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THE WELLS CREEK METEORITE IMPACT SITE AND CHANGING VIEWS ON IMPACT CRATERING

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Abstract: Wells Creek is a confirmed meteorite impact site in Tennessee, USA. The Wells Creek structure was first noticed by railroad surveyors around 1855 and brought to the attention of J.M. Safford, Tennessee's State Geologist. He included an insert in the 1869 Geologic Map of Tennessee, which is the first known map to include the structure. The origin of the Wells Creek structure was controversial, and was interpreted as being either the result of volcanic steam explosion or meteorite impact. It was only in the 1960s that Wilson and Stearns were able to state that the impact hypothesis was preferred. Evidence for a Wells Creek meteorite impact includes drill core results, extreme brecciation and shatter cones, while a local lack of volcanic material is telling. Just to the north of the Wells Creek Basin are three small basins that Wilson concluded were associated with the Wells Creek impact event, but evidence regarding the origin of the Austin, Indian Mound and Cave Spring Hollow sites is not conclusive.

Keywords: Wells Creek, Tennessee, impact crater, extreme brecciation, shatter cones, J.M. Safford

1 INTRODUCTION

The state of Tennessee in the USA boasts two undisputed impact craters, Wells Creek and Flynn Creek, and two possible impact craters, the Dycus Structure and the Howell Structure (e.g. see Berwind, 2006, 2007; Deane et al., 2004; 2006; Evenick, 2006; Evenick et al., 2004; Milam et al., 2006; Mitchum, 1951; Roddy, 1977; Schedl et al., 2010; Schieber and Over, 2005; Stearns et al., 1968; and Woodruff, 1968). Of these, the Wells Creek site has played a major role in increasing our awareness of the nature of terrestrial impact cratering, and is referred to by Dietz (1963: 650), not as the 'prototype', but rather as the 'syntype' cryptoexplosion structure for the United States. As such, the knowledge gained from its recognition as an impact structure is worth revisiting.

Impact cratering was the dominant geological process in our Solar System, and was responsible for shaping surfaces on the terrestrial planets and their moons, and on the asteroids (Melosh, 1989). Shotts (1968: 459) points out that "For lunar craters, diameter and depth of floor can be measured, but neither true depth below the original surface nor depth of brecciation can be measured." These last two can be determined for terrestrial impacts, though, and the knowledge gained applied in studies of our Solar System. Despite the advances made in our understanding of Solar System impact cratering, it took many years before the idea that the Earth also was subjected to these bombardments was widely accepted by astronomers and geologists (e.g. see French, 2004; Reimold, 2003; Reimold and Koeberl, 2008).

In her catalog of meteorite impacts sites O'Connell (1965: 1) states that

> … the study of terrestrial craters and similar geological features of known and possible meteorite-impact origin … has become a major interdisciplinary effort carried on by astronomers as well as geologist and by other scientific specialists such as geophysicists and astrophysicists.
>
> But these books are written by, and primarily for, astronomers, whose main interest in terrestrial meteorite craters is their many analogies to lunar craters. Otherwise, information about terrestrial craters is widely scattered throughout the scientific and general literature, where it is presented in many forms ...

Accordingly, she prepared her 1965 catalog in an attempt to index "… this widely scattered and often elusive material … [in response to] the difficulties encountered in gathering material." Likewise, much of the material regarding the Wells Creek impact site is scattered through the seemingly-unrelated astronomical and geological literature. This paper reviews the compiled information on the Wells Creek structure generated by researchers during the past one hundred and fifty years.

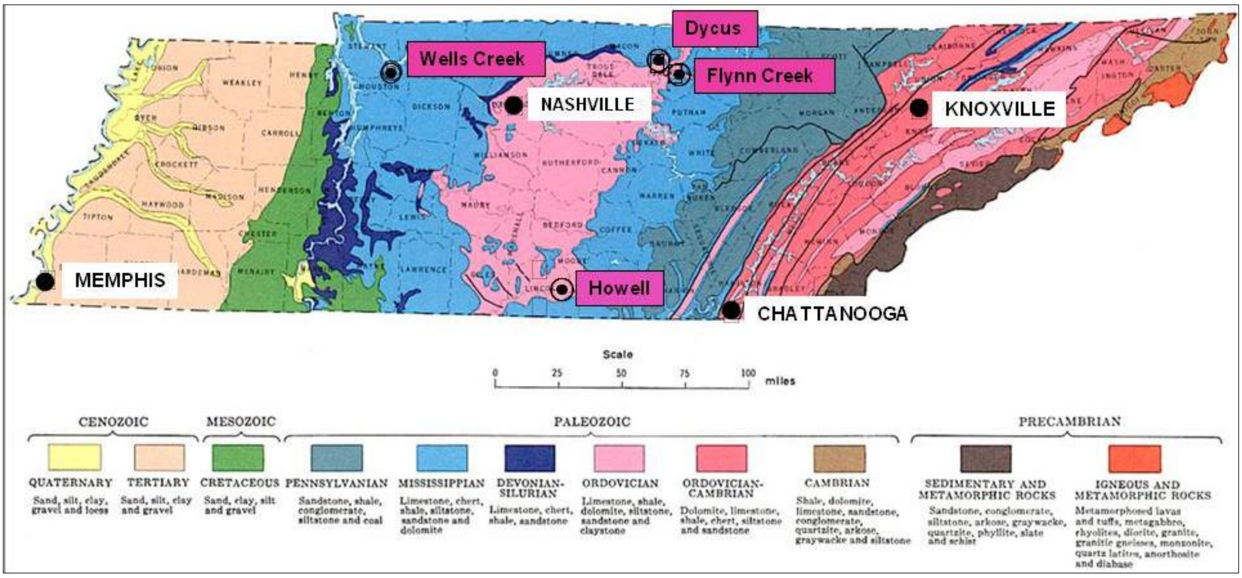

Figure 1: Generalized geological map of Tennessee showing the locations of the four largest cities (black dots) and the two confirmed and two suspected meteorite impact sites (small black dots with circles). These sites are located on the Highland Rim (Wells Creek), a Highland Rim outlier remnant (Howell), 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).

2 TENNESSEE GEOGRAPHY AND GEOLOGY

Situated in eastern, south-central USA, Tennessee is a long narrow state. Figure 1 is a geological map of the state and shows the four largest cities, and the locations of two confirmed impact sites, Wells Creek and Flynn Creek, as well as the two suspected impact sites, Howell and Dycus.

The Wells Creek structure (36°23′ N, 87°40′ W) is located about 210 meters above sea level in the northern part of middle Tennessee, in a region known as the Western Highland Rim. This forested area is characterized by rolling terrain and is graced by numerous creeks and streams. The Wells Creek Structure is about 13.7 km in diameter and is situated to the south of the Cumberland River. It is not easily discernible on aerial or satellite photographs (cf. Stratford, 2004: 10). This is not surprising as Dietz (1963: 653) notes that “Most structures of this type do not stand out on aerial photos.”

However, Wells Creek does stand out as a ‘bullseye’ on geological maps of Tennessee (Miller, 1974: 9). Tennessee was covered by shallow seas during most of the Mississippian Period, 345 to 310 million years ago, and sediments were deposited then which now cover most of the Highland Rim. Rocks comprising the Knox Group, deposited earlier, during the Ordovician and Cambrian Periods, 500 to 425 million years ago, are exposed in only two locations in the Highland Rim, namely at the Wells Creek and Flynn Creek impact structures (Miller 1974: 19). Figure 1 shows the distribution of exposed rock units across the State and on the original version of this map the Wells Creek site is obvious, displaying uplifted older rocks surrounded by younger rock units.

3 HISTORICAL CONTEXT

In August 1854 the Memphis, Clarksville, and Louisville Railroad started work on a new railway line which would eventually run from Paris (Tennessee) to Guthrie (Kentucky) via the Wells Creek Basin (Price, 1991). Engineers and surveyors noted the area’s strange, twisted rocks and tilted bedding planes which stood out in stark contrast to the region’s usual horizontal stratigraphy.

Dr J.M. Safford’s first report as State Geologist of Tennessee in 1855 included a geological map of the State, but did not show the Wells Creek structure. The structure, however, was included in his 1869 Tennessee geological map, with descriptions given on pages 147-148, 220, and 257 of his report. Figure 2 is the geological map of Tennessee that Safford

Figure 2: Safford’s 1869 Geological Map of Tennessee (courtesy: Birmingham, Alabama Public Library Cartography Collection).

drew to go along with his 1869 report. In addition, a detailed geological map of the Wells Creek structure was placed in the corner of the main geological map of Tennessee (Wilson and Stearns, 1966: 37). Figure 3 shows this inset, which is titled "The Well's Creek Basin in Stewart Country". Safford (1869: iv-v) indicated in the report's preface that "A great amount of labor has been bestowed upon the Map … Aside from its Geology, the Map, so far as it goes, is the best geographical map of Tennessee yet published." In this report, Safford (1869: 147; his italics) states that there are exceptions to the generally-horizontal positions of the rock layers he located in Tennessee's Middle Division, and that

> The most interesting of these localities is in the region of Cumberland City, a small town on the Cumberland River, in Stewart County. This town is on the side of an elliptical area, or basin, containing six or seven square miles, and surrounded by hills. The river cuts through the northern end of the basin. Wells Creek enters it on the south and flows through it to the river. From this circumstance I have named it the *Wells Creek Basin*. Within this area the strata are highly inclined. We have here a very considerable upheaval of the formations. The strata were lifted in a high dome, the top of which has been worn and washed away.

Safford notes that the lowest strata have been elevated at least 760 meters and that the dip is found to be at high angles, even vertical at some points. He also points out that the Wells Creek disturbance is not confined to the Basin, but extends several kilometers beyond Cumberland City and that the rock lay- rock layers are folded, fractured and dislocated, and have inclinations at all angles (e.g. see Figure 4). This deformation is confined to the rocks of the Lower Carboniferous. Safford (1869: 220) refers to Wells Creek as the "… exceptional spot, in Middle Tennessee, showing outcropping Knox Dolomite …" and he notes that the basin is highly valued for farming. Furthermore, "The dome has a depression all around it – a ring of valleys, in which outcrops the Trenton, Nashville, and Niagara rocks." (ibid.).

J.B. Killebrew and Safford gave a more detailed description of the central part of the Wells Creek basin on pages 761-762 of their 1874 monograph:

> This is an area, nearly circular, containing six or seven square miles, and touching the Cumberland River. Wells' Creek runs through it, the rocks in the basin dip at a very great angle, and in some places are nearly vertical. *There are evidences of a terrible subterranean convulsion at one time*. (Our italics).

Between 1889 and 1893, based on the dates listed in their field notebooks, Safford, who was by then a Vanderbilt University Professor, and W.T. Lander, a Vanderbilt Graduate Fellow, mapped the structure in detail (Wilson and Stearns, 1966: 37). It was during this time that the actual size of the Wells Creek structure was recognized. Their circa 1895 manuscript based on this field work includes a geological map and cross sections. According to Wilson and Stearns (ibid.) "… this manuscript with its map and drawings is probably the first detailed geologic report on a cryptoexplosive (perhaps meteor impact) structure in the United States." Wilson (1953: 755) believes that Lander also "… prepared a detailed manuscript on the annular rings of faults that encircle the central uplift (ca. 1899)." We doubt that this manuscript has

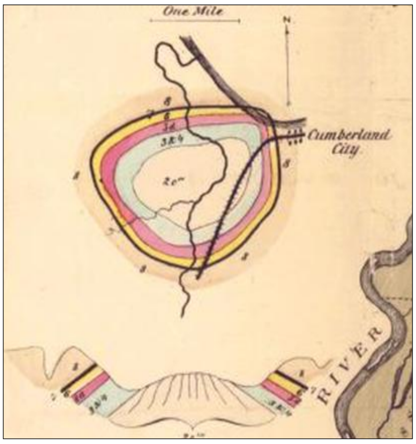

Figure 3: An enlargement of the small map inset on the upper left of Figure 2 (courtesy: :Birmingham, Alabama Public Library Cartography Collection).

Figure 4: A recent photograph illustrating "… the rock layers are folded, fractured and dislocated, and have inclinations at all angles." (photograph by the first author).

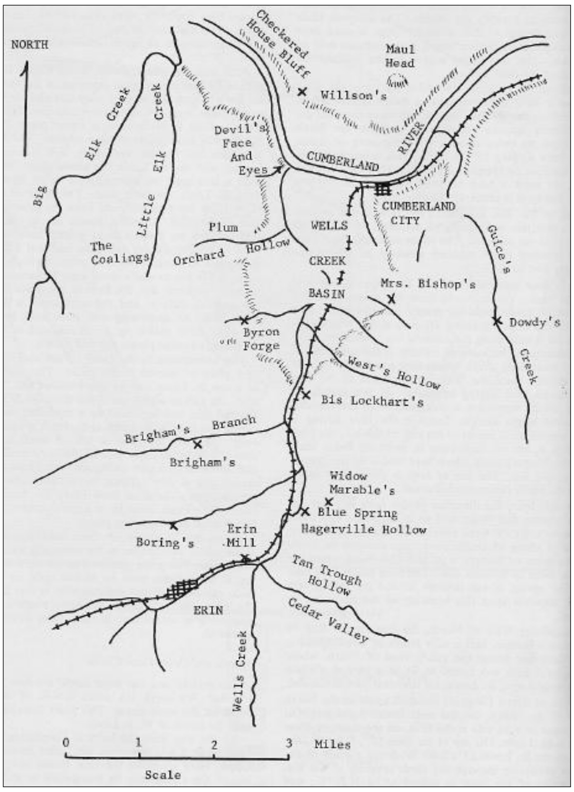

Figure 5: Safford and Lander's geographical map of the Wells Creek Basin (after Wilson and Stearns, 1966: 42).

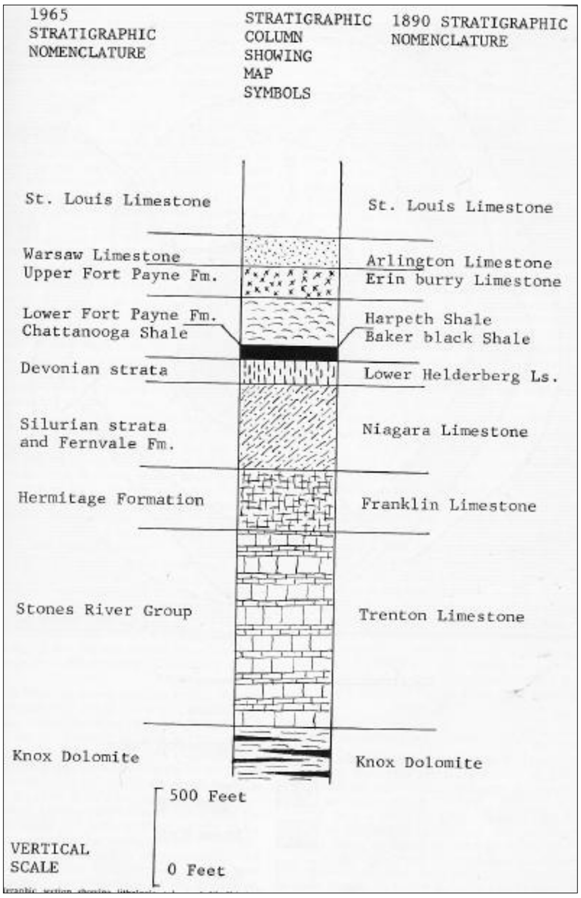

Figure 6: A stratigraphical section showing the lithological column with symbols as well as the stratigraphical nomenclature used in 1890 and 1965 (after Wilson and Stearns, 1966: 39).

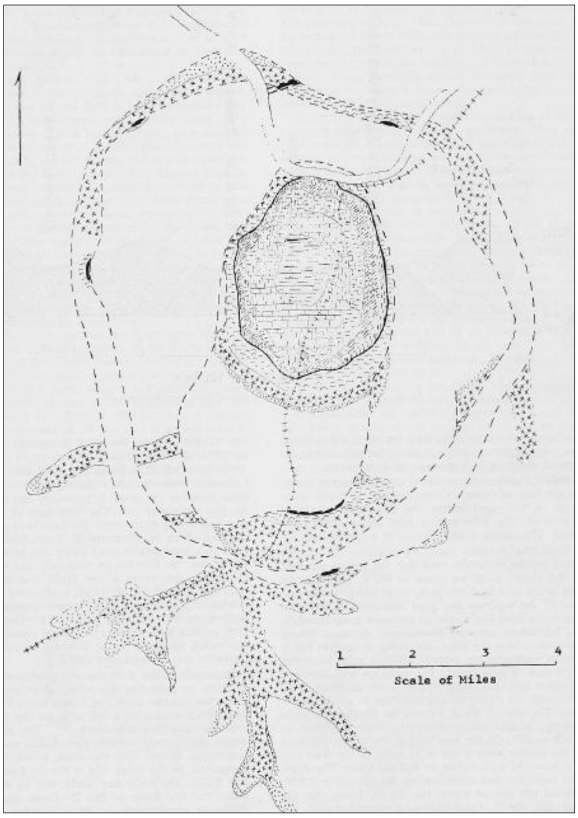

Figure 7: Geological map of the Wells Creek structure drawn by Safford and Lander circa 1895 (after Wilson and Stearns, 1966: 43).

survived as we were unsuccessful in locating it.

Figure 5 is a geographical map that shows the locations of the various features in Wells Creek that were studied and referred to by Safford and Lander in their 1895 manuscript (which was eventually published by Wilson and Stearns in 1966). Figures 1 and 3 record the formations of the Wells Creek basin they discovered. The nomenclature of the formations has changed over time and these changes in terminology are summarized in Figure 6.

Safford and Lander noted that the first five formations shown in Figure 6 were found to be confined to the central part of the Basin. The next five lay outside of and around the central part. It is in this outside area that the most striking faults were located (see Wilson and Stearns, 1966: 38). In an earlier publication, Killebrew and Safford (1874: 761-762) described their surprising findings:

> … a lower formation is never superimposed on a higher one without showing signs of great distress … This is precisely the case with the Wells' Creek basin. The center of the basin has been elevated by subterranean forces, and the elevation or cone swept away by abrasion. The surrounding rocks belong to the silicious group of the lower carboniferous formation; the other formations – the Black Shale of the Devonian, the lower Helderberg, and the limestone of the upper Silurian; the Nashville and Trenton limestones, and lastly, the Knoxville limestones of the lower Silurian, all appear in regular succession until the center of the basin is reached. Walking across the valley, all the formations are passed over twice, except the lowest – the Knoxville.

The Knoxville Dolomite marks the center of the Wells Creek structure and is the oldest geological formation.

Around 1895 Safford and Lander wrote that they "… found so many exposures of the Baker black shale on the rim of the Basin as virtually to make a continuous outcrop, evidently produced by the general Basin erosion …" (cited in Wilson and Stearns, 1966: 38). In their circa 1895 manuscript Safford and Lander stated:

> On locating these exposures, on the map, it was suggested that they were likely produced by a roughly circular fault surrounding the Basin. As the work continued, many observations and facts appeared to favor this view. But faults were found which could not be placed in this circle; so that it became manifest that, if there were one circle of faults, there must be two other concentric circles also. On the map, the three circles proposed are indicated, no fault being laid down except such as were carefully located …
>
> In defense of the proposition that there are three concentric circles of faults around the Basin, we not only offer a description of the faults found, but add that the position of most of them was predicted with satisfactory accuracy before they were visited; and furthermore, that no prediction as to the position of a fault was unverified, except in a few cases where no rocks were exposed to indicate the lay of the formation. (ibid.).

The geological map of the Wells Creek structure drawn by Safford and Lander around 1895 is shown in Figure 7 (after Wilson and Stearns, 1966: 43). Wilson and Stearns (ibid.) point out that "… the geology set forth is amazingly accurate, as anyone familiar with Safford's work would readily believe." It is interesting, though, to compare the map by Safford and Lander with the geological map of Wells Creek showing the fault patterns as they were understood in 1965 by Tiedemann, Marsh, and Stearns (see Figure 8). Figure 7 includes yet another main fault around the structure and shows that these circular faults define a set of concentric rings. Wilson and Stearns (1966: 47) note the excellent field work completed by Safford and Lander, but add that with the luxury of hindsight it is clear that

> … Safford and Lander found three faults everywhere around the structure. Unfortunately, they did not find the same three faults all the way around. They did not find the outermost fault in the northern portion of the structure … [where the] fault [is] difficult to see. In the southern part of the structure, they did not find the innermost fault, mainly because of unfavorable exposures.
>
> They connected the three faults known to them (through areas of scant exposure on the east and west sides of the structure) in such a manner that each fault on the north side connected with a fault of opposite vertical movement on the south side.

W.H. Bucher was the next to study the Wells Creek site, and he produced a geological map of the structure for the Tennessee Division of Geology that he included in his 1936 paper on cryptovolcanic structures. At the time this was the second known map of Wells Creek since Bucher did not know of the work of Safford and Lander; their circa 1895 manuscript was lost for sixty years, and was only published in 1966 (Stearns, 1988: 1). Wilson and Stearns (1968: 15) state that Bucher's (1936) paper and map "… showed his remarkable knowledge and understanding of the structure."

4 STRUCTURAL FEATURES

As Miller (1974: 55) points out, "The term cryptoexplosion was first used in 1959 (Dietz) to designate a generally circular structure that was formed in some manner by a natural release of energy …" This energy was thought to come from either a cryptovolcanic steam explosion driving rocks upward and outward, or a meteorite impact. A high-velocity meteorite, which possesses a large quantity of kinetic energy before penetrating the Earth's surface, will explode after impact resulting in a great release of energy. Shock waves will move outwards from the focus of the meteorite impact, forming ring synclines and anticlines. Baldwin (1949: 101) states that the Wells Creek structure is similar to that seen in "… high-speed pictures of a drop of liquid falling into water." This type of structure is a complex crater with a central uplift and two fault rings surrounding the basin. Figure 9 shows Baldwin's (1963: 50) idealized cross-sections of simple and complex craters indicating distortions of rock layers and zones of brecciation.

In 1947 the Ordman Company cored the Wells Creek Basin in the belief that it was a salt dome. The core was given to the Tennessee Division of Geology and studied in 1951 by R.E. Hershey and C.W. Wilson with the following results:

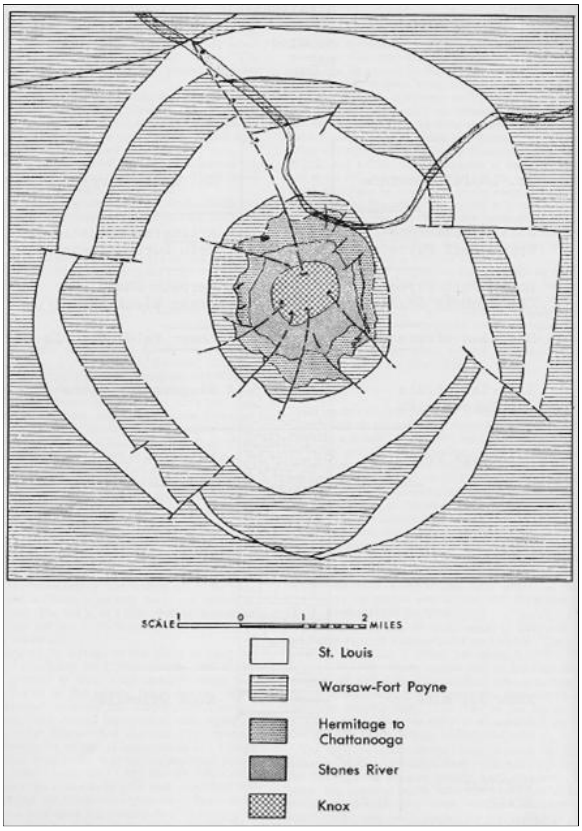

Figure 8: Geological map of Wells Creek Basin showing fault patterns as understood in 1965 (after Wilson and Stearns, 1966: 40).

> The core is essentially complete from a depth of 23 [7 m] to 2000 feet [610 m]. It started and bottomed in Knox dolomite …
>
> The injected breccia consists of a matrix of pulverized rock containing fragments of chert, limestone, and dolomite of great variety and usually less than half an inch [1.3 cm] in maximum dimension ... It is believed that the fragments in the breccia came from many of the formations present in the sequence …
>
> The examination of this core was an unusual privilege and in a way an eerie experience. The deep fingers of grotesque injection dikes and the intense, bizarre, ever-changing pattern of brecciation and deformation are awe-inspiring. Each new box of cores revealed new, strange, and different intricacies. (Wilson, 1953: 766).

Research on the Wells Creek Basin accelerated during the 1960s. The decision to undertake a series of manned landings on our Moon unleashed "… un-

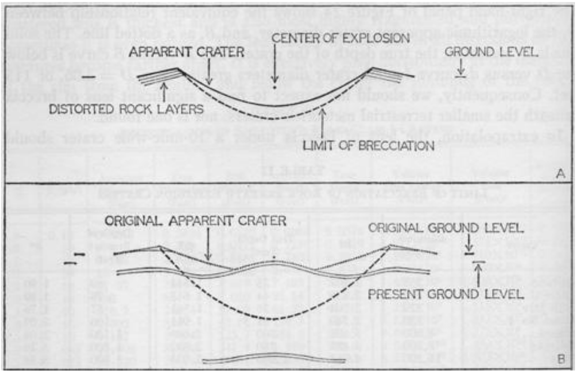

Figure 9: Idealized cross-sections through impact craters showing distortions of rock layers and zones of brecciation. At the top is the Odessa No. 1 crater, an example of a simple crater. Below is the Wells Creek Basin, an example of a complex crater (after Baldwin, 1963: 50).

heard-of levels of funding to research programs … and scientists in university, industry, and government labs were encouraged to do research on problems related to impact cratering." (Melosh, 1989: 11). Work on every aspect of impact cratering was stimulated. Accordingly, in 1963 NASA gave Vanderbilt University a grant to study the Wells Creek impact structure (Wilson and Stearns, 1968: 17), and most of the mapping and much of the information currently known and available concerning this site came from that study. Figure 10 is a map produced during this time showing the major structural features of Wells Creek (after Wilson and Stearns, 1968: 55).

Although Wells Creek is highly eroded, the structure's original faulting is still evident. The structure is about 13.7 km in overall diameter and Wilson and Stearns (1968: 3-4) describe it as having five structural subdivisions that are given below in order outwards from the center:

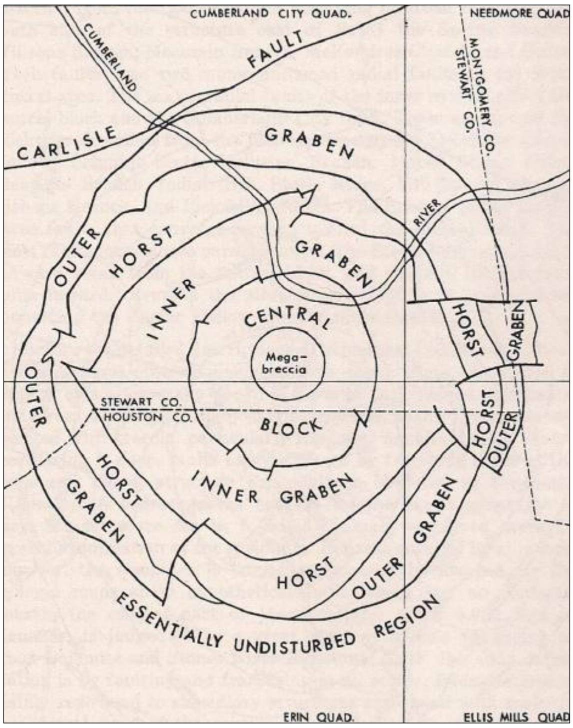

Figure 10: Map showing the major structural features of the Wells Creek structure (after Wilson and Stearns, 1968: 55)

(1) the circular central block – diameter 5.03 km, containing a circular core of megabreccia about 1520 m in diameter
(2) the annular inner graben, a downthrown block – width 1.83 km
(3) the annular horst, an upthrown block between two fault blocks – width 1.22 km
(4) the annular outer graben, a downthrown block – width 1.08 km
(5) the essentially undisturbed region surrounding the Wells Creek structure

The graben subdivisions dropped by as much as 170 m, while the rock at the center was uplifted by at least 760 m. The above dimensions were determined from surface measurements.

Wilson and Stearns (ibid.) also noted the structure's inward movement pattern. The dip of the outside fault of the outer graben is nearly vertical, but the inside fault dips outward from 30° to 60°. The result is that the outer graben narrows as the bounding faults converge with depth. Likewise, the dip of the outside fault of the inner graben is also nearly vertical; however, the inner fault dips steeply outward from 45° to 70°. Again the result is that the inner graben also narrows with depth. This means that the horst widens between the inner and outer grabens. Wilson and Stearns (1968: 89-92) note that although the outer edge of the central block does not appear to have moved from its original level as a result of the Wells Creek event, the cylindrical central block is uplifted in the center. 'Central Hill' rises some 137 meters near the center of the basin (Wilson and Stearns, 1968: 8). In this central block, a central zone 1.6 km in diameter is megabrecciated (Wilson and Stearns, 1968: 5). The conclusion is that the grabens dropped as material moved inwards when the central block was uplifted (Wilson and Stearns, 1968: 5-6).

Baldwin (1963: 108) points out that "…at larger impact structures, the anticline is itself bordered by a second ring syncline … and it is well developed at the Wells Creek Basin." He believes that the Wells Creek Basin structure originally was a 10 km diameter crater, and that it "… shows a definite ring syncline around it, and fragmentary indications of a ring anticline …" about 16 km in diameter (Baldwin, 1963: 109).

Wilson and Stearns (1968: 5) report that the uplifted central block consists of jumbled blocks of all sizes and megabreccia, and that it contains a core of Knox dolomite. The megabreccia includes both Knox and younger strata. They also note that "As well as can be measured, the volume of rock downthrown in the two ring grabens appears to be equal to the uplifted rock in the central block. This is consistent with the geophysical evidence that there is no intrusion at depth or uplift of basement rocks." (ibid.). Wilson and Stearns (1968: 4-8) believe that the horst and grabens are primarily exterior structures resulting from elastic rebound due to shock pressure following the impact and subsequent explosion. Hence, "The grabens occur where rock fell downward and outward into ring cracks; these ring cracks developed during inward movement of rock that formed the central uplift."

In his M.S. thesis S.M. Puryear (1968: 4) includes the following description of the Wells Creek structure. The outer graben is downfaulted 60 meters; the horst is basically level with the surrounding region, and the inner graben is downfaulted between 90 and 180 meters. The central cylinder of rock is uplifted at least 600 to 760 meters. The central uplift is topographically a 3.2 km basin. Puryear (1968: 27) believes there is a relationship between the general shape of the Wells Creek structure and two main joint sets that existed prior to the impact event, and he states:

> The Wells Creek structure demonstrates a pattern, especially the second and third concentric faults, which is "squarish" in shape. Shoemaker (1959) observed at Meteor Crater that "the regional jointing has controlled the shape of the crater, which is somewhat squarish in outline; the diagonals of the 'square' coincide with the trend of the two main sets

> of joints." Like Meteor Crater, Wells Creek shows a relationship between the shape of the structure and the trend of the two major joint sets. The two major joint sets parallel the diagonals of the square. (Puryear, 1968: 25).

Miller (1974: 56) also notes that the roughly circular inner basin is about 3.2 km across and adds that "Some of these blocks are dropped down relative to others, indicating great uplift followed by differential subsidence of the earth in the vicinity of the structure." He describes the breccia in the central part of Wells Creek as consisting of highly-fragmented angular-edged pieces that have been strongly re-cemented. He also confirms the findings of Safford and Lander made 80 years earlier: the central uplift is a core of the older rocks, the Knox Group, located in the center of the basin, with younger rocks found progressively farther away from the center. Wilson and Stearns (1968: 8) agree, describing Wells Creek as a circular basin with 'Central Hill' near its center, rising some 25 m above "… a belt of prominent inner annular valleys." The central block contains Knox Dolomite, which is surrounded by concentric belts of "… post-Knox Ordovician, Silurian, Devonian and lower Mississippian formations." (Wilson and Stearns, 1968: 5).

A simple crater is a small, bowl-shaped crater, often with a raised rim, that originally had a depth that was as much as one quarter to one third its diameter before being partially filled with fallback breccias. A complex crater will display a central uplift, consisting of strata lifted above pre-impact levels, surrounded by a ring depression, or syncline. The syncline is usually filled with fragmented material, breccias, and is often surrounded in turn by a terraced rim. These larger craters experience the inward and upward movement of rock from below the crater as a result of the impact-produced central uplift. Figure 10 compares Baldwin's idealized cross-sections of the Odessa Crater number 1, a simple crater, and the Wells Creek Basin, a complex crater (after Baldwin, 1963: 50). Mark (1987: 162-163) points out that "… central uplifts are now considered analogous to the central peaks of lunar craters."

Fallback breccia and impact melt are concentrated toward the center of simple craters whereas in complex craters these deposits are thickest in a ring surrounding the central uplift. The original, transient crater walls in complex craters have most often been modified by collapse due to gravity, thus forming the terraced walls seen today. These structures are also much shallower in comparison to their diameters than simple craters. Wells Creek fits the description of a complex crater. This is as expected since Wells Creek is around 13.7 km in diameter and the transition from simple to complex craters occurs on Earth somewhere between 3 and 5 km, depending on whether the crater forms in sedimentary or crystalline rock (see Melosh and Ivanov, 1999).

Stratford (2004: 6) points out that "On geologic maps these … structures appeared as circular inliers of older rocks surrounded by concentric circular outcrops of successively younger rocks; this concentric pattern was, however, disturbed, and often disguised, by intense faulting." He also notes that the Wells Creek pattern of central uplift with radial faulting surrounded by concentric circular outcrops of rock is characteristic of terrestrial impact structures that formed in sedimentary terrains.

According to Milam and Deane (2005), brecciated material was found in significant amounts in the major faults at the Wells Creek site. They refer to these breccias produced along the major fault lines of the uplifted central area as 'fault breccias'. At Wells Creek the fault breccias contain pebble- to silt-size angular grains with many showing fine-grain outer margins surrounding course-grained centers. Some flow texture was noted along some of the outer margins.

5 THE AGE OF THE WELLS CREEK STRUCTURE

Since 325 Ma Mississippian rock is deformed at Wells Creek, the structure must have been formed after these rocks were deposited, and because the Cretaceous Tuscaloosa Formation (which dates to 75 Ma) has been found in the deformed area, the Wells Creek event must have occurred prior to the deposition of this Formation. No rock from any periods between these units have been found in any part of the structure, so on the basis of this geological evidence the age of the Wells Creek structure can only be estimated at 200 ± 100 million years. Referring specifically to the Wells Creek structure, Baldwin (1949: 103) points out that

> It is well to realize that, while this is the only method capable of dating these cryptovolcanic structures, the great discontinuities in geologic history as shown by the rock layers at any particular point leave tremensdous spans of time unaccounted for. Hence the dates of formation of these objects are uncertain usually by tens of millions of years and often by hundreds of millions.

Wilson (1968: 15) states that "… it is now believed that the Wells Creek structure is Late Mississippian in age rather than 'post-Eutaw, pre-Wilcox' (post-Late Cretaceous, pre-Eocene)."

6 THE 'CRYPTO CONTROVERSY'

Wells Creek is highly eroded. Erosion over long time periods will reduce the height of the crater wall and sediment will begin to fill the crater depression. The creek which gives this structure its name cuts through and erodes the basin on its way to the Cumberland River. However, Wilson (1953: 756) notes that some structural features at Wells Creek are still discernable, including the central uplift, since "… the relatively resistant Knox dolomite and chert form a low rounded hill in the center of the basin, above which it rises about 75 feet [23 meters]." Dietz (1959: 497-498) points out that "Meteorite craters are, of course 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."

The doctrine of catastrophism was not in favor during the early part of the twentieth century. The idea that the Earth had ever been impacted by meteorites large enough to pierce its surface and penetrate layers of subsurface rock seemed absurd to many in the scientific community (e.g. see Hoyt, 1987). W.H. Bucher (1936) became interested in the Wells Creek structure around 1930 and promptly applied the term 'cryptovolcanic' to it. Dietz (1959: 496) notes that "The term 'cryptovolcanic' is derived from the belief that these structures are formed by volcanic explosions, although the evidence of volcanism is hidden." This term was first used by Branca and Freas in 1905 (see Bucher, 1963a: 1241).

The largest structure included in Bucher's 1936 list of known cryptovolcanic structures in the United States is the Wells Creek structure (cf. Mark 1987: 66). Baldwin (1949: 110) includes Wells Creek, Flynn Creek, and Howell Tennessee in his list of the twelve best-known cryptovolanic structures. Bucher (1963a: 1243) states that Wells Creek stands out among American cryptovolcanic areas because of its size, the intensely broken-up condition of the rocks in the uplifted center caused by a subterranean explosion, and because of the "… distinct, anticlinal ring between the outer limits of the structure and the central uplift, suggestive of an elastic damped wave effect." (cf. Bucher, 1963b).

Several decades before Bucher made this statement, though, Boon and Albritton (1936: 7) described just such a scenario in a paper on meteorite craters.

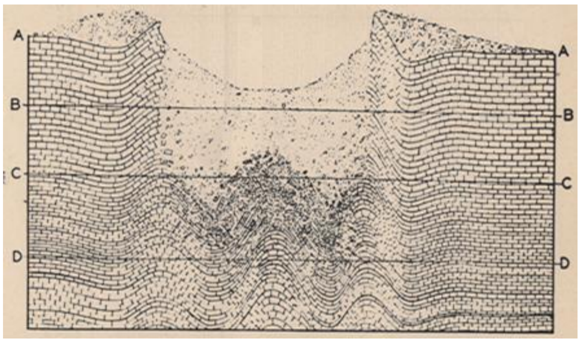

Figure 11: The probable structure beneath a typical meteorite crater (after Boon and Albritton, 1937: 57).

They recognized that identifying ancient impact structures would be difficult, and so they attempted to understand and describe what effect the impact would have at various depths. They hypothesized that when shocked, rock layers would behave in a fluid-like manner, and when the pressure lifted, the rocks would instantly freeze, and remain frozen in position:

> Therefore, as a result of impact and explosion, a series of concentric waves would go out in all directions, forming ring anticlines and synclines. These waves would be strongly damped by the overburden and by friction along joint, bedding, and fault planes. *The central zone, completely damped by tension factures produced by rebound, would become fixed as a structural dome.*
>
> 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 possibly other ring folds, the whole resembling a group of damped waves. (Boon and Albritton, 1936: 7; our italics).

Based on a similar interpretation of the impact process and its results, Boon and Albritton (1937: 57) drew the diagram shown in Figure 11 depicting the probable structure of a typical meteorite crater. The A-level in this diagram shows an impact site with an obvious crater of recent origin. The B-level represents an impact crater that has eroded to the point that it is barely discernable. The Level-C, however, shows the underlying strata of an impact structure becoming somewhat apparent as erosion continues. By the time that an impact structure has eroded to the D-level, the central uplift and ring folds have become conspicuous. This is the level that the Wells Creek structure has now reached. Over time, erosion will wear even this basement structure away and it will no longer be recognizable as an impact site.

Baldwin (1949: 101-103) notes that the Wells Creek structure clearly reveals the dominant pattern of a cryptovolcanic structure "… which arises from a sudden impulse, such as an explosion." He refers to the structure as having "… the appearance of damped waves …", with a central uplift that is "… surrounded by two pairs of up-and-down folds with diminishing amplitude …", and he notes that these damped waves appear to be nearly circular. Interestingly, Boon and Albritton (1936: 8) state that Bucher's assignment of Wells Creek to his list of cryptovolcanic structures was based on this very structure. But Boon and Albritton (1936: 9) conclude:

> It appears that some of the structures which have been assigned to volcanic origin are equally as well interpreted as meteorite structures. Certainly it can no longer be maintained that all explosion structures are necessarily volcanic. The meteorite hypothesis explains the occurrence of folds resembling damped waves, and evidences of violent explosion (breccias, shatter-cones, etc.) as well as does the cryptovolcanic hypothesis … It 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 [here on Earth] in the geologic past.

Giving further credence to the meteorite impact hypothesis Baldwin (1949:112) notes that in his 1941 study of the ordinary volcanic craters in Arizona, Hack "… was not able to find any deformation of the bedrock in the rims of the many volcanoes which he investigated." In addition, although the Wells Creek breccias were found to vary in texture, their mineral composition did not, and "… minerals generally considered indicative of elevated temperatures (e.g. calc-silicates such as wollastonite or diopside) are also apparently absent." (Stearns et al., 1968: 320).

Baldwin (1949: 108-110) notes that some researchers, while rejecting the idea of meteorite impact, still expressed reservations concerning a possible volcanic origin. The objections were based on "… the fact that no volcanic explosion of such a magnitude is known to have occurred anywhere on Earth." Yet the fact that the meteorite impact theory avoids this difficulty seemed to have made little difference in their opinions. Baldwin (1949: 112) concludes: "The meteorite-impact theory thus seems to fit the observed facts better than any other. It alone seems capable of supplying the vast amounts of energy which are needed to give the observed results."

Actually, it was D.M. Barringer's work (1905; 1914; 1924) concerning the impact origin of Meteor Crater in Arizona that played a key role in invalidating the old argument "… that there was no evidence that such [meteorite] impacts had ever occurred on the earth …" (see Hoyt, 1987: 184). W.H. Pickering (1920: 120), referring to terrestrial meteorite impact craters, asked "But why are there not more of them, or at least some evidence of their remains, since Earth is so much more massive than the Moon, has not been explained." By 1925, however, those promoting a volcanic explanation for lunar craters "… were clearly on the defensive." (Hoyt, 1987: 211). The tide had turned as was shown during the early part of the 1930s when the meteoritic origin of the Henbury cluster of craters in Australia was accepted almost immediately based on the criteria introduced by Barringer and other researchers at Arizona's Meteor Crater (see Hoyt, 1987: 246).

The origin of lunar craters also played a part in this evolving discussion. One of the key problems was to explain how meteorite impacts could result in crater formation, and this was addressed by the Estonian astronomer, E.J. Öpik, in a paper that was published in an obscure journal in 1916. He noted, based on the equation

$$E = 0.5mv^2 \qquad (1)$$

(where E is the energy generated, m is the mass of the impactor and v is its impact velocity), that impacts on the lunar surface occurring at cosmic velocities would result in the release of huge amounts of energy and result in the formation of explosion craters that would be circular no matter the angle of incidence. Öpik (ibid.) also pointed out that only relatively small amounts of energy would be needed for the mechanical work of penetrating, shattering, and pulverizing target material before the explosion. Unfortunately, Öpik's paper remained unknown to most astronomers until it was publicized by Hoyt in his 1987 book.

The theme Öpik pursued was developed independently by New Zealand's A.C. Gifford (see Jenkinson, 1940) in a paper titled "The mountains on the Moon" that was published in the *New Zealand Journal of Science and Technology* in 1924. Gifford queried the volcanic explanation for the origin of lunar craters and the idea that the mechanical effects of impact could only result in a circular crater if the impactor's path was nearly vertical. He noted that most lunar craters are circular, yet only a small fraction of lunar impactors should have an incoming trajectory nearly perpendicular to the lunar surface. In supporting the 'meteoric hypothesis' Gifford argued that the circular lunar craters were the result of explosive impacts that transformed kinetic energy into thermal energy and thereby obliterated the pit just dug by the meteorite itself. Gifford later expanded on these ideas in a further paper, published in 1930. According to Hoyt (1987), Gifford later credited another New Zealand-based scientist, Professor A.W. Bickerton (see Burdon, 1956; Gilmore, 1982), with first suggesting this meteorite impact theory during discussions held at two successive meetings of the British Astronomical Association in London in 1915. Bickerton's original idea required supplementary volcanic action, but Gifford decided that impact alone was sufficient for explosive crater formation. Gifford's two papers appeared in a general scientific journal and, as in Öpik's case, they only reached a wide astronomical audience much later when they were discussed by Hoyt (1987).

Returning now to terrestrial impact craters, in 1959 Dietz suggested the term 'cryptoexplosion' to designate structures which were the apparent result of an explosive release of energy. Such structures are generally circular and show extensive folding, faulting, and brecciation of the target rock and are, in his opinion (which was definitely a minority opinion at the time), meteorite-impact scars. He continues:

> The writer prefers to call them "cryptoexplosion structures", since this term has less limited genetic implications … The term "cryptovolcanic" has tended to become a "wastebasket" term and now includes many structures which are unquestionably of volcanic origin. (Dietz, 1959: 496).

Dietz (1960: 1782; his italics) gives the definition of a cryptovolcanic structure as a "… deformation formed by a hidden explosion somehow considered to be related to volcanism although no direct evidence of this volcanism, such as volcanic rocks or hydrothermal alteration is found." He continues: "I prefer the term *cryptoexplosion structures* to *cryptovolcanic structures*, so as not to exclude the possibility of an extraterrestrial origin." He points out that the meteorite impact hypothesis, as originally developed by Boon and Albritton (1937; 1938), explains cryptoexplosion structures as explosion deformations produced by the explosive impact of crater-forming meteorites that are of asteroidal size (Dietz, 1959: 497).

Though a consensus was developing among researchers, the origin of impact structures was still being debated by some during the latter part of the twentieth century. Puryear (1968: 4) gives a description of the Wells Creek structure in his thesis and then concludes that it could be the result of volcanic explosion or meteorite impact. Miller (1974: 55) states that the most widely-accepted theory is that cryptoexplosion structures were created by comet or meteorite impact, but adds that many researchers still favor volcanic explosion as the cause, believing that "… upward moving steam drove the rocks outward …" to form the structure. Others disagreed. Sawatzky (1977: 462-463) included Wells Creek in his list of confirmed meteorite impact sites. But as late as 1991 a staff geologist at the Tennessee Division of Geology in referring to the Wells Creek structure stated: "The origin of this crater and similar features is still under debate …" (Price, 1991: 24). Even though no volcanic material had ever been found in the Wells Creek area, to his way of thinking the idea of a volcanic steam explosion was still considered plausible.

7 IMPACT MECHANICS

Barringer's original argument concerning the impact origin of Meteor Crater was made in 1906. He thought that the iron impactor was buried in the crater and planned to mine the metal. In 1911, M.E. Mulder also proposed impact by a meteorite, but with the interesting suggestion that meteorites could well explode just after impact and "… very little if any of the original meteoritic mass would remain in the crater itself, a circumstance which … Barringer and his associates might well consider." (cited by Hoyt, 1987: 192).

Many researchers have searched for some form of igneous rock or remnant of meteoritic material at the Wells Creek site in order to understand its origin.

Wilson (1953: 755) writes concerning his own research: "The writer studied the stratigraphy of the [Wells Creek] area for the [Tennessee] Division of Geology in 1940. About the same time he made a magnetic map of the region surrounding Wells Creek Basin. This map showed no magnetic anomaly associated with the structure." Some fifteen years later, Wilson and Stearns (1968: 7) noted that a "Lack of magnetic anomaly at the center is consistent with a lack of volcanic material and absence of a buried meteorite at depth, and with the idea that the basement is not uplifted beneath the structure." If this structure is indeed the result of a meteorite impact, then why is there a complete lack of meteoritic material on site or mixed in the breccia?

Boon and Albritton (1937: 54) point out that:

> It is difficult to comprehend the tremendous pressures which would be produced in the brief interval between impact and explosion of a large meteorite … these unprecedented pressures should be kept in mind, for they bring about the terrific explosions, the excavation of the craters, and the backfiring and shattering of the meteorites.

Dietz (1960: 1781) adds that "… meteorites have never been found in ancient rock, and this suggests that such fragments as are preserved from volitization during a hypervelocity impact weather rapidly." Miller describes a possible scenario in which the Wells Creek impactor would have penetrated to a depth of over 600 meters with the subsequent explosion resulting in a transient crater around 6.5 km across and 0.8 km deep. He also points out that "… a meteor presumably might be totally vaporized from the great heat involved in the impact." (Miller, 1974: 55). Dietz (1959: 498) says that "… it is physically naïve to expect the preservation of such a body; in fact, the preservation of any meteoritic fragments in ancient impact scars seems unlikely."

The shock wave resulting from meteorite impact will not only melt and vaporize target rock; it will impart a particle velocity to the shocked material. Velocities are radial in direction during compression, but then are deflected outwards and upwards by rarefaction wave interaction. These deflected particle motions are responsible for transient cavity growth during the excavation stage of an impact event (Grieve et al., 1977). As crater development moves from the excavation stage to the modification stage, the transient cavity rapidly readjusts to produce the final impact crater form. With increasing cavity size, collapse of the transient cavity leads to the formation of complex craters, such as Wells Creek, where the outer edge of the transient cavity rim has dropped down to form distinct annular grabens and the center of the cavity floor has experienced uplift (ibid.).

8 SHATTER CONES

One of the most important developments in the study of impact structures during the 1960s "… was the recognition of unique and geologically durable petrographic and mineralogical effects that could be used to unambiguously identify geologically old impact structures …" (French, 2004: 171). During impact, shock levels encountered in the rocks forming the central uplift of a complex structure such as Wells Creek cause the formation of characteristic microscopic planar deformation features in quartz and feldspars (Robertson and Grieve, 1977). Therefore, rather than requiring the discovery of associated meteoritic material to confirm an impact origin, shatter cones and planar deformation features [PDFs] in quartz became accepted as proof of impact since PDFs "… are uniquely produced by high shock pressures and their occurrence is restricted in nature to meteorite impact sites …" and shatter cones were found to be associated with PDFs in quartz (French, 2004: 171). In addition, the high-pressure polymorphs of quartz, coesite and stishovite, found in impact structures were shown to require pressures so high that only meteorite impact could account for their formation (ibid.). Coesite and stishovite "… have not been found in any natural environment that is clearly *not* related to a meteor impact." (Wilson and Stearns, 1968: 152).[1]

Wilson and Stearns (1968) found no evidence of coesite or stishovite in Wells Creek petrographic studies, though they note that the zone in which shock pressures were great enough to develop these minerals could have been removed by erosion. The most severe deformation Wilson and Stearns (1968: 153) noted in Wells Creek quartz was "… somewhat widely spaced fracturing …" They also state that the "… most pronounced evidence for severe deformation is distortion and fracturing and undulatory extinction in carbonate crystals …" which was observed in the Knox Dolomite and in calcite in the breccia (ibid.). Calcite crystals in the breccia were observed to be broken into platy fragments and Wilson and Stearns (ibid.) found that "Twinning is prominent in the calcite of this breccia but not in the dolomite of the central block …"

Shatter cones, however, are abundant in rocks of the Wells Creek central uplift. Shatter cones (see Figure 12) are distinctive fan-shaped features in rock with radiating fracture lines (see Sagy et al., 2004). They are not found in normal geological situations, and they do not seem to be formed by tectonic stresses, static loading or volcanic activity. Military explosives with high detonation velocity and shattering effect do form cones with surface marking similar to shatter cones, "… but not so perfectly formed as shatter cones …" (Baldwin, 1963: 75), while dynamite can produce "… rude cones … [but these] lack the surface markings of shatter cones." (Baldwin, 1963: 75).

Dietz (1960: 1781) explains that a primary effect of a meteorite impact and the resulting explosion is the generation of a high-velocity shock wave which spreads out from the point of impact and engulfs a large volume of rock before decaying into an elastic wave. He continues:

> Volcanic explosions are steam explosions involving not more than several hundred atmospheres, so it is extremely doubtful that a shock wave can be developed in rock as part of volcanic phenomena … It would seem, 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. Fortunately, at least under favorable conditions, rocks when shocked appear to fracture into a curious pattern, forming shatter cones which are preserved and may be readily identified in the field.

According to Wilson and Stearns (1968: 108), shatter cones were first located in the United States by Bucher in the Wells Creek Basin. Back in 1959, Dietz wrote that "Shatter cones (striated percussion fracture cones), apparently formed by explosive percussion, are known only from four cryptoexplosion (i.e. "cryptovolcanic") structures, viz., Steinheim Basin, Wells Creek Basin, the Kentland deformation, and the Crooked Creek structure." (page 496). As early as 1946, Dietz had proposed shatter cones as a criterion for the identification of terrestrial meteorite craters, "… in the course of suggesting that cryptovolcanic, or cryptoexplosion structures were possibly related to craters on the moon." (Hoyt, 1987: 356). In fact, by the late 1950s, Dietz was convinced that they provided a definitive criterion for impact identification as a result of his successful search for shatter cones at other cryptoexplosion sites (see Mark, 1987). Shatter cones are now considered to be unambiguous shock features associated with meteorite impacts and are, in fact, the only shock indicators that can be seen with the unaided eye.

Dietz collected several compression fracture cones that were produced by high explosive detonation in a Nashville (Tennessee) limestone quarry and compareed one of these with a Wells Creek shatter cone, noting that the compression cone "… lacks striations, and is crude and irregular in form." (Dietz, 1959: 498). He also noted (Dietz, 1959: 500) that shatter cones are not found in rock that has been subject to known volcanic explosion. Explosions due to the expansion of compressed gases and steam, in his opinion, were not violent enough to produce an intense shock wave in the upper rock layers. Dietz (1963: 661) believes shatter cones are usually limited to the intensely-deformed center of cryptoexplosion structures, such as Central Hill in the Wells Creek structure, whereas the outer rings show only heaving, suggesting rapid decay of shock waves. Dietz (1960: 1782) adds that shatter cones have only been found in the USA in the central sections of structures that were identified as cryptovolcanic in the 1940 edition of the *Structural Map of the United States*. He also states that shatter cones have never been reported resulting from any other natural geological situation.

Mark (1987: 124) notes that "… as of 1959, they [shatter cones] were known only in ... three locations in the United States …", including the Wells Creek basin, and that these shatter cones are found in dolomite and show "… uniform orientation. The cones are interlaced, and new fractures of the rock reveal new shatter cones." Figure 12 shows

shatter cones found in the central uplift of Wells Creek, which is known for its fine, easily-located, and pro-fuse shatter cones. Perhaps this is due to the fact that the Wells Creek central uplift is composed of Knox Dolomite. Dietz (1960: 1781) indicates that shatter cones are usually found in carbonate rocks, but they have also been identified in shale and chert; he concludes: "Presumably, a fine-grained homogeneous rock like dolomite favors their development, but it is not an absolute requirement."

Figure 12: Wells Creek shatter cones (photograph by Andrew Tischler).

Dietz (1960: 1784) points out that in addition to indicating a meteorite impact, shatter cones provide an additional clue as to the origin of impact structures. The initial impulse delivered by a meteorite is carried into the target rock by stress waves, and so the shatter cones usually "… point toward the locus of pulse source." Dietz (1963: 661; his italics) states:

> I retain the conviction that shatter cones are truly indicative of intense transient shock loading, far in excess of any known volcanic forces. Their concentration in the bulls-eye of cryptoexplosion structures indicates a highly localized ground zero. And when the preferred orientation of the cones can be worked out, the apices *do* point toward the direction of oncoming shock wave. When definitely recognized, they seem to me a valid criterion for intense shock such as can be derived only from a cosmic impact.

Milton (1977: 704) also considers shatter cones to be a diagnostic feature of impact structures and states that "Shatter cones form during the compression stage, as is indicated by the occurrence of broken cones in breccia and also by the orientation of cones in place in the crater floor and central uplift …" Shatter cones were found in the Knox group rocks exposed in the Wells Creek central uplift and the orientation of these shatter cones indicates a point of explosion at about 610 meters below the surface at the time of the event, which strengthens the meteor impact theory (see Miller 1974).

In 1956, Gilvarry and Hill published a monograph on meteorite impacts which estimated pressures and temperatures during the early stage of an impact event. They stated that

> … the explosive pressures and temperatures are created in a time of the order of that required for the impinging mass to traverse a distance equal to its diameter. Hence the effective center of the explosion must lie within a depth below the impact surface of the order of a linear dimension of the impinging mass. (Gilvarry and Hill, 1956: 620).

Stearns et al. (1968: 335) note that "The Wells Creek structure has, at its center, a remarkable development of shatter cones …" on Central Hill. Wilson and Stearns (1968: 108) note that in the Wells Creek structure, "… all known shatter cones are in the Knox Dolomite." They continue by noting that "Shatter-cone orientation data support the interpretation of a meteorite penetrating from an ancient surface to such a depth that shock waves emanated mainly from near the top of the Knox Dolomite (a position at least 2,000 feet [610 m] underground at the time." (Wilson and Stearns, 1968: 130). Milton (1977: 704-706) continues:

> As measured, orientations show little pattern, but at those craters that formed in horizontal strata, displacements during the excavation stage can be determined and if shatter-coned outcrops are restored to their pre-impact position, cone axes point inward and upward toward a point near the original ground surface at the center of the structure. This is striking evidence for, beyond the basic hypothesis that cryptoexplosion structures are caused by impact, the formation of shatter cones during the compression stage with their axes normal to an advancing hemispherical shock front.

Shock wave reflections can explain multidirectional cones. Instead of experiencing a simple spherical spread, a shock wave would be expected to reflect from interfaces and discontinuities resulting in a complex shatter cone orientation. Dietz (1959: 501) writes that "According to J. Rinehart (personal communication), who has experimented extensively with shaped charges and high-speed impact phenomena, minor inhomogeneities, such as bedding planes and especially the bottoms of strata, can strongly reflect shock waves." Shatter cones formed by meteorite impact might tend to have a preferred orientation toward the explosion, but cones with their axes pointed in other directions are likely to occur as well. If an impact explosion-induced shock wave encounters a pebble, the pebble will in turn act as a secondary shock wave source forming a shatter cone, and this cone will point toward the oncoming shock wave. Cones pointing in other directions can be explained by reflection. Dietz (1963: 658-661) also states "I cannot agree with Bucher's interpretation that shatter cones pointing upward are explainable by a cryptovolcanic pulse coming from below."

Wilson (1963: 767) reports that he found shatter cones after studying a 610-m core drilled near the center of the Wells Creek structure, and states that he found three features that were especially significant:

(1) Deformation was instantaneous, and did not result from normal tectonic forces;
(2) Progressive downward dying out of deformation may be traced, in spite of the brecciation between 1743 and 1930 feet [530 and 590 meters];
(3) In the top 200 feet [60 m] of the core, the shatter cones are all horizontal, except for some that point obliquely upward.

He found horizontal shatter cones to be concentrated at a depth of 30 meters, and the few shatter cones found below 60 meters were not complete or well defined, except for a single exception located at a depth of 377 meters. He noted that "As the core was not oriented, it is impossible to state in which direction these cones pointed." (Wilson, 1963: 767). Some 200 meters to the south of this location, horizontal shatter cones were also located in an exposure. Wilson believes that these shatter cones "… were not formed by the impact of the meteorite, as such should be normal to the bedding and oriented stratigraphically up, but rather by the explosion of the rocks compressed beneath the penetrating meteorite." He also points out that this block was most likely moved from its original position when the meteorite impacted and penetrated the surface rocks just before the explosion. He concluded (ibid.) that these features "… present definite evidence that the deformative force came from above and not from below." After their formation, some shatter cones at the Wells Creek site were cut by faults and fault breccias, indicating that the target rock layers were displaced after the formation of shatter cones (Milam and Deane, 2005).

Although numerous shatter cones were found in the drilled core at Wells Creek, this did not reveal the presence of an igneous core. The fact that this core indicated that the structure appeared to die out with increasing depth emphasized its non-volcanic origin. Studies of impact structures show that, unlike volcanoes, there is a lower limit to the depth below the Earth's surface of disrupted rocks, indicating that the cause of the disturbance was not endogenic.

9 BILATERAL SYMMETRY

Both the cryptovolcanic and meteoritic hypotheses could explain the formation of the structures in question as the result of tremendous explosions. In the cryptovolcanic case, an explosive release of subterranean gases is considered to be the cause, while in the other case the explosion results from the impact of a massive high-velocity meteorite. Both of these could explain the existence of circular structures with central domes, surrounded by ring folds. Both could also explain the observed brecciation and faulting. However, Boon and Albritton (1937: 57) state that

> … the meteoritic hypothesis can account for two features which are unsatisfactorily explained by the alternate mechanism. These are (1) the distinctly bilateral structural symmetry found in several American examples, such as Wells Creek … and (2) the absence of volcanic materials and signs of thermal activity. It is more difficult to explain how an upwardly directed explosion alone could produce a bilaterally symmetrical structure … than it is to see how an obliquely impinging meteorite could produce a radially symmetrical structure.

In fact, Boon and Albritton (1936) regard bilateral symmetry as a basic criterion for the identification of an impact structure.

Baldwin (1949: 101) observes that Wells Creek "… exhibits a distinct bilateral symmetry." Safford and Lander also comment on this: "The fault circles are longer North and South than East and West, the direction of the long diameter being about N.N.E. and S.S.W." (see Wilson and Stearns, 1966: 38). Baldwin (1949) states that the proportion of those cryptovolcanic structures that show bilateral rather than radial symmetry is what should be expected if the structures were actually the result of meteorite impact, since the majority of impactors would come from some non-vertical angle. He continues: "Although the resultant surface craters probably would be very similar to those formed by impacts of bodies falling perpendicularly, the subjacent rocks would indicate both the fact that an angular fall had occurred and its direction." (Baldwin, 1949: 110).

Wilson and Stearns (1968: 5) also note this north-northeast axis of bilateral symmetry in the basically circular and symmetrical Wells Creek structure which "… is manifested by the linear occurrence of several structural features along this line and by the 'enantiomorphic pairings' of other structural features in reference to this line." Gravity patterns also show this bilateral symmetry which Wilson and Stearns (ibid.) believe to be related to trends of pre-existing joints and controlled by the north-northeast joint set.

10 THE WELLS CREEK 'SATELLITE CRATERS'

Meteoroids often break up as they travel through the Earth's atmosphere (see Baldwin and Sheaffer, 1971; Melosh, 1989; Pierazzo and Artemieva, 2005). Usually, only iron or tough stony-iron meteorites survive the aerodynamic atmospheric stresses and reach the Earth's surface intact without first breaking up. If a meteorite disintegrates in the Earth's atmosphere, the resulting cluster of separate fragments will continue to fall forming an elliptical strewn field or crater field upon impact, as illustrated in Figure 13. In these fields, the smaller fragments fall short of the larger ones due to air drag, causing the largest craters to be at the far end of the impact ellipse, as is shown in the Henbury and Odessa schematic maps. Note that some of the larger Henbury craters overlap.

In their discussion of the Wells Creek structural data, Wilson and Stearns (1968: 88) include the following interesting comments:

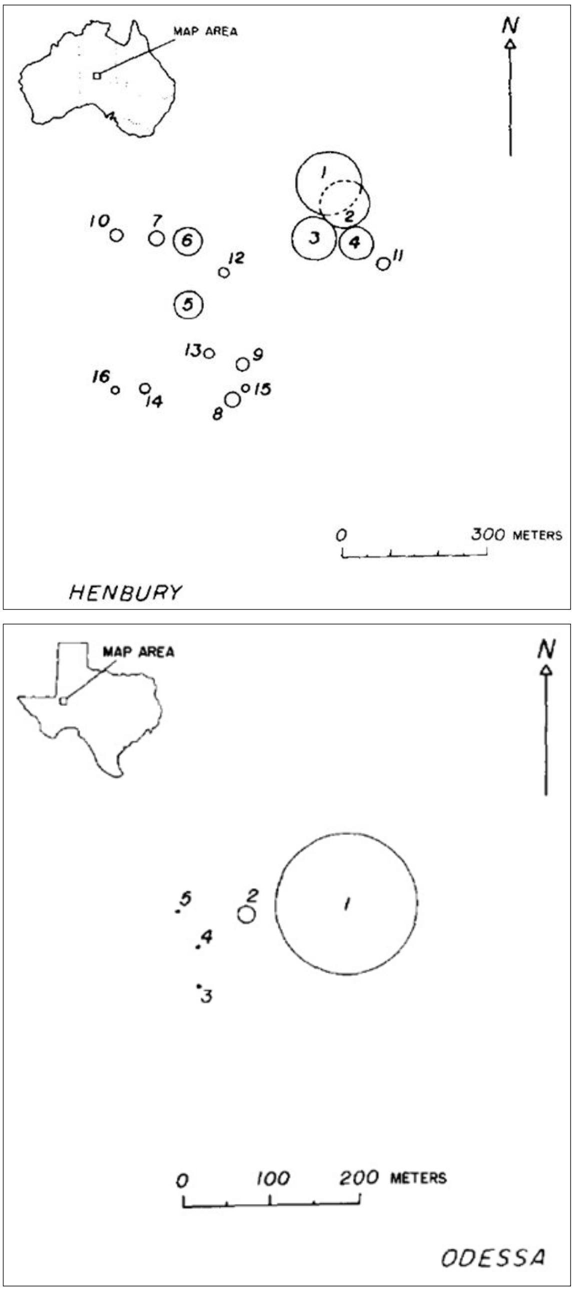

Figure 13: The Henbury, Australia (upper) and Odessa, Texas (lower) crater fields (after Passey and Melosh, 1980: 214, 217).

> If a line is projected north-northeastward from the center of the Wells Creek structure along the symmetry axis, it intersects the Indian Mound craters (6 miles [9.7 kilometers] north-northeast of the edge of the Wells Creek structure). These features have been interpreted as subsidiary meteor impact scars by Wilson (1953), and therefore their relationship to the Wells Creek structure is genetically significant.

Referring to Wells Creek, O'Connell (1965: 126) states that there are actually five different craters (cf.

Hey, 1966), and he includes their depths and diameters drawn from data included in Wilson (1953). Table 1 is based on this information, but note that Wilson (ibid.) stresses that the figures listed in the third column are minima. Figure 14 shows the locations of these deposit-filled satellite craters with respect to the main Wells Creek structure (after Wilson, 1953: 754). Note their alignment with the north-northeast axis of symmetry of the main structure.

Table 1: Wells Creek Basin, Tennessee, and its satellite craters (after O'Connell, 1965: 126).

Feature	Diameter	Depth
Wells Creek Basin	2 × 3 miles (3.2 × 4.8 km)	---
Little Elk Creek Deposit	---	---
Cave Spring Hollow	1 mi (1.6 km)	---
Indian Mound	2000 ft (610 m)	>263 ft (70 m)
Austin	375 ft (115 m)	>40 ft (12 m)

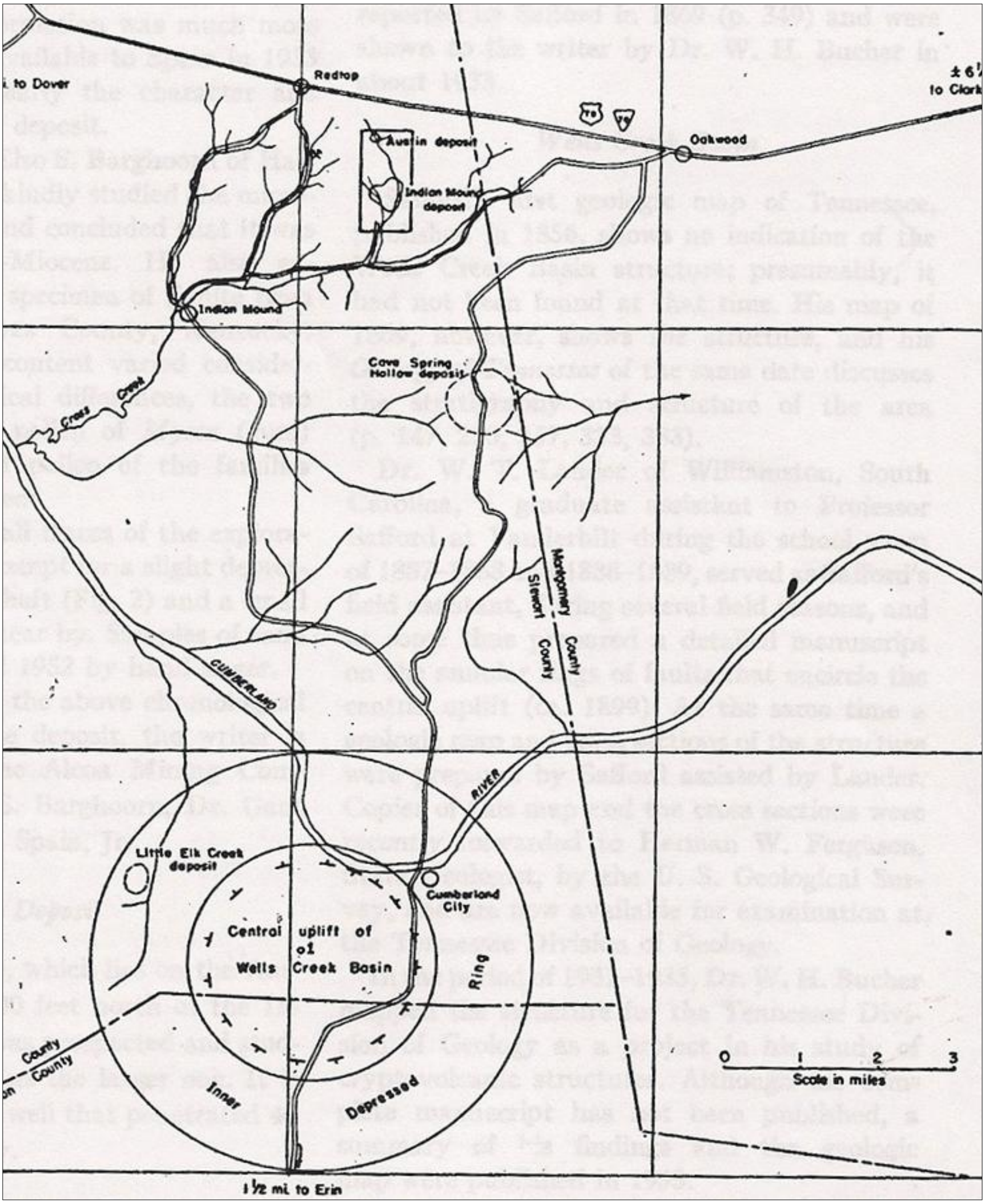

Figure 14: Map showing the locations of the Wells Creek Structure and the Little Elk Creek, Cave Spring Hollow, Indian Mound and Austin 'satellite craters' (after Wilson, 1953: 754).

Comparing the diameters given in O'Connell's table above with Wilson and Stearn's map shown in Figure 14, it is obvious that these craters show decreasing diameter with increasing distance from the main impact crater.

Wilson (1953) continues his discussion, noting that the four basins are all oriented along basically the same line within a relatively small distance, and that they contain similar sediments, in fact the only such deposits known in the Western Highland Rim. Wilson (1953: 753) describes these small craters as follows:

> Four small deposits of Wilcox sediments occur in Stewart County, Tennessee. One of these deposits is in the inner depressed ring, or crater, of the Wells Creek Basin structure. It is concluded that these four craters had a common post-Eutaw, pre-Wilcox age and common origin by impact and resulting explosions of fragments of a meteor.

What originally was the largest of these satellite craters is Little Elk Creek, which is located on the inner depressed ring of the Wells Creek structure that contains the central hill or uplift. Eight kilometers north-northeast of its northern rim is the much smalller Cave Spring Hollow basin, the extent of which is unknown. Almost five kilometers farther north is the Indian Mound basin, at least 610 meters in diameter and greater than 80 meters in depth, but with a central hill rising above the level of the floor of the basin (Baldwin, 1963). Classen (1977) lists the largest of the Odessa craters as having a diameter of 168 m. This gives the Indian Mound basin a diameter almost four times that of the largest of the Odessa craters. Around 520 meters farther north is the very small Austin basin, over 12 meters deep. Wilson (1953: 764) states that

> It seems logical that the four basins, or craters, had a similar origin at the same time. That origin would have been related to the phenomenon that formed the Wells Creek Basin structure."

Wilson (1953) believes that the Little Elk Creek deposit resulted from the explosion that formed the Wells Creek structure. He notes that several small deposits are exposed in a tributary of Little Elk Creek, and that these were first reported by Safford (see Safford, 1869: 349). Bucher showed Wilson these deposits around 1933.

The Indian Mound satellite crater was first investigated around 1930 when the first drilling and opening of shafts in this area occurred, as a result of Dr Gant Gaither's interest in the deposit (see Wilson, 1953). A Master's thesis for Vanderbilt University concerning the deposit was completed by Ernest Spain in 1933, but "… the findings of the preliminary exploration … were insufficient to reveal the full significance of the unique deposit." (Wilson, 1953: 754). The area was prospected in more detail during 1934 by the Alcoa Mining Company, and although the information obtained was not released for publication until 1948 it showed more clearly the characteristics and surprising thickness of the deposits (Wilson, 1953). Wilson (1953: 761) provides the following description of Indian Mound: "It is shaped like a doughnut with the central hill of chert occupying the 'hole' of the doughnut."

This central hill is puzzling since the diameter of Indian Mound is ~610 meters, and central uplifts are characteristic of complex craters which have diameters ≥2 km. Indian Mound has a diameter that is within the range of a simple crater and so should be bowl-shaped if it is the result of a meteorite impact. However, Wilson (1953: 764) states that

> No evidence of uplift was found, unless the loose blocks of Warsaw chert in the central area of residual chert are higher than their normal position. If the blocks are from the lower part of the Warsaw, then uplift of over 100 feet [30 meters] is possible.

An explanation may be found in the idea that

> … large simple craters often possess low central or near-central mounds … [which are] probably the result of the convergence and pileup of high-speed debris streams sliding down the walls and onto the crater floor. (Melosh 1989: 136).

The Cave Spring Hollow satellite crater is located 7.2 kilometers south-southeast of Indian Mound (Wilson, 1953). The deposit was prospected around the same time as Indian Mound, however "The indefinite limits of this deposit are based on local reports of where the drilling was concentrated." (Wilson, 1953: 755).

The Austin satellite crater is about 520 meters north of the Indian Mound deposit and although it was also studied and prospected at the same time, just one well was drilled, and this only went down 12 meters (ibid.). Wilson (1953: 764) notes that

> No structural disturbance was noted in the Austin and Cave Spring Hollow deposits, but again the bedrock is chert rubble yielding no information as to its structure.

According to Wilson (1953: 756) the Cave Spring Hollow deposit is just over 180 meters above sea level and the Indian Mound and Austin deposits are at an altitude of between 140 to 165 meters. He adds that "These deposits of clay do not affect the topography in any way, nor do they show up in the aerial photographs." (Wilson, 1953: 758). The rectangular area in the upper part of the Figure 14 map, which includes Indian Mound and Austin, is enlarged in the geological map shown in Figure 15.

Wilson summarizes the Wells Creek structure as follows. Around the central uplift the beds dip away from the center as expected, except for the Ross and Decatur formations which dip steeply southward toward the center of uplift for some 305 meters along the northern boundary of the structure. This asymmetry when superimposed upon the otherwise circular structure was also noted by Bucher and by Boon and Albritton. Lander and Safford also recognized this bilateral asymmetry. In fact, Lander's 1887-1889 manuscript included a sketch with the line of asymmetry plotted with a strike of N. 25°E. This axis, along with the southward-dipping Ross and Decatur formations on the northern side, point unerringly to the Indian Mound crater. Wilson (1953: 764) believes that

> … only two known forces could account for the origin of Indian Mound crater; (1) a local, abnormally deep sink hole; (2) the depression ring of an explosion crater. It seems to the writer that the sink hole can be eliminated when … it must have been cut: (1) 130 feet [40 meters] below the present level of bedrock in Cumberland River valley, and (2) through at least 200

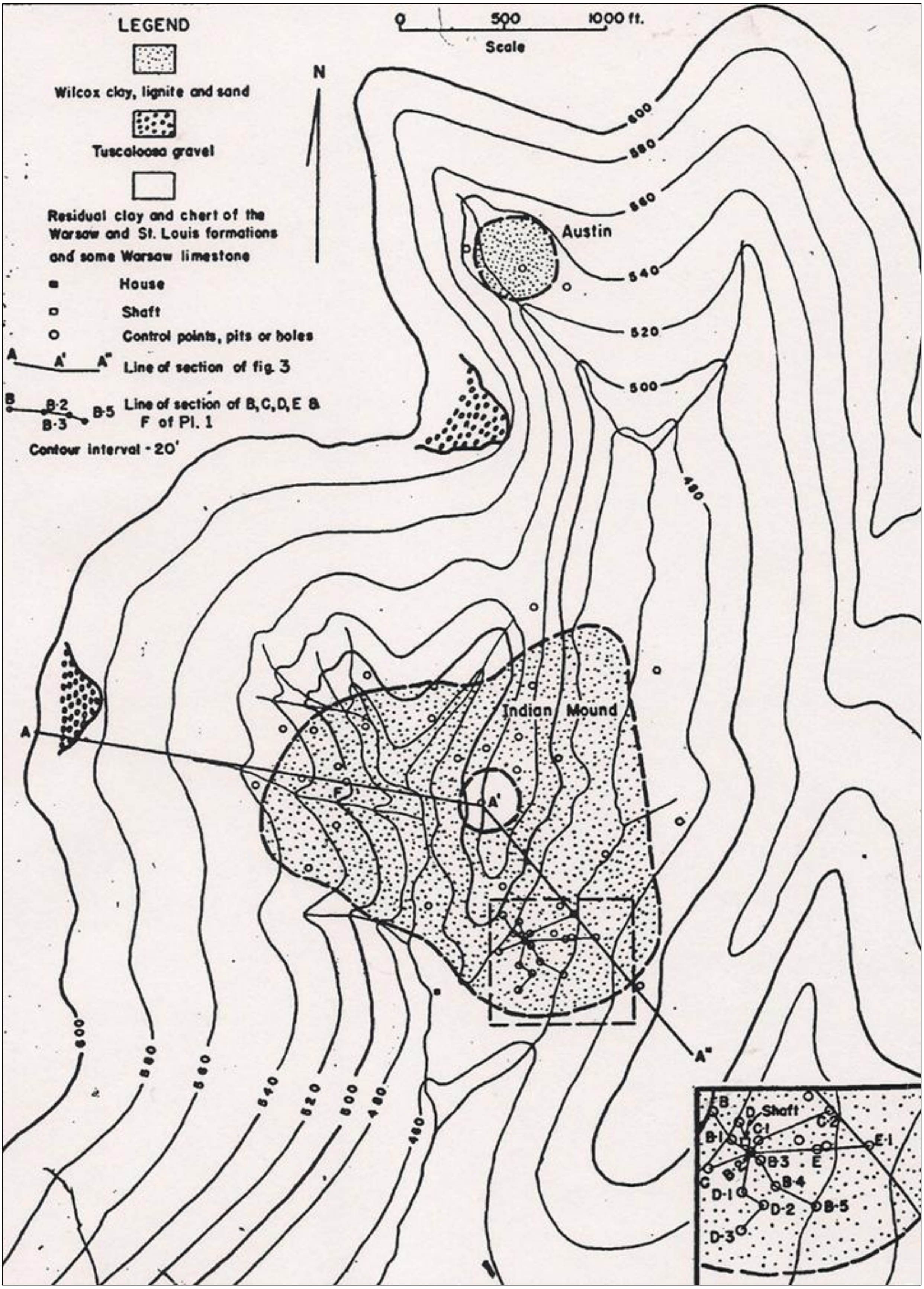

Figure 15: Geological map showing the presumed areal extent of the Indian Mound and Austin structures, based on shafts, pits and holes. The inset shows in detail the investigation of the southeastern section of the Indian Mound site (after Wilson, 1953: 759).

feet [60 meters] of Fort Payne and Ridgetop beds. These relatively insoluble beds are underlain by the Chattanooga shale and about 50 feet [15 meters] of Devonian Harriman chert, a sequence that would have prohibited, or made improbable, the cutting of such a deep sink hole … Austin and Cave Spring Hollow cra-

> ters represent small meteoritic pits, or craters ...
>
> It is concluded that a swarm of meteors approached the earth's surface from the south, or a single meteor fragmented into at least four pieces before striking the surface. The largest fragment struck at the present position of Wells Creek Basin, and the second in size struck at the Indian Mound locality. Smaller fragments ploughed into the earth to form the Austin and Cave Spring Hollow craters.

The son of D.M. Barringer recognized several small craters at Odessa, Texas, in 1922 (e.g. see Figure 13, lower map), that were associated with iron meteorites (see Barringer, 1967). Baldwin (1963: 19) describes the formation of the Odessa group of craters by a nickel-iron meteorite as follows: "Accompanying the main body were at least four smaller companions. They also struck, exploded, or partially exploded and formed lesser craters." (cf. Holliday et al., 2005). In addition to the main crater, Crater No. 2 is nearby, and

> Three other craters, much like No. 2 but smaller, have also been identified … many of the other recently discovered meteoritic craters occur in bunches … Usually there is one rather large crater and numerous smaller pits. (Baldwin, 1963: 21).

The similarity of this description to the structures found at Wells Creek is striking.

However, due to their distances from the Wells Creek structure, one has to query whether Cave Spring Hollow, Indian Mound and Austin can be explained as secondary craters produced by fragments from the explosive impact of a single large meteorite. Wilson's statement that the supposed approach of the fragmenting meteoroid was from the south is also puzzling, as the smaller fragments tend to fall first, yet the main impact site is to the south of Indian Mound. Nonetheless, Wilson (1953: 768) concludes that the

> … evidence combined with the occurrence of four aligned craters, of which the Indian Mound crater has critical depth and cross section, and the southward dip of the Ross and Decatur limestones on the north periphery of the uplift of Wells Creek Basin all harmonize to tell the same story of meteoritic origin.

Considering Indian Mound's critical depth and cross section, it is unfortunate that the depth of the Cave Spring Hollow deposit was not determined. Its larger diameter, 1.6 km compared to Indian Mound's 610 m, could indicate that its depth could be even greater than the 70-80 m determined for Indian Mound, making it a third structure in the Wells Creek group with critical depth and cross section.

McCall, however, has reservations regarding Wilson's conclusions. He refers to Wilson's paper when stating that

> Wilson (1953) believed that the deformation came from above and was produced by a group of objects approaching from the south. He believed that the five structures were more or less contemporary. (McCall, 1979: 279-280).

Then McCall (1979: 279-281) gives his own opinion:

> Wilson (1953) mentions also three small craters to the north and one inside the main structure. Of these satellite craters, Indian Mound is 80 m deep and contains a central knoll 650 m in diameter; Cave Springs Hollow is 1.6 km in diameter; and Austin is 120 m in diameter and 12 m deep. Little Elk, in the northwest quadrant of the main basin is reported to be 500 m in diameter …
>
> However, the alternative, that the craters are not contemporary with the main structure, seemed only compatible with endogenic theory, unless there was a remarkable overlap of impacts. If the Little Elk structure is a crater, it would represent a major problem in terms of impact theory for it is clearly absurd to suppose that a small contemporaneous crater could be superimposed in a deeply eroded structure such as the Wells Creek Basin … If these [craters] are related to the [Wells Creek] structure, it is difficult because of their smaller size, to reconcile them with a contemporaneous larger explosion 2500 ft [760 m] below the existing land surface, for much smaller scale impacts such as those would have fragmented at no significant depth and the traces of their impact would have been obliterated by erosion. It is probable that the Little Elk crater does not exist, but the others certainly do. They are either fortuitously related to the main basin, or must be explained in any hypothesis of the Wells Creek origin. (ibid.).

In contrast to McCall's view, Wilson (1953: 765) was of the opinion that "A fourth craterlet, the Little Elk Creek depression, lies within the Wells Creek Basin …" and that it was produced by a smaller meteoritic fragment that trailed behind and fell inside the main crater. It is worth noting that according to Bucher (1963b), similar small craters exist on the floor of the Ries Basin, a proven impact crater in Bavaria, Germany (Shoemaker and Chao, 1961).

In reference to the north-northeast axis of bilateral symmetry, it must also be pointed out that Wilson and Stearns (1968: 5) state that "A structure map drawn by projecting contours across the structure shows that the regional north-south trending highs and lows continued across the area before the [Wells Creek] structure was formed." This may be the cause of the structure's bilateral symmetry rather than the meteorite's direction of approach.

Bucher presents his own ideas. He believes Wells Creek to be aligned with the Hicks Dome and the Avon area, both of which he considers to be volcanic in origin. Hicks Dome is located some 145 km NNW of Wells Creek and the Avon Area is around 255 km NW of Wells Creek. Bucher (1963b, 626) notes that "… the Hicks Dome with its explosion breccia pipes … [is located] along the same, now curving, belt … [as] the Avon area of 78 volcanic breccia pipes ..." Bucher (1963a: 1243) also states that:

> About 145 km (90 miles) to the south-south-east of the Hicks Dome, three diminutive craterlets filled with Cretaceous sediments trend north-north-westward a short distance beyond the Wells Creek Basin, that is, essentially in the same direction as the basic dikes farther north, and, more important, in the direction of the anticlinal flexure zone. Dr. Wilson, who described them, called them impact craters, caused by small meteorite fragments running ahead of the master meteorite … it is assumed that a giant and baby meteorites hit the ground in line with the axis of an independent major flexure zone.
>
> About 168 km (105 miles) west-north-west of the Hicks Dome lies the Avon area …
>
> Here then, of three structures lying on a major flexure zone (of purely terrestrial origin), one is supposed to

> be the product of meteorite impact, while the other two are undoubtedly volcanic in origin.
>
> I cannot accept a hypothesis which holds that … multiple meteorites … struck a clearly defined terrestrial flexure zone so that their impact scars are aligned parallel to its axis and with structures of proved volcanic origin.

Dietz (1963: 654-655) responds to Bucher's objecttions:

> The Wells Creek disturbance … makes a useful "syntype" for the United States … Bucher argues that the Wells Creek basin must be terrestrial in origin because of its regional associations. To me, this seems to be only a possibility rather than a probability. It is difficult to lay down any point upon the tectonic map of the United States without finding associated regional trends, etc. If we consider all of the cryptoexplosion structures, they seem to be randomly disposed …

In his description of Wells Creek, Baldwin states that the Wells Creek Basin structure is not alone and that during the post-Eutaw-pre-Wilcox (Cretaceous) interval, at least four basins were located in the region, the largest one being what we now know as the Wells Creek structure. He also concludes that the four basins were all formed by the Wells Creek event. Baldwin (1963: 92) concludes that this is a group of four associated meteorite impact structures around 100,000,000 years old. He also takes note of the fact that the rock layers along the structure's northern boundary dip southward toward the center, which is "… consistent with the idea that the meteorites approached from the south …", while the resulting axis of asymmetry "… points unerringly toward the Indian Mound Crater." (Baldwin, 1963: 89).

Finally, in their 1968 interpretation of the origin of the Wells Creek structure Wilson and Stearns dispute Baldwin's conclusion that the disintegrating meteoroid approached from the south. They note that the direction of approach of the impactor can be derived from the positioning of the shatter cones, and that these are found in greater abundance in the southern part of the Knox Dolomite. From this they conclude that the meteoroid came in from the north-northeast, resulting in a greater compression of this section of the impact site and causing more shatter cone development. They also suggest that

> Perhaps lesser accompanying meteors were slowed sufficiently by the atmosphere that they fell more vertically and behind the main meteor to form the Indian Mound craters. (Wilson and Stearns, 1968: 177).

Unfortunately, the precise origin of these supposeed 'satellite craters' may never be determined as Wilson and Stearns noted in 1968 (page 166) that they "… unfortunately [are] now largely concealed …", although these authors do not reveal whether by erosion, deposition, pasture, human activity or some combination of these. Fortunately, the conclusion as to the origin of the main Wells Creek structure is much clearer.

11 CONCLUDING REMARKS

The Wells Creek structure was discovered in the late 1800s when a railway line was constructed from Tennessee to Kentucky and passed through the Wells Creek Basin. The first professional investigators simply described the structure's features, and did not include any suggestions about its origin in their manuscripts or field notes. Discussions during the 1930s concerning the structure's origin led to two strongly-opposing views: that it was either crypto-volcanic or cryptoexplosive (and therefore resulted from a meteorite impact). Detailed studies of the structure were completed during the 1960s in preparation for the first lunar landings. Our Moon is covered with craters, and NASA wanted to learn whether lunar craters were related in any way to these terrestrial structures. The primary investigators, Wilson and Stearns, came to prefer the meteorite impact hypothesis to explain the origin of the Wells Creek structure.

Evidence for a Wells Creek impact event includes: drill core results; extreme brecciation; and shatter cones oriented to indicate explosive force from above; while the lack of local volcanic material is telling. The fact that the shatter cones preferentially point to a location that would have been over 600 meters underground at the time of the structure's formation adds credence to the meteorite impact hypothesis. A volcanic origin would not have left space for rock to move inwards toward the center of the structure nor are volcanic pressures sufficient for shatter cone formation. The fact that meteoritic material has not been found is no longer seen as an issue given the fact that any fragments that could have survived the explosive event would have eroded away long ago.

The Wells Creek impact site is now recognised as the 'syntype' cryptoexplosion structure for the United States. Early investigators recognized that it revealed more clearly than most other structures the pattern of impact, presenting the appearance of damped waves and a conspicuous central uplift.

Dietz (1963: 663), an early advocate of the meteorite impact theory, has stated that "Astrogeology is a subject which must concern the earth, as well as the moon …", but we must now add the terrestrial planets, some of their moons, asteroids and cometary nucleii to this 'portfolio'. Over the passage of more than a century, Tennessee's Wells Creek structure has been a source of controversy and of knowledge as researchers slowly came to recognize that we do not live on a planet which is isolated from the rest of our chaotic Solar System (see Koeberl, 2009). In the opinion of at least one noted meteoriticist, "… future historians will accord the recognition of [terrestrial] impact cratering an equal importance with the development of plate tectonics." (Melosh, 1989: v).

12 NOTES

1. Apart from the presence of shatter cones, veins of pseudotachylyte containing coesite and/or stishovite (Dressler and Reimold, 2001) and planar deformation features (PDFs), undisputable proof of meteoritic impact is also afforded by planar fractures (PFs), crystallographic configurations of feldspars (Shoemaker, 1983) and by basal Brazil twinning and alteration in zircons (Kamo, Reimold, Krogh, and Colliston, 1996). Note, however, that some of these 'indicators' were unknown when Wilson and Stearns conducted their research at Wells Creek site.

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