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AN HISTORICAL PERSPECTIVE ON THE SUSPECTED METEORITE IMPACT SITES OF TENNESSEE.
1: THE DYCUS STRUCTURE

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Abstract: The Dycus Structure is one of two suspected meteorite impact sites in Tennessee, USA, and first came to the attention of geologists during the 1940s, but it was only investigated in 1951 when Robert M. Mitchum conducted research at this site for a M.S. in geology through Vanderbilt University. The few subsequent investigations that have occurred at this site have revealed it to be oval in shape rather than circular, with the central uplift located near the north-eastern end of the site, reminiscent in many ways of the lunar crater Schiller. The Dycus Structure may have been formed at the same time as the nearby Flynn Creek impact site, by an asteroidal body that impacted at an oblique angle.

Keywords: Dycus Structure, Tennessee, possible impact site, oblique impactors, Schiller lunar crater, R.M. Mitchum

1 INTRODUCTION

Impact cratering was an important feature of the early Solar System, but it took many years before geologists and astronomers were willing to seriously entertain the idea that some of the craters identified on the Earth were of extraterrestrial origin and not the result of volcanic activity or other geological processes (e.g. see Boon and Albritton, 1936; 1937; Bucher, 1936; Dietz, 1963; Hoyt, 1987; Mark, 1987; McCall, 1979; Melosh, 1989). Now terrestrial impact-cratering is universally accepted (e.g. see Grieve and Pilkington, 1996; Koeberl, 2009), and Hey (1966) and O'Connell (1965) amongst others have produced catalogues of meteorite craters. There are currently around 230 confirmed or suspected meteorite impact craters in the USA (Classen, 1977), the first of which was described by Safford in 1869. This is located at Wells Creek in the state of Tennessee in the south-eastern United States (Berwind, 2007).

In addition to Wells Creek (see Ford et al., 2012; Wilson, 1953; Wilson and Stearns, 1966, 1968), Tennessee has one other confirmed impact crater, Flynn Creek (Evenick et al., 2004; Ford et al., 2013; Milam and Deane, 2005; Milam et al., 2006; Roddy, 1997; Schieber and Over, 2005), and two suspected impact sites, the Dycus Structure (Deane et al., 2006; Schedl et al., 2010) and the Howell Structure (Born and Wilson, 1939; Deane et al., 2004; Ford et al., 2015). As Figure 1 indicates, all of these sites are found in the Highland Rim Physiographic Province which surrounds the Nashville Central Basin in middle Tennessee (see Deane et al., 2004; Deane et al., 2006; Roddy, 1963; Wilson and Stearns, 1968). Specifically, the Dycus Structure is located in the northern section of the Eastern Highland Rim Escarpment. Although meteorite impacts most certainly also occurred in the eastern and western sections of the state, the structural features of those that occurred to the east of the Highland Rim in the deformed rocks of the Appalachians have been obliterated (Woodruff, 1968), while impact craters in the western part of the state have been covered by coastal plain marine and transitional sediments during the formation of the Mississippi Embayment (Miller, 1974).

Interest in the known and suspected Tennessee impact sites has waned over time and only sporadic field work has taken place in the decades since their recognition as sites of interest.

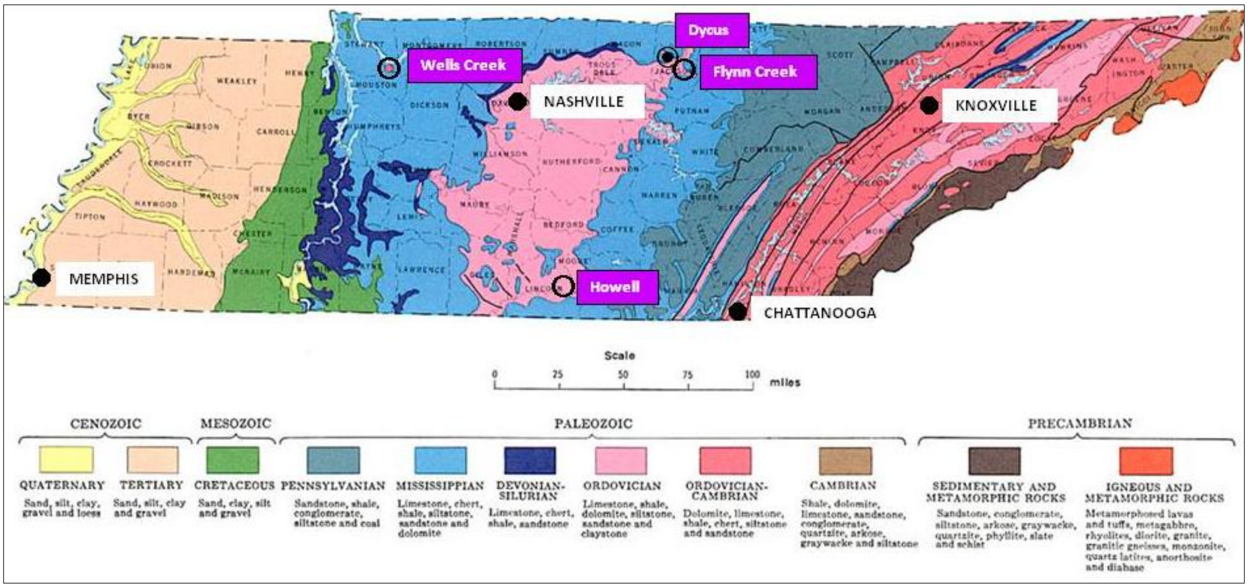

Figure 1: Generalized geological map of Tennessee showing the locations of the four largest cities (black dots) and the two confirmed and two suspected meteorite impact sites (black circles). The Dycus Structure, which is the focus of this paper, is marked by the circle and black dot. All four confirmed or suspected impact 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 of Environment & Conservation, Division of Geology, 1966).

Hopefully in the near future the Dycus and Howell Structures will be shown to be actual impact sites or their alternative origins will be determined. In this paper we review the evidence that has been assembled to date for the Dycus Structure.

2 THE DYCUS STRUCTURE

2.1 Introduction

Although the Dycus Structure is located only 13 km north-northwest of the Flynn Creek impact site and in the same county of Tennessee (Jackson), it is a surprisingly long drive from one site to the other due to the remote location of the Dycus Structure and the difficulty involved in navigating the highly dissected terrain of the Highland Rim Escarpment along which these two sites are located. This structure has not been subjected to the intense scrutiny that Wells Creek, Flynn Creek, or even the Howell Structures in Tennessee have received over the years, and its initial discovery apparently went unrecorded (see Deane et al., 2006). The earliest written work on the Dycus Structure is in an unpublished M.S. thesis submitted to Vanderbilt University in 1951 by Robert M. Mitchum. This structure was still not well known afterwards, and it is not even mentioned in the Tennessee Division of Geology's 1974 publication, *The Geologic History of Tennessee*, even though an entire section of the publication is dedicated to "Cryptoexplosion Structures in Tennessee" (see Miller, 1974: 55–58).

2.2 Historical Context

According to Deane et al. (2006: 1)

> Richard Stearns (Prof. Emeritus, Geol. Dept., Vanderbilt Univ.) believes his colleague, Dr Charles W. Wilson, Jr. was told about, or discovered, the Dycus Disturbance while conducting field work in Jackson County sometime in the 1940s …

Later Mitchum (1951: 1), one of Wilson's graduate students, wrote that early in 1950 he and Wilson investigated "… a local structural disturbance in the Ordovician rocks of Jackson County, Tennessee …" Figure 2 is a view of the area. The most intensely-disturbed section is located in the forested area in the center of the photograph. Wilson considered this structural disturbance warranted further investigation, and he wanted to determine whether it should be included in the growing list of U.S. cryptovolcanic structures (ibid.).

Although the Dycus Structure had been known for a few years before his field work commenced, Mitchum (ibid.) stated that no research had been carried out to determine its origin. He described the known structure in detail, including the stratigraphy of the local rocks, and completed a geological map of the disturbed area that was included in his thesis and is shown here in Figure 3. This map shows that the structure is just over 760 meters by 885 meters, and based on his analysis Mitchum (1951: 2) concluded that it was the result of a meteorite impact.

2.3 Structural Features and Age

The Dycus Structure is located in the northern part of middle Tennessee on the edge of the Nashville Central Basin, adjacent to the Eastern Highland Rim Escarpment, and stands out from

Figure 2: A view of the Dycus Structure looking northeast. The zone of greatest disturbance is in the forested area in the center of the photograph. The ridge approximates the northern boundary of the structure (photograph: Jana Ruth Ford).

the surrounding regional terrain:

> The regional dip of the area is so slight that, except for local minor irregularities, the rocks appear horizontal in the field. The occurrence of a localized area of intense deformation such as the Dycus disturbance in ordinarily relatively undisturbed strata is of more than casual interest. (Mitchum, 1951: 13).

Later investigators agreed with this description:

> This province is characterized by very flat-lying, Middle to Upper Ordovician to Lower Mississippian-aged sedimentary strata. In a major unconformity, the Silurian and most of Devonian is absent … Regional folding and faulting are rare within this area … Unfortunately, hill slopes are commonly covered with rubble, detrial material from overlying formations, and vegetation, so exposures are limited. (Deane et al., 2006: 1).

O’Connell (1965: 35) stated that the Dycus Structure was Ordovician in age. Rock exposures in the disturbed area were primarily limestone that ranged from Ordovician to Mississippian in age (Mitchum, 1951). The Chattanooga Shale, so prominent in the nearby Flynn Creek impact site, occurred near the tops of high hills in the region of the disturbance, but it was not present in the area mapped by Mitchum. The northern and north-eastern sections of the disturbed area were covered by rubble containing the Mississippian chert that was usually found to cap high hills in the surrounding area. The chert was not found to occur in place within the intensely-deformed part of the structure (ibid.).

Mitchum (1951: 15) noted that the Dycus Structure was a “… very localized structure.” The portion he investigated and determined to be disturbed approximated a half-circle with a radius of only 610 meters. He wrote that “… about half the structure is covered by rubble and debris from younger formations …” (ibid.), and he assumed that the entire structure was probably circular in plan. During his investigation Mitchum (ibid.) wrote that he found the following elements present (in order from the center of the structure to its periphery):

> (1) A small, relatively subordinate central uplift occupied the approximate center of the disturbance and marked the area of most intense deformation.
> (2) Surrounding and subordinating the uplift was an annular depressed area that was accompanied by buckling and tight folding. The

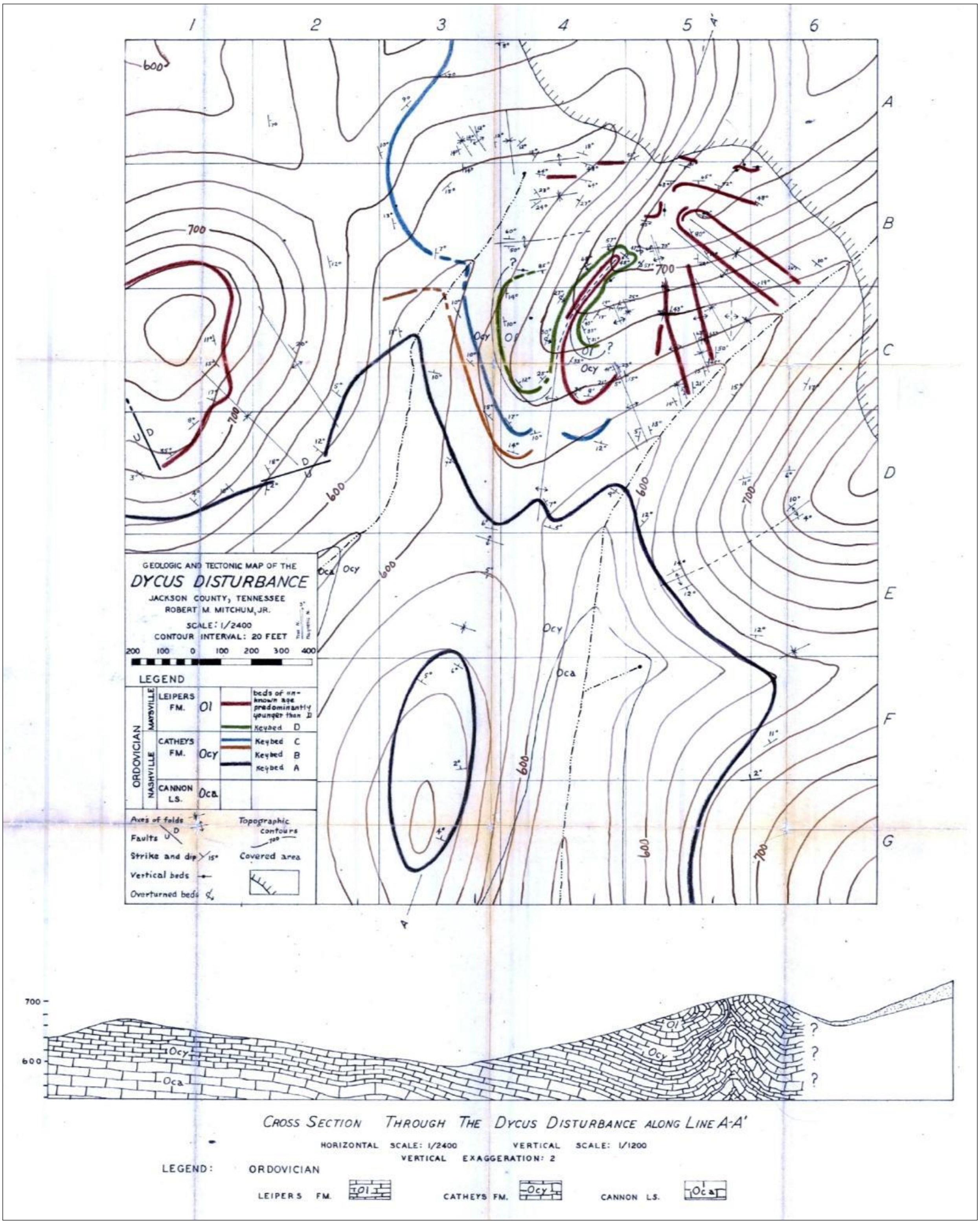

Figure 3: A geological map of the Dycus Structure. A cross-section through the structure along line A–A′ is included at the bottom of the figure (after Mitchum, 1951).

axes of the folds were roughly radial from the central uplift. The down-bowing had greater magnitude than the uplift, both vertically and horizontally, so that the center of the structure, although higher than the surrounding depressed area, was still lower than its normal altitude in this vicinity.

(3) A gentle ring-shaped anticline occurred on the outer periphery of the down-warped area. This peripheral fold surrounded the central area for at least three-fourths of the circumference of the exposed half-circle.

(4) At least two normal faults occurred outside the ring-shaped anticline.

(5) Outside the area of intense disturbance the rocks dipped gently toward the center of deformation. This dip died out with increasing distance from the center.

Most of the radial folds seemed to have a common origin in a small section of the structure that was just over 90 meters across, and Mitchum (1951: 16) referred to this as the "… focal point of the Disturbance …" He also noted that although no pattern of deformation could be established, tight folding, high dips, faulting and shearing could be discerned in this area along with some brecciation that was apparently connected with the folding and faulting. The folding "… was very intense and produced crumpling rather than well-defined folds …" (ibid.). Slickensides were found mostly along the tight folds (ibid.).[1]

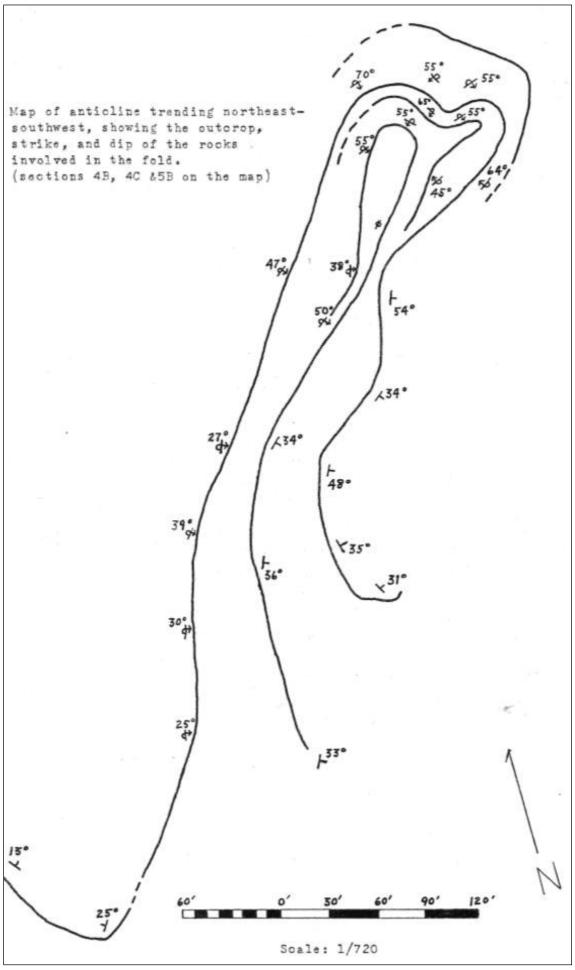

Figure 4: Map of anticline trending northeast-southwest, showing the outcrop, strike, and dip of the rocks involved in the fold (after Mitchum, 1951: 21). This map includes sections 4B, 4C & 5B from the 1951 geological map shown in Figure 3.

Mitchum (ibid.) considered this intense folding to be the most important feature of the Dycus Structure, more so than the faulting or brecciation. This intensely-disturbed area

> … has been lifted above the immediately surrounding annular depressed area. Although no indisputable evidence has been found to prove that the uplift has actually occurred, there are certain lines of evidence that strongly support such a possibility. (Mitchum, 1951: 17).

Basal granular facies of the Leipers Formation were found at an altitude of some 230 meters in the center of the Dycus Structure instead of at an altitude of 190 meters where the same facies was found outside of and to the east of the central area. Mitchum also determined that radial folds surrounding the central area rose toward the center, and

> In several instances the same bed can be traced along the axis of a fold for over 300 feet [90 meters], the extremity of the exposure nearest the center being at least 70 feet [20 meters] higher than the outer extremity, (ibid.).

Deane et al. (2006: 2) observed that this zone of maximum deformation "… is the most impressive part of the Dycus Disturbance to visit, with dips as high as 85°, tight folds, and an overall chaotic nature …"

Mitchum (1951:18) noted that the zone of greatest deformation in the Dycus Structure was apparently 20 to 35 meters higher than the depressed area surrounding it. This area was considered an annular depression although it had been lowered by at least 42 meters below its normal position, and it surrounded what Mitchum referred to as 'the central uplift'. In addition, Mitchum (ibid.) noted that the basal granular facies of the Leipers Formation was at least 43 meters below its normal position found just to the east of this central disturbed area, and

> This down-bowing affects the entire structure and all the other major structural features are subordinate to it. The central uplift, although higher than the surrounding depressed area, is lower than its normal altitude, since the magnitude of the lowering is greater than that of the uplift. The ring-shaped fold is superimposed on the flanks of the depressed area as are the peripheral faults. (ibid.).

However, there was not much deformation on the outer flanks of the depressed area "… except for the gentle to steep dip into the center." (Mitchum, 1951: 19). Moving toward the center, though, Mitchum (ibid.) noted the increasing deformation and radial folds that were superimposed on the structure from the depressed area to the central area of uplift.

A short distance to the north the beds were vertical and then they remained nearly vertical for some distance. Overturned beds were also seen along some of the folds. As an example, an anticline in the east-central section of the disturbance was overturned to the west and an anticline striking northeast-southwest was overturned to the northwest (ibid.). Figure 4 is a map of the anticline trending northeast-southwest, and shows the outcrop, strike, and dip involved in the fold.

Concerning this anticline, Mitchum (1951: 20) stated that "The disturbed attitude of the rocks precludes a complete understanding of the folding …" He noted that it was only as the zone of most intense deformation was approached that the beds were overturned, however

> … it appears that the northwest limb remains overturned and that the dip of the southeast limb gradually increases along the axis, the beds first becoming vertical, then overturned and dipping very steeply to the northwest. Both the northwest and southeast limbs are overturned at this location. Farther to the northeast, the surface manifestations of the fold are terminated where the beds, still overturned, swing around the nose of the fold. (ibid.).

Rock layers were found throughout the Dycus Structure to be tilted at all angles, some vertical, others overturned. Figure 5 includes two photographs of moss-covered rock layers standing vertically, or nearly so, in the disturbed area.

The general fold pattern in the Dycus Structure was radial, and Mitchum (1951: 22) noted the existence of a circumferential anticline on the outer flanks of the depressed area which "… forms a semi-circle around the exposed portion of the disturbance …" This semi-circle had a radius from 365 to just over 425 meters , and the limbs of this ring-shaped anticline showed gentle dips which never exceeded 14 degrees in the central and eastern exposures and never exceeded 20 degrees in the rest of the structure. Although the dips were somewhat steeper and the vertical movement had been greater than elsewhere in the structure, the intensity of deformation was less than in the central zone (ibid.).

Mitchum (1951) noted that there was a syncline located between the dip into the central zone of greatest disturbance and the reversal of the dip on the outer part of the ring-shaped anticline. Its axis was concentrically parallel to that of the anticline, and just over 90 meters from it. Two faults were located on the outer periphery of the ring fold which Mitchum interpreted as being medium to high angle normal faults. Though he was unable to determine the displacement of one of these faults, he noted that

Figure 5: Two views of rows of moss-covered rocks standing on edge in the Dycus Structure. The view on the right is downrange from the photograph on the left: the distant dark rock in the center top of the left hand photograph is the same dark rock slightly to the right of center in the right hand photograph and just beyond the foreground tree. Note the slight change in direction of the rows just beyond the dark rock in the right hand photograph (photograph: Jana Ruth Ford).

a key bed was offset by the fault by at least 6 meters vertically and over 60 meters horizontally. He construed that pre-existing joint planes influenced the orientation of the two faults by offering the least amount of resistance to re-adjustment, thereby causing the lack of expected parallelism with the peripheral folds. The faults along the southwest section of the central zone and the relatively greater intensity of folding of the southwest section of the ring anticline were significant in Mitchum's view, indicating "… a higher degree of deformational intensity in this section than in any other part of the exposed periphery …" (Mitchum, 1951: 24). Breccias composed of angular fragments of limestone up to 7 or 8 centimeters long were found along the fault planes imbedded in a limestone matrix.

Mitchum (ibid.) noted the lack of interesting features beyond the disturbed area. Outside the zone of peripheral faults the rocks were undisturbed, except for a gentle dip into the central area of the disturbance. With increasing distance from the center this dip gradually decreased until the rocks approach their normal approximately horizontal attitude.

2.4 Crypto-Controversies

Bucher (1963: 1242) described a 'cryptovolcanic structure' as being a

> … roughly circular structure … [that] consists of: (1) a central uplift within which the strata are highly contorted and broken up, surrounded by (2) a more or less continuous ring-shaped depression which tends to be bounded and cut by faults.

Dietz (1946: 466; our italics) suggested that "Until the mode of origin of these features is definitely established, the present writer suggests that they be termed "*crypto-explosion*" structures." Dietz (1946: 465) stated that these cryptoexplosive structures were characterized by:

> (1) a roughly circular outline and a radial symmetry which, in some cases, was slightly bilateral; (2) a variation in size from less than a mile [1.6 km] to at least eight miles [12.9 km] in diameter …; (3) an intensely-shattered and jumbled central uplift surrounded by a ring-shaped depression and sometimes by other ring-shaped uplifts and depressions of diminishing amplitude forming a 'damped-wave' structure; (4) the central part of these structures contained sheared, shattered, and powdered rock and, in some cases, 'shatter-cones' which were indicative of explosive shock; and (5) volcanic, plutonic, or hydrothermally-altered rock was not found.

Dietz (ibid.) also noted that "Identified examples of these structures in the United States include the Flynn Creek disturbance in Tennessee, the Wells Creek Basin structure in Tennessee, [and] the Howell disturbance in Tennessee …", while Mitchum (1951: 26–27) argued that the Dycus Structure should be included in this list:

> Any acceptable theory of origin for the structural features in the Dycus area must explain the following: (1) a circular localized area of intense deformation in a region of relatively undisturbed strata; (2) a central uplift which is at least 70 feet [20 meters] above the surrounding depressed area, but which is below its normal position in that region; (3) an annular area depressed at least 140 feet [45 meters] below its normal altitude in that region; (4) a pattern of radial folds superimposed on the depressed area; (5) at least two peripheral faults outside the ring-shaped fold; and (6) the fact that folding is more prevalent than faulting in the structure.

Furthermore, Mitchum (1951: 27) pointed out that there were striking similarities between the Dycus Structure and the general description of a cryptovolcanic, or cryproexplosive, structure:

> The most striking similarities include the localized nature of the disturbance, the roughly circular plan, the central uplift, the annular depressed area, and the ring-shaped folds. The intense structural derangement in the center of the disturbance, as well as the lack of any volcanic materials, conform to the requirements for cryptovolcanic structures.

Mitchum (1951: 28–29) also noted a similarity between "… the ring-shaped folds of the Dycus structure … [and] a series of marginal ring-shaped concentric folds …" that surrounded the central uplift of the Wells Creek Basin. He pointed out that they differed only in size and intensity (ibid.).

However, there also were differences between the Dycus Structure and most other recognized cryptoexplosive structures: (1) Most of the disturbance seemed to be the result of folding rather than faulting; (2) As a result, there was correspondingly less breccia; (3) The intensity of deformation was not as great as is usually found in other structures; (4) The radial folds were more distinct than in most other structures; (5) The central uplift was far less important than the depressed area, both vertically and horizontally (Mitchum, 1951: 27). Furthermore,

> In most cryptovolcanic structures the rocks of the central uplift have been raised above their normal position in the region, but, at Dycus, although the rocks are raised above the immediately surrounding depressed area, they are below their normal position in the region … [and] The movement appears to have been predominately downward. (Mitchum, 1951: 27–28).

Historically, cyptovolcanic or cryptoexplosive structures have been attributed to a variety of causes, most of which were refuted by Mitchum (1951: 30; our italics):

> In the Dycus Disturbance, the high degree of folding and the central uplift would tend to eliminate the collapse of a cavern roof as a possible origin. An origin by the intrusion of a salt dome, or the expansion caused by the hydration of anhydrite, is unlikely, since there are no appreciable salt or anhydrite-gypsum deposits in the rocks of Central Tennessee (Wilson and Born, 1936, p. 829). A natural gas explosion is not likely since the Ordovician rocks of Central Tennessee are not known to have large accumulations of natural gas. Furthermore, according to Wilson and Born (1936, p. 830), a natural gas explosion has never been known to produce a structure similar to the localized circular structures of Tennessee. *The only origins that cannot readily be eliminated are those postulating a cryptovolcanic (gas and steam) explosion and a meteoritic explosion*.

Having said that, he then addressed the cryptovolcanic option:

> The strongest argument against the cryptovolcanic explosion theory is that no igneous materials, alteration products, or metamorphic rocks have been found around any of the true cryptovolcanic structures. Furthermore, they occur in areas marked by lack of volcanism. It seems unlikely, also, that the texture of the rocks near the surface, especially in a limestone section, would be such that it could confine magmatic gases and steam to the point where pressures could increase enough to produce such an explosion. (Mitchum, 1951: 32–33).

Mitchum (1951: 38) then pointed out that

> The facts that the deformational intensity is not as strong as in other structures and that the action was predominately downward, with a relatively minor central uplift, probably add weight to the meteorite hypothesis of origin.

He noted (Mitchum, 1951: 33–34) that most energy during an impact event would be in the form of vibrational shock waves which would radiate outward from the center of the explosion, forming the wave structure that surrounded the uplifted area of most cryptoexplosive structures. However, those structures that are seen today have experienced significant erosion, and so are actually the roots—the basements—of the original explosion craters (ibid.). Mitchum (ibid.) concluded that if the erosion was sufficient, the crater would not be preserved today, and the existing surface would be below the original level where the most intense faulting and brecciation took place (ibid.). The current surface, therefore, would show deformation predominately caused by folding, so if the Dycus Structure was a heavily-eroded impact site, then the fact that the deformation found there was less intense would be readily explained by the fact that the "… impact is a near-surface process, [so] the deformation associated with impact structures dies away rapidly with depth …" (French, 1998: 29). The amount of elastic rebound would decrease with depth, and in the case of a deeply-eroded structure the amount of central uplift probably would be subordinate to the down-bowing action. After accessing the available evidence, Mitchum (1951: 38) concluded that the Dycus Structure

> … may serve as an example of a deeply eroded explosion structure and afford some knowledge of the mechanics of the deformational stress at depth …

2.5 Cratering Mechanics

Although the majority of suggested origins of the Dycus Structure can be eliminated on the basis of the available evidence, to date a meteoritic origin has not been proven. But if, in fact, this is the relic of a meteoritic impact then it must be defined as an aberrant impact structure. This is because examination of Mitchum's 1:2400 scale geological and tectonic map (see Figure 3) shows that the Dycus Structure is not circular, even though the boundary of the structure is not fully defined on this map (Deane et al., 2006: 2). Yet at the time he conducted his thesis research Mitchum (1951: 15) believed that the structure probably was "… roughly circular … [and that the] uncovered portion of the disturbed area is limited to that of an approximate half-circle." He further presumed (ibid.) that about half of the structure was covered by rubble and debris from younger formations, and he also assumed that the "… small, relatively subordinate central uplift occupies the approximate center of the disturbance and marks the area of most intense deformation …" (ibid.).

One important question that immediately arises is why a structure that is only 600 meters in diameter would have any sort of central uplift. Simple craters are small, bowl-shaped structures without central uplifts, while complex craters are larger structures that "… display a different and more complicated form, characterized by a centrally uplifted region, a generally flat floor, and extensive inward collapse around the rim …" (French, 1998: 24). Here on the Earth the transition from a simple to a complex crater occurs at a diameter of around 2 km in sediments and 4 km in massive crystalline rocks (ibid.). Either Mitchum is correct in his assumption that there is a central uplift—which suggests that the structure is larger than is shown on his map—or else the structure is not circular and the uplift, as seen in the cross-section through the Dycus Structure (shown at the bottom of Figure 3), is not centrally located. Later investigations supported this latter conclusion:

> Continuing to the northeast, beyond Mitchum's

> map, the same strata are exposed in Long Branch Hollow and lie well within the 0.6 km radius of this proposed central uplift. Our field investigation in Long Branch revealed flat-lying rock with no deformation. Therefore, the area of maximum deformation does not lie in the center of the structure, but rather defines the northeastern boundary … While we have confirmed the occurrence of the deformation to the northeast, we have extended the northern boundary a couple hundred meters farther north with the discovery of bedding dipping 8° radially away from the structure …. (Deane et al., 2006: 2).

Although the Dycus Structure is slightly larger than Mitchum realized (ibid.), it is oval in shape rather than being circular. The similarity of this structure to the unusual lunar crater Schiller is striking, and is discussed in Section 2.6 below.

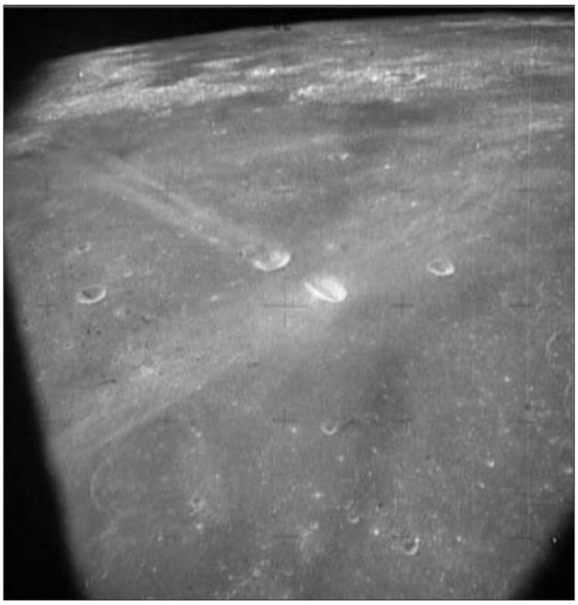

Figure 6: A NASA Apollo 11 photograph showing a close-up of the lunar craters Messier A (left) and Messier (right), with Messier A's two prominent downrange ejecta streaks and Messier's butterfly ejecta (after Forsberg et al., 1998: 1).

Unusual impact craters and structures can result from unusual formation conditions regarding either the impactor, its trajectory, or the target body. Kenkmann and Poelchau (2008b: 1) refer to craters formed by an impact of between 15° and 35° from the horizontal as 'oblique' and those formed by an impact of less than 15° from the horizontal as 'highly oblique'. They continue, noting that "… crater outline is insensitive to the impact trajectory and remains circular with the exception of highly oblique impacts." (ibid.). These very shallow or grazing impacts will result in craters with butterfly-shaped ejecta blankets as shown by the lunar impact crater Messier A in Figure 6 (ibid.). Hessen et al. (2007) found that impact craters 15° or greater from horizontal remain circular, but become increasingly more elliptical as the angle of impact decreases. Ejecta blankets become asymmetrical around 60° from horizontal and develop an up-range forbidden zone around 20° that continues to increase as the angle decreases (ibid.). Since ejecta blankets for terrestrial impact structures, however, are subject to erosion and not likely to be preserved, other "… unequivocal attributes for oblique impact craters such as … elliptical outlines …" can be utilized as indicators of highly-oblique impact (Kenkmann and Poelchau, 2008b: 2).

A detailed examination of the oblique impact scenario for the Dycus Structure will be presented by Beech, Ford, Orchiston and Clendening in a later paper.

2.6 Comparisons with Lunar and Terrestrial Oblique Craters

Kenkmann and Poelchau (2008b: 1–2) discuss oblique impact craters as follows:

> Statistically, 50% of all collisions of asteroids or comets occur at angles of less than 45°, and about 7% at angles less than 15° … Experimental and numerical studies have shown that the distribution of peak shock pressures within the target is asymmetrical in the case of oblique impacts with a concentration down range … With regard to experimental and numerical studies of oblique impact cratering, we infer that this lateral displacement component reflects a shift in the onset of crater collapse and the migration of the up-lifting crater floor down range, i.e. in the impact direction …

These researchers did state, however, that

> … a systematic offset of the central uplift with respect to the crater center could not be verified … [although] unequivocal attributes for oblique impact craters … [include] elliptical outlines … (Kenkmann and Poelchau, 2008b: 2).

In other studies of lunar craters that are considered to be the result of oblique impacts, preliminary results show that in all of these craters the central peak is located away from the geometrical center, with a slight trend that it is offset in the downrange direction (Goeritz et al., 2009).

The lunar crater Schiller is an example of an elliptical crater in which the uplifted area is a linear central ridge that is located at the northern end of the structure (see Figure 7). Schultz (1992) considers that oblong 'Schiller-like' craters are the result of grazing impacts, and an investigation by Herrick and Forsberg-Taylor (2003: 1554, 1557, 1565) of craters formed by oblique impacts produced

> … experimental results that show the rim lowered in the uprange direction and ejecta concentrated in the downrange direction for impact angles below 30° ... the crater becomes highly elongated in the downrange direction … [and] In some cases, the low point of the rim for an oblique impact is at the level of the surrounding terrain …

Other researchers have posed the question, "Is Dycus a secondary of Flynn?" (see Deane et al., 2006: 2), and this aspect also will be discussed later by Beech, Ford, Orchiston and Clendening. Perhaps the relationship between the Dycus Structure and the Flynn Creek impact scar is that they are double craters formed during the grazing impact of a single impactor that skipped on impact similar to the impact that formed the lunar craters Messier and Messier A (Herrick and Forsberg-Taylor, 2003). Messier and Messier A are the only known example of a pair of low angle ricochet craters on the lunar surface (Melosh, 2002). The Dycus Structure is just 16km from Flynn Creek, and Stratford (2004: 22) believes that they may be the result of a double impact. Bottke and Melosh (1996: 389) note that ~15% of all Earth-crossing asteroids should have satellites, and therefore "The steady-state binary asteroid pop-ulation in the Earth-crossing asteroid region is large enough to produce the fraction of doublet craters found on Earth and Venus (~10%)." Rampino and Volk (1996) also discuss the possibility of multiple impact events during the Paleozoic.

Oblique impact events here on the Earth are exceedingly rare, so "It is the rarity of such impacts that potentially makes the Dycus structure so very interesting." (Martin Beech, pers. comm., September 2014).

The only known confirmed terrestrial impact crater caused by an oblique impact is the Matt Wilson Structure in northern Australia which is described by Sweet et al. (2005) and by Kenkmann and Poelchau (2008a).

Still of questionable origin (see French, 2004) are the ten or eleven elongate depressions in the Pampean Plain north of Rio Cuarto, Argentina that are considered by some to be the possible result of a low angle, highly oblique impact (Bland et al., 2002; French, 2004). However, satellite images revealed "… nearly 400 elongated depressions of nearly identical morphology …" in the surrounding area that are "… aligned with the prevailing wind direction …" (Melosh, 2002: 1037). The Rio Cuarto structures were considered to be aeolian features until impact-produced glasses and two meteorites found in one of the depressions convinced some researchers that these were indeed impact craters (Bland et al., 2002; Melosh, 2002). If these are impact-produced structures, then according to Beech (2014) the most likely scenario involved a coherent mass travelling at low speed, ~5 km/s, with an angle of impact of <5°. However, the origin of these features is still controversial.

According to Melosh (2002: 1037), "The discovery of meteorites and impact-produced glass in the craters swept away all criticism …", however, the variation in long-axis orientations of these features is "… difficult to reconcile with the break-up and ricochet of a single impactor, but supports an Aeolian formation mechanism …" (Bland et al., 2002: 1110). Two more meteorites found in the depressions were studied and found to be different classes of meteorite, one of which fell around 36,000 years ago and the other >52,000 years ago, rather than fragments of a single impactor (Bland et al., 2002; Melosh, 2002). In addition, while "… it is clear that the glass found at Rio Cuarto is derived from an impact …", evidence indicates that these glasses "… are representatives of a wide-spread tektite strewn field in Argentina with an age of ~0.48 Ma …" (Bland et al., 2002: 1111). The glass is older than either the meteorites or the craters, which are estimated to be ~ 4,000 years (Bland et al., 2002: 1110; Melosh, 2002).

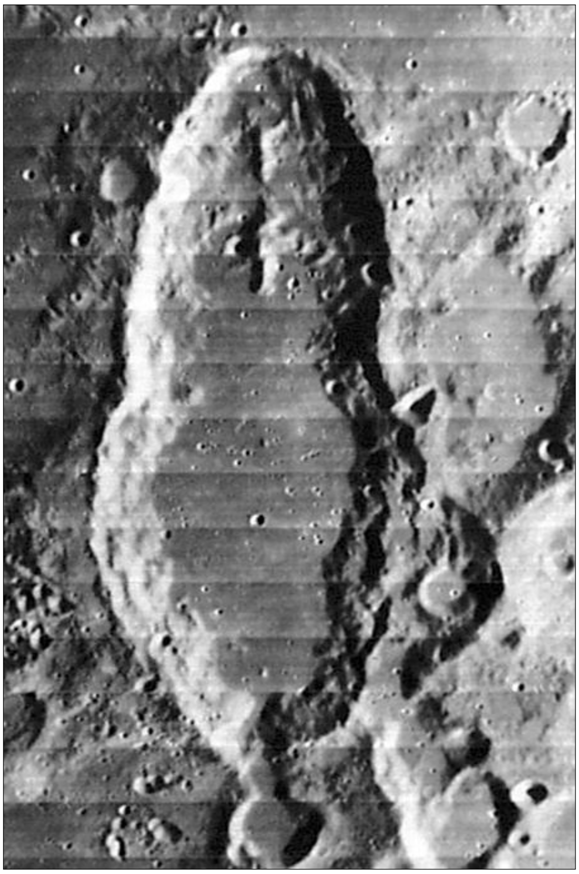

Figure 7: The elongated crater Schiller. Note the uplifted ridge located near the crater's edge in the top of the photograph (Lunar Orbiter IV image IV-155-H1).

Melosh concludes that Bland et al. (2002) have "… revealed, not an oblique impact crater, but a much larger strewn field of tektites …" (ibid.). Schultz et al. (2004: 236), however, maintain that "… the hypothesis of a recent oblique impact for the RC [Rio Cuarto] materials (and some of the structures) not only remains viable, but is also consistent with data in hand." These researchers conclude that at least two different impact events with clearly distinguished ages can be recognized at Rio Cuarto, one around 3–6 ka and the other about 114 ka (ibid.). The Rio Cuarto glasses are believed to represent impact melt breccias and "… do not meet the established criteria for tektites …" but incorporate near-surface material which is "… consistent with shallow excavation by an oblique impact (or near-surface break-up) …" (Schultz et al., 2004: 236–237). If the Rio Cuarto elongate structures are proven to be impact generated, then comparison with the similarly-elongated Dycus Structure and Schiller may provide an explanation for these enigmatic structures.

3 CONCLUDING REMARKS

Although first investigated decades ago, the Dycus Structure has received little attention from those researching meteoric impacts (see Deane et al., 2004: 1). Mitchum investigated this site in 1951 and recorded steeply-dipping beds which indicated that some sort of explosive event took place in a small, localized area within a region of Tennessee that is otherwise noted for its horizontal and undisturbed lithology. Gently dipping beds just to the northeast of the area of greatest deformation indicate that though the structure's boundary is likely somewhat farther north than is shown on Mitchum's 1951 map, this structure is not circular. However, the decrease of the bedding angles in this same direction indicates that the boundary does not extend any great distance beyond that which was originally mapped, indicating that it is not large enough to be a complex crater with a central uplift. Shatter cones are a distinctive easily-identified feature of craters caused by meteoric impact (e.g. see Dietz, 1959, 1960; Milton, 1977; Sagy et al., 2004), but no evidence of these was found by Mitchum during his 1951 survey of the Dycus Structure, or by Larry Knox, Marvin Berwind, and the first author of this paper when they visited the site in March 2012. Nonetheless, Mitchum (1951: 38) believes that the accumulated evidence "… adds weight to the meteoritic hypothesis of origin …", while Officer and Carter (1991) feel that there is insufficient information to assess the origin of the Dycus Disturbance.

Clearly what is needed is evidence of shock metamorphism that can be attributed to impact cratering. Planar fractures (PFs) and planar deformation features (PDFs) in quartz grains often are diagnostic of such impacts (French, 1998), as are the high-pressure silica minerals coesite and stishovite, but in deeply-eroded sites like the Dycus Structure all traces of these will have vanished.

As French (2004: 177) has pointed out, our knowledge is incomplete and "The deformation of quartz is a fundamental problem … in shock and impact studies." To date,

> … field and experimental studies of shock-metamorphic features in quartz have concentrated on the unique features (e.g., PDFs) formed at high shock pressures ($\geq$ 5 GPa), which are diagnostic for meteorite impact.
>
> … virtually no information exists on quartz deformation in rocks subjected to still lower shock pressures (e.g., < 5 GPa) where the peak stresses (but not the strain rates) may be similar to those produced under tectonic conditions. (French, 2004: 178).

The greater volume of target rock during impact, primarily the basement rock, is subject to lower pressure shock waves, which raises the questions "What deformation features in quartz are produced by shock waves at pressures, <5 GPa?" and "Can such features (like PDFs) also be used as unique and diagnostic indicators of shock waves and meteorite impact?" (ibid.). If low-shock features unique to impact can be identified, then the question of whether deeply-eroded sites like the Dycus Structure are of meteoritic origin may be resolved.

Regrettably, until such evidence is assembled, the Dycus Structure must remain a suspected impact crater.

4 NOTES

1. Slickensides are smoothly polished rock surfaces with parallel striations caused by frictional movement between the rocks along two sides of a fault. The striations are usually in the direction of movement indicating slippage along bedding planes.

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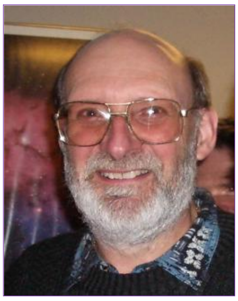

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