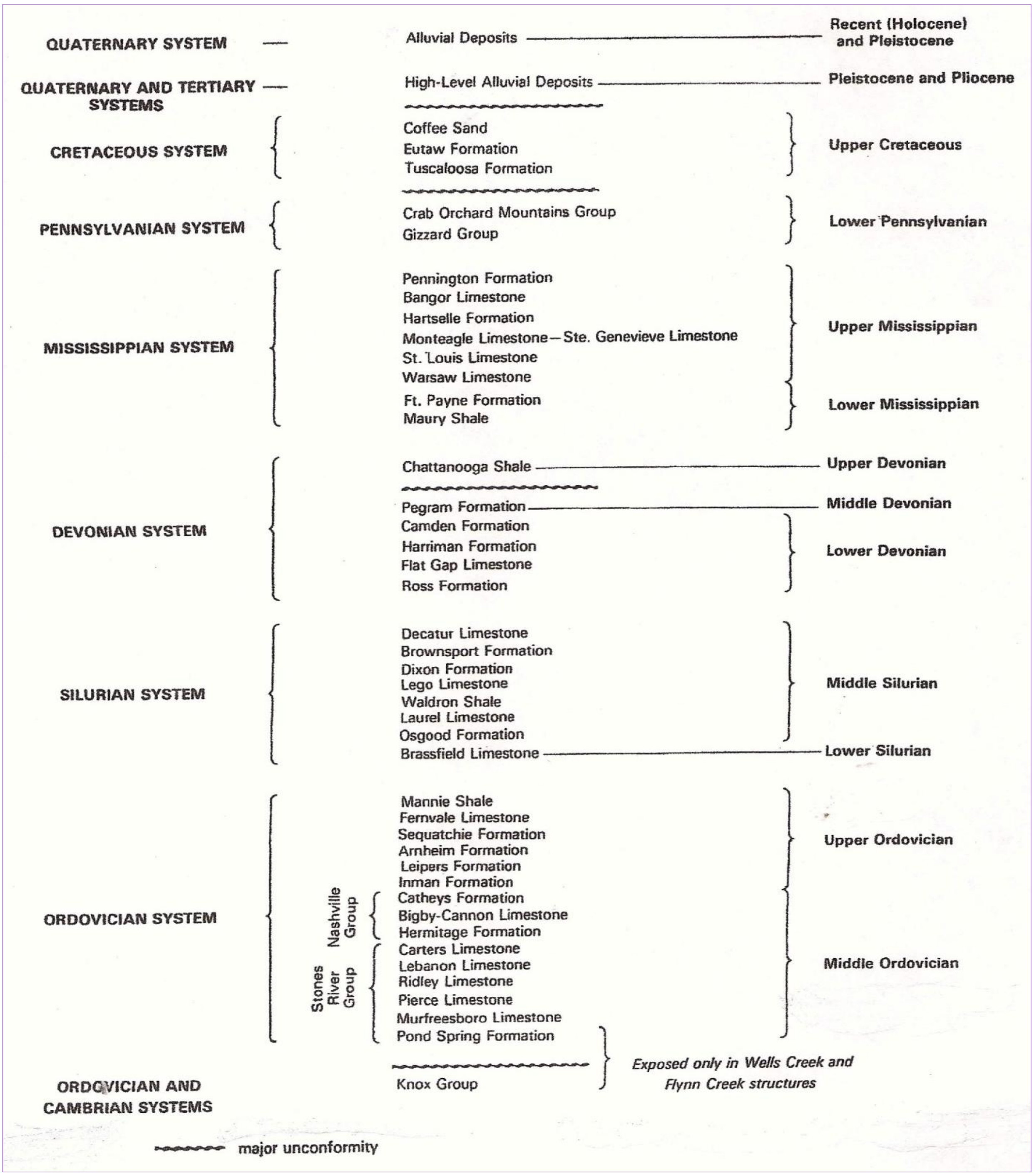


Figure 4: Composite stratigraphic section for Middle Tennessee (after Miller 1974: 59).

see usage, the Pond Spring Formation is equivalent to the Wells Creek Formation (Brahana and Bradley, 1985).

The oldest rocks in central Tennessee are dolomite and limestone of the Knox Group, which range in age from Upper Cambrian to Lower Ordovician, and these are found exposed "… at the surface only in the faulted, folded and brecciated central parts of the Wells Creek and Flynn Creek structures …" (Roddy, 1966c: 34; cf. Miller, 1974). Roddy (1966c: 46) states that "… it is common in subsurface studies to refer to the strata below the Wells Creek dolomite only as upper Knox Group." Normally, the Knox strata are over 300 meters below the middle Tennessee surface in flat-lying beds (ibid.). The Knox Group in central Tennessee is around 1.5 km thick and may rest directly on the crystalline basement. As can be seen in Figure 4, a major unconformity exists in central Tennessee between the Stones River Group and the Knox strata.

It is interesting to compare and note the similarities in Miller's stratigraphic section for Middle Tennessee, shown in Figure 4, and Figure 5, the "Generalized columnar sections from the Western Rim to the Central Uplift of the Flynn Creek Crater" by Roddy (1966c: 38). Out-

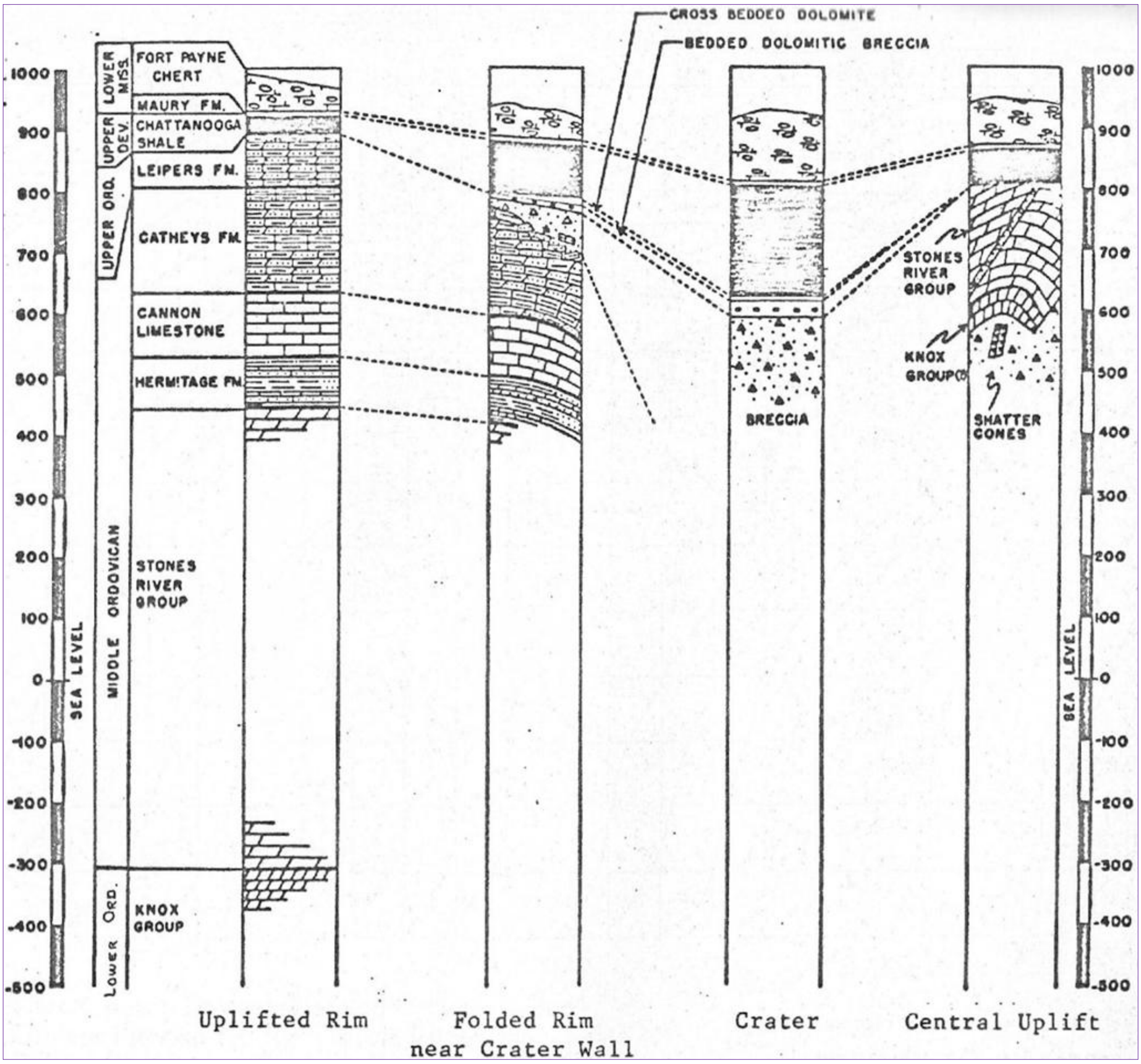


Figure 5: Generalized columnar sections from Flynn Creek Western Rim to Central Uplift (after Roddy, 1966c: 38).

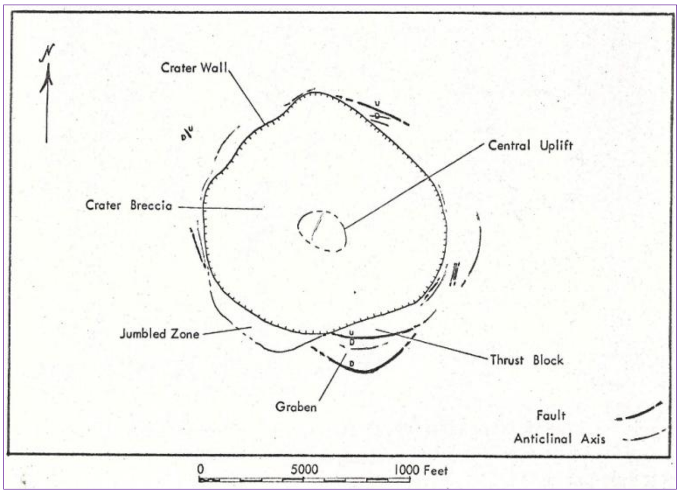
side of the Flynn Creek area of deformation, rocks range from the Cannon Limestone of the Middle Ordovician to the Fort Payne Formation of Early Mississippian age (Roddy, 1968b). Inside of the crater, however, rocks from the upper Knox Group of Early Ordovician age through the Stones River Group and Hermitage Formation of the Middle Ordovician age are exposed (ibid.). Beds of Cannon Limestone up to the Leipers Limestone are exposed in the crater rim and walls. The only rocks found to be involved in the structural deformation of the crater are of pre-early Late Devonian age. Roddy (ibid.) also points out that no Silurian or Lower or Middle Devonian strata have been recognized in the area of the Flynn Creek impact site.

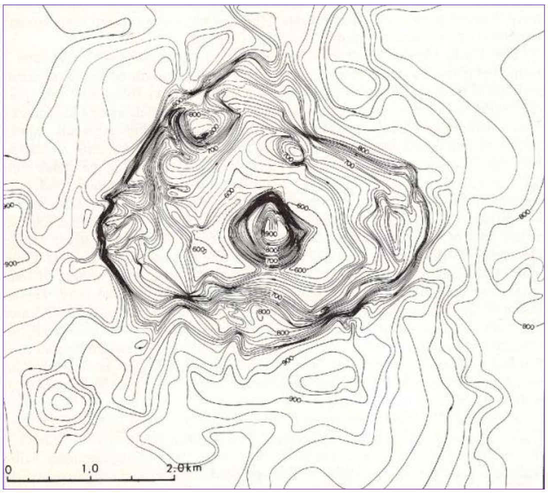
The Flynn Creek event occurred on either "… a low, rolling coastal plain or in the very shallow waters of the Chattanooga Sea." (Roddy, 1977a: 211). Breccia first washed down from the crater rim onto the crater floor, followed by dolomites derived from the rim crest and then early Late Devonian marine conodonts of the Chattanooga Sea. Flynn Creek

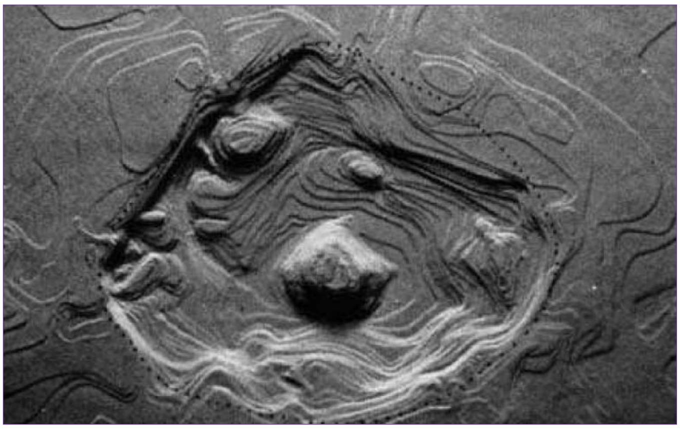
> … experienced both limited erosion in the higher elevations as well as marine deposition at approximately the same time on the crater floor, or shortly thereafter … The important result was that the crater experienced relatively little erosion before complete burial under the fine silty muds of the Chattanooga Shale … (ibid.).

Unlike most impact structures, because of its quick burial Flynn Creek suffered little alteration and thereby retained the basic morphology of the original crater (cf. Boon and Albritton, 1937).

As an overview, the Flynn Creek Structure's primary features are its central uplift, which consists of limestone blocks raised over 150 meters, and a depressed ring of breccias that surrounds the uplift and contains blocks of all the rock layers involved in the disturbance (Baldwin, 1963). Breccia overlying a graben in the southern rim is still preserved and this "… is the







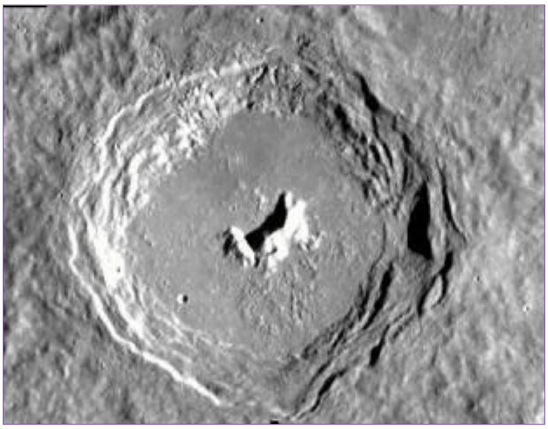


Figure 6 (top left): Schematic map of major structural elements at Flynn Creek (after Roddy, 1966c: 98). Figure 7 (top right): Contour map of the Flynn Creek Crater (after Roddy 1977b: 280). Figure 8 (bottom left): The 3-D model of the Flynn Creek Crater made by Roddy (1968b: 303; courtesy: Planetary and Space Science Centre, University of New Brunswick, Fredericton, New Brunswick, Canada). Figure 9: The lunar crater Pythagoras (courtesy: European Space Agency).

first indication from any of the cryptoexplosion structures that an ejection of crater breccia definitely occurred …" (Roddy, 1968b: 297). The breccia layers are covered by Chattanooga Shale which apparently filled the crater when a lake occupied the crater during pre-Chattanooga times. Strata dip away from the central uplift on the western, northern, and eastern sides of the Structure; however, to the south of the uplift the rock layers dip inward and are overturned. In the central zone of the Structure, powdered breccia is found injected into dikes along fractures in the limestone, along with some injections of rock flour into minor fissures, only visible on a microscopic scale (Baldwin, 1963).

Roddy (1979b: 2519) summarizes the morphological and structural classes of craters formed by a hypervelocity impact as follows:

> Impact craters on most of the terrestrial planets and satellites have been shown to follow a clear trend of increasing morphological complexity with increasing size, ranging from (a) bowl-shaped at the smaller sizes, to (b) flat-floored, to (c) flat-floored with a central peak, to (d) flat-floored with a central peak and terraced walls, to (e) flat-floored with multiple central peaks and multiple terraced walls, to (f) flat-floored with multirings and multiple terraces, and finally to (g) large, flat-floored basins.

Flynn Creek falls into category (d).

Figure 6 is a schematic map of the Flynn Creek Crater by Roddy which shows the basic structural similarity to lunar craters, with terraced walls and central uplift. Figure 7 is a much more detailed contour map of the Flynn Creek Crater by Roddy (1968b: 302; cf. 1977b: 280). Note that though the crater is basically circular in shape, sections of the crater walls, specifically the northeastern and northwestern rims, are relatively straight for around 1500 meters (ibid.). Roddy (1968b: 303) utilized this particular contour map to construct the 3-D model shown in Figure 8. In this model, Flynn Creek is seen to be flat-floored with a single central uplift and terraced walls, and the dotted line "… indicates the position of the top of the crater wall in areas where large volumes of ejecta have washed back into the crater, modifying the original crater shape …" (ibid.). The terraces are not prominent due to this erosional redistribution of ejecta on the crater rim (Roddy, 1979b). Large hills visible near the outer sections of the crater are underlain by megabreccia blocks, derived from the crater walls, which also washed back into the crater along with the ejecta and formed "… a terraced effect along the crater walls …" (Roddy, 1968b: 302). Note that the Flynn Creek model, with its central uplift, shallow flat floor, and terraced walls, bears a remarkable similarity to the lunar crater Pythagoras, as seen by comparing Figures 8 and 9.

Lusk (1927: 580) described his 1926 observations at Flynn Creek as follows:

> The extent of the increased thickness of the Chattanooga shale and the presence of the conglomerate-breccia coincide in an irregular area about two miles [3.2 km] in diameter with outcrops visible in the valley of Flynn Creek and its tributaries, Rush Fork, Cub Hollow, Lacey Hollow and Steam Mill Hollow, where they join that stream. Outside this area the Chattanooga shale is about 20 feet [6 meters] thick…
>
> The shale is completely exposed in sections up to ninety feet [27 meters] thick in single outcrops, and it crops out practically continuously in the bed of Flynn Creek and its tributaries with the same system of joints throughout.

In the surrounding region the Ordovician limestone strata dip is gentle, but in the Flynn Creek area the dips are 15-20° or even greater. On the south, east, and north sides of the Structure, the dips are only for short distances and toward the center, but that to the west "… there may be surficial faulting of the Ordovician ... [and] The top of the Chattanooga shale is at a lower altitude where it rests upon the brecciated limestone than at adjacent outcrops, in general being lowest where the shale is thickest …" (ibid.). This difference in altitude is greater than 30 meters. In contrast, in locations where the shale is near its normal altitude, it is thin and lies upon hills of the conglomerate-breccia. Lusk (ibid.) surmised that the shale's fissility, its ability to split, was determined by the orientation of the flakes of minerals during the deposition and dehydration processes. He observed that the fissility of the Chattanooga Shale is parallel to the bedding "… except where it conforms to ancient hillslopes …" and on these slopes he found that "… the fissility is inclined as much as 30° …" (ibid.).

Wilson and Born (1936: 815) visited the area in 1935 and concluded that the Flynn Creek Structure is "A small, intensely disturbed area … [with] highly disturbed beds along Flynn Creek." After mapping and studying the Structure in detail, they wrote the following historical description:

> The history of this disturbed area is interpreted as follows: Shortly preceding Chattanooga deposition an explosion took place near the surface, blowing out a crater 2 miles [3.2 km] in diameter and 300 feet [90 meters] deep. The Ordovician limestones forming the floor and walls of this crater were shattered into breccia composed of angular fragments of varying sizes imbedded in a matrix of smaller fragments and "rock flour." The deeper parts of the crater were filled with redeposited breccia, either as talus breccia or as bedded breccia deposited in a fresh-water lake that occupied the crater at one time. The Chattanooga sea invaded central Tennessee and filled the crater with black mud, now represented by about 250 feet [75 meters] of black shale. Fort Payne chert was later deposited upon the relatively smooth surface of the black shale.

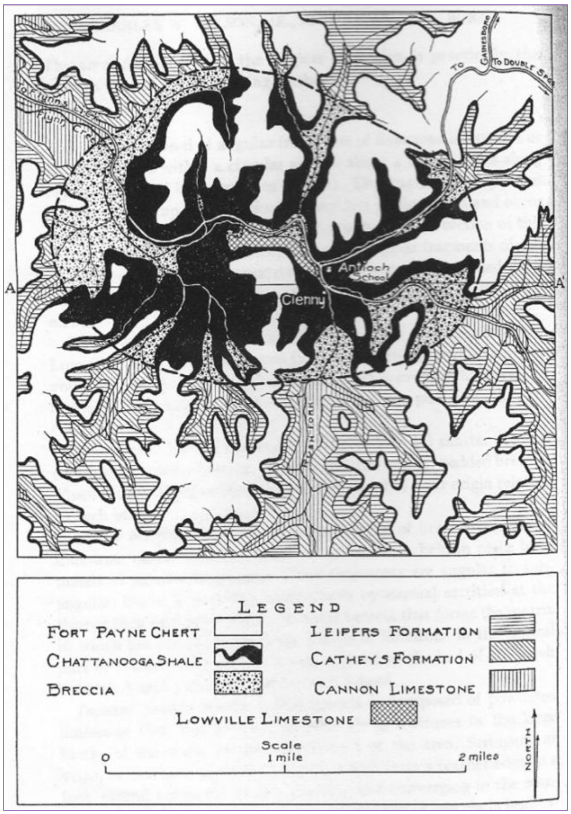
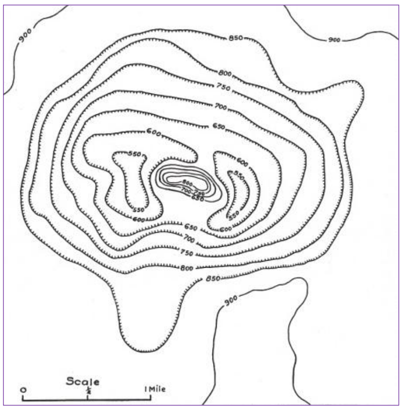
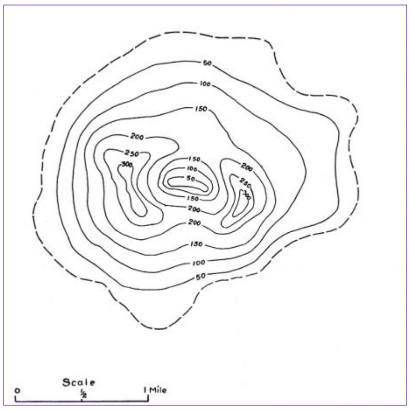


Figure 10: Areal geologic map of Flynn Creek area (Wilson and Born, 1936: 818)

The consolidated rocks in the area were found to range in age from Ordovician to Mississippian, the oldest rock being dense Lowville Limestone which was found in "… the center of the disturbed area and is composed of many large, disconnected blocks, some of which are several acres in size …" (Wilson and Born, 1936: 817). Figure 10 is a geological map of the Flynn Creek area by Wilson and Born which shows that this area of intense brecciation is somewhat elliptical in shape. They note an interesting fact concerning the Hermitage Formation at Flynn Creek:

> In the normal stratigraphic succession along the eastern edge of the Central Basin, the Hermitage formation overlies the Lowville limestone; but this formation was not found in the Flynn Creek area. It is believed that the Herm-





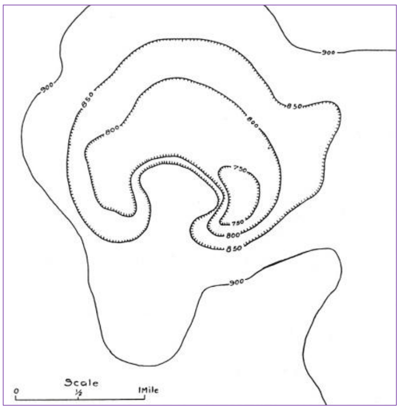


Figure 11 (left): Contour map on the pre-Chattanooga topographic surface (after Wilson and Born, 1936: 827). Figure 12 (centre): Isopach map showing thickness of Chattanooga shale (after Wilson and Born, 1936: 828). Figure 13 (right): Contour map showing the post-Chattanooga structure (after Wilson and Born, 1936: 829).

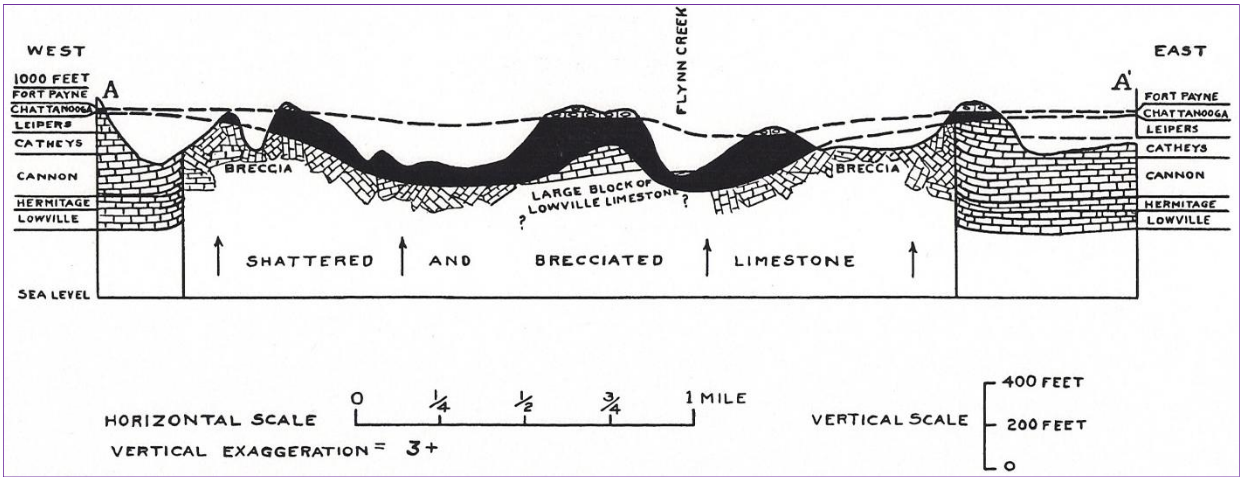


Figure 14: East-west structural cross section of the Flynn Creek site (after Wilson and Born, 1936: 824).

> itage formation was originally deposited in this region but that during the local deformation and subsequent erosion all traces of it were removed. (Wilson and Born, 1936: 819).

The Lowville, Cannon, Catheys, and Leipers Formations were found to comprise the underlying intensely-deformed Ordovician strata, and are limited to a circular area with a diameter of about 2 miles [3.2 km] (Wilson and Born, 1936). The black Chattanooga Shale and Fort Payne Chert made up the overlying, relatively undeformed strata, with the Chattanooga Shale directly covering the intensely-deformed Ordovician strata.

At the Flynn Creek site the Chattanooga Shale had "… its characteristic lithology, being a black, fissile, highly carbonaceous shale." (Wilson and Born, 1936: 822). Figure 11 is a contour map by Wilson and Born showing the topographic surface on which the Chattanooga Shale was deposited and Figure 12 is a map by Wilson and Born which shows the thickness of the black shale in the Flynn Creek structure. Around the structure, the shale has its normal thickness for the region, which is around 6 meters, but within the structure, the shale attains a thickness of more than 75 meters. Wilson and Born (1936: 826) explain that "Such variations in thickness indicate that the black shale filled a pre-existing topographic basin …", which would have been some 90 meters deep at the time. Figure 13, after Wilson and Born, is a structure contour map showing Flynn Creek to be a closed, synclinal basin. Wilson and Born (1936: 826) note that "The overlying Fort Payne chert was deposited upon a relatively level surface of black shale …" and unlike the Chattanooga Shale, does not show any abnormal areas of thickness within the structure. The Fort Payne Chert does gently dip toward the center of the basin "… paralleling the slightly greater dips of the underlying black shale …" (ibid.).

Figure 14 is an east-west structural cross section, as mapped by Wilson and Born, which shows the thick black Chattanooga Shale overlying the shattered and brecciated Ordovician limestone. These two series of strata were found by these researchers to be separated by a marked unconformity with a maximum differential relief of around 90 meters within 0.8 kilometers. Wilson and Born (ibid.) give the following description:

> The plane of the unconformity coincides with the pre-Chattanooga surface, which was a

> closed topographic basin about 2 miles [3.2 km] in diameter and about 300 feet [90 meters] below the level of the surrounding area. In the center of this depression was a hill, composed chiefly of large blocks of Lowville and possibly older limestone, that rose 200 feet [60 meters] above the general floor level.

The blocks were found to vary "… in size from several acres down to small fragments, and abutting against each other at all possible variations of strike and dip …" (Wilson and Born, 1936: 825).

Flynn Creek breccia consists of angular fragments of limestone that range from pea-size to large blocks in a matrix of shatter breccia and powdered limestone. The breccia contains limestone from the Leipers Formation and is, therefore, younger than the Leipers: "As it is overlain by normally bedded Chattanooga shale, its age must be post-Leipers, pre-Chattanooga …" (Wilson and Born, 1936: 820).

According to Wilson and Born (1936: 820), there are four main types of breccia found in the Flynn Creek area along the Creek itself as well as its tributaries. The shatter breccia "… consists of limestone blocks and fragments of various sizes held in place by a matrix of smaller fragments …" This is the breccia that forms the matrix in which the large limestone blocks in the center of the disturbance are imbedded. The injected powder breccia flowed around the blocks and was found to consist of "… powdered limestone that was injected dikelike along fractures in the large blocks of limestone …" in the central zone of the Flynn Creek structure (ibid.). Stringers, or veins of this breccia range in width "… from a feather edge to a foot …" and extend across the limestone blocks (ibid.). The injections seemingly took place "… while the material had a 'mushlike' consistency …" (Wilson and Born, 1936: 821). Milam and Deane (2005) note that the term 'microbreccia' is used interchangeably with the terms 'breccia dikes' and 'clastic dikes' by other researchers.

The talus breccia is composed of fragments and subangular blocks which display a "… slight rounding, such as would result from traveling a short distance down a steep slope under the influence of gravity rolling or slope wash …" (Wilson and Born, 1936: 821). The bedded breccia was measured along a road and on a hillside and found to have a maximum thickness of 3.7 meters. "The fragments in this bedded deposit grade in size from course grained in the lowest beds to medium grained in intermediate beds, and to fine grained in the upper beds of each local sequence …" (ibid.). Wilson and Born observed that this breccia was deposited in layers that are parallel to the overlying layers of Chattanooga Shale. Their explanation for this observation is as follows:

> The most plausible explanation of the origin of this breccia is that it was deposited in a freshwater lake occupying the depression that existed in the Flynn Creek area for part of the post-Leipers, pre-Chattanooga interval. The uniform stratification, locally suggesting lamination, demonstrates its aquatic origin. It is believed that any Silurian or Devonian epi-continental sea which might have reached this region would have filled the crater with sediments that would have been preserved, for the later Chattanooga sea filled the depression with its sediments and these have been preserved. For this reason the origin of the bedded breccia is attributed to deposition in a fresh-water lake, such as would have formed in the depression. (Wilson and Born, 1936: 821-822).

Various researchers noted the abnormal thickness of the black, highly carbonaceous Chattanooga Shale in the Flynn Creek Structure. In the greater part of central Tennessee this Shale has a uniform thickness of around 6 meters, but in several localities within the Flynn Creek Structure 30 to 60 meters of continuous exposures of the black Chattanooga Shale were measured (Wilson and Born, 1936: 821). Near the junction of Flynn Creek and one of its tributaries, Rush Fork, a continuous section of some 40 meters of Chattanooga Shale was encountered. Wilson and Born (1936: 822) noted that next to Flynn Creek itself, the lower 15 cm of the black shale contained of "… rounded fragments of the underlying breccia …" On the higher hills in the area, Fort Payne Chert covers the Chattanooga Shale, and this lower Mississippian formation is not strongly tilted and is the youngest exposed formation in the area (ibid.).

According to Wilson and Born (1936: 825), "The major structural feature consists of a circular uplift which has raised a small central mass of blocks of Lowville limestone vertically into juxtaposition with the Liepers formation …", a vertical distance of some 150 meters. Around the central uplift is a ring of breccia which contains blocks of all the Ordovician formations involved in the disturbance. The strata dip away from the central uplift on the eastern, northern, and western flanks of the structure. However, the strata dip toward the center of the uplift on the southern flank. Wilson and Born (1936: 826) explain this as being "… the result of thrusting outward from the center, evidence for which is seen in an exposure on the south bank of Flynn Creek …" where the outward-pushed strata are seen to be overturned and thrust away from the central uplift.

Figure 15 is a "Diagrammatic restoration of a section across the Flynn Creek disturbance" by Wilson and Born. The diagrams show Wilson and Born's interpretation of the structure shortly after the Flynn Creek event in diagram A, after a period of erosion and pre-Chattanooga deposition in diagram B, and after the compacstion of the Chattanooga Shale in diagram C (ibid.). In their opinion, the Flynn Creek explosion blew limestone blocks out of the crater, with some of the debris falling back into the crater and the rest scattering around the rim within a radius of several kilometers (ibid.).

Post-explosion and pre-Chattanooga erosion succeeded in removing all traces of the 'cone' of brecciated limestone that surrounded the crater, as the writers were unable to find fragments of breccia at the base of the Chattanooga Shale around the crater. The time interval between the explosion and the deposition of the Chattanooga Shale must have been sufficiently long for the removal of the debris from the vicinity of the crater. On the other hand, the explosion could not have occurred long before Chattanooga times as the crater would probably have been filled with sediments. Since the time necessary for the removal of the unconsolidated debris would not have been long geologically, and since the crater probably would have been filled during its long existence as an open depression, the writers believe that the explosion shortly predated the deposition of the Chattanooga Shale.

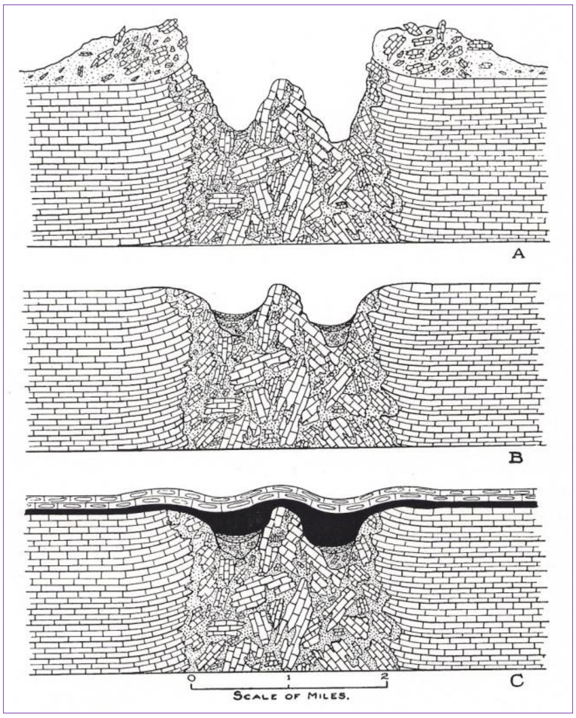


Figure 15: Diagrammatic restorations of a section across the Flynn Creek Structure (after Wilson and Born, 1936: 834).

In diagram C in Figure 15, the abnormal thickness of the Chattanooga Shale is seen, which can be attribute to the filling of the crater during the deposition of this formation. According to Wilson and Born (1936), the gentle dips, also shown in diagram C, are a result of the following:

1. The initial dip of the steeply-sloping walls of the crater and the central hill would undoubtedly have been an appreciable factor in explaining the high dips (as high as 25°) present in the base of the thick Chattanooga Shale, as contrasted with the much lower dips at the top of the Shale.
2. Compaction and proportional thinning of the 20 feet [6 meters] of Shale around the crater and of the 250-300 feet [75-90 meters] within the crater would form an appreciable synclinal basin on top of the Shale.
3. Subsurface collapse and settling due to deep-seated readjustment would undoubtedly have resulted in post-explosion synclinal sagging and possible faulting due to differential settling.

Boon and Albritton (1937: 58) agreed on some points with Wilson and Born, stating that in their opinion Flynn Creek "… was partly filled with lake deposits and the surrounding region eroded before it was covered over by the sediments of the Chattanooga sea." They also noted that the Ordovician limestones found around the crater walls dip radially away from the Structure's center on all sides except to the south where "… they have been thrust away from the center and overturned …" (ibid.). The points on which they disagree with Wilson and Born will be discussed in a subsequent Section of this paper.

Roddy (1963: 118) began his work on the Flynn Creek Structure around 1962 when he began preparing a detailed geological map of the structure. His numerous publications on Flynn Creek provide a steady stream of information regarding his research on the structure that lasted until the earliest years of the current century. In 1963, Roddy gave the following description of the Flynn Creek Structure in that year's *Astrogeologic Studies Annual Progress Report* for the United States Geological Survey:

> It consists of a circular rim of folded and faulted limestone beds of Ordovician age; the circular rim encloses an area of brecciated rocks two miles [3.2 km] in diameter. Steeply dipping, faulted, and brecciated limestone of Ordovician age occupies the central part of the structure. The deformed rocks are overlain by structurally simpler formations, which include the Chattanooga Shale (Devonian) and the Fort Payne Chert (Mississippian). The Flynn Creek structure is moderately well exposed as the result of dissection of the Eastern Highland Rim by the nearby Cumberland River and its tributaries. (Roddy, 1963:18).

Two years later, Roddy (1965: 50, 52) again described the Flynn Creek Structure based on his continuing fieldwork:

> Flat-lying Middle and Upper Ordovician limestones and dolomites surround the Flynn Creek structure but are folded and faulted into a circular rim which encloses a partly buried crater

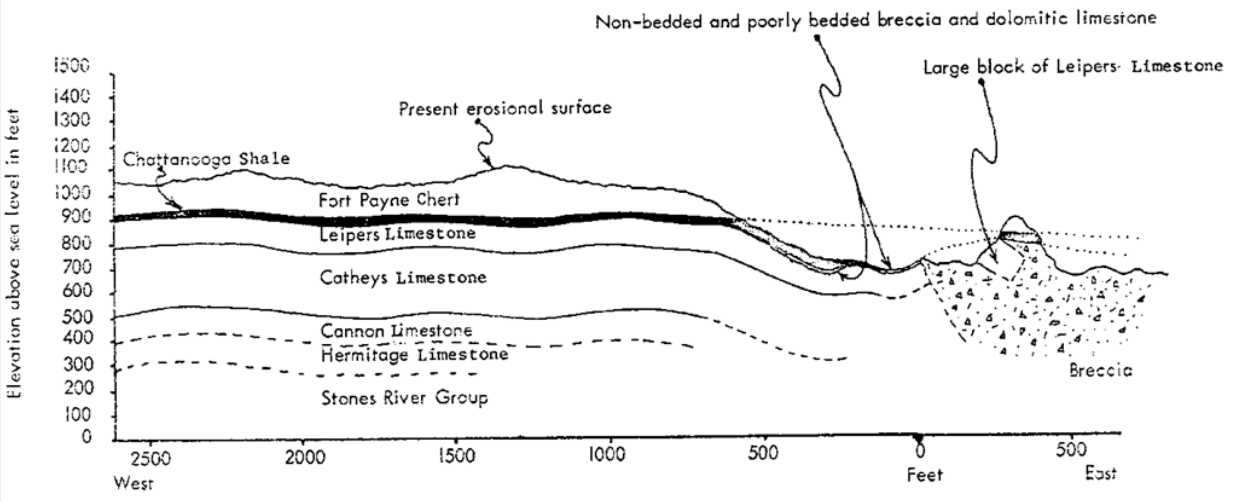


Figure 16: Cross-section of the western rim of the Flynn Creek Structure (after Roddy, 1963: 121).

> about 3.5 km in diameter. The crater floor is underlain by breccia of Middle and Upper Ordovician limestone and dolomite fragments ranging in size from a fraction of a millimeter to nearly 100 meters. In the central part of the crater, a partly buried hill consisting of intensely deformed Middle Ordovician limestones and dolomites of the Stones River and Knox Groups rises nearly 100 meters above the surrounding crater floor. Brecciated rocks of the Knox Group containing shatter cones have been raised at least 300 meters above their normal level.

This is the first mention of the existence of shatter cones, which are a diagnostic feature of meteoritic impact structures (Milton, 1977). Roddy (1965) also pointed out that sections of the raised crater rim experienced nearly 50 meters of uplift, while in other sections, only a few meters of uplift occurred, and later he noted that the original crater was some 100 meters deep on average "… after an unknown amount of breccia washed back over the earliest crater floor …" and that its walls were moderately to steeply dippiing (Roddy, 1966c: 154). He believed that the crater had experienced only moderate erosion.

Roddy's (1963: 121) diagram of the stratigraphic succession he found in the western section of the Flynn Creek Structure and the geological cross-section of the western rim of the Structure is shown in Figure 16. He notes in his description that the valleys surrounding the structure have as their lowest exposed stratigraphic unit Cannon Limestone which is conformably overlain by the Catheys Limestone, both from the Middle Ordovician. The Catheys Limestone is in turn overlain by the Late Ordovician Leipers Limestone. The next youngest stratigraphic unit is a breccia mass that "… occurs in a nearly circular area slightly more than 2 miles [3.2 km] in diameter …" (Roddy, 1963: 120). This breccia unit contains fragments of the Cannon, Catheys and Leipers Limestones as well as the even older Stones River rocks from the Middle Ordovician, all of which range in size from under a millimeter to blocks measuring up to hundreds of meters. In exposures, fragments of these different formations appear to be unsorted and set in a matrix of very fine crystalline and dolomitic limestone (ibid.).

In the center of the breccia core are steeply-dipping, slightly brecciated limestone beds of the Stones River Group which contain shatter cones (ibid.). Next youngest is a ~6 meter thick breccia sequence which is non-bedded at the base but bedded at the top, and this material "… is a record of deposition that is found nowhere else in the region, presumably it was deposited in a local topographic depression in an otherwise nearly featureless surface …" (Roddy, 1966c: 124). A thin unit of dolomitic limestone up to 1.5 meters thick locally caps this breccia sequence which in turn overlies the dipping central beds and the central core breccia as well as the deformed rock (Roddy, 1963).

The entire Flynn Creek Structure, as described above, is overlain by undeformed Chattanooga Shale of the Late Devonian. Fort Payne Chert of Early Mississippian age in turn overlies the Chattanooga Shale. Roddy (ibid.) concluded that since the youngest brecciated rocks were from the Late Ordovician, the Flynn Creek Structure must have formed sometime between the Late Ordovician and the Late Devonian.

Roddy (1963) noted that in this region of Tennessee the Chattanooga Shale was an extensive black shale unit with a nearly uniform thickness of some 8 meters. He also pointed out that outside of the Flynn Creek structure the Chattanooga Shale overlies the Upper Ordovician Leipers Limestone and that the contact does not contain breccia. Within the Flynn Creek Structure the Chattanooga Shale increases abruptly to over 35 meters above the depressed and deformed rim and to some 60 meters above the main breccia mass; however, it is only the

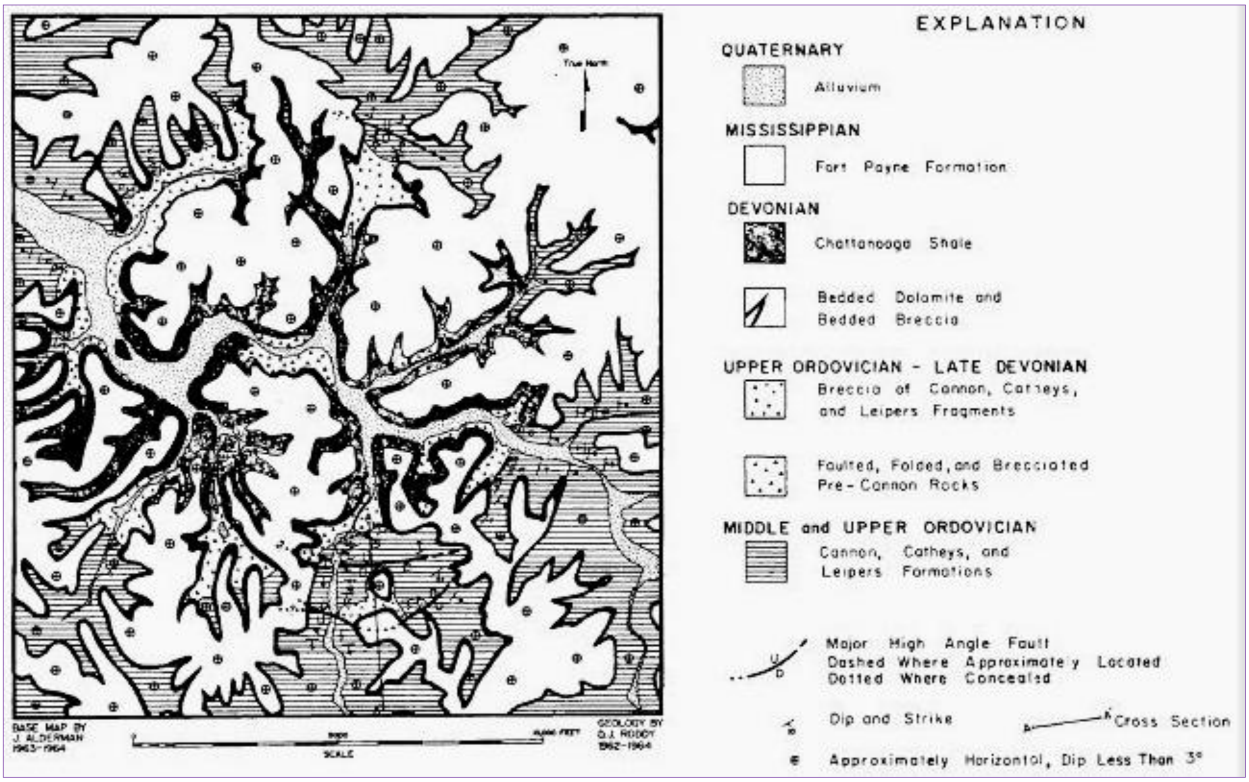


Figure 17: Generalized geological map of the Flynn Creek Structure (after Roddy, 1964: 166)

lower member of the Chattanooga Shale that appears to increase in thickness (ibid.). In addition, away from the Flynn Creek Structure the Chattanooga Shale is nearly flat-lying, although in the Structure it dips as much as 21° and "All of the relatively high dips are inclined toward the thicker parts of the shale, which overlies the breccia …" (Roddy, 1963: 123).

Figure 17 is a 1964 generalized geological map of the Flynn Creek Structure by Roddy. During the Late Devonian to the Early Mississippian time the structure was buried under hundreds of meters of rock, much of which was later removed by erosion. The crater floor is underlain by a mixed breccia except at the center where the partly-buried central hill rises around 100 meters above the crater floor. Roddy (1964: 164-165) describes this central uplift:

> The hill consists of steeply dipping, folded, faulted, and brecciated Middle Ordovician dolomitic limestone that has been raised several hundred meters above its normal stratigraphic position. A thin marine deposit of bedded breccia and cross-bedded dolomite overlies the mixed breccia of the crater floor and covers the lower slopes of the central hill. These marine beds have been identified as early Late Devonian in age.

Before erosion, the central uplift was completely covered by the Chattanooga Shale (Roddy, 1964), and "In the Flynn Creek area the Knox Group is exposed only in the central uplift of the crater." (Roddy (1966c: 46). The Stones River (including Wells Creek dolomite) and Knox strata occur in the crater's center as "… folded, faulted, and brecciated rocks which form the central uplift. Neither the Stones River Group nor the Knox Group are exposed elsewhere in the Flynn Creek area." (Roddy, 1966c: 63). The Flynn Creek central hill consisted entirely of breccia and megabreccia.

According to Roddy (1966c: 104), "Deformation along the extreme northwestern rim is the least complex of the whole crater." Here the rim strata 300 meters from the crater wall are raised 6 to 9 meters above the local level and gently dip into the crater at 1-2º. Within 75 meters of the crater breccia the dips increase to 7-10º as the folded rim strata displays an increasingly jumbled aspect. The jumbled zone dips into the crater at an angle which varies from 25-35º. Roddy (1966c) noted that a complex set of tight folds trend in a manner parallel to the rim and are cut by two faults that are also parallel to the crater rim. The rim strata rise some 35 meters toward the crater starting about 760 meters from the crater wall. This rim uplift continues for around 1.2 km to the east. The rim strata and crater breccia contact consists of a jumbled zone "… which varies in dip from vertical to about 50° towards the crater …" (Roddy, 1966c: 106).

The eastern rim of the Flynn Creek Structure includes "… chaotic crater breccia which includes many large megabreccia blocks …" (Roddy, 1966c: 107). These blocks are around 45m long and 15m thick and dip toward the crater center at various angles. Here the rim tilts away

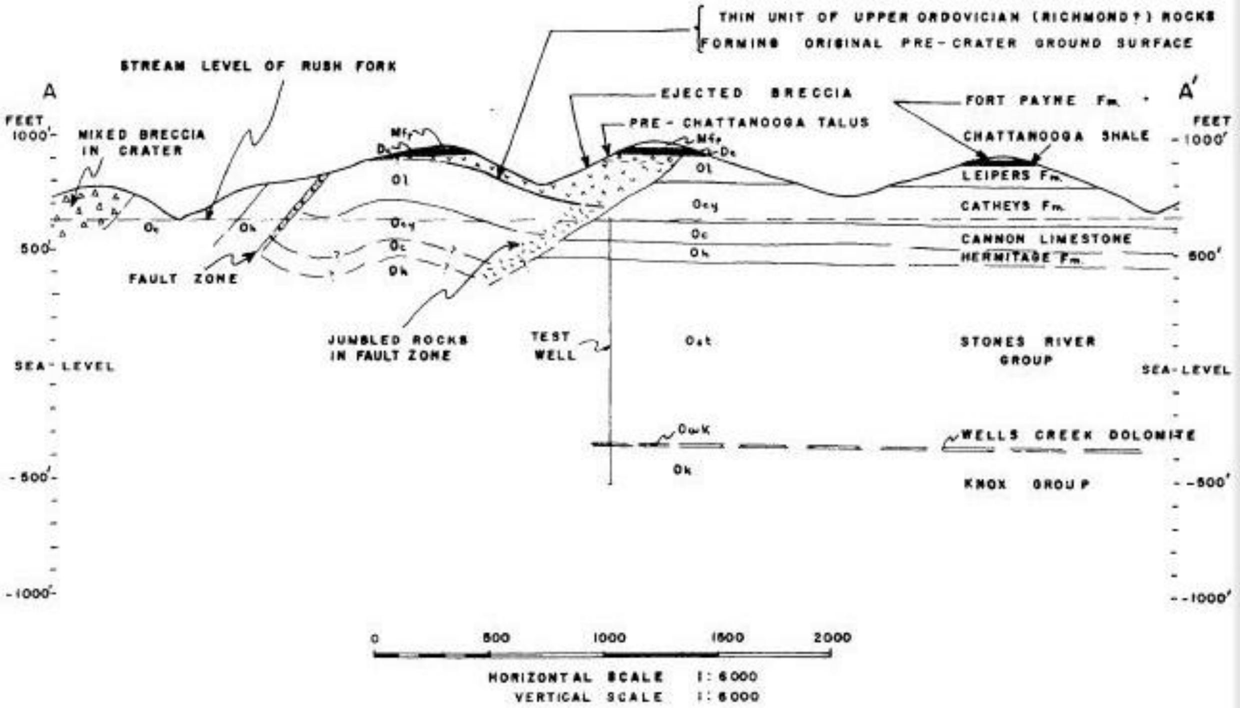


Figure 18: Geological cross-section of the southeastern rim of the Flynn Creek Structure (after Roddy, 1964: 167).

from the crater and observed uplift near the breccia contact is some 45 meters over a horizontal distance of 760 meters. Roddy (1966c: 108) notes an unusual find in the eastern side of the Flynn Creek structure:

> At 100 feet [30 meters] east of the breccia contact the dip of the beds steepens to 25° on the eastern flank of an asymmetrical anticline. The trend of the nearly vertical axial plane of this anticline is approximately parallel to the eastern crater wall. The beds on the western flank of the anticline dip as steeply as 80° west, but flatten rapidly and proceed through a reversal in dip until the beds dip again to the east. Beds 100 feet [30 meters] above this incline are nearly flat-lying, a most remarkable change in attitude considering the very sharp folding in the adjacent lower beds.

Roddy (1964: 163-164) states that his previous Flynn Creek field studies left some unanswered questions and did not address "… the geologic history of the southeastern rim and its bearing on the origin of the Flynn Creek structure." Breccia overlying the graben in the southeastern rim are 50 meters above the crater floor, and yet are essentially identical to the breccia on the floor, "… except for a crude inversion of stratigraphy, and is interpreted as ejecta," (Roddy, 1968b: 297). Roddy (ibid.) determined that a section of the original, pre-crater ground surface is located at the base of the ejecta, and he noted that "The southeastern and southern rim contains the most complicated structures exposed in the entire rim …" (Roddy, 1966c: 115). Figure 18 is the geological cross-section of the southeastern rim of the Flynn Creek Structure by Roddy (1964: 167). Roddy points out that although the entire rim surrounding the Flynn Creek crater is tilted, folded and locally faulted, it is this southeastern section that is most intensely deformed; in this section "… there are faults with displacements on the order of 100 meters …" (ibid.).

Starting from 1200 meters south of the point where the crater breccia makes contact with the southeastern deformed rim, the Middle and Upper Ordovician beds are found to be in their normal sequence (Roddy, 1964). Going 400 meters north, these beds are found to be 10 to 15 meters higher. Another 150 meters north, "… a 300 meter deep test well showed no deformation of the subsurface strata …" except for the slight 10 to 15 meter uplift previously noted in the beds (Roddy, 1964: 168). About 50 meters north of the test well is a major, curved fault that is approximately concentric with the contact of the crater breccia, and the north side of this fault is displaced a minimum of 100 meters downward and dips north at angles that vary from 30º to 70º. Roddy (ibid.) reports that "… the displacement dies out to the northeast, and within 600 meters is only 10 meters …" The fault grades into a fractured, brecciated zone around some 800 meters to the west.

North of this fault the rocks of the Catheys and Leipers Formations, both Upper Ordovician, along with the Leipers Formation, are stratigraphically higher than any of the other Upper Ordovician beds observed in the region around Flynn Creek, and it is here that Roddy (ibid.) makes a most interesting observation:

> A few feet of pale green, argillaceous, dolomitic limestone occurring at the top of this section are unlike any units in the Silurian and Devonian sections of central Tennessee but closely resemble rocks of the Richmond Group (Upper Ordovician) found elsewhere in central Tennessee. If these beds belong to the Richmond Group, they furnish the first proof that seas covered this part of the Nashville Dome in Richmond time.

These beds are overlain by a thick unit of mixed breccia similar in lithology and texture to the breccia found within the crater (Roddy, 1964). The lower part of the breccia includes angular fragments from the upper part of the Leipers Formation mixed in with angular fragments from these underlying beds which decrease as a percentage of the fragments higher up in the breccia. The percentage of rocks fragments high in the breccia that is from the lower part of the Leipers Formation and the upper part of the Catheys Formation increases. In other words, "… the breccia fragments roughly are distributed in an order inverted from the normal sequence of the beds from which they were derived …" (Roddy, 1964: 169). The mixed breccia near the fault is in turn overlain by a few meters of breccia that consists solely of upper Leipers Formation fragments; perhaps a talus deposit formed soon after the mixed breccia was emplaced (ibid.).

Some 150 meters south of the crater rim and breccia contact is another steeply-dipping fault that is concentric with the crater (Roddy, ibid.). To the north of this fault, the rock beds, Hermitage Formation of Middle Ordovician age, are raised 100 meters and tilted to the north up to 65 degrees. These beds are overlain by Cannon Limestone of Middle Ordovician age which is intensely deformed farther to the north.

Roddy (1964) believes that the folding and tilting with simultaneous faulting described above occurred during the formation of the Flynn Creek crater, and he summarizes his findings regarding the southeastern rim of the Flynn Creek:

> It also seems likely that rock fragments in the breccia in the down-faulted block were forcefully ejected from the crater because they are older than the surface on which they are now found and a topographic high probably separated them from the crater. The crude inversion of stratigraphy in the fragments of this breccia is consistent with ejection from the crater, and the similarity in lithology and gross texture of breccias inside and outside of the craters suggest that they were formed by the same process. (Roddy, 1964: 170).

Using field evidence gleamed from his study of the southeastern rim of the Flynn Creek Structure Roddy (1964) was able to estimate the thickness of strata removed by erosion before deposition of the Chattanooga Shale commenced. In the down-faulted block, the probable Richmond age beds underlying the ejected breccia were the pre-crater ground surface and "With this information, it is calculated that about 60 meters of rock were eroded from the structure before deposition of the Chattanooga Shale …" (ibid.). Additionally, Roddy (ibid.) noted that a pre-crater ground surface on the probable Richmond age beds explains the absence of Silurian and Devonian age fragments in the crater breccia: either these rocks had not yet been deposited or they were removed by erosional processes before the event that formed the Flynn Creek Structure.

After two years of further field work, Roddy (1966c: 183) added the following observation:

> Field studies have shown that the pre-crater ground surface is present in the tilted graben on the southeastern rim. Thickness measurements made from this surface down to older horizons indicate that less than 150 feet of strata, and more probably less than 50 feet, have been removed after the crater was formed.

The crater rim experienced only moderate erosion in pre-early Late Devonian times on the north, central and the southwestern parts of the rim, and "The heads of these ancient valleys did not erode completely through the raised rim strata to the lower level of the surrounding surface, and the crater was not exposed to external drainage systems …" (Roddy, 1966c: 122). Roddy (ibid.) also found that some parts of the rim displayed minor irregularities in the form of short shallow valleys and gulleys in an otherwise relatively smooth crater wall.

In the outermost sections within the crater structure the surface on top of the breccia presents a complicated picture. Near the western and northwestern wall, there is a continuous mass of breccia underlain by megabreccia blocks for over 900 meters, and "In fact, it seems to be the rule that where extensive masses of breccia are located near the rim, they are underlain by many large megabreccia blocks …" (ibid.). On the western side, the deepest low within the crater is around 90 meters below the highest area on the on the western rim and about 105 meters below the highest area on the southeastern rim. The eastern low point in the crater, however, is only about 5 meters shallower than its western counterpart (Roddy, 1966c).

The base of the central uplift is about 920 meters in diameter. The central uplift is some 5 meters higher than the average rim height, but 5 meters lower than the highest point on the southeastern rim. The sides have an average dip of 10-15º, but some are up to 30º (ibid.). The uplift is composed of Stones River, Wells Creek, and Knox strata which primarily dip to the west and northwest from 24-60º (ibid.).

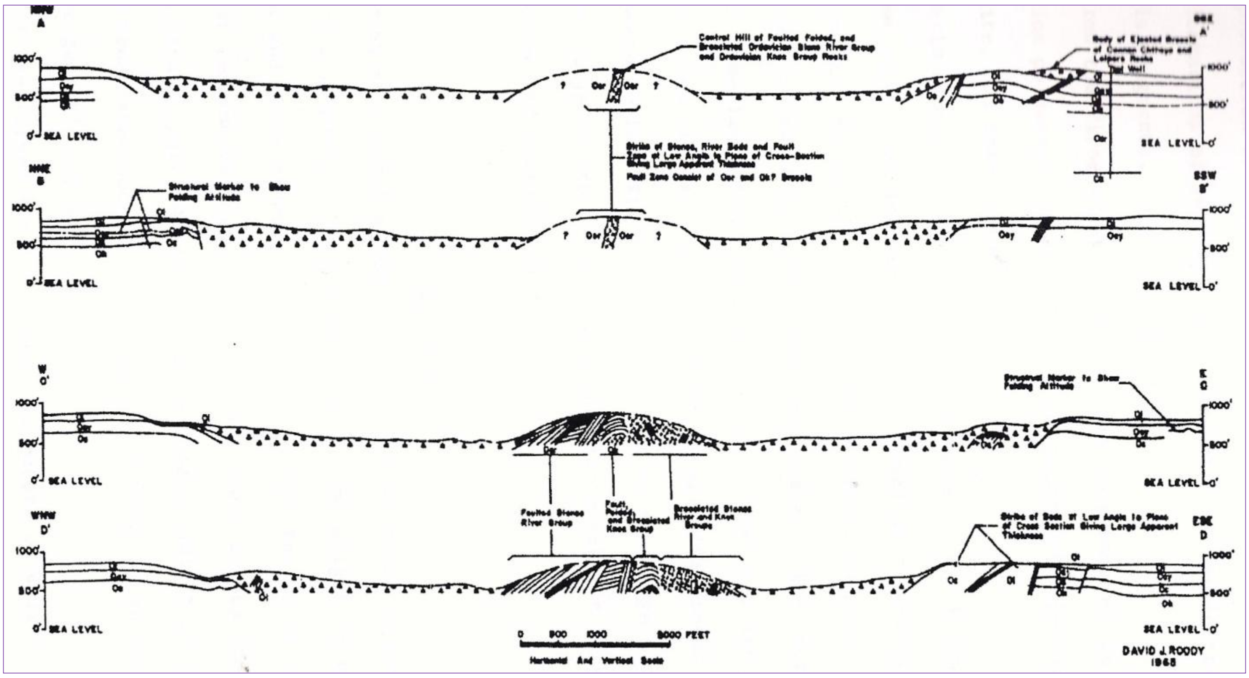


Figure 19: Generalized geological cross sections of the Flynn Creek Structure (after Roddy, 1965: 57).

Roddy (1966a: 270) adds to the growing body of knowledge concerning Flynn Creek in a discussion of his finding that "… a thin deposit of cross-bedded carbonates and bedded breccia form a unique and unusual basal facies of Chattanooga Shale within the crater." These units thicken to a minimum of 15 meters in the center of the structure, but rapidly thin on the upper parts of the crater walls. Evidence for a Late Devonian age for the Flynn Creek crater had previously led to speculation that these beds are actually lake deposits that consist of fresh-water limestones and breccia cemented in a matrix of fresh-water limestone. However, early Late Devonian conodonts found in the rocks indicate deposition took place in a shallow-water, marine environment that preceded the introduction of sediments of the Chattanooga Shale (ibid.).

Based on his field work, Roddy (1965: 52) found that the structural deformation of the Flynn Creek crater "… occurred in the interval between Richmond and early Late Devonian time (between about 420 and 350 million years ago)." He adds (ibid.) that "Dissection during Recent time by Flynn Creek and its tributaries has produced one of the best exposed crypto-explosion structures in the United States …"

Roddy's fieldwork led him to conclude that any post-explosion debris on the crater rim was removed before the deposition of the black Chattanooga Shale since the contact between the basal unit of the Chattanooga Shale and the early Late Devonian erosional surface rocks is quite sharp. He also concluded that the crater was not in existence for a long enough period of time to have completely filled during the time the rim eroded and was probably around 100 meters deep before deposition of the Chattanooga Shale began (Roddy, 1965).

Figure 19 shows generalized geological cross-sections of the Flynn Creek Structure prepared by Roddy "… shortly before deposition of Chattanooga Shale in early Late Devonian time." He points out an unusual type of fold shown in cross sections B-B' (northeast rim) and in C-C' (east rim) that suggests strong horizontal compression. These two folds "… have vertical axial planes, approximately concentric with the rim, and with horizontal shortening on the order of 35 percent …" (Roddy, 1965: 59). The rock beds below the folds are not exposed, but the beds above flatten rapidly which suggests that considerable bedding plane slippage took place within the tightly folded strata, and "The beds forming these folds were less than 100 meters below the ground surface when the Flynn Creek deformation occurred …" (ibid.).

The cross-sections in Figure 19 show "… a major body of continuous breccia within the crater; a localized body of probable forcefully ejected breccia; and a central uplift of faulted, folded, and brecciated rocks." (Roddy, 1965: 58). Analysis of the breccia indicated that it was derived from the upper quarter of the rim's deformed strata. The breccias in the structure were all formed from the same rocks that are exposed in the surrounding sedimentary section, but do not contain any igneous or metamorphic rocks from depth, and "Deposition of the bedded breccia and cross-bedded dolomite probably occurred in a coastal plain environment in the shallow waters of the slowly advancing Chattanooga sea …" (Roddy, 1965: 54). Roddy (1965) believed that for some time after the crater formed, the area consisted only of very low hills ranging from a few meters to perhaps as much as 20 meters with slopes less than 4º.

After several years of study, Roddy (1966b: 494) still described Flynn Creek as a probable impact crater formed in the Middle or Late Devonian time, around 3.5 km in diameter and some 110 meters deep, in a region of flat-lying carbonates. He again described the limestones of Middle and Upper Ordovician age as being folded, faulted, and brecciated in an irregular band several hundred meters wide in the rim of the crater. In addition, an irregular and discontinuous zone next to the crater wall, ranging in width from just a few to several hundred meters, was found to contain extensive fractures, microfractures, and calcite twin lamellas. Irregular fractures and microfractures were abundant in the breccia and in the central uplift, especially in the gradational transition between the breccia and deformed rim strata. Roddy (ibid.) determined that microtwinning was prominent close to the crater wall in crystals as small as 20 microns and that kink bands occurred in calcite crystals larger than 100 microns. He noted that the patterns of deformation for the calcite appeared to be consistent with patterns for explosive shock loading and were, therefore, "… interpreted as caused by high stress imposed during the passage of a shock front(s) produced during impact …" (ibid.). Rocks that contained moderately- to intensely-twinned calcite were distributed in a fashion similar to the strata containing the microfractures which was abundant in the central uplift, the crater breccia, and in a narrow band around the rim adjacent to the crater wall. The exception was in the fine-grained dolomites of the central uplift and other fine-grained rock strata; these did not exhibit noticeable twinning.

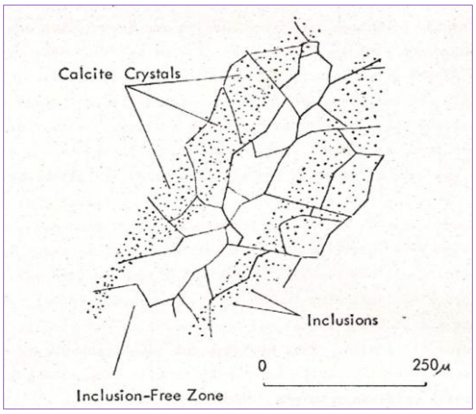


Figure 20: Calcite crystals with abundant inclusions cut by a zone free of inclusions (after Roddy, 1966c: 130).

According to Roddy (1966c: 157) "… the most intense twinning and microtwinning … is generally confined to the rocks immediately adjacent to the crater wall." Normal twin lamellae were common in the calcite found both within the Structure and in the surrounding undeformed strata. In the undeformed strata, however, twin lamellae were seen only in calcite crystals that were larger than ~100 microns. Twinning in these crystals consisted of one, two, or occasionally three sets of lamellae which ranged from 50 to 100 microns in width. These crystals rarely contained more than 10 lamellae and these were usually spaced at least 150 microns apart. Roddy (1966c) found two to three times the normal twin lamellae in the same size crystals outside of the deformed area and these were more likely to have two or more sets of normal twin lamellae as well as twinning in crystals as small as 20 microns. He also found a large increase in microtwinned lamellae in the deformed rim strata and some of the breccia fragments. In addition to highly-twinned calcite found in the crater rim, Roddy (1966c: 127, 129) found microfractures to be common in the fine-grained dolomites of the central uplift that appeared to be recrystallized or 'healed' fractures. Figure 20 is a sketch by Roddy of some of these calcite crystals. Roddy (1966c: 129) states that in these rocks, "… thin, irregular, clear bands up to 50 microns wide cut across grain boundaries without visibly disturbing each individual crystal, except that all inclusions are absent from the band."

The report on the last phase of Roddy's Astrogeologic Studies at Flynn Creek, which was included in the 1967 *Annual Progress Report*, involved core drilling at six locations along an east-west line across the crater (*Astrogeologic Studies*, 1967: 28). The cores were 5.5 cm in diameter and totaled 762 meters (Roddy, 1980). The results, combined with Roddy's surface geological mapping, showed that the Flynn Creek structure was comprised of a crater containing "… a very shallow, bowl-shaped lens of breccia underlain by faulted and folded limestone …" (Roddy, 1980: 941). The drill core sequence was reported by Roddy:

> The drill cores contain a sequence of bedded dolomite 1 to 2 m thick which is underlain by a graded, bedded dolomitic breccia as much as 15 m thick … The bedded dolomitic breccia is underlain by a course, chaotic breccia with fragments derived from the local strata; the size of these fragments increases near the base of the chaotic breccia. The Hermitage Formation, a 20-m-thick shale with interbedded limestone, is the lowest unit completely brecciated … it forms the matrix for much of the chaotic breccia. The thickness of the chaotic breccia lens averages about 35 m.
>
> Limestones directly below the base of the breccia lens are highly faulted and folded, but the deformation decreases downward and the rocks are nearly flat-lying and relatively undisturbed below about 100 m beneath the breccia lens … Folding immediately below the base of the breccia lens extends 30 to 40 m deeper on the eastern side of the crater than on the west-

> ern wide [side].
>
> The absence of lake deposits and a fall-back zone and the occurrence of the bedded dolomitic breccia containing marine conodonts suggest that the shallow waters of the initial Chattanooga Sea occupied the area when the crater formed, probably in early late Devonian time. (*Astrogeologic Studies*, 1967: 29).

In his research for the Branch of Astrogeologic Studies, Roddy's (1968a: 272) final conclusion was that the Flynn Creek crater, "… was formed in flat-lying limestones in northern Tennessee approximately 360 × $10^6$ years ago." He pointed out that most of the structural elements he found at Flynn Creek, "… including a central uplift, occur in two craters formed by a 500-ton TNT hemisphere and a 100-ton TNT sphere detonated on alluvial surfaces at the Defense Research Establishment, Alberta, Canada …" (ibid.). The structural similarities between Flynn Creek and these chemical explosion craters indicated that a shock-wave process was responsible for the formation of the structure at Flynn Creek and that the deformational energy was concentrated in only the upper 300 meters of rock strata. This was confirmed to be the case by the six drill cores which also indicated that a surface-generated energy source was responsible for the cratering event:

> These conditions … and the similarities in rim deformation and central uplift between Flynn Creek crater and surface-produced explosive craters, are interpreted as consistent with a hypervelocity impact process … (ibid.).

Roddy stated that his calculations indicated that the "… depth of impactor penetration was less than 150 meters, which is in agreement with field evidence …" (ibid.).

In 1968 Roddy confirms his previous findings by stating that the highly-deformed Lower and Middle Ordovician limestone and dolomite were uplifted in the center of the crater over 300 meters resulting in a central hill some 100 meters high. This central uplift consisted of the oldest Flynn Creek strata and contained shatter cones. Rim strata were raised 10-50 meters as well as forced outward which resulted in moderate to intense folding and faulting. Breccia was ejected onto the crater rim and was found to still be partly preserved in a rim graben, although erosion had removed most of the ejecta blanket and also filled the crater "… until it was 100 m deep …" (Roddy, 1968c: 179). The crater then completely filled with Chattanooga Shale during early Late Devonian times.

In his 1966 thesis, Roddy stated that the crater first filled with Upper Devonian shale which was later covered by Lower Mississippian chert. Strata in some sections of the rim were lifted by as much as 50 meters and tilted outwards. "Most axes of folds in the rim are concentric with the crater wall, but some folds have axes radial to the crater wall …" (Roddy, 1966c: 179). Tight folding in some sections of the rim produced radial shortening as great as 35 percent. Roddy (1966c: 216) also discussed the age of the Flynn Crater in his thesis:

> The apparent absence of any type of Silurian and Lower or Middle Devonian rocks in the bottom of the crater suggests the age is considerably younger than post-Richmond and more probably is Middle to post-Middle Devonian age. If the crater had been present during this period of time, and if no Silurian or Devonian seas had covered the area, then almost certainly lake deposits would be present above the crater breccia. Instead, the first bedded deposits that are observed are marine breccias derived locally within the crater and which are of early Late Devonian age.

Roddy (1966c: 218) noted that "… it does not appear that the rim was ever breached and opened to outside drainage."

After receiving his Ph.D. and completing his Astrogeologic Reports for NASA and the U.S. Geological Survey, Roddy continued his field work and research on the Flynn Creek Structure for many years. A decade after completing his Ph.D. he explained the preliminary information he gathered from a second set of cores drilled in the Flynn Creek Structure, commencing in November 1978:

> This crater, approximately 360 million years old, was initially ~3.8 km in avg. rim crest diameter (~ 3.5 km apparent) and ~ 180 m in avg. rim crest depth (~80 m apparent). Previous core drilling of six holes (762 m total) in the crater floor showed limestone and dolomite beds immediately below the base of the breccia lens (35 m avg. thickness) are intensely faulted and locally folded and brecciated, however deformation decreases downward and the strata is nearly flat-lying at depths of about 100 m below the base of the breccia lens.
>
> Core drilling completed in the outer crater floor area shows the strata underlying the breccia lens to be nearly 50 m lower than that in the adjacent inner rim and that the rocks are extensively faulted and locally brecciated. At depths of 350 m to 400 m in the same drill cores the relative displacement between the sub-crater floor and inner rim strata decreases to less than 30 m ...
>
> Preliminary reduction of the drill data from the central uplift indicates an abrupt transition from limited deformation in the rocks underlying the breccia lens on the crater floor to very complex deformed rocks beneath the central uplift. Uplift, including extensive faulting and brecciation, beneath the flanks of the central uplift is over 130 m at a depth of 50 m below the level of the original crater floor. Uplift in this same region decreases to only 15

> m at depths of 340 to 360 m below the original floor. Exposures in the top of the central; uplift show a maximum uplift of Knox strata of about 450 m. The drill data confirm uplift is due, in part, to extensive faulting and brecciation beneath the uplift region creating a locally decreased mass/volume relationship. The ring fault and clear-cut inward movement of subcrater floor strata also contribute to sustained uplift. The drill data completed to date suggest that the central uplift formed so rapidly that the large sequence of exposed Knox strata was violently uplifted over 450 m to form a massive detached block underlain by previously higher strata. (Roddy, 1979a: 1031).

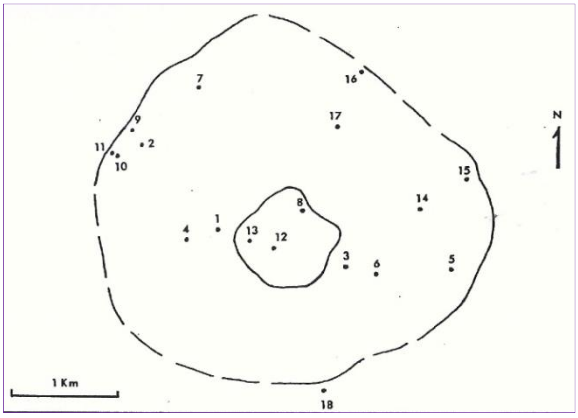


Figure 21: Location of 1967 and 1978-1979 drill holes at Flynn Creek (after Roddy, 1980: 942).

Originally, six cores were drilled in 1967 for the Astrogeologic Studies, but at least 14 more were drilled by 1979. In 1979, at the Lunar and Planetary Institute's tenth conference, Roddy described his interpretation of the preliminary results from the second round of deep drilling at Flynn Creek. During the impact and subsequent explosion, approximately 3 × $10^9$ metric tons of rock were brecciated to a depth of 130 to 150 meters below the original ground surface and around 2 × $10^9$ metric tons or rock was ejected from the crater (Roddy, 1979b). Beneath the central uplift, rock was brecciated and excavated to a depth of 200 to 250 meters with the deeper strata uplifted over 450 meters. The resulting uplift reached 110 to 120 meters above the crater floor. Roddy (ibid.) estimates that the initial rim crest diameter was about 3.8 km on average with the depth measured from the rim crest averaging 198 meters.

Figure 21 is a map by Roddy (1980: 942) showing the locations of the 1967 and 1978-1979 drill holes at Flynn Creek. Drill hole numbers 1 through 6 were drilled in 1967 along an approximate east-west diameter of the crater in order to investigate the thickness of the breccia lens and determine the nature of the underlying formation. The second phase of core drilling at Flynn Creek occurred from November 1978 to November 1979 and consisted of 12 holes that were 3.5 cm in diameter and totaled 3064 meters:

> Four holes, up to 625m deep, were devoted to determining the structure of the innermost western rim, crater walls and floor. Four holes, up to ~ 166m deep were devoted to crater floor structure along north and northeast radials. Three deep holes, up to 853m deep, were drilled in the central uplift, and one 216m deep hole was drilled in the terrace graben on the southern rim. (Roddy, 1980: 941).

The "… shallow depth of excavation and deformation underlying essentially all the crater floor, except for the central uplift region …" was absolutely confirmed (ibid.). The crater floor averaged around 80 to 98 meters in depth below the pre-impact crater surface, the breccia lens was only 35 to 50 meters in thickness, and the strata underlying the breccia were undeformed, continuous, and flat-lying around 100 meters below the base of the lens which was around 200 meters below the pre-impact ground surface. The crater was the result of a broad, but shallow excavation cavity, with "… the crater diameter/depth of cavity ~ 1/23 …", associated with a deep, but narrow central cavity containing the uplifted strata in the center (ibid.). The new 216 meter drill core from the southern graben in-

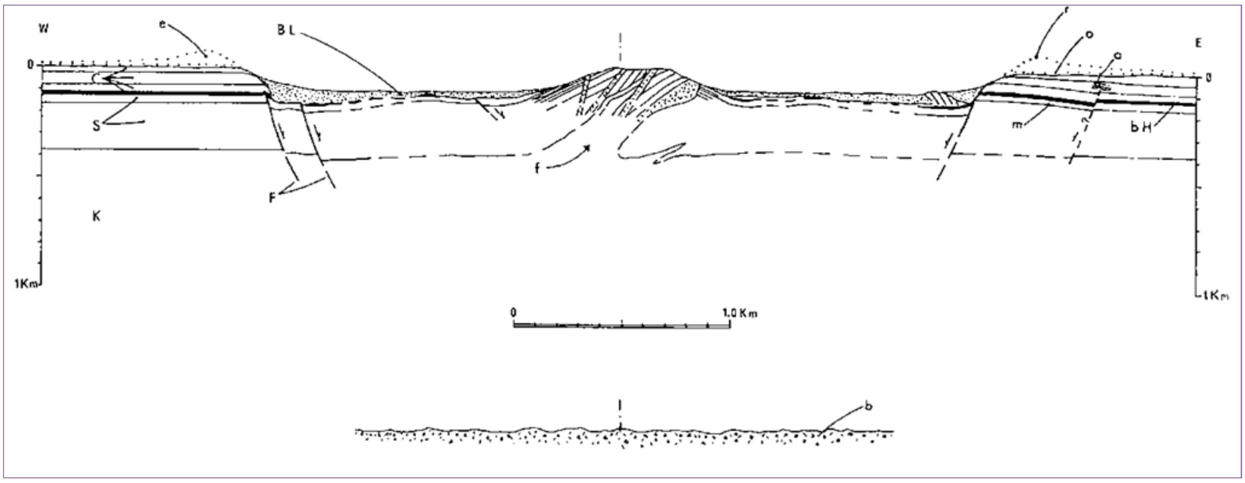


Figure 22: Schematic geological cross-section of Flynn Creek (after Roddy, 1979b: 2523).

dicated that the strata were basically flat-lying at depths of 50 to 75 meters below the pre-impact ground surface which led Roddy (1980: 942) to conclude that "… the graben or terrace block moved downward and slid towards the crater with relatively little secondary deformation or tilting."

Figure 22 is a cross-section of the Flynn Creek impact crater based upon surface geological and core drilling studies. Deformation in the eastern rim was primarily due to simple uplift. The western and northern rims were relatively flat except for some limited folding immediately outside the walls which caused the rock to dip into the crater. It was the southern rim that was home to the most developed terraces and the most complex deformation of Flynn Creek including "… a major rim graben partly overlain by a large thrust sheet …" (Roddy, 1979b: 2524).

Surface mapping and drill data indicated that the folded strata in the inner rim, crater wall, and outer crater floor were underlain by one or more concentric ring faults on the western, northern, and eastern sides of the crater. The down-dropped sides of these faults were towards the crater and maximum displacement appeared to have been no more than around 40 meters. "These faults appear to be relatively high-angle normal faults immediately below the folded strata …" as is shown in Figure 22 (Roddy, 1979b: 2527). The net effect of the concentric faulting served to lower the outer part of the crater floor from a few meters up to some 40 meters and tilt the subcrater floor strata away from the crater center. Roddy (ibid.) states that "… the drill data indicate that the total vertical displacement across the rim to the outer crater floor strata commonly takes place in a horizontal distance of 50 m or less …"

The most complex structure in the Flynn Creek crater was still considered to be the large graben and thrust sheet contained in the southern rim. This section was of great interest due to the "… 0.5 km$^3$ of ejecta with a crudely inverted stratigraphy that remained trapped in the down-dropped part of the southern rim graben …" (ibid.). Of additional interest was the original ground surface from the time of impact that was partially exposed beneath the ejecta. Roddy (1977b: 303) estimated that the original ejecta blanket had an approximate radius of 2.5D, where D is the diameter of the crater.

The second round of drill data also showed that a thin breccia lens underlay the crater floor and averaged 35 to 50 meters in depth. The lens thinned a little towards the central uplift and covered its lower flanks. The lower part of the breccia lens was well defined in the drill cores and contained "… fragments with lithologies mixed from all of the rock formations encountered in the cratering, except for the central uplift strata …" (Roddy, 1979b: 2528). The breccia lens plus the ejecta that washed back into the crater increased the thickness to around 100 meters near the outer edges of the crater floor. Roddy (ibid.) states that the additional drill data showed that rock immediately beneath the breccia lens base was highly faulted, fractured, and locally brecciated; however, no lithological mixing was noted in the disturbed rock. Deformation decreased rapidly downward and was basically absent around 100 meters below the breccia lens, which would be around 250 meters below the original ground surface. The lower limit of brecciation and ejection as determined by the deep core drilling was interpreted by Roddy (1979b: 2530-2531) to "… define the approximate extent of the transient cavity formed during the cratering event." The deep sub-surface strata beneath all but the central uplift

> … of Flynn Creek *do not* exhibit total fragmentation and mixing, such as that expected with a deep transient cavity and subsequent deformation ... We therefore conclude that Flynn Creek formed with only a broad shallow flat excavation cavity and a central uplift … [and never did go through] a deep transient cratering phase … (Roddy et al., 1980: 944; his italics)..

Roddy's field studies suggested that the upper part of Flynn Creek's central peak was composed of a complex sequence of highly brecciated, faulted, fractured, and locally folded limestones and dolomites which "… moved inward and upward to form a domical-shaped central peak that rose 110 to 120 m above the initial crater floor." (Roddy, 1979b: 2529). Extensively uplifted and deformed Stones River and Knox strata are now exposed due to a narrow valley that eroded through the central uplift by Flynn Creek. Numerous stratigraphic omissions and repeats occur in the uplift due to fault zones which vary from low to high angle. A road cut through the central peak exposes a westerly dip, varying from 24º to 60º, in most of the western and central sections of uplifted strata. Chaotic breccia separates the westward-dipping strata from the eastward-dipping strata found in the eastern section of the central uplift. Upper Knox stratigraphic units in the central hill contain shatter cones and were "… uplifted through 450 m to the original level of the pre-impact ground surface …" (ibid.). Deep drilling in the central uplift and its outer flanks produced 8 cores which indicated that the disrupted zone under the central peak "… has an irregular shape that dips asymmetrically to the west …" (ibid.). Roddy (1979b: 2529) explains the significance of this:

> Both the extensive surface exposures through the middle of the central peak above the crater floor level and the deep drill data indicate a westward plunge of this zone of subsurface

> deformation. The continuation of the dipping geologic contacts in the exposed rocks with the deep subsurface data on Knox and Stones River contacts indicates that the source of the uplifted Knox lies under the western flanks of the central peak and that it was uplifted and displaced strongly to the east.

The drill core results are important for our current understanding of the Flynn Creek central uplift since "The southern two-thirds of the central uplift remains buried beneath the Chattanooga Shale and Fort Payne Formation, making study difficult …" (Milam and Deane, 2006b: 1).

Interpretation of the drill core data by Roddy indicated that total fragmentation and ejection only extended some 200 to 250 meters below the original ground surface and below that massive readjustments took place in which blocks tens of meters across were either uplifted or down-dropped tens of meters. According to Roddy (1979b: 2530, his italics),

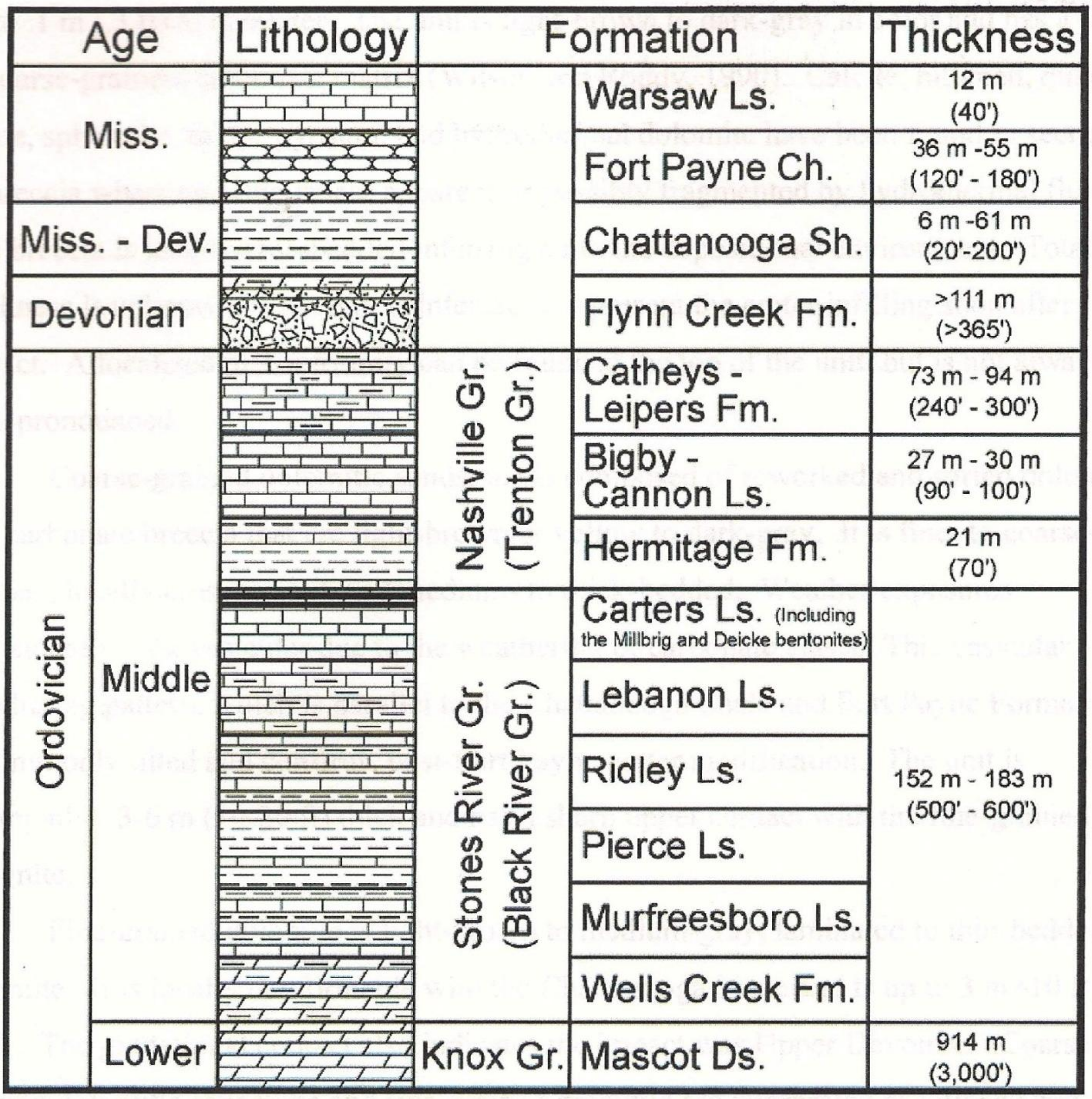
> This would suggest that a narrow, *partly open* transient cavity may have extended to perhaps as deep as 300 to 500 m to allow the megablocks to rapidly shift into their final positions. Ejection of rocks from this deep level does not appear to have occurred … The gradual termination of major disruption in the strata beneath the central uplift appears to be approximately 700 m below the pre-impact ground level … No structural uplift could be determined below this level.

Roddy (1979b: 2532) summarized his interpretation of the sequence of cratering events at Flynn Creek as follows: (1) oblique impact of a low density body such as a comet nucleus or carbonaceous chondrite … (2) oblique penetration into the rocks, including a possible very shallow body of water, to depths on the order of 100 to 200 m; (3) vaporization and melting of carbonate rocks and impacting body along penetration cavity; (4) total brecciation and ejection of a small bowl- to conical-shaped region which had a diameter of less than ~900 m and a very approximate depth of 200 to 250 m; (5) intensive bulking and disruption of the rock surrounding the central impact area and violent expansion and uplift into the *partly opened* central transient cavity; (6) broad anticlinal folding and faulting of sub-crater floor region caused by shock compression and initial outward expansion and relaxation; (7) continuous brecciation and excavation of the strata over the present crater floor area to a depth no greater than 150 m and out to approximately the present crater walls. This stage is probably continuous with the ends of stages (5) and (6); (8) continuous ejection of rocks from crater floor region to form an ejecta blanket with crudely inverted stratigraphy surrounding the crater; (9) formation of concentric ring fault zones, probably as early as the end of state (6), with down-dropping and inward movement of sub-crater floor strata completing final reposition of deeper rocks. Terrace formation probably continued to occur during this time. Final inward movements in the lower disrupted central uplift zone probably continued to close the deepest part of the *partly opened* transient cavity and sustain the uplifted strata. Elsewhere in this paper Roddy (ibid.) points out that these suggested stages most likely overlap and are transitional in time with each other.

From time to time during the latter half of the last century researchers other than Roddy were interested in Flynn Creek. Miller (1974) summarized the structural features of the Flynn Creek crater by stating that the rocks there are intensely deformed and brecciated and there are numerous faults and folds. He noted that there is a central uplift in which the Knox and Stones River strata are not only exposed, but are found to have been raised some 300 meters above their normal position. He also mentioned the fact that shatter cones are present in the Flynn Creek Structure.

Officer and Carter (1991: 24) state that the Flynn Creek structure "… consists of a shallow crater, 3.6 km in diameter and about 150 m deep …" with a large central uplift, deformed rim strata, and a breccia lens. Shatter cones were found within the central uplift where strata are raised some 350 m above their normal stratigraphic position. More than 2 km$^3$ of Upper and Middle Paleozoic limestone and dolomite were brecciated and mixed to a depth of 200 m. Officer and Carter believe that around half of the Flynn Creek breccia was ejected from the crater, but the rest remained as a lens of chaotic brecciated dolomite and limestone with fragments ranging from under a meter to blocks up to 100 meters long. Drill core reports indicated that "… the limestone and dolomite beds immediately below the base of the breccia lens are highly faulted and folded, but deformation decreases downward, and the rocks are nearly flat lying and undisturbed about 100 m beneath the breccia lens …" (ibid.). Officer and Carter state that no gravity or magnetic anomalies were ever found to be associated with the Flynn Creek Structure (ibid.).

Recent research has led to the recognition that some of the Flynn Creek breccias primarily consist of black shale clasts that are most likely derived from the Upper Devonian Chattanooga Shale and apparently do not contain limestone or dolomite clasts derived from the Nashville, Stones River, or Knox Groups which are Ordovician in age, which "… suggests an early syndepositional impact event rather than Ordovician or pre-Chattanooga Shale impact …" (Evenick et al., 2004: 1). Thin sections prepared from Flynn Creek breccia have been found to display rare flow textures and minor spot melt at grain



| Age | | Lithology | Formation | | Thickness |
|---|---|---|---|---|---|
| Miss. | | | | Warsaw Ls. | 12 m (40') |
| | | | | Fort Payne Ch. | 36 m -55 m (120' - 180') |
| Miss. - Dev. | | | | Chattanooga Sh. | 6 m -61 m (20'-200') |
| Devonian | | | | Flynn Creek Fm. | >111 m (>365') |
| Ordovician | Middle | | Nashville Gr. (Trenton Gr.) | Catheys - Leipers Fm. | 73 m - 94 m (240' - 300') |
| | | | | Bigby - Cannon Ls. | 27 m - 30 m (90' - 100') |
| | | | | Hermitage Fm. | 21 m (70') |
| | | | Stones River Gr. (Black River Gr.) | Carters Ls. (Including the Millbrig and Deicke bentonites) | 152 m - 183 m (500' - 600') |
| | | | | Lebanon Ls. | |
| | | | | Ridley Ls. | |
| | | | | Pierce Ls. | |
| | | | | Murfreesboro Ls. | |
| | | | | Wells Creek Fm. | |
| | Lower | | Knox Gr. | Mascot Ds. | 914 m (3,000') |

Figure 23: Stratigraphic column of Gainesboro quadrangle (after Evenick, 2006: 3).

boundaries. "The presence of spot melt and flow textures further confirm the structure's impact origin …" (ibid.).

The Flynn Creek crater fill recently has been "… separated into four categories (called the Flynn Creek Formation): non-bedded breccia, bedded breccia, course-grained dolomitic sandstone, and fine-grained dolomite. The Formation is found only within the crater …" (Evenick, 2006: 1). Drilling data indicate that the Flynn Creek Formation is over 111 meters thick, as is shown in Figure 23, a stratigraphic column of rock exposed in the Gainesboro quadrangle, which includes the Flynn Creek area (cf. Evenick et al., 2005). The basal breccia unit in the Flynn Creek structure is the non-bedded breccia, predominately composed of angular and unsorted limestone along with minor dolomite and chert clasts that are up to 0.3 meters in diameter.

The bedded breccia overlies the non-bedded breccia and is composed of angular and unsorted limestone, minor dolomite, chert and shale clasts up to 0.1 meters in diameter. "The breccia is locally crossbedded inferring a marine depositional environment … This unit is inferred to represent the crater infilling soon after impact …" (Evenick, 2006: 4).

The coarse-grained dolomitic sandstone is around 3 to 6 meters thick and composed of reworked and sorted dolomite and carbonate breccia. It has a sharp upper contact with the fine-grained dolomite which is light-brown to medium-gray and laminated to thin-bedded dolomite. This unit is up to 3 meters thick and locally conformable with the Chattanooga Shale. The gradational contact also indicates the impact was upper Devonian. "Course-grained dolomitic sandstone and fine-grained dolomite are interpreted as fallback and ejecta that washed into the crater following impact …" (ibid.).

Although most previous researchers have placed the age of the Flynn Creek Structure at ~360 ± 20 Ma, corresponding to the initial deposition of the Chattanooga Shale, fossil evidence found in the breccias indicates that the impact most likely occurred around 382 Ma (Evenick, 2006: 4; Schieber and Over, 2005: 51). Confirmed Flynn Creek target rocks range from the Knox and Stones River Groups in the central uplift to the Catheys-Leipers Formation in the rim exposures (Evenick, 2006). Recent field mapping yielded the following results:

> 1) fracture patterns in the Flynn Creek Formation are similar to Devonian fracture sets; 2) a gradational contact between the basal Chattanooga Shale and the uppermost unit in the Flynn Creek Formation (fine-grained dolomite); 3) hydrothermal dolomite in the crater rim and fill; 4) Chattanooga Shale clasts reworked into the basal member of the Chattanooga Shale near the modified crater rim; and 5) rare impact breccia clasts with possible Chattanooga Shale affinity. This new information, along with the previously confirmed thickened Chattanooga Shale sequence and the Devonian conodonts within the basal impact breccias, strongly constrains the impact age to the Upper Devonian. (Evenick, 2006: 4-5).

This Upper Devonian impact crater filled with the dark marine mud which became the Chattanooga Shale, then uplift during the late Paleozoic led to partial exposure of this buried crater at Flynn Creek (Evenick, 2006).

Schieber and Over (2005: 64) state that

> Conodonts from the fill of the Flynn Creek structure clearly constrain the relative age of the Flynn Creek Member basal breccia, bedded breccia, and black shale submembers, as well as the overlying Dowelltown Member of the Chattanooga Shale.

The basal and bedded breccia submembers were found to contain mixed fauna of Late Ordovician and Devonian conodonts. Overlying the Flynn Creek Member and Ordovician strata, the Dowelltown Member is marked by a disconformity and basal lag which, regionally, contains Ordovician through Late Devonian conodonts. Schieber and Over (2005: 66) come to the following conclusion concerning the age of the Flynn Creek impact crater:

> With some limitations, and acknowledging analytical error ranges of ±2 m.y. for published radiometric dates, as well as competing geochronological schemes … the 0.42 m.y. time interval from 382.24 to 381.82 Ma. thus brackets the time of impact.

Schieber and Over (2005: 66-67), therefore, conclude that "The asteroid that produced the Flynn Creek crater struck … during the Lower Frasnian, approximately 382 million years ago, and the marine crater fill sedimentation commenced immediately after impact." They also note:

> The late Dave Roddy generously shared his understanding of the Flynn Creek Structure and provided access to drill cores and sample materials. Dave was able to comment on the first draft of this manuscript, but his untimely death in 2002 prevented him from seeing it go into print. Flynn Creek was one of Dave's favorite impact structures. (Schieber and Over, 2005: 67).

## 4 CRATERING MECHANICS

Roddy (1977b: 278) pointed out that "Hypervelocity impact cratering has proven to be one of the dominant physical processes affecting the surfaces and evolution of the terrestrial planets." He also noted that large craters apparently have played a major role in the evolution of the crusts and upper mantles of most of the bodies in our Solar System that have solid surfaces, and concluded that "… an understanding of their cratering processes is essential to any comprehensive study of the terrestrial planets …" (ibid.).

According to Boon (1936), it is difficult to determine the energy changes that occur when a meteorite impacts the surface of the Earth or the Moon. An early unexpected finding noted is that meteorite impact craters, such as the Barringer Crater in Arizona, "… show little evidence of heat." (Boon, 1936: 57). Small meteorites lose most of their high initial velocity, and thus their kinetic energy, to friction while passing through the Earth's atmosphere. Massive meteorites, on the other hand, are many times heavier than the column of air they displace as they descend, therefore, their impact velocities are close to the velocities with which they travelled through space before entering the Earth's atmosphere (see Boon and Albritton, 1936). The kinetic energy, *KE*, of a massive falling meteorite is given by the following equation:

$$KE = (½)MV^2 \qquad (1)$$

where *M* in the mass and *V* is the initial velocity. Given their high velocities, Boon and Albritton (1936: 3) conclude that massive meteorites must possess huge amounts of kinetic energy and, therefore, "… must explode when they strike the earth …"

The radial distribution of ejecta (both country rock and meteorite fragments) around craters, the intense local brecciation and powdering of the country rock, the occasional manifestations of intense but localized thermal metamorphism, and the radially-outward dip of rim rocks lead to the same conclusion: that tremendous explosions have occurred at these localities.

In their discussion, Boon and Albritton divide an explosive event due to meteoritic impact into three intervals in order to discuss the ways in which a meteorite's kinetic energy is either converted or dissipates during the event. The first interval covers the time the meteorite spends traveling through the Earth's atmosphere "… which may last for several seconds …", and due to friction with the atmosphere "A relatively small amount of this energy is dissipated as heat …" (Boon and Albritton, 1936: 4). Boon and Albritton (ibid.) also point out that since the time interval is so short, frictional heat will penetrate only the outermost layer of the meteorite and note that "The inside of a large meteorite would probably have a temperature near absolute zero at time of impact …"

Boon and Albritton's second interval covers the time period in which the meteorite comes to rest after striking the Earth's surface. The impact of a massive meteorite would deal surface rocks "… a terrific blow … [and in only] a fraction of a second the body would penetrate the earth a short distance and be brought to rest." (ibid.). During this brief time interval, the meteorite's energy is stored in two places: the first is "*In a thin, intensely hot, gaseous layer surrounding the bottom of the meteorite* …" (ibid.; their italics). If all of the massive meteorite's kinetic energy was transformed into heat, then the meteorite itself would likely be melted or vaporized (ibid.). However, "… it would be impossible for more than a small part of the kinetic energy to be so transformed in the fraction of a second between impact and explosion …" (ibid.). Heat travels by convection and conduction with comparative slowness, so this 'zone of vaporization' would comprise only a small part of the transformed kinetic energy. This small portion of the energy would likely vaporize only a thin layer of material underneath the meteorite, but this would be an intensely hot zone and "… would be the locus for thermal metamorphism …" which accounts for the silica glass that is found in some meteorite impact craters (see Boon and Albritton, 1936: 5).

The second and greater portion of the transformed kinetic energy "… is momentarily stored in *a zone of highly compressed rock beneath the locus of impact …"* (ibid.; their italics). As a massive meteorite penetrates the Earth and comes to rest, it compresses the target rock beneath, and by the time the meteorite has come to rest the greater portion of its energy is stored "… in this zone of compression as *pressure potential energy …*" (ibid.; their italics).

The third time interval designated by Boon and Albritton is that of the explosion. They state that

> The instant a large meteorite is brought to rest, the highly compressed materials beneath it would expand with explosive violence … (Boon and Albritton, 1936: 6).

The energy released would dissipate during the formation of a crater by the brecciating or pulverizing and then excavation of target rock, the formation of elastic waves, and the deformation of rock strata. Taking into consideration

> … all of the explosive forces brought into play by meteorite impacts, it would seem that a body sufficiently large to reach the earth with virtually undiminished velocity would be backfired and shattered upon impact … (ibid.).

Boon and Albritton (1936: 6) suggest that the target material of a meteorite strike has

> … a limited degree of freedom, and a high degree of elasticity of volume … Brittle substances are not shattered by pressure, if pressure be applied to all sides, but by tension. Hence after compression they all rebound.

They point out that after a meteorite impact and explosion, concentric waves would be expected to move outward in all directions from the center of impact forming ring anticlines and synclines. Roddy (1977b: 295) infers that the expanding shock wave may likely be "… slightly flat due to differential travel velocities in the vertical and horizontal directions." The waves, however,

> … would be strongly damped by the overburden and by friction along joint, bedding, and fault planes. *The central zone, completely damped by tension fractures produced by rebound, would become fixed as a structural dome …* (Boon and Albritton, 1936: 7; their italics)

Boon and Albritton (ibid.) give the following description of a meteorite impact structure:

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

Roddy (1977b: 296) points out that an effect of the very high shock pressures during an impact event is that the impactor and the target rock "… respond hydrodynamically, temporarily exhibiting a fluid behavior." This is because the strength of the impactor and the target rock would be exceeded by factors of $10^3$ or more, literally causing them to flow. Roddy (1977b: 297) describes the excavation of a crater as follows:

> The basic mechanism for pressure release lies in the interaction of the shock waves with all free surfaces. Stated simply, material semi-infinitely deep in a shocked zone moves only in the direction induced by the shock wave. Near a free surface, however, material experiences a different unloading path due to the fact that an unconfined free surface cannot support stress across that surface, i.e., continuity conditions require an instant equilibration

> of the stress field. Consequently, the high pressure zones created in the target and projectile, together with very low surface pressures, define a decreasing stress gradient along which material can be accelerated and ejected. The practical result is that the free surface moves. The point is that impact craters, at least in hard rock systems, are *not* formed during the very high pressure compression stage. Instead, they form as a response to the later dynamic rarefaction fields developed along all free surfaces.

Boon and Albritton (1937: 56) point out that long after a meteorite crater and its associated ejecta and meteorite fragments have been removed by erosion and weathering, an impact structure, the "... meteorite scar …", may long persist in the geologic record. Figure 24 is a section through a typical meteorite impact crater according to Boon and Albritton, but the actual appearance of the crater will depend on the extent to which it has been eroded (as shown in Figure 24):

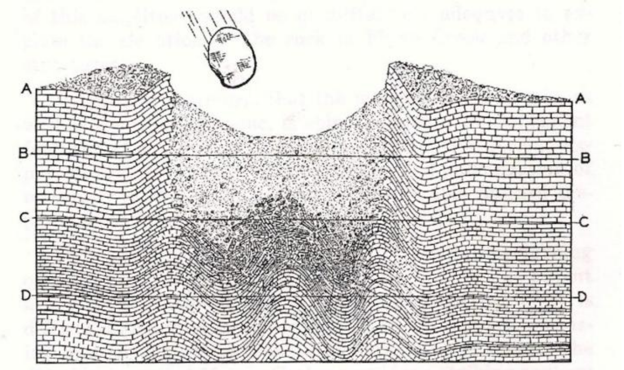


Figure 24: A section through a typical explosive impact crater caused by a meteorite (after Boon and Albritton, 1937: 57).

> It is only in the initial stage (along the profile AA) that the crater clearly reflects its origin in the rim of ejected material, silica glass, and meteorite fragments distributed around it. The scar will become inconspicuous when the country is denuded to level BB. When the area is down to the level CC the underlying structures begin to appear, and when the depth DD is reached the central uplift and ring folds become apparent. Should erosion proceed to depths below those affected by the meteoritic disturbance, the scar would be obliterated. On the other hand if the scar should be submerged and covered with sediments, it might be preserved and subsequently revealed in the course of regional uplift and erosion. (Boon and Albritton, 1937: 56).

Roddy (1976: 121) describes Flynn Creek as a "… large, flat-floored crater, 3.6 km in diameter and over 200 m deep." He then discusses the formation of this crater, and states that the impactor violently fragmented over 2.0 cubic km of flat-lying Middle and Upper Paleozoic limestone and dolomite. He then describes the structural deformation and cratering process as follows:

> Total brecciation and mixing of rock units to a depth of about 0.2 km were completed in seconds with over 1.5 cubic km of rock ejected during the event. Within the crater a thin breccia lens of limestone and dolomite, averaging 40 m in thickness, remained as fallback and locally disrupted country rock. Fragments in this lens lie in chaotic orientations in a carbonate powder matrix and range in size from a fraction of a millimeter up to blocks 100 m across. Drill core data now indicate that the limestone and dolomite beds immediately below the base of the breccia lens are highly faulted and folded with deformation rapidly decreasing downward until the rocks are nearly flat-lying and relatively undisturbed at depths of about 100 m beneath the breccia lens.
>
> During the evacuation phase, a massive central uplift over 1.0 km across and 120 m high formed in the middle of the crater. This dynamic structural uplift consists of steeply-dipping, faulted, folded, and brecciated Middle Ordovician limestone and dolomite which have been raised as much as 350 m above their normal stratigraphic positions. Shatter cones are common in the dense dolomites from the deeper units.
>
> During the latter stages of excavation, flat-lying Middle and Upper Ordovician limestones and dolomites in the rim were moved outward during compression and abruptly uplifted a minimum of 10 to 50 m … During the final stages of cratering normal, reverse, and thrust faulting remained a common mode of structural failure. (ibid.).

Roddy (1968b: 307) notes that the Flynn Creek ejecta blanket, which has for the most part been lost to erosion, is partially preserved overlying a rim graben and displays only the local sedimentary rock in a "… crude inversion of the stratigraphy."

Milam and Deane (2005: 2) describe the probable sequence of events for formation of the central uplift of a complex crater such as Flynn Creek. Pre-impact deposition of target rock and its subsequent lithification and diagenesis may involve the generation of some microfractures. However, the passage of the compressional front of the shock wave due to impact results first in the production of shatter cones and shocked minerals and then, due to subsequent decompression, the generation of microfractures (ibid.). The result of such deformation is the weakening of target rock material which in turn allows for "… potential pathways for subsequent movement of large blocks of material from the centers of craters …" (Milan and Deane, 2005: 1). During the rise of the central uplift, microfault movement and microbreccia generation take place which is immediately followed by major fault movement and fault breccia generation.

Major faults are likely responsible for and represent the final stages of central uplift formation. Roddy (1977b: 302-303) estimates that for Flynn Creek, the entire cratering process and sequence of events took 20-60 seconds. Following formation of the central uplift, more fracturing due to weathering will most likely occur as part of the overall, long-term modification process (see Milam and Deane, 2005).

## 5 CRYPTO-CONTROVERSIES

Many decades passed between the first recognition of a disturbance at Flynn Creek and the acceptance of the fact that massive meteorites had not only impacted the Earth in the past, but that the scars of these impacts are in some cases still visible today. According to Lusk (1927: 580), "Several hypotheses were considered at the time the writer was investigating and mapping this peculiar feature." Although the figure obtained for the thickness of the Chattanooga Shale found in the Flynn Creek structure was questioned, Lusk (ibid.) found it was "… completely exposed in section up to ninety feet [27 meters] in single outcrops, and it crops out practically continuously in the bed of Flynn Creek and tributaries …"

Another suggestion was that there were post-Chattanooga local forces that were restricted just to this structure with the result being a "… subsidence, or perhaps uplift followed by subsidence which deformed the shale so that at this one place it is exposed in the bed of Flynn Creek …" (ibid.). Lusk noted that in contrast, though, the base of the Chattanooga Shale was only found high on the valley sides both upstream and down-stream from the Structure. In such a scenario, these same local forces would also have to be responsible for the brecciation and high dips in the limestones that Luck observed. However, Lusk noted (ibid.) that the great thickness of the Chattanooga Shale and the lack of folding or brecciation of not only the Shale, but also the overlying beds, showed that the Chattanooga Shale and the later formations were not affected by these local forces. In addition, where the contacts of the Shale and breccia were observed, there were irregular erosion surfaces which were not parallel to that of the Chattanooga Shale or to the formation overlying it.

Lusk (ibid.) pointed out that "Bucher has described a circular area of intense folding and faulting … [and referred to it as a] crypto-volcanic … [structure]. However … the conglomeratic nature of the breccia and the absence of veins or dikes of possible igneous origin discourages the view that sub-surface vulcanism may have been the cause …" (ibid.). After considering all of the observed facts discussed above, Lusk (1927: 580) concluded:

> It is clear that at the inception of the deposition of the Chattanooga shale there must have been a depression with an irregular outline and an uneven floor. In the bottom of the depression and along the walls there were considerable thicknesses of slightly rounded fragments of limestone derived in part from the Ordovician limestones still represented in the surrounding area. Possibly there were also fragments from still higher strata, now eroded and entirely removed except at this one place where they are thus represented.
>
> A depression of this sort could be formed by the collapse of the roof of an irregular branching cavern or series of caverns. The fragmentation induced by collapse, together with the slope wash of talus towards the lines of collapse, would form the conglomerate-breccia.
>
> The Chattanooga shale was deposited in this depression when the general area was receiving carbonaceous mud in the latest Devonian or earliest Mississippian time. With the loading of the region by later sediments, the mud was compacted by the squeezing out of its fluids… The average altitude of the top of the shale is generally less in this area because in so thick a body of shale the total amount of compacting was proportionally greater.

Lusk (ibid.) concluded that the existence of a sinkhole some 60 meters deep could only be possible, though, if this region was at least 60 meters above sea-level for a long enough period during pre-Chattanooga time for a sinkhole of this depth to form.

Although Lusk (1927) considered the Flynn Creek structure to be a pre-Chattanooga sinkhole with a depth of some 60 meters resulting from a cavern collapse, Wilson and Born (1936: 832-833) disagreed with the cause and the depth:

> The only possible means of excavation by agents of erosion is by sinkhole solution, as the topographic basin was completely closed, having no outlet. There are no evidences of sinkhole solution in the pre-Chattanooga rocks of this region; and, also, it is believed that elevation above sea-level of central Tennessee during the Maysville-Chattanooga interval was never sufficiently high to permit the erosion of a 300 foot [90 meters] sinkhole, of which this would be the only known example.

They concluded (Wilson and Born, 1936: 831) that although Lusk correctly eliminated any post-Chattanooga volcanic origin, he was not correct in eliminating a pre-Chattanooga volcanic origin on the basis of the conglomeratic nature of the breccia and the absence of veins or dikes of igneous origin:

> The present writers did not find sufficient evidence of rounding, or "conglomeratic nature," of the breccia, and hence believe that all breccia but that designated as talus breccia resulted from the mechanical fragmentation of

> limestone and subsequent cementation. Also, they cannot accept the absence of veins or dikes of igneous origin at the surface as sufficient to eliminate a possible volcanic origin.

Wilson and Born (1936: 815-816), in fact, agreed with R.S. Bassler (1932) and stated that for Flynn Creek, "All the data accumulated indicate a crypto-volcanic origin of the structure." Boon and Albritton (1936: 7) concisely describe 'cryptovolcanic structures' as "… subcircular, complex, domical structures characterized by intense deformation and brecciation within an area of a few square miles." Bucher (1936: 1075-1076) describes cryptovolcanic structures in great detail as a natural series of disturbances which mark the beginning or the attempted beginning of volcanism in a region and which may be classified as follows:

> 1. Disturbances produced by the explosive release of gases under high tension, without the extrusion of any original magmatic material, at points where there had previously been no volcanic activity ("abortive volcanism"): Cryptovolcanic structures.
> (a) The explosion, too deep-seated, too weak, or too-unconcentrated ("muffled"), results merely in the more or less circular dome and ring structure …
> (b) The explosion, shallow and strong enough, blows out a shallow more or less circular explosion basin filled with a jumble of distorted blocks and surrounded by a zone of materials blown or pushed out from it …
> 2. Features produced largely by the explosive release of gases under high tension, with magmatic materials more or less subordinate to fragments of the overlying rocks, at points where there had previously been no volcanic activity ("embryonic volcanism"): "Funnels," "chimneys," "pipes" filled with volcanic breccias or tuffs …
>
> The explanation of the cryptovolcanic structures here presupposes that in plateau regions seemingly devoid of volcanic activity magma is at times working its way locally upward through the crystalline basement complex into the sediments above, without actually breaking through. The few examples in which erosion has cut low enough to expose such places are of unusual interest.

Roddy (1966c: 17) notes that Bucher (1936), although greatly interested in cryptovolcanic structures, apparently never visited Flynn Creek even though he was aware of the site and it was only recently that Wilson and Born "… proved the cryptovolcanic nature of …[the] structure …" In this context, Wilson and Born (1936: 832) conclude that

> … the closed, topographic depression on the pre-Chattanooga erosion surface was a crater formed by explosion … [and the Flynn Creek disturbance is] of volcanic origin and should be classed in the general group of crypto-volcanic structures … It is believed that (1) the small circular central uplift of approximately 500 feet [150 meters], (2) the intense brecciation of limestone, (3) the intrusive character of the breccia, and (4) the shattering and jumbling of limestone blocks could have been caused only by a relatively rapid, deep-seated volcanic explosion accompanied by a gas explosion near the surface. The features are diagnostic of the examples of crypto-volcanic structures described by Bucher.

Wilson and Born (1936) point out that the Flynn Creek disturbance is not unique, and that there are other small, circular structures similar in shape, size, and depth in many locations on Earth. Suggested origins for these structures (after Wilson and Born, 1936: 828-829) include all of the following:

> (1) fall of a meteorite, with the resulting impact and explosion crater;
> (2) local collapse of a cavern roof;
> (3) salt domes;
> (4) local expansion by hydration of anhydrite;
> (5) natural gas explosion; and
> (6) crypto-volcanic (gas and steam) explosion.

Wilson and Born (1936: 828) considered each of these possible origins for the Flynn Creek Structure, taking into account the fact that any theory of origin for the structural features in the Flynn Creek area must explain the following: (1) a central uplift of approximately 500 feet [150 meters], bringing relatively old beds (Lowville) up to the level of younger beds (Leipers); (2) the intense brecciation of the Ordovician limestone, and the grinding, or pulverizing, of much of the limestone into 'rock flour'; (3) the striking ability of breccia to actually force its way into fractures in unbrecciated limestone in a way suggesting dike intrusion; (4) the shattering of the Ordovician limestone into large blocks, and the irregular jumbling of these blocks; (5) the dip away from the central uplift on the northern, eastern, and western flanks; (6) the dip into the central uplift on the southern flank, and the thrusting away from the center of uplift on that side; (7) a closed, irregular topographic depression with 300 feet [90 meters] relief on the pre-Chattanooga surface, the deformation being post-Leipers, pre-Chattanooga in age; (8) the abnormal thickness of the black shale (250 feet) [75 meters]; (9) the closed synclinal basin in the black shale and overlying Fort Payne chert, centered over what was originally an uplift (this is rather unusual in a region where anticlines and synclines were formed early in the Paleozoic, and all subsequent diastrophic movements rejuvenated these earlier structures as anticlines and synclines, respectively); (10) a well-developed magnetic high centered about 4 miles south-southwest of the disturbed area. (This magnetic high is believed to be the surface expression of the postulated buried plug of igneous material responsible for the Flynn Creek disturbance. The offset of 4

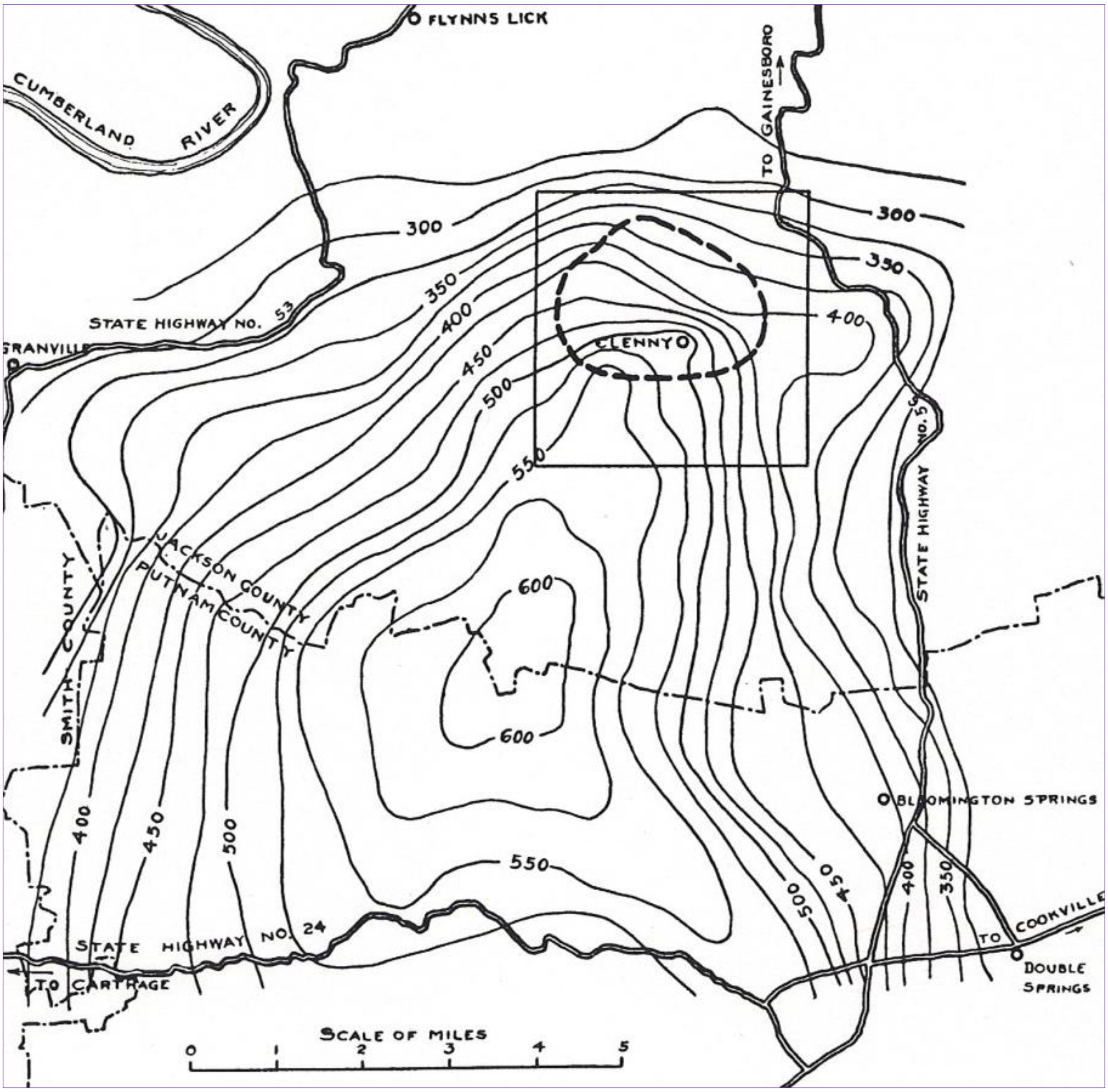


Figure 25: Isogammal map showing magnetic intensity in the Flynn Creek area (after Wilson and Born, 1936: 830).

miles [6.4 km] to the south-southwest is the result of the high-angle dip to the north of magnetic lines of force in the earth's surface.) Figure 25 is a map showing magnetic intensity found in and around the Flynn Creek structure, as well as the location of the crater in relation to the magnetic high mentioned above.

With all of the requirements as listed above in mind, Wilson and Born (1936: 829-830) ruled out most of the possible explanations for the Flynn Creek crater:

> The central uplift of 500 feet [150 meters] in the Flynn Creek area that raised the Lowville limestone up to the level of the Leipers formation definitely eliminates a meteorite crater or collapse of a cavern. The absence of any known salt or anhydrite deposits in this region makes an origin by salt-dome intrusion or by expansion of anhydrite unlikely. The stratigraphic horizon (Lower Ordovician) makes it improbable that sufficient natural gas occurred deep enough below the pre-Chattanooga surface to have blown out a crater. Further, although natural gas occurs at other localities in great quantities and under enormous pressure, it has never been known to have formed such a crater by natural explosion. Cryptovolcanic explosion is the only possible origin among those listed that cannot be readily eliminated.

In hindsight, it is interesting that Wilson and Born so confidently ruled out a possible Flynn Creek meteorite impact based on the existence of a central uplift.

Wilson and Born (1936: 832) believed that "… this pre-Chattanooga topographic basin was an actual crater formed by explosion …" but they make special note of the fact that the Flynn Creek crater coincided in position with the central uplift. They also point out that "… rocks were forced upward as much as 500 feet [150 meters], giving an excess of material near the surface that must be accounted for …" (ibid.). As a possible explanation for cryptovolcanic structures such as Flynn Creek that possess central uplifts, Wilson and Born suggested: "… it is probable that a shallow saucer-shaped explosion funnel was first formed and that the central hill was formed a short time later by a second weaker explosion …" (ibid.).

Taking into account Bucher's description of cryptovolcanic structures, Wilson and Born (1936: 835) summarize the order of events they believe took place at Flynn Creek:

> 1. Deposition of the Lowville, Hermitage, Catheys, Cannon, and Leipers formations. If younger Ordovician or Silurian formations were deposited, they were removed by pre-explosion erosion, as the Leipers is the youngest formation involved in the explosion.
> 2. A volcanic explosion, blowing out a crater 300 feet [90 meters] deep and 2 miles [3.2 km] in diameter, and piling up limestone debris in the vicinity of the crater at some time between the deposition of the Leipers and Chattanooga formations [see Figure 15A]. This explosion preceded the deposition of the Chattanooga shale sufficiently to permit removal of all blocks of limestone around the crater [see Figure 15B].
> 3. Accumulation of talus in the deeper part of the crater, resulting from gravity rolling and slope wash of rock debris into the crater [see Figure 15B].
> 4. Formation of a fresh-water, ring-shaped lake that occupied the crater and surrounded the central hill leaving it an island. In this lake was deposited as much as 12 feet [3.7 meters] of bedded breccia [see Figure 15B].
> 5. Transgression of Chattanooga sea, which filled the crater with 250-300 feet [75-90 meters] of black mud and covered the surrounding region with 20 feet [6 meters] of similar sediments [see Figure 15C].
> 6. Deposition of Fort Payne chert.
> 7. Subsequent local synclinal sagging caused by compaction of the underlying Chattanooga shale and by subsurface readjustment following explosion.

Boon and Albritton disagreed with this interpretation. They noted that prior to 1927 the Barringer 'Meteor Crater' in Arizona was the only known structure of that kind, and using this as an example of a confirmed impact crater they pointed out that "… in addition to creating ephemeral depressions, meteorites deform surficial rock layers when they strike the earth." (Boon and Albritton, 1936: 2). Therefore, a meteorite impact will produce a geological structure underlying the actual impact crater which may be preserved long after the crater itself has been destroyed by erosion. Boon and Albritton (ibid.) then posed an important question: "… where is the evidence for the falling of meteorites on the earth during geologic antiquity?" In seeking to answer this they suggested that certain structures "… previously described by geologists as 'cryptovolcanic' may be old meteorite scars …" (Boon and Albritton, 1936: 3). They then pointed out that adopting a meteorite hypothesis for the origin of structures like Flynn Creek

> … removes the embarrassing question as to the reason for lack of associated volcanic materials. Finally, it gives a tentative answer to astronomers who have long reasoned that large meteorites must have fallen in the geologic past … (Boon and Albritton, 1936: 9).

Boon and Albritton (1937: 56-57) also noted the striking similarity between certain American so-called 'cryptovolcanic structures' and those that would be produced by the impacts of giant meteorites (cf. Bucher, 1963). They pointed out that both the cryptovolcanic and meteoritic hypotheses postulate structural deformation through "… tremendous explosions …", but whereas the cryptovolcanic hypothesis assumes a sudden release of subterranean gases, it cannot account for two features which are explained by an explosive meteorite impact: (1) bilateral structural symmetry, and (2) the lack of volcanic material or other local signs of thermal activity (Boon and Albritton, 1937: 57-58). They reminded their colleagues that no volcanic material had been found in association with the Flynn Creek Structure.

Boon and Albritton (1937) also addressed one of the features that led Wilson and Born to conclude that Flynn Creek was a cryptovolcanic structure. They noted that Wilson and Born dismissed an explosive impact origin for the disturbance because "The central uplift of 500 feet [150 meters] in the Flynn Creek area that raised the Lowville limestone up to the level of the Leipers formation definitely eliminates a meteorite crater …" (Wilson and Born, 1936: 829). However, Boon and Albritton (1936: 7; their italics) stated that "… as a result of impact and explosion … *The central zone*, *completely damped by tension fractures produced by rebound*, *would become fixed as a structural dome.*" Furthermore, the argument put forth by Wilson and Born

> … overlooks the fact that elasticity of rocks would cause a strong rebound following intense compression produced by impact and explosion … [and] It is not unreasonable to suppose that the height of this rebound would be directly proportional to the diameter of the crater … [a ratio of around one to ten, and that] a rebound of this amplitude would be quantitatively adequate to explain the elevation of the rock in Flynn Creek … (Boon and Albritton, 1937: 58-59).

Dietz (1959: 498) believed that the most remarkable aspect of a cryptoexplosion structure is the central uplift, surrounded by a ring syncline which gives the structure a remarkable resemblance to that of a damped wave. A meteorite-impact structure therefore should have the following characteristics:

> (1) it would appear to have been instantaneously and completely formed;
> (2) it would show evidence of great shock by the presence of breccia, rock flour, etc. (this intense deformation would be centrally concentrated and would rapidly diminish outward and downward);
> (3) it might have extensive concentric and radial fracturing, dominated by high-angle normal faulting;
> (4) it would be 'geophysically empty' (especially magnetically), since there would be no intrusive body or salt plug or any large buried meteorite (it is physically naïve to expect the preservation of such a body; in fact, the preservation of any meteorite fragments in ancient scars seems unlikely);
> (5) the explosion crater would be essentially circular, regardless of the angle of impact, but the underlying rock deformation might display some asymmetry, since this is mainly a percussion feature; and
> (6) as explained above, the crater would tend to have the form of a damped wave. Cryptoexplosion structures seem generally to conform to these criteria.

Dietz (1959: 499) explained that according to the meteorite hypothesis, a central uplift may be formed by an elastic rebound of the highly-compressed target rock following an explosive impact, and it "… is likely that giant meteorites strike the earth's surface at hypervelocities, defining this term here to mean velocities in excess of the speed of sound in average rock, i.e., in excess of 5 km/sec …" (ibid.). The target rock would be subjected to an intense shock wave which would greatly compress a cylinder of rock beneath the meteorite. Following the impact explosion, "… compressed rocks might elastically recoil past the zero position into a dome. This dome would be damped or 'frozen' by the formation of tension cracks …" (ibid.).

In contrast, according to the cryptovolcanic hypothesis, the central uplift is a product of a 'muffled steam explosion', which would require an initial strong explosion followed by a second, muffled explosion. Further, Dietz (1959: 499) stated that this double explosion requirement appears to be reasonable when applied to an isolated case, but "… becomes suspect when it is necessary to apply the same unusual explosion sequence to several cryptoexplosion structures."

Boon and Albritton (1937: 59) also addressed the conclusion that Wilson and Born came to regarding the magnetometer survey of the Flynn Creek area. Wilson and Born (1936: 828) found "… a well-developed magnetic high centered about 4 miles [6.5 km] south-southwest of the disturbed area." Boon and Albritton (1937: 60) reasonably pointed out that magnetic anomalies are not uncommon in this region of the United States, as can be seen on any magnetic map, so this association may be coincidental. However, Wilson and Born (1936: 828) stated that "This magnetic high is believed to be the surface expression of the postulated buried plug of igneous material responsible for the Flynn Creek disturbance …", to which Boon and Albritton (1937: 60) responded:

> Granting this magnetic high reflects the presence of a plug, one wonders if the offset of four miles from the center of the disturbance is adequately explained by the 'high-angle dip to the north of magnetic lines of force in the earth's surface'.

Taking the magnetic dip from Boon and Albritton (ibid.) to be 68° in order to solve for the depth of the igneous plug and utilizing the complementary angle, gives tan 22° = 0.40. If the right angle is placed well below the magnetic high at the location of the supposed igneous plug and the side opposite to the complementary angle measured to be 4 miles [6.4 km], the distance from Flynn Creek to the magnetic high, then the adjacent side, the depth of the igneous plug, is given by adjacent = 4 miles **/** (0.40) = 10 miles, or 16 km. Boon and Albritton concluded that "It is difficult to see how a relatively small plug at this depth could greatly affect the magnetic field at the surface …" (ibid.). These researchers also pointed out that even if "Granting that the plug is approximately beneath the structure, it is not evident why the shattering of the roof above the intrusion did not allow ejection of igneous materials …" (ibid.). Boon and Albritton concluded: "With the exception of the anomalous magnetic high to the south of the structure, the meteoritic hypothesis seems adequate to account for the Flynn Creek disturbance …" (ibid.).

Dietz (1959: 496) noted that the term 'cryptovolcanic' comes from the fact that structures, such as Flynn Creek, are assumed to have formed by volcanic explosion, even though the evidence of volcanism is not obvious. The missing evidence includes features such as volcanic rocks, hydrothermal alteration, contact metamorphism, and mineralization (ibid.). Dietz agreed that the evidence indicated these structures were the result of an explosion, therefore, he preferred the term "… *cryptoexplosion structures to cryptovolcanic structures,* so as not to exclude the possibility of an extraterrestrial origin …" (Dietz, 1960: 1782; his italics). He also said that he favored the 'Boon-Albritton hypothesis':

> According to the meteorite-impact hypothesis, cryptoexplosion structures are explosion-per-

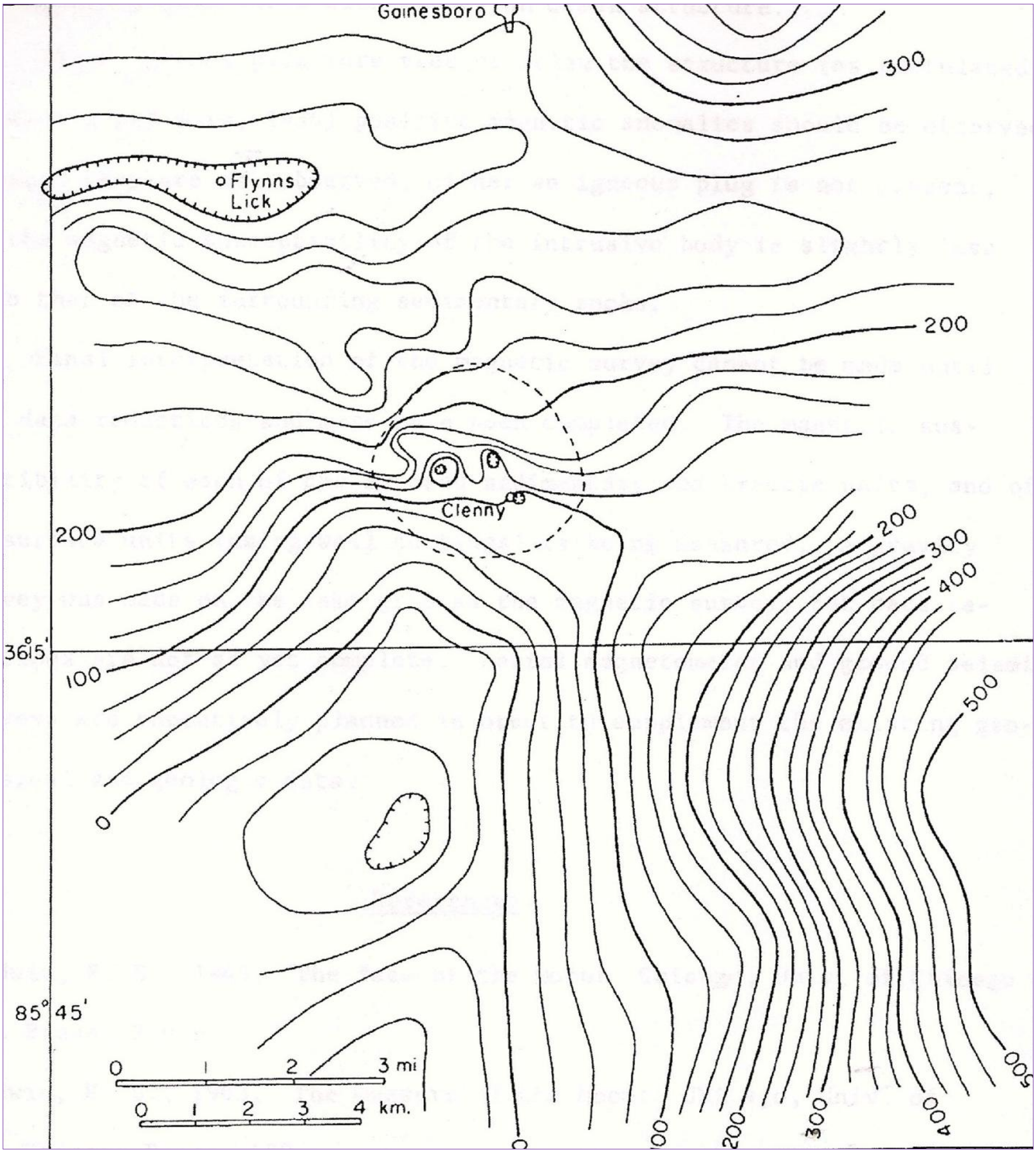


Figure 26: Total intensity magnetic anomalies in the Flynn Creek area (after Roddy, 1964: 176). The Flynn Creek Structure is shown by the dashed outline.

> cussion deformations produced by the hypervelocity and explosive impact of crater-forming meteorites of asteroidal dimensions – a concept developed by J.D. Boon and C.C. Albritton … [These] meteorite-impact scars … [are] ephemeral geologic features which are rapidly eroded away, but the jumbled mass of shattered rock which must extend for several thousand feet beneath an impact crater stands an excellent chance of geologic preservation. (Dietz: 1959: 497-498).

Dietz (1959) reported that in 1946, he and Wilson, in the faint hope of discovering small meteorite fragments, surveyed an outcrop of explosion breccia exposed in the central uplift of Flynn Creek with a mine detector, but no nickel-iron siderites were found (ibid.). He then pointed out that the chance of finding meteorite fragments was extremely small anyway considering the high percentage of stony meteorites, the rapid weathering of any meteorite, the probably almost complete vaporization of any impacting bolide, as well as the eroded nature of the structure itself.

Roddy (1963: 124) agreed with the conclusions reached by Dietz, and Boon and Albritton, and included the following comment in his 1963 paper on Flynn Creek:

> The presence of a core of unsorted, angular breccia, surrounded by a circular, depressed ring of strata; associated structurally complex beds containing low-angle faults, bedding plane faults and shatter cones; and both broad and detailed stratigraphic relations, can best be interpreted as having formed during or after meteorite impact.

The following year Roddy (1964: 171) again explained why he considered a cryptovolcanic origin for the Flynn Creek Structure to be unlikely:

> If a gas is introduced under high pressure from depth, failure of rocks near the surface by brittle fracture is to be expected. Although such a process is capable of explaining the origin of the breccia, it encounters difficulties in application to the rim structure which appears to have had the major stress component in a horizontal direction. Preliminary calculations of the dynamic conditions necessary to produce the rim folding indicate that … It is not likely that gas pressures could build up to the necessary level before fracturing the rocks and thereby releasing the pressure. Large meteorite impacts, on the other hand, can generate pressures that are adequate to cause the rim folding and as well cause brecciation.

Roddy's 1964 report on the Flynn Creek Structure included a magnetic field study in order to obtain information on the subsurface structure. The result of the magnetic measurements "… shows there is no large magnetic anomaly associated with the structure …" (Roddy, 1964: 175). Roddy noted the northeast-southwest trending magnetic trough extending across the area, as is shown in Figure 26. This map shows that a closed magnetic low around 6.5 kilometers southwest of the crater forms the lower end of the magnetic trough. Based on this map, Roddy (1964: 175, 177) made the following observations:

> The observed magnetic anomaly is opposite to the magnetic data reported by Wilson and Born (1936). The total magnetic intensities and trends of this anomaly suggest it is not directly associated with the Flynn Creek structure.
>
> If an igneous plug were present below the structure (as postulated by Wilson and Born, 1936) positive magnetic anomalies should be observed. Because they are not observed, either an igneous plug is not present, or the magnetic susceptibility of the intrusive body is slightly less than that of the surrounding sedimentary rocks.

Neither gravity nor magnetic studies indicated any large anomalies directly associated with the Flynn Creek structure (Roddy, 1966c). Figure 27 is a complete Bouguer anomaly map of the Flynn Creek area (after Roddy, 1968c: 305), which shows the location of the Flynn Creek crater in relation to the locations of the gravity stations utilized in the geophysical study.

Roddy (1964: 173) states that a search also was made at the Flynn Creek site for the high-pressure polymorphs coesite and stishovite. Seven rock samples, four from the shattered Knox Group beds in the center of the structure where the shatter cones were located and three more samples from the mixed breccia near the structure's eastern rim were collected for examination, but no trace of either coesite or stishovite was found (ibid.). Roddy (1965: 55) tellingly also pointed out that an analysis of the breccia mix and breccia fragments found in Flynn Creek indicated that there were no traces of either meteoritic or volcanic constituents in any of the ten samples studied. In addition, he reported that in six cores drilled across the Flynn Creek Structure, no volcanic or meteoritic materials were found (see *Astrogeologic Studies*, 1967: 29).

Miller (1974: 58) also reported that neither volcanic nor meteoritic material has ever been found at Flynn Creek and that "… studies show no magnetic anomalies which might be associated with buried meteoritic material." He concluded that "Comparison with other craters of known meteorite impact origin shows similarities, therefore, it is assumed that either a meteorite or comet impact formed this structure …" (ibid.). Milam and Deane (2007: 1) also examined Flynn Creek breccias, and their preliminary results suggest "… a lack of chondritic or iron meteoritic component remaining in the breccias or post-impact fill of the Flynn Creek impact structure …"

In his Ph.D. thesis Roddy (1966c: 152) addressed various origins suggested for the Flynn Creek structure. He rejected the possibility of a cavern collapse because rocks in the crater were raised far above their normal stratagraphic level. The possibility that Flynn Creek was a salt dome or the result of anhydrite expansion or a natural gas blowout was rejected, primarily because neither evaporites nor high pressure gas deposits had ever been found in central Tennessee, nor did Flynn Creek resemble the types of structures these would produce. He ruled out tectonic folding, stating that the type necessary to form a structure such as Flynn Creek was not present in the area. Hydraulic fracture by water was not considered to be likely because there was no known way for sufficient water pressure to build up; nor would this method produce a structure that resembled Flynn Creek. He also noted that "Mineralization related to hydrothermal or volcanic processes has not been recognized in the Flynn Creek area …" (Roddy, 1966c: 179), and "No thermal metamorphic effects have been noted either in the field or in petrographic studies …" (Roddy, 1966c: 183). He further pointed out that in the Flynn Creek rim strata, large-scale folding appears to have had the major stress compon-

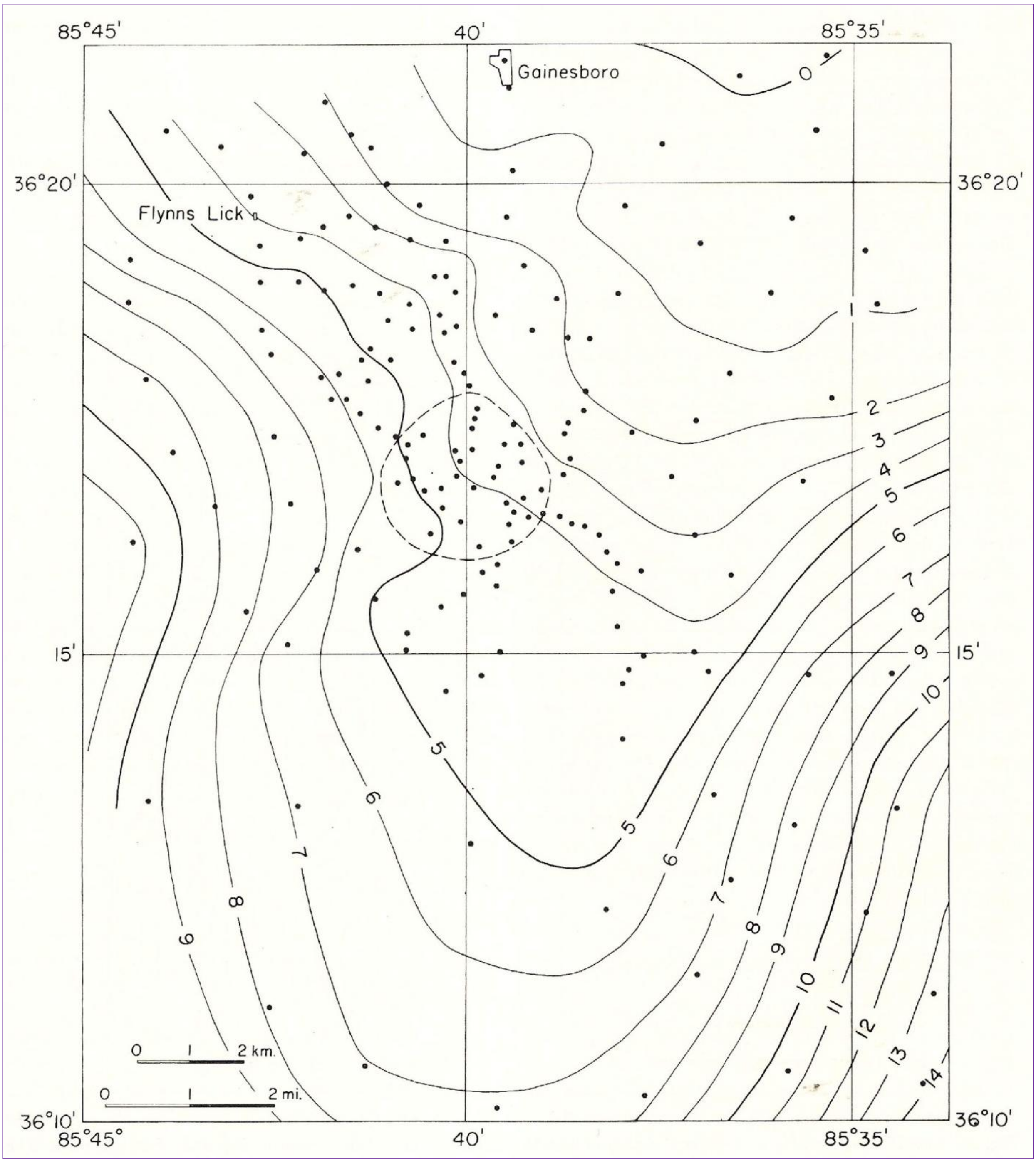


Figure 27: Complete Bouguer anomaly map of the Flynn Creek area (after Roddy, 1968b: 305). Gravity stations are indicated by dots. The Flynn Creek Structure is shown by the dashed outline.

ent in the horizontal direction. Roddy (1966c: 186) therefore concluded that the simple build up of gas pressure near the surface, in other words, a volcanic gas or steam explosion, would not explain the Flynn Creek rim folds having their major stress component in the horizontal direction.

In his 1967 *Astrogeologic Studies Annual Progress Report*, Roddy stated that core drilling gave evidence of "… a shallow lower boundary of the chaotic breccia lens … [and] a decrease in deformation in the rocks below the breccia lens …", which indicate an impact origin (*Astrogeologic Studies Annual Progress Report* (1967: 29). Roddy's overall conclusion as to the origin of the Flynn Creek structure is:

> The very shallow breccia lens, the absence of mineralization and volcanic or meteoritic materials, the types of rim deformation, and the central uplift are consistent with the impact of a low-density body, possibly a comet. The structural information from surface mapping, combined with the core-drilled data strongly suggests that the Flynn Creek crater was produced by the impact of a cometary body. (*Astrogeologic Studies Annual Progress Report*, 1967: 29-30).

Roddy (1968a) was of the opinion that the formation of a central peak in an impact crater was dependent on a low-density ($\rho \leq 1$ g/cm$^3$) body that volatized upon impact. He observed that

> … deformation at Flynn Creek, particularly the central uplift, has marked structural analogs with most of the other cryptoexplosion structures … [so] It is suggested that terrestrial (and lunar) craters with central peaks produced by structural uplift are formed by comet impact … (Roddy, 1968a: 272).

When Roddy was close to completing his Ph.D. research, and his Astrogeologic Studies reports on Flynn Creek for the United States Geological Survey, he made the following observation:

> The study at the Flynn Creek crater has now provided sufficient information to see close structural similarities with several of the different "shocked-produced" craters such as meteorite craters, nuclear craters and chemical explosion craters. Deformation in the rim strata, ejecta, and crater breccia are similar in these craters to that seen at the Flynn Creek crater. One of the chemical explosion craters has a pronounced central uplift and exhibits deformed rim strata with types of deformation nearly identical to that at the Flynn Creek crater. (Roddy, 1966c: 187).

Researchers at the Suffield Experimental Station in Alberta, Canada, detonated a 500 ton TNT charge on the ground surface in June 1964 which produced a chemical explosion crater with "… such pronounced structural similarities to the Flynn Creek crater that a visit was arranged for the author [Roddy] by the U.S. Geological Survey and the Canadian Government." (Roddy, 1966c: 201). The resulting crater was shallow, flat-floored, around 100 meters in diameter, and originally 6.5 meters deep with a 5.5 meter high central uplift (Roddy, 1968b). Material thrown out of the crater formed an ejecta blanket that was continuous to around 130 meters from the crater walls (ibid.). The following quotation is taken from Roddy's (196cb: 203, 205) Ph.D. thesis, and is based on his observations and on interviews with Suffield Experimental Station personnel, including Dr. G.H.S. Jones, who was in charge of the large-scale explosion experiment (see Schaber 2005: Appendix A, page 256):

> The explosive was stacked in a hemispherical shape measuring about 30 feet [9 meters] in diameter and 15 feet [4.5 meters] in height and was detonated at the center of the charge at ground level. The resulting crater was somewhat irregular in outline and measured from about 240 to 330 feet [75 to 100 meters] in diameter at the original ground level, and was about 15 feet [4.5 meters] in final depth after a later deposition occurred. The most striking departure from normal explosion craters included a large central uplift, a local depression or down-folding of parts of the rim, and large concentric and radial fractures …
>
> Tension fractures began to open and continued to open for several days after the event. Less than 5 minutes after the detonation, water started to flow into the crater from fractures in the central mound. Within ten minutes or less water was also flowing from fractures in the crater floor and continued until the crater contained a lake with the central mound forming an island. Large concentric fractures in the rim at a distance of about 210 feet [65 meters] and 260 feet [80 meters] from the crater wall also continued to open for several days after the detonation …
>
> A few feet from the original crater wall the slightly depressed rim rises abruptly into a tightly folded and distorted anticline … although the sand beds are unconsolidated, it appears that a thrust was developing during the folding of the anticline. The beds are highly deformed and mixed with other fragments in the crater wall and appear similar to the highly jumbled to brecciated rim strata in parts of the crater wall at Flynn Creek …
>
> Although the beds in the central mound are greatly disturbed by folding, shearing, brecciation and a great amount of thickening and thinning, a general pattern can still be seen … it is clear that the type of structural deformation bears a close similarity to parts of the central uplift at Flynn Creek.
>
> Information recording total ground movement was accurately determined by burying 1650 marker cans in ordered arrays and excavating these cans and surveying their position after the detonation. The down warping beyond the crater wall and the central uplift are confirmed by these markers.

Figure 28 is a schematic cross section of the 500-ton TNT Crater at the Suffield Experimental Station based on sketches Roddy (1966c: 204) made in the field. Affectionately known as the 'Snowball Explosion Crater', this "… has nearly identical structural deformation in all respects with the Flynn Creek crater … In fact, this particular surface burst produced nearly every structural feature found in the Flynn Creek crater …" (Roddy, 1966c: 207, 210), and "The three ratios of diameters vs. shear strengths, diameters vs. distances to concentric fracture zones, and diameter vs. depth to deepest horizons exposed in the central uplifts, are nearly identical for both the Flynn Creek crater and the 500-ton TNT crater …" (Roddy, 1968b: 318).

Figure 29 is a view of the 'Snowball Explosion Crater' one day after its formation. The photograph shows the central uplift as an island, in addition to the concentric fractures which formed around the crater. Figure 30 is another view of the crater on the same day from a different angle, allowing a better view of the terraced wall. Jones (1977) states that the terracing was

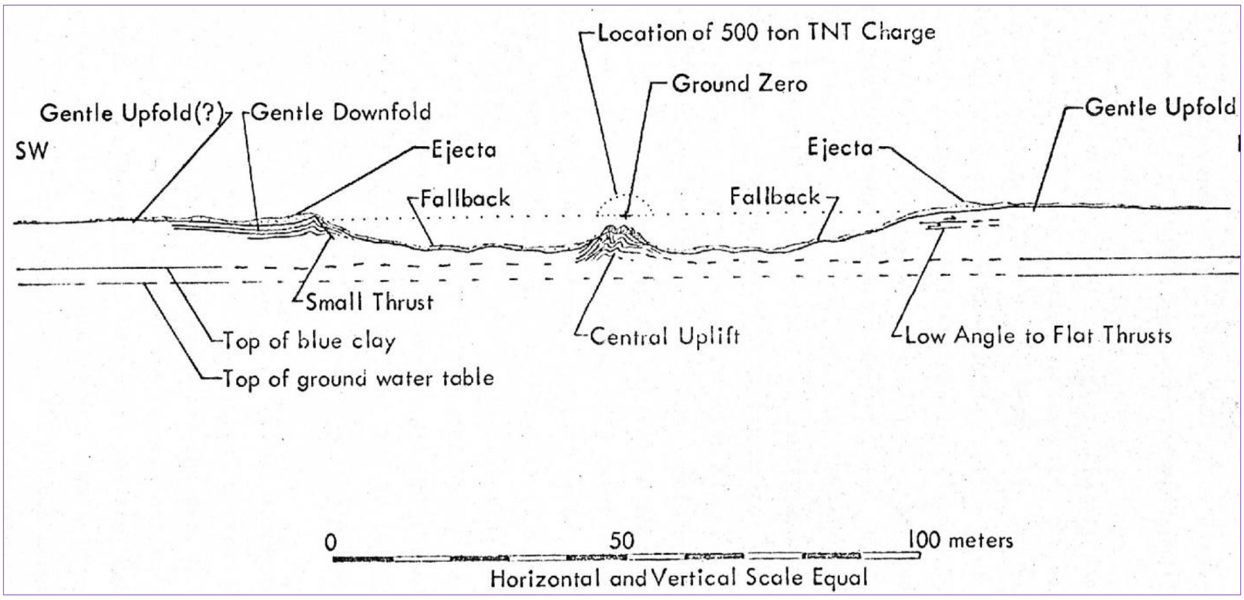
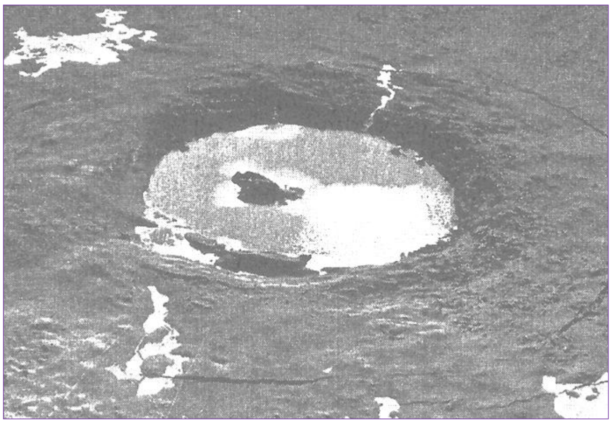


Figure 28: Schematic cross section of the 500-ton TNT Crater at the Suffield Experimental Station, Alberta, Canada (after Roddy, 1966c: 204).



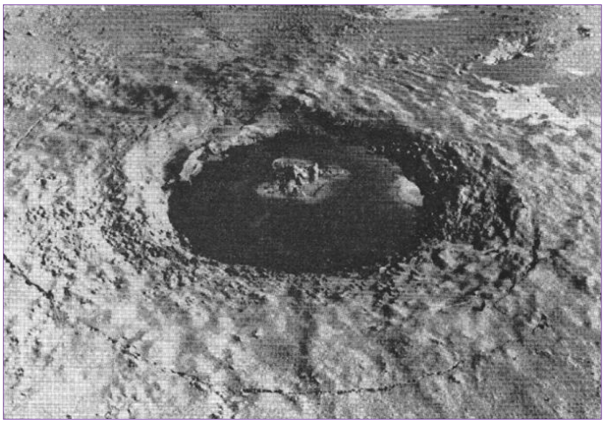


Figure 29 (left): An aerial view of the 500-ton TNT Crater one day after formation, showing concentric fractures and the central hill. The light-colored areas are sands deposited during water flow from the fractures and the lake in the crater was formed by water flow from fractures within the crater (after Jones, 1977: 164; cf. Roddy, 1968b: 314).

Figure 30 (right): Another aerial view of the 500-ton TNT Crater one day after formation, showing concentric fractures, the central hill, structural terraces on the crater walls and the irregular distribution of eject blocks (courtesy: Dr G.H.S. Jones; after Roddy, 1968b: 315).

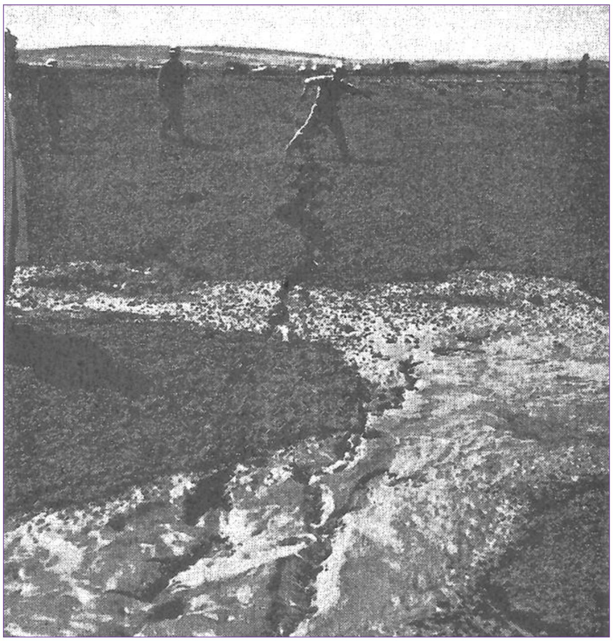


Figure 31 (left): A close-up view of one of the concentric fractures at the 500-ton TNT Crater, and the light-colored sand deposited during water flow from the fracture (after Roddy: 1968b: 317).

produced by late stage slumping. Figure 31 is a ground view of the crater showing a close up of the concentric fracture that developed around 110 meters from ground zero and the sand that was deposited when water flowed from the fractures. Jones (1977: 182) stated that "… the ejecta blanket consisted of a coherently overturned, stratigraphically inverted expression of the pre-existing stratigraphy." Jones also pointed out that "This overturning is clearly not due to sequential fall-out of the ejected material, but is a coherent roll-back of the strata …" (ibid.). Taking into consideration the close structural similarities between Flynn Creek and the 500-ton TNT crater, Roddy (1966c: 201) concluded that the Flynn Creek crater was "… also produced by

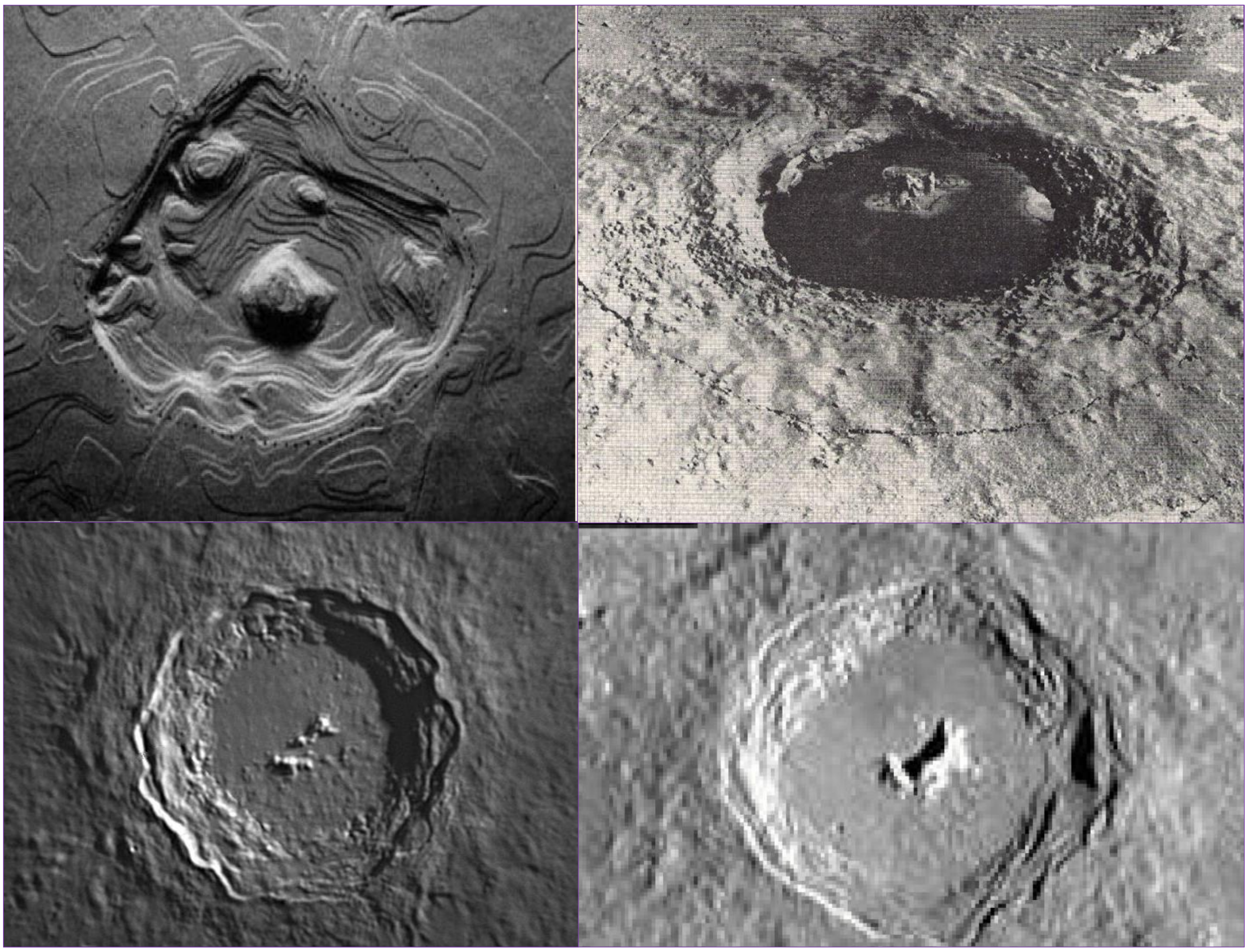


Figure 32: Crater comparisons. Left top: The Flynn Creek model (Roddy, 1977b: 206); right top: the 500-ton TNT ‘Snowball Crater’ (Roddy, 1977b: 206); bottom left: the lunar crater Copernicus (www.footootjes.nl/Astrophotography_Lunar); and bottom right: the lunar crater Pythagoras (European Space Agency).

a shock-mechanism, in this case an impact …”

The morphological and structural features of the Flynn Creek Crater, the 500-ton TNT ‘Snowball Crater’ and the lunar crater Copernicus were then compared by Roddy (1977a: 205). The terrestrial, the chemical explosion and the lunar crater all display a flat floor, central uplift region, and terraced walls, as does the lunar crater Pythagoras, which is shown in Figure 32 with the other three craters. The similarities are striking, and Roddy (1977b: 302) concluded that all of the terraces resulted from late-stage slumping. Figure 33 further explores their similarities, with geological cross-sections of the Flynn Creek crater, the ‘Snowball’ 500-ton TNT explosion crater and lastly, a “… schematic of the lunar crater, Copernicus, drawn with the actual lunar curvature …” (Roddy, 1977a: 209). Roddy (1977a: 193) pointed out another interesting similarity that these three craters share: estimating the immediate post-crater diameter, *D*, and depth, *d*, based on their rim crests, he found *D*/*d* to be 3830m/198m = 19 for Flynn Creek, 108.5m/7.5m = 15 for ‘Snowball’, and 79km/4km = 20 for Copernicus.

Roddy (1966c: 211-212) discussed the physical parameters of the Flynn Creek impactor as follows:

> Considering the shallow nature of the Flynn Creek crater, the presence of a central uplift, and the anticlinal folding in the rim, one would conclude that if an impact occurred, it probably was a “shallow impact.” That is to say the center of energy was near the surface … It appears possible that such conditions could be met by a comet impact in which the comet would not act as a dense body and would not penetrate as deeply as an iron meteorite.

Two years later Roddy (1968b: 318) stated that since the Flynn Creek crater is shallow and has a central uplift, this may indicate that a large amount of deformational energy was concentrated within 200 m of the surface. He was of the opinion that “Shallow penetration and large energies …” appear to be necessary in the formation of a central uplift (Roddy, 1968b: 319), and he pointed out that since a comet is primarily composed of frozen volatiles, a cometary impact would explain the absence of chemical, mineral, and magnetic anomalies (ibid.). Roddy (1968b: 320) then discussed various origin and impactor possibilities based on his study of the Flynn Creek crater:

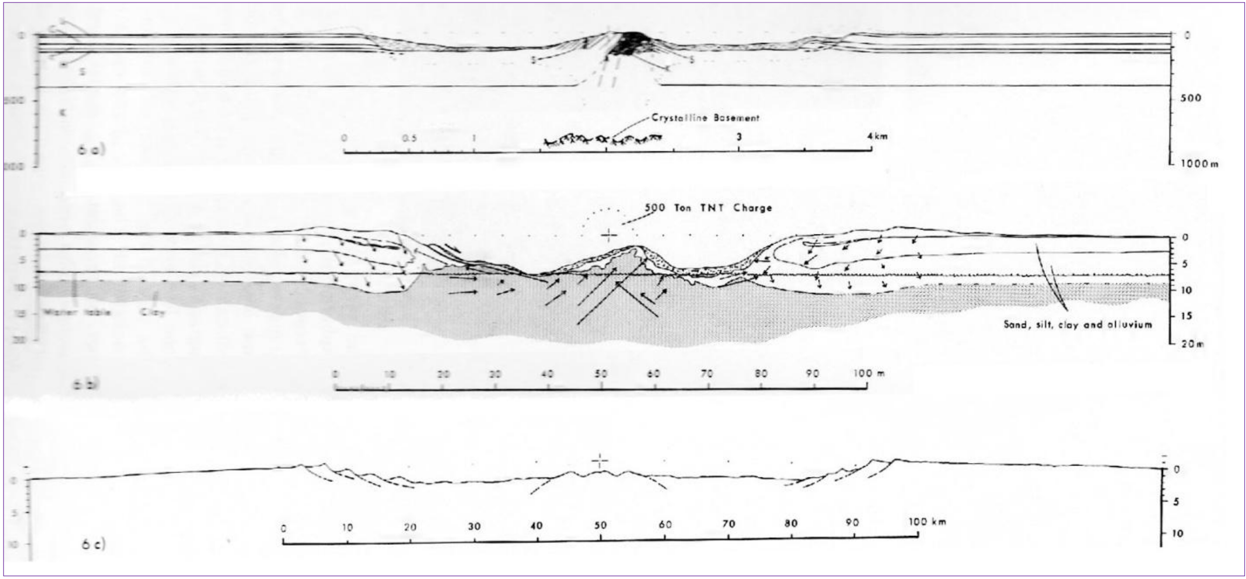


Figure 33: Geological cross-sections of the Flynn Creek, 'Snowball' and Copernicus craters (after Roddy, 1977a: 208-209).

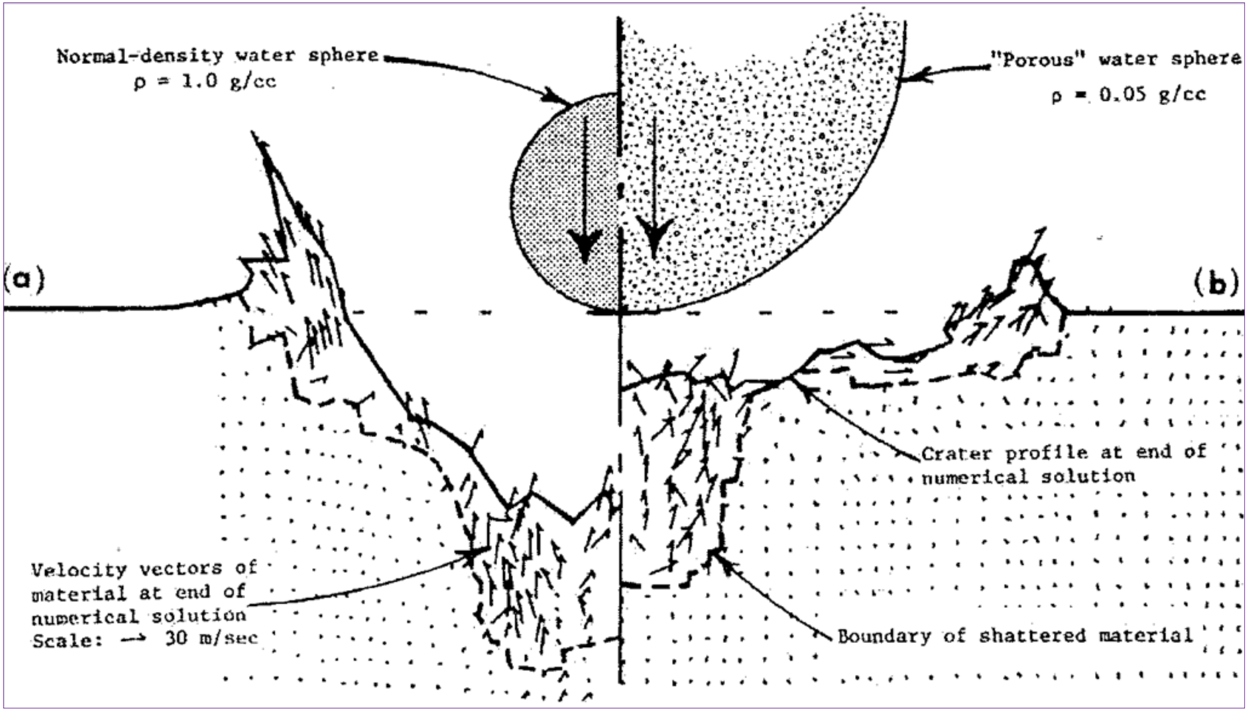


Figure 34: Calculated profiles of craters formed by ρ = 1.0 g/cc and ρ = 0.05 g/cc impactors (after Roddy et al., 1980: 945).

> If volcanic material had been initially present in the breccias, even in small amounts, it would be difficult to explain their present absence by weathering processes, since such materials have remained in similar environments for equal lengths of time. The same argument can be made for the silicate phases of a stony meteorite. Fragmental material from an iron meteorite, however, most probably would not survive the weathering processes that have operated since middle Paleozoic time. A cometary body, on the other hand, presumably would leave no mineralogical or chemical evidence of impact and is considered, at present, as the most likely type of impacting body.

Roddy (1966c: 213) calculated that if a comet was the impactor that produced the Flynn Creek crater, then it would have had a diameter of around 85 meters. Two years later, based on updated information, he (Roddy, 1968b) calculated that for a comet with a density of 1.0 g/cm$^3$ and an impact velocity of 15 km/sec to have formed the Flynn Creek crater, it would have had a diameter of around 250 meters. He also acknowledged, though, that a "… very high velocity meteorite … is a possible alternative to a comet impact …" (Roddy, 1968b: 319).

Later Roddy et al. (1980: 943) argued that low-density impactors such as cometary nuclei or carbonaceous chondrites would form flat-floored craters with central uplifts because "… the impacting bodies act as distributed energy sources that never produce deep transient cavities … [and that Flynn Creek] is quite shallow with an aspect ratio of crater diameter/crater depth ~ 1/35 …" In addition, excluding the central uplift, the depth of the breccia lens underlying the crater floor plus the depth to the bottom of the deformed strata underlying the breccia lens is around 250 meters below the pre-impact ground surface, which indicates a crater diameter/deformation depth ~1/14. Figure 34 shows "… calculation profiles of two impact craters at end of numerical solutions in graphite target …" (Roddy et al., 1980: 945); Figure 34a shows "… a water sphere ($\rho$ = 1.0 g/cm$^3$) impacting a graphitic solid at ~4 km/sec …" which results in a bowl-shaped crater (Roddy et al., 1980: 944); and Figure 34b shows a comparison impact produced by "… a *very low density* (0.05 g/cm$^3$) porous water sphere onto the same graphite …" also traveling at 4 km/sec, and producing "… a very broad, shallow, flat-floored crater with an aspect ratio of *only* ~1/14," (ibid.; his italics). Roddy (ibid.) pointed out that the theoretical calculations of such a cratering event indicated that a low-density impactor was at least capable of producing a flat, shallow crater, with the subsurface deformation limited to very shallow layers and to a small central section, as is seen at Flynn Creek.

Utilizing his own observations of the 'Snowball' Explosion Crater in addition to data provided by Jones (1977: 165), Roddy (1977b) estimated the energy of formation for Flynn Creek by scaling from explosion cratering data. It is interesting to note that high explosive chemical charges "… are twice as efficient as nuclear charges in excavating a crater … due, in part, to the nuclear release of other types of energy, such as radiation, that do not effectively contribute to cratering …" (Roddy: 1977b: 287). For cube-root scaling, where *E* is the energy of formation and *D* is the diameter of the resulting crater, the equation is:

$$D_1 = D_2\,(E_1/E_2)^{1/3} \qquad (2)$$

Roddy (ibid.) states, however, that "… as crater sizes increase into the tens-of-meters range new exponents have been found necessary …" and the best empirical fit for craters larger than a few tens of meters is the 1/3.4 root. In addition, utilizing volume and equivalent length factor scaling also gave "… an average energy of formation of approximately 4 × 10$^{24}$ ergs …" (ibid.). Roddy chose to scale from the 'Snowball' Explosion Crater data due to its great similarity in morphology and structural deformation to Flynn Creek (ibid.). He also determined that based on the fact that a "… simple comminution estimate of fragment crushing energies also gave 10$^{24}$ ergs … the value of 10$^{24}$ ergs is reasonable using scaling of dynamic explosion energies …" (ibid.). Assuming that the energy of formation as determined by explosion scaling is about equal to the kinetic energy of the impactor allows for some 'back-of-the-envelope' calculations.

For an impactor velocity, *V*, of 20 km/sec and for a kinetic energy, *KE*, of 4 × 10$^{24}$ ergs, which equals 4 × 10$^{17}$ Joules, the mass, *M*, of the impactor can be estimated by the following equation.

$$KE = (½)MV^2 \qquad (3)$$

This gives the mass of the impactor as 2.0 × 10$^9$ kg.

Roddy (1977b) believes that the Flynn Creek impactor was not an iron meteorite but more likely a stony meteorite or a cometary mass. Assuming the stony meteorite to be an ordinary chondrite, then the density, $\rho$, would have been ~3300 kg/m$^3$. The volume, *vol*, can then be found by rearranging the following equation:

$$\rho = M/vol \qquad (4)$$

The volume would then be 6.1 × 10$^5$ m$^3$. Since the volume of a sphere with radius, *r*, is $(4/3)\pi r^3$, the chondrite's diameter would be 105 meters.

An icy comet would have a density less than that of water, but for simplicity, a density, $\rho$, of 1000 kg/m$^3$ is assumed. Using Equation (4) gives a volume of 2 × 10$^6$ m$^3$, and thus a diameter of 156 meters. But Roddy (1977b: 292) reminds us that such low density bodies "… may not survive the atmospheric passage, as with Tunguska."

A second chemical explosion crater was produced at the Suffield Experimental Station with a 20-ton TNT detonation (see Roddy, 1966c). Figure 35 shows the alluvium displacement patterns below the 20-ton TNT hemispherical charge, as determined by marker cans that were buried in sand columns located on radial lines from ground zero. The post-shot positions of the marker cans shown in this figure "… were used to determine the direction and displacement of the ground …" (Roddy, 1966c: 206). The major horizontal component of displacement is easily seen. Another interesting find from the study of this chemical explosion crater is visible in this figure and is described by Roddy (1966c: 207):

> A significant result in the 20 ton TNT experiment is the reversal in displacement direction below ground zero … Possibly under higher energy explosions, such as the 500 ton experiment which has a central uplift, the reversal in particle displacement aids in the formation of an uplifted zone. It is not known as yet what specific conditions are necessary to form the central uplift, but it is now clear that shock mechanisms from a surface burst can produce such a structure.

Roddy (1968b: 316) reports that another con-

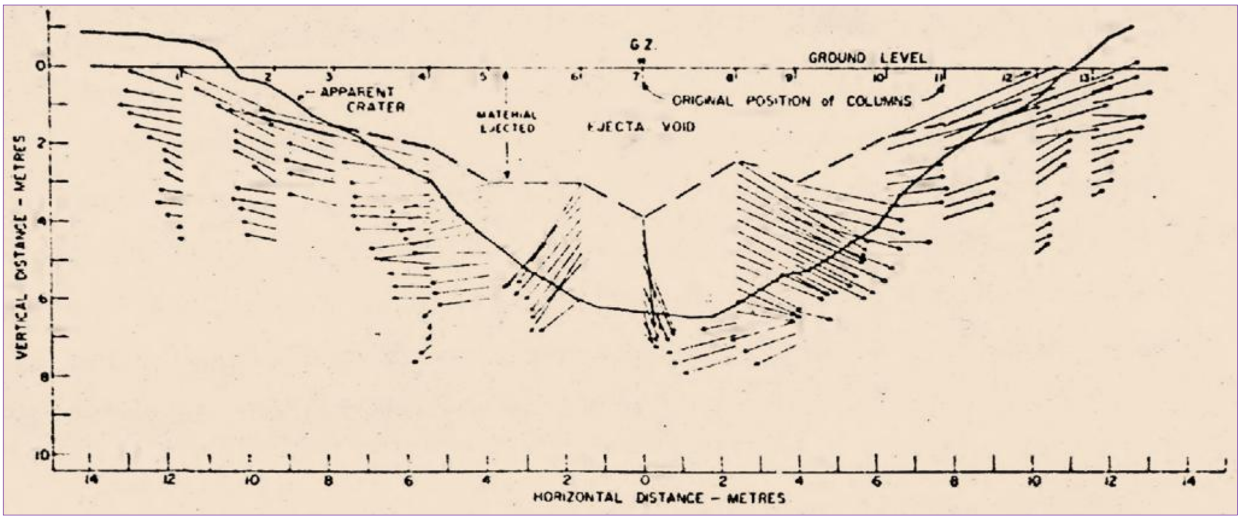


Figure 35: Alluvium displacement below the 20-ton TNT Crater at the Suffield Experimental Station, Alberta, Canada (after Roddy, 1966c: 206).

firmation in support of an impact origin for Flynn Creek came in July 1967 when "… the Defence Research Establishment, Suffield, Canada, detonated 100 tons of TNT in the shape of a sphere lying tangential to the ground surface …" thereby producing a third chemical explosion crater for comparison. The resulting crater was 30 meters across, ~5.5 meters deep and also included a "… large, well-developed central uplift …" (ibid.). Beds in the central uplift were raised 3 to 5 meters and formed a "… tightly folded and faulted dome …" (Roddy, 1968b: 317). The 100-ton TNT crater displayed "… low-angle thrust zones and high-angle faults and folds that are concentric to the crater walls … [plus] pronounced structural similarities to the Flynn Creek crater …" (Roddy, 1968b: 318).

In contrast, Roddy (ibid.) noted that "… structural comparisons of the Flynn Creek crater with volcanic explosion craters and their vents have demonstrated a notable lack of similarity." He also pointed out that drill core evidence indicated a shallow, lower boundary to the breccia and a decrease in deformation in the rocks below this breccia lens, both of which strongly indicated an origin involving a surface or near-surface explosion. He concluded (Roddy, 1968c: 179) that Flynn Creek was an impact crater which "… was formed during a single dynamic event in Middle or Late Devonian time …" based on the following evidence:

> Structural comparisons between Flynn Creek crater and volcanic explosion craters show little or no similarities in type of deformation … Structural comparisons between Flynn Creek crater and meteorite impact, nuclear-explosion, and chemical-explosion craters, however, show good agreement in nearly all types of deformation. Considerations of impact mechanics and similarities in structural deformation between shock-produced craters and Flynn Creek crater indicate an impact origin. (ibid.).

An impact origin can be confirmed with the identification of unambiguous shock features such as shatter cones. Dietz (1960: 1781) pointed out that a massive meteorite, too large to be appreciably decelerated by Earth's atmosphere, "… should on the average strike the earth with a velocity of about 15,000 meters per second." An impact of this magnitude would generate an intense, high-velocity shock wave that would spread out from the point of impact, 'ground zero', and engulf a great volume of rock before it decays into an elastic wave (ibid.).

He also pointed out that volcanic steam explosions only involved "… pressures of not more than several hundred atmospheres, so it is extremely doubtful that a shock wave can be developed in rock as a part of volcanic phenomena …" (ibid.). Dietz (1959: 500) noted that volcanic explosions involved the expansion of steam and other compressed gasses which was why they were not likely to be sufficiently violent to produce an intense enough shock wave in rock to form shatter cones. In fact, he stated that "Shatter cones seem to be completely absent from rocks which have definitely been subjected to volcanic explosion …" (ibid.). He reasoned then that "… if one can produce evidence that a large volume of rock has been intensely and naturally shocked, this would constitute definitive evidence of a meteorite impact …" Dietz (1960: 1781). Dietz stated that fortunately, rocks, when shocked, fracture into striated cup-and-cone structures called shatter cones, which often are easily identified in the field (ibid.).

Dietz (1960: 1783) noted that the Flynn Creek structure was studied by Wilson and Born, "… who [originally] considered that it was created by a cryptovolcanic explosion. Wilson now has revised this opinion, attributing the origin of the structure to a meteorite impact …"

This was in part due to the fact that he, Wilson and Stearns found shatter cones along a new road cutting near the Structure's center in November 1959 (Dietz, 1960: 1783; cf. Baldwin, 1963: 89;). Whereas the dolomite shatter cones from the Wells Creek site are described by Dietz (1968) as 'excellent', the limestone shatter cones from Flynn Creek were "… poorly developed … [but] the identification is unquestionable." (Dietz, 1960: 1783). Dietz (1968: 271) described the Flynn Creek shatter cones in more detail:

> I have always tended to consider the shatter cones at Flynn Creek to be of rather marginal quality, and not as fully confirmed as those I have collected elsewhere. However, Roddy (1963 and personal communication), who is mapping the structure in great detail, assures me that Flynn Creek is definitely shatter-coned in its center although there is a very limited outcrop area of shatter-coned rock.

Dietz also noted that the shatter cone orientation at Flynn Creek was upwards. This determination is important since "The orientation of shatter cones is useful for establishing the impact direction … In most cases the cones point … toward the locus of pulse source …" (Dietz, 1960: 1784). This upwards orientation of the shatter cone at Flynn Creek suggests impact percussion rather than volcanic forces which would have come from below (ibid.). Dietz (1963: 661) stated that "… shatter cones are truly indicative of intense transient shock loading far in excess of any known volcanic forces … a valid criterion for intense shock such as can be derived only from cosmic impact."

Later on, Roddy also found shatter cones in the vertical megabreccia beds of Knox strata in the Flynn Creek central uplift. Roddy (1966c: 65) described the shatter cones he found in the Flynn Creek structure:

> Where cones are present, they generally consist of many cones pointing in a common direction … The most common orientation for the cone axis is normal to the bedding, but many examples were found where a freshly fractured block had one set of cones pointing in one direction, while another set of cones pointed in the opposite direction. In some blocks sets of cones axes were seen to point in several different directions.

Milam et al. (2006: 1) state that "… the Knox Dolomite contains the only known shock indicators, shatter cones, at the Flynn Creek structure…", while after more than a decade of research, Roddy (1979a: 1032) finally added that "Excellent shatter cones also now have been recognized at a depth of ~406 m (below original pre-impact surface) in the drill cores in the same stratagraphic units exposed at the surface." The pre-impact depth of these rocks was around 420 meters below the original pre-impact ground level."

## 6 BILATERAL SYMMETRY

Boon and Albritton (1936: 9) stated that the meteorite hypothesis explained the folded rocks and evidence of violent explosions, such as breccias and shatter cones found in structures such as Flynn Creek, just as well as the cryptovolcanic hypothesis, however, the meteorite hypothesis "… offers a better explanation for the bilateral symmetry of many of the structures than does the volcanic hypothesis." They pointed out that "If these structures had been formed by a single upward- and outwardly- directed explosion, as postulated by the cryptovolcanic hypothesis, they would possess radial rather than bilateral symmetry …" (ibid.). Few, if any, meteorites strike the Earth at right angles; therefore, unless a falling meteorite does strike the Earth's surface vertically, a meteorite impact structure should not be expected to display radial symmetry (Boon and Albritton, 1936: 7). They pointed out that bilateral symmetry is significant in a meteorite impact structure since this feature would be indicative of "… an obliquely-impinging meteorite …" (Boon and Albritton, 1936: 8).

Boon and Albritton (ibid.) noted that meteorite crater rims "… commonly show opposed points of minimum and maximum uplift …" which is suggestive of oblique rather than vertical impact. Though an oblique impact would impart bilateral rather than radial symmetry to the underlying impact structure, the crater itself, which is the result of the upward and outward-moving explosion, should display radial symmetry. Boon and Albritton (1937: 59) stated that the bilateral symmetry noted at Flynn Creek, with only the beds to the south overturned, "… appears to be a cogent argument in favor of the meteoritic hypothesis, for it is difficult to imagine an upwardly-directed gas explosion causing overturning on one side of the crater only."

In 1967 Roddy (*Astrogeologic Studies*, 1967: 29) stated that the asymmetry he noted in the surface and subsurface deformation indicated that the Flynn Creek impactor traveled from southeast to northwest. More than a decade later Roddy (1979b) concluded from a second round of drilling that the basic shape of the Flynn Creek transient cavity was that of a very shallow, flat-floored crater with a deep and narrow central core of disruption dipping to the west, as shown in Figure 36. He determined that the depth of total disruption and uplift in the center of the crater extended to around 450 meters and then continued downward with decreasing deformation to around 770 meters, again dipping to the west. "The implication is that the impacting body has an oblique angle of entry tentatively interpreted here to be from the east or southeast …" (Roddy, 1979b: 2531). Roddy (ibid.) then pointed out that the "… per-

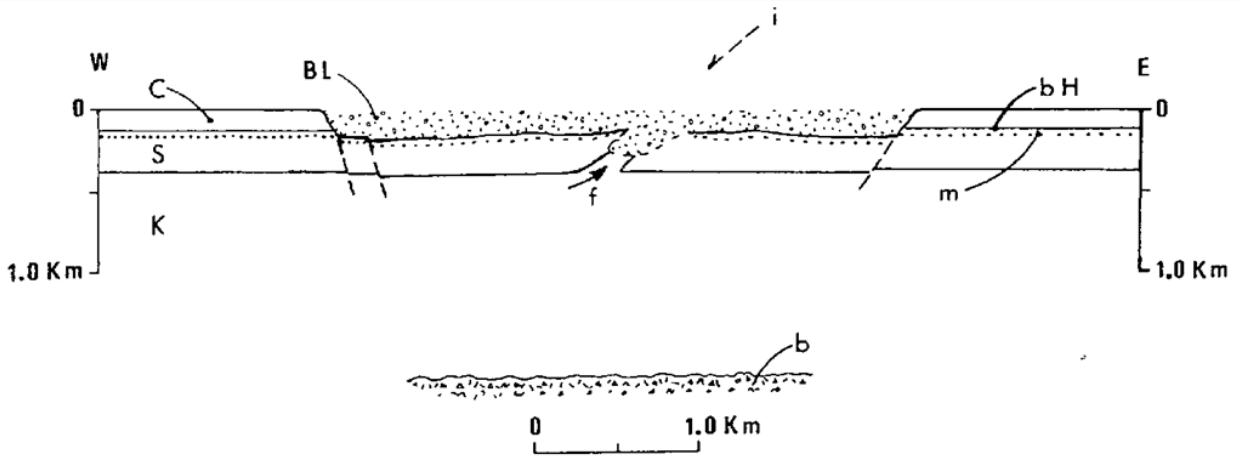


Figure 36: Schematic cross-section showing the Flynn Creek cratered region, where 'i' is the inferred direction of the impactor. The 'b' region immediately above the scale is the crystalline basement beneath the crater; there is no vertical exaggeration (after Roddy, 1979b: 2531).

vasive westerly to northwesterly dips [of the exposed rocks in the central peak] … are consistent with such an entry angle …" Although other researchers agree that Flynn Creek's bilateral symmetry indicates an oblique impact, not all agree with Roddy on the azimuthal impact direction.

Gault and Wedekind (1978: 3856) state that "… bilateral symmetry around craters on planetary surfaces is a firm basis for recognizing structures formed from oblique trajectories and provides a basis for determining the direction of approach of the impacting object." Lunar craters which result from oblique impact consistently have depressed rims in the up-range direction (Forsberg et al., 1998). For craters that result from shallow impact angle, less than ~30º, "… the circularity of the rim, the crater profile, the distribution of the ejecta, and other characteristics are all affected by the lateral transfer of energy in the downrange direction …" (Milam and Perkins, 2012: 1). Obliquity of impact craters on Solar System bodies, including the Earth, can be determined by studying these characteristics, unless erosion or sedimentary processes have obscured or destroyed all of the evidence (ibid.). For example, the Flynn Creek ejecta pattern has been removed by erosion, and observation of the crater shape is difficult due to the fact that it is partially buried, however, "… topographic and structural data have provided a means of assessing the impact trajectory, obliquity, and post-impact erosion associated with the Flynn Creek impact event …" (ibid.).

Data from the Milam and Perkins' study (ibid.) suggest that the Flynn Creek impact occurred at a shallow (5°) impact angle along an approximately NW to SE present-day trajectory (uprange: ~310-323°; downrange 130-143°). This conclusion is supported by additional asymmetrical and morphological relationships that exist around the crater rim. The largest dip angles, around +30°, occur in the SE crater rim between 135-185°, "… suggesting the downrange portion of the trajectory lies in the present-day SE …" (Milam and Perkins, 2012: 2), and this section of the rim displays the greatest uplift, between 110° to 130°, "… which is consistent with a NW to SE impact …" (ibid.).

An interesting observation is that the Dycus Disturbance, a suspected Tennessee impact site, is only 13 km north-west of Flynn Creek, so close that they may be the result of a double impact (Stratford, 2004). If the Flynn Creek impactor broke into two major, but unequal, parts during its transit through the Earth's atmosphere, then the smaller fragment would be expected to fall short of the larger section, which could explain the close proximity of the small Dycus Disturbance. Of particular interest is the fact that Herrick and Forsberg-Taylor (2003, 1576) point out that "… at the lowest impact angles, the planform becomes elliptical …", and Dycus is oval-shaped (Deane et al., 2006: 2), indicating another possible oblique impact.

On the other hand, the oblong lunar crater Messier is thought by Gault and Wedekind to be the result of a grazing impact event (with θ <5°). Gault and Wedekind (1978: 3843) state that "Impacts at shallow incidence, which are not uncommon, lead to ricochet of the impacting object … at velocities only slightly reduced from the pre-impact value." In addition, ricochet may occur with the projectile remaining intact, rupturing into several large fragments, or shattering into a myriad of small fragments. They note (Gault and Wedekind, 1978: 3873) that "Lunar crater Messier is, of course, the prime type-example of an oblique impact along a grazing trajectory …" Herrick and Forsberg-Taylor (2003, 1556) support this interpretation: "Messier A appears to have resulted from a ricochet downrange from Messier, the original point of impact …" The shape of Messier A resembles shapes formed by experimental impacts with impact angles of 5° (Herrick and Forsberg-Taylor, 2003, 1557). Messier and Messier A, shown in Figure Figure 37 with their ejecta patterns, may be the result of a single impactor first creating Messier and its butterfly ejecta pattern and then ricocheting to form Messier A with its forward ejecta rays.

Herrick and Forsberg-Taylor (2003: 1557-1558) noted that "Messier A also bears some resemblance to experimental clustered impacts … [which] are more shallow than similar diameter craters resulting from a single impactor …" Interestingly, Roddy et al. (1980) considered Flynn Creek to be a shallow impact crater. Of course, Flynn Creek and Dycus could simply be the result of a double impact. "Doublet craters are a product of binary asteroid impact, and the amount of asteroid separation determines whether overlapping or separated craters form … [around] 16% of the near-Earth asteroid population are doublets …" (Herrick and Forsberg-Taylor, 2003: 1558; cf. Bottke and Melosh, 1996).

## 7 MARINE IMPACT

At Flynn Creek, the bedded breccias and dolomite "… were apparently deposited in a marine environment, because conodonts of early Late Devonian age are present in these rocks." (Roddy, 1966c: 219). A decade later, Roddy (1976: 121-122) describes the process as follows:

> Erosion began to modify the crater immediately after its formation, washing part of the debris back into the crater and lowering the regional surface of the order of a few meters. A thin deposit of marine sedimentary breccia overlain by a thin marine dolomite of early Late Devonian age form the first crater deposits. Deposition remained continuous during this time until the crater was filled by the black muds of the early Late Devonian Chattanooga sea.

Therefore, sometime during the early Late Devonian, Chattanooga Shale filled the crater and prevented further erosion. After that "… the Flynn Creek area remained under water through at least Early Mississippian time, when the Fort Payne sediments were deposited." (Roddy, 1976: 123).

At the Lunar and Planetary Institute's Tenth Conference, Roddy (1979b: 2519) stated that the Flynn Creek Crater was formed "… by a hypervelocity impact event in a shallow-water coastal plain environment." He continued by describing the crater as being around 3.8 km in diameter and 200 meters deep, which initially had "… a broad flat floor, a large central peak, locally terraced walls, and an ejecta blanket …" (ibid.). Subsequently, he stated that Flynn Creek was the result of "… an impact event in a very shallow-water (~10 to 20m deep) coastal plain environment …" (Roddy et al., 1980: 943). The Flynn Creek impact has been described:

> The impact event occurred in a well-consolidated, flat-lying, sequence of limestone and dolomite overlying crystalline basement at a depth of about 1700 m. Field studies indicate that the impact occurred on a low, rolling coastal plain at the edge of the Chattanooga Sea, or actually, in its very shallow coastal waters which are tentatively interpreted from field relationships to have been on the order of only 10 to 12 m deep. (Roddy, 1979b: 2520).

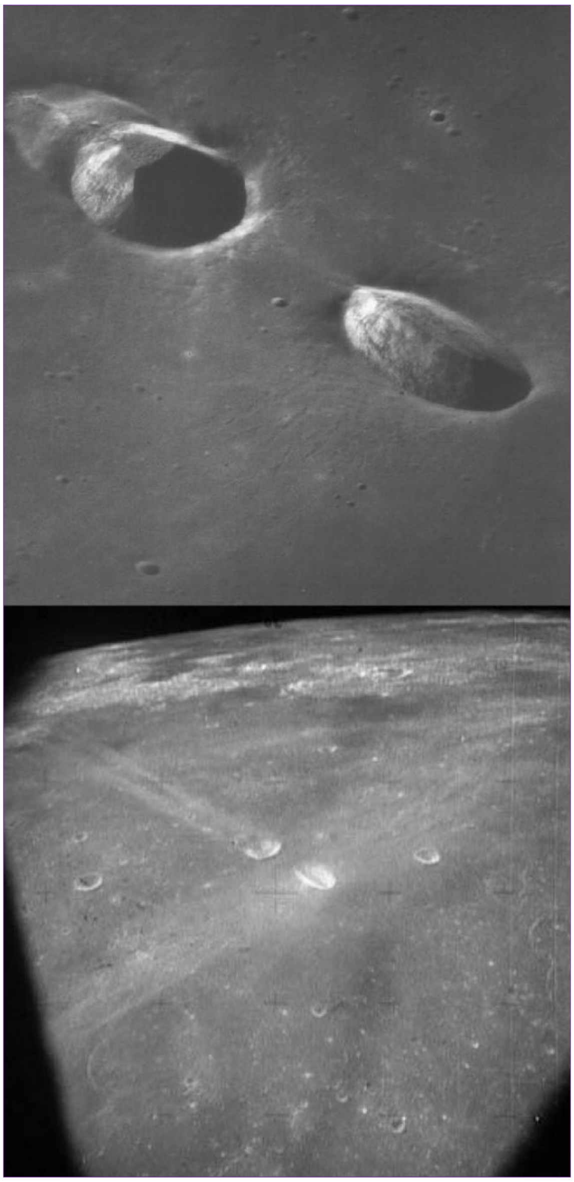


Figure 37: NASA Apollo 11 photographs showing the lunar craters Messier, on the right, and Messier A, on the left—with its two prominent downrange ejecta streaks (after Forsberg et al., 1998: 1).

Immediately upon formation of the crater "… very shallow subaqueous erosion apparently associated with the Chattanooga Sea …" began to wash much of the fallout and ejecta blanket from the crater walls and central uplift and deposit it over the crater floor (Roddy, 1979b: 2522). Any sub-aerial erosion that occurred, however, was limited. Around 10 meters of bedded breccias and bedded dolomite were deposited over the crater floor and lower walls, which was then directly overlain by the black muds of the wide-spread Chattanooga Sea of early Late Devonian age. These muds were later overlain by hundreds of meters of other sediments before regional uplift along the Nashville Dome allowed for enhanced erosion of the region to occur (Roddy, 1979b).

Roddy (1977b: 298) stated that even though the Flynn Creek impact most likely took place in a shallow sea about 10 m deep, "… it probably would not have seriously affected the penetration or cratering process of this impact event …" because such shallow water would simply be "… equivalent to a layer of rock with no effective tensile strength." If the Flynn Creek impactor was around 100 meters in diameter and the water depth only 10 meters, then the primary effect of such a thin layer of water would simply be the production of steam and water vapor that dispersed over such a large area that "… probably did not seriously augment the cooling or deceleration of high speed ejecta …" (ibid.). According to Dypvik and Jansa (2003: 332), though, the steam expels more ejecta than would be generated by a dry impact.

After crater formation, the rim "… was apparently above water for a period of time long enough to develop talus deposits, but was breached shortly thereafter …" (Roddy, 1977b: 278). When the crater rim was breached, the deposition abruptly changed to the black, silty, muds of the shallow Chattanooga Sea which eventually filled the crater (ibid.), and "The entire crater and central uplift were quickly protected from any significant erosion by the rapid deposition and complete filing by marine sediments of early Late Devonian age …" (Roddy, 1977b: 279). Meanwhile, the limited erosional lowering of the rim "… indicate[s] that the crater … is very close to its original gross morphologic form except for the erosion of the ejecta blanket …" (Roddy, 1977b: 283).

This indicates that whereas most terrestrial impact craters have been subject to long periods of erosion and only their basement structures have survived, Flynn Creek was basically cocooned in mud, and thus its form was preserved. As such, it is one of the few ancient terrestrial impact structures that can be reasonably referred to today as a 'crater'. Mitchum (1951: 29) notes that one reason the Flynn Creek Structure is especially interesting is that the actual explosion crater has been preserved.

Roddy (1977b: 283) points out that if the Flynn Creek event occurred in a standing body of water, "… and the waters were moderately deep, then the impact would involve a two-layered target with the attendant terminal, but transient, result of one layer being fluid." On the other hand, if the water was shallow, only a few meters deep, then its effect would be negligible (ibid.). Roddy (1977b: 283-286; his italics) discussed in detail his interpretation of the impact event environment:

> The thick mass of very crudely lineated breccia locally overlapping the crater walls and terrace blocks strongly suggests the inner part of the ejecta blanket was redeposited into the crater very irregularly as a chaotic mass on top of the breccia lens …
>
> Another result of the erosional processes leads to the deposition of a variety of types of sediment in the crater and on the rim grabens. The important yet puzzling aspect of these rocks, however, is that those on the crater floor are definitely of marine origin whereas those on the higher rim graben do not appear related to marine processes. No lake or playa beds are present in either exposed sections or in drill cores anywhere on the crater floor. Instead, the first crater floor deposits are related to marine waters clearly indicating that a sea was in the area. Isolated subareal-like talus deposits on the rim graben, however, imply that the sea was quite *shallow* and *below* the uplifted rim area …
>
> The bedded dolomitic breccia and bedded dolomitic are thickest on the lowest parts of the crater floor and thin out entirely part way up the crater walls. The bedded dolomite, up to 3 m thick locally, is the last unit to be deposited in the crater that includes very fine fragments of the underlying breccia and fragments from the upper Leipers rocks. The important point regarding these last two units is that they both contain *marine* fossil fragments of early Late Devonian age … and consequently were deposited with *access* to the marine sea water in the area. A second critical point is that the specific marine fossil fragments in the bedded dolomite breccia and bedded dolomite are identical to those in the basal Chattanooga Shale Formation which has an extremely wide-spread distribution over several states and lies in conformable contact immediately on top of the bedded dolomite. A third critical point is the distinct change in lithology from the dolomite to the black Chattanooga Shale sediments, a transition that takes place vertically and very abruptly over a centimeter or two. Obviously the extremely wide-spread black muds of the Chattanooga Sea were not introduced immediately onto the floor of the crater since other deposits have been identified, yet the same marine conodonts in the basal Chattanooga *were* included, at least, in the earliest bedded dolomitic breccia on the crater floor. This suggests the waters of the Chattanooga Sea were in the immediate area at the time of impact but were not deep enough to flow directly over the crater rim and ejecta blanket. Instead, it appears that the marine waters carrying the microscopic conodonts fragments flowed or were initially filtered through the

> ejecta blanket and rim into the crater at a reduced rate such that the coarser black silty muds were initially deposited outside the crater … Immediately thereafter, the black silty muds of the Chattanooga Shale appear to have spilled over the crater rim to eventually fill the crater over the next few million years. The conclusion one draws is that of a shallow sea with abundant black silty muds … that did not immediately flood the crater, perhaps because of the barrier of the uplifted rim and the 100 m or so thickness of ejecta blanket. After a limited period of probable wave and other types of erosion, the ejecta was removed and the black silty muds were rapidly deposited over the crater floor, walls, and rim …
>
> Another line of evidence regarding the *depth* of the Chattanooga Sea at the time of impact lies in an explanation of *talus-like* deposits at the base of a cliff formed by the rim graben. This ancient talus has the character and composition of subareal deposits with no apparent marine influence of its matrix chemistry and no black, silty, mud additions. Since the presence of the Chattanooga Sea in the immediate area has been established, it would appear that the evidence of no direct communication of the talus with the sea indicates that it was formed above the local water level … This shallow sea depth would still allow local wave action to remove the ejecta, flow over the stripped rim, and deposit marine sediments on the crater floor. In any case, the overall impression remains that of a very shallow sea, a few meters or so in depth, in this area *at* the time of impact …
>
> The actual impact event may have occurred *in* these very shallow waters, but the depths were apparently only on the order of approximately 10 m.

Schieber and Over (2005: 67) also agree that evidence indicates the regional water depth at the time of the Flynn Creek event was around 10 meters or even less, and furthermore, due to a general sea level rise, gradually increased after impact. Evidence from the crater fill shows that repeated regressions and transgressions occurred during the time of this gradual rise in the sea level (ibid.).

Acceptance of Flynn Creek's marine origin was noted by Shoemaker (1983: 484) when he stated that the Flynn Creek crater was formed in the Devonian on the floor of a shallow epicontinental sea and then buried beneath marine sediments. According to Milam and Perkins (2012: 1), Flynn Creek "… formed in a marine environment with a seabed of Middle Ordovician carbonates …" and was rapidly buried by Late Devonian and younger sediments. Redistribution of the ejecta due to water column collapse following impact and erosion from resurge removed most of the ejecta from the crater rim. The crater fill and remaining target rock in the crater rim, floor, and central uplift has only recently been exposed by stream erosion (ibid.).

Studies of the Flynn Creek crater stratigraphy and sedimentary features by Schieber and Roddy (2000: 451) suggest the following sequence of events in the formation of the Flynn Creek Crater:

> (1) impact in shallow water during the lower Frasnian (381-382m.y.); (2) formation of the basal chaotic breccia as a fall-back deposit; (3) deposition of graded breccia as displaced water rushed back into the crater; (4) while the sea was still shallow, ejected material was washed back into the crater by storm-induced waves and currents; (5) with rising sea level, black shales were able to accumulate, first in the crater, and later also outside the crater.

Four years later, Schieber and Over (2004: 165) added the following description and details:

> The Flynn Creek crater … was produced by a meteorite that struck a flat lying succession of Ordovician carbonates. The crater is filled by a basal breccia and a thick succession (55 m) of Late Devonian black shales. Lower Frasnian conodonts in shallow water lag deposits that overly the Ordovician succession in the region indicate that the Devonian sea had flooded the area by that point in time. The impact occurred in shallow water and marine sedimentation commenced immediately after settling of impact-related deposits …
>
> The post-impact fill of the crater consists of black shales that were long thought to be equivalent to the Late Devonian Chattanooga Shale. Only the upper third of the black shale succession, however, is correlative to the Chattanooga Shale. Most of the black shales in the crater are older, and are separated from the overlying Chattanooga Shale by an erosional truncation.

One year on, Schieber and Over (2005: 51) explained some apparently conflicting features found in the Flynn Creek crater, which

> … was produced by an asteroid that struck a flat lying succession of Ordovician carbonates …The continuous stratigraphic record in the crater spans impact and post-impact deposits; the recovery of shallow water components and lower Frasnian conodonts in initial marine deposits above the crater fill breccia indicate that marine sedimentation commenced immediately after impact and that the impact occurred in shallow water …
>
> Because the target rocks were lithified carbonates, the Flynn Creek crater has the morphologic characteristics of a subaerial impact. The sediment fill, however, reflects the shallow marine setting of the impact site.

In addition, Schieber and Over (2005: 53) state that sedimentological and petrographic examination of the Flynn Creek Crater fill gives conclusive evidence of a shallow marine impact. These researchers determined that the Chattanooga Shale only comprises a small part of the black shale fill inside of the crater and that "…

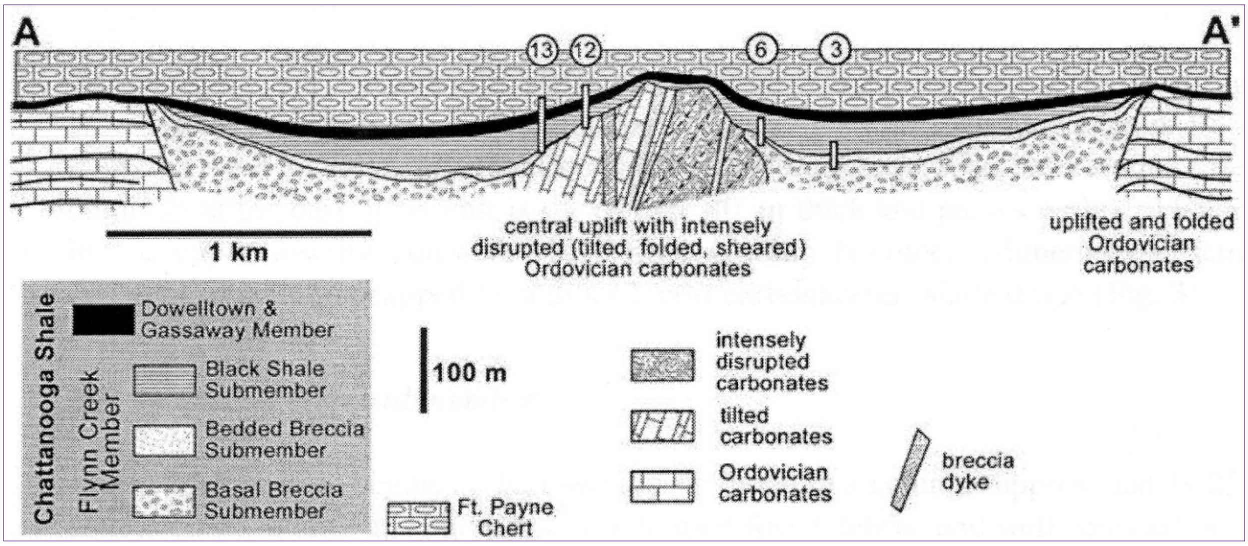


Figure 38: Schematic presentation of the Flynn Creek crater stratigraphic relationships (after Schieber and Over, 2005: 53).

the bulk of the black shale is part of an earlier deposited member of the Chattanooga Shale, largely absent elsewhere, that extends the record of Devonian black shale deposition in central Tennessee …" (ibid.). They propose the name 'Flynn Creek Member' "… for the portion of the crater fill that underlies the Dowelltown Member of the Chattanooga Shale …", which consists of three distinct units that in ascending order are the basal breccia, bedded breccia and black shale submembers (ibid.). The distribution of these litho-stratigraphic units in the Flynn Creek crater is shown in Figure 38, along with the locations where drill cores 3, 6, 12 and 13 were obtained (ibid.). Meanwhile, Figure 39 shows the black shale stratigraphy based on information from drill cores 12 and 13, obtained from the western flank of the Flynn Creek central uplift (after Schieber and Over, 2005: 62).

Results indicate that the basal breccia averages 40 meters in thickness and consists of a poorly sorted, chaotic mix of angular carbonate clasts which range from granule to boulder size and were derived from the underlying strata. This unit is capped by a 2 cm carbonaceous shale drape. The bedded breccia unit starts at the lowest shale drape and contains "… around 25% carbonate clasts, quartz and chert grains, silicified fossil debris, and well-rounded phosphate granules in a fine-grained matrix of organic matter, dolomicrite, and clays …" (Schieber and Over, 2005: 54). The shale is overlain by beds of gravel, granule, sand, and silt-size carbonate debris ranging in thickness from 0.5 to 1.5 meters and cemented by dolomite. These beds vary in number depending on their location in the crater, but are each separated by shale drapes. They "… are massive to crudely wavy-parallel bedded …" on a centimeter to decimeter scale, and in places, fine upwards (ibid.). The poorly-bedded breccia is primarily located along the crater margins, while the bedded dolomitic breccia and bedded dolomite is prominent in the crater interior. "Within bedded dolomite layers occur thinner (2-5 cm), graded dolomite beds that have horizontal lamination, water escape structures, and fading ripples … in the basal portions …" (ibid.). Dolomite beds that are overlain by a shale drape have "… an irregular bumpy surface, probably a result of water escape …" (ibid.).

Depending on the location within the crater, the bedded breccia and bedded dolomite may be directly overlain by Devonian black shales or by a layer of course sandstone consisting of 75% carbonate clasts, subordinate quartz and chert grains, silicified fossil debris, and rounded phosphate granules (Schieber and Over, 2005). Sandstone layers ranging from a few millimeters up to 3 cm in thickness occur throughout the basal 13 meters of the black shale succession, and "Thin beds containing sand-sized quartz and pyrite grains, usually with diffuse lower and upper boundaries, carry the imprint of early diadenetic infilling of cysts of the marine alga *Tasmanites* …" (Schieber and Over, 2005: 56). Schieber and Over (2005: 57) also pointed out that the "… black shale of the Flynn Creek Member forms a thick succession … and lacks an obvious equivalent outside the crater."

After comparing it with other marine impact craters, Schieber and Over (2005) interpreted the chaotic basal breccia in Flynn Creek as a fall-back deposit that formed immediately after impact. They noted that the graded top portion indicates that the deposition was controlled by the settling velocity of particles, which is "… commonly observed where particles settle through a turbulent fluid/sediment mixture …" (Schieber and Over (2005: 59). They concluded:

> Thus, impact occurred while the area was cov-

> ered by water. Impact-displaced water rushed back into the void and carried freshly ejected material back into the crater. The turbulence associated with such a scenario is extreme and allows for short-term suspension transport of pebble-size particles … The basal breccia submember, including the graded top portion, probably represents a time interval measureable in hours.
>
> The shale drape over the basal breccia indicates low energy conditions after impact-related turbulence had subsided … Outside the crater … Conodonts from the basal Dowelltown lag range in age from upper Givetian to lower Frasnian and suggest that shallow water conditions persisted for a long time period in the region and prevented accumulation of fine-grained sediments … The epicontinental setting of the Devonian inland sea and water depth estimates for shale deposition in the Chattanooga Shale suggest a water depth of 10 m or less … The composition of the shale drape that covers the basal breccia implies that the carbonate particles were derived from an ejecta blanket outside the crater, were washed across the crater rim during storm events … Considering the overall shallow water conditions in the area this should have been a frequent occurrence. Abundant course material in this shale drape suggests rapid accumulation, possibly representing only a few hundreds to thousands of years ...
>
> Because the bedded breccia and black shale submembers span several conodonts zones … this suggests an initial time interval of several hundred thousand years when black shale deposition occurred only within the crater, while shallow water conditions and lag formation persisted outside. (Schieber and Over, 2005: 59-61).

Preservation of the Flynn Creek Member equivalent outside of the crater indicates that the sea level rose sufficiently during its deposition to allow mud accumulation outside of the crater. Thus, water depth may have increased from 10 meters up to 50 meters (Schieber and Over, 2005).

Dypvik and Jansa (2003: 309) state that in subaerial impacts, the target rock is generally hard igneous or metamorphic rock, but in submarine impacts, the target rock is primarily composed of "… unconsolidated or poorly lithified sediments, or sedimentary rocks, with high volumes of pore water." They point out that the lack of an elevated rim in a shallow-water marine impact is thought to result from current reworking and resurge of the water back into the excavated crater as the water in the crater is vaporized during impact. Another characteristic they noted of marine impact sites is the presence of resurge gullies that cut across the rim: "Such erosional features result from submarine erosion which bevels off the crater rim, causing lower, more subtle rims or almost complete removal of a rim …" (Dypvik and Jansa, 2003: 332; cf. Dalwigk and Ormo, 2001). Schieber and Over (2005: 64) point out that Flynn Creek, in contrast, possessed "… an uplifted rim that was not significantly beveled by post-impact erosion and was not dissected by resurge gullies." This indicated that the Ordovician target rock was already lithified by the time of the Flynn Creek impact (ibid.). In fact, the Flynn Creek Crater's morphology was " … a close match to that expected of a sub-aerially produced crater …" (ibid.), but Dypvik and Jansa (2003) pointed out that in shallow submarine impacts, the top of the central uplift is usually flat as a result of waves and shallow currents scouring and reworking the impact deposits. As can be seen in Figure 8, Flynn Creek possesses a flattened central peak in contrast to the sharp central peaks most terrestrial impacts craters display, suggesting that post-depositional modification by wave action, associated with the shallow water at this site altered the crater's morphology to an extent (Schieber and Over, 2005).

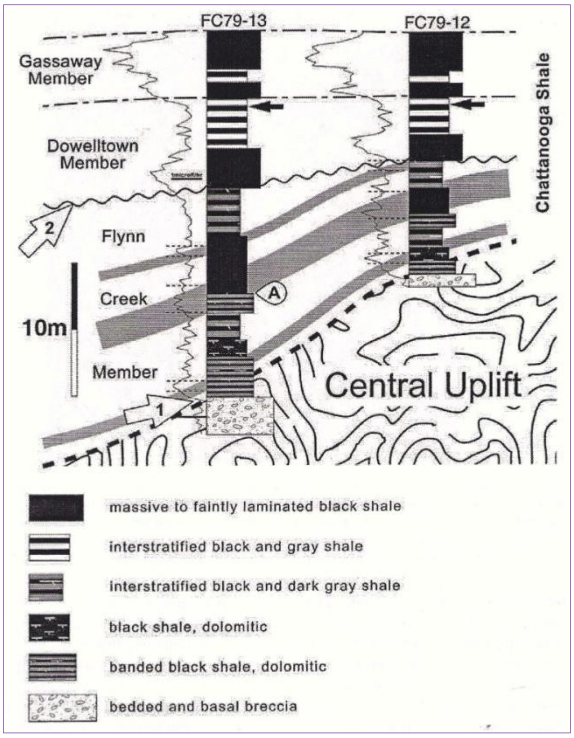


Figure 39: Black Shale stratigraphy from western flank of the central uplift drill cores (after Schieber and Over, 2005: 62).

The Wetumpka impact crater in Alabama, a coastal state bordering Tennessee to the south, is a confirmed shallow marine impact that took place 83.5 million years ago in 30 to 100 meters of sea-water (King and Petruny, 2003; King et al., 2002; 2008). Field work completed by Roddy, Schieber, and Over proves that Flynn Creek is the result of an *extremely* shallow (~10 meters deep) marine impact. At the outset of this study, it was hoped that comparisons between known shallow marine impact sites such as Wetumpka,

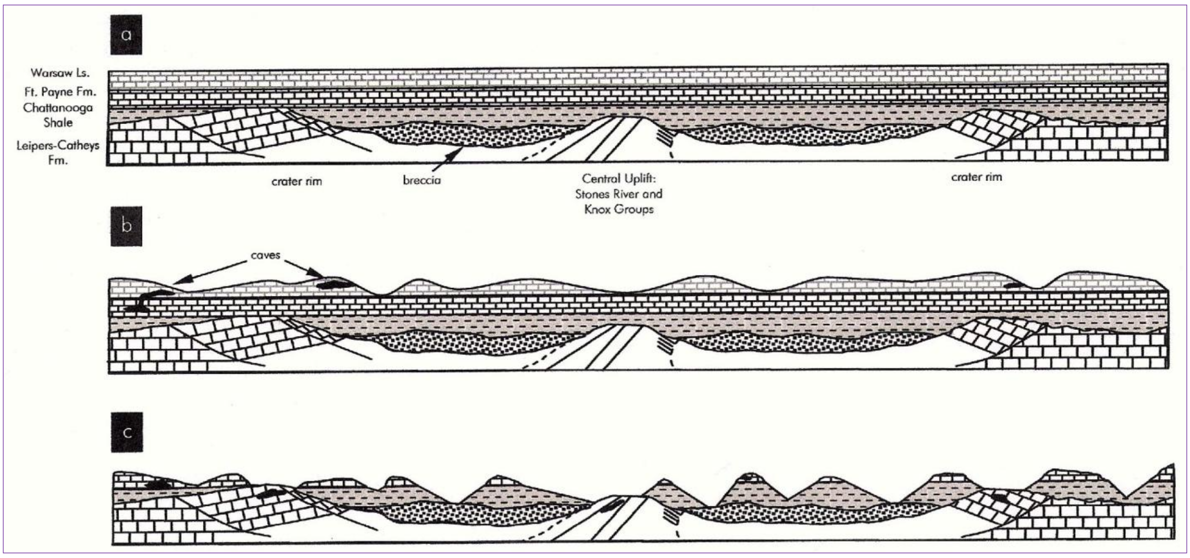


Figure 40: Generalized model for the speleogenetic modification of the Flynn Creek Structure; for details see the associated text (after Milam, Deane and Oeser, 2005b: 34).

and extremely shallow marine impacts sites such as Flynn Creek, might provide an understanding on a macroscopic level of the similarities and differences in shallow and extremely shallow impact craters that could then be applied to identify liquid depth at times of impact on other Solar System bodies, perhaps Titan, or Mars of long ago. Unfortunately, this has not proven to be possible since the morphology of the Flynn Creek crater so closely resembles that of subaerial impact craters.

## 8 CAVE DEVELOPMENT

Caves have formed in the Flynn Creek Structure where slightly acidic groundwater has leaked through cracks and crevices in the limestone gradually dissolving it and creating passages and caverns. Caves form by dissolution along zones of weakness "… such as bedding planes, fractures, and faults …" (Milam and Deane, 2006a: 82). Milam and Deane (ibid.) have discovered that "… impact cratering, one of the dominant surface-modifying forces on Mars and elsewhere in the Solar System, can also exert control over cave passage development …" Regional uplift due to the formation of the Nashville Dome in what is now central Tennessee caused the uplifted strata to have higher potential erosive energy. The Pennsylvanian rocks were breached and erosion exposed the underlying Upper Mississippian Warsaw Limestone and Lower Mississippian Fort Payne Formation, and "It was in these geologic units (and once overlying Upper Mississippian rocks) that a first generation karst landscape developed …" (Milam et al., 2005b: 30). Cave passages developed in Flynn Creek along strike and/or dip and/or joint orientations, and continued erosion exposed the underlying Chattanooga Shale and below that, the Ordovician carbonates. As a result, "… a second generation karst landscape was formed locally in the Leipers-Catheys, Bigby-Cannon, and Hermitage Formations, as well as the underlying Stones River and Knox Groups …" (ibid.). Figure 40 shows Milham, Deane and Oeser's (2005b) generalized model for the speleogenetic modification of the Flynn Creek Structure. Figure 40a shows the buried crater, with only the Knox Group through the Warsaw Limestone sediments depicted (ibid.). Figure 40b shows the first generation karst development, and Figure 40c the second generation karst development (along the rim of the crater and in the central uplift).

One cave apiece is known to be associated with the Wells Creek and Howell Structures (Deane et al., 2004: 2; Milam, Deane and Oeser, 2005b: 31), but there are at least twelve caves at the Flynn Creek Structure, although two of these, in the crater fill, do not seem to correlate with Flynn Creek's structural features (Milam, Deane and Oeser, 2005b). The other ten formed in Flynn Creek target rock and seem to be controlled by the crater's structural geology (ibid.). Nine of the caves are concentrated along or just outside of the crater rim and one is located in the Stones River Group strata of the central uplift (Milam and Deane, 2006a). At one cave per 2.38 square km, the Flynn Creek target rocks contain 5.5 times the concentration of solutional caves that are known to exist elsewhere in Jackson County (ibid.). In addition, "… 7.5x more total cave passages can be found associated with the crater area, compared to surrounding areas …" (Milam, Deane and Oeser, 2005b: 32).

Flynn Creek cave development first occurred at the highest elevations of the limestone and dolostone exposures along the crater rim with the lowering of the regional base level. Though many of the Flynn Creek caves developed according to the strike and dip of the crater rim, "… others formed along extensional fractures in the fold axes of anticlines and along major faults where compression of the crater rim and wall collapse, respectively, occurred …" (Milam and Deane, 2006a: 82). Fractures and faults are zones of weakness where limestone dissolution is enhanced resulting in longer passage lengths. Though caves have developed in other parts of Jackson County, the Flynn Creek impact seems to be responsible for most of the cave development seen in the area today (Milam, Deane and Oeser, 2005b).

In the absence of the Flynn Creek impact Structure, a dual-generation karst landscape would have developed in this area anyway, similar to that seen outside the crater and elsewhere in Jackson and surrounding counties. However, the higher density of caves in target rocks, longer average cave lengths, their spatial association with Flynn Creek crater, and specific correlation with impact-related structures suggest that the impact crater has exerted some control over subsequent karst development in target rock caves.

Milam and Deane (2006a: 82) point out that caves may have formed on Mars in ways that are similar to those that formed in Flynn Creek, and may provide subsurface environments that are potential environmental niches for extant life:

> The control of cave development by impact-related geomorphology and structural geology features have resulted in subterranean environmental niches along the crater rim and central uplift. The caves here are home to diverse fauna and somewhat buffered ecosystems common to caves elsewhere in the region. Thus, the constraining of karstification in impact craters may serve as a predictive tool for locating subterranean environments on Mars.

The two crater fill caves, Mahaney Pit and Antioch School Cave, are first generation caves that formed in the Fort Payne Formation. Mahaney Pit is located along the southwestern rim of Flynn Creek at an elevation of ~280 meters above sea level (ibid.). The cave entrance consists of two 5 meter drops, beyond which exploration has not continued (Milam, Deane and Oeser, 2005a). Antioch School Cave is located in the eastern half of the crater, ~244 meters above sea level, and is 198 meters long. This cave developed along joints in the Fort Payne Formation (ibid.).

Additional uplift of the Nashville Dome allowed the Chattanooga Shale to be breached, exposing the underlying target rock in the crater's rim, floor, and central uplift. A second generation karst development began, and continues to this day. Nine of the second generation caves have formed along the crater rim in anticlines and along bedding planes (ibid.).

Wave Cave "… is located in the outermost concentric fault that defines the modified crater …" (Evenick, 2006: 7), and was formed in a tightly-folded asymmetric anticline on the east side of Flynn Creek (Roddy, 1966c: 109). The fragmented rock in the anticline core has been replaced by the cave (ibid.). A lack of tectonic deformation in this area indicates that this anticline formed as a result of the Flynn Creek impact (Evenick, 2006). The passageway is around 43 meters long and near the end, two side crawls lead to a ~6 × 12 meter room, and "An unusual inverted breakout dome is forming on the western side of this room due to gravitational collapse along bedding planes …" (Evenick, 2006: 7). Figure 41 shows two structural models for Wave Cave. Model A shows that Roddy's "Normal fault model … does not balance nor take asymmetry into account …" (Evenick, 2006: 9), while Model B is a new interpretation of Wave cave:

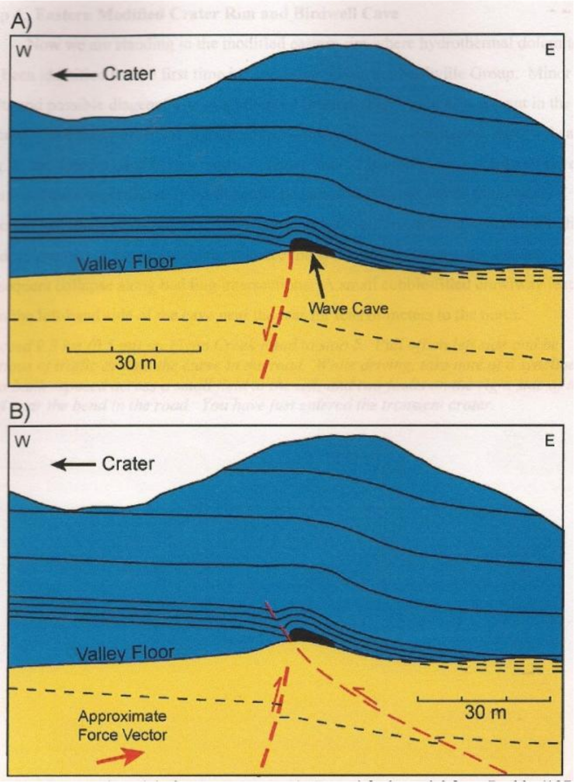


Figure 41: Two different structural models for Wave Cave (after Evenick, 2006: 9).

> Most normal faults that define the crater's modified crater rim are associated with a breached anticline, suggesting the region beyond the transient crater is first uplifted via thrusting during the initial excavation phase and later inverted during the final crater development and modification phases (ibid.).

Figures 42 and 43 show the entrance area of Wave Cave and an interior view, and Figure 44 is a map of the Cave (after Milam, Deane and Oeser, 2005a: 43). The Tilted Room in Wave Cave shown on the map "… developed along the

Figure 42: Jana Ruth Ford (foreground) and Larry Knox (to her left) examine the entrance to Wave Cave (courtesy: Jessica Tischler).

strike of steeply-dipping (61°) beds of the western limb of the anticline …" (Milam, Deane and Oeser, 2005b: 33).

Another Flynn Creek cave is Birdwell Cave, which formed in the eastern modified crater rim parallel to a modified crater fault (Deane et al., 2005). Both Birdwell and Wave Cave are oriented approximately north-south, which is perpendicular to the center of the crater and probably perpendicular to the maximum stress of impact (ibid.). Birdwell Cave is at least 116 meters in length with a 3 meter-high entrance (see Milam,

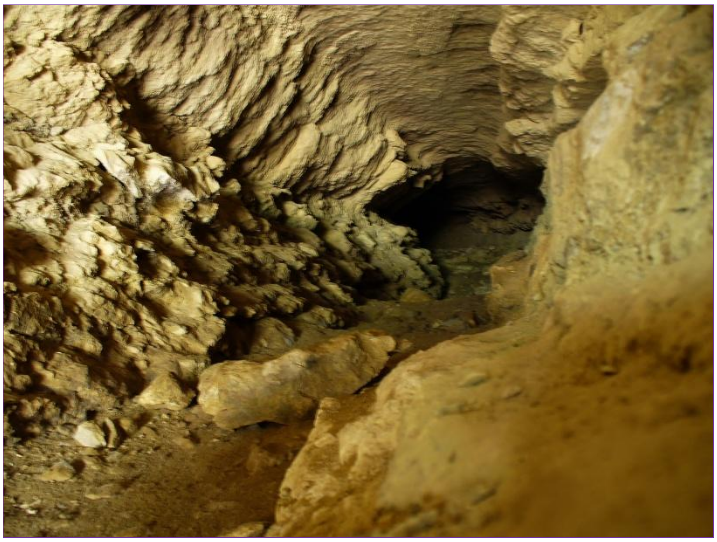


Figure 43 (above): A view within Wave Cave (courtesy: Rebecca Tischler).

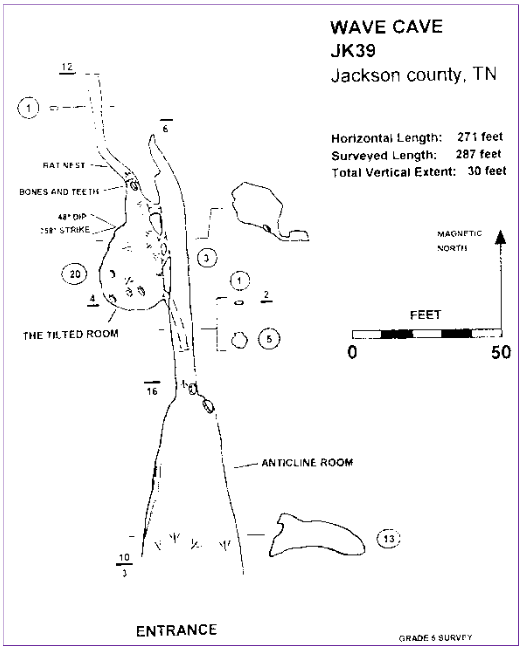


Figure 44 (right): A map of Wave Cave (after Milam, Deane and Oeser, 2005a: 43).

Deane and Oeser, 2005a). A passageway continues from the entrance for some 30 meters, and then splits. A short climb up to the right leads to a small passage that lies 2.5 meters above the entrance elevation. The left branch is a crawlway, only 30-40 cm high in some places, which developed along bedding planes. This crawlway in turn opens to a passage which is in places filled with pools of water. A blue hole, located around 100 to 150 meters to the south, is split by a north-south trending natural rock bridge as shown in the upper right of Figure 45, a map of Birdwell Cave. Milam, Deane and Oeser (2005a: 37) suggested that "Based on the proximity of Birdwell Cave to this blue hole and their similar structural patterns, it is possible that these two karst features may be connected hydrologically …" A small cobble-filled crawlway leads from the left, rear side of Birdwell Cave northward for some tens of meters (Deane et al., 2005).

Cub Hollow Cave is located along the eastern rim of the crater around 232 meters above sea level (Milam, Deane and Oeser, 2005a). The cave entrance is reached by descent into a narrow gorge which has flooded repeatedly. Inside, a stream flows swiftly through a wide crawlway to the northwest. This cave has only been mapped for 30 meters, but "… during low water, the cave was observed to continue to the northwest for another 12 to 15 meters …" (Milam, Deane and Oeser, 2005a: 38).

Flatt Cave is located along the southern crater rim and may have been mined in the past (Milam, Deane and Oeser, 2005a). A small, 1 by 2 meter entrance opens to an approximately 122 meter long dry passage which formed along an anticline. At the end of the passageway is a crawlway, which leads to a large, ~15 by 23 meter room. Several passages branch from this room and contain even more small side passages and wet drains. "At least four major (and sharp) changes in bedding orientations occur through-out Flatt Cave …" (Milam, Deane and Oeser, 2005a: 38). Flatt Cave developed within at least four major fault blocks (Milam, Deane and Oeser, 2005b). The bounding faults do not limit passageway development, but rather serve as groundwater conduits along which speleothems have formed in the cave (ibid.).

Forks Creek Cave is about 172 meters above sea level and was exposed in a road cut along

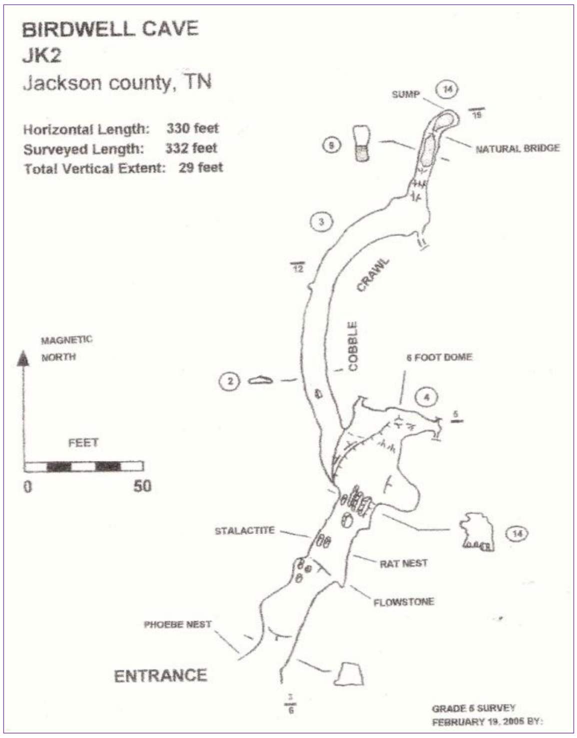


Figure 45: Map of Birdwell Cave (after Milam, Deane and Oeser, 2005a: 44).

the southern bank of the Flynn Creek. This cave has four entrances that lead to tight and interconnected crawlways (Milam, Deane and Oeser, 2005a).

Spalding Cave is located along the southeastern crater rim at an elevation of ~213 meters above sea level Milam, Deane and Oeser, 2005a). It is estimated to be 91 meters long with an entrance that is 1 meter high and 2 meters wide. Water flows out of the entrance which is located on the east side of Steam Mill Hollow, a tributary of Flynn Creek. A wet crawlway leads east from the entrance for some 17 meters. The crawlway is 50 to 60 cm in height with only 15 to 18 cm of airspace, but leads to a small room that is 4.5 meters long, 1.5 meters wide and 4.5 meters high. From here, a waterfall can be climbed 2.5 meters to a 1 meter by 1 meter passage that continues around 70 meters to another waterfall dome. This second dome is 4.5 meters high, 2.5 meters wide, and 4.5 meters in length. About 3 meters above the floor, a small waterfall flows in from the east wall. At the top another small passage leads to a second entrance which is simply a small hole on the side of a hill (ibid.).

Kelson Cave is located along the rim to the southwest of Spalding Cave in Steam Mill Hollow (Milam, Evenick and Deane, 2005). The entrance is 50 cm in diameter and leads to a small room that is about 1 meter tall. "A low, wet, sinuous crawl to the southwest and an upward squeeze leads into a muddy room in which three side passages diverge …" (Milam, Evenick and Deane, 2005: 39).

The entrance to Mahaney Cave is located at the base of a hill on the southwest side of Flynn Creek (Milam, Deane and Oeser, 2005a). "A low, tight crawlway, artificially opened about 1947, leads into a cave of several irregularly-shaped chambers …" (Milam Deane and Oeser, 2005a: 40). The entrance leads to a crawlway that slopes down to the left for 9 meters to a junction. Another crawlway to the right of the entrance is 9 meters long leading to a climb-up that is blocked by boulders, but a room can be seen on the other side. Other passages lead to a stream, "… a room with flowstone hanging on the walls …" a stoopway that continues for 21 meters, and even more crawlways (ibid.).

Rash Spring Cave has a 2 by 3 meter entrance on the west bank of Flynn Creek itself. This cave is 262 meters long with an active stream which runs through it to the entrance where it has served as a water source for the property owners (ibid.).

In addition to these caves in the Flynn Creek structure, collapsed caves can be seen along road cuts in the crater, such as one along Flynn Creek Road, which are indications of fault or fracture systems that are associated with the western modified crater rim (Evenick, 2006).

Of special interest is Hawkins Impact Cave, "… the only known cave in the world developed in a central uplift of a complex crater …" (Milam and Deane, 2006b: 81). The central peak, ~0.75 km in diameter, "… was buried by Devonian/Mississippian-aged marine sediment that later became the Chattanooga Shale, Fort Payne, and other formations …" (Milam et al., 2006: 1). Milam and Deane (2006b: 81) believe that the Hawkins Impact Cave exposures "… provide a unique perspective into processes of central uplift formation …" This cave was discovered by the landowner, Michael Hawkins, in 1989 and was subsequently mapped in 2003 and found to be 277 meters in length (ibid.).

Expeditions to Hawkins Impact Cave reveal that around 30 large megablocks comprise the central uplift (Milam et al., 2006). Within some megablocks, there are bedding and monoclinic folds that are dissected by extensive networks of microfractures and microfaults (Milam and Deane, 2006b). Some megablocks contain no microfractures or microfaults while others have up to 3.1 per centimeter. Major fault dissection of the microfractures and microfaults indicate that subsequent movement occurred after their formation. Megablocks investigated inside Hawkins Impact Cave have volumes ranging from 20 to 3,200 cubic meters, whereas the megablock volumes on the northern flank of the central uplift are as large as 72,000 cubic meters. The former megablocks "… are separated by discrete major faults that both truncate and occur normal to bedding … Bedding orientations to either side of some major faults indicate that substantial rotation (up to 90°) occurred during megablock transport …" (Milam and Deane, 2006b: 81). Both microfractures and microfaults are less than 0.25 mm in width and extend for several meters through strata at angles of 60-85° to the bedding (ibid.).

Exploration of Hawkins Impact Cave indicates that after compression due to impact, the initial microfractures were generated (Milam et al., 2006). Cross-cutting relationships show that this first generation of microfractures was subsequently cut by microfaults and both terminate at major fault boundaries. Microfault movement followed with the subsequent generation of more microfractures and microfaults followed in turn by the rise of the central uplift, and "This is expressed by major fault movement along megablock boundaries, which truncate all of the above features …" (Milam et al., 2006: 2). Figure 46 is a map of the Hawkins Impact Cave (after Milam, Deane and Oeser, 2005a: 45). "Two large rooms (the Mars and Upper rooms) were formed by dissolution and subsequent collapse at the

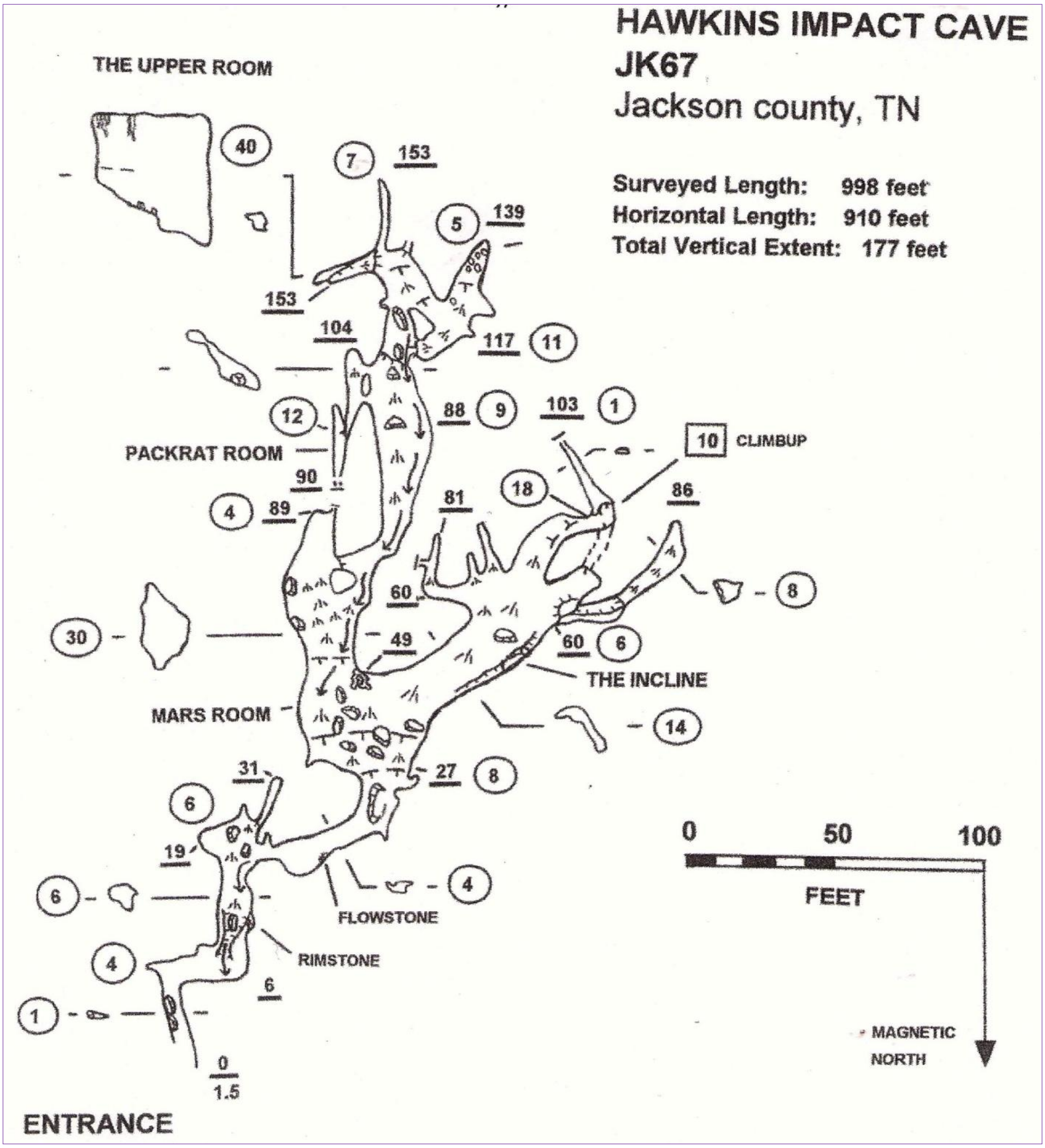


Figure 46: Map of Hawkins Impact Cave (after Milam et al., 2005a: 45).

intersection of several major faults …" (Milam, Deane and Oeser, 2005a: 33).

## 9 CONCLUSION

The Flynn Creek Structure is located on the Highland Rim escarpment in middle Tennessee and was first noted by Safford in his 1869 report of the geology of Tennessee. Described originally as a sinkhole, then as a cryptovolcanic structure, it was finally recognized as a site of meteorite impact when shatter cones found in the structure confirmed its origin. Decades of research by Roddy have provided a great deal of information regarding its formation and structural features. Masursky (1977: 637) explains a primary reason for studying impact craters such as Flynn Creek:

> We have learned from past planetary missions that an understanding of the processes involved in both crater formation and degradation provides clues to the age and geologic history of an area. Additional studies of the mechanics of crater formation and degradation derived from Earth-analogue studies … will help to define the geologic age relationships of the various geologic units on Mars; from these studies a more detailed history of the planet can be developed.

Flynn Creek is thought to be the result of an extremely shallow marine impact that occurred in perhaps 10 meters of sea water. Comparisons of Flynn Creek with confirmed shallow marine impact craters such as Wetumpka, in Alabama, show that Flynn Creek closely resembles subaerial impact craters except for its central peak, which is thought to have been flattened by subsequent wave action. It was hoped at the outset of this study that similarities and differences in the features of these two marine impact structures could be used to identify similar impact craters, which also occurred in a surface liquid, on other Solar System bodies such as Mars or Titan. Specifically, the differences might indicate liquid depth at the time of impact. However, water depth during the Flynn Creek impact was apparently too shallow to produce marine impact features that would be obvious to spacecraft such as the Mars Reconnaissance Orbiter.

Flynn Creek did prove valuable, however, to the National Aeronautics and Space Administration (NASA). Unlike most terrestrial impact structures, rapid burial by sediment that would later become Tennessee's Chattanooga Shale preserved the form of this crater, which is strikingly similar to lunar craters such as Pythagoras and Copernicus. As such, a detailed study of the Flynn Creek Structure was supported by NASA and the United States Geological Survey's Branch of Astrogeologic Studies in preparation for the Apollo Program, which resulted in astronauts walking on the lunar surface.

Flynn Creek may prove useful again in the exploration of our Solar System. Since Flynn Creek is home to numerous caves, and is the "… birthplace of impact speleology …" (Milam and Deane, 2006a), understanding cave development within an impact structure may serve as a basis for predicting the locations of caves on other planets, such as Mars (see Cushing et al., 2007). Such subterranean locations could offer protection to human explorers from hazards such as UV radiation, solar flares, high energy cosmic particles or even Martian dust storms.

The NW to SE bilateral symmetry noted by several researchers in the Flynn Creek Structure and the complex deformations found in the southeastern rim indicate that this crater was formed by an oblique impactor that came from the present-day northwest. It is of interest that the small oval-shaped Dycus Disturbance, a suspected site of meteorite impact, is located just 13 km to the northwest of Flynn Creek. As to future research, it would be most useful to determine whether or not there is a relationship between Flynn Creek and the Dycus Disturbance, and if so, the nature of that relationship. Comparison with the lunar craters Messier and Messier A may prove useful in this context.

## 10 NOTES

1. Koeberl (2009: 14) explains the distinction between an 'impact crater' and an 'impact structure':

> The distinction between an impact *crater* (i.e., the feature that results from the impact) and an impact *structure* (i.e., what we observe today, long after formation and modification of the crater) should be made clear. Unless a feature is fairly fresh and unaltered by erosion, it should be called an "impact structure," rather than an "impact crater."

2. Dietz (1963: 663) describes 'astrogeology' as "… a subject which must concern the earth, as well as the moon."

## 11 ACKNOWLEDGEMENTS

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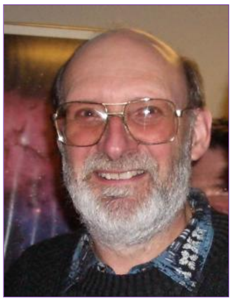

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