UNIVERSITY OF SOUTHERN QUEENSLAND

THE TENNESSEE METEORITE IMPACT SITES AND CHANGING PERSPECTIVES ON IMPACT CRATERING

A dissertation submitted by

Janaruth Harling Ford
B.A. Cum Laude (Vanderbilt University),
M. Astron. (University of Western Sydney)

For the award of
Doctor of Philosophy

2015

ABSTRACT

Terrestrial impact structures offer astronomers and geologists opportunities to study the impact cratering process. Tennessee has four structures of interest. Information gained over the last century and a half concerning these sites is scattered throughout astronomical, geological and other specialized scientific journals, books, and literature, some of which are elusive. Gathering and compiling this widely-spread information into one historical document benefits the scientific community in general.

The Wells Creek Structure is a proven impact site, and has been referred to as the 'syntype' cryptoexplosion structure for the United State. It was the first impact structure in the United States in which shatter cones were identified and was probably the subject of the first detailed geological report on a cryptoexplosive structure in the United States. The Wells Creek Structure displays bilateral symmetry, and three smaller 'craters' lie to the north of the main Wells Creek structure along its axis of symmetry. The question remains as to whether or not these structures have a common origin with the Wells Creek structure.

The Flynn Creek Structure, another proven impact site, was first mentioned as a site of disturbance in Safford's 1869 report on the geology of Tennessee. It has been noted as the terrestrial feature that bears the closest resemblance to a typical lunar crater, even though it is the probable result of a shallow marine impact. Flynn Creek is home at least ten caves including the only cave known to have formed in the central uplift of a terrestrial complex crater.

The Dycus Structure lies only 13 km to the north-northwest of Flynn Creek and may be associated with the Flynn Creek impact event. It is not a proven impact site, but shows strong evidence of meteorite impact with features that reflect on the rock pressures attained during the deformation process. Dycus is elliptical in shape and possesses an offset 'central' uplift even though it is too small to be a complex crater.

The Howell Structure was included in a 1949 list of the twelve best-known 'cryptovolcanic' structures. Features that may be shatter cones have been found in the Howell Structure, but they are poorly formed and indistinct. Breccias and planar fractures in quartz grains found within the circular structure are evidence of a disturbance, but whether or not this disturbance was due to an impact has yet to be determined. Howell remains a suspected impact site.

CERTIFICATION OF DISSERTATION

I certify that the ideas, experimental work, results, analyses, software and conclusions reported in this dissertation are entirely my own effort, except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award, except where otherwise acknowledged.

Signature of Candidate:

Date:

ENDORSEMENT BY SUPERVISORS

Signature of First Supervisor:

Date:

Signature of Second Supervisor:

Date:

Signature of Third Supervisor:

Date:

ACKNOWLEDGEMENTS

I am grateful to Professor Brad Carter (University of Southern Queensland), Professor Wayne Orchiston (National Astronomical Research Institute of Thailand) and Ron Clendening (Tennessee Division of Geology) for supervising this thesis project. I also appreciate the time that Marvin Berwind (Tennessee Division of Geology) has taken to tour the Wells Creek, Howell, and Dycus sites with me in addition to the Tennessee geological information he has been so generous in sharing. Larry W. Knox (Professor of Earth Sciences, Tennessee Technological University) served as tour guide for the Dycus structure and for the Flynn Creek site, including Wave Cave and the central uplift. He also provided geological maps of the Flynn Creek area. Richard S. Stringer-Hye (Stevenson Science and Engineering Library, Vanderbilt University) has also been of great assistance in locating some of the more obscure articles and papers. Rebecca F. Tischler (Williamson County Public Library) has provided invaluable technical and research assistance as well as photographed shatter cones and various sites in and around the Flynn Creek structure. I also wish to thank my husband, Heinrich Tischler, for his patient support and sacrifices, my son Andrew for his enthusiasm and willingness to climb central uplifts in all types of weather, my daughter Jessica for her constant encouragement, and my daughter Rebecca for sharing her time and insights as well as her many technical skills in this endeavor. Though my father, Hugh Green Ford, M.D., shared many interesting views through microscopes with me, it was the views he showed me of celestial objects through binoculars and rocks through magnifying glasses that kindled my early interest in Astronomy and Geology that eventually led to this study. My mother, Aidalu Butenschön Ford, a scholar and historian, made sure I had access to the books, places, and experiences that could feed my growing, though mysterious to her, interest in these disciplines. Therefore, I acknowledge, with gratitude, their influence from long ago on my current work.

TABLE OF CONTETS

Page

LIST OF FIGURES

Page

Chapter 1

Chapter 2

Chapter 3

Chapter 4

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 Topic Outline

The primary focus of this project is to provide a compilation of the information on and the history of the confirmed and suspected Tennessee impact sites (see Figure 1.1) culled from a variety of sources. In addition, a secondary focus is to either find answers to lingering questions concerning these sites or encourage further research into these areas by others. Confirmation of the impact status of the Howell and Dycus Structures should be considered a priority. Other questions include whether or not the Indian Mound craters are actually associated with the Wells Creek impact event. Further, insight into the ways structures resulting from non-marine impacts differ from marine impacts, such as Flynn Creek, will add to the general information regarding such structures on Earth and possibly structures on other Solar System bodies such as Titan or the Mars of long ago. My main objective is to gather, critically evaluate, and compile into one location as much information concerning these sites as possible.

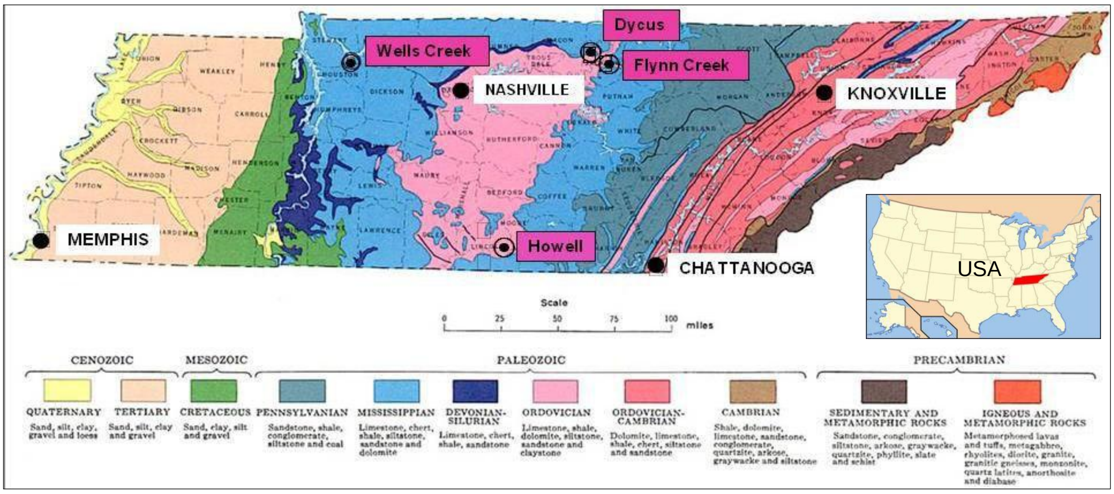


Figure 1.1: Generalized geological map of Tennessee showing the locations of the four largest cities (black dots) and the two confirmed and two suspected meteorite impact sites (small black dots with circles). These sites are located on the Highland Rim (Wells Creek), a Highland Rim outlier remnant (Howell), 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 of Conservation, Division of Geology, 1966). The inset in the bottom right corner shows the location of the State of Tennessee in red within the USA.

1.2 Specialist Terms and Definitions

A terrestrial impact event is one in which a meteorite, asteroid, or comet survives passage through the Earth's atmosphere and penetrates the planet's surface to explosively release large quantities of energy. This process, known as impact cratering, produces with few exceptions a generally circular crater (e.g. see Figure 1.2). Morphology refers to the form and structure of an impact crater. Smaller craters are simple and bowl-shaped with raised rims. Larger craters are more complex with a central region of uplifted rock and walls that have slumped to form terraces.

Figure 1.2: The Barringer Meteor Crater in Arizona (D. Roddy).

Most terrestrial impact craters have been subjected to long periods of erosion and other geological processes, such as deposition, which alter their appearance. These are called impact structures rather than craters and are the scars of ancient impact events. Early researchers referred to impact structures as 'cryptovolcanic', assuming that they resulted from violent explosions of subterranean gases, even though they lacked any evidence of such in the form of igneous rock or signs of volcanic activity. Robert S. Dietz (1914–1995, Figure 1.3) suggested the term 'cryptoexplosive' be used to designate these circular structures formed by an explosive release of energy, without restricting their origin to a particular process (Dietz, 1960: 1782).

Figure 1.3: Robert S. Dietz (foreground) looks on as as Robert F. Dill monitors a precision depth recorder on the *Oceanographer* in 1967 during its around the world cruise. Dietz's other area of international expertise was oceanography (oceanexplorer.noaa.gov).

Impact structures have certain characteristics in common such as brecciated rock, which is rock that has been violently broken or shattered into sharp-edged fragments and then melded back together in a fine-grain matrix. Other geological processes can also brecciate rock, so this is not a unique feature of impact. Shatter cones are cone-shaped rock features that are unique to impact or explosive cratering. Shatter cones have not been found at all confirmed impact sites, though.

1.3 Literature Review, Topic Justification and Importance

“When an irresistible force meets an immovable object, the only thing that can happen is a meteorite crater.” (Baldwin, 1963: 6). The most obvious surface features on our own Moon are its numerous craters. Views provided by robotic spacecraft, as far back as the 1960s, demonstrate that the most widespread and fundamental geological process in our Solar System is impact cratering. Asteroids, terrestrial planets, and most moons in our Solar System show extensive evidence of this process in which a meteorite, comet, or small asteroid impacts a solid surface at high speed and explosively excavates a crater. “Impact cratering … acquires great significance when studied in the context of planetary surfaces and planetary formation …” (Croft, 1977). Shoemaker (1977b: 1) points out that “The terrestrial planets were formed by this process; the last stage of accretion is still proceeding at a very slow rate.” Near-Earth asteroids such as the Amors, Apollos, and Atens pay frequent visits to our neighborhood and have more than sufficient mass to produce devastating impacts such as those recorded on the lunar surface.

It is apparent from viewing the heavily-cratered lunar highlands that our Moon suffered heavy bombardment in its past. The lunar surface differs from the Earth’s, though, in that it does not have a geological history that includes erosion and deposition as well as other events that would serve to erase its impact scars. Due to the close proximity of our Earth and Moon, it would seem that our planet also should have suffered numerous impacts throughout its history.

Opinions in the scientific community have historically been divided regarding the reality of terrestrial impacts and the origin of certain circular structures. Some very prominent scientists, Ralph B. Baldwin (1912-2010), Robert S. Dietz (1914-1995), and Eugene M. Shoemaker (1928-1997; Figure 1.4), to name only three, saw no reason why our planet should be spared from impacts when our nearby celestial neighbor was not. Others declared that no impact craters exist on the Earth or have ever existed on the Earth and that the so-called terrestrial impact craters and structures were actually of volcanic origin.

Figure 1.4: E.M. Shoemaker, (USGS photo, http://astrogeology.usgs.gov/About/AstroHistory/shoemaker.html).

Astronomers, geologists, physicists, chemists and mathematicians have spent many decades studying craters and structures that show the distinguishing characteristics of an impact-induced explosive origin. Indeed, the most practical way to study the mechanics of this process is to study the Earth's own impact structures. Tennessee has four 'laboratories' available for study, two proven and two suspected impact sites.

Wells Creek is the largest impact structure in Tennessee. According to Wilson and Stearns (1966: 37), the 1869 "Manuscript on the Faults of the Wells Creek Basin ..." by Safford and Lander, "... with its map and drawings is probably the first detailed geologic report on a cryptoexplosive (perhaps meteor impact) structure ..." in the United States. This is not the only 'first' involving the Wells Creek site. Wilson and Stearns (1968: 108) state that shatter cones, which are unambiguous proof of an impact event, were first located in the United States by W.H. Bucher in the Wells Creek Basin. Dietz (1963: 650) referred to the Wells Creek impact site as the 'syntype' cryptoexplosion structure for the United States. This was most likely, as also noted by Bucher, due to the observation of the structure's resemblance to "... damped waves, a central uplift surrounded by two pairs of down-and-up folds, with diminishing amplitude ..." (Bucher, 1936: 1068). In 1963, during preparations for the first manned lunar landing, the National Aeronautics and Space Administration provided funds for a detailed and thorough study of Wells Creek (Wilson and Stearns, 1968). The knowledge gained from its recognition as a proven impact structure is worth revisiting.

Wells Creek may be the best-known impact structure in Tennessee, but it is not alone. Baldwin (1949: 110) includes not only Wells Creek, but also the Flynn Creek and Howell Tennessee sites in his list of the 12 best known 'cryptovolcanic' structures. As such, they are also important to the study of impact cratering. Studies of the features found in the Hawkins Impact Cave, located in Flynn Creek's central uplift, will likely increase our understanding of impact cratering events, not only on Earth, but also on the surfaces of other terrestrial bodies in our Solar System. The Dycus Structure is still an enigma, worthy of further study in an attempt to understand it aberrant morphology which may shed light on some of the more unusual craters seen on the lunar surface.

Each of Tennessee's impacts structures, whether proven or suspected, has a story to tell. Each is unique with an interesting personality of its own. The Tennessee impact sites are all located in the Highland Rim or on the Highland Rim escarpment of middle Tennessee, but neglecting the information that can be gained from any of these structures would leave a gap in our understanding of the impact cratering process. Material regarding these Tennessee sites is scattered through seemingly unrelated astronomical and geological literature. Gathering and compiling findings regarding all of the Tennessee impact sites into one document would benefit the scientific community. Dietz's summation is still true: "Astrogeology is a subject which must concern the earth, as well as the moon …" (Dietz, 1963: 663).

1.4 Research Methodology

The research for this topic has been accomplished through an extensive literature review, archival work completed through the State of Tennessee's Division of Geology and Vanderbilt University's Stevenson Science and Engineering Library, as well as site visits to all of the Tennessee impact structures and suspected impact structures.

1.5 Thesis Structure

Chapter 2 provides an overview of the morphology of meteorite craters and structures, astronomical and geological evidence of their existence, and the mechanics of impact cratering. Chapter 3 contains a summary of the history of the changing views of astronomers and geologists as they first accepted the fact that rocks do fall from the sky and that these ‘space rocks’ can have sufficient mass and velocity to cause explosive impacts on the Earth as well as on the Moon.

Chapter 4 briefly discusses the geography and geology of Tennessee and then focuses on each of the sites of interest individually. Wells Creek is the largest and best known of Tennessee’s impact sites. Though it is a proven site of impact, there is uncertainty regarding three possible associated or satellite craters that lie in a north-northeast line that matches the bilateral symmetry of the Wells Creek Structure. Flynn Creek is also a proven site of impact and is home to the only cave known to exist in the central uplift of a complex crater, the Hawkins Impact Cave. The question of whether or not the Flynn Creek Structure is the result of a shallow marine impact has only recently been resolved since it seemingly shows evidence of being the result of both a ‘wet’ and a ‘dry’ impact event. The enigmatic Dycus Structure seems to defy understanding. Unlike the majority of impact craters, it does not exhibit a generally circular structure. It also seems to have an offset ‘central’ uplift even though it is too small to be a complex crater. After years of neglect, though, there is new ongoing research at Dycus that may finally settle the question of its origin. The Howell Structure displays characteristics related to confirmed impact structures such as a localized and intense brecciation of rock that decreases and finally ceases with depth. However, definitive evidence of impact such as planar deformation features in shocked quartz is lacking. Possible shatter cones photographed in 1968 have not been relocated for confirmation and drill cores have been lost with the passage of time. Hopefully, this paper will encourage researchers to address this current lack of evidence and settle the question of whether or not Howell is an impact scar.

CHAPTER 2: TERRESTRIAL METEORITE IMPACT SITES

The following discussion of the morphologies of meteorite impact structures, the astronomical and geological evidence for their origins, and the mechanics involved in their formation is *not* an exhaustive literature review. It primarily focuses on those aspects that relate to the Tennessee Structures, whether proven or only suspected sites of impact, and the questions concerning the origins of these sites that are still unanswered.

2.1 Meteorite Crater Morphology

The 'Principle of Original Horizontality' was first proposed by the pioneering Danish geologist Nicholas Steno (1638–1686), and states that terrestrial rock material was originally deposited in an orderly fashion resulting in horizontal layers (see Figure 2.1). This material then underwent lithification and became coherent, solid rock with the various layers still evident. If these rock layers are later discovered to be in non-horizontal positions, then they must have been tilted out of their original position some time after deposition. In addition, the Principle of Superposition states that younger rock materials are always deposited on top of earlier, older deposits so in any horizontal sequence of rock layers, or strata, the youngest rock will be found at the top and the oldest at the bottom.

Figure 2.1: A geological location in north central Tennessee, around 40 km from the Wells Creek Impact Structure, showing a clear example of Ordovician marine sediments that were horizontally deposited in successive strata, with the oldest at the base and the youngest at the top of the exposed section (courtesy: Heinrich Tischler).

An impact crater is created by the high-velocity explosive impact of a small celestial body on the solid surface of a much larger body. Impact craters are for the most part circular features with raised rims and floors that are below the surrounding ground-level, characteristics manifested by craters visible on the lunar surface (e.g. see Figure 2.2). Impact structures are often located in flat and otherwise undisturbed and undeformed rock and so are quite obviously the results of an intense, but localized event. Impact craters, especially lunar craters, not subject to erosion, are frequently found to be surrounded by an ejecta blanket consisting of materials ejected from the crater during the impact and explosion process (e.g. see Figure 2.3).

Figure 2.2: Isidorus D, a 15-km diameter crater located in the Lunar Highlands (Apollo lunar image AS16-4502(P)).

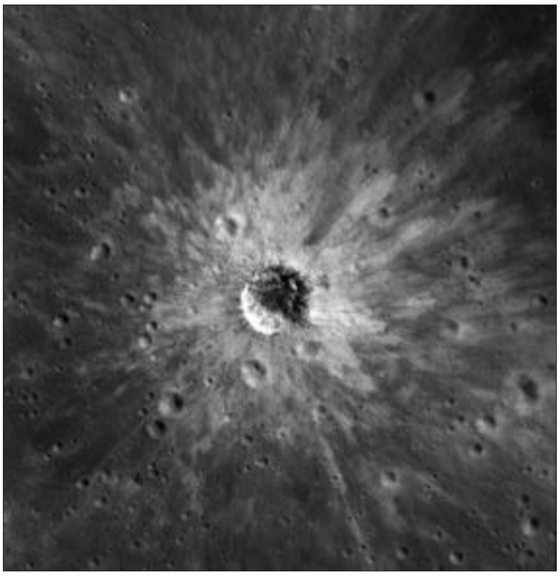


Figure 2.3: An unnamed lunar crater, ~270 m in diameter, with a symmetrical ejecta blanket (NASA/ Goddard Space Flight Center /Arizona State University).

Some lunar as well as terrestrial craters, those more than 2 to 4 kilometers in diameter on Earth, show greater complexity (e.g. see Figure 2.4) possessing central uplifts, flat floors, ring depressions and terraced walls due to an inward collapse of the rim (French, 1998: 24).

Figure 2.4: The lunar crater Tycho, 86 km in diameter, showing a central uplift surrounded by a flat floor and terraced walls due to the inward collapse of the original crater rim (Lunar Orbiter 5 (NASA)).

2.1.1 Impact Craters and Structures

On the Earth, impact craters are modified and altered by erosion, deposition and other geological processes over long periods of time to form the scars of impact seen today and referred to impact structures (Koeberl, 2009: 14). An impact structure is an eroded impact crater that consists simply of the "… basement structure, the modification of which is produced deep below the earth's surface by the unimaginable great pressures which developed as the intruding mass came to a halt and exploded …" (Baldwin, 1949: 94). The features normally associated with an impact cratering event such as an upturned rim, meteorite fragments and target rock ejecta are erased from the Earth's surface over time by erosional and tectonic processes.

After an impact crater has been subjected to erosion for an extended period of time, the underlying structure is all that is preserved as is shown in Figure 2.5, a schematic diagram illustrating the successive phases of erosional modification of an impact crater by Mitchum (1951: 35). Mitchum's diagram is based on a 1937 diagram by Boon and Albritton (1937: 57). Terrestrial weathering will continue the modification process until a structure is no longer recognizable as the scar of an impact. The A-level in this diagram shows an impact site with an obvious crater of recent origin. The B-level re-presents an impact crater that has eroded to the point that it is barely discernible. The Level-C, however, shows the underlying strata of an impact structure becoming somewhat more apparent as erosion continues. By the time an impact structure has eroded to its basement, the central uplift and ring folds have become conspicuous (Baldwin, 1949: 106). Over time, though, erosion will wear even this basement structure away and it will no longer be recognizable as an impact site. In addition, existing impact structures may not be recognizable as such due to extended periods of folding, faulting or mountain building.

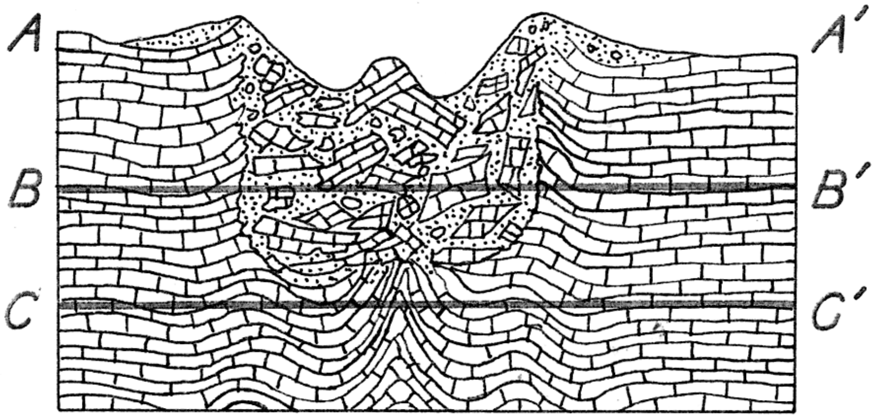


Figure 4. Ideal section through a typical cryptovolcanic structure, according to the meteoritic theory of origin. (For explanation of lettered lines, see text). (Adapted from Boon and Albritton, 1937, and Wilson and Born, 1936).

Figure 2.5: A schematic illustrating successive phases of modification of an impact crater (after Mitchum, 1951: 35).

The age of some impact structures can be difficult to determine. A lack of continuity or a gap in the logical sequence of rock layers due to erosion is referred to as a discontinuity. Baldwin (1963: 93) points out that "… the great discontinuities in geologic history as shown by the rock layers at any particular point leave tremendous spans of time unaccounted for. Hence the dates of formation of these objects are uncertain by tens of millions of years and often by hundreds of millions." This is the case for the Wells Creek Structure (Miller, 1974: 56).

Lunar impacts differ from terrestrial impacts in one important aspect: our Moon is essentially without an atmosphere. The Earth's atmosphere prevents small meteoroids from reaching the surface by deflection or ablation. Somewhat larger bodies, including fragments of meteoroids resulting from atmospheric breakup such as the Sikhote-Alin bolide, may be slowed to terminal velocity and merely fall to ground level at subsonic speeds creating a pit (e.g. see Figure 2.6) rather than an explosive impact crater (Killgore and McHone, 1998). A meteoroid moving through the Earth's atmosphere will deflect a volume of gas approximately equal to the length of its trajectory times its cross-sectional area and if this volume of gas has a mass that is greater than ten times the meteoroid's mass, then, due to the conservation of momentum, the velocity of the meteoroid is reduced to less than ten percent of its original velocity (Melosh, 1989: 205).

Figure 2.6: The 1947 Sikhote-Alin meteorite fall left many small impact pits such as the one shown above (http://www.arizonaskiesmeteorites.com/AZ_Skies_Links/SikhoteBackground/index.html).

Projectiles can be distorted or even fragmented as they plough through the Earth's atmosphere and may or may not survive to produce a crater or pit. However, objects with sufficient mass, tensile strength, and diameter can travel through the Earth's atmosphere intact and retain enough of their original velocity to create a hypervelocity impact crater through violent excavation (as in the case of the Barringer Crater for example—see Figure 1.2). These high-velocity impacts produce craters by conversion of their kinetic energy into shock waves and thermal energy

(French, 1998: 7-8). According to Melosh (1989: 206) the minimum diameter for a meteoroid that is able to penetrate the Earth's atmosphere at vertical incidence and form a hypervelocity impact crater is 150 meters for an icy body, 60 meters for a stony meteorite, and 20 meters for a nickel-iron impactor.

2.1.2 Simple Craters

Small meteorites are slowed by the Earth's atmosphere to a velocity that is below the velocity required for an explosive impact. Terrestrial meteoritic pits up to about 10 meters in diameter are most likely the result of gouging of the ground by the actual meteorite collision with the Earth rather than the result of an explosive impact event (Baldwin, 1949: 77-79). Small impactors often form clusters of craters on the Earth (e.g. see Figures 2.7 and 2.8) reflecting the atmospheric breakup of a much larger projectile (Melosh, 1989: 101). Small explosive impact structures, referred to as simple craters whether terrestrial or not, are usually bowl-shaped with raised rims (Figure 2.9).

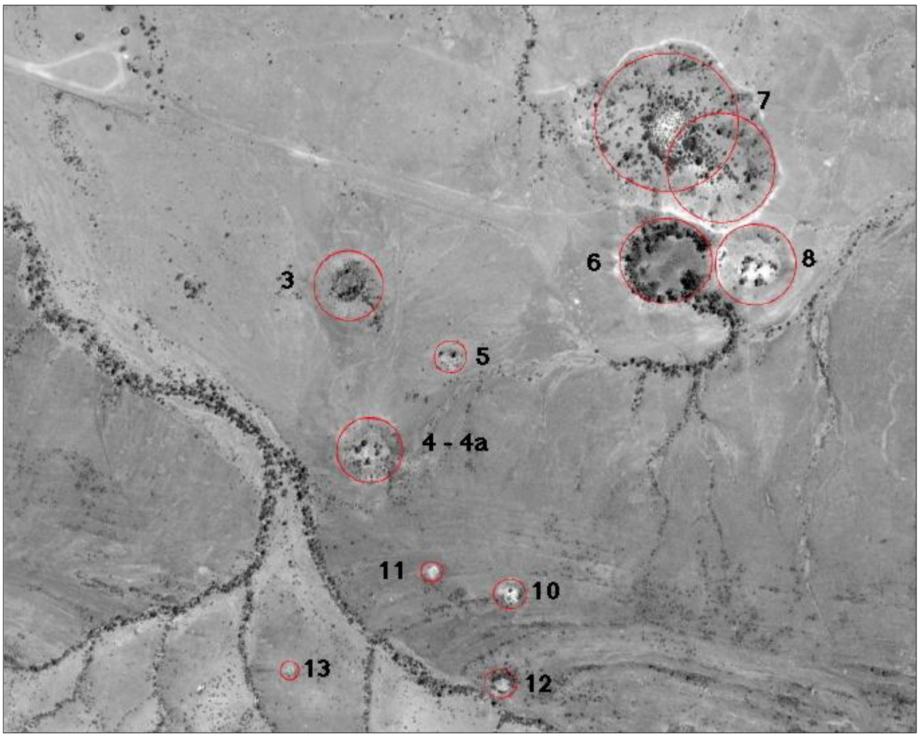


Figure 2.7: Image of the Henbury Crater cluster compiled and adapted from maps.google.com (www.k12.hi.us/ ~tbrattst/Craters/henbury_guide.htm).

Figure 2.8: Photograph of one of the small Henbury craters - approximately 30 m across and 8 m deep (courtesy: David McKinnon and the Planetary and Space Science Centre, University of New Brunswick, Canada).

Figure 2.9: Located on the lava plains of the Elysium Planitia, this unnamed Martian crater, 2.3 km in diameter, is an example of a typical 'simple crater' (Mars Global Surveyor image PIA02084).

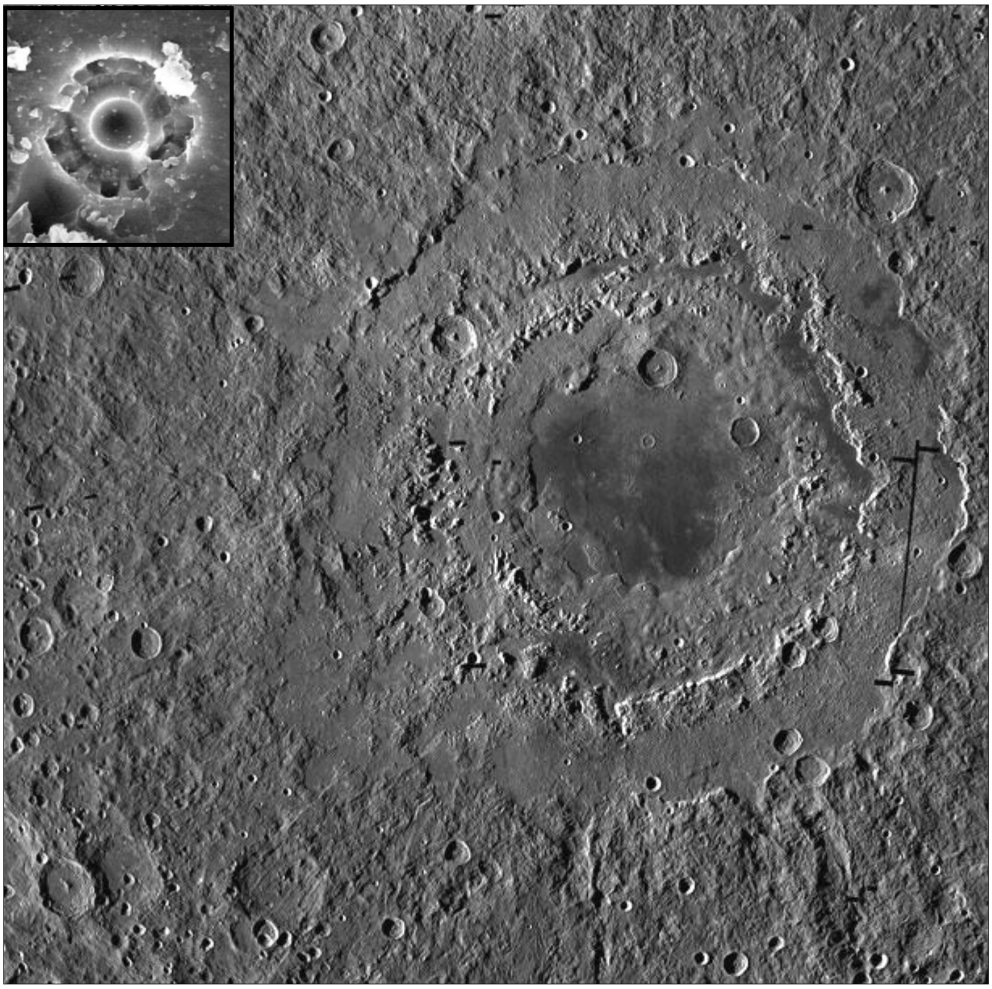


Figure 2.10: Lunar Orientale Impact Basin, a multi-ring crater 950 km across (Lunar Reconnaissance Orbiter, NASA/ Goddard Space Flight Center/Arizona State University). Insert: A 10-micron diameter microcrater made when a particle of cosmic dust struck a small bead of lunar glass on the Moon's surface (NASA- http://stardust.jpl.nasa.gov/photo/cometwild2.html#row7).

Simple craters have a classic parabolic form with an interior slope which is steepest near the raised rim and decreases smoothly to the crater center. "The rim-to-floor depth of such craters is generally about one-fifth of their rim-to-rim diameter, and the rim height is about 4 percent of the diameter." (Melosh, 1989: 14). The upper size limit for a simple crater appears to reflect its modification by some minor rim wall collapse due to gravity. French (1998: 23) notes that "… the crater diameter may increase by as much as 20% …" during modification.

Crater size depends not only on the target material and the target body's gravitational acceleration, but also on the impactor's size, speed, composition, and angle of impact (Melosh, 1989: 50, 77). Lunar craters run the gamut from microcraters to multiringed basins with diameters in the hundreds of kilometers (e.g. see Figure 2.10). Simple and more complex craters fall between these two extremes. Microcraters consist of a bowl-shaped pit, often lined with melted material, surrounded by shattered rock (Melosh, 1989: 14). The primary difference between microcraters and larger craters is that target strength dominates microcrater excavation rather than gravity which plays the dominant role for larger craters (ibid.).

2.1.3 Complex Craters

At some point, an abrupt change in crater morphology takes place that is related to diameter which results in a more complex crater (see Figure 2.11). The noted American geologist G.K. Gilbert (1843–1918) recognized as early as 1893 that there is a relationship between a crater's diameter and its morphology (Melosh, 1989: 14). This point is different for each planet and moon and depends on their acceleration due to gravity (French, 1998: 24). These morphology transitions correlate inversely with gravity. On the Earth the changeover from a simple to a complex crater occurs for diameters between 2 and 4 kilometers and for lunar craters the changeover occurs around 20 kilometers, in accordance with the fact that Earth has six times the gravity of our Moon (French, 1998: 27; Melosh, 1989: 18). The difference in terrestrial crater transition diameter is based on whether a particular impactor's target material is crystalline rock or sediment (French, 1998: 24; Melosh, 1989: 18).

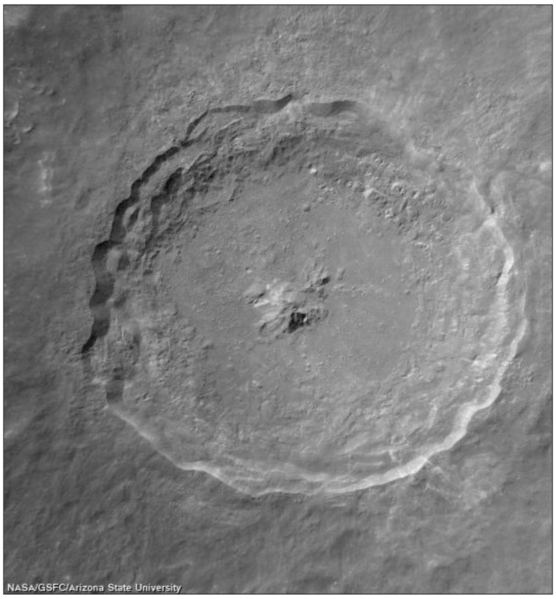


Figure 2.11: Tycho, an 85-km lunar complex crater - LROC Wide Angle Camera, 11 June 2011 (NASA/GSFC/Arizona State University).

As crater morphology transitions from simple to complex, crater floors flatten due to a covering of material that has slumped inward from the steep crater walls. This causes complex craters to be shallower for their diameters than simple craters and some complex craters even exhibit slumped terraces due to crater collapse (French, 1998: 24). Complex craters may also exhibit one or more ring grabens, depressed rings (Figure 2.12), due to a downward and inward collapse of the original crater along concentric faults (ibid.).

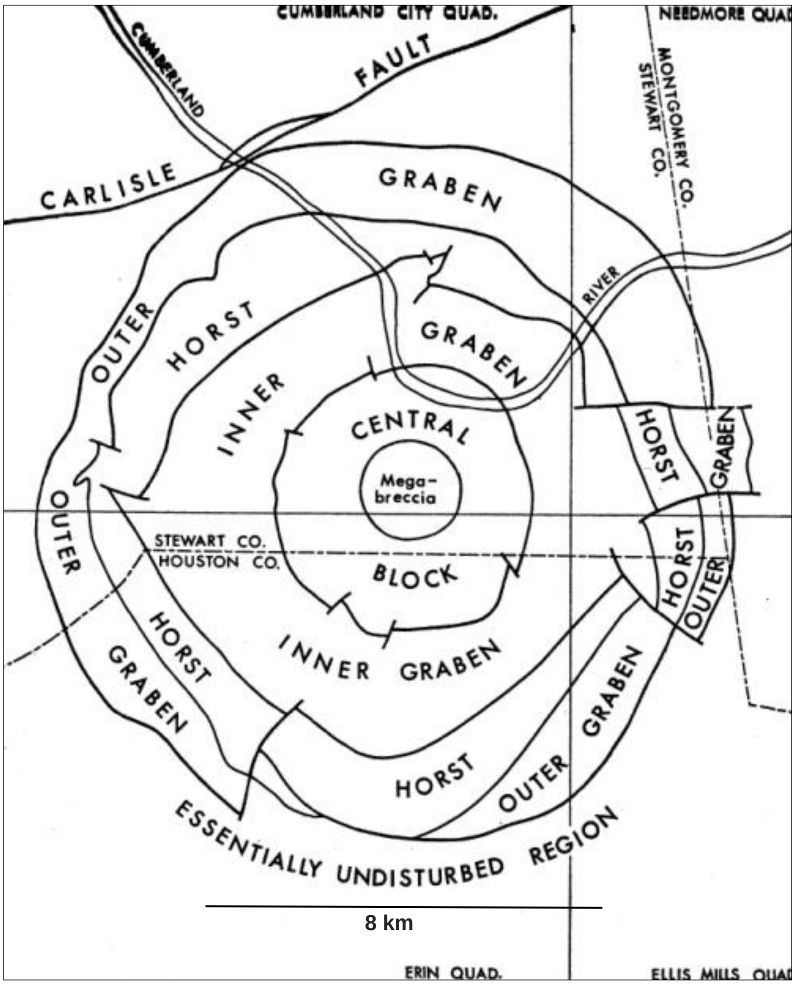


Figure 2.12: The Wells Creek Structure consists of annular outer and inner grabens with an intervening horst surrounding the central block (after Wilson and Stearns, 1968: 55).

Another profoundly different characteristic of complex craters is the central peak (Figure 2.13). A true central peak does not consist of landslide debris piled or mounded into a central heap, but is composed of rock that was originally below the crater floor and then uplifted a distance that is typically around 8 percent of the crater's final diameter (Melosh, 1989: 18). In larger complex craters the central peak is replaced by a concentric ring of peaks (e.g. see Figure 2.14). Such peak-ring craters have an inner ring diameter that is about half of the rim-to-rim diameter (Melosh, 1989: 21). The largest impact structures are often referred to as impact basins (see Figure 2.10). "At least three types of complex impact structures can be distinguished with increasing crater diameter: central-peak structures, central-peak-basin structures, and peak-ring basin structures." (French, 1998: 25-27). The transition diameter of complex to peak-ring is again inversely proportional to gravitational acceleration in the same manner as the simple-to-complex crater diameter transition (ibid.).

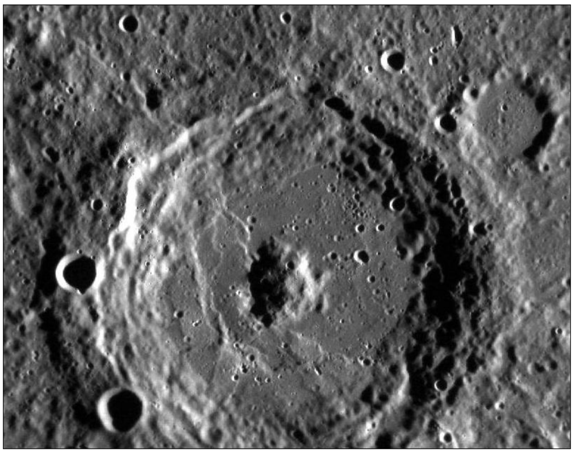


Figure 2.13: Donne, a complex crater on Mercury, 88 km in diameter, displaying a central peak and well-developed wall terraces (Image Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington, 2 August 2011).

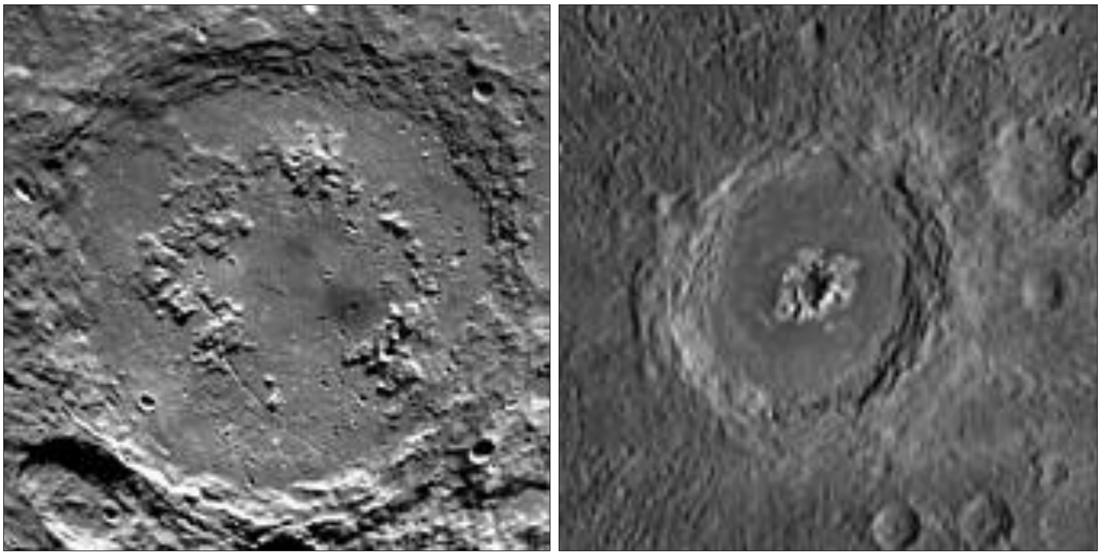


Figure 2.14: Peak-ring craters. Left: lunar crater Schrodinger, diameter 320 km (NASA). Right: Eminescu crater on Mercury, 125 km in diameter (NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington, MESSENGER Narrow Angle Camera, 14 January 2008).

It should be noted that some simple craters may have a low central or near-central mound that formed within the broken rock filling the crater that is "… 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). This is not a true central uplift. The Barringer Crater in Arizona, a simple crater just over 1 km in diameter, possesses such a mound that is about 15 meters high, but slightly displaced to the northwest of the center of the crater (ibid.).

Milam and Deane (2005: 1) have identified the following features as common to terrestrial complex craters. Blocks of material, centimeter to meter in size, are found in the central uplifts, often with internal faults and fractures. These features are frequently microscopic, less than one millimeter thick and not visible in the field. Such microfaults terminate at block boundaries and cause millimeter offsets to occur in the target rock (ibid.). Whether or not the microfractures date from or before impact versus after the event can usually be determined by noting their termination at block boundaries and lack of extension (Milam and Deane, 2005: 1). Microbreccia, silt to clay-size, is often found in the microfaults. Milam and Deane (2005: 1) also point out that major faults in central uplifts bound major blocks and the target strata may be offset by hundreds of meters. These faults, centimeters to meters in thickness, most likely allowed for stratigraphic uplift of the crater floor material. According to Milam and Deane (2005: 2), "… the above features are not unique to impact sites …" however, they are closely associated with the unambiguous shock features due to impact and found to be concentrated in central uplifts and along the crater floors of complex craters.

2.1.4 Distinctive Craters and Structures

Unusual impact craters and structures can result from unusual formation conditions regarding either the impactor, its trajectory, or the target body. Kenkmann and Poelchau (2008: 1) refer to craters formed by an impact of between 15 to 35 degrees from the horizontal as 'oblique' and those formed by an impact of less than 15 degrees 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.). Very shallow or grazing impacts will result in craters with butterfly-shaped ejecta blankets as is shown in Figure 2.15, a Martian impact crater in the Melas Dorsa region. Hessen et al. (2007) found that impact craters 15 degrees or greater from horizontal remain circular, but become increasingly more elliptical as the angle of impact decreases. Ejecta blankets become asymmetrical around 60 degrees from horizontal and develop an up-range forbidden zone around 20 degrees 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, 2008: 2).

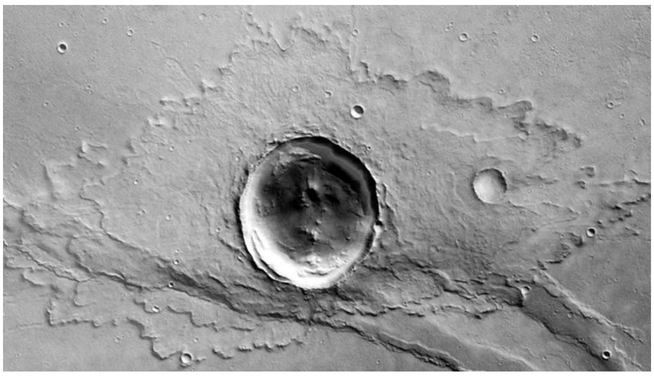


Figure 2.15: The High Resolution Stereo Camera (HRSC) operated by the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt; DLR) on board ESA's Mars Express spacecraft acquired the above image of a large, oval crater measuring about 16 kilometres across. Its ejecta blanket is in the shape of a butterfly. To form such an ejecta blanket, the impact must have occurred at a very shallow angle with respect to the planet's surface. Credit: ESA/DLR/FU Berlin (G. Neukum).

Since approximately two-thirds of the Earth is covered by water, terrestrial impacts should most often occur in a marine environment. Due to the difficulties encountered in exploring submarine impact structures, though, most impact studies have focused on structures found on the continents. Marine impact craters can deviate structurally from the generalized morphologies described previously for land-target craters. According to Ormö and Lindström (2000: 1),

> Marine-target craters form only if the target sea is shallow enough to admit sufficient kinetic energy into the sea bed. When the crater diameter is large compared to the water depth, the crater resembles its counterparts that are formed on land. Craters formed in deeper water are concentric, and often lack melt sheets and rim walls, but have deposits and radial gullies formed by the resurge of the sea.

Resurge gullies form as water surges back into the just-formed crater. "One of the important differences from land-target craters is the presence of abundant resurge deposits in craters where the water depth of the impact site was sufficient to overcome any rim wall formed …" (Dalwigk and Ormo, 2001: 359). Craters formed at great water depths likely suffer rim destruction, however, "At shallow water depths the water cannot break through the rim wall of the crater." (ibid.). If the crater rim height is about the same as the same as the water height, though, gullies could still form if water is able to breach or cut through the crater wall (see Figure 2.16).

Figure 2.16: A painting by Jerry Armstrong of the Wetumpka Crater in Alabama, which was formed in a shallow marine environment. This painting is based on Professor David King's research on the crater and shows the initial breaching of the crater walls by the sea (courtesy: http://wvaughan.org/wetumpka.html).

The asymmetrical distribution of ejecta around the Lockne marine impact structure in Sweden indicates that it is the result of an oblique impact. Numerical simulations of the impact event suggest that the 600 m in diameter impactor deformed and partially fragmented during a 500 m water passage (Lindström et al., 2004). The crater excavation depth reached 250 m under the sea floor with about half of the ejected material consisting of sediments and the other half basement rock. Around 70% of the ejected rocks experienced shock compression below the level that would form shock metamorphism features such as PDFs. Due to the curtain of ejected water, the expansion of the main mass of ejecta was restricted, though a few large fragments passed through the water curtain forming the local areas of distal ejecta that have been observed around the Lockne structure.

Numerical modeling of a hypervelocity marine impact indicates that the cratering process depends only on the ratio of the projectile diameter, d, and the water depth, H (Wünnemann et al. 2007: 1894). For $d/H < 0.1$, a deep-water impact, the projectile does not penetrate the entire water column and no underwater crater is formed in the seafloor. For $0.1 < d/H < 1.0$, the water column has significant influence on crater formation. For $1.0 < d/H$, a shallow-water impact, the water layer does not significantly affect the cratering process. In the latter case, the crater rim may reach above the pre-impact sea level and prevent water from flowing directly back into the crater. Instead the water may erode deep channels in the crater rim resulting in a slow filling of the crater. Resurge channels, or gullies, were first recognized at Lockne, however, numerical modeling and facies analysis indicate that $d/H \sim 1$ for Lockne, so it is unlikely that the crater rim reached above sea level (Wünnemann et al. 2007: 1896). Kenkmann et al. (2007) consider it likely that Lockne is not a pristine crater, though. They interpret the radially oriented depressions not as resurge gullies, but as open synclines, the result of post-impact deformation by orogeny, in which resurge deposits were well preserved. Still, Lockne is regarded as reference crater for marine impacts in which the impactor diameter is similar to the water depth.

2.2 Astronomical and Geological Evidence

Meteorite fragments are regarded as conclusive evidence of impact, but unless a terrestrial impact crater is of relatively recent origin, any remnant of the impacting body has usually been destroyed through weathering. When a large object impacts rock, the explosive release of energy most often results in the vaporization of the impactor along with some of the target rock. Any remaining rock is usually folded, faulted, melted, shocked or brecciated. "A wide variety of distinctive rock types – breccias, melts, and shock-metamorphosed target rocks – are produced during formation of impact structures …" (French, 1998: 61).

2.2.1 Breccias

Breccia is target rock that is broken into angular fragments during impact, then chaotically mixed, and subsequently cemented together in a granular matrix (Miller, 1974: 56; Mark 1987: 66). In impact structures, breccias (e.g. see Figure 2.17) are one of the most prominent macroscopic features of impact cratering. Even in deeply-eroded structures, breccias and melt rock may be preserved (French, 1998: 98). A breccia lens, that is a lens-shaped mass consisting of angular breccias within a crater, may contain several times the original impactor's mass and consist of melted target rock along with heated and impact-shocked rocks (French, 1998: 63, 69-70). The local rock layers may not only be brecciated, but pulverized into 'rock flour' such as that found at the Barringer Meteorite Crater (Hoyt, 1987: 81).

There are many phases in the cratering process when breccias or even microbreccias can form. Lithic breccias form "… by the shattering and pulverizing of target rock essentially in place (*auroclastic)* typically form irregular bodies tens to hundreds of meters in size …" (French: 1998: 64). "Other bodies of breccias in the subcrater rocks contain significant amounts of material that have been clearly introduced into them from elsewhere …" (ibid). These allogenic breccias can be "… angular to rounded and range in size from < 1 mm to several meters … indicating mixing over distances of at least several hundred meters …" (ibid.). Breccias may incorporate previously-formed breccias mixed with bodies of impact melt (French, 1998: 69). Much of the final crater fill consists of redeposited breccias and melt rock (ibid.). Milam and Deane (2005: 1) point out breccias can form along major faults in central uplifts during an impact event as well as from ejecta. Brecciation is associated with impact cratering, but is not unique to it (French, 1998: 36).

Figure 2.17: A breccia sample from the Howell suspected impact site in Tennessee (courtesy: William Deane).

Impact cratering research often involves an interdisciplinary approach. Input from those trained in different fields previously led to some confusion in the use of terms related to impact cratering. Stöffler and Grieve (1994) proposed impactite nomenclature be standardized as shown in the following table.

Table 2.1: Classification and nomenclature of impactites
(after Stöffler and Grieve, 1994: 1347).

I. Impactites from single impacts	
A. Classification according to components, texture and shock metamorphism	*B. Classification of impactites according to mode of occurrence*
1. Shocked rocks	1. Massive impactites (irregular bodies, layers, lenses, blocks)
2. Impact melt rocks (clast-free)	1.1 Autochthonous (authigenic)
2.1 Glassy impact melt rocks (impact glasses)	1.2 Allochthonous (allogenic)
2.2 Hypocrystalline impact melt rocks	1.2.1 Inside crater rim (crater fill)
2.3 (Holo)crystalline impact melt rocks	1.2.2 Outside crater rim (ejecta blanket)
3. Impact breccias	2. Impact breccia dikes
3.1 Monomict (cataclastic) impact breccias	2.1 Fragmental breccia dikes
3.2 Polymict clastic impact breccias	2.2 Suevite breccia dikes
3.2.1.1 Fragmental impact breccias (without melt particles)	2.3 Melt breccia dikes (clast-bearing impact melt)
3.2.1.2 Suevite breccias (with melt particles)	2.4 Pseudotachylite (calst-bearing frictional melt)
3.3 Impact melt breccias (clast-bearing)	3. Impactoclastic air fall beds and tektite strewn fields
3.3.1 Glassy impact melt breccias	
3.3.2 Hypocrystalline impact melt breccias	
3.3.3 (Holo)crystalline impact melt breccias	
II. Impactites from multiple impacts	
1. Impact regolith (unconsolidated impactoclastic debris)	
2. Shock lithified impact regolith (consolidated impactoclastic debris)	
2.1 Regolith breccias (with matrix melt and melt particles)	
2.2 Fragmental breccias (without matrix melt and melt particles)	

2.2.2 Shatter Cones

In addition to brecciation of the nearby rock strata during an impact event, shatter cones and shocked minerals are produced by the passage of an impact-induced compressional shock wave. "Shock waves are intense, transient, high-pressure stress waves that are not produced by ordinary geological processes." (French, 1998: 17). The effects of these waves have been studied in nuclear explosions and laboratory-scale shock experiments. Impact-induced shock waves travel with velocities greater than that of sound, are accompanied by high temperatures and produce "… unique and permanent deformation effects in the rocks through which they pass." (ibid.).

Milam and Deane (2005: 2) state that unambiguous shock features include "… shocked mineral phases, high pressure phases, melting, and shatter cones." Of these, the only macroscopic impact features are shatter cones (Figure 2.18). Shatter cones were described first by Branco and Fraas in the Steinhein Basin crater in 1905 (see Roddy and Davis, 1977: 716). These are nested, conical fractures that occur in impacted rock and cut across sedimentary features. They are easily recognized by the distinctive striated conical lines along which the rocks fracture as a result of the shock waves generated by impact. Some researchers have found that shatter cone tips point in the direction of applied pressure (French, 1998 40; Roddy and Davis, 1977: 715), though evidence to the contrary has been located in the Vredefort Dome of South Africa (Wieland et al., 2003).

Figure 2.18: Shatter cones found at the Wells Creek impact site in Tennessee (courtesy: Andrew Tischler).

According to Wieland et al. (2003) shatter cone apeces do not point uniformly to the center of the Vredefort Dome structure, but show a variety of prominent orientations, primarily normal to the strike of the bedding and parallel to the dip direction of the bedding plane as well as parallel to the strike and normal to the dip direction of the bedding plane or with apex directions varying 30 to 60 degrees with respect to the strike of the bedding. The back-rotation of strata to pre-impact position model previously invoked to explain variety in shatter cone orientation does not account for the variety of apex orientations observed in Vredefort field work. Wieland et al. (2003) find that both complex pre-impact structure and post-impact deformation due to faulting and folding can also be excluded as possible explanations since a consistent behavior should have been observed for all Vredefort site measurements taken within a few meters in extent, which is not the case. The most common, or primary apex orientation observed, however, is *compatible* with the rotation model. Scattering or reflection of the shock wave as it propagates through target rock due to inhomogeneities in the rock or changes in lithology or mineral content could explain the other shatter cone orientations observed.

Roddy and Davis (1977: 718) state that "… tests demonstrate *unequivocally* that shatter cones are formed by shock waves in laboratory experimental hypervelocity impacts." Shatter cones are usually found in central uplifts, but are occasionally found within isolated breccia units. They may occur individually or in composite groups and in many types of rock with the cones ranging in length from millimeters to meters (French, 1998: 36-38). Well-formed shatter cones are easily distinguished in the field, however, "In coarser rocks, shatter cones are cruder, and their striations are larger, making the cones more difficult to recognize and distinguish from nonshock deformational features." (ibid.). Shatter cones can form at low shock pressures of 2 to10 Gpa up to 30 GPa (ibid.). This allows for shatter cone development in large volumes of target rock. French (1998: 40) points out that "Even in well-established impact structures, shatter cones may be entirely absent or poorly developed …" so an absence of shatter cones should not be considered proof of a non-impact origin.

2.2.3 Shock Melt

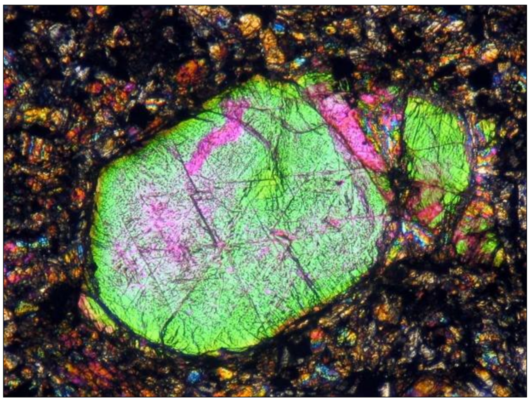
Other distinctive shock features also occur in impact structures. After release from the high pressures of impact, decompressed target material is seldom found in its original state. Target rock may not only be fractured, but pore space in sedimentary rock can be crushed causing water in these pores to be vaporized or, if temperatures are sufficient, the rock may melt or even vaporize (Melosh, 1989: 42). According to Baldwin (1949: 97), the production of shock-melted glass through the melting of target rock (see Figure 2.19) is indicative of an impact event, however, the possibility of a volcanic or tectonic melt origin must be ruled out for any suspected impact glass. French (1998: 36) states that for shock pressures greater than 35 GPa up to 60 Gpa, partial melting of minerals such as feldspar occurs, and from 60 GPa to 100 GPa, all minerals experience complete melting resulting in "… a superheated rock melt." Above 100 GPa, rock will vaporize and then condense to glassy materials (ibid.).

Figure 2.19: A 4-inch wide slice of shock-melted glass from the Tenoumer Impact Crater in Mauritania, Africa (http://astrobob.areavoices.com/tag/coesite).

D.M. Barringer's original argument concerning the impact origin of the crater that would eventually be named for him was made in 1906. He thought that the iron impactor was buried in the crater and planned to mine the metal (Hoyt, 1987: 75). 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." (Hoyt, 1987: 192). Bomblets of silica glass formed from melted sandstone and limestone in the Barringer Meteor Crater were indeed found to contain minute metallic fragments that tested positive for nickel, most likely from the vaporized iron-nickel meteorite that caused the crater's formation (Baldwin, 1963: 16).

2.2.4 Planar Microstructures

Most metamorphic changes in rock due to pressure and heat occur over long periods of time. Shock metamorphism involves changes due to instantaneously-applied pressure and heat. When minerals such as quartz are subjected to impact-produced shock waves, unusual microscopic planar features develop, some of which are considered diagnostic of meteorite impact (French, 1998: 49). These shock features are most often seen "… as sets of parallel deformation planes within individual crystals …" (French, 1998: 42). Planar fractures (PFs) are "… parallel sets of multiple planar cracks …" in a quartz grain that develop at pressures ranging from 5 to 8 GPa (ibid). These fractures are usually 5-10 μm in width and are spaced 15-20 μm or greater apart (ibid.; e.g. see Figure 2.20). PFs suggest shock, but are not unique to meteorite impacts (ibid.).



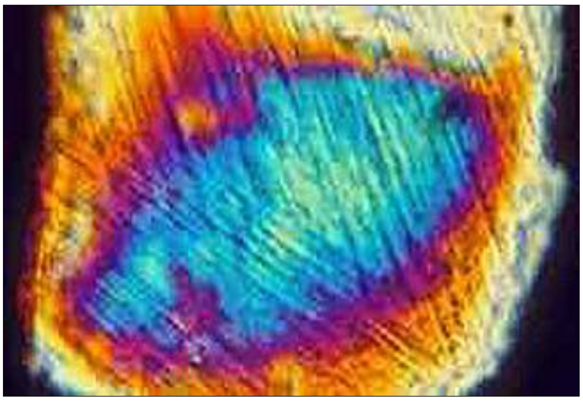


Figure 2.20 (left): A thin section showing planar fractures in three orientations in olivine crystals (after Kashuba, 2013). Figure 2.21 (right): A thin section showing planar deformation features in shocked quartz from the Chesapeake Bay impact structure (Glen A. Izett - http://geology.er.usgs.gov/eespteam/crater/shockquartz.html).

Planar deformation features (PDFs) are not cracks in quartz, but are "… multiple sets of closed, extremely narrow, parallel planar regions …" that are typically less than 2-3 μm wide and spaced around 2-10 μm apart (French, 1998: 42). They are thus narrower and more closely spaced than PFs and are "… clearly distinct from deformation features produced in quartz by non-impact processes." (French, 1998: 44). PDFs consist of "… highly deformed or amorphous quartz, and they are generally oriented parallel to specific rational crystallographic planes in the host quartz crystal." (ibid.). These features form at shock pressures that range from around 7 to 35 Gpa (French: 1998: 49). Multiple sets of PDFs can appear within quartz grains (see Figure 2.21). "At higher pressures, e.g., 20-35 GPa, the total number of PDF sets increases, and additional orientations appear.” (French, 1998: 52).

Although French (1998: 52) states that “PDFs and their orientations can be reliably used as indicators of shock and impact events …” he also cautions that appearance alone is inadequate for identifying PDFs as features produced during an impact event (French, 1998: 49). He notes that PDFs tend to form along certain planes in a quartz grain’s crystal lattice and in order to prove an impact origin for a specific structure using PDFs, measurements of the PDF orientations within the quartz grain must be made (ibid.). “The procedures involve measuring, in a single quartz grain, both the orientation of the pole (normal) to each set of PDFs and the orientation of the c-axis (= *optic axis*) of the grain.” (ibid). The optic axis of a quartz crystal is the only direction in which a transmitted light ray will not experience a double refraction. These measurements are expressed as the angles between the quartz c-axis and the poles to the PDF planes (ibid.).

Table 2.2: Shock pressures and their effects (after French, 1998: 33).

Approximate Shock Pressure (GPa)	Estimated Postshock Temperature (°C)*	Effects
2–6	<100	Rock fracturing; breccia formation
		Shatter cones
5–7	100	Mineral fracturing: (0001) and $\{10\bar{1}1\}$ in quartz
8–10	100	Basal Brazil twins (0001)
10	100*	
		Quartz with PDFs $\{10\bar{1}3\}$
12–15	150	Quartz → stishovite
13	150	Graphite → cubic diamond
20	170*	
		Quartz with PDFs $\{10\bar{1}2\}$, etc. Quartz, feldspar with reduced refractive indexes, lowered birefringence
>30	275	Quartz → coesite
35	300	
		Diaplectic quartz, feldspar glasses
45	900	Normal (melted) feldspar glass (vesiculated)
60	>1500	Rock glasses, crystallized melt rocks (quenched from liquids)
80–100	>2500	Rock glasses (condensed from vapor)

* For dense nonporous rocks. For porous rocks (e.g., sandstones), postshock temperatures = 700°C (P = 10 GPa) and 1560°C (P = 20 GPa). Data from *Stöffler* (1984), Table 3; *Melosh* (1989), Table 3.2; *Stöffler and Langenhorst* (1994), Table 8, p. 175.

Stöffler and Langenhorst (1994: 162, 165-168) propose the following petrographic classifications for shocked quartz. In the low pressure regime: planar microstructures divided into planar fractures (PF), planar deformation features (PDF) which are subdivided into non-decorated PDFs and decorated PDFs, and mosaicism, which is a highly-irregular mottled optical extinction pattern. Planar fractures appear in parallel sets of open fissures, and spacing per grains for PFs is greater than 15μm, typically more than 20 μm. Fractures are evidence of very weakly-shocked quartz and should not be considered as diagnostic shock effects. Planar deformation features occur as multiple sets of parallel, planar optical discontinuities, which are in fact amorphous lamellae, with spacing that ranges from 2 to 10 μm. With increasing shock intensity, PDfs become more closely spaced. Another type of PDFs consists of thin multiple lamellae of Brazil twins (ibid.). Stöffler and Langenhorst (1994: 168) state that "It is absolutely mandatory that any claim to have observed shock-induced PDFs in quartz at least must provide data on the crystallographic orientation and the (clearly defined) frequency of PDFs based on stereographic projections of universal or spindle stage data." Table 2.2 gives shock pressure and effects during impact (French, 1998: 33).

Multiple PF sets are the product of impact generated shock waves. Natural quartz from nonimpact settings does not generally show planar fractures, or cleavage, and this rarity, "if not complete absence" of cleavage in natural quartz from nonimpact settings indicates that PFs, when intensely developed in multiple sets, can be used provisionally as indicator of shock metamorphism and meteorite impact. (French et al. 2004: 211; French and Koeberl, 2010: 134). This is especially important for the study of structures showing no other evidence of shock metamorphism such as the Rock Elm Structure in Wisconsin.

2.2.5 High-pressure Polymorphs

Loring Coes Jr. produced a high-pressure polymorph of quartz in 1953 which was named coesite (Hoyt, 1987: 343). H.H. Nininger suggested early as 1956 that coesite might be present in the Barringer Meteorite Crater in Arizona, USA (ibid.). His prediction was realized in 1960 when E.M. Shoemaker located samples of sandstone in the crater which did indeed contain coesite (Baldwin, 1963: 17). Another high-pressure polymorph of quartz, discovered in 1961 by S.M. Stishov and S.V. Popova and named stishovite, was also found in the shocked sandstone of the Barringer Crater two years later (Hoyt, 1987: 343; Baldwin, 1963: 18). These high-pressure minerals gave impact researchers another diagnostic tool. "The identification of coesite and stishovite at several sites in the early 1960s provided one of the earliest criteria for establishing the impact origin of several structures." (French: 1998: 42). However, French (ibid.) points out that most of the subsequent confirmations of impact have been based on PDFs in quartz since these features are more common and easier to identify.

In the high pressure regime, shock effects include: diaplectic quartz glass (shock-amorphized quartz), the high-pressure polymorphs coesite and stishovite, silica glass (lechatelierite) and the condensation products of shocked vaporized quartz (Stöffler and Langenhorst, 1994: 162, 169-172, 177). Stishovite is formed at lower pressures than coesite due to the fact that stishovite is formed during shock compression and coesite crystallizes during pressure release.

Shock pressures from around 12 to 15 GPa can convert quartz to stishovite and shock pressures over 30 GPa can convert quartz to coesite (French, 1998: 40). However, under normal geological conditions, pressures just over 2 GPa are sufficient to transform quartz into coesite (French, 1998: 42). Coesite and stishovite when "… found in near-surface rock, are unique and reliable indicators of meteorite impact." (ibid). French cautions, however, that care must be used when using coesite as proof of impact since it can occur naturally if formed at depths greater than 60 km under static pressures over 2 GPa and carried to the surface by tectonic processes (ibid.). Stishovite, though, formed only at pressures greater than 10 GPa, "… has never been identified in a nonimpact setting." (ibid.). It should be noted that neither of these minerals has ever been found to be associated with volcanic explosions (Baldwin, 1963: 74; French, 1998: 42). According to Melosh (1989:41), "… volcanic explosions cannot approach the pressures at which Stishovite and Coesite form." Naturally-occurring shock metamorphic effects have been shown to be exclusively associated with meteorite impact craters and no other natural process on Earth can account for the observed results. French and Koeberl (2010: 132-133) note that even though post-stishovite phases have recently been reported from deep-seated mantle rocks under ultra-high pressure, stishovite remains an excellent indicator of impact when found in sediments or upper crustal rocks.

2.3 Impact Cratering Mechanics

"Impact cratering, an extremely complex phenomenon worthy of study in its own right, acquires great significance when studied in the context of planetary surfaces and planetary formation …" (Croft: 1977: 1279). After decades of controversy, a modern understanding of the high energies associated with impact cratering finally led investigators to the realization that impact crater excavation is similar to an explosion (Hoyt, 1987: 196, 198; Melosh, 1989: 48). Small meteoritic masses are slowed by air resistance to the point that air drag balances their acceleration due to gravity and they impact the Earth's surface with only a terminal velocity. Without high kinetic energy due to high velocity, meteorites will not explode on impact.

2.3.1 Impact Velocity and Energy

The Earth's atmosphere provides protection against small meteorites, but is no match for the more massive ones which enter our atmosphere carrying large amounts of kinetic energy. Loss of mass due to ablation depends on a meteoroid's composition, size, mass, altitude and entry velocity. The density of the Earth's atmosphere varies from 10^{-13} g/cm^3 at an altitude of 200 km to 10^{-3} g/cm^3 at ground level, and meteoroids entering the Earth's atmosphere have masses ranging from ~10^{-18} to ~10^{15} kilograms (Popova, 2004). Meteoroids larger than ~100 m and ~10^9 kg loose only a small part of their initial mass and energy while traveling through the atmosphere.

The sufficiently-massive cosmic bodies are not significantly slowed by friction in the Earth's atmosphere and so impact the ground at cosmic velocities, typically tens of kilometers per second (French, 1998: 7). The maximum possible impact velocity of an impactor that is gravitationally bound to the Sun is 72 km/sec (Collins et al., 2005), however, the average asteroidal impact velocity on Earth is 17 km/sec (Collins et al., 2004: 221). A meteorite's kinetic energy changes with the square if its velocity. This energy is released upon impact and, if sufficiently high, will result in an explosion. Even if a meteoroid does not survive to impact the Earth's surface, but instead explodes in the air low over the Earth's surface, powerful shock waves and radiation fluxes can still occur which may result in fires, and the destruction of objects on the Earth's surface (Nemchinov et al., 1999).

For large meteoroids, ablation from the surface is not significant because of shielding by the vapor produced and so the mass of the meteoroid or its fragments changes little with fragmentation (ibid.). Modeling indicates that the size of a dense vapor cloud formed around a meteoroid is around 5-10 times its size (Popova, 2004: 311). Vapor parameters depend on the meteoroid's size, velocity, altitude and composition. According to Nemchinov et al. (1999), the actual velocity, V, including atmospheric retarding effects, of a meteoroid of mass M, with cross sectional area S, at a height of Z_r below the defined atmosphere Z ($Z = 0$ at the Earth's surface), where the expected velocity is V_r, for a trajectory of angle θ, is given by:

$$V^2 = V_r^2\, e^{[-m_a/(m_0 sin\theta)]} \qquad \text{Eq. 2.1}$$

where C_D is the drag coefficient and the effective mass per unit of area of the meteoroid is found by $m_0 = M/SC_D$. In the exponent, the mass of the atmospheric column per unit area, m_a, is defined by the integral of the density of air, ρ_a, so $m_a(Z) = \int_Z^{Z_r} \rho_a\, dZ$ (Nemchinov et al., 1999: 1196). Retardation begins where the specific mass of the atmosphere becomes comparable to the specific mass of the meteoroid. It should be noted that equation 2.1 assumes an exponential atmospheric model allowing for the development of analytic expressions, however, the actual atmosphere is only approximately close to being exponential in true nature.

Blast waves generated by high-velocity meteoroids in the atmosphere are similar to shock waves generated by a line charge (Ivanov, 1991: 68). The blast wave generated during the 1908 Tunguska event when a meteoroid, perhaps a comet, decelerated and exploded above Earth's surface rather than impacting it, starting a forest fire and felling trees in a 50 by 60 km area in central Russia. For a high-velocity meteoroid, the distance scale of its atmospheric blast/shock wave, λ, can be found by:

$$\lambda = [\eta (e/\rho_a)]^{½} \qquad \text{Eq. 2.2}$$

where ρ_a is the ambient atmospheric pressure, e is the energy of the explosion or deceleration per unit length of the trajectory, and η is the efficiency of the transformation of this energy to blast waves. For high-velocity bodies, $\eta = 2$ (Ivanov, 1991: 68). Shock vapor is produced by a high-velocity impact. Expanding shock vapor in turn generates atmospheric shock waves. If the impact velocity is greater than 30 km/sec for a projectile impacting 'typical igneous rock', then the mass that is vaporized may be found by:

$$M_V = 0.05\, E \qquad \text{Eq. 2.3}$$

where M_v is the mass of the vapor and E is the kinetic energy of the impactor in units of TNT equivalent (Ivanov, 1991: 69).

Meteoritic material strengths and densities differ from one meteorite to another and even within one body. Strengths of different pieces of the same meteorite can differ by a factor of 2-3 correlating weakly with the meteorite's chemical-petrological composition (Nemchinov et al., 1999). The surprising result is that some stony meteorites are stronger than some iron meteorites. Also, the strength of a large meteoroid or its fragments is lower than the strength of the small specimens upon which experiments are made. The characteristic loads for which bodies of mass *M* break up in the atmosphere is lower than the strength limits of the small specimens of a meteorite σ_s of mass $m_s << M$. The variation of strength of a meteoroid of mass *M* can be found by:

$$\sigma = \sigma_S (m_S/M)^{\alpha} \qquad \text{Eq. 2.4}$$

where α is determined by the degree of homogeneity of a body. The more homogeneous a meteoroid is, the smaller α will be, with a good estimate being $\alpha = ¼$ (Nemchinov et al., 1999). However, if α is established on specimens of different dimensions in the range of 1-10 cm, extension of dependence to bodies with dimensions of 1-100 m can result in significant errors.

A terrestrial meteorite impact crater is not formed by the impact itself, but by the blast of "… superheated, compressed air and other vaporized matter." (Baldwin, 1949: 135). "The known terrestrial meteorite craters were all blasted into being by the almost instantaneous release of the kinetic energy of motion of the [impacting] mass." (Baldwin, 1949: 68). According to Baldwin (1949: 97) the few relatively modern meteorite impact craters recognized on Earth show evidence of "… tremendous explosive activity …" including the radial distribution of explosively-shattered meteorite and target rock fragments as well as blocks of target material spread over an area ten times the resulting crater's radius.

An impact crater's radius and depth depends on the energy of impact as well as the density, composition, and size of the impactor and the surface composition and gravitational acceleration of the planet (Masaitis, 2005; de Vet and de Bruyn, 2007). Surprisingly, de Vet and de Bruyn (2007) found that when a spherical projectile is dropped vertically into a container of granular material, glass beads, the excavation energy required for crater formation is only a small fraction, 0.1%-0.5%, of the projectile's kinetic energy. For a flat surface defined to have the vertical coordinate $z = 0$, so that a crater's interior has $z < 0$, the excavation energy, E_x, required to eject the crater volume out of the crater and deposit it on the surrounding surface is given by:

$$E_x = \pi \rho_b g \int_0^{R_0} z(r)^2 r \, dr \qquad \text{Eq. 2.5}$$

where ρ_b is the bulk density of the granular material, $z(r)$ is the azimuthally averaged crater profile, r is the radial distance, and R_0 is the crater's radius at $z = 0$. While both are dependent on impact energy, a crater's radius depends on the projectile size and depth depends on projectile density. The rim height was found to depend only on the projectile's size (de Vet and de Bruyn, 2007).

The mass of the meteorite needed to account for a given impact crater is inversely proportional to the striking velocity of the meteorite. As a meteorite penetrates the Earth's layers, it initially moves faster than the impact-induced shock waves compressing an ever-increasing amount of target rock. This material combined with the meteorite's mass will slow rapidly, but momentum will be maintained as the combined mass increases. Baldwin states that "Essentially no momentum will be lost during this interval … " (1949: 139). Momentum is the product of the mass and velocity of an object, therefore a higher-velocity meteorite will form a larger crater than a meteorite of equal mass moving at a lower velocity.

In hypervelocity impact experiments carried out on low density materials, the penetration track of the projectile becomes longer as the target medium density is lowered (Kadono, 1999). At low impact velocity, V_0, the strength of a projectile, Y_p, is greater than the dynamic impact pressure, so the projectile penetrates the target intact and the resulting crater is narrow and deep. Assuming a spherical projectile of diameter D_p, and density ρ_p, collides vertically with a surface having target strength, Y_t, and target density, ρ_t, and the initial impact pressure, P_0, is low enough for the projectile to remain intact after target penetration, then according to Kadono and Fujiwara (2005: 1311), the resulting crater depth/projectile diameter ratio, T/D_p, can be determined by:

$$T/D_p \sim (⅓)(\rho_p V_0^2/Y_t) \qquad \text{Eq. 2.6}$$

With increasing impact velocity, the point at which the initial impact pressue, P_0, equals Y_p, the deformation or fragmentation of the projectile begins (Kadono and Fujiwara, 2005: 1310, 1316). As the impact velocity is further increased, the projectile shatters and penetration depth decreases. If the initial impact pressure, P_0, is higher than the projectile strength, Y_p, then the situation is similar to cratering with chemical explosives. Where U_p is the shock wave velocity, C_{Rp} is the rarefaction velocity, and α is the attenuation rate of pressure, the crater depth/projectile diameter ratio, T/D_p, becomes:

$$T/D_p \sim (\rho_p/\rho_t)(P_0/Y_p)^{1/\alpha}(Y_p/Y_t)^{1/\alpha} \ln[1 + (\rho_t V_0/\rho_p)(1/U_p + 1/C_{Rp})] \qquad \text{Eq. 2.7}$$

Numerical simulations show $\alpha \sim 3$ for high velocity impacts and experimental values obtained give $\alpha \sim 2\text{-}3$, which is not surprising since this cube-root scaling form is often realized in chemical explosive cratering (Kadono and Fujiwara, 2005: 1312). After impact, strong shocks propagate into the target and projectile which brings them to a common pressure P (Melosh, 1989: 54). The rarefaction wave speed, C_{Rp}, can be found by:

$$C_{Rp} = [(K_0 + nP)/\rho_{Cp}]^{½} \qquad \text{Eq. 2.8}$$

where the projectile bulk modulus is $K_0 = \rho_{0p}C_p^2$ and $n = 4S_p–1$ utilizing the uncompressed density of the projectile, ρ_{0p}, the compressed density of the projectile, ρ_{Cp}, and empirically-determined parameters of the projectile material C_p and S_p. This same equation can give the rarefaction speed in the target if the target's parameters C_t, S_t, and ρ_{0t} are used instead. For an iron projectile impacting a Gabbroic anorthosite target, C_t = 7.71 km/sec, S_t = 1.05, ρ_{0t} = 3.965 Mg/m^3, C_p = 4.05 km/sec, S_p = 1.41, and ρ_{0p} = 7.8 Mg/m^3 where S is dimensionless (Melosh, 1989: 56-57).

Shoemaker (1983) utilized data from the Jangle U nuclear crater in Yucca Flat, Nevada, USA, in the following equation used to determine the diameter, D_t, of a terrestrial impact crater:

$$D_t = c_f K_n (W\rho_a/\rho_t)^{1/3.4} \qquad \text{Eq. 2.9}$$

In this equation, the kinetic energy of a projectile of diameter d, density ρ, and velocity v, all measured in cgs units, is represented by $W = (^1/_{12})(\pi d^3\rho v^2)/(4.19 \times 10^{10})$ kilotons TNT equivalent. The scaling coefficient, K_n = 0.074 km kilotons$^{-1/3.4}$, is an empirical constant derived from the diameter and explosive yield for the Jangle

U nuclear crater. The estimated density of the alluvium at the Jangle U site is ρ_a = 1.8 g/cm^3 and ρ_t is the mean density of the target rocks. The crater collapse factor, c_f, is considered to be 1 for craters with diameters $\leq$ 3km and 1.3 for craters with diameters $\geq$ 4 km. Shoemaker considers 30% to be a conservative estimate for the diameter enlargement of an impact crater due to wall collapse.

When these large quantities of energy are released quickly and close to Earth's surface, a rapid and orderly series of events is initiated that will result in an explosion crater. This process is continuous but can be divided into three main stages: contact and compression, crater excavation and material ejection, followed by modification of the transient crater (Gault et al., 1968; Melosh, 1989: 46; French, 1998: 17-23). Craters at the end of the excavation/ejection stage are unstable due to the steepness of their walls and experience some modification due to collapse, so craters at this stage are referred to as transient craters. Transient craters will experience initial modification to the 'final' crater form as well as continued modifications that are due to normal geological processes (French, 1998: 23). The area of destruction due to impact is much smaller than the size of the final crater due to the modifications which start almost immediately after impact (French, 1998: 20).

2.3.2 Contact and Compression

The first stage begins when a meteorite makes contact with the target surface and compresses it creating shock waves through conservation of energy (French, 1998: 18). High pressures develop along the interface as the target rock's resistance begins to decelerate the impactor. A hemispherical shock front spreads and propagates during the time that the meteorite's initial kinetic energy is transferred to the target rock which is compressed, distorted, heated and accelerated (ibid.).

Immediately after initial contact, two shocks actually propagate away from the meteorite-target interface, one reflected back into the impactor and the other downward into the target material (French, 1998: 18). By the time the impactor and target interface has reached a depth of approximately one-half of the impactor's original diameter, the meteorite itself is engulfed by the shock wave which is in turn reflected as a rarefaction or release wave when it reaches the meteorite's rear surface. A free surface cannot sustain a state of stress, so a rarefaction wave allows for decompression from the high pressure state behind the shock wave to ambient pressure (Gault et al., 1968). Unloading to near zero pressure from the high pressures created during compression may cause both the meteorite and target rock to melt or vaporize (French, 1998: 18). As the shock waves travel through target rock and their velocity drops to that of sound, 5-8 km/s, the shock waves become elastic or seismic waves (French, 1998: 9, 18). Weak disturbances produce elastic waves in solids or sound wave is liquids. Stronger disturbances cause plastic waves and irreversible deformation in the solids through which they travel. The strongest disturbances produce shock waves which travel faster in uncompressed material and are, therefore, supersonic (Melosh, 1989: 37). The relationships between parameters across a shock were derived by P.H. Hugoniot in 1897. His equations along with the equation of state are used to model the impact cratering process (Pierazzo and Collins, 2004).

The Hugoniot equations use the conservation of mass, momentum, and energy across a shock front to relate the density ρ, pressure P, and internal energy per unit mass E, in front of the shock wave to the values of these same variables after the shock wave has passed (Melosh, 1989: 228). The reference frame is usually chosen so that the unshocked material is at rest and shock velocity, U, and particle velocity, u_ρ, are unknown. Density is sometimes expressed as specific volume $V = 1/\rho$. For an initial density ρ_0, pressure P_0, and internal energy E_0, conservation of mass leads to the first Hugoniot equation:

$$\rho(U - u_\rho) = \rho_0 U \qquad \text{Eq. 2.10}$$

Conservation of momentum leads to the derivation of the second Hugoniot equation:

$$P - P_0 = \rho_0 U u_\rho \qquad \text{Eq. 2.11}$$

Conservation of energy leads to the third Hugoniot equation:

$$E - E_0 = (P + P_0)(V_0 - V)/2 \qquad \text{Eq. 2.12}$$

An equation of state relates the thermodynamic variables for pressure, density or specific volume, and specific internal energy or temperature T. "The equation of state is different for different materials and is a complex function of the molecular and atomic structure of the given substance," (Melosh, 1989: 230). The response of a given material to an impact shock is governed by its equation of state since the above Hugoniot equations are the same for all materials (ibid.). The Tillotson equation of state was derived specifically for high-velocity impact computations and also has parameters which allow for the description of unloading of shocked material into the vapor phase (Melosh, 1989: 231). The first form of the equation is for use when material is compressed to higher density than its zero-pressure form, $\rho/\rho_0 \geq 1$, and the energy density, E, is less than the energy of incipient vaporization.

$$P = [a + b/(E/(E_0\eta^2) + 1)]\rho E + A\mu + B\mu^2 \qquad \text{Eq. 2.13}$$

In this equation $\eta = \rho/\rho_0$ and $\mu = \eta - 1$. The Tillotson parameters are a, b, A, B, and E_0, however, E_0 is not the initial energy density, it is a parameter often close to the vaporization energy (Melosh, 1989: 233). The parameter a is usually equal to 0.5 based on observational data. The second form of the Tillotson equation is utilized when material is expanded to lower density, that is $\rho/\rho_0 \leq 1$, and internal energy exceeds the energy of complete vaporization. Here, the pressure is found by:

$$P = a\rho E + \{b\rho E/(E/(E_0\eta^2) + 1) + A\mu e^{-\beta(\rho_0/\rho - 1)}\} e^{-\alpha(\rho_0/\rho - 1)^2} \qquad \text{Eq. 2.14}$$

The constants α and β control the rate of convergence of this second equation to the perfect gas law (ibid.).

Contact and compression is the shortest stage of the impact cratering process. At the point of impact, the Earth itself offers strong resistance to meteoritic penetration, so a meteorite's rate of deceleration is quite rapid, and "Even the high-velocity meteoritic masses moving more rapidly that the velocity of shock waves in the earth's crust must be brought to rest within a very small fraction of a second." (Baldwin, 1963: 9). "The contact/compression stage lasts no more than a few seconds, even for impacts of very large objects … For most impact events, the entire contact/compression stage is over in less than a second …" (French, 1998: 19).

“This stage lasts a second or more only for the very largest impacts …” (Melosh, 1989: 46). The contact/compression stage duration is given by:

$$\tau = L/v_i \qquad \text{Eq. 2.15}$$

where v_i is the meteorite’s initial velocity and τ is the time required for the impactor to travel through the target rock a distance equal to its diameter L in a vertical impact. Note that $v_f = 0$.

The kinetic energy of a high-velocity meteorite that is transformed into compression waves and heat energy may be practically unlimited, though most of the meteorite’s kinetic energy is stored in the compressed rock rather than transformed into heat. According to Baldwin (1963: 69-70), during an impact event “ … much of the energy is transmitted in shock waves through the crust and air and thence gradually converted into heat [and] … It is only after the velocity drops below that of the shock waves that the phenomenon of heat enters the picture.” Estimates are that around “… 25-50% of the projectile’s original kinetic energy was converted into heat …” during the Chicxulub impact event (French, 1998: 8). Hot rock may be buried, though, at a depth that is as great as the final crater depth. Melt layers near the surface would cool quickly, but the cooling time of that which is buried deeply would be much slower. “Melt in the breccias lens underlying a 15-km diameter crater is thus about 100,000 years.” (Melosh: 1989: 129).

The meteorite’s kinetic energy is distributed over both the impactor and the target rock. Some of the kinetic energy becomes internal energy during compression and can initiate shock-metamorphic effects in the rock (French, 1998 18). The shock wave in target rock propagates outwards in a hemispherical shape with the center on average about one impactor diameter below the surface. In solid rock, the impactor will penetrate “… no more than 1-2x its own diameter before its kinetic energy is transferred to the target rocks by shock waves generated at the interface between projectile and target …” (French, 1998: 18).

When the shock wave traveling through the meteorite reaches the rear surface, it is reflected back into the now-compressed impactor as a rarefaction or release wave unloading the impactor from the high shock pressures. The contact and compression stage is considered to be over when the release wave hits the front of the impactor (French, 1998: 18-19). After the release wave reaches the leading edge of the impactor and completely unloads it, “… the projectile itself plays no further role in the formation of the impact crater, and the actual excavation of the crater is carried out by the shock waves expanding through the target rocks …” (French: 1998: 19). At this point, the remaining energy is around 90 percent of the total energy of the impactor, and “The lion’s share of the projectile’s initial energy is thus transferred to the target.” (Melosh, 1989: 66-67). As the impactor unloads from the high pressures it may expand into the vapor phase (Melosh, 1989: 57). In fact, if the shock pressures are sufficient for the vaporization of the meteorite, the vapor will expand out of the crater as a high-speed vapor plume (Melosh, 1989: 68-71).

The onset of ‘jetting’, a hydrodynamic ejection of material at high velocities, occurs with the appearance of rarefaction waves (Gault et al., 1968). The jet comes from the interface of the compressed target rock and the impactor which is the region that has been subjected to the highest pressures, and therefore, the highest temperatures. The jet, therefore, includes material in a liquid state and superheated vapor.

It is during the contact and compression stage of impact that the largest shock pressures are attained and these pressures are far greater than pressures generated during volcanic or chemical explosions. The hemispherical shock wave that propagates through the target rock weakens with expansion, but “Rock-hard substances suddenly become compressed to unusual densities. Matter acts as though it were liquid, or at least extremely plastic … Compression effects will make rock rebound like rubber …” (Baldwin, 1963: 6).

A change in the physical and chemical properties of a solid induced by a shock wave is called a shock effect. Impact or shock metamorphism results in shock effects generally seen on the scale of mineral grains and represents unequivocal evidence of impact (Stöffler and Langenhorst, 1994). Quartz is the most reliable indicator of shock metamorphism because it is an abundant, widely-distributed rock-forming mineral and displays the greatest variety of well-defined permanent shock effects. The stable form of SiO_2 in rocks of Earth’s upper continental crust is trigonal α-quartz which behaves differently under shock compression than in static laboratory experiments and natural tectonic environments (ibid.).

2.3.3 Excavation and Ejection

The high pressures of the contact and compression stage decline rapidly during the excavation stage as the shock wave expands and weakens due to being spread over a larger volume of target material. Excavation begins and the crater cavity opens, forming the transient crater as ejecta begins to move upward and outward (French, 1998: 20-22). The shock pressures are greatest directly below the impact site, but do not vary much over the expanding hemispherical shell (Melosh, 1989: 60). As pressure increases, yield strength for intact target rock increases, however the strength of rock, both intact and fragmented, decreases with increasing temperature (Collins et al., 2004). Target rocks are heterogeneous and so respond non-uniformly to shock and deformation during the cratering process, resulting in a range of deformation features displayed in any particular zone (Collins et al., 2004).

The shock wave continues to expand throughout excavation, degrading into a stress wave and then into an elastic wave. The rate of decline of the strength of the shock wave determines the amount of vaporized or melted target rock (Melosh, 1918: 61). “The mass of melt is roughly ten times larger than the mass of vapor. This general relation is a simple geometrical consequence of the rate of decline of pressure with radius.” (Melosh, 1989: 64). Energy available to drive the expanding shock decreases as it spreads and is consumed in heating, melting, and vaporizing material. An excavation flow begins after the shock wave has passed the now shocked target materials and the first ejecta to leave an impact crater is the vaporized meteorite and target material expanding out of the growing crater. “Impact velocities must exceed about 10 km/second for significant amounts of vaporization in either silicate or water ice impactors or targets.” (Melosh, 1989: 68). A gas plume will move faster than the classic ejecta and enclose the expanding crater in an atmosphere of vaporized meteorite and target (ibid.). Although jetting initiates mass ejection from the forming crater, most of the ejected material is removed later under lower stress conditions and with modest ejection velocities (Gault et al., 1968). The ejected material moves up and out from the growing crater in a steady flow that develops into an inverted, conical-shaped debris curtain above the target surface.

Fractured rock is weaker than intact rock and porous rock, when compressed, initially compacts with no associated rise in strength (Collins et al., 2004). Porous target material is not an effective translator of shock waves, consequently, the shock exists only in the vicinity of the projectile (Kadono, 1999). Porous target material contains a solid component and a void-space component. Wünnemann et al. (2006) investigated the effect of porosity and internal friction on transient crater formation through numerical modeling and found that both play a role in limiting crater growth, especially in cases where gravity<<Earth's gravity. Their porous-compaction, ε-alpha, model accounts for the collapse of pore space by assuming the compaction function depends, not on pressure, but on volumetric strain. The crushing of a large volume fraction of void space in porous targets absorbs shock waves and results in higher post-shock temperatures than impacts into nonporous targets. More energy is required to produce impact craters of the same size in porous targets than in nonporous targets.

As discussed by Wünnemann et al. (2006), the volume fraction of void space in target material, or porosity, ϕ, for a target of total volume V_T, with solid component volume V_S and pore space volume V_V, is given by:

$$\phi = (V_T - V_S)/V_T = V_V/V_T \qquad \text{Eq. 2.16}$$

If $\phi = 0$, then there is no void space in the target, whereas $\phi = 1$ implies no solid component. Therefore, if ρ_T is the bulk density of porous rock and ρ_S is its solid component density, then

$$\rho_T = \rho_S(1 - \phi) \qquad \text{Eq. 2.17}$$

Changes in the bulk density of porous target material are due to both the compaction of pore space and compression of the solid component. In an idealized example, all pore space is crushed out before any compression of the solid component takes place.

The amount of resistance to volume change and amount of irreversible work done in porous versus non-porous material is different because it is easier to compact a porous material than to compress a non-porous sample of the same material. The ε-alpha model is a way of describing the crushing of pore space as a function of compressive stress (Wünnemann et al., 2006). The P-alpha model provides a simple way of computing the compaction of void space in porous material from applied pressure, P. In this model, a distension parameter, α, is given by:

$$\alpha = 1/(1 - \phi) = V_T/V_S = \rho_S/\rho_T \qquad \text{Eq. 2.18}$$

So, for some amount of porosity, $0 < \phi < 1$, the model indicates $\alpha > 1$ (ibid.).

The greater amount of irreversible work performed on porous target material raises its internal energy to a higher level as compared to non-porous material. In non-porous target material, the kinetic energy of impact results in rapid material compression giving rise to the generation and propagation of a shock wave. In porous material, most of the impact energy is utilized in the irreversible crushing of void space. Shock waves decay more rapidly in porous material due to the compaction of pore space. Therefore, a crater formed in porous material is deeper and smaller in diameter than one formed in non-porous material by the same amount of impact energy since the lower bulk density of the porous material allows for the deeper penetration of the projectile (Wünnemann et al., 2006). It is also possible that lower shock pressures in porous target material may result in less resistance due to friction. The ε-alpha model indicates that the effect of porosity is to reduce the diameter of a transient crater in porous relative to non-porous material uniformly for all projectile sizes and all gravitational accelerations. However, when internal friction is varied independently, the reduction of transient crater size becomes more significant with decreasing gravity and projectile size (ibid.).

A projectile appears as a point source when any crater-related phenomena occur far from the point of impact (Housen and Holsapple, 2011). Small craters in cohesive materials form in a "strength regime", because it is the impactors' material strength, *Y*, which determines the crater size. For larger craters, gravitational forces dominate any strength, so gravity, *g*, determines the crater size in the "gravity regime" (Housen and Holsapple, 2011: 858). There are various strength measures of a material including compressive, shear, tensile, and others. The effect of target properties such as strength and porosity on ejecta are not understood as well as the effects of speed. Housen and Holsapple (2001) developed a point-source scaling model for ejecta mass and velocity distribution to fit to data for materials distinguished by porosity. Energy is lost during compaction of pore spaces which results in a reduction of ejection speeds. For launch position, *x*, at which a particle with ejection velocity, *v*, crosses through the plane of the original target surface of density ρ, and *a*, *U*, and δ are the impactor's radius, velocity, and mass density respectively, the ejecta velocity distribution can be described by either

$$v/U = C_1[x/a(\rho/\delta)^{v}]^{-1/\mu} \qquad \text{Eq. 2.19}$$

where C_1 is a constant determined from fits to data, and the exponent μ depends on the high-pressure properties of the target, or

$$v/(gR)^{1/2} = C_2(x/R)^{-1/\mu} \qquad \text{Eq. 2.20}$$

where *R* is the apparent radius of the final crater. The choice of which equation to use depends on whether the impactor properties or the crater size is known (Housen and Holsapple, 2011: 858-859). Experimental results indicate that μ ~0.41 for dry soils and μ ~0.55 for non-porous materials such as metal, water, or rock. Though it has not yet been determined, it is expected that $\mu < 0.4$ for highly-porous materials.

In high-speed impacts, the impactor and part of the target rock vaporize and expand back out of the forming crater as a hot gas, while other target rocks are melted and line the crater or accumulate in a pool at the bottom. As the hot gas expands, around 50 percent of it condenses into liquid droplets or solid particles while the rest may end up as free atoms and molecules in the atmosphere or space (Melosh, 1989: 70). Nininger discovered large quantities of 100 to 200 μm nickel-iron spherules surrounding the Barringer Crater in Arizona in 1946 and believed that "… they condensed from the nickel-iron projectile that produced the crater, and their abundance supports his view." (Melosh, 1989: 70). He also notes that the spherules, however, may have "… originally formed from splashes of melted, but not vaporized, nickel-iron." (ibid.). Based on FeO content, commonly around 25-30%, Hörz et al. (2002: 513) found that Barringer Crater melts incorporate exceptionally large amounts of projectile material. Analysis of the target rock indicates that less than 2% of the FeO was contributed by the rock. At least some meteorite component was found in every sample Hörz et al. (2002: 527) analyzed. Altered glass that is optically isotropic was found to occupy large fractions of some individual melt beads. The altered glasses, mostly red but occasionally brown, yellow, or honey colored, were found to be compositionally distinct from the clear impact glass. Comparison of the altered glasses with the clear impact glass reveals that the alteration process greatly enriched Fe content, but Hörz et al. (2002: 528) suggest that these alterations occurred over prolonged time and are not related to the impact event.

Ejecta begins to cover the surrounding area as the excavation opens a transient crater that is many times larger than the meteorite (Melosh, 1989: 47). Excavation is completed in seconds to minutes depending upon crater size (French, 1998: 20). The impact-induced shock wave expands hemispherically away from the shock point reaching the surface, which is a "... plane of zero pressure …", producing a rarefaction wave "… equal in strength but of opposite sign to the shock wave, which starts downward from the surface as soon as the shock wave arrives." (Melosh, 1989: 71). The sum of the pressures exerted by these two waves is zero on the surface; however, the rarefaction wave propagates downwards fracturing the rock as it goes. "Where the stresses in the tensional release wave exceed the mechanical strength of the target rocks, the release wave is accompanied by fracturing and shattering of the target rock …" (French: 1998: 20). This causes the brecciation and fracturing found in impact structures as the target rock is usually not crushed by the shock wave; instead, "… the rarefaction following the shock propagation downward and outward is many times the crater depth or diameter, fracturing the rock *in tension* as it goes" (Melosh, 1989: 72; his italics).

Near-surface rocks are not only shattered, but are ejected at high speed due to the wave "… reflection process which converts some of the initial shock-wave energy to kinetic energy …" (French, 1998: 20). As the shock wave passes through, it leaves the target rock behind in motion, so this zone near the surface is "… the source of an extraordinary body of ejecta …" (Melosh, 1989: 73). The excavation flow is considered to be ejected when it rises above the original target surface

Debris ejected from an impact crater is deposited with the greatest thickness along the crater rim, thinning out with increasing distance from the crater. If the ejecta forms a continuous deposit, then it is referred to as an 'ejecta blanket'. Impact crater debris tends to travel together after ejection forming, as stated earlier, an ejecta curtain with the greater proportion of melt glass and highly shocked fragments occurring higher up in the curtain (Melosh, 1989: 92-93). If an ejecta curtain forms, it has the shape of an inverted cone because "Ejecta from near the impact site travels at high speed, whereas ejecta emerging at larger distances travels at lower velocities …" (Melosh, 1989: 75). Melosh (ibid.) notes that high-velocity ejecta are usually highly shocked, but even the lowest velocity ejecta which will form the crater rim will contain some highly-shocked impact melt (cf. French, 1998: 61-62).

Crater rims are not composed only of material ejected from the crater during excavation, but of rock that has been pushed outward and upward. Strong compressive forces press horizontally outward from the excavating crater causing rock to fracture and then be squeezed upward. According to Baldwin (1949: 97) the radially outward dip of the upraised crater rim is indicative of an impact event. About half of the rim height is due to structural uplift of target rock which is greatest beneath the crest of the crater rim and then decreases with increasing distance from the point of impact dropping off to "… zero approximately 1.3 to 1.7 crater radii (center-to-rim-crest radius) from the crater's center." (Melosh, 1989: 87). In addition, brecciated rock is emplaced into fractures and dikes beneath the crater floor and rim during the brief time of low vertical stress after target material is thrown upward but has yet to settle back down to the floor and growing crater rim (French, 1998: 65). Only the top third of the transient crater material is ejected, the "… rest of the crater is excavated by displacement of target material downward and outward beneath the crater rim." (Melosh, 1989: 88).

The rest of the rim height is due to the ejecta that then lands on top of this uplift. Some of the ejected debris moves at such low speed that it retains its stratigraphy and forms an "… overturned flap …" seen as an area of "… inverted rock units." (Melosh, 1989: 87). If this material collapses into the crater, however, an overturned fold may not survive the modification stage. Ejecta that lands beyond the crater rim mixes into jumbled breccia that includes material from the target surface.

According to Melosh (1989: 88), crater rim height, h, for uncollapsed simple craters where D is the crater's rim-to-rim diameter is given by

$$h = 0.036\,D \qquad \text{Eq. 2.21}$$

This formula was derived from measurements "… of many lunar, terrestrial, explosion, and laboratory impact craters." (Melosh, 1989: 88). For larger transient craters that experience a subsequent collapse as the overturned flap and rim crest slide down into the crater, the equation's coefficient and power of D varies depending on the surface material and gravity. According to Melosh (1989: 88), for a lunar crater with a diameter of over 15 km, this equation takes the form

$$h = 0.236\,D^{0.399} \qquad \text{Eq. 2.22}$$

Ejecta deposits consist of broken rock fragments, called, clasts, mixed with glass. Though small rock fragments dominate the ejecta, clast size can reach many meters in diameter; in fact, the largest fragments that are ejected may form secondary craters. The larger impact craters can be accompanied by one or even more secondary craters that form clusters or lines. Secondary craters usually have steeper slopes in the direction of the primary crater, becoming more circular with increasing distance from the primary. Secondary crater clusters also become more widely dispersed with increasing distance from the primary (Melosh, 1989: 101). Clast size also decreases with increasing distance from the crater, "… an expectation that has been quantitatively verified in numerous small-scale impact experiments …" and at the Barringer Crater in Arizona (Melosh, 1989: 91). According to Baldwin (1963: 69), there is "… always a radial distribution of both meteoritic matter and crustal rock scattered over perhaps ten times the radius of the crater proper."

Comparisons made of fresh complex craters on Mercury and the Moon indicate that gravity is the controlling factor during the excavation stage of a complex crater, although impact velocity and target material properties also affect the excavation process (Xiao et. al., 2014). Crater depth is determined by the resistance of the underlying target material, but the crater will still continue to grow in diameter after its maximum depth has been reached (Melosh, 1989: 77). The result is a crater that is wider than it is deep. According to Melosh (ibid.), the time, T_d, required for this maximum depth, H, to be reached is

$$T_d \approx (2H/g)^{1/2} \qquad \text{Eq. 2.23}$$

This is basically the equation for free fall of an object falling from a height, H, with an initial velocity of zero, and with an acceleration due to gravity, g. Melosh (ibid.) also states that the time, T_f, for the transient crater with final diameter, D, to be completed is

$$T_f \approx (2D/g)^{1/2} \qquad \text{Eq. 2.24}$$

"The excavation stage, although longer than the contact/compression stage, is still brief by geological standards …" (French, 1998: 20). Depending on the transient crater size, the entire excavation process takes only a few seconds for a simple crater to less than two minutes for a transient crater that is 200 kilometers in diameter (ibid.). Gault et al. (1968) suggest that formation times for large planetary cratering events scale directly with the square root of the crater dimensions, which would indicate that the Barringer Meteor Crater formed in around 10 seconds.

2.3.4 Crater Modification

The excavation/ejection stage ends as soon as the transient crater has reached its maximum size (French, 1998: 23). The final stage of impact crater formation involves modification due to gravity and the elastic rebound of compressed rock layers. Masaitis (2005) points out that crater modification should be divided into early and late stage modification since gravitational adjustment, viscous relaxation and doming, cooling, solidification, and compaction of the hot disturbed bedrock, fallback and material ejected from the crater may continue for thousands of years.

The diameter of the modified final crater is rarely the same as the diameter of the transient crater that forms during the excavation stage. The collapse of the transient crater due to gravity "… may enlarge this diameter by roughly 20 percent for small, bowl-shaped simple craters or by as much as 30 to 70 percent for the larger, more thoroughly collapsed complex craters." (Melosh, 1989: 112). Figure 2.22 shows a transient crater and the final modified simple crater it would form according to Melosh (1989: 129). Figures 2.23 and 2.24 show the structure of a complex crater after modification (Melosh, 1989: 144 and 132 respectively). After the initial modification is complete, "… the diameter of the final crater is many times larger (typically 20-30x) than the diameter of the projectile itself …" (French, 1998: 20).

After the transient crater has formed by excavation and the ejecta have been launched, the debris momentarily halts and then begins to move downward. In simple craters, this motion involves fallback ejecta and debris sliding down the transient crater walls resulting in "... a bowl-shaped depression, partially filled with complex breccias and bodies of impact melt ..." (French, 1998: 20). Modified simple craters are rimmed, bowl-shaped pits that are not very different from the transient craters that formed them (French, 1998: 23). Figure 2.22 shows the difference between the transient and final simple crater according to Melosh (1989: 129). The primary difference between the two is the breccia lens that covers the floor of a modified simple crater. The breccia lens consists of broken rock mixed with shocked fragments and impact melt that slides back into the crater along with part of the inner rim. The slope of the crater walls gradually decreases in the direction of the crater's center until the floor becomes flat. The thickness of the breccia lens is about half of the rim top to floor depth (French, 1998: 23). The final simple crater size "... is only slightly larger in diameter than the transient crater but is significantly shallower." (Melosh, 1989: 129).

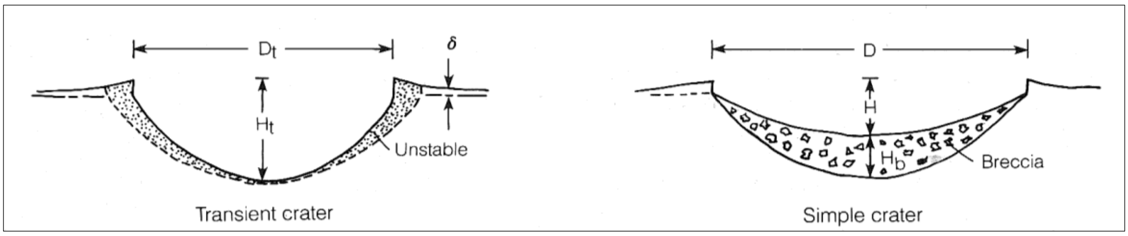


Figure 2.22: Diagrams showing a transient crater and the resulting simple crater (after (Melosh, 1989: 129).

In matching observational data to model predictions, Collins et al. (2005: 824) found a first order approximation of the final rim-to-rim diameter, D_{fr}, for a simple crater in relation to the transient crater diameter, D_{tc}, measured at the pre-impact surface is given by:

$$D_{fr} \approx 1.25\, D_{tc} \qquad \text{Eq. 2.25}$$

For a 'fresh' complex crater measured from rim crest to rim crest, where D_c is the diameter at which the transition from a simple to a complex crater occurs, that is 3.2km on Earth (ibid.):

$$D_{fr} \approx 1.17 D_{tc}^{1.13} / D_c^{0.13} \qquad \text{Eq. 2.26}$$

Pilkington and Grieve (1992) use known morphometric scaling relationships to develop models relating impact crater diameter, D, and gravity effect. The true impact crater floor, marked by the base of allochthonous breccia lens, may be filled with postimpact sediments. For this apparent crater depth, d_a, and true crater depth, d_t, (both in km) of simple craters the following empirical relationships, independent of target lithology, have been determined.

$$d_a = 0.13 D^{1.06} \qquad \text{Eq. 2.27}$$

$$d_t = 0.28 D^{1.02} \qquad \text{Eq. 2.28}$$

For complex craters formed in sedimentary lithologies:

$$d_a = 0.12 D^{0.3} \qquad \text{Eq. 2.29}$$

$$d_t = 0.20 D^{0.4} \qquad \text{Eq. 2.30}$$

For complex craters formed in crystalline lithologies:

$d_a = 0.15D^{0.4}$ Eq. 2.31

$d_t = 0.52D^{0.2}$ Eq. 2.32

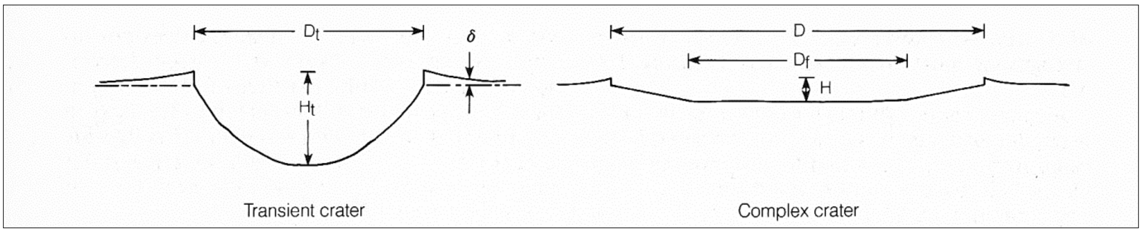


Figure 2.23: These diagrams show the final crater diameter, *D*, of a complex crater compared to the smaller diameter, D_t, of the transient crater, and the transient crater's depth, H_t, which is greater than the complex crater depth, *H* (after Melosh, 1989: 144).

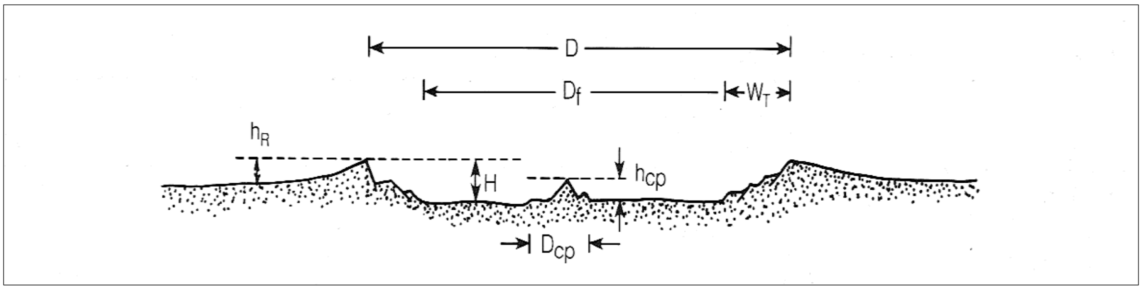


Figure 2.24: The final form of a complex crater, including the central uplift and terraced walls. Here W_t is the width of the terraced zone, D_{cp} is the diameter of the central uplift and h_{cp} is its height (after Melosh, 1989: 132).

While simple craters experience primarily the collapse of the steep crater rim, larger transient craters are completely altered in appearance upon collapse producing central peaks surrounded by a flat floor and terraced walls due to slumping. A complex crater's final depth is shallow and the width much greater than that of the transient crater preceding collapse as shown in Figure 2.23 (after Melosh, 1989: 144). However, this diagram is an over-simplification since it does not show the terraced walls and central uplift that are typical of a complex crater (see Figure 2.24). Terrestrial complex craters have depths over 0.5 km , but their central peaks are seldom higher than the crater rim and are usually closer in height to the elevation of the unaltered area surrounding the crater (Melosh, 1989: 131). Central peak diameter is 0.22 $\pm$ 0.03 of the crater's diameter and is "… apparently independent of the planet on which the crater forms." (Melosh, 1989: 132). This statement includes not only Earth, Mercury, and Mars, but also our Moon and perhaps Ganymede and Callisto (ibid.). For larger craters, the diameter of an inner peak ring is about half the crater rim diameter, or $D_{PR} = (½)D_F$ (ibid.).

The sudden onset of complex crater collapse indicates that a definite strength threshold has been exceeded beneath craters larger than a critical size (Melosh, 1989). This strength threshold can be estimated by dividing the negative buoyancy force associated with the crater cavity by the area of a hemisphere enclosing the crater, that is:

Strength threshold (kg/ms^2) = $(\pi/8)\rho gHD^2/(\pi/2)D^2 = \rho gH/4$ Eq. 2.33

for rim-to-rim diameter *D*, rim-to-floor depth *H*, density ρ, and *g* is the acceleration due to gravity. Slip-line analysis applied to the collapse of impact craters gives an accurate description of their collapse (Melosh, 1989: 145). Materials fail when the shear strength exceeds a defined yield stress called cohesion, *c*. In terms of the transient crater diameter D_t and height H_t, parabolic craters are stable until the parameter $\rho g H_t/c > 5$. Slope failure, that is when a rim segment slides into the crater producing a terrace, occurs for $10 > \rho g H_t/c > 5$. If $\rho g H_t/c > 15$, then "… the floor beneath the center of the crater rises almost vertically upward as the rim slumps downward …" (ibid.). For a transient crater diameter $D_t = 0.27H_t$:

$0 \leq D_t \leq 13.5\ c/\rho g$, stable Eq. 2.34

$13.5 \leq D_t \leq 27\ c/\rho g$, slope failure Eq. 2.35

$27 \leq D_t \leq 40\ c/\rho g$, floor failure Eq. 2.36

Final depth of a complex crater, H, is independent of the initial crater's diameter and is found by:

$H \sim 5c/\rho g \sim H_{\text{threshold}}$ Eq. 2.37

Roddy and Davis (1977: 744) determined that *in situ* shatter cones "… point in the direction of the shock wave source with their axes normal to direction of shock wave propagation." French (1998: 49) agrees that the orientations of shatter cones axes found in rock surrounding terrestrial complex craters point to the location of the source of the shock wave that formed them. Though it has now been determined that shatter cone apeces do not uniformly point to the center of an impact structure, the most common, or primary apex orientation observed is compatible with the rotation model (Wieland et al., 2003) as previously discussed in Section 2.2.2. Mappings of shatter cones do often show them pointing upward or even outward in the crater's central region. "The simplest explanation of this observation is that the rock units were uplifted and tilted away from the crater center following the passage of the shock wave …" (Melosh, 1989: 140). If the original crater shape is reconstructed from the orientation of shatter cones, then the crater is found to originally have a deep bowl shape with a depth/diameter ratio about equal to that of the transient crater (ibid.). Terrestrial crater structural studies indicate that modification from the transient to the complex crater involves the extensive and general collapse of the initially-deep transient crater, and is achieved by uplift of target rock under the crater center and by rock nearer the crater's rim slumping downward and inward (ibid.).

The central uplifts found in terrestrial complex craters are composed of fractured and deformed rock that was originally under the transient crater. This rock has been uplifted a distance that is comparable to the transient crater depth and is *not* a breccia mix like that found in simple craters. Melosh (1989: 136) also notes that the central stratigraphic uplift, *SU*, referred to as the height, *h*, in this equation, can be related to the final diameter of the crater, *D*, by

$h_{SU} = 0.06D^{1.1}$ Eq. 2.38

The stratigraphic uplift is about half the depth of the transient crater (ibid.). From a study of 24 complex terrestrial impact structures, Grieve and Pilkington (1996: 404) suggest that structural uplift (*SU*), where *D* is the rim diameter of the impact structure, is given by:

$SU = 0.086D^{1.03}$ Eq. 2.39

All dimensions for *SU*, *h*, and *D* in the two equations given above are in kilometers.

French (1998: 25) points out "… the two equations [38 and 39] are virtually identical, and a value of SU= 0.1 D is a reasonable approximation to either." He also states that even in the largest structures, "… both theoretical and field studies indicate that central uplifts form in only a few minutes, almost instantaneously by geological standards …" (ibid.). Table 2.3 below compares measured and calculated values for the structural uplift, apparent and true crater depth of two confirmed impact sites using equations 2.29, 2.30, 2.31, 2.32, and 2.39 with the measured or preferred minimum estimates of Wilson and Stearns (1968), Hagerty et al. (2013), Roddy (1976), and Schieber and Over (2005).

Table 2.3: Comparison of Measured or Estimated Dimensions to Formula Approximations for the Wells Creek and Flynn Creek Impact Structures

Equations	**Wells Creek, D = 6.6 km**	**Flynn Creek, D = 3.8 km**
Eq. 2.39 $SU = 0.086D^{1.03}$	minimum uplift = 610 m *calculated SU = 600 m*	minimum uplift = 350 m *calculated SU = 340 m*
Eq. 2.29 $d_a = 0.12\ D^{0.3}$	preferred min = 760 m *calculated = 210 m*	accepted value = 150 m *calculated apparent depth = 180 m*
Eq. 2.30 $d_t = 0.20\ D^{0.4}$	preferred min = 550 m *calculated = 425 m*	*calculated true depth = 340 m*
Eq. 2.31 $d_a = 0.15\ D^{0.4}$	preferred min = 760 m *calculated = 320m*	confirmed shallow marine impact
Eq. 2.32 $d_t = 0.52\ D^{0.2}$	preferred min = 550 m *calculated = 760 m*	confirmed shallow marine impact

Calculated structural uplift values for both Wells Creek and Flynn Creek agree with the minimum accepted values and the calculated apparent depth of Flynn Creek is close to the accepted value. However, none of the calculated values agree with the minimum values preferred by Wilson and Stearns (1968: 173).

According to Baldwin (1949: 149), during the contact/compression stage of an impact event, a great deal of momentum is transferred to the compressed target rock which then rebounds during the initial modification stage to become fixed as a structural dome. When the tremendously-hot and compressed plug of rock and meteorite explodes violently, it results in "… a series of concentric waves …" that move outward in all direction which will result in ring synclines and anticlines in rock at the site of impact (Baldwin, 1949: 99). Anticlines fold downward on both sides and synclines fold upward on both sides from a median line of rock strata. The largest structures have more than one ring surrounding the impact site, and they are referred to as multi-ring basins (French, 1998: 27).

Central peaks form in the modification stage of impact according to Milam and Deane (2005: 1-2) as follows. During the contact/compression stage, deformation causes weakening of the rock which allows for the movement of large blocks of rock in the central area of the impact crater. The target rock typically is fractured, faulted and shows signs of melting and shock deformation. When the resulting pressure is released, a rebound of target material occurs allowing large blocks of rock to move upward. The "… major faults are likely responsible and represent the final stages of central uplift formation." (Milam and Deane, 2005: 2). This rock then becomes fixed structurally as it is damped by tension fractures. They also note that an uplift is often surrounded by a ring syncline and possibly an anticline. If the central peak is over-steepened or weak, then it may collapse forming a series of structural ring structures in sedimentary target rock since it is much less resistant to horizontal movement than crystalline rock (Ferriere et al., 2011). Luizi is a confirmed impact structure in the Democratic Republic of Congo that displays just such structural rings: a ~2 km wide central ring surrounding a central depression along with a ~5.2 km intermediate ring which is in turn surrounded by an annular depression and an elevated rim some 17 km in diameter.

French (1998: 24) agrees that it is during the modification stage after the excavation and ejection of target rock that the central uplift will rise. Once a meteorite impacts a solid surface and blasts out a large impact crater, the underlying rock is compressed downward and outward and then rebounds upward and inward. The rock cannot fall back to its original position since that original space is now filled in by rock that has moved in from the sides. French (1998: 24) gives the following description:

> A simple model of the formation of a complex crater and its central uplift is presented by the familiar slow-motion movies of a drop of liquid hitting a liquid surface … There is the same initial cavity formation, the same outward and downward ejection of target material, the same upward rebound of the central cavity floor, and the same collapse of the periphery back into the cavity.

During impact, “Rock-hard substances suddenly become compressed to unusual densities. Matter acts as though it were liquid, or at least extremely plastic … Compression effects will make rock rebound like rubber …” (Baldwin, 1963: 6).

As stated, Baldwin (1963:107) suggests that rebound is responsible for central uplifts. In this scenario, rocks below the crater have been strongly compressed by the impact force and then spring back when the stress is relieved, causing the crater floor to move upward and form a structural dome. Most structures exhibit this shock-wave rebound pattern with a central dome when enough time has passed for erosion to expose the basement structure, and in the central regions a jumble of shattered and brecciated rock is found. The impact structures we study today, though, may not give a true indication of the appearances that complex craters would have originally had since it is only the basement structure of an impact crater that is visible after extensive erosion. “The fact that all the highly eroded impact structures show a central rebound dome does not imply that all the original craters exhibited central peaks.” (Baldwin, 1963: 108). If enough fallback breccias filled the crater, the peaks may have not have been of a sufficient height to extend through the breccias.

Melosh (1989: 141) makes an interesting observation: “This process has no obvious dependence on gravity or crater size, and so probably cannot explain the central peaks of complex craters …” though it may explain central peak formation in impact craters where the impactor made only a very shallow penetration of the target rock. Melosh instead believes that geologic and morphologic evidence supports complex crater development from a bowl-shaped transient crater and that it is gravity driven (ibid.). Melosh (1989: 142) gives the time for the rise of the central peak to be

$$T \leq (D/g)^{1/2} \qquad \text{Eq. 2.40}$$

and believes that the crater floor uplift starts before the rim fully forms. This would indicate that the complete parabolic transient crater never completely forms since the uplift begins as soon as the final transient depth is reached and before the rim is completed.

Melosh also notes that breccia lenses are not found in the centers of complex craters, indicating a collapse that is so rapid that there is not enough time for debris to slide down the transient crater walls (ibid.). Instead, breccia in complex craters fills a ring depression located between the crater's rim and central uplift. Complex crater floors are covered with breccias and melt rock that lie in the same stratigraphic sequence that lined the transient cavity (Melosh, 1989: 142).

Melosh (1989: 142) believes that the terraces surrounding the crater floor form quickly before the impact melt has time to solidify. He points out that complex crater "… terraces fade smoothly into the solidified impact melt covering the crater floor without any sign of disruption by movement after the melt solidified …" (Melosh, 1989: 142). Crater terraces are widest near the rim and tend to narrow toward the central region.

Melosh (1989: 143) points out that rock debris motion within a forming crater is apparently "… fluidlike, involving rapid uplift of a central peak, analogous to the central jet that forms when a cavity in water collapses …" which is in agreement with Baldwin (1963: 6) and French (1998: 24), indicating that if central peaks do form by a hydrodynamic mechanism then the rock beneath the crater must behave as a fluid during uplift. Unlike the flow in a fluid, however, the flow in a forming crater is 'frozen' at some point depending upon the crater's size and the viscosity of this fluid: "The central peak is, in effect, a damped harmonic oscillator …" (Melosh, 1989: 147).

One early idea that was proposed for the fluid-like behavior of rock debris in impact craters was that it is "… fluidized by impact melt. The debris flows briefly as a melt-solid slurry until it cools and solidifies …" (Melosh, 1989: 151). Although some impact melt is found on complex crater floors, it is only rarely found in central uplifts or in the stratigraphic uplift region beneath the crater where the fluidization would be required. Melosh (1989: 154) suggests that "… crater collapse was facilitated by acoustic fluidization."

Although the crater collapse process is reasonably well understood for the smaller, simple craters, the collapse of complex impact craters is still a poorly-understood process that has a profound influence on the final morphology of the crater (Collins et al., 2004). This is due to the fact that there has not been a direct observation of complex crater collapse in recorded history, and the limitations of small-scale laboratory experiments. Since crater collapse is gravitationally driven, small-scale experiments cannot be extrapolated meaningfully to the scale of complex craters. There is evidence that natural rock is weaker on scales of tens to hundreds of meters with respect to laboratory strength measurements of centimeter-scale rock samples. The best avenues for studying complex crater collapse are computer simulations and observational analysis of impact structures, however, damage due to impact must be carefully interpreted when numerical modeling is utilized (Collins et al., 2004).

Shatter cones have been considered proof of impact for decades; however, their formation is still not well understood. Numerical simulations of impact using the hydrocode SALE 2D, enhanced by the Grady-Kipp-Melosh fragmentation model, suggest that shatter cones are initiated by heterogeneities in the target rock (Baratoux and Melosh, 2003). Within pressures of 3-6 GPa, if the shock wave travels faster in target rock than in the heterogeneity by a minimum factor of around 2 and the dimensions of the heterogeneity are comparable to the width of the shock wave, both of which are smaller than the resulting shatter cone, then a shatter cone will form according to the model. Based on this model, the apical angles of shatter cones seem to depend on the properties of the heterogeneity and the decay time of the shock wave. The angle of the shatter cone, θ, may be found by:

$$\theta(t) = 2 \arccos (1-\beta\tau/\delta t) \qquad \text{Eq. 2.41}$$

where τ is the rise time and $\beta\tau$ is the decay time of the stress wave, and δt is the time elapsed since contact between the shock front and the heterogeneity (Baratoux and Melosh, 2003: 52). The authors suggest that this model should be validated by new measurements of the shapes, sizes and distribution of shatter cones at various impact sites.

Collins et al. (2005) have developed a Web-based program that calculates regional environmental devastation of a terrestrial impact requiring only six descriptors: meteoroid diameter and density, meteoroid velocity before atmospheric entry, impact angle, the distance from impact at which the environmental effects are to be calculated, and whether the target is sedimentary rock, crystalline rock, or a water layer above rock. The most far-reaching environmental consequence is seismic shaking since ejecta deposit thickness and air-blast pressure decay more rapidly with distance than does seismic ground motion. The most devastating effect is thermal radiation close to the impact site. Melosh (1989: 212) gives the radius, R (in meters), of a vapor cloud (or fireball) formed in a high velocity impact as:

$$R = [(3V_i/2\pi)(P_i/P_a)^{1/\gamma}]^{1/3} \qquad \text{Eq. 2.42}$$

where V_i and P_i are the initial pressure and volume of the gas, P_a is the pressure of the ambient atmosphere, and γ is the ratio of specifics heats of the gas. If the energy, E_a (in joules), deposited in the atmosphere by the vapor plume is known, then $R = 0.009E_a^{1/3}$ (ibid.).

2.3.5 Oblique Cratering Events

Non-circular craters may form in several ways. These rare and enigmatic craters may be the result of grazing or oblique impacts, binary impactors, fragmentation of the impactor into two or more components before impact due to tidal disruption or atmospheric breakup, or they may even be secondary impact craters. Shallow craters with an irregular morphology that are within a few crater radii of the rim of a primary impact crater may be secondary craters. These craters are often highly elliptical with the long axis radial to the much larger primary crater. Impactors that create secondary craters near the primary have lower velocities than those that create the more distant secondary craters. Due to the higher velocities, distant secondary craters usually display a more normal morphology and are difficult to identify (Bart and Melosh, 2007; Melosh, 1989).

Oblique impacts, projectiles impacting a planetary surface at very shallow angles, produce elliptical craters. An impact crater's final shape is nearly independent of the meteorite's mass, velocity, or angle of impact within broad limits: "All but the most oblique impacts produce circular craters." (Melosh, 1989: 49). This was the fact that eluded early investigators leading them to reject an impact origin for both lunar and terrestrial craters. Kenkmann and Poelchau (2008: 1) state that "… crater outline is insensitive to the impact trajectory and remains circular with the exception of highly oblique impacts …", that is, those formed by a shallow impact of <15% from the horizontal (ibid.). Shallow impact angles result in a crater that is elongated along the impactor's direction of flight. Vertical impact events release energy from the point of impact, whereas oblique impact events release energy along the line of projectile penetration with the propagating shock front strongest in the downrange direction (Gault and Wedekind, 1978; Pierazzo and Melosh 2000).

Cratering efficiency depends only on the vertical component of velocity (Davison et al., 2011). Diameter is frequently used to describe crater size, but does not serve well for oblique impacts (ibid.). Since crater diameter decreases with increasing obliquity, the displaced mass of target material normalized by the projectile mass is utilized to express the change in crater dimensions (Gault and Wedekind, 1978: 3851):

$$M_e = \rho_t W \qquad \text{Eq. 2.43}$$

where M_e is the mass displaced, ρ_t is the target density, and W is the crater volume. The displaced mass in granite varies as $\sin^2\theta$ and is proportional to $\sin\theta$ for particulates (Gault and Wedekind, 1978; Pierazzo and Melosh, 2000).

Gault and Wedekind (1978) performed experimental studies of oblique impact on the Vertical Gun Ballistic Range at NASA's Ames Research Center, Moffet Field, California, firing primarily aluminum, pyrex or lexan projectiles of into granite, quartz sand and pumice powder. They define a crater's measure of circularity to be D_t/D_c where D_t is the long axis along the path of the projectile's trajectory and D_c is the length of the short axis at right angles to the projectile's path. Gault and Wedekind (1978) found the depth/diameter ratio of d/D_a, where $D_a = ½(D_t + D_c)$, to be constant for craters formed in granite and pumice in contrast to craters formed in quartz sand, which decreases slightly from 90 to 30 degrees and then decreases suddenly for more shallow angles where elongation and ricochet take place. Gault and Wedekind (1978) found that craters formed by oblique impact in most target media displayed elongation along the path of the projectile except for those formed in pumice powder by pyrex projectiles, which became elongated at right angles to the trajectory path for $10 \leq \theta \leq 30$ degrees. Steeper interior slopes were observed in all cases for the uprange final crater walls for $\theta \leq 30$ degrees.

Ricochet occurs when part of the impactor rebounds from the target surface and continues downrange intact, as several large components, or as many small fragments. Gault and Wedekind (1978: 3863) state that "Richochet occurs for all low-angle impacts … There is no unique "critical" value of the trajectory angle for the onset of ricochet as θ is decreased." The products of ricochet can retain a large portion of the projectile's impact velocity. Gault and Wedekind (1978) found that increasing velocity decreases the ricochet angle-of-ejection causing greater disturbance downrange from the primary crater.

Hessen et al. (2007) conducted experimental studies of oblique impacts and found that craters remain circular down to angles of 15% from the horizontal. Below this threshold, as the impact angle decreases, craters become more elliptical. Figure 2.25 shows this dependence of crater shape on impact angle utilizing crater elongation, D_{max}/D_{min}, which is the ratio of the maximum crater diameter to the minimum crater diameter.

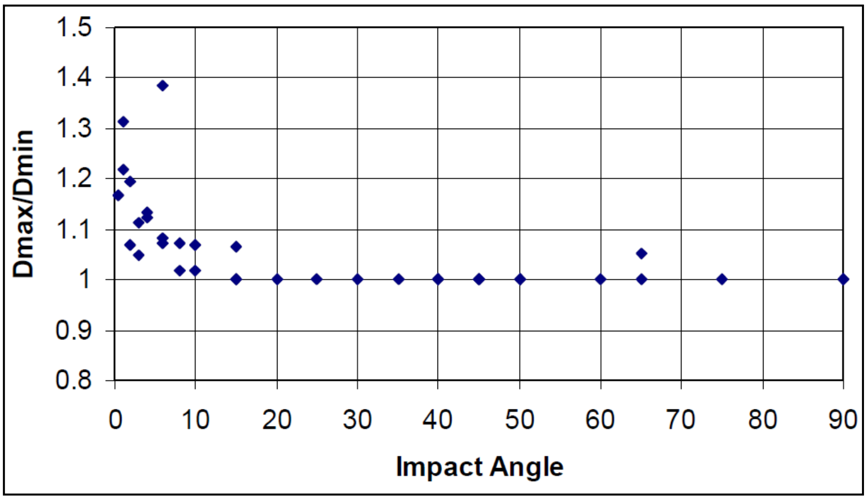


Figure 2.25: Graph showing dependence of crater elongation (D_{max}/D_{min}) on impact angle (after Hessen et al., 2007: 2142).

Few impacts are highly oblique (Shoemaker, 1983). Likewise, few impacts are nearly vertical. The probability, *P*, of an impact at an angle that is between θ, measured from the vertical, and $\theta+d\theta$, is independent of the target body's gravitational field and is given by:

$$dP = 2 \sin\theta \cos\theta \, d\theta \qquad \text{Eq. 2.44}$$

(Gilbert, 1893; Gault and Wedekind, 1978; Pierazzo and Melosh, 2000). The most likely angle of impact for a random meteorite is 45%. The "… probability is zero for vertical or grazing impacts (θ = 90° or 0°) and reaches a maximum at θ = 45 degrees." (Melosh, 1989: 49; cf. Pierazzo and Melosh, 2000).

Bottke et al. (2000) report that survey results indicate around 5% of all kilometre-sized craters on Mars, Venus, and the Moon are elliptical. Their model, which interpolates between experimental impact data utilizing sand and aluminum targets, suggests an elliptical threshold angle of 12% from horizontal for these planetary bodies. The lunar craters Messier and Messier A may be examples of a primary oblique impact (Messier) and a secondary oblique impact (Messier A) due to ricochet of the impactor. Herrick and Forsberg-Taylor (2003) suggest that these two craters formed as the result of a single impact event.

The origin of the Rio Cuarto Crater Field in Argentina has been debated since the early 1990s (Schultz and Lianza, 1992; Bland et al.; Schultz et al., 2004). Though these elliptical craters may be of terrestrial origin (Bland et al., 2002), several possible asteroid impact scenarios have been investigated by Beech (2014). The most likely scenario is a less than 5 degree from horizontal impact of a coherent mass at low speed, ~5 km/s. In this model, the largest crater was produced by the initial impact and the smaller craters were formed downrange by fragments of the decapitated impactor. Beech notes that though the initial conditions required for this model are improbable, it does indicate that the Rio Cuarto features could be the result of a single impactor.

Though many asteroids are loosely consolidated or fractured, coherent asteroids are known. The largest known meteorite on Earth, the Hoba iron located in Namibia, Africa, was apparently a single, non-fragmenting homogeneous, 10^5 -10^6 kg initial mass, which entered Earth's atmosphere at a shallow angle and impacted Earth's surface at a velocity of less than 0.25 km/s (Beech 2013). Of great interest is the fact that no evidence of an impact crater has been found. The kinetic energy of the Hoba meteorite at impact would have been low due the slow impact velocity, thus causing only local damage and deformation. Numerical simulations indicate that a simple crater, diameter ~20 m and depth ~5 m, formed due to a long atmospheric flight path and stabilization of the maximum area impactor profile toward the oncoming airflow during flight, which allowed for a "soft" impact leaving few traces that could survive terrestrial erosion till now (Beech, 2013: 18, 28).

Based on Lunar Topographic Orthophotomaps from Apollo mission data, Herrick and Forsberg-Taylor (2003) found that crater rims become depressed uprange and ejecta becomes concentrated downrange with decreasing impact angles. As the impact angle decreases even more, the rim becomes saddle-shaped with ejecta concentrated in the cross-range direction. In figure 2.26, the bilateral symmetry of the butterfly wing pattern of ejecta from Messier is easily seen as are the downrange rays extending form Messier A. In figure 2.27, the elongated, saddle-shape of Messier with its rim depressed both uprange and downrange is more apparent.

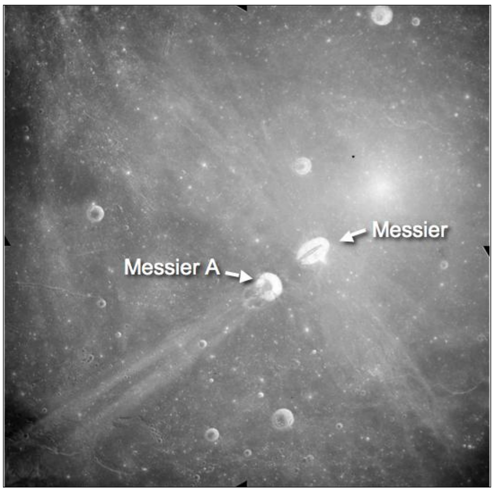


Figure 2.26 (left): Impact craters Messier and Messier A are highlighted. The elongated Messier crater displays a cross-range, butterfly-shaped ejecta blanket. Messier A displays two lines of ejecta in the downrange direction. (Apollo 11, Credit: NASA/JSC/Arizona State University).
Figure 2.27 (right): Messier (upper right, 14 × 6km) and Messier A (lower left) close-up (Apollo 15, Credit: NASA).

The angle of impact has a greater effect on the shape of an ejecta blanket than it does upon the shape of an impact crater. Ejecta blankets show a bilateral symmetry that is inversely proportional to the impact angle, that is, as the angle decreases, the down-range concentration of ejecta increases to the point that an uprange wedged-shaped 'forbidden zone' appears at angles < 45% (Gault and Wedekind, 1978). The

"… elongated canoe-shaped shock wave produced by low-angle impactors … mainly expands sidewise and throws the ejecta out away from its line of advance …" concentrating the ejecta perpendicular to the direction of impact (Melosh, 1989:101). The wedge size increases until impact angles that are ≤ 20% produce a second downrange forbidden zone. Extremely low impact angles, therefore, form elliptical craters with ejecta patterns that have 'butterfly wing' shapes (Gault and Wedekind, 1978; Melosh, 1989). Terrestrial erosion obscures this important tool for identifying oblique impact structures on Earth, however, this feature of oblique impact is clearly visible in the photographs of a Martian crater below in Figure 2.28 and the Messier crater in Figures 2.26 and 2.27.

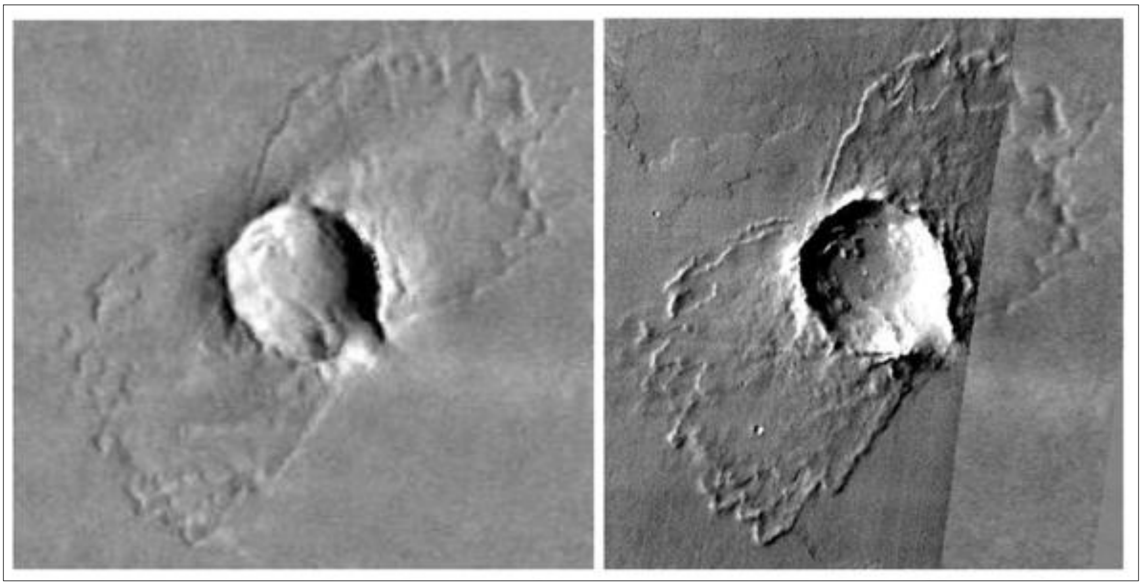


Figure 2.28: The left image is from the Viking Mars Digital Image Mosaic, Version 2 (MDIM2), and the right image shows the same crater in THEMIS imagery from the Thermal Emission Imaging System camera on board the Mars Odyssey orbiter. Butterfly crater: 9.2°N, 279.6°E, diameter = 13 km, azimuth = 139°, interpreted impact direction in degrees clockwise from north (after Herrick and Hessen, 2006: 1488).

Numerical simulations performed by Shuvalov (2011) for a gravitational acceleration of $9.81 m/s^2$ and impact angle of 45% indicate that for a 0.1 km diameter impactor, the ejecta blanket is almost circular, but is offset downrange from the crater rim. Impactors of 1 km and 10 km diameters form ejecta blankets with uprange forbidden zones. The ejecta blanket formed by a 10 km impactor, even at a 60% impact angle, displays asymmetry that increases with increasing distance from the crater. The same projectile at an impact angle of 30% forms a somewhat butterfly-shaped ejecta blanket. Only at an angle of 15% from the horizontal, however, does an impact produce an elliptical rather than a circular crater.

According to Melosh (1989: 49) "… elongated craters, and downrange streaks appear at very low angles of incidence (less that 6° at impact speeds of 6 km/second or more)." He also states that craters resulting from an oblique impact are smaller for a given meteorite mass and velocity since the shock is not as strong as it would be in a vertical impact due to the large horizontal component of velocity. Shoemaker (1983: 473) gives the following relationship for a crater with mean diameter D_i formed at impact angle i compared to a crater with diameter D_{90} formed by a vertical impact:

$D_i = [1–0.095(1 – \sin i)] D_{90}$ Eq. 2.45

Though Shoemaker points out that the frequency distribution is such that few cases of impact angle *i* approaching 0 degrees would be expected, he cites the lunar craters Messier and Messier A as examples of the effect that an extremely shallow angle has which is to elongate the resulting crater in the direction of the impactor's trajectory.

The shock wave in an oblique impact will always be weaker and more diffuse than one from a vertical impact at the same velocity. Melosh (1989: 50) states:

> The shock wave in the target is similar to that produced by a vertical impact, but the target material has a horizontal velocity component perpendicular to the line of approach that is probably responsible for the asymmetric ejecta patterns … The projectile penetrates less deeply in an oblique impact than in a vertical one and deposits a smaller fraction of its energy in the target.
>
> Elementary geometry suggests that the energy deposited in the target during contact and depression stage fills a canoe-shaped elongated trough in the target's surface, rather than the hemispherical region created by vertical impacts.

The final crater will be circular only if its diameter is appreciable larger than the above-mentioned canoe-shaped, elongated trough length. If the trough length is comparable to the final diameter of the crater, then the crater will be elliptical (ibid.).

The time of contact and compression for an oblique impact is longer than that required for a vertical impact. For a meteorite with initial velocity v_i and diameter L, theduration τ of contact and compression is

$\tau = L/(v_i \sin \theta)$ Eq. 2.46

for an oblique impact (Melosh, 1989: 50).

Gault and Wedekind (1978: 3856-3873) consider the butterfly wing pattern to be "… persuasive evidence for Messier's origin by a grazing impact event ($\theta < 5^o$) of a body that approached from an easterly direction …" and call Messier the "... prime type-example of an oblique impact along a grazing trajectory." Fosberg et al. (1998: 1691) created digital elevation models of Messier and Messier A from Lunar Topographic Orthophotomaps based on imagery and data from the Apollo missions. The models show that Messier has morphology similar to experimental oblique ricochet impacts at 1% and Messier A, "… the presumed ricochet …", displays uprange steepening and downrange elongation in the manner of a 5% experimental impact. Herrick and Fosberg-Taylor (2003) surveyed impact craters on the Moon and Venus and report that as the impact angle decreases from vertical, the uprange rim first decreases in elevation and then the downrange rim followed suit while the cross-range rim remains at a constant elevation.

When an impactor fragments at an impact angle of <30% from the horizontal resulting in downrange ricochets, the fragments retain a significant fraction of the meteoroid's initial impact velocity. Impact angles of 5–15% generally lead to 5–10 dominant fragments that retain around half of the original impact velocity, and impact angles <5% can result in a ricochet of an intact projectile with nearly original impact velocity (Schultz and Gault, 2013). Therefore, for increasingly shallow angles, the distance from the primary impact to the downrange secondary impact increases.

Figure 2.29: Martian crater SL82, No. 37 (Viking Frame 516A24).

As shown in Figure 2.29, Martian crater SL82, No. 37, is oval-shaped, 35 × 18 km in diameter (ellipticity $\varepsilon = 1.9$), and sports a central ridge along one side of its long axis. It is considered to be the product of an oblique impact (Bottke et al., 2000). Schultz and Lutz-Garihan (1982: A84) note that Messier also contains a median ridge and state that "Although such floor ridges are not produced in the laboratory, they are characteristic of planetary-scale craters inferred to be products of grazing impacts." Herrick and Fosberg-Taylor (2003: 1565) point out that the central ridge in Messier is tens of meters high and runs the length of the floor. In their search for Martian craters formed by grazing impacts, Bottke et al. (2000: 110) considered only craters that possessed at least two of the following diagnostic characteristics: an elongate form, butterfly wing ejecta pattern, saddle-shaped rim and median floor ridge. Singer and McKinnon (2011) report a 35 × 15 km elliptical crater on the leading hemisphere of Saturn's moon, Iapetus, that sports a linear central peak. Two more craters with linear central peaks are located on the trailing hemisphere of Iapetus, each 15 to 20 km in length. The three most prominent examples of linear central peaks on Iapetus occur in elongated craters. These features may have been formed by closely spaced, similar-sized impactors or be the result of oblique impacts. Singer and McKinnon (2011: 203) state that "Linear central peaks are associated with highly oblique impacts such as Schiller on the Moon." Figure 2.30 shows the 179 × 71 km elliptical crater Schiller with its distinctive median ridge at the far end in the photograph.

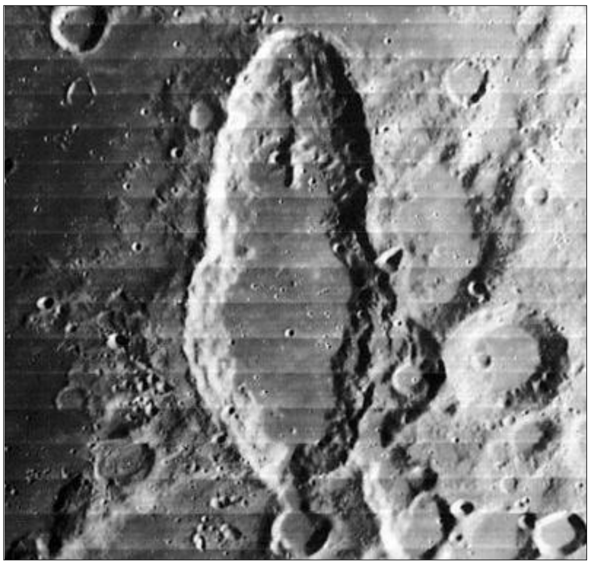


Figure 2.30: Lunar crater Schiller (Credit: NASA - Lunar Orbiter IV 155-H1).

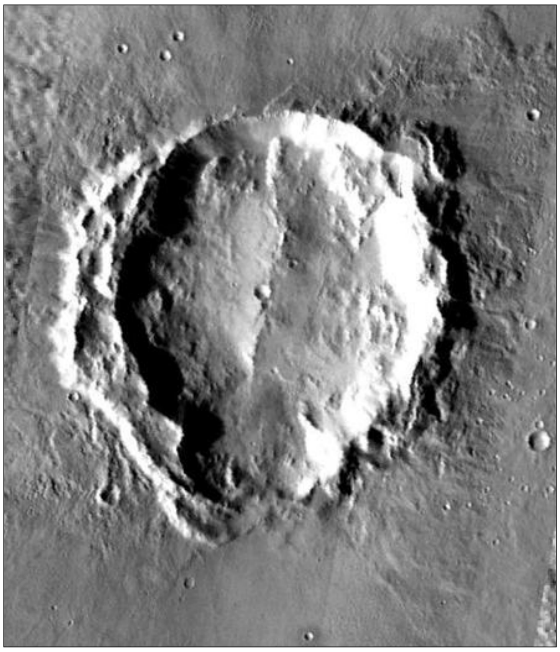


Figure 2.31: Martian butterfly crater at 29.7°N, 87.3°E with a diameter of 30.6 km and a linear ridge.

Herrick and Hessen (2006: 1489) point out a butterfly crater on the surface of Mars, shown in Figure 2.31, with a central ridge that runs subparallel to the direction of impact and truncates against the crater wall on one side, but does not continue to the crater wall on the other side, and has no surface expression exterior to the crater on either side. They note that the three largest butterfly craters on Mars, with diameters of 28.1 km, 30.6 km, and 33.4 km, all display linear ridges subparallel to the major axis of the crater rim.

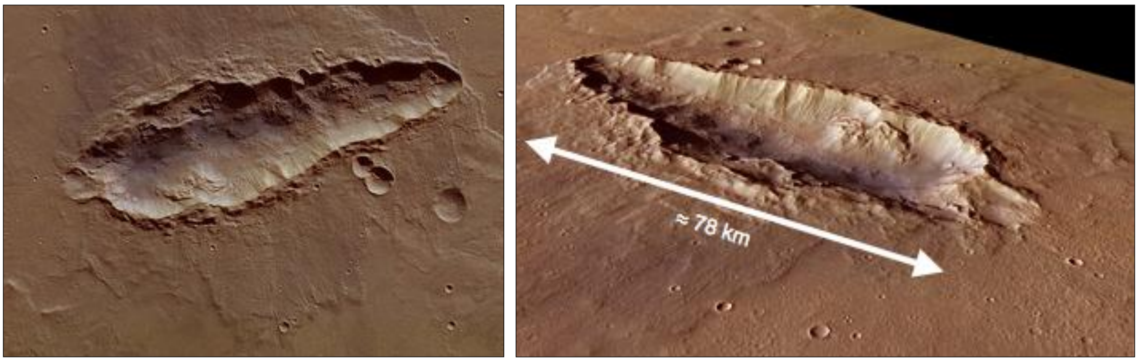


Figure 2.32: Two views of an un-named elongated crater on Mars (Credit: European Space Agency's Mars Express Photographs). Note the butterfly wing ejecta pattern visible on both sides of the crater.

The European Space Agency's Mars Express photographed an un-named elongated impact crater, shown in Figure 2.32, in the southern hemisphere of Mars just south of the Huygens basin. Elbeshausen et al. (2013) utilized 3D-hydrocode iSALE-3D for hypervelocity impact simulations which produced a series of elliptical craters excavated as a result of shock compression in contrast to subsonic impacts that produce elliptical craters by material displacement, that is 'dug craters', as described by Hodge (1994). Elbeshausen et al. (2013) found that the Martian crater shown in Figure 2.32 resembles a simulated crater formed by a 5% above horizontal impact which also widened in the downrange direction. Likewise, a downrange secondary structure was caused by projectile motion in both 5% and 10% simulated impacts similar to that shown in Figure 2.32. The left hand image in this Figure shows ejecta at right angles to the crater's long axis. According to a European Space Agency 4 March 2011 press release, this particular Martian crater could have resulted from "... a train of projectiles striking the planet at a shallow angle ..." (www.esa.int/Our_Activities/Space_Science/Mars_Express/The_scars_of_impacts_on_Mars).

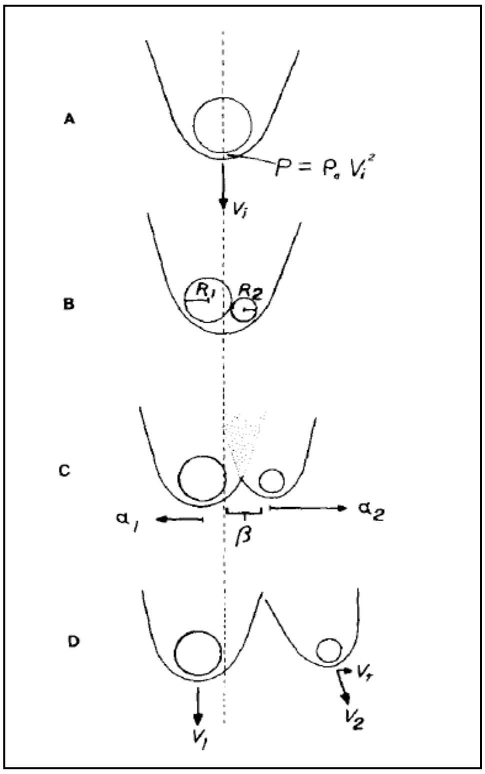


Figure 2.33: Schematic diagram showing the effect of Bow Shock Interaction (after Passey and Melosh, 1980: 224).

As a meteoroid enters Earth's atmosphere at high velocity it is subjected to high stresses and a bow shock forms as is shown in Figure 2.33. When stresses exceed the meteoroid's yield strength, fragmentation will occur. Planes of weakness or pre-existing defects in a meteoroid contribute to breakup, so the mechanics of fragmentation are unique to each individual body and difficult or impossible to predict. The difference in pressure between the leading and back edges of a meteoroid is responsible for its deceleration and fragmentation (Passey and Melosh, 1980). Pressure in a meteoroid's wake is near zero, and the pressure, *P*, behind the bow shock exerted on the leading edge of the meteoroid is given by

$$P = \rho_{\mathrm{atom}} V_{\mathrm{met}}^2 \qquad \text{Eq. 2.47}$$

The condition for atmospheric breakup of a spherical meteoroid is given by

$$0.365\rho_{\mathrm{atom}} V_{\mathrm{met}}^2 = \sigma_{\mathrm{met}} \qquad \text{Eq. 2.48}$$

where ρ_{atom} is atmospheric density, V_{met} is meteoroid velocity and σ_{met} is meteoroid tensile strength (Kadono, 1999: 309-310).

If the swarm of fragments resulting from breakup survives atmospheric ablation and impact a target surface, then either a single crater or a crater field, such as the Henbury crater field, will form depending on the lateral spread of the cluster at impact (Collins et al., 2005). Larger fragments are slowed less by atmospheric drag than smaller fragments and so travel farther downrange. The result is a strewn field in which the largest crater or craters are located at the downrange end of a scatter ellipse. The downrange crater dispersion in a scatter ellipse is primarily due to drag and gravity forces for entry angles that are less than ~30% (Passey and Melosh, 1980).

The crossrange dispersion of meteoroid fragments after breakup is due to a combination of bow shock interaction, differential acceleration, angle of entry, and differential lift of fragments less than ~100 kg (Passey and Melosh, 1980). The angle of entry is relatively insignificant except for shallow entry angles less than around 8–10%. Cross-range spread observed in crater fields is primarily due to the interaction of bow shocks producing transverse velocity components in the trajectories of individual fragments after breakup as is shown in Figure 2.33. In this schematic diagram, the pressure P behind the bow shock is given by

$$P = \rho_a V_i^2 \qquad \text{Eq. 2.49}$$

where ρ_a is the atmospheric density, and V_i is the incoming velocity. For a short time after fragmentation, the fragments, shown with radii R_1 and R_2 in Figure 2.33, travel together behind a single bow shock. After the fragments have separated sufficiently, they have individual bow shocks that interact, producing acceleration, α, transverse to the meteoroid's incoming trajectory. The bow shocks exert forces on each other until the fragments have a separation of β as shown in Figure 2.33. The time of interaction, t, is

$$\Delta t = (2\beta/\alpha)^{½} \qquad \text{Eq. 2.50}$$

which gives the final transverse velocity,

$$V_T = \alpha \Delta t = (2\beta\alpha)^{½} \qquad \text{Eq. 2.51}$$

as shown in the last frame of Figure 2.33 (Passey and Melosh, 1980: 224). At this point, the bow shock interaction and transverse acceleration cease leaving the fragments to travel their individual trajectories leading to a cross-range spread in the resulting scatter ellipse. If an incoming meteoroid is rotating at the time of breakup, then fragments may separate with tangential velocities that are horizontally transverse to the initial trajectory, again leading to cross-range dispersion at impact. Deviation in scatter ellipse distribution can be explained by multiple breakups during descent.

Reports of meteoric iron found in several "… crater-like depressions …" near the Henbury Cattle Station in Central Australia caught the attention of A.R. Alderman, Lecturer in Geology and Mineralogy at the University of Adelaide, Australia (Alderman, 1932: 19). Alderman carried out the first scientific study of the craters in 1931 expecting to find 3 to 5 craters based on reports by local residents, but instead found 12-13 craters ranging from 9 to 200 meters, as well as some 800 pieces of meteoritic material ranging from a few grams up to 24 kilograms. The following month another expedition collected 550 meteorites ranging from 3 grams to 77.5 kilograms. The next year another crater was identified and 80 more kilograms of meteoritic material was excavated (Hodge, 1965). The area around the Henbury craters has since been set aside as a protected area, the Henbury Meteorites Conservation Reserve.

The larger Henbury craters are located at the NE end of a scatter ellipse that contains some 15 to 16 craters indicating the probable flight direction of the fragmenting impactor was from SW to NE (Passey and Hodge, 1980). The Henbury crater field contains several overlapping craters as shown in Figures 2.34, 2.35 and 2.36. Crater 7 is an oval actually consisting of two coalescing craters, designated as craters 7a and 7b.

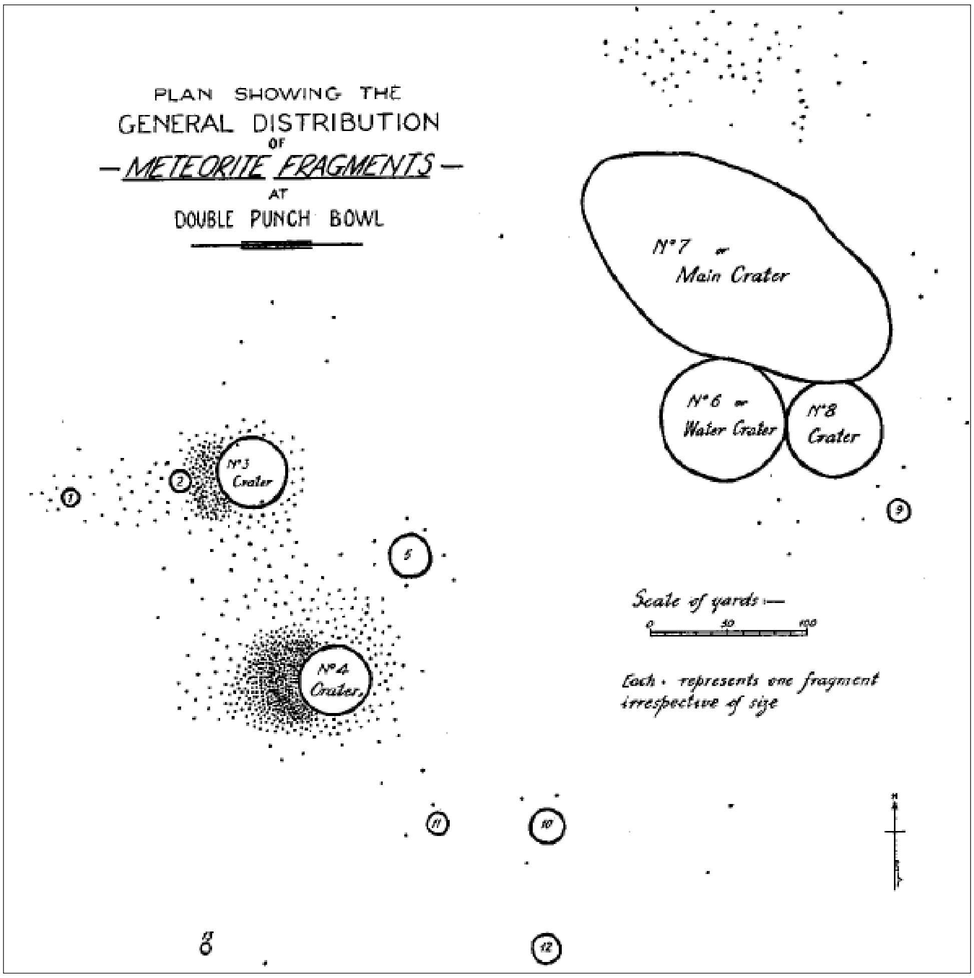
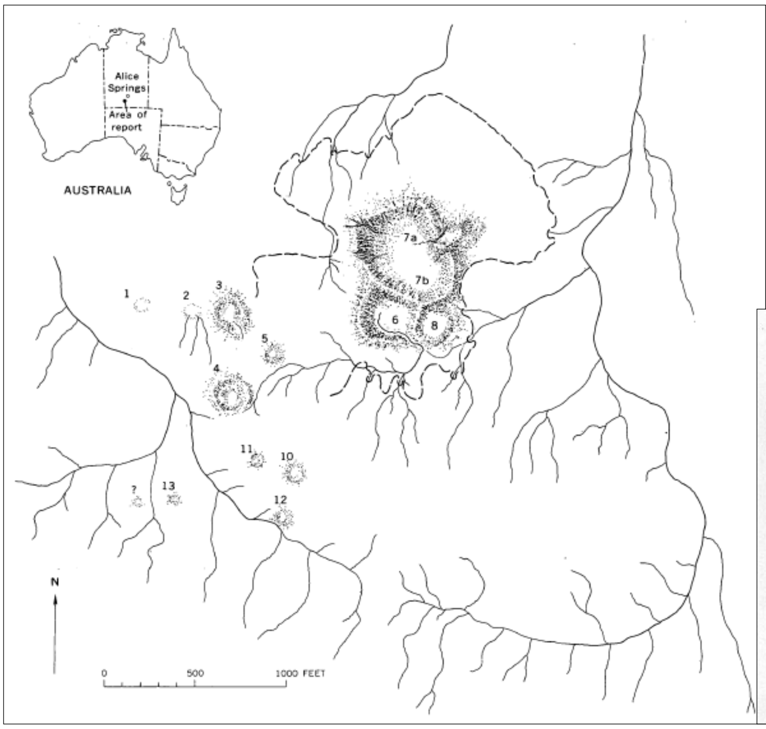


Figure 2.34: Plan showing the general distribution of the Henbury craters and the meteorites scattered around them (after Alderman, 1932: 21).

Crater 6 shares common walls with craters 7 and 8 giving it squared off appearance on one side while remaining circular on the other as is shown in Figure 2.35.

Radial rays consisting of concentrated rock debris extend from Henbury crater 3 primarily to the north, as shown by the dashed lines in Figure 2.37, but a shorter ray is also shown to the south by Hodge. However, Alderman (1932) reported that four-fifths of the 160 iron fragments he found were located to the west of crater 3 as shown in Figure 2.34. The Henbury rays seem to be similar to rays of ejected material seen on the lunar surface emanating from impact craters such as those shown in Figure 2.26. The only other known rayed crater on Earth is the Kamil Crater, a confirmed impact crater located in southern Egypt. It is around 45 meters in diameter and less than 5,000 years old with a pristine ejecta ray structure. Such well preserved ejecta ray patterns have been previously observed only on extraterrestrial planetary bodies (Folco et al., 2011).



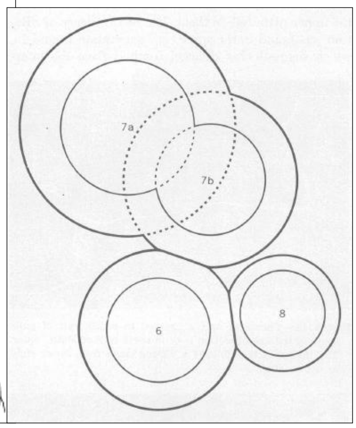


Figure 2.35 (left): Outline map of the Henbury crater field in Central Australia based on aerial photographs in the Division of National Mapping, Australia, and a plane table survey by D.J. Milton and F.C. Michel. The dashed line indicates the approximate outer limit of ejecta from the three main craters (after Milton, 1968: C4).
Figure 2.36 (right): Diagram showing the relationship of the larger Henbury craters in Figure 2.34. The heavy lines indicate the rim crests and light lines the bases of the walls; the dotted lines complete craters 7a and 7b showing each crater as it would have been had the other not formed (after Milton, 1968: C13).

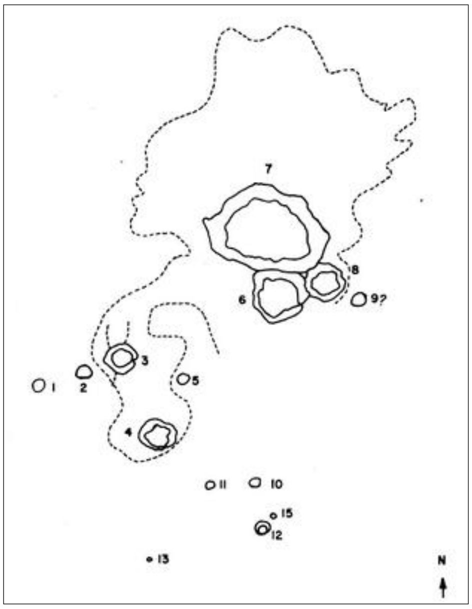


Figure 2.37: Outline map of the Henbury crater field showing the tops of the crater rims and outer perimeters of the crater floors. The dashed lines indicate the area over which ‘rock debris’ can be traced on aerial photographs (after Hodge, 1965: 202).

If meteoroid fragments are not separated sufficiently to form individual or overlapping craters due to low altitude breakup or an angle of entry greater than ~ 10%, then a crater is formed that is virtually indistinguishable from a crater formed by a meteoroid having the same total mass and velocity (Passey and Melosh, 1980). Flynn Creek in Tennessee shows evidence of a broad, but shallow, excavation around a central region of shattered rock possibly indicating atmospheric breakup of the impactor into a cluster of fragments that nearly simultaneously impacted and excavated a single crater (Melosh, 1989). Single craters are formed if the largest crater has a diameter greater than the separation of the fragments or if the largest fragments are separated at impact by a distance that is the same order of magnitude as their diameters (Passey and Melosh, 1980).

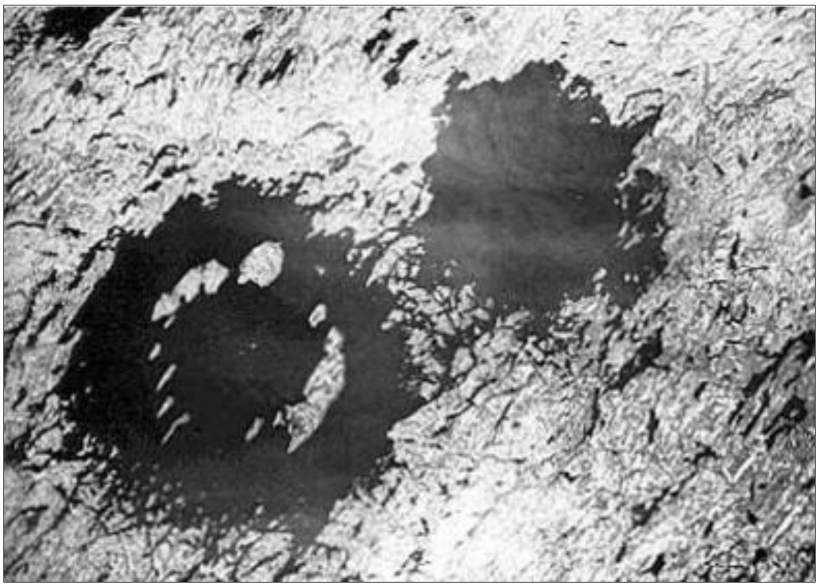


Figure 2.38: An aerial view of the Clearwater Lakes impact craters (Credit: NASA/LPI).

The Clearwater Lakes in Canada (Figure 2.38) are thought to be the result of a terrestrial double impact around 290 Ma (French 1998; Miljkovic et al., 2013; Oberbeck and Aoyagi, 1972). The larger crater is 32 km in diameter, the smaller 22 km in diameter, and their separation is 28 km (ibid.). The Reis and Steinheim impact craters in Germany are thought to be the result of an oblique impact of a double asteroid around 15 Ma (Ivanov and Stoffler, 2005). The Reis crater is 24 km in diameter, Steinheim is 3.8 km in diameter, and their separation is 46 km (Ivanov and Stoffler, 2005; Miljkovic et al., 2013). Such large separations cannot be due to atmospheric breakup (Miljkovic et al., 2013; Passey and Melosh, 1980).

Around 15-16% of near-Earth asteroids that are greater than 200 meters in diameter are binaries that revolve around a common center of mass (Margot et al., 2002; Miljkovic et al., 2013). A binary asteroid impact can result in a single crater that may or may not be elongated, an overlapping crater, or a doublet crater where the separate crater formations had little if any influence on the other even though they formed at the same time (Miljkovic et al., 2013). On both Earth and Mars a doublet crater forms in simulations when the separation, L, between the binary components is greater than 8 times the primary impactor's diameter, $D_{p,}$ or $L/D_p > 8$. For $L/D_p > 6$, two craters overlap but can be distinguished. Smaller separations result in an overlapping crater or a single crater that is circular, elliptical, peanut or tear-drop shaped. For $L/D_p > 2$, a single circular or nearly circular crater forms. Miljkovic et al. (2013) conclude that 2-3% of all impacts on Earth should produce elongated craters via binary impact rather than oblique impact. Doublet craters also occur on Venus, however, its dense atmosphere screens out the smaller impactors leading to a smaller proportion of double impacts than found on Earth (Cook et al., 2003).

Terrestrial double impact craters, such as the Clearwater Lakes, may be more common than previously thought. A conspicuous geophysical signature of impact craters is a residual negative gravity anomaly caused by low-density material resulting from impact such as fractured and brecciated target rock, however, a relative gravity high may exist in the central area of some large complex craters due to denser material brought nearer to the surface in a central uplift (Pilkington and Grieve, 1992). Utilizing a detailed gravitational potential model of 5-arc minute resolution, Klokočník et al. (2010a; 2010b) conclude that some confirmed impact sites show possible evidence of actually being double or multiple craters, including Chicxulub, Manicouagan and Puchezh-Katunki. They also conclude that Popigai may be a chain of craters.

A series of ten oblong, rimmed depressions in the Argentinian Pampa are thought to be oblique impact structures by Schultz and Lianza (1992). Bland et al. (2002) disagree. The Rio Cuarto depressions have yielded meteorites, two found by Schultz and Lianza that are fusion crusted ordinary chondrites, and two found by Bland et al. that were determined to be an ordinary chondrite and a basaltic achondrite (Bland et al., 2002). The latter chondrite was determined to have a ^{14}C terrestrial age of 0.036 $\pm$ 0.004 Ma and the achondrite > 0.052 Ma. The fact that the meteorite terrestrial ages are older than the surface ages for the depressions estimated to be < 0.005 Ma to < 0.01 Ma seems to indicate that the meteorites are not related to the depressions. Bland et al. (2002) note that elongate aeolian landforms, with raised rims and bases lower than the surrounding plain, are located in the vicinity and match the morphological characteristics of these depressions. It is noteworthy that their long axes are consistent with the prevailing wind directions recorded in the area. Glasses found at Rio Cuarto, however, are clearly derived from an impact. Impact glass similar to the Rio Cuarto glass was also recovered some 500 km south of Rio Cuarto suggesting that these samples may be from a widespread tektite strewn field in Argentina (Bland et al. 2002; Melosh, 2002). Based on other impact glasses found at Rio Cuarto, Schultz et al. (2004) dispute this conclusion, stating that two distinct and separate impact events have been recognized near Rio Cuarto dated 3-6 ka and 114 ka and that the Rio Cuarto depressions are indeed the result of an oblique impact event.

There is no question concerning the impact origin of the Amelia Creek Structure, located in Australia's Northern Territory, which Macdonald and Mitchell (2003: 1) consider "… the world's type locality for oblique impacting …" in part due to the structure's well-exposed impact-deformed rocks. It is a confirmed 20 × 12 km impact structure without a central uplift, but with a canoe-shaped central trough, or syncline, that runs NNE-SSW and is around 1 km wide and 5 km long. Scenarios suggested by Macdonald et al. (2005) that may explain this structure's lack of a circular form include the pre-existing structure within the target rock, or it is the result of an oblique impact, or both. Impact breccias and shatter cones were found in the structure's central region and numerous shatter cones were also found in a 1 by 3 km crescent shaped area on the southern, downrange side of the structure. No shatter cones were located uprange, however, the uprange rock were "… anomalously deformed, so there is a distinct possibility that Amelia Creek is part of a crater field or a ricochet structure …" similar to highly oblique impact sites on the Moon and Mars (ibid.).

Though elliptical craters are usually attributed to oblique impacts, other possible explanations do include binary asteroid/meteoroid impact or the fragmentation of a single impactor resulting in overlapping or elliptical craters. Secondary craters may also be elliptical with the long axis radial to a primary crater. Considerations of these possibilities may help explain some aberrant terrestrial structures such as the Dycus Disturbance in Tennessee.

CHAPTER 3: CHANGING PERSPECTIVES ON IMPACT CRATERING, PRIMARILY FROM AN AMERICAN VIEWPOINT

3.1 A Brief History of the Origins of Meteoritics

Asteroids, comets, and meteoroids are small Solar System bodies composed of rock and metal or ice that are basically the left-over debris from the formation of our Solar System around four and a half billion years ago. Though small in size compared to the planets, these bodies are now known to have played a significant role in shaping the surfaces of solid bodies in our Solar System (Shoemaker, 1977b).

As soon as Galileo Galilei focused his tiny telescope on the lunar surface in 1609, he saw craters (Koeberl, 2001). Galileo's earliest sketches of the Moon showed several of the circular structures he was able to view (Baldwin, 1949). Some were bowl-shaped depressions; others had central peaks or were surrounded by concentric circles (Koeberl, 2001). He recognized these as depressions since their raised rims were lit before their floors as he watched sunlight slowly move across the lunar surface at low angles (Melosh, 1989). Though the surfaces of Mercury and Mars are also covered with craters and large craters have been detected on the hidden, cloud covered surface of Venus, these structures are not obvious to the casual Earth-bound observer through a small telescope, so at this point in time, the only craters known were located either on Earth or our nearest celestial neighbor, the Moon. Historically then, since most craters known on Earth were formed by volcanoes, the majority of scientist assumed that the lunar craters were also volcanic in nature (Koeberl, 2001; Reimold and Koeberl, 2008).

The first to consider that lunar craters may not be the result of volcanic processes was the British physicist, architect and polymath, Robert Hooke (1635–1703) (Koeberl, 2001; 2009). Initially, Hooke suspected that these lunar structures were due to internal volcanic activity after observing their similarity to pits that form on the surface of boiling alabaster (Koeberl, 2001; Melosh, 1989). In his *Micrographia* ... (Hooke, ca 1665), suggested that "… tremendous bubbles, gas filled, rose slowly through the hot viscous matter of the primitive surface [of the Moon] and then burst …" forming the craters we now see on the lunar surface, however, these bubbles would have to have been over 160 km in diameter in order to form the largest craters seen on the Moon (Baldwin, 1949; Koeberl, 2001). Baldwin (1949) considers this to be mechanically impossible and also notes that this explanation cannot account for the numerous central peaks observed in lunar craters. Hooke also dropped objects into mud and noted that the results looked similar to lunar craters (Koeberl, 2001; 2009). Although he then considered the idea of an impact origin, Hooke dismissed it as being most unlikely since space was thought to be empty (Koeberl, 2001). Small Solar System bodies, such as asteroids and meteoroids, were not known at the time and the idea of meteorites falling from the sky was considered to be the result of superstition and folklore professed by the uneducated (Hoffleit, 1945). Therefore, the idea of extraterrestrial bodies impacting the Moon's surface, much less the Earth's surface, was roundly rejected (Koeberl, 2001). Astronomers and geologists still favored the hypothesis that volcanoes, not space rocks, were responsible for lunar as well as terrestrial craters (Koeberl, 2001; 2009).

Ceres was discovered in 1801 and the discoveries of other smaller bodies in the asteroid belt followed until finally these numerous objects were referred to collectively as the vermin of the skies (Sears, 1930)! Interplanetary space was no longer considered empty. Other ideas also began to change on 26 April 1803 when meteorite fragments fell by the thousands on the French town of L'Aigle (Hoffleit, 1945; Koeberl, 2009; Melosh, 1989; Nininger, 1972). Previously, the French Academy of Sciences had ridiculed any report of rocks falling from the sky and claimed that only a basic ignorance of the facts of science would allow for belief in such a "… physically impossible phenomenon." (King-Hele, 1975: 4). The French astronomer, Jean-Baptiste Biot (1774–1862; Figure 3.1), was sent to investigate the 1803 meteorite fall and report his findings to the Academy (Gounelle, 2006). His report stated that the fragments must be extraterrestrial and he gave credence to the previously-rejected claims of rocks seen falling from the sky (Koeberl, 2009; Thomas, 2000). Though some consider the 1803 event and Biot's report to have effectively given birth to the science of meteoritics, it should be noted that the German physicist, Ernst Florens Freidrich Chladni (1756–1827), had already suggested in a book published in 1794, and did so again in 1819, that "… meteors are associated with stony or metallic objects falling from space." (Hoffleit, 1945: 30; cf. Koeberl, 2009; Melosh 1989; Nininger, 1972). Marvin (1996) examines the case for identifying Chladni (Figure 3.2) as the 'founding father' of meteoritics (cf. Ullman, 2007).

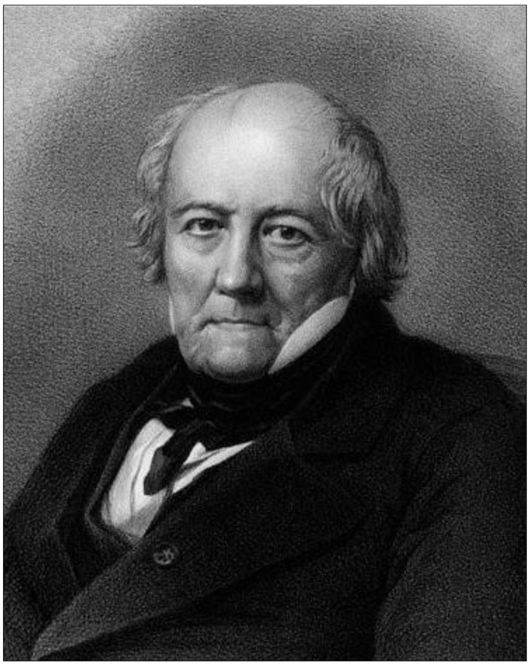


Figure 3.1: J-B Biot, from a lithograph by A.C. Lemoine
(http://www.sil.si.edu/digitalcollections/hst/scientific-identity/cf/display_results.cfm?alpha_sort=b)
Figure **3**.2: E.F.F. Chladni, from an engraving by Henry Adlard, 19th C.
(http://www.sil.si.edu/digitalcollections/hst/scientific-identity/cf/display_results.cfm?alpha_sort=C)

Thomas Jefferson, the third President of the United States and "… one of the most advanced thinkers of his time… ", was reluctant to accept as fact the idea that stones could fall from the sky (Baldwin, 1963: 8). Although he is considered to have been a wise and rational man, "… a scientist as well as a statesman…", when two Yale professors described a meteorite fall in 1808, Jefferson responded: "It is easier to believe that two Yankee professors would lie, rather than that stones would fall from heaven." (King-Hele, 1975: 4-5; cf Nininger, 1972: 4). Other accounts state that Jefferson actually said "It is all a lie" when referring to the meteorite that fell in

Weston, Connecticut during the early morning hours of 14 December 1807 (Melosh, 1989).

Within the United States, the term ‘Yankee’ has historically not referred to Americans in general, but to descendants of the early colonial settlers living in the northeastern section of the country. The two Yankee professors referred to by Jefferson, a Southerner, were James Luce Kingsley (1778–1852) and Benjamin Silliman (1779–1864; Figure 3.3). Though the meteorite fall occurred in December 1807, their account of the Weston Meteorite, based on *Memoirs of the Connecticut Academy of Arts and Sciences*, was not actually published until 1869 (Silliman and Kingsley, 1869: 1). These careful researchers made sure their report included eyewitness accounts of the actual event given by those considered to be of unquestionable integrity. A principal eyewitness, Nathan Wheeler of Weston, was described as “… one of the justices of the court of common pleas for the county of Fairfield, a gentleman of great respectability, and of undoubted veracity, who seems to have been entirely uninfluenced by fear or imagination …” (ibid.). Silliman and Kingsley also made note of the fact that Wheeler’s location at the time of the meteorite fall gave him “… an opportunity of witnessing the whole phenomenon …” (ibid.).

Figure 3.3: Benjamin Silliman from an engraving by W.G. Jackman, (http://www.sil.si.edu/digitalcollections/hst/scientific-identity/cf/display_results.cfm?alpha_sort=S)

The meteor was first seen at about 6.30 a.m. moving with great velocity and so bright that it “… illuminated every object …” before exploding over Weston, Connecticut, around 40 km from New Haven (ibid.), the location of Yale College (now Yale University). During flight, the meteor appeared to be “… one-half or two-thirds the apparent diameter of the full moon …” before witnesses heard “… three loud and distinct reports …” followed by “… a continued rumbling, like that of a cannon-ball rolling over a floor …” (Silliman and Kingsley, 1869: 2). Silliman and Kingsley estimated the real diameter of the meteorite to be over 90 meters before it exploded (Silliman and Kingsley, 1869: 3). Several residents witnessed falling stones and others reported “… they heard a noise like the fall of a very heavy body, immediately after the explosions …” (Silliman and Kingsley, 1869: 4). Fragments of the meteorite were recovered from various locations, some immediately and “… still warm …” to the hand, others after a several day search (Silliman and Kingsley, 1869: 4-6). Silliman and Kingsley (1869: 5, 7) recovered some fragments themselves and bought others from local landowners. In the course of interviewing eyewitnesses, Silliman and Kingsley found that "… no one in this vicinity, with whom we have conversed, appeared to have ever heard of the fall of stones from the skies …" and they simply assumed at the time that the flash of light, thunderous noise, and holes in the ground resulted from lightning that had struck the earth (ibid.). Silliman and Kingsley (1869: 6-7) recorded the following account from one of the eyewitnesses, a Mr. Elijah Seeley.

> After the last explosion, he says, a rending noise like that of a whirlwind passed along to the east of his house and immediately over his orchard … At the same instant a streak of light passed over the orchard in a large curve, and seemed to pierce the ground. A shock was felt, and a report heard like that of a heavy body falling to earth; but no conception being entertained of the real cause … it was supposed that lightning had struck the ground. Three or four hours after the event, Mr. Seeley went into his field to look after his cattle. He found that some of them had leaped into the adjoining enclosure, and all exhibited strong indications of terror. Passing on, he was struck with surprise at seeing a spot of ground which he knew to have been recently turfed over, all torn up, and the earth looking fresh, as if from recent violence. Coming to the place, he found a great mass of fragments of a strange looking stone …
>
> [The stone] forced itself into the earth to the depth of three feet [1 meter], tearing a hole of five feet [1.5 meters] in length and four and a half feet [1.4 meters] in breadth, and throwing large masses of turf and fragments of stone and earth to the distance of 50 and 100 feet [15 and 30 meters]. Had there been no meteor, no explosions, and no witnesses of the light and shock, it would have been impossible for any person contemplating the scene to doubt, that a large and heavy body had really fallen from the skies with tremendous momentum.

Silliman and Kingsley (1869: 7) state that their stone "… specimens obtained from the different places are perfectly similar …" and even the "… most superficial observer would instantly pronounce them portions of a common mass." The stone was found to have a specific gravity of 3.6 and on larger specimens they "… distinctly perceived portions of the external part of the meteor. It is everywhere covered with a thin black crust, destitute of splendor …" (ibid.). They also note that the external part of the meteorite "… is sometimes depressed with concavities …" (ibid.). The interior is a dark ash color, granular and course, "… interspersed with distinct masses, from the size of a pin's head to the diameter of one to two inches [2.5 to 5 cm], which are almost white … " and also "… thickly interspersed with black or grey globular masses, most of them spherical, but some are oblong …" (Silliman and Kingsley, 1869: 8). They also found the "… whole stone is interspersed with malleable iron, alloyed with nickel. These masses of malleable iron are very various in size, from mere points to the diameter of half an inch [1.25 cm] …" (ibid.). Silliman and Kingsley also noted some masses of yellow pyrites and "… a few instances of matter dispersed irregularly through the stone, which are considered as intermediate between pyrites and malleable iron … sometimes attractable by the magnet, and sometimes not …" (ibid.).

Evidence such as that presented by Biot, Silliman and Kingsley for the interplanetary origin of meteors and meteorites continued to accumulate until scientist as well as the general public eventually accepted the fact that these objects do not originate on Earth. This acceptance came slowly, however.

A legendary Leonid meteor storm (see Figure 3.4) occurred during the night of 12-13 November 1833 that was visible across the eastern United States, including the state of Alabama directly to the south of Tennessee. One observer stated that "…

stars descended like snow …" at an approximate rate of 100,000 per hour (Olmsted, 1834: 372; cf. Thomas, 2000: 38). In Alabama, it became known as "… the year the stars fell …" and this event became a part of Alabama folklore inspiring the song, the book, and the phrase on Alabama automobile license plates, "Stars Fell on Alabama" (King and Petruny, 2003: 1). "Carl Carmer's 1934 book *Stars Fell on Alabama* recounts how this meteor shower was so spectacular in Alabama's skies that – even a century afterward – 'memories of the oldest ones' marked time from 'the year the stars fell' …" (ibid.).

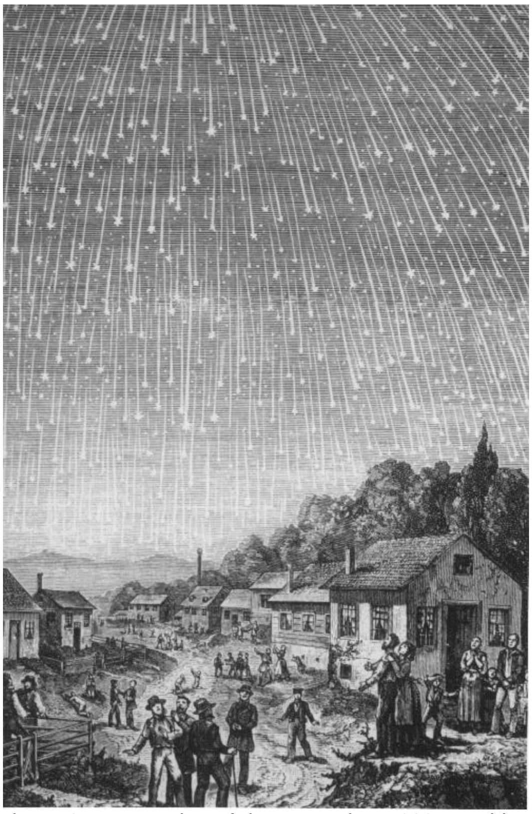


Figure 3.4: Engraving of the November 1833 Leonid meteor shower by Adolf Vollmy (1889). It is based on a painting by Swiss artist Karl Jauslin, which, in turn, was based on a first-person account of the 1833 storm by Joseph Harvey Waggoner, a minister, who saw the 1833 shower on his way from Florida to New Orleans. (http://earthsky.org/todays-image/leonid-meteor-shower-1833)

This same meteor storm was witnessed far to the north of Tennessee in the state of Illinois by a young Abraham Lincoln, later the sixteenth President of the United States (Thomas, 2000). Those around him assumed that the end of the world, the Day of Judgment had come, but Lincoln calmly noted that although the stars seemed to be falling in great showers, "… looking back of them in the heavens, I saw all the grand constellations with which I was so well acquainted, fixed and true in their places …" (Olson and Jasinski, 1999: 35). He quickly concluded that not all of the stars were falling from the heavens and, therefore, the world was not coming to an immediate end (ibid.).

Expecting only an ordinary night, Yale University's Professor of Mathematics and Physics, Denison Olmsted (1791–1859; Figure 3.5), was asleep, but "… through the kindness of a friend, awaked in season to witness the spectacle in much of its grandeur …" (Olmsted, 1834: 364). As a result, the 1833 Leonid meteor storm is generally regarded as marking the birth of meteor astronomy after Olmsted, Alexander Catlin Twining (1801–1884), who was then a civil engineering student at West Point, New York, and a Professor Aikin from Mount St. Mary's College in

Maryland, as well as others, determined that all of the meteors seemed to radiate throughout the storm from a fixed point in Leo. Olmsted (1834: 366) noted that the radiant was "… within the bend of the sickle, a little to the westward of Gamma Leonis …", while to Twinning " … I should select as near the truth a small star in the Lion's neck …" (Olmstead, 1834: 370). Olmsted (1834: 405) stated that Twining's opinion was "… that although the luminous appearances were within our atmosphere, the source or cause lay far beyond. My own impressions were, that the radiant point did not partake of the earth's rotation …". Aiken stated that "The radiant point … maintained the same relative position in regard to Gamma Leonis during the whole time of observation … a space of about two hours …" (Olmsted, 1834: 406).

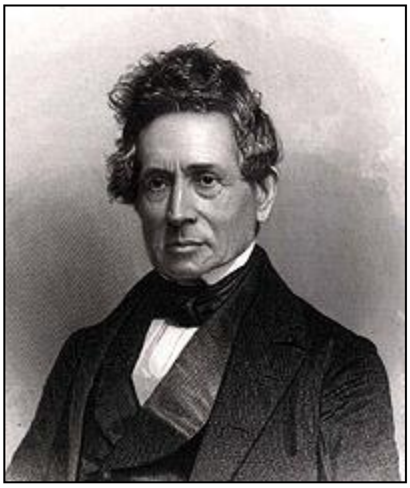


Figure 3.5: D. Olmsted from an engraving by A.H. Ritchie based on an earlier piece attributed to the artist Reuben, Son of Moulthrop (http://www.sil.si.edu/digitalcollections/hst/scientific-identity/cf/display_results.cfm?alpha_sort=O).

Olmsted's account of the meteor storm was published the morning after its occurrence in the *New Haven Daily Herald* and the article concluded with a request for information from other observers. To Olmsted's surprise, "… the request has met with a response from scientific gentlemen residing in different parts of the Union …" due to the fact that the article was "… copied into other papers of a wider currency …" (Olmsted, 1834: 364). One response came from the Reverend Dr Humphreys, President of St. John's College in Annapolis, Maryland:

> A remarkable phenomenon of *shooting stars* was seen at Annapolis, about 4 or 5 o'clock, on the morning of Wednesday, the 13th instant; the number of the meteors was far greater than in any former instance ever observed by the writer. They all appeared to move from a common centre, at or near the zenith; and at times, they completely filled the whole heavens, particularly towards the East, with beautiful brilliant streams of light, extending to the horizon. It is not meant that all the trains actually extended from the zenith to the horizon; but that the lines of light were *so directed*, that if *produced*, they would all converge to a point in the zenith. Their appearance was so incessant during some part of the phenomenon, that all of the stars of the firmament, seemed to be darting from their places. (Olmsted, 1834: 371-372).

Olmsted's paper also included eyewitness accounts, gathered by Twining in New York and sent to Olmsted, of the meteor storm as seen from fifteen ships that ranged in location from the Gulf of Mexico to the Hudson River in New York (Olmsted, 1834: 399). One ship, located in the Gulf of Mexico, was sailing from Mobile, Alabama to New York, when, around three o'clock in the morning, its Captain "… first noticed the unusual number of falling stars, and began to count their number, but was forced to desist, by their rapid increase …" (ibid.). Other accounts included the ship *Tennessee* which "… was in view of meteors on every side, from 4 to 6 o'clock, A.

M. …" (ibid). Due to the enthusiastic and varied responses he received to his request for information, Olmsted decided to "… render an acceptable service to science, by collecting and classifying the facts already ascertained, and recording them in a work more permanent than the ephemeral publications, in which they have hitherto appeared …" (Olmsted, 1834: 407).

Olmsted (1834: 383) states that "It was not until after the first sheets of this article were put to press, that the writer obtained the following ingenious observations …" which were made by a surveyor named James N. Palmer:

> Mr. Palmer, being abroad in the earlier parts of the night, and having observed an unusual number of falling stars, was induced to read over an account of the meteors described by Andrew Ellicott, which occurred Nov. 12, 1799. This being the same time of year, his curiosity was excited, and he mentioned to members of his family his expectation of a similar phenomenon.

As Dick (1998) has recounted, Olmsted's report and accounts such as the one above led later researchers, including Yale Professor of Mathematics Hubert Anson Newton (1830–1896; see Figure 3.6), to investigate the historical records of many cultures concerning previous "November Star-showers …" and he reports:

> In the following pages I propose to give, so far as I can, the original accounts of those displays of shooting stars which may be considered the predecessors of the great exhibition on the morning of Nov. 13th, 1833. These accounts afford data for the determination of the length of the annual period, and the thirty-three year cycle. They furnish additional arguments (if such arguments are needed) for the theory that the shooting stars are small bodies moving originally each in its own orbit, until they come into the earth's atmosphere, where they burn for an instant and are dissipated into smoke or dust. They show that the time during which the swarm of bodies furnishing the November meteors revolves about the sun must be limited to one of five accurately determined periods, one of which is more probable than the others. They will serve to direct future observation, and perhaps verify or correct such hypotheses as have been, or may be presented. (Newton, 1864b: 377-378).

Figure 3.6: Portrait of H.A. Newton by an unknown artist, 1879. In Kingsley, W.L., (Ed). *Yale College: A Sketch of Its History*, New York City, Henry Holt & Co., 426.

After completing his research in 1864, Newton (1864b: 96-97) predicted in a British journal that "A maximum display on the morning of the 14th November, 1866, is expected to be chiefly visible on the western Atlantic …" based on the following argument:

> Comparing together the dates of thirteen historic star-showers, from October 13th, 902, to November 13th, 1833, the existence of a *common meteoric shower* becomes apparent. The node of the ring has an annual *pro*-cession of 1'.711 (reckoned from mean equinox), or of 52".56 reckoned from a fixed equinox along the ecliptic. By this amount the date of the return has been delayed one day in every 34 years since the first appearance of the shower; and the narratives are in accordance with a single meteoric phenomenon, of which the yearly period is 365.271 days, returning with especial intensity four times in every 133 years. A want of punctuality of one, two, or even three years in the return of the display may be accounted for by the revolution of the earth on its axis, by which observers were deprived of a view of the spectacle during a part of its existence. The explanation of the periodicity depends, not upon the perturbations of the earth or of the ring, but upon the true periodical time of revolution of the cloud … moreover, the true motion of the November meteors is sensibly perpendicular to a radius-vector from the sun … with a velocity nearly equal to that of the earth, but in a retrograde direction. The inclination observed corresponds to nearly 17° with the ecliptic … The orbit is nearly circular, with a semi-major axis 0.9805 …

On the first night of the 1866 observation, November 12-13, Newton's party consisted of 15 or more observers; however on the second night, November 13-14, "… a new relay of observers began to count at 11 o'clock. They were relieved by a fourth party about 2 o'clock A.M. …" (Newton: 1867: 78, 80). During this second night of observation, 901 meteors were counted in the five hours between 11:00 pm and 4:00 am giving an average of 180 per hour (Newton, 1867: 80). During the first hour of observation 122 meteors were counted and during the last hour a total of 212 meteors were counted (ibid.).

Twining was in New Haven, Connecticut, during the 1866 meteor shower watching alone on the morning of November 14 when he recorded the following (Newton, 1867: 82):

> Again I watched from $3^h\ 8^m$ A. to $4^h\ 8^m$ A.M., or one hour. In a space equal to the former and looking toward the radiant I saw 43 meteors, of which 38 were conformable to an area covering the bend of the Sickle, - but far the greater number radiating closely from the small star in its middle, being the old radiant of Nov. 13th, 1833.

Though notable, the 1866 Leonid meteor shower was not as spectacular in numbers as the 1833 storm when there appeared to be an "… *almost infinite number* of the meteors …" (Olmsted, 1834: 372). Its historical importance lies in the fact that it brought the debate of whether or not meteors and meteorites have a celestial or terrestrial origin to a close (Thomas, 2000: 14).

His 1864 prediction verified, Newton (1867: 78) states that "The brilliant exhibition of the November [1866] meteors witnessed in Europe on the 14th of that month is a confirmation (if such confirmation was needed) of the astronomical character of these bodies, and of the thirty-three year cycle." Newton acknowledged that "The European observations are evidently those which will throw most light upon their cosmical relations …" however, he points out that the American observations on the nights of November 12-13 and November 13-14 also "… have decided value …" (ibid.). Newton notes that the American observations of the 1866 Leonid meteor shower "… from midnight onward on the morning of the 14th may be regarded as a continuation of those which in England were interrupted by the approach of daylight …" (ibid.).

Research continued on the Leonids, as noted by Newton (1868: 225, 237) in his report on the "Shooting Stars of November 14th, 1867", when he includes the statement that "It is now known that the entire stream of November meteoroids follows Comet I of 1866, commonly called Temple's Comet." Since the comet was also independently discovered by H.P. Tuttle of the U.S. Naval Observatory, today it is known as Comet Temple-Tuttle, the parent body of the Leonid meteor shower (United States Naval Observatory, 1867: 12).

Meteorite falls have been known for centuries, but these space rocks usually land without incident. On 30 November 1954, however, a meteorite fell in Sylacauga, Alabama, hitting and injuring Ann Hodges (see Figure 3.7) as she slept in her home (Provenmire, 1995; Swindel and Jones, 1954). This event resulted in the first well-documented case of a human being struck by a meteorite (Bryant, 2004). The incoming chondrite was observed to fragment into at least three pieces (Povenmire, 1995). The 3.86 kg Hodges fragment (Figure 3.8) landed some 3750 meters from the 1.68 kg McKinney fragment, which fortunately fell into an open area near the McKinney home causing no injury, but the third fragment was not recovered (ibid.; Swindel and Jones, 1954). The Hodges Meteorite is on display in the Alabama Museum of Natural History located on the Tuscaloosa campus of the University of Alabama.

Figure 3.7 (left): A doctor examines the bruise on Ann Hodges caused by the meteorite (http://pbsthisdayinhistory.tumblr.com/post/43160047609/laphamsquarterly-deja-vu-skyfall-2013a).
Figure 3.8 (right): Donna Rentfrow, Director of the Anderson Comer Museum in Sylacauga, holds a replica of the 'Hodges meteorite' that is now in the Alabama Museum of Natural History (wikipicks.blogspot.com).

A more recent meteorite impact occurred in Peru, fortunately without injury to any of the numerous witnesses, forming a 14.2 m impact crater. The Carancas meteorite struck south of Lake Titicaca on 15 September 2007. The meteorite, an H4-5 chondrite, predominately remained intact during its atmospheric passage which is unusual for a stony meteoroid. Kenkmann et al. (2009) surveyed the impact site and carried out numerical simulations of the event which indicated that the meteorite experienced low aerodynamic stress due to a shallow atmospheric entry angle which resulted in a strong deceleration and deflection to a steeper impact angle. Even so, the impactor was still capable of producing a small impact crater in a populated area. A most interesting aspect of this event is that "the impact was not sufficient to cause any significant shock metamorphic overprint in the rocks" (Kenkmann et al., 2009: 998).

Since rocks falling from the sky seemed to cause so little harm, the idea that asteroid-size objects have struck Earth's surface forming craters kilometers in diameter was difficult for many to accept, even as late as the 1960s (Amstutz, 1964; Bucher, 1963a, 1963b). However, "Established ideas have been completely overturned … former heresies are now respectable 'truth', and old accepted truths are now despised …" (King-Hele, 1975: 1). So it has also been with the idea of large meteorites leaving scars on Earth in the form of impact structures.

3.2 Impact Structures and Lunar Correlations

Inside the cover of Mitchum's 1951 thesis on the Dycus Structure, readers are asked to sign a statement indicating they will respect the literary rights of the author. The first signature there is by E. O'Connell, and dated 15 February 1964. At that time, O'Connell (1965: 1) was gathering information relating to meteorite craters as she prepared a catalog and guide to the pertinent literature. This was then published in 1965, with the following introduction:

> As lunar expeditions become more and more probable, the study of terrestrial craters and similar geological features of known and possible meteorite-impact origin has moved out of the fringes of geology … It has become a major interdisciplinary effort carried on by astronomers as well as geologists and by such other scientific specialists as geophysicists and astrophysicists.
>
> The knowledge of terrestrial features of meteoritic origin has become important not only in itself, but also an essential part of current studies of the effects of meteorite impacts on the Moon. In fact, one of the main sources of information about terrestrial meteorite craters is modern works on selenology. For instance, about one-fourth of Baldwin's important Measure of the Moon (1963) is devoted to discussions of geological features of meteoritic origin …
>
> But these books are written by, and primarily for, astronomers, whose main interest in terrestrial meteorite craters is their many analogies to lunar craters.

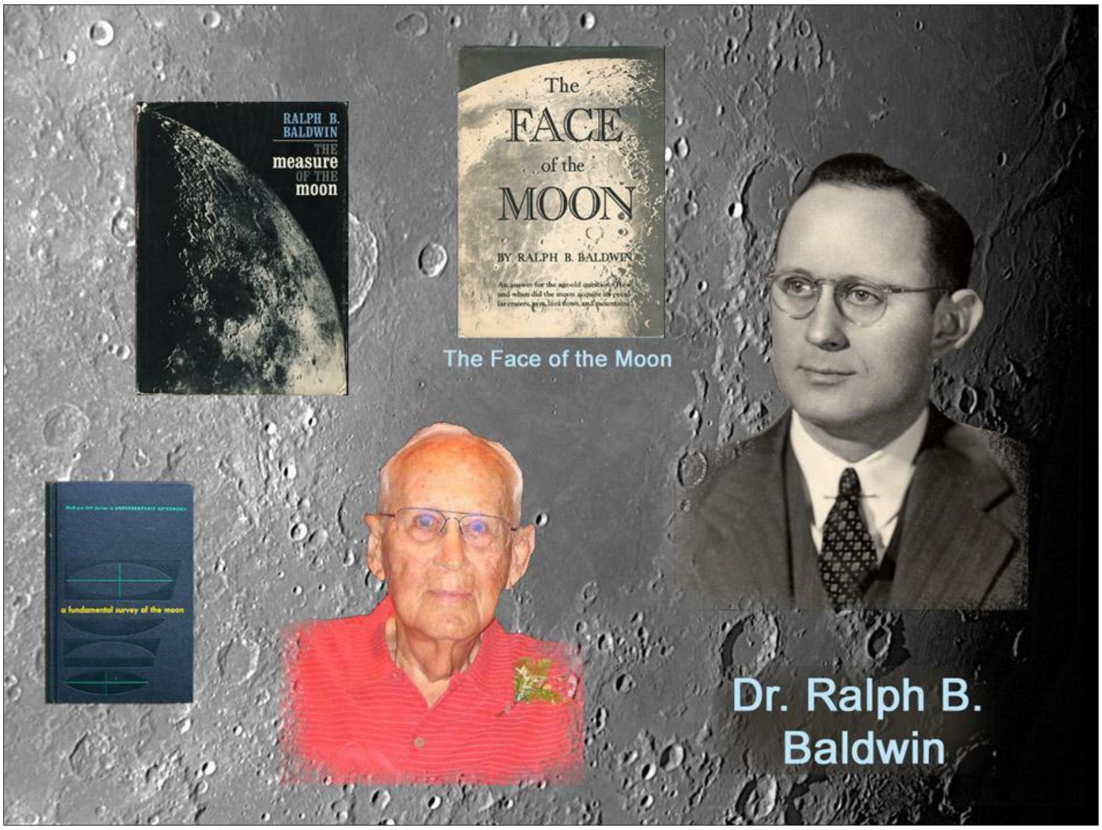


Figure 3.9: A composite image prepared by Howard Eskildsen in 2009, one year before Ralph Baldwin died, to honor his long and important contribution to planetary science (lpod.wikispaces.com/November+29,+2009).

One of those who revolutionized our thoughts concerning terrestrial impact cratering was the American planetary scientist Ralph Belknap Baldwin (1912–2010; Figure 3.9). Baldwin (1963: 4) states that the "… terrestrial meteoritic craters are the Rosetta stone of the moon." He continues with this idea pointing out that in order to "… study the moon, we shall start on the earth … We can study, for example, the Arizona Meteorite Crater far more thoroughly than one of the same size on the moon." (Baldwin, 1963: 5).

Baldwin (1949: 48) notes that "Observers for more than three centuries have considered the lunar craters to be enlarged versions of the normal terrestrial volcanoes." This commonly-held view was in part due to an optical illusion causing craters to appear deeper than they actually are. Baldwin explains that during Full Moon lunar features fade and are not sharply defined, however, contrasts are sharp during other phases since there is no atmosphere to diffuse the incoming sunlight and shadows are, therefore, disproportionally long near the terminator due to the Sun's lower angle in the lunar sky. Baldwin points out that "This contrast causes craters to appear many times deeper relative to their diameters than measurements actually show them to be …" (ibid.).

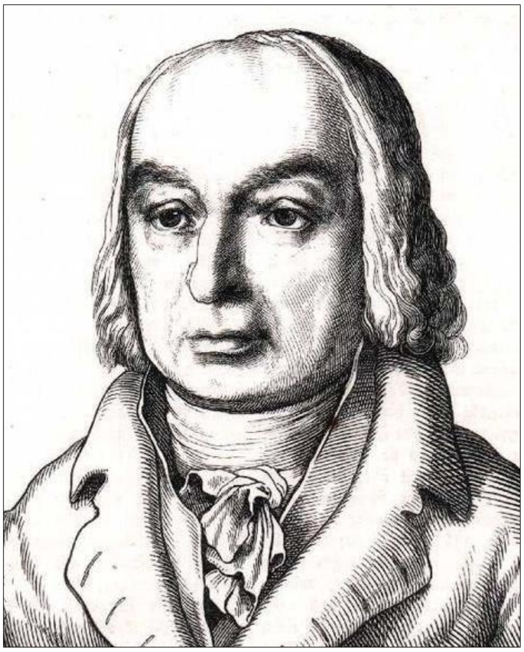
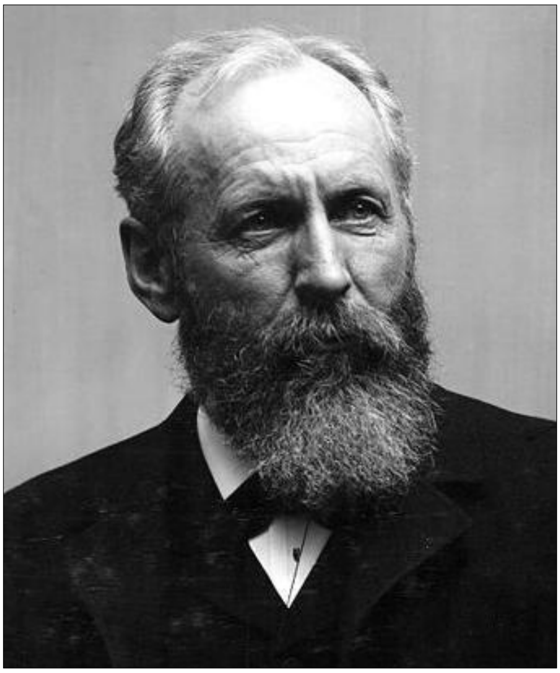


Figure 3.10: Baron von Gruithuisen (http://www.sil.si.edu/digitalcollections/hst/scientific-identity/cf/display_results.cfm?alpha_sort=G)
Figure 3.11: R. A. Proctor, photograph by W.S. Warren, Boston. (http://www.picturehistory.com/product/id/18521).

The hypothesis that lunar craters formed as a result of meteoritic impact was apparently first proposed in 1829 by the German astronomer Baron Franz von Paula Gruithuisen (1774–1852; Figure 3.10) even though credit is often given to the English astronomer Richard A. Proctor (1837–1888; Figure 3.11; Baldwin, 1949; Koeberl, 2001; Melosh, 1989). The first geologist to seriously study lunar craters was Grove Karl Gilbert (1843–1918; Figure 3.12; Koeberl, 2001: 216-217; Koeberl: 2009: 10). After observing lunar craters, Gilbert performed impact experiments and eliminated other proposed crater origins as not being possible (Koeberl, 2001: 217). He tabulated data on the depth/diameter ratios of lunar craters and recognized a crater size-morphology relation (Melosh, 1989: 4). He also suggested that central peaks are the result of rebound in a viscous target and that the terraces of large lunar craters are slump features like those he had seen on Earth in Colorado (Melosh, 1989: 4-5). In addition, Gilbert recognized that high velocity impacts would produce temperatures sufficient to melt the impactor and target rock (Melosh, 1989: 5).



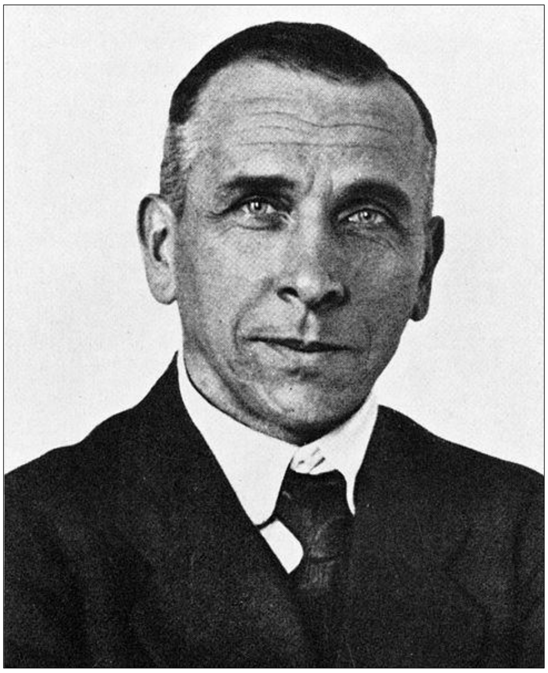


Figure 3.12: G.K. Gilbert (public domain-en.wikipedia.org). Figure 3.13: A. Wegener (http://www.zechlinerhuette.com/de/tourismusinfo/wegener_gedenkstaette.php).

The experiments Gilbert performed were in a hotel room in 1891 and necessarily produced only low velocity impacts (Koeberl, 2001: 217; Melosh, 1989: 5). Nevertheless, he endorsed the impact hypothesis in 1892 (Baldwin, 1949: 64; Koeberl, 2001: 217) with one restriction: all lunar craters had to be the result of vertical impacts (Koeberl, 2001: 217; Melosh, 1989: 5). Gilbert was Chief Geologist of the US Geological Survey and President of the Philosophical Society of Washington in 1892 when he published this conclusion (Koeberl, 2001: 217). His paper, "The Evolution of the Moon", was read during the 1 November 1892 meeting of the National Academy of Sciences and its abstract, published in *The American Naturalist,* included the following discussion of the lunar surface (Gilbert, 1892:1056-1057):

> The mountains are usually in the form of rings, each ring inclosing a hollow, and to this form the name crater is given. They are scattered over the surface of the plains, and on the uplands they are thickly set, overlapping one another in every variety of relation. They are of all sizes, from the smallest that the telescope can discern to a diameter of several hundred miles. Those of medium and larger size are usually characterized by a smooth circular plain in the interior and a hill or group of hills rising in the center of the plain. They differ from the craters of the earth in various ways, especially in the fact that their bottoms are below the level of the surrounding country, and in the fact that the central hill bears no crater on its summit.
>
> The origin of these craters has been the subject of many theories. Despite their marked peculiarities of form, they have more commonly been ascribed to volcanic action; but they have also been referred to the bursting of gigantic bubbles, to the evaporation of water and its accumulation about the point of evaporation as ice, and to the impact of bodies from without. Personally, I favor the last mentioned explanation, but I differ from other writers in respect to the origin of the colliding bodies. It has previously been surmised that these might be rocks hurled from terrestrial volcanoes; that they might be meteors from the recesses of space, such as are continually burned in the upper layers of our atmosphere, giving rise to shooting stars,

> and that they might be aggregates of such meteors constituting balls of cosmic dust. Now my idea of their origin is based upon the phenomena of the planet Saturn and its ring. About that planet is a disc-like ring which astronomers believe to be constituted of an indefinitely large number of very small bodies revolving about the planet in parallel orbits – a symmetrically shaped form of satellites. Assume that a similar ring of minute satellites once encircled the earth, and that these gradually became aggregated into a smaller number of larger satellites, and eventually into a single satellite – the moon. The craters mark the spots where the last of the small bodies collided with the surface when they finally lost their independence and joined the larger body.

Gilbert's error was that he assumed "… the pits were formed by mechanical impacts rather than by tremendous explosions … [and the] absence of large numbers of elongated craters …" led him to conclude that the impactors must have fallen vertically (Baldwin, 1949: 64).

The distinguished German geophysicist Alfred Wegener (1880–1930; Figure 3.13) published his own conclusions in 1921 based on his experiments and likewise endorsed the impact hypothesis for both terrestrial and lunar craters (Koeberl, 2001: 217; Koeberl: 2009:10). However, simple low-velocity impacts such as those done by Gilbert and Wegner will produce circular craters only if the impactor falls vertically (Melosh, 1989: 5). In their experiments, oblique impacts produced elliptical craters, but as the professional astronomers continuously noted, nearly all lunar craters are circular (ibid.). Gilbert recognized this difficulty, which is the reason he made the suggestion that lunar impact craters were all the result of objects that fell vertically rather than at random angles (Koeberl, 2001: 217; Melosh, 1989: 5). Noting that this explanation is statistically unlikely, neither the geological nor the astronomical community gave much credence to the concept of impact cratering on the Moon, or Earth (ibid.). For the most part, geologist still held to the uniformitarian view that changes seen in the geological record took place gradually, which would automatically exclude any possibility of a catastrophic explosive impact origin for craters (Koeberl: 2009: 10).

Figure 3.14: E.J. Öpik (image kindly shared by the Google Freebase project, https://www.freebase.com/m/029nh1k).
Figure 3.15: H.E. Ives (The Library of Congress - http://www.flickr.com/photos/library_of_congress/3819812229/).

At this time, a primary hindrance to acceptance of the meteorite impact theory was the assumption that craters are formed by mechanical impact, a splash, rather than by explosive impact (Baldwin, 1949: 64; Melosh, 1989: 5). Astronomer W.H. Pickering (1920: 125) concluded that lunar craters show no evidence whatever of having a meteoric origin. However, the Estonian-Irish astronomer Ernst Julius Öpik (1893–1985; Figure 3.14) noted in a 1916 paper that a high-velocity impact would produce results similar to an explosion and so circular craters could be produced for most angles of incidence (Koeberl, 2009: 12; Melosh, 1989: 5). The American physicist Herbert Eugene Ives (1882–1953; Figure 3.15) expressed a similar idea in a 1919 *Astrophysical Journal* article noting that bomb craters he observed during the First World War often had central peaks (Koeberl, 2001: 219; Melosh, 1989: 5). Ives (1919: 245) introduces his ideas as follows:

> The origin of the characteristic crater-like features of the moon's surface has been the subject of frequent discussion … The explanation readiest to hand, that the rings, pits, and peaks are the result of volcanic action, does not appear to be adequate when closely studied. While superficially similar in appearance to terrestrial volcanoes, the lunar "craters" exhibit significant differences of structure from these. The crater floors are lower than the surrounding country instead of higher, as they are in most terrestrial volcanoes, the central peak is often missing, and the amount of material piled up in the ring mountain is less than would be deposited there by the volcanoes we know…
>
> Opposed to the volcanic theory is the meteoric or impact hypothesis. This assumes that the lunar craters are the result of the impact of meteors. Objections that have been raised to this theory are the almost uniformly circular shape of the craters, which offer difficulty on the ground that many meteors would strike at a glancing angle, the elevated central peak, and the enormous number of the impacts represented, while the earth has apparently been immune.

Ives' (1919: 251) paper includes Plate IX with Figures 1-5, all of which are reproduced here as Figure 3.16. In Plate IX, Ives' Figures 1 and 2 show the craters (a) Copernicus, (b) Archimedes, (c) Plato and (d) the overlapping craters Theophilus and Cyrillus (ibid.). Ives (1919: 246) notes that such overlapping craters "… must be readily covered by any suggested explanation of lunar configurations." In Ives' Plate IX, Figures 3, 4 and 5 show photographs taken from an airplane of "… craters made by the explosion of experimental bombs, dropped from airplanes at Langley Field, Virginia …" (Ives, 1919: 247). Some of the lunar craters in Plate IX display central peaks which Ives (1919: 246) notes can be produced "… in experiments made by shooting lead bullets at a lead surface … [resulting in] the occurrence of the central elevation or peak, formed apparently by a species of rebound." Ives points out that "This answers one of the earlier objections which appeared rather difficult to meet on the meteoric theory …" (ibid.). The smaller bomb crater in Figure 3 in Plate IX displays a "… circular surrounding wall, the central peak, and a few short radiating streaks …" while the small crater in Figure 4 in Plate IX is a striking example of a crater with a central peak (Ives, 1919: 247). Ives considers these bomb craters to be "… a most conclusive demonstration of the ability of a body (of the proper sort) striking a surface to produce an elevation… " (ibid.). Figure 5 in Plate IX shows a large crater which greatly resembles the lunar crater Copernicus with its "… central peaks, circular wall, and radiating streaks …" that Ives (1919: 248) notes bore an even greater resemblance "… a few weeks before these pictures were taken, before the collection of water in the cavity." To the left of this large crater is "… a pair of overlapping craters, similar to Theophilus and Cyrillus, easily explainable on an impact theory, but harder as a result of volcanic action …" (ibid.). Ives (1919: 248-249) explains his observations and compares lunar craters to the bomb craters shown in Figure 3.16 as follows:

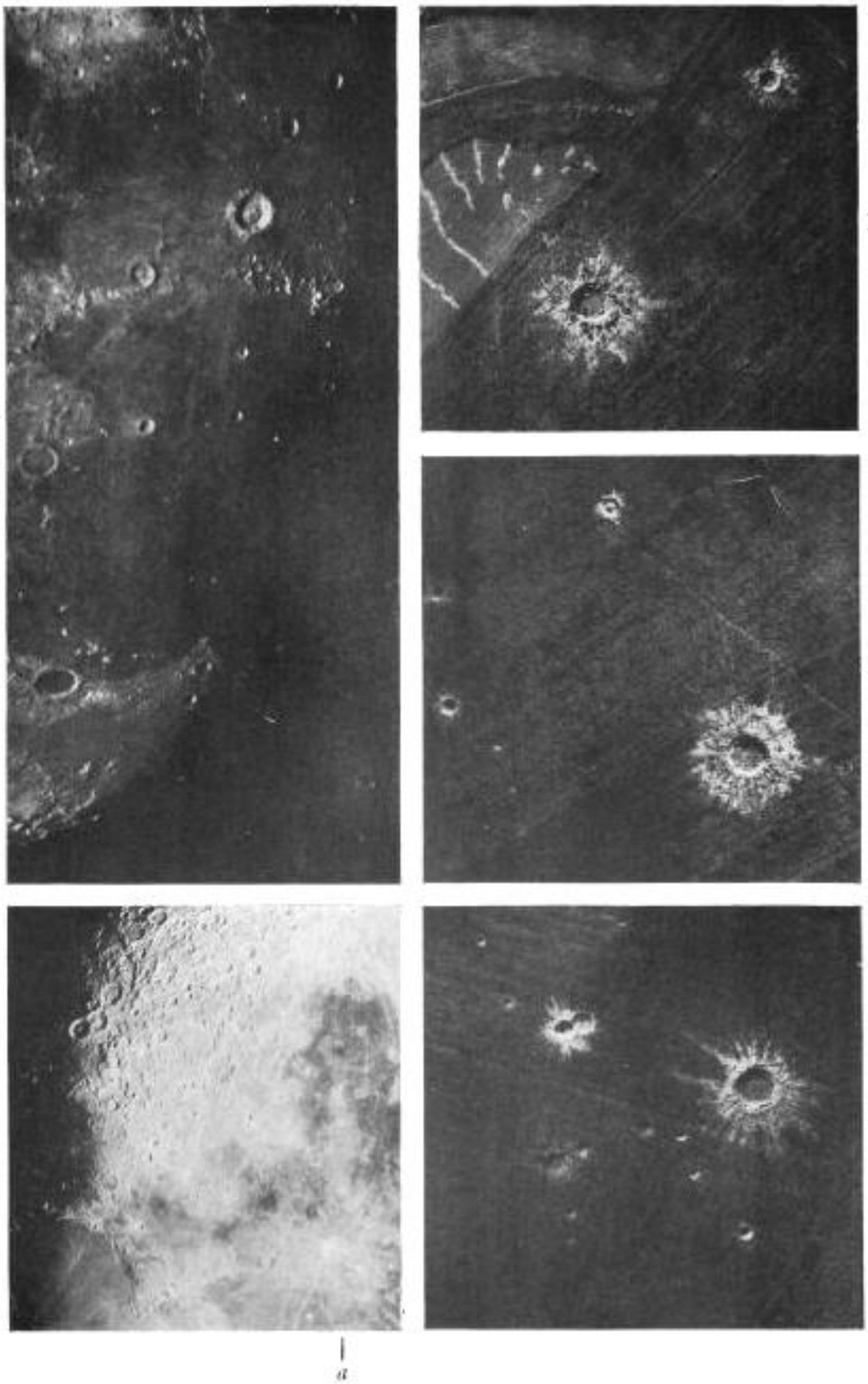


FIG. 1 (a—, b—, c—) FIG. 2 (d—) FIG. 3 FIG. 4 FIG. 5

FIG. 1.—REPRODUCED FROM W. H. PICKERING'S *The Moon*

FIG. 2.—FROM A PHOTOGRAPH OF THE MOON at 18 days, Yerkes Observatory

a, Copernicus | *c*, Plato

b, Archimedes | *d*, Theophilus and Cyrillus

Figure 3.16: Comparisons of lunar craters (Figures 1 and 2 above), and bomb craters (Figures 3, 4 and 5 above) at Langley Field, Virginia, USA (after Ives, 1919: Plate IX).

These few words of description are sufficient, since the photographs largely speak for themselves. It is believed to be evident that they show very striking similarity between the craters produced by the explosion of bombs and the craters of the moon. What then is the significance of this similarity of appearance?

> It may at first thought seem far-fetched to liken meteors to explosive bombs … But on further study this interpretation … adds to their significance. It may first of all be pointed out that meteors striking the earth's atmosphere not only flash into incandescence, but do frequently burst with terrifying reports, spreading their fragments over a considerable territory.

In 1919, Ives utilized the concept that motion and heat energy are mutually interchangeable in his argument. Using numbers suggested by Ives (1919: 248-249), let the speed of a meteor be v = 16 km/sec, the specific heat of the meteor s = 0.2 cal/g/°C, the mechanical equivalent of heat or Joule's constant $J = 4.186 \times 10^7$ erg/cal, m = the meteor's mass and T = the temperature. Then,

$$\text{Kinetic Energy} = (½)mv^2 = ms(\Delta T)J \qquad \text{Eq. 3.1}$$

Assuming the initial temperature of the meteor is 0°C gives $T = 1.5 \times 10^5$ °C. Ives (1919: 249, his italics) explains the significance he attaches to this number:

> Even if we assume that nine-tenths of this heat is given up to the surroundings, we still have in the 15,000°C, a temperature amply sufficient to gasefy any known material, that is, *to produce an explosion.*
>
> Thus our calculation leads to the conclusion that a meteor striking the moon, even with the lowest velocity at which these are observed, would become a very efficient bomb, and should therefore produce the kind of crater we can imitate on the earth only by filling our slowly moving military aerial bombs with explosive material. And not only does this explanation take care of the general appearance of the craters, but it affords an answer to the perplexing question presented by the almost uniformly circular shape of the lunar craters; for it is clear that the shape of the cavity has no reference to the angle at which the bomb strikes, but takes its form from the symmetrical explosive forces. Moreover, the available energy is so great that even if the meteor strikes at very great angles to the vertical the result will be an explosion.

Having thus answered two of the major objection to explosive impact, the elevated central peak and the circular shape of most lunar craters, Ives (1919: 250) discusses the absence of impact craters on the Earth:

> The most complete answer to this criticism is found by noting, first, that the earth is surrounded by an atmosphere which … would dissipate the energy of falling meteors, as indeed we see it doing now; and second, that the earth's surface has been undergoing the processes of upheaval and weathering for perhaps countless ages since the collision with the giant meteor swarms which permanently marked the dead and atmosphereless lunar surface.

Such ideas and observations were not taken seriously, however, until New Zealand's A.C. Gifford (1861–1948; Figure 3.17), an astronomer, published papers in 1924 and 1930 pointing out that the kinetic energy of a massive meteorite traveling at high velocity was equivalent to the chemical energy possessed by TNT (Koeberl, 2001: 219; Melosh, 1989: 5-6). Gifford realized that impact craters result not from a vertical splashing process, but from an explosion due to impact, so no matter the original angle, except for extremely low-angle impacts, the resulting crater would be circular (Baldwin, 1949: 64).

On 26 June 1924 the *Evening Post* newspaper in Wellington, New Zealand, reported that Gifford "… read a paper on the subject [of the origin of lunar craters] before the Philosophical Society last night." The article, "Lunar Craters," from Volume CVII, issue 150, page 8, included the following based on Gifford's presentation:

> Nobody has yet explained in a satisfactory way the clearly visible and remarkable features on the moon's surface. To bring Mr. Gifford's discussion into reasonable length, only the principle points can be referred to. There are two principal "theories" for the formation of the

> lunar topography … The second hypothesis is that the craters are in some way the result of meteoric impacts … Mr. Gifford was able to show that not only was there little evidence to suggest that volcanoes could have produced the lunar crater – they have no resemblance to volcanoes as they are known on the earth; nor do any earthly volcanoes really resemble those of the moon. Earthly volcanoes have high cones and small craters. Lunar craters are of enormous diameter, but very small height, and their floors are always below the level of the surrounding country; and if, as is often the case, there is a central cone, it is small. The only known earthly counterpart is "meteor crater," in Arizona, which, by general consent, was formed by the impact of a meteor …
>
> Mr. Gifford's paper was a discussion of the way in which meteors may have made lunar craters. In previous discussions of the subject, he said, the inquirers were unable to make the meteoric explanation plausible. They neglected the factor of the velocity of meteors. He produced a table showing how velocity endues a body, such as a meteor, with enormous energy … If the velocity is 40 miles a second – not an unusual speed for meteors – the energy is 500 times that of dynamite … It is evident, therefore, that meteors striking the moon, and not retarded by any atmosphere, are equivalent to a bombardment with masses of an excessively violent explosive … Then Mr. Gifford showed, it will blow out a saucer-shaped crater. The lecturer then showed a curious fact – derived mathematically – that an explosive and equal scattering of material from a central point results, when the material falls, in the formation of a ring of debris and a small central heap. Superposed upon a saucer-shaped depression this will cause a formation which irresistibly recalls the lunar crater form …
>
> Mr. Gifford pointed out that the theory he had suggested got over one of the three chief objections to the meteoric hypothesis. It was not necessary, as in the mere "splash" explanation, that all the impacts must be vertical. A sloping stroke would have a similar result. Another objection was that if the moon had been so terrifically bombarded, so must the earth, and there were no signs of such a history. He presumed that the earth also was just as heavily assaulted; but the absence of markings had several explanations … the earth's atmosphere was highly protective. An important factor was that, while the feature's of the earth's surface were continually being changed by erosion, nothing of the sort happened on the moon owing to the absence of an atmosphere and of water …
>
> At the conclusion of the address, which was liberally illustrated with lantern slides and diagrams, an interesting discussion took place. Dr C.A. Cotton … discussed the possibility that the earth may have been very largely built up of meteoric fragments, which may have resulted in either a solid or a molten whole. Dr. E. Marsden …praised the lecturer highly for the ingenuity of his argument which, he said, was much in advance in any of the existing textbooks on the subject.

According to Koeberl (2001: 219), it was Gifford's papers, "… published in 1924 and 1930 in English in a more widely read journal …" which finally caused astronomers and physicists to take notice. However, the Canadian-American geologist, Reginald Aldworth Daly (1871-1957; Figure 3.18), also refuted the idea that lunar craters are the equivalent of terrestrial volcanic calderas or Hawaiian sinks. He points out terrestrial calderas are characteristically asymmetric, whereas lunar craters display a "… high degree of symmetry ..." (Daly, 1946: 111). Daly (1946: 112) also notes that terrestrial volcanoes are "… more or less conical piles … [with] the bottoms of their craters higher than the corresponding outer plains, while … lunar 'craters' have their bottoms lower than the surrounding plains." Daly (1946: 111) describes the formation of Hawaiian sinks as follows:

> The Hawaiian sinks are surface effects of slumping, caused largely by withdrawal of lava through fissures that have been opened in the mighty lava-dome of Hawaii, this withdrawal being possible because the high elevation of the visible dome above the Pacific floor affords the required condition for the draining of lava from active pipes or conduits. In the moon there is no such difference of level to induce important withdrawal of lava in depth.

Figure 3.17: A.C. Gifford (teara,govt.nz).

Figure 3.18: R.A. Daly (http://earth.geology.yale.edu/~ajs/DalyVol.html)

Baldwin (1949:50) agrees, stating that lunar craters tend to be broad with gently sloping rims and large sunken basins, a form that does not have any structural counterpart of *igneous* origin on Earth. Figure 3.19, shows a "… scale model of a typical lunar crater and a typical terrestrial volcanic cone …" which Baldwin (1949: 51) utilizes to make his point that in comparison to volcanic cones and calderas, explosion craters are formed by the displacement of material upward and outward forming a pit sunken below the surrounding ground level, not built up above it.

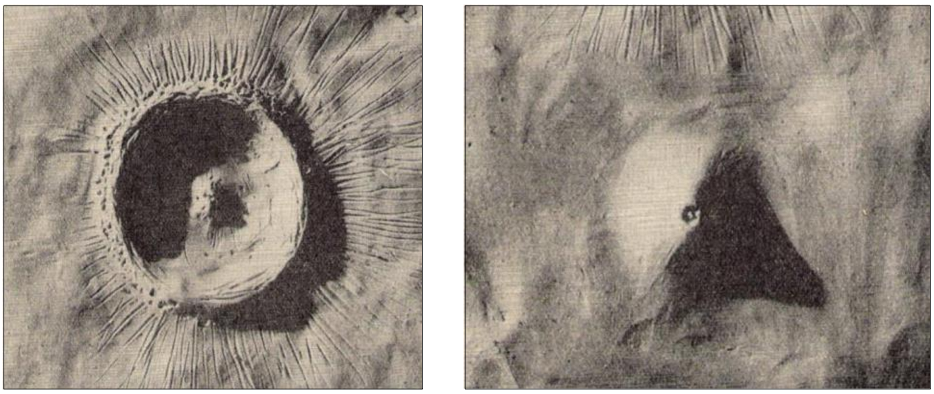


Figure 3.19: Scale models comparing a typical lunar crater and a typical terrestrial volcanic caldera (after Baldwin, 1949: 51).

The exceedingly large apparent diameter of some 'lunar volcanoes' had concerned some researchers, but was considered by most to simply be a result of the Moon's lesser gravitational acceleration (Baldwin, 1949). Baldwin points out that with one possible exception, large volcanic calderas on Earth are formed by collapse, not by explosion, and there is apparently a size limit to terrestrial craters caused by volcanic explosion (ibid.). He argues that since Earth's gravitational pull is six times that of the Moon and the largest terrestrial explosive craters are around 3.2 km, then the corresponding lunar craters resulting from volcanic explosions should be less than 20 km, however, there are well over 200 craters on the near side of the Moon in excess of 20 km (Baldwin, 1949: 49, 118-122). Baldwin concludes that “It is quite evident without probing into the matter further that if the craters of the moon were formed by explosive volcanism, they indicate an entirely different order of applied power than has been demonstrated on earth/” (Baldwin, 1949: 49). “The magnitude of the energies involved far transcends that of any explosion recorded in terrestrial volcanic processes,” (Baldwin, 1949: 154).

The force of an impact explosion brecciates target rock and accelerates the resulting rock fragments. Force is mass times acceleration and this acceleration can be up to thousands of times the acceleration due to gravity (Baldwin, 1949: 49). Baldwin argues that the forces operating on Earth and the Moon in these cases are just about the same since mass, not weight, is the determining factor (ibid.). Though the resulting debris of an explosion would fly farther on the Moon due to its lower gravity, the crater itself would not be of any significantly different size (ibid.). Baldwin (1949:61) notes that craters on the Moon are most often surrounded by jumbled breccia, which is similar to the case of the relatively young Barringer Meteorite Crater on Earth. Baldwin (1949: 49-50) points out that since sometime around 1800, it has been noted that material from the rims of most lunar craters would be almost exactly what would be needed to fill up the craters.

Based on his study of the lunar surface, J.H. Schröter established a general relationship known as Schröter’s Rule which states that “For each crater the part of the material above the surface is approximately equal to the volume of the interior depression below the surface …” and Baldwin notes that a tremendous number of lunar craters, though not all, have been found to follow this rule (Baldwin, 1949: 114-115). This rule strongly indicates that the material in a crater’s rim is comprised of shattered rock that was displaced by a single explosion rather than multiple explosions (Baldwin, 1949: 115). Baldwin (1949: 61) also notes that the rays surrounding some lunar craters can be by an explosion, but cannot be explained by a fracturing and melting model and concludes that the “… lunar craters were not formed by laccolithic intrusions and updomings or by any other nonexplosive method.” Baldwin (1949: 127) states that whether a crater is “… produced by bomb or shell, military mine or meteorite; the effect is the same.” Each produces the same result and again, so Baldwin concludes that “The case for the explosive origin of the craters of the moon appears to be unassailable” (ibid).

In support of the above argument, Baldwin (1949: 36-37) points out that numerous investigations have shown, “… except for the modifications produced by the great overflowing lava sheets the craters are distributed essentially at random … [in contrast to] the well-defined zonal distribution of past and present volcanoes on the earth.” He also notes that spectral studies of the Moon show that “… sulphur, which is often found associated with terrestrial volcanoes, is missing, or at least extremely rare, around the lunar craters” (Baldwin, 1949: 22). Baldwin (1949: 13) points out that polarized light from our Moon and the asteroid Vesta is essentially the same and concludes that the same processes have taken place on both of these bodies.

Lunar craters become shallower as their diameters increase and the greater the crater diameter, the smaller the slope of the raised rim’s inner wall (Baldwin, 1949:

115-116). Baldwin (1949: 136) states that on average, the lunar crater rim width is about one-fourth of the crater diameter and the central peak rises around half of the way from the floor of the crater to that of the surrounding surface. Baldwin (1949: 53) also points out that in lunar craters "… the central peaks never attain the level of the surrounding external plain." In contrast, terrestrial volcanoes typically have small craters high in the peak rather than a shallow crater below the surrounding surface (Baldwin, 1949: 115). Volcanic cones tend to be smooth and symmetrical due to the buildup of volcanic material above the surrounding plain, but non-concentric with respect to the volcanic caldera (Baldwin, 1949: 146-148). In contrast, terrestrial central peaks consist of jumbled and chaotic blocks of rock (ibid.). This is a strong argument against lunar volcanism as the cause for lunar craters (Baldwin, 1949: 148). Baldwin concludes that there is no "… true volcanic cone …" known anywhere on the near side of the lunar surface, and "It is manifest, therefore, that the craters of the moon are not counterparts of terrestrial volcanoes." (Baldwin, 1949:50).

World War II brought explosion cratering under scientific scrutiny (Baldwin, 1949: 62, 68, 127, 129). Baldwin (1949: 131-133) collected data on bomb as well as terrestrial and lunar craters which he plotted together as the logarithm of the diameters versus the depths and found that the result was a smooth curve described by the following equation where *D* is log diameter and *d* is log depth:

$$D = 0.1083d^2 + 0.6917d + 0.75 \qquad \text{Eq. 3.2}$$

Baldwin (1949: 131) states that this relationship is "… too startling, too positive, to be fortuitous." Similar plots utilizing data from terrestrial volcanic calderas and lunar craters show no such correlation (Baldwin, 1949: 147). Based on numerous studies of shell and bomb craters, Baldwin states (1949: 138) that the "… linear dimensions of the craters are directly associated with the violence of the explosions and with the depths at which at which they occurred, but the relative dimensions are almost independent of the depth." For terrestrial explosions, the crater form is not sensitive to changes in the explosion depth unless the explosion occurs at a depth of more than one-half of the resultant crater's apparent diameter (Baldwin, 1949:138). Baldwin feels that this same rule is followed by the larger terrestrial meteorite craters (ibid.). The reason is that although larger masses do penetrate to a greater depth, the difference in crater form for a smaller mass is not much since penetration depth is proportional to the meteorite's radius, but the increase in mass is proportional to the radius cubed (Baldwin, 1949: 139).

Many lunar craters are in apparently pristine condition as if they were formed yesterday and Baldwin (1949:128) puts these craters, presumably younger than their near-by neighbors, in what he refers to as Class 1 craters. Class 1 craters have shapes that seem to have changed little over time and show no sign of modification (ibid.). They appear sharp and clean when compared to more dilapidated lunar craters (ibid.). Baldwin (1949: 131) explored the relationship between two groups of craters; the Class I lunar craters and craters formed on Earth by bombs and shells. The effects of explosions due to shells and bombs are well known from commercial and military applications (Baldwin, 1949: 125). When the data are plotted, these two main groups, terrestrial explosion craters and Class I lunar craters, do not overlap; however, Baldwin (1949: 131) found that four known terrestrial meteorite craters fill in the gap nicely. Australia's Henbury No. 13 crater, the Odessa No. 1 and No. 2

craters in Texas, and Arizona's Barringer Meteor Crater all have associated metallic meteoritic fragments and thus are confirmed sites of meteorite impact (Baldwin, 1949: 70, 74, 77). Thousands of meteorites have been found around the Barringer Meteor Crater, however, "No sizeable metallic fragments have been found within the crater … [since] It seems certain that the main mass was shattered in the explosion and that many of the fragments were ejected along with great numbers of rock particles …" (Baldwin, 1949: 70). The Odessa No. 1 crater is apparently the result of a shallow explosion since the shale found some 60 meters below the structure is undisturbed (Baldwin 1949:141). Odessa No. 2 "... represents a transition type [of crater] in which much of the meteoritic material remains in the pit." (Baldwin, 1949: 75). Henbury No. 13 was found to contain four large meteoritic masses, but Baldwin (1949: 78-79) states that "It clearly represents a case in which the mechanical impact rather than the subsequent explosion produced the crater."

These four terrestrial impact craters lie "… well within the scatter …" of a smooth curve from the largest of the Class 1 lunar craters to the smallest of the plotted terrestrial explosion pits (Baldwin 1949: 131). Baldwin states that "… these two groups, tied together perfectly by craters of known meteoritic origin, form a relationship which is too starling, too positive, to be fortuitous." (Baldwin: 1949, 131). Baldwin (1949: 135) states that the "… only reasonable interpretation of this curve …" is that the craters form a continuous sequence of single blast explosion pits. Baldwin (1949: 136) also found a simple and definite relationship exists between the rim height and crater diameter of terrestrial explosion pits through the same four meteorite craters to the lunar craters. For E = log rim height and D = log diameter, Baldwin (1949: 136-137) plotted the data and found the following relationship:

$$E = -0.097D^2 + 1.542D - 1.841 \qquad \text{Eq. 3.3}$$

Baldwin (1949: 141) found that bomb and shell craters have relative dimensions that are almost independent of the depth at which the explosion occurred until an explosion depth of greater than one-half of the resulting crater is reached, at which point a cavern rather than a crater is formed.

The diameter and depth of terrestrial volcanic craters do not seem to correlate with the diameter and depth of lunar craters; most have small summit craters and show no similarity to lunar craters (Baldwin, 1949: 145, 147). The terrestrial form most similar in appearance to the lunar craters and explosion pits is a volcanic caldera of collapse (Baldwin, 1949: 145). Most caldera, however, have floors raised above rather than sunken below the surrounding ground-level (ibid.). Baldwin (1949: 49) also points out that the weaker lunar gravity should result in stronger rock layers and thus prevent collapse or at least reduce the effect. Baldwin found poor agreement, no trend is perceived between collapsed caldera on Earth and Class 1 lunar craters (Baldwin, 1949: 147).

Baldwin (1949: 146) makes the point that if there is a known process able to explain most lunar craters, then it is not necessary to develop an alternative explanation requiring a process unknown on Earth.

> To claim that the moon's craters are volcanic is tantamount to postulating an entirely new, entirely hypothetical mode of origin and to fly in the face of the fact that a known process is completely able to explain the vast majority of observed lunar features … (ibid.).

Baldwin (1949: 153) continues, stating that "… craters of the moon fulfill every logical extrapolation of the known explosion pits and the terrestrial meteoritic craters and cannot be correlated successfully with any known form of volcanism." The impact and sudden halting of large meteorites easily explains the energies needed to form impact craters which greatly exceed any explosion recorded in any terrestrial volcanic process (ibid.). Baldwin (1949: 217) concludes that "Any nonmeteoritic hypothesis represents a fanciful extrapolation beyond anything known on earth."

Decades later, Melosh (1989: 6) agrees stating that the collective evidence from "… countless remote investigations of lunar craters at ever-increasing resolution, direct geologic investigation of lunar craters by the Apollo astronauts, and images of craters on planets and satellites throughout the solar system … " has convinced most all skeptics that lunar craters are of impact origin. He continues, "The discovery of bona fide volcanic calderas on Mars, Venus, and Io has made it clear that volcanoes can be readily recognized on extraterrestrial bodies and differentiated from impact craters." (Melosh, 1989: 6).

3.3 Changing Perspectives on Cryptoexplosive Structures

The term 'cryptoexplosion structure' was coined by Dietz (1959: 496) to stay descriptive, but neutral, in the crypto-volcanic/meteorite impact debate. A generally-circular structure formed in some natural way by an explosive release of energy that resulted in extensive folding, faulting, and brecciation of rock was originally referred to as a cryptovolcanic structure (Baldwin, 1949: 100; cf. Baldwin, 1963: 73). The origin of these structures was debated for decades (Dietz, 1963: 650). The idea as described by Bucher (1963b: 597) was that some type of volcanic explosion, involving upward moving steam, drove rocks upward and outward although the evidence of volcanism remained hidden (cf. Dietz, 1946: 466; Dietz, 1959: 496). Creation of these structures by meteorite or cometary impact was, for most, a difficult idea to accept (Bucher, 1963a: 1241). However, over time it was recognized that meteorites with sufficient mass moving at an enormous velocity can account for the deformation observed in cryptoexplosive structures (Boon and Albritton, 1936; French and Koeberl, 2010; Reimold, 2007; Reimold and Koeberl, 2008).

One result of the sudden explosive release of energy due to impact is a crater which is huge in comparison to the small relative size of the impactor (Baldwin, 1949: 155). A surprisingly small mass would be needed to create a crater such as the 1.2 km Barringer Meteor Crater in Arizona (Baldwin, 1949: 154). If the Barringer meteorite was around 15 meters in diameter, then it blasted a volume of target material some sixty thousand times larger than its own volume and deposited most of this material in the crater rim (ibid.). According to Wilson and Stearns (1968: 177), the meteorite that caused the Wells Creek structure was around 300 meters in diameter, but its explosive impact resulted in a nearly 6.5 km diameter crater. Baldwin (1949: 62) points out that experiments conducted by the United States Army show that inert missiles will explode when striking a solid at only 6.5 to 8.0 km/s. Even if a meteorite originally has no motion relative to Earth before entering its atmosphere, gravitational acceleration will result in a minimum speed of 11.2 km/s (Bevan and Laeter, 2002: 30) which is greater than that required for an explosive impact.

Melosh (1989: 67) calculates that:

> A 30-m diameter projectile striking at 20 km/second would produce a seismic disturbance equivalent to a magnitude 5.6 earthquake … such an impact would produce a 1-km-diameter crater on earth, about the size of Meteor Crater, Arizona.

However, Melosh (ibid.) also points out that impact-generated seismic waves are generally thought not to be as severe as those of an earthquake of the equivalent magnitude due to the different types of waves that are emitted and the duration of shaking. He suggests that an impact-generated seismic disturbance is about equal in destructiveness to a one magnitude smaller earthquake.

When it comes to ancient scars of meteorite impact, Baldwin (1963: 67) states:

> All that could reasonably be expected to remain would be the basement structures, the modifications produced deep beneath the earth's surface by the unimaginably great pressures and shock waves which developed as the intruding mass came to a halt and exploded.

Baldwin (1963: 106) adds that "It may be considered presumptuous by some to identify the cryptovolcanic structures as old meteoritic craters, but at the present writing the evidence is so strong that no other conclusion seems tenable." Figure 3.20 by Boon and Albritton (1937: 57) shows the structure beneath a typical impact crater and its changing appearance at the surface over time. Boon and Albritton (1936: 2-3; their italics) stated "… it is possible to predict what *general types* of structures should underlie a large meteorite crater. The writers believe that certain structures previously described by geologists as 'cryptovolcanic' may be old meteorite scars." Balwin (1963: 71) credits these two researchers for their early recognition that only one kind of known structure fitted the predictions of their model, the cryptovolcanic, or cryptoexplosive, structures:

> The characteristics of the upper parts – the crater, the rim, and the upturned rocks – were familiar. Little was known about the lower parts. They recognized that, under the influence of the shock, the rock layers would behave as though they were fluid and would react against the impact thrust. They also saw that the instant the pressure was released, the rocks would freeze in whatever contorted position they might find themselves.

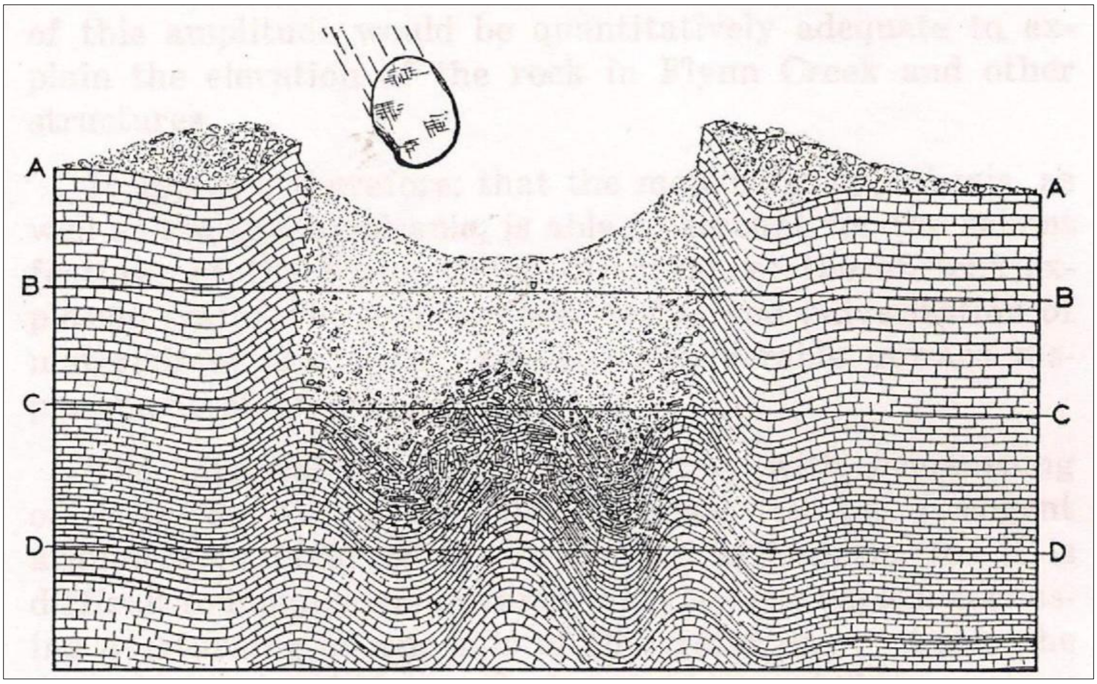


Figure 3.20: Schematic cross-section showing the changing appearance of an impact crater from its initial modification (A) to the erosional uncovering of its basement structure (D). The relative size of the meteorite believed to be capable of forming this impact scar is indicated above the crater (after Boon and Albritton, 1937: 57).

The Boon and Albritton diagram in Figure 3.20 depicts their interpretation of the appearance of an impact crater from its initial modification, due to collapse and fall-back ejecta covering the crater floor and rim, over time to being inconspicuous, to the appearance of its underlying structure, and eventually to the long-term erosion of the structure's central uplift and ring folds. Their model bears an amazing similarity to cryptovolcanic/cryptoexplosive structures according to Baldwin (1963: 72). Such structures: 1 – are circular in outline, 2 – possess a central uplift surrounded by a ring-shaped depression, 3 – have small central uplifts when compared to the sunken area in large disturbances, 4 – show evidence of a violent and sudden release of pressure such as would occur in an explosion, 5 – exhibit no evidence of volcanic materials or thermal action (Baldwin, 1963: 73).

The acceptance of the impact hypothesis as the explanation for a terrestrial crater first occurred in the study of what is now known as Barringer Crater or Meteor Crater in Arizona, USA (Barringer, 1905: 861-862, 885). The Barringer Meteorite Crater was originally called Coon Butte due to its appearance as a flat-topped structure from a distance with a rim that rises to an average of 40 meters above the surrounding plain (Barringher, 1905: 861, 866). However, it "… resembles no ordinary butte, as it has no capstone." (Baldwin, 1963: 10). Gilbert and other geologists noted that meteoritic iron was discovered surrounding the crater area in 1891 and should have called into question its supposedly volcanic origin (Baldwin, 1949: 68; Barringer, 1905: 861; 1914: 558, 563; 1924: 275; Boon and Albritton, 1938). Extinct volcanoes are located around 50 km away, though, and old lava flows are found within 16 km of the crater (Baldwin, 1949: 68). Since volcanoes were known to be located nearby and no large meteorites were found within the crater, the general conclusion was that the crater was a volcanic feature (Baldwin, 1949: 70). The lack of volcanic rock exposures in the crater caused geologist to speculate that the crater was formed by some sort of volcanic steam explosion and that the presence of iron meteorites in the area was sheer coincidence, as noted by Dietz (1963: 654):

> Although there are numerous associations that argue against Barringer Crater's meteoritic origin, it indubitably is meteoritic. Landing amidst this full span of volcanic effects was a most confusing thing for a meteorite to do but, with the perversity of nature, it apparently did so anyway. The argument of geological associations for Barringer Crater being cryptovolcanic can be strongly based, but it fails.

The presence of meteorites was considered insufficient; for years some geologists still argued that Barringer Crater was volcanic in spite of the evidence of the meteorites adjacent to the crater, or the dying out of deformation with increasing depth (Baldwin, 1963: 10-11). This may have been the result of "… poor contemporary understanding of impact cratering mechanics …" misleading competent investigators (Melosh, 1989: 6). A drill core taken from around 110 meters east-southeast of the crater's center found over 9 meters of surface soil, then from 9 to 27.5 meters down were lake-bed deposits, and below that about 165 meters of "… sand (rock flour), and sandstone, in part metamorphosed …" (Baldwin, 1963: 11). Below that, from 192 to 253 meters below the crater floor, rock was found "… at first soft and shattered but becoming gradually harder as greater depths were reached …" and finally undisturbed rock was found at a distance of 335 meters below the original surface (ibid.).

Mining engineer Daniel Moreau Barringer (1860–1929; Figure 3.21) came to a different conclusion than most after studying the evidence (Barringer, 1905: 861;

Barringer, 1964: 191-192). Convinced that the presence of the nickel-iron meteorites was not a coincidence, he acquired the land rights to the crater and spent the remainder of his life searching for the main body of the iron impactor he was convinced was buried beneath the floor of the crater (Barringer, 1905: 862; Barringer, 1964: 196). Not yet understood was the fact that high, astronomically possible, velocity implies high kinetic energy, which upon a meteorite's impact must be suddenly, explosively released and will most likely result in the nearly complete vaporization of the meteorite and the excavation of a large crater (Baldwin, 1963: 9; Gilvarry and Hill, 1956, 610).

Figure 3.21: D.M. Barringer (http://www.barringercrater.com/about/history_3.php).
Figure 3.22: H.H. Nininger (http://www.aerolite.org/site-art/nininger-portrait-cp-2.jpg).

Benjamin Chew Tilghman (1821–1901), Barringer's original business partner, however, "… correctly estimated the velocity of the impact … and deduced that the atmosphere would not much hinder a large projectile …" Melosh (1989: 7) states, however, that Tilghman did not appreciate the energy a massive, high-velocity projectile possesses and "… supposed a large iron mass must underlie the crater." It is interesting to note that according to Barringer's son, Brandon, "In 1909, Tilghman suddenly lost all confidence in the commercial possibilities on which he had spent over $45,000 and dropped out …" (Barringer, 1964: 197). Though no large deposit of iron or nickel was located, breccia was found in the crater floor and small particles of iron with 0.4% nickel were found within the breccia (Barringer, 1964: 186). Many, however, taking note of the fact that after extensive drilling no large meteorite was found within the crater, became convinced that this crater was not be the result of a meteorite impact and, therefore, shied away from investing (Barringer, 1964: 187). Though an impact origin was not well accepted during his lifetime, Barringer's work did provide a detailed geological study of the structure that was eventually named for him (Barringer, 1964: 197).

As the understanding of high-velocity mechanics grew, estimates of the size and mass of the iron meteorite responsible for the Barringer Crater shrank (Melosh, 1989: 7). As a result, in 1929, an astronomer, Forest Ray Moulton (1872–1952), was asked to analyze the probable amount of iron in the crater (Barringer, 1964: 196; Melosh, 1989: 7; Nininger, 1972: 175). Moulton determined that the impact and subsequent explosion could have been caused by a "… far smaller projectile than Barringer had supposed …" (Melosh, 1989: 7). His most important realization, however, was that most of the meteorite would have vaporized and not be buried in the crater (Nininger, 1972: 175). "It is truly unfortunate that Moulton's results were never published. Only recently has this interesting episode in the history of impact cratering been told in detail." (Melosh, 1989: 7). The fact that Meteor Crater is the result of an impact and yet there is no massive meteorite mass to be found under the crater floor was explained by F.R. Moulton to the meteorite collector and researcher Harvey Harlow Nininger (1887–1986; Figure 4.22):

> He explained that he had investigated this whole matter mathematically and had concluded that it was impossible for a mass of any such magnitude as that which produced the crater to stop suddenly and remain intact. On impact it would have to be transformed into gas; it would explode …
>
> When Dr. Moulton theorized mass of only three million tons at the most, perhaps as little as fifty thousand tons, that could have survived the impact, the financial sponsors panicked and withdrew their support. (Nininger, 1972: 175).

The meteorite mass had shattered in the explosion and its fragments were ejected along with target rock fragments and blocks found as far away as 10 km (Baldwin, 1949:70). H.H. Nininger discovered large numbers of nickel-iron spherules around the crater in 1946 which were only 100 to 200 microns in diameter (Nininiger, 1972: 176-179). In Nininger's opinion, "… they condensed from the vaporized nickel-iron projectile that produced the crater …" (Nininger, 1972: 176, 178-179; cf. Melosh, 1989: 68). In the explosion not only was a "… large cloud of metallic vapors …" generated (Nininger, 1972: 178), but the crater rim was forced upward and outward and the strata are almost vertical in the southwestern and southeastern sections of the crater (Baldwin, 1949: 71). It is apparent from the crater's structure, that the effective upward explosive force was much greater than the downward percussion force as the normally horizontal rock layers are blown upward and dip radially outward rather than toward the center (ibid.).

It is interesting to note that W.W. Campbell (1920: 126), Director of the Lick Observatory, referring to the Barringer Meteor Crater stated that:

> The Arizona crater is familiar to geologists; several geologists have visited the crater and have made extensive studies of it. The literature of the subject, embracing full two scores of papers, is due almost wholly to those whose chief interests are geologic … Astronomers have not, in my opinion, given the crater the attention it deserves from them. To the best of my knowledge no astronomer has visited the crater, and its existence and character have not been recognized in astronomical text books.

Fortunately, at least one astronomer, Ralph Baldwin, did take notice of 'The Great Arizona Crater', and he wrote *The Face of the Moon* in 1949 where he merged impact evidence from Meteor Crater with his lunar observation and "… presented a consistent theory for the formation of lunar craters by impact, and not by volcanism …" (Baldwin, 1949: 68-73; cf. Koeberl, 2001: 220). In this book he concluded that the only process capable of producing the energy required to form the craters observed on the lunar surface was an impact since "No available source of sufficient energy is known other than that carried by meteorites." (Baldwin, 1949: 135).

Not long after the Coon Mountain Controversies occurred, the cryptocontroversies moved into high gear. As early as the 1930s, the American geologist Walter Herman Bucher (1888–1965) cited characteristics of structures he referred to as being cryptovolcanic; circular structures with a central uplift surrounded by a ring-shaped depression, in other words, a complex crater (Bucher, 1936: 1074). Bucher agreed that evidence indicated only the sudden release of pressure, an explosion, can explain these characteristics (ibid.). However, only one 'cryptovolcanic' structure known at the time, Decaturville, showed any signs of volcanic material or thermal activity that could explain such an explosion (ibid.). Baldwin (1949: 100) points out, however, that evidence indicates the igneous material located at Decaturville predates the structure.

Cryptovolcanic structures were, therefore, explained to be the result of an explosive release of gases without the presence of magmatic material and in a location that showed no sign of previous volcanic activity (Bucher, 1936: 1074, 1076). Baldwin (1949: 111) notes, however, that no recognized channel or 'neck' for subterranean gases to escape was found in these structures. Baldwin also points out that if these structures were formed by a gas explosion, then the gas pressure must have been near the surface; however, rock layer strengths indicate that this is not the case (ibid.). The rock materials are simply not strong enough to allow for an accumulation of gases with the necessary pressures at such shallow depths (ibid.). Cryptovolcanic structures appear to die out with increasing depth which would also tend to indicate a non-volcanic origin (ibid). Baldwin (1949: 112) states that other cryptovolcanic explanations including subterranean gas pressure explosions cannot account for the upraised and overturned rims seen in these structures. According to Baldwin, volcanic craters in Arizona show no deformation of the bedrock in their rims (ibid.). Baldwin (1949: 67) further states:

> Mother Earth shows a somewhat pock-marked face. In recent years it has become increasingly apparent that there exist numerous small craters on the surface, which, beyond the shadow of a doubt, were produced by the explosions resultant from the impacts of high-velocity meteorites…
>
> Progress was slow, however, and it was not until the turn of the present century that the Barringers positively identified the Coon Butte crater of Arizona as having been caused by the impact and explosion of a large nickel-iron meteorite.

Baldwin (1949: 68) discusses the ages and individual features of a few "… small craters which are known to be meteoritic …" in order to explain some of the structures we see today. The five Odessa craters in Texas are older than the Barringer Crater and so filled in and eroded that they are relatively inconspicuous (Baldwin, 1949: 73-74). They do, however, contain meteoritic fragments and so have been regarded by most as meteorite impact sites (Baldwin, 1949: 73). The main crater was discovered in 1921 (ibid.). Usually an impact crater can only be dated by saying that it is younger than the youngest disturbed rock layers, however, the fossil of a horse that has been long extinct was found buried in material deposited within the main crater (Baldwin, 1949: 74). This "… is only the second well-dated Pleistocene hypervelocity impact crater in North America." (Holliday et al., 2005: 946-947). Baldwin (1949: 75) concludes from Odessa that many of the meteoritic craters found "… in bunches …" indicate that metallic bodies move through space together in swarms held together by mutual gravitational forces and the Odessa craters are the result of either just such a swarm impacting Earth. These craters could also be due to the breakup of a large meteorite within Earth's atmosphere (Melosh, 1989: 209).

The Henbury group of craters in Australia is another example of bunched craters. Baldwin (1949: 77) states that the Henbury series of craters "… beautifully demonstrates the transition from a small crater formed by simple splashing or gouging of the ground to the true explosion crater …" in which the meteorite is vaporized and/or shattered and backfired out of the crater. He notes that few meteorite fragments have been located near the larger Henbury craters, however, crater number 13 contained a "… considerable mass of meteoritic iron …" and represents the case in which the "… mechanical impact rather than the subsequent explosion produces the crater." (Baldwin, 1949: 79). The four main meteorite masses in crater 13 have been shown to have come from a single meteorite (ibid.). The Henbury meteorite fragments display Widmanstätten patterns all the way to their edges indicating that they are the remnants of larger masses and that collision occurred so quickly and violently that most of the meteorite either vaporized or was not heated internally by conduction (Baldwin, 1949: 79).

In the absence of meteoritic fragments, the first reliable criterion for recognizing a structure as being the result of an impact was established by Robert S. Dietz in 1947 (Baldwin, 1963: 74, Melosh, 1989: 8). Dietz (1959: 503) noted "… peculiar fractures in the rock that caused it to break into striated cones …" in the Kentland structure in Indiana (cf. Melosh, 1989: 9). Dietz's (1960: 1784) observations were confirmed in high explosion trials by Roddy and Davis (1977: 744): "In situ cones point in the direction of the shock wave source with their axes normal to direction of shock wave propagation." Though shatter cones had been found at Steinheim as early as 1905, Dietz was the first to argue that they were the direct result of impact event and so would only be found in impact craters (Melosh, 1989: 8). Milton states (1977: 703):

> Shatter cones occur in nature only in crypto-explosion structures … One must be unusually broadminded to entertain hypotheses for shatter coning other than it results from shock generated by impact.

Coesite, a high pressure phase of quartz, was discovered in the laboratory in 1953 (Coes, 1953: 131), and when it was found in the Barringer Meteor Crater in 1960 researchers recognized that "… the polymorphic transformation from quartz to coesite may occur under shocks generated by meteorite impact." (Chao et al., 1960: 220). In fact, "… the occurrence of coesite at Meteor Crater suggests that the presence of coesite may afford a criterion for the recognition of other impact craters." (ibid.). The pressures required to transform quartz into coesite are so great that coesite has only been found in ultra-high pressure metamorphic rocks here on Earth and at meteorite impact sites, but never associated with volcanoes. Volcanic explosions "… are merely due to the release of pent-up pressure and seem to be incapable of producing shock features in surrounding rocks." (Melosh, 1989: 8).

3.4 The Astrogeology Research Program

French (2004: 171) states that "… the first systematic studies of terrestrial impact craters were largely a byproduct of the space program, the Apollo landings on the Moon, and the unmanned exploration of the planets." He points out that the early contributors to the field of impact studies were astronomers such as Baldwin and geologists such as Dietz and Shoemaker (ibid.). The website of the United States Geological Survey, http://astrogeology.usgs.gov/missions, states that

> The USGS has worked with NASA and other space agencies to lead scientific investigations, select rover landing sites, create geologic maps and cartographic products for numerous spacecraft missions throughout our solar system.

In documenting the USGS Branch of Astrogeology's Chronology of Activities from Conception through the End of Project Apollo (1960-1973), Schaber (2005: 23) states that the Branch of Astrogeology began officially on 25 August 1960 when the National Aeronautics and Space Administration (NASA) funded a small Astrogeologic Studies Unit within the United States Geological Survey (USGS). Schaber (2005: 2) includes the following in his introduction:

> Dr. Eugene M. Shoemaker (1928-1997), who coined the term [astrogeology] in 1960, first established the U.S. Geological Survey's Astrogeologic Studies Unit in Menlo Park, California. In September 1962, Shoemaker's Astrogeologic Studies Unit formally became the Branch of Astrogeology and on 1 July 1963 moved its permanent headquarters to the 7,000foot-high [2.1 km] town of Flagstaff in the scenic Ponderosa pine forest of Northern Arizona **…**
>
> It was centrally located near a number of natural landmarks which would be well-suited for developing both unmanned and manned lunar exploration procedures for training NASA's astronauts in general geologic field procedures, including first-hand study of landforms resulting from volcanism as well as impact cratering. The landmarks within easy reach of Flagstaff included Gene's favorite Astrogeologic feature, Meteor Crater, about thirty-five miles [56 km] east of town. Also of primary importance in Shoemaker's decision to move the Branch to Flagstaff was the presence of well-established observatories. Gene thus reasoned that Flagstaff was the logical place to build a telescope for the Branch of Astrogeology, one designed specifically for lunar observing and mapping.

After all, NASA was planning the Apollo missions at the time and since the Moon has craters, the Branch of Astrogeology wanted to study lunar as well as terrestrial craters. Schaber (2005: 33) reports the following:

> On March 5 1962, the Branch of Astrogeologic Studies in Menlo Park, California submitted its first Astrogeologic Studies Semi-Annual Report to NASA covering work accomplished during the period 26 February 1961 to 24 August 1961. This report was submitted to Homer Newell, NASA Officer of Space Sciences, with a letter of transmittal by Vince McKelvy, Chief Geologist of the USGS. The reports included research results on Extraterrestrial Materials, Crater Investigations, and Geologic Mapping of the Moon.

On 29 January 1964, the U.S. Geological Survey "… accepted the keys to its first astronomical telescope facility … [which housed] the astrogeology branch's new 30inch reflecting telescope that the branch will use to probe the geologic secrets of the moon, the nearby planets, and the enigmatic asteroids …" (Schaber, 2005: 72).

Terrestrial crater investigations were also high on the Branch of Astrogeology's agenda. In 1961, Dick Eggleton, Danny Milton as well as Gene Shoemaker visited several of the structures in the Mississippi valley area, including Tennessee, which had been designated as crypto-volcanic by Walter Bucher (Schaber, 2005: 31). Shoemaker and Eggleton (1961: A-4) wrote the following concerning the Tennessee impact sites:

> One structure of possible impact origin in Tennessee was first noticed during reconnaissance geologic studies and reported in 1869. Starting 67 years later, in a period of 17 years C.W. Wilson, Jr., with his colleague K.E. Born, and later with students, increased the reported list of possible impact features in Tennessee to seven.

Shoemaker and Eggleton (1961: A 14-15) include Flynn Creek and Howell in the category of "Buried Craters with the Form and Structure of Meteorite Craters", which were "… completely covered with sediments and are now partly exhumed by later erosion." They believe Flynn Creek to be a crater formed in Ordovician rocks which was covered with sediment during the Devonian and Mississippian time (Shoemaker and Eggleton, 1961: A-15). They consider Howell to be a crater in Ordovician rocks, but extensively eroded before being filled by younger Ordovician rocks. Wells Creek and Dycus are categorized as “Deeply Eroded Structures of Possible Impact Origin ….” (Shoemaker and Eggleton, 1961: A-15, A-26). “Putative impact craters for which more data are needed for classification …” include the Wells Creek associated craters: Cave Spring Hollow, Indian Mound, Austin, and possibly Little Elk Creek (Shoemaker and Eggleton, 1961: A-26). Baldwin (1963: 89) states that “The Wells Creek Basin structure is not alone.” He does not include Little Elk Creek, but believes it is logical that Cave Spring Hollow, Indian Mound, and Austin Basin “… had a similar origin at the same time. That origin would have been related to the phenomenon that formed the Wells Creek Basin structure …” (Baldwin, 1963: 90-91). Baldwin’s tally then matches that of Shoemaker and Eggleton (1961: A-4), seven possible impact features in Tennessee.

More details are given on the Tennessee sites in various Astrogeology reports. According to Schaber (2005: 31):

> The following was taken from the Branch of Astrogeology Monthly Report for November 1961 to V.E. McKelvey from the Chief, Branch of Astrogeology; dated 30 November 1961 … Field examination of the Howell disturbance, Tennessee, by E.M. Shoemaker, R.E. Eggleton, and D.J. Milton, in company with C.W. Wilson Jr. of Vanderbilt University, led to the conclusion that if this structure is of impact origin, as has been suggested by Wilson and others, the structure was probably formed at a time when the epi-continental Ordovician sea had significant depth at the site of the Howell disturbance.

Several years later, geologists, led by John Bensko, from NASA’s Marshall Space Flight Center in nearby Huntsville, Alabama, were involved in field work and core drilling within the Howell Structure (Woodruff, 1968: 1, 3). Woodruff (1968: 3) reports that “Further interest was given to the Howell area by NASA. A magnetometer survey was undertaken by Charles R. Seeger of the Goddard Space Flight Center, Maryland.”

Other structures in Tennessee also caught the attention of NASA and the USGS. Shoemaker visited Flynn Creek more than once (Schaber, 2005, appendix A: 251, 255). During an interview as recorded in Appendix A of Schaber’s Chronology (Schaber, 2005: appendix A, 251) D.J. Roddy states:

> Gene [Shoemaker] said why don’t you consider a place called Flynn Creek in Tennessee? Gene said I am convinced that it is an impact structure.
>
> Walter Bucher had listed it as a cryptovolcanic structure. So Gene said of all the “crypto” structures, this one holds the most promise of being the most complete – and we can get the most information from it. So why don’t you attack the following problem – solve the origin of this structure completely, and to everyone’s satisfaction, as a Doctoral thesis …
>
> In any event, Gene said if you can marshal enough evidence, you’ll be able to solve all the rest of the similar structure’s origins too, and no one will be misled calling them crypt-this and that.

Roddy promptly became a member of Shoemaker’s Astrogeology team and spent much of his life studying Flynn Creek (Schaber, 2005: 26-27):

> Geologist and cratering expert David J. Roddy (1932-2002) first joined the Astrogeologic Studies Unit of the USGS in early 1961, only a few months after Shoemaker started the Unit in Menlo Park on 25 August 1960. Dave was Gene Shoemaker’s very first Doctorate student at Caltech …
>
> In September 1967, Roddy moved to Flagstaff to work full time for the Branch of Astrogeology. Roddy served as Project Officer in explosion cratering, ejecta processes, and shock effects … Roddy, like his mentor Gene Shoemaker, was considered an expert in the formation and geology of Meteor Crater, and other impact craters in general. Roddy also

> served as a Principal Investigator in the U.S. Geological Survey for NASA to investigate impact cratering processes and ejecta formation in the field, in experiments, and in theory and numerical simulations since 1961. Dave Roddy earned the Barringer Medal in 1994 for exceptional achievements in meteoritics …

D.J. Roddy was still a graduate student at the California Institute of Technology when he began his field work in Flynn Creek and published his first paper on the structure in the 1963 Astrogeologic Studies: Annual Progress Report for the United State Geological Survey (Roddy, 1963: 118). He wrote many more papers on Flynn Creek through the years. His unpublished 1966 Ph.D. thesis was a comprehensive study of the crater at Flynn Creek in which he noted that "Since 1961 increased interest in the lunar craters has been stimulated by the efforts directed toward manned lunar exploration. This interest in lunar craters in turn revived an interest in terrestrial crater studies …" (Roddy, 1966c, 10).

One of the current Working Groups of the USGS is the Astrogeology Science Center. Its website, http://astrogeology.usgs.gov/about, states:

> The USGS Astrogeology Science Center has a rich history of participation in space exploration and planetary mapping, starting in 1963 when the Flagstaff Science Center was established to provide lunar geologic mapping and assist in training astronauts destined for the Moon.

Schaber (2005: 46) notes that "The very first geologic field training trip for NASA astronauts was carried out at Meteor Crater and the San Francisco Volcanic Field near Flagstaff under the leadership of Gene Shoemaker on 16-18 January 1963." Of the nine astronauts present, six would go on to orbit or land on the Moon.

In January 1963, Shoemaker had become the Principal Investigator of NASA's Surveyor Project (Schaber, 2005: 48). According to the National Space Science Data Center website, http://nssdc.gsfc.nasa.gov/planetary/lunar/, there were also other lunar missions in the lead-up time to the Apollo missions. In fact, during 1963 alone, NASA Headquarters almost doubled in size (Schaber, 2005: 61). During an interview with Schaber (2005: 97) on 19 February 2001, Jack McCauley of the Branch of Astrodeology states,

> Ranger VII succeeded [on 28 July 1964] and obtained the first close-up pictures of the Moon … That showed convincingly – at least to those who had open minds – that the impact crater theory and the business of the saturation of the lunar surface with these impact craters, was the correct interpretation. That was, our model was correct. The craters went down to a condition that was fully documented in the Ranger imagery – of what they called A STEADY STATE. In other words, every time you add a new crater, it knocks out some that are already there – and you can only see that at the highest resolution.

Interest in terrestrial craters was also increasing. Shoemaker and Eggleton (1961: A-15) note that a drill hole in the center of the Wells Creek structure showed the breccia to be around 600 meters thick and "Surrounding the breccia and enclosing upturned beds is a concentric series of faulted anticlines and synclines that extend as far as 6 kilometers from the breccia." Wells Creek is the largest such structure in Tennessee and "In June 1963 the National Aeronautics and Space Administration gave Vanderbilt University a grant … for the study of the Wells Creek structure." (Wilson and Stearns, 1968: 17). The USGS and the Tennessee Division of Geology prepared topographic maps of the area and the Tennessee Valley Authority prepared a highly-detailed map of the Wells Creek Basin. The geologic mapping went from June 1963 to June 1965 (Wilson and Stearns 1968: 19). These maps in addition to the thorough field studies completed by Wilson and Stearns assisted by Tiedemann, Wilcox, and Marsh, culminated in the Tennessee Division of Geology's Bulletin 68, *Geology of the Wells Creek Structure,* published in 1968, the most comprehensive study of Wells Creek to date.

According to Schaber (2005: 87), "In May 1964 the Branch of Astrogeology submitted its second Annual *Astrogeology Progress Report* to NASA covering research carried out during the period 25 August 1962 to 1 July 1963." The report was in four parts: Part A- Lunar and Planetary Investigations, Part B- Crater Investigations, Part C- Geochemistry and Petrology, Part D- Studies for Space Flight Program (ibid.). Schaber (2005: 110) also reports that "The following was taken from the Branch of Astrogeology's Monthly Report for December 1964 to Dick Wilmarth of NASA; dated Dec. 31, 1964":

> In December 1964 Harold Masursky, working with Michael Carr and Henry Moore (from Astrogeology's Menlo Park Office), devised a hypothesis for the development of lunar crater central peaks. The hypothesis is based on high-speed cinematography by Don Gault of Ames Research Center of hypervelocity cratering experiments in rock targets and on field studies of terrestrial craters by David Roddy (Branch Of Astrogeology) at Flynn Creek, Tennessee … The movies show development of this peak by violent decompressional uplift of a central column that emerges after the initial cone of ejecta emerges. Supporting evidence at the Flynn Creek crater indicates that the rocks of the central peak are derived from strata that are 900 feet [275 meters] lower than the crater floor.

Roddy started mapping Flynn Creek during the summer of 1961 or 1962 and gave Schaber (2005 appendix A: 252, 255-257) the following details of his work during a 2001 interview:

> I was immensely happy, but tremendously disappointed in the amount of exposures that you have in Tennessee in the summer … I ended up literally throwing all of my mapping away that I had done during the first two or three months because you just couldn't tell hardly weeds from the rocks … have to come back here and map in the winter … So I spent the next four or five years mapping, and doing lab work when I was back at Caltech for eight or nine months—and then mapping for three or four months.
>
> So I spent well over a year of mapping at Flynn Creek—a 10 mile by 10 mile [16 km by 16 km] section at 1:6,000-scale—which is fairly detailed. It became clear after a while that this was not a crypto-volcanic kind of feature in any sense of the word. It became clearer and clearer that this was consistent with the deformation of a very highly centralized energy source …
>
> So Flynn Creek not only played enormous dividends in those days, but it had continued to be of prime use for the planetary world and the DOD [United States Department of Defense] world with regard to large-scale cratering ever since Gene got me started. He sure picked the right site for me.
>
> D. Gareth H.S. Jones was a geophysicist of considerable repute and mental capabilities at the Defense Research Establishment, Suffield, Alberta, Canada … Jones was the program manager for the Snowball explosion experiment in 1964. There was a 500-ton hemisphere on alluvium at the Defense Research Establishment in Suffield, Alberta, Canada. It produced a large, flat-floored, relatively shallow, crater that was very large in diameter over a hundred meters. They were quite surprised at how flat the floor was and how big the crater was, but they were really surprised at the miniature mountain in the middle of it—a central uplift—which they didn't understand was a central uplift[or central peak] at the time …
>
> … what Gene wanted done on the Flynn Creek thesis was a once and for all—put to rest—the crypto-explosion, crypto-explosion theory—because Flynn Creek was one of those craters so-classed by Walter Bucher.
>
> Well, we had a major breakthrough with the Snowball [TNT} crater (in Canada) and because I was working on Flynn Creek at the same time, I knew in some detail what the deformation at Flynn Creek looked like, and I could see great similarities in the 500-ton crater.

> So I began to draw analogs wherever I could on the central uplift in terms of analogs at the impact site—at Flynn Creek—and then I began to extend out underneath the crater floor. Then I was about to get drilling out there …
>
> Anyway, we eventually got a complete package of cross-sectional and structuraldeformational information both for Flynn Creek and for Snowball; and they matched so extremely well that I was compelled to speculate some kinds of initial explosion shock-wave generation activity or configurations—and went from there. I eventually concluded, for the sake of general argument, that the Flynn Creek structure was clearly produced by a shockwave process, and it had to have been from above because there was nothing coming up from below—because I drilled through those areas. In fact, I drilled six holes (I think) in 1967, and we drilled the next batch in 1977-78 …
>
> … all blessings and accolades go to Gareth Jones for having the good sense to recognize what this thing looks like. In fact, Jones told Gene this thing looks just like Copernicus on the Moon.

Flynn Creek, like the Barringer Meteor Crater, was chosen by NASA and the USGS for training the Apollo astronauts, as is noted in Figure 3.23, the Flynn Creek Historical Marker that is located within the structure.

Figure 3.23: The Flynn Creek Historical Marker (photograph: Jana Ruth Ford).

Roddy is known also to have worked in the Flynn Creek (Tennessee) area during 1964 (ibid.). Although no actual record of NASA or USGS research conducted at the Dycus Disturbance location or of a Dycus site visit by Roddy has been found, it is known that Roddy was aware of the structure's existence while working in nearby Flynn Creek for the United States Geological Survey's Branch of Astrogeologic Studies on behalf of NASA (Roddy, 1966c: 17, 153). Roddy checked out the unpublished Master's thesis on the Dycus Disturbance by R.M. Mitchum from the Vanderbilt University Library in Nashville, Tennessee. Just inside the thesis cover there is a form asking readers to sign indicaing they will respect the literary rights of the author, and the second signature there is Roddy's, dated August 1964. The primary land owner of the Dycus Disturbance stated in 2006 that "...the last time anybody visited the feature was in 1964 …" (Deane et al., 2006: 1). One may conclude that since Roddy was doing field studies at an impact structure only 13 km away and was reading the primary source of information available on the Dycus Structure at the time, that he must have been the 1964 visitor. Roddy (1966c: 153) states in his 1966 Ph.D. dissertation that Dycus is a deformed area "… similar to the Flynn Creek structure."

According to Schaber (2005: 242), in January 1970, the Branch of Astrogeologic Studies submitted its last *Annual Astrogeologic Progress Report* for research carried out from 1 October 1968 to 1 October 1969 in five parts: Part A-Lunar Investigations, Part B-Crater Investigations, Part C-Cosmic Chemistry and Petrology, Part D-Geologic Support for Planetary Missions; and Part E-Spaceflight Investigations. The Apollo Era came to an end with Apollo 17 in December 1972. The last astronaut to step onto on the lunar surface, Harrison "Jack" Schmitt, formerly of the USGS Branch of Astrogeology, was the only geologist-astronaut to explore the lunar surface (Schaber, 2005: 12).

3.5 Future Research on Ancient Impact Sites

Officer and Carter (1991: 21-22) point out that the Midcontinent, United States has "… provided a relatively stable environment for the preservation of impact structures throughout the Phanerozoic … [and that] the cryptoexplosion structures of the Midcontinent, United States have been studied extensively." Based on structural, stratigraphic, and petrologic features as well as core drilling and geophysical studies, they conclude "… that all of the cryptoexplosion structures for which there is sufficient geologic information available are of impact origin …" (ibid.). The cryptoexplosion structures they determined to be confirmed sites of meteorite impact include Wells Creek, Flynn Creek, and the Howell structure (Officer and Carter, 1991: 21). This assessment is partially based on the observation of shatter cones *in situ* within these structures (Officer and Carter, 1991: 22). French (2004: 171) states that "Today, well-developed shatter cones are generally accepted as definite impact criteria." Positively-identified shatter cones have been located at Wells Creek (Bucher, 1936: 1070; Wilson and Stearns, 1968: 108) and Flynn Creek (Dietz, 1960: 1782). Shatter cones are well-formed and abundant in the center of the Wells Creek structure and although Dietz (1960: 1783) states that the Flynn Creek "… shatter cones are poor examples …" he considers their identification to be unquestionable. Woodruff (1968: 25, 26) includes photographs of "… a poorly formed shattercone … [and other] possible shattercones …" *in situ* in his thesis at the Howell structure, but Miller (1974: 56) states that "… they are indistinct …" and most researchers agree that the evidence for impact is not conclusive (Deane et al., 2004: 2). Officer and Carter (1991: 21, 22) feel that there is "Insufficient information for assessment of origin …" for the Dycus Disturbance (ibid.).

Prior to 1960, the only unambiguous identification of an impact structure was the presence of associated meteorite fragments (French, 2004: 171). Since then shatter cones, planar deformation features [PDFs] in quartz, and the high-pressure silica minerals coesite and stishovite have been determined to be "… durable geological criterion [sic.] to identify meteorite impact structures so old that the meteorites themselves no longer survive …" (ibid.). Gibson and Reimold (2010: viii) discuss the identification of impact structures:

> Whilst hundreds of probable and possible (but not yet confirmed) impact structures are listed in various databases, the confirmation rate for impact structures has not increased in recent years and only 176 impact structures are currently listed by the Earth Impact database (2009; last

> accessed 8 July 2009) … The only impact-diagnostic recognition criteria that are generally accepted are the presence of projectile remnants, the detection of shock metamorphic effects (e.g., microdeformation effects such as planar deformation features [PDF]) and mineral transformations such as coesite and stishovite found in supracrustal rocks, diaplectic glasses, and other high-pressure polymorphs such as reidite (after zircon) or diamond (after graphite), as well as shatter cones and chemical evidences for traces of an extraterrestrial projectile in impact breccias … Efforts are currently being made to investigate possible diagnostic impact indicators in the structural geological characteristics of craters and in the low shock-pressure range. Considering that the largest portion of the rock volume of any impact crater structure will only have experienced low-pressure shock overprint, and that many structures have been significantly eroded since their formation, this approach could provide important support for the recognition/confirmation of many more impact structures on Earth that would otherwise be impossible without having to resort to costly drilling ventures. (cf. Reimold, 2007).

Officer and Carter (1991: 5) state that "Most silicates shocked in nature display some sort of brittle response including fracturing, fragmentation, and brecciation." However, French (2004: 177) points out that our knowledge is incomplete and "The deformation of quartz is a fundamental problem … in shock and impact studies." French (2004: 178) continues the discussion by noting:

> 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. However, in natural impact structures, such shock pressures, and the resulting PDFs, are restricted to relatively small regions of the parautochthonous crater floor or to discrete lithic and mineral clats in the crater-fill breccia deposits breccia deposits and ejecta …
>
> … 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.

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 structures, such as Howell, may be resolved. French states that one obvious solution is to study deformation features that result from low shock pressures in impact events (ibid.). "Cleavage in quartz is an obvious candidate. It occurs as multiple parallel sets (also called PFs) in impact structures …" (ibid.). However, French also notes that cleavage has been produced in non-shock experiments and there are reports, though rare, of quartz cleavage in non-impact, natural environments (ibid.). French (2004: 178) suggests that future research be directed towards answering the following questions:

> How, and under what conditions, does cleavage develop in natural quartz? Can cleavage be produced naturally in quartz in non-impact (e.g., volcanic, tectonic) environments? Can the presence of multiple cleavage sets be used as an independent criterion for shock and meteorite impact?

French et al. (2004) note that well-developed cleavage in quartz, often occurring in multiple sets, has been found in numerous confirmed sites of impact. They suggest that multiple sets of cleavage in quartz be used provisionally as an indicator of meteorite impact in structures that show no other evidence of shock metamorphism (French et al., 2004: 26).

Another issue yet to be resolved is the age of some terrestrial impact structures. French (2004: 181) states that "Because impact structures have characteristic geometric shapes, their appearance can be used to estimate such geological factors as post-crater erosion and age." If this area of research proves fruitful, then questions concerning the impact rate, possible variations in this rate, the existence of impact clusters or comet showers may be answered by a "… database of well-dated impact structures."

A meteorite impact event takes only a few minutes, but with more energy than the total annual energy release from Earth (Osinski, 2008). Reimold (2003: 1889-1890) points out that the impact of Shoemaker-Levy 9 fragments into Jupiter's atmosphere in 1994 demonstrated that impact cratering is an on-going process in our Solar System and we need to know more about past catastrophic impacts on Earth and their environmental consequences such as mass extinctions. French (2004: 189) makes the following observation:

> The once-exotic area of impact crater studies is now becoming an important part of the study of our own planet and its history. In this process, the field has changed and grown, moving from the simple identification of individual impact structures to exploring the effects of impacts in the geological record.

CHAPTER 4: THE TENNESSEE METEORITE IMPACT SITES

4.1 The Geography and Geology of Tennessee

Tennessee is a long, narrow state located in the central southeastern United States and bordered by five coastal states as is shown in Figure 4.1. It is around 790 kilometers from east to west and about 185 kilometers from north to south according to the Tennessee Government website (http://www.tn.gov/local/). Figure 4.1 shows Tennessee and the southeastern States surrounding it along with their proximity to the Atlantic and Gulf Coasts. Figure 4.2 shows known and suspected impact site in the central southeastern States, including Tennessee. Site 8, the Wetumpka Structure in the state of Alabama, is a confirmed shallow–marine impact crater (King et al., 2002). Figure 4.3 is a generalized geologic map of Tennessee that shows the distribution of rocks by age across the State, the oldest only found in isolated exposures in eastern Tennessee and the youngest next to the Mississippi River in the west (Miller: 1974). Tennessee‘s western border is the Mississippi River and its eastern border lies along the Unaka Mountains, locally known as the Appalachian or Blue Ridge Mountains, as shown in Figure 4.4, a generalized physiographic map of Tennessee modified from Miller (1974: 2).

Figure 4.1: Location of Tennessee in the USA (GraphicMaps.com).

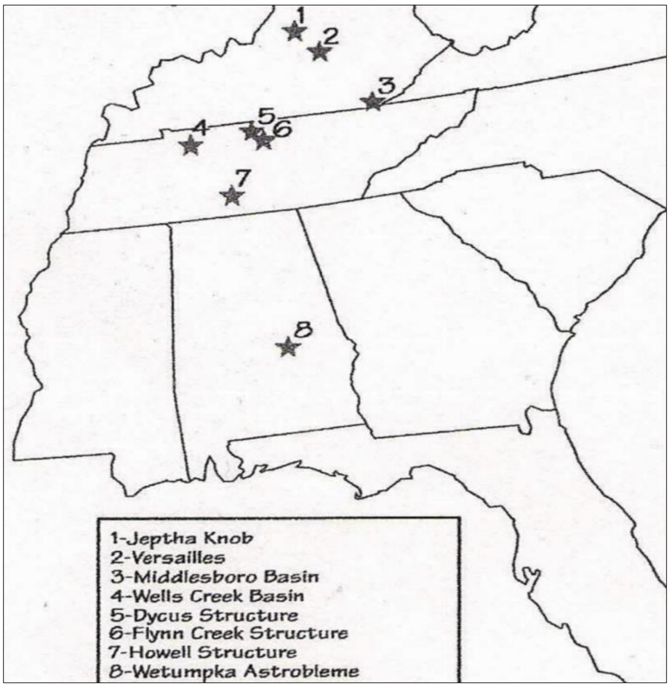


Figure 4.2: Map of the Central Southeastern USA showing known and suspected meteorite impact sites (map adapted and modified from Picconi, J.E., 2003. *Guide to the Geology of the Southeastern USA*. Ithaca, Paleontological Research Institution).

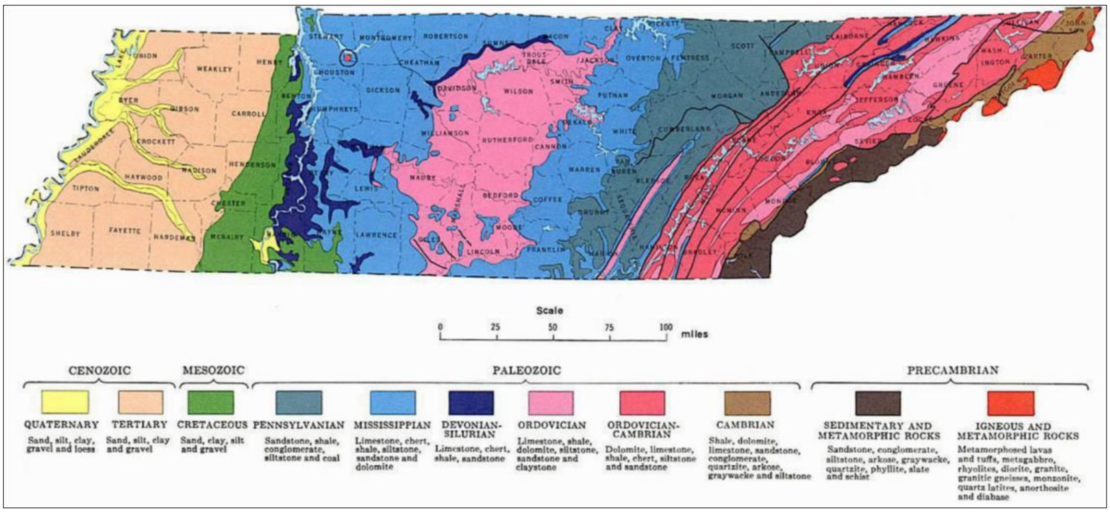


Figure 4.3: Geological map of Tennessee (after Miller, 1974: 9).

Figure 4.4: Map of Tennessee showing the different physiographical regions (adapted and modified from Miller, 1974: 2).

Tennessee is divided into three primary topographical sections. The western section, consisting of the flat lowlands of the Mississippi River Valley, Gulf Coastal Plain, and Western Valley, has experienced repeated advances and retreats of seas with associated sedimentation (Miller, 1974). The Gulf Coastal Plain "… was covered by the sea (the Mississippian Embayment) during the Late Cretaceous Period and much of the Tertiary Period, as was all the lowland area along the southern and eastern borders of North America …" (Miller, 1974: 7). Any ancient impact structures in the western section of Tennessee are likely covered by sediment from the Mississippi Embayment. The eastern section, which runs from the Cumberland Plateau eastward through the Great Valley and Ridge region to the Unakas, or Appalachian Mountains, has experienced episodes of mountain building with subsequent erosion (Miller, 1974). Any ancient impact structures in this wrinkled section of Tennessee were likely deformed by uplift and then obliterated by erosion.

Central Tennessee is dominated by rolling hills with some level areas in the Highland Rim, an elevated cuesta that completely surrounds the Central Basin, also known locally as the Nashville Basin. This is due to the fact that the state‘s capital, Nashville, is located in the north-western portion of the Basin. The Nashville Basin is an elliptical area that was formed by erosion of the Nashville Dome. Within the Nashville Basin, the Inner Basin consists of flat terrain and includes the geographic center of the state, which was originally the crest of the Nashville Dome (ibid.).

According to Miller (1974: 18), "The Nashville Dome must have been part of an area above water at least as early as Late Precambrian time and was eroded throughout Early Cambrian time …" In the later part of Early Cambrian time, the seas advanced and covered what is now Middle Tennessee with deposits of carbonates interbedded with mud and sand in a shallow continental shelf environment. Toward the end of the Ordovician Period, an uplift of the Nashville Dome occurred. Uplift of the Nashville Dome resulted in higher potential erosive energy of the overlying strata and once the resistant overlying rocks were breached, rapid removal by solution of the underlying limestones took place (Miller, 1974).

In the late Devonian, the sea again advanced across the region "… depositing a black, carbonaceous mud over hundreds of thousands of square miles. This black mud, containing rotted organic matter, became the Chattanooga Shale …" (Miller, 1974: 26). Radioactive dating of micas in the Chattanooga Shale gives an age of 340 million years, or Late Devonian. The Chattanooga Shale is widely distributed throughout Tennessee and "… is probably the most easily recognized rock formation in the state …" (Miller, 1974: 28). There were a few islands in the area, though, which "… are evidence for a shallow water origin for the Chattanooga …" (ibid.).

Conodonts, tooth-like microfossils, are present in the Chattanooga and are used as guide fossils. During most of Mississippian time, Tennessee was covered by shallow seas. After the Permian, most of the eastern interior of the North American continent was above sea level and was never again covered by seawater. Extensive erosion took place and by the middle of the Mesozoic Era, excavation of the Nashville Dome had begun. Miller (1974: 42) describes the development of the Nashville Basin:

> Once the resistant sandstones of Pennsylvanian age were removed from the central part of the structure, erosion became more rapid in the underlying Mississippian limestones. This breaching of the once-continuous expanse of Pennsylvanian sediments formed an escarpment and initiated its subsequent retreat in all directions away from the dome …
>
> Erosion continued both downward and outward in the area of the dome and resulted in a rolling, low relief plain-like surface in Late Cretaceous time.

Erosion during the Mesozoic Era initiated the development of the Highland Rim. Today, headward erosion by streams continues to cut away the resistant rock, and "The resulting Highland Rim Escarpment is still retreating from the Central Basin area …" (Miller, 1974: 49).

The Highland Rim is divided officially into eastern and western components; however, the part that lies between the Basin and Tennessee‘s northern border is locally referred to as the Northern Highland Rim. The section that lies to the south of the Nashville Basin and extends on into the northernmost part of the state of Alabama is called the Southern Highland Rim. It is these various sections of the Highland Rim of Tennessee that are of interest here since all of the state‘s confirmed, probable, and possible impact sites are located within the Highland Rim or on the Highland Rim escarpment. Tennessee is home to two proven impact sites, the Wells Creek Basin and the Flynn Creek Crater, as well as two suspected impact sites, the Howell Structure and the Dycus Disturbance (e.g. see Berwind, 2006, 2007; Deane et al., 2004; 2006; Evenick, 2006; Evenick et al., 2004; Milam et al., 2006; Mitchum, 1951; Roddy, 1977b; Schedl et al., 2010; Schieber and Over, 2005; Stearns et al., 1968; and Woodruff, 1968). The largest of the Tennessee structures is the Wells Creek Basin.

4.2 The Wells Creek Structure

4.2.1 Introduction

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 (see Ford et al., 2012).

Impact cratering has been 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 section reviews the compiled information on the Wells Creek structure generated by researchers during the past one hundred and fifty years.

4.2.2 Historical Context

Figure 4.5 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."

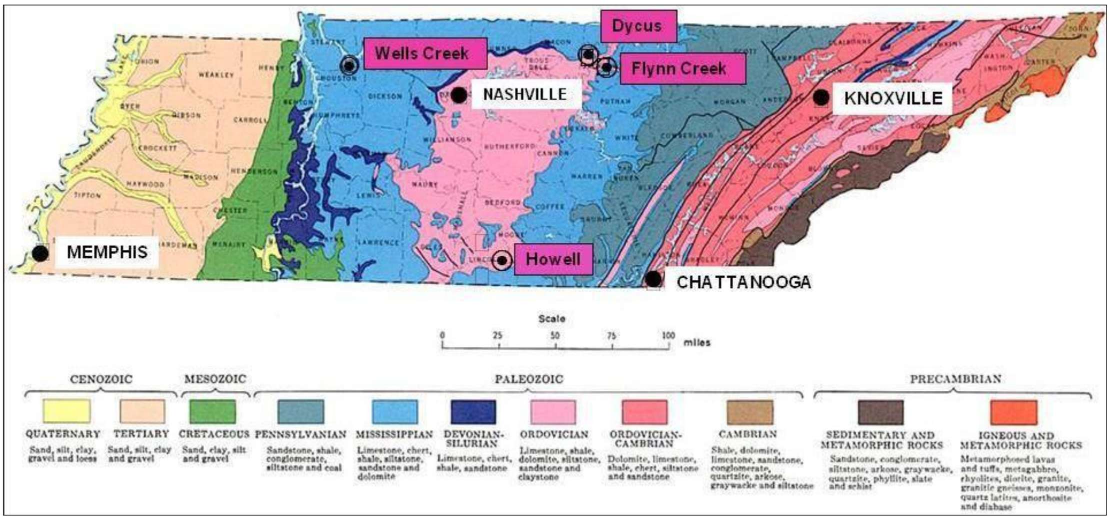


Figure 4.5: Generalized geological map of Tennessee showing the locations of the four largest cities (black dots) and the two confirmed and two suspected meteorite impact sites (small black dots with circles). These sites are located on the Highland Rim (Wells Creek), a Highland Rim outlier remnant (Howell), 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).

However, Wells Creek does stand out as a 'bulls-eye' 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 4.5 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.

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 4.6 is the colorful geological map of Tennessee that Safford drew to go with his 1869 report.

Figure 4.6: Safford"s 1869 Geological Map of Tennessee (courtesy: Birmingham, Alabama Public Library Cartography Collection).

In addition, a detailed geological map of the Wells Creek structure was placed in the upper left corner of the main geological map of Tennessee (Wilson and Stearns, 1966: 37). Figure 4.7 shows this inset, which is titled "The Well‘s Creek Basin in Stewart Country."

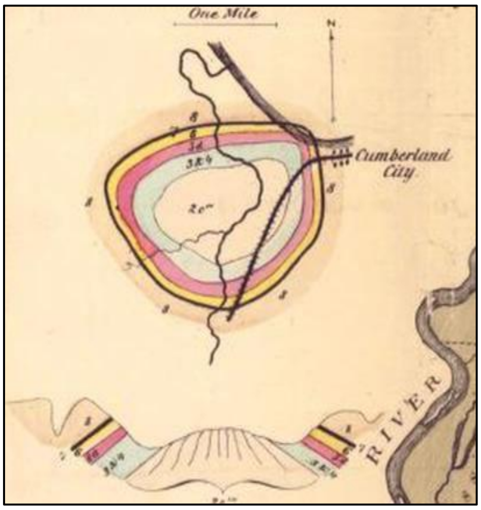


Figure 4.7: An enlargement of the small map inset on the upper left of Figure 4.6 (courtesy: Birmingham, Alabama Public Library Cartography Collection).

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 layers are folded, fractured and dislocated, and have inclinations at all angles (e.g. see Figure 4.8). 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.).

Figure 4.8: A recent photograph illustrating "… the rock layers are folded, fractured and dislocated, and have inclinations at all angles." (photograph: Jana Ruth Ford).

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)." Since recent attempts made by this author and others to locate it have been unsuccessful, the survival of this manuscript is in doubt.

Figure 4.9 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). Figure 4.10 records the various 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 4.10.

Safford and Lander noted that the first five formations shown in Figure 4.10 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.).

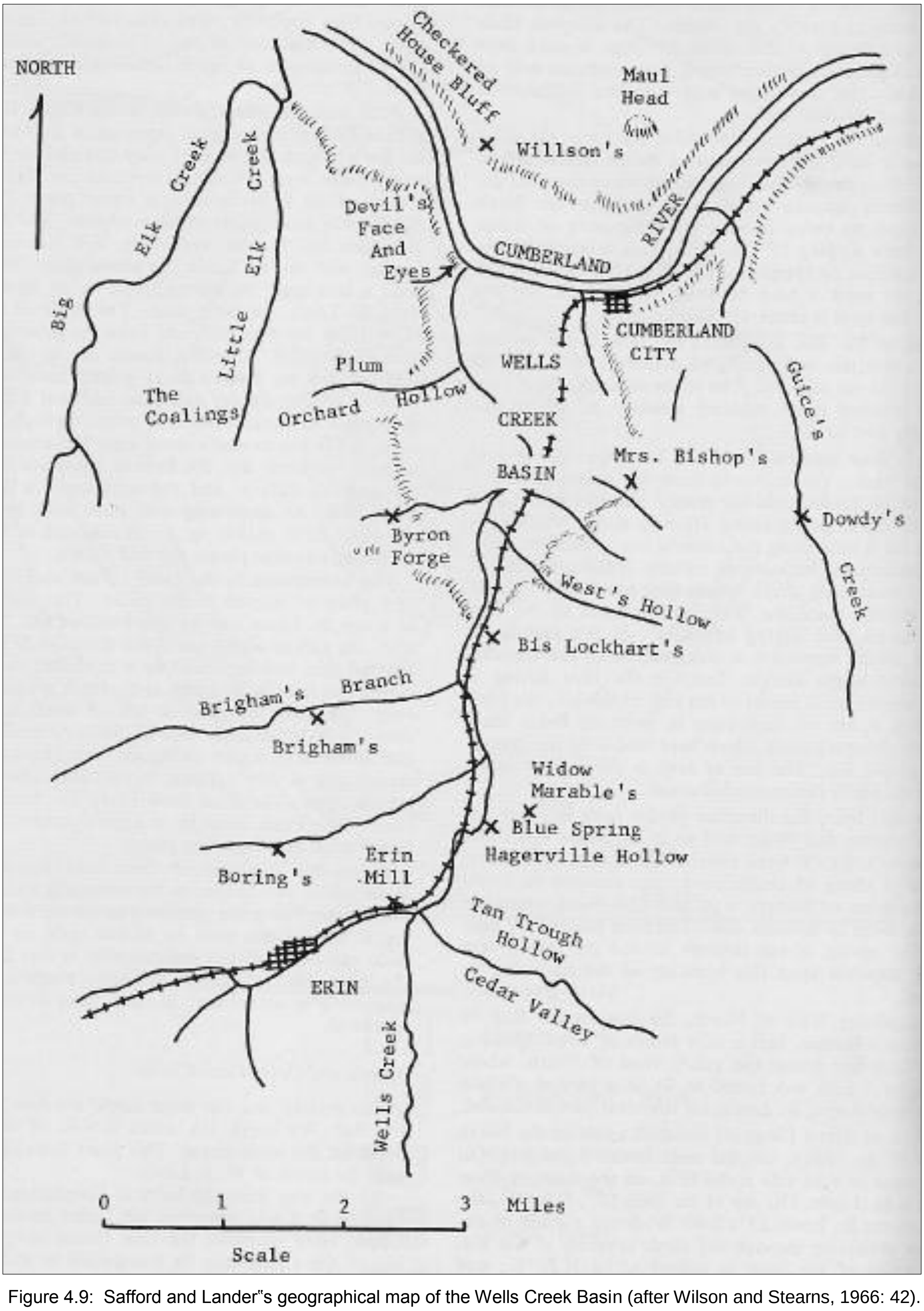


Figure 4.9: Safford and Lander"s geographical map of the Wells Creek Basin (after Wilson and Stearns, 1966: 42).

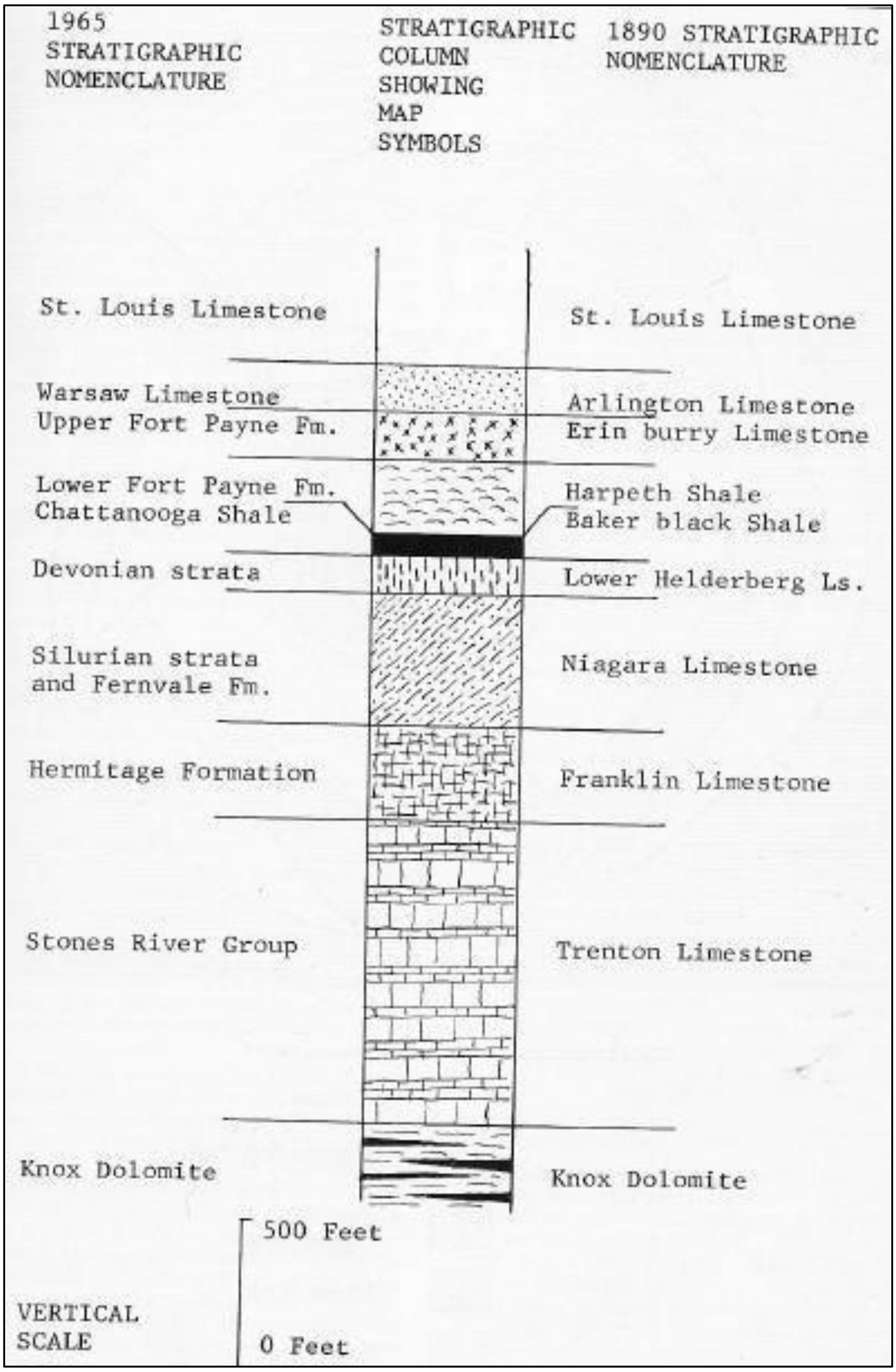
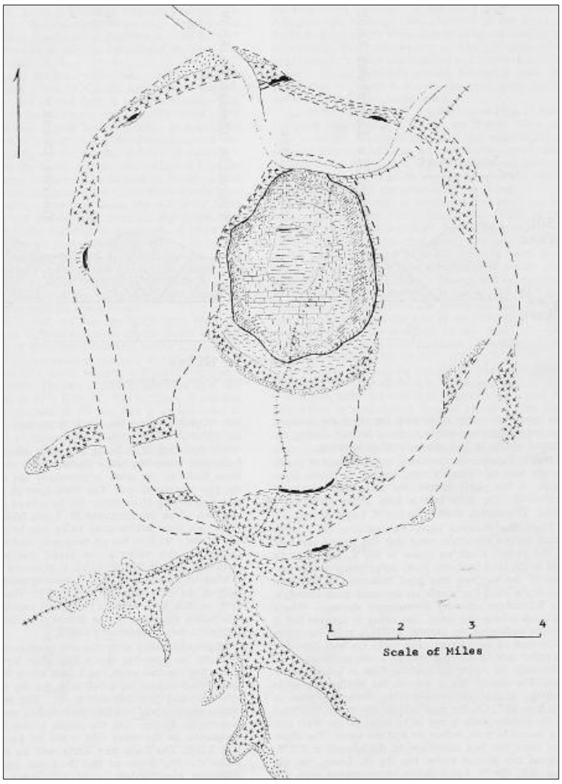


Figure 4.10: A stratigraphical section showing the lithological column with symbols as well as the different stratigraphical nomenclatures used in 1890 and 1965 (after Wilson and Stearns, 1966: 39).

The geological map of the Wells Creek structure drawn by Safford and Lander around 1895 is shown in Figure 4.11 (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 4.12). Figure 4.11 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.



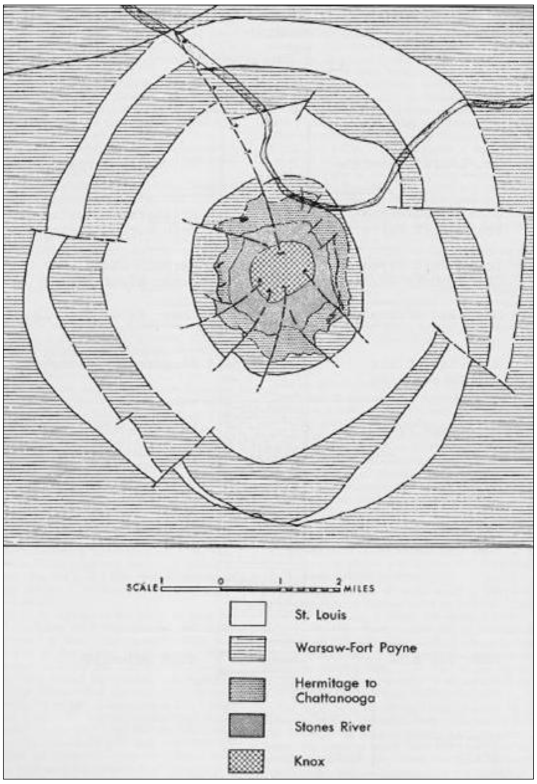


Figure 4.11 (left): Geological map of the Wells Creek structure drawn by Safford and Lander circa 1895 (after Wilson and Stearns, 1966: 43). Figure 4.12 (right): Geological map of Wells Creek Basin showing fault patterns as understood in 1965 (after Wilson and Stearns, 1966: 40).

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. When Bucher created his map, the unpublished manuscript of Safford and Lander (circa 1895) had been lost for close to seventy years and since it was only unearthed and published in 1966 (Stearns, 1988: 1), Bucher's map was the second *known* map of Wells Creek in 1936. Wilson and Stearns (1968: 15) state that Bucher's (1936) paper and map "… showed his remarkable knowledge and understanding of the structure."

4.2.3 Structural Features and Age

As Miller (1974: 55) points out, "The term crypto-explosion 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 4.13 shows Baldwin's (1963: 50) idealized cross-sections of simple and complex craters indicating distortions of rock layers and zones of brecciation.

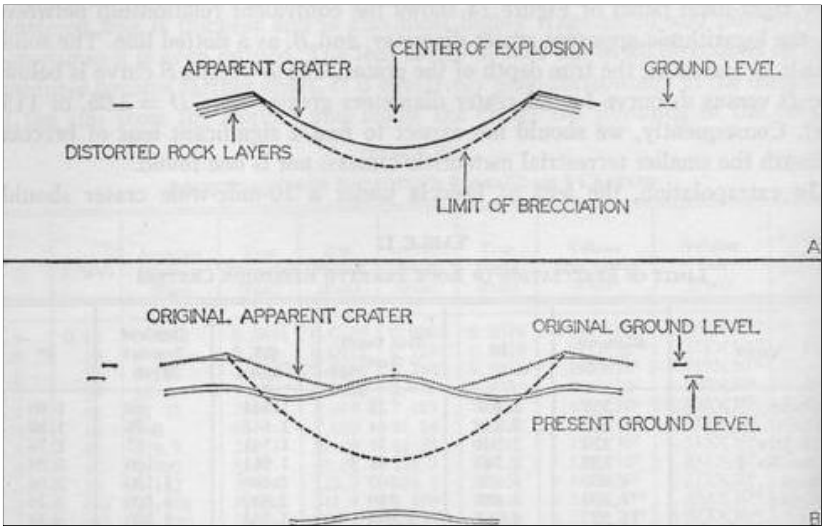


Figure 4.13: Idealized cross-sections through impact craters showing distorted rock layers and zones of brecciation. At the top is the Odessa No. 1 crater, an example of a simple crater. Below is the Wells Creek Basin, an example of a complex crater (after Baldwin, 1963: 50).

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:

> 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 "… unheard-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 4.14 is a map produced during this time showing the major structural features of Wells Creek (after Wilson and Stearns, 1968: 55).

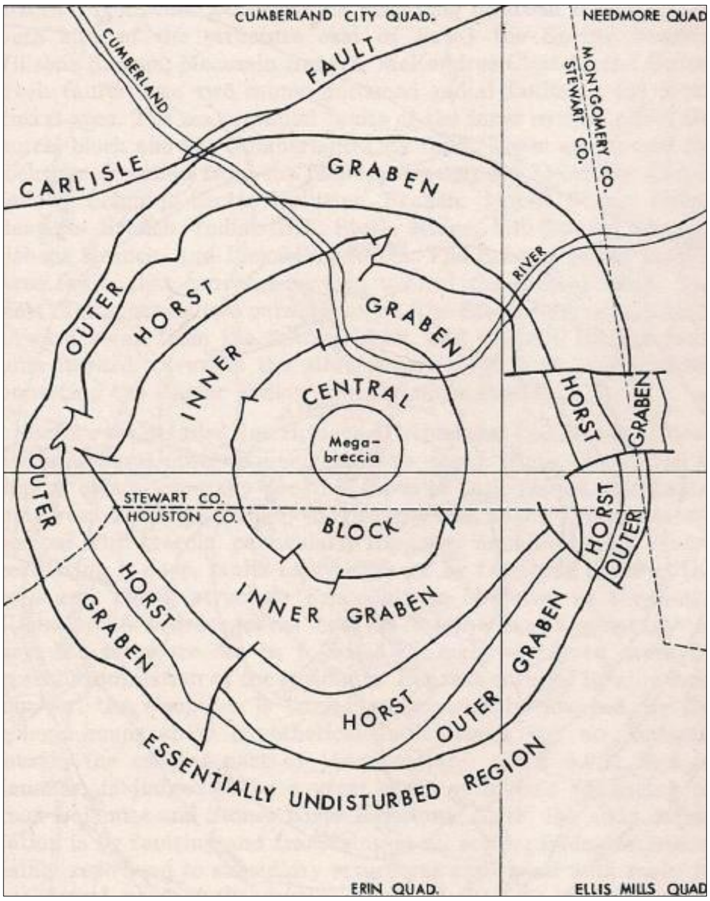


Figure 4.14: Map showing the major structural features of Wells Creek (after Wilson and Stearns, 1968: 55).

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:

(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 in 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 recemented. 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 4.13 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 km 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.

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 tremendous 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)."

4.2.4 Crypto-Controversies

Wells Creek is highly eroded. Erosion over long time periods will reduce the height of a 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 discernible, 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. 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; my italics).

Based on their interpretation of the impact process and its results, Boon and Albritton (1937: 57) drew the diagram shown in Figure 4.15 (which we first met as Figure 3:20) depicting the probable damped-wave basement structure of a meteorite crater. The A-level in this diagram shows a modified impact crater of recent origin with ejecta still visible on the rim. The B-level represents an impact site that has eroded to the point that it is barely discernible. In their interpretation, the C-Level shows the underlying strata of an impact structure becoming apparent as erosion continues. By the time that an impact structure has eroded to the D-level, the central uplift and ring folds will not only have become conspicuous, but will also have experienced some significant erosion, and this is the level that the Wells Creek structure has now reached. Boon and Albritton also note that over time, erosion will wear even this basement structure away and it will no longer be recognizable as a scar of impact.

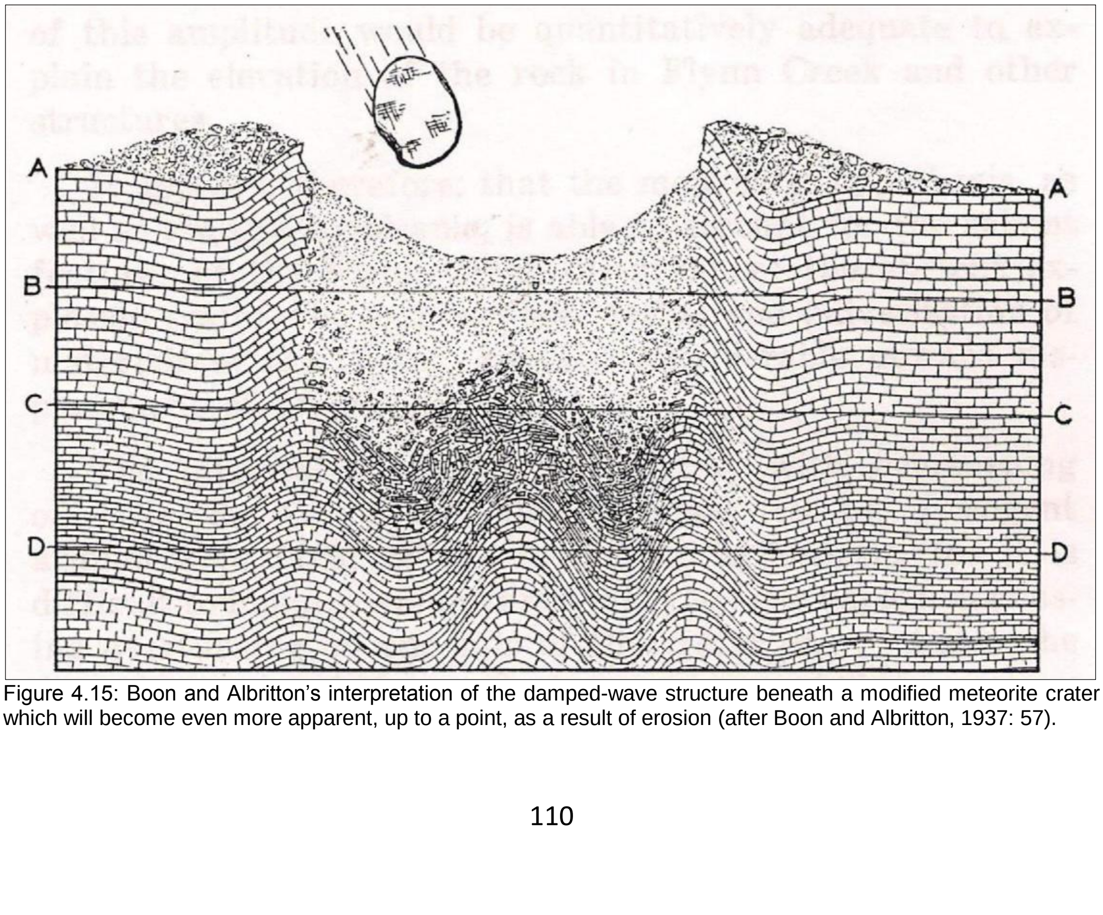


Figure 4.15: Boon and Albritton's interpretation of the damped-wave structure beneath a modified meteorite crater which will become even more apparent, up to a point, as a result of erosion (after Boon and Albritton, 1937: 57).

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 crypto-volcanic 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).

Although a consensus was developing among researchers by the 1960s, 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 stated in reference to the Wells Creek structure: "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.

4.2.5 Cratering 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."

4.2.6 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).

Apart from the presence of shatter cones, veins of pseudotachylyte containing coesite and/or stishovite (Dressler and Reimold, 2001) and planar deformation features, PDFs (French, 1998), are considered undisputable proof of meteorite impact. Proof can also afforded by planar fractures, PFs (French and Koeberl, 2010: 134), crystallographic configurations of feldspars (Shoemaker, 1983), basal Brazil twinning and alteration in zircons (Kamo, Reimold, Krogh, and Colliston, 1996).

However, most of these ‘indicators’ were unknown when Wilson and Stearns conducted their research at Wells Creek, the most comprehensive study to date.

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 …”

Rock samples were collected from three different locations within the Wells Creek Basin in November 2014 by this author along with John C. Ayers and Xiaomei Wang, Department of Earth and Environmental Sciences, Vanderbilt University. Observations with optical microscope and SEM and EDS analyses on thin section were made by Ayers and Wang during the early months of 2015. Zircon U-Pb geochronology analyses performed by Ayers and Wang were not conclusive as to the date of impact. No high-pressure phases such as coesite were observed in any of the samples. No microscopic evidence of shock metamorphism was found. Even the Knox dolomite collected from the central uplift showed no evidence of impact other than numerous macroscopic shatter cones. (John C. Ayers, personal communication.)

Shatter cones are abundant in the rocks of the Wells Creek central uplift. According to Wilson and Stearns (1968: 108), they were first located in the United States by Bucher in the Wells Creek Basin. 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).

Dietz collected several compression fracture cones that were produced by high explosive detonation in a Nashville (Tennessee) limestone quarry and compared 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 …", one being 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 4.16 shows examples of shatter cones found in the central uplift of Wells Creek, which is known for its profuse fine and easily-located 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."

Dietz (1960: 1784) suggests that in addition to indicating a meteorite impact, shatter cones can 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." The orientation of the shatter cones found in the Knox group rocks exposed in the Wells Creek central uplift 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).

Figure 4.16: Wells Creek shatter cones in snow (photograph by Andrew Tischler).

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) point out that in the Wells Creek structure "… all known shatter cones are in the Knox Dolomite" and state 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).

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 noted horizontal shatter cones were concentrated at a depth of 30 meters and the few shatter cones he found below 60 meters were not complete or well defined, except for a single exception located at a depth of 377 meters. He notes that "As the core was not oriented, it is impossible to state in which direction these cones pointed." (Wilson, 1953: 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." (See Section 2.2.2). 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 from 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 nonvolcanic 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.

4.2.7 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). 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.

4.2.8 Associated Craters: Cave Spring Hollow, Indian Mound, and Austin

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 4.17. 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.

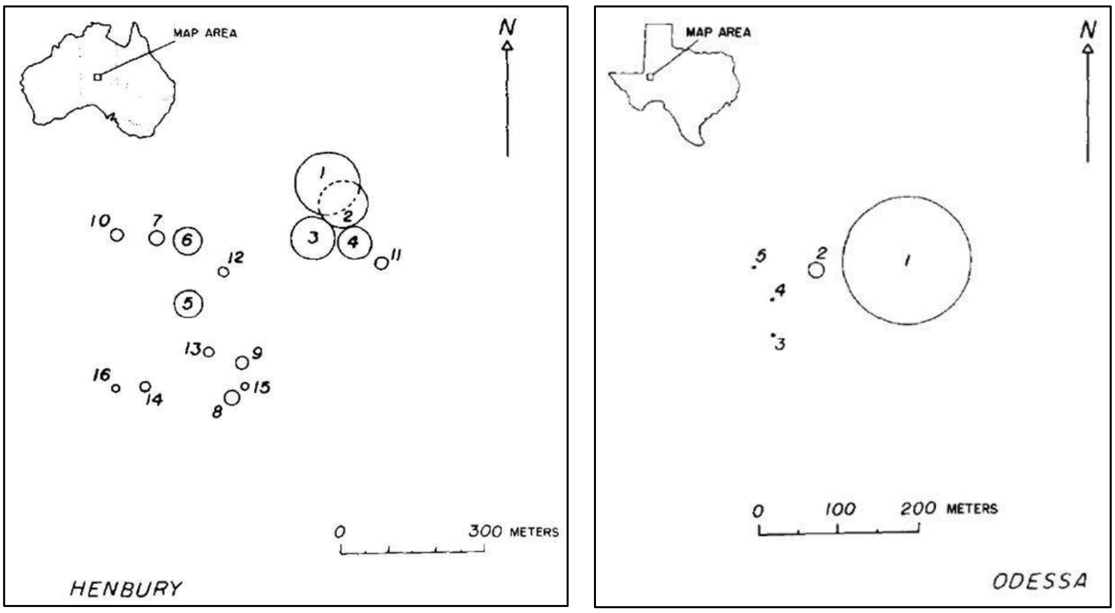


Figure 4.17a: The Henbury crater field, Australia (left), and Figure 4.17b: The Odessa crater field, Texas, (right), (after Passey and Melosh, 1980: 214, 217).

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

> 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] northnortheast 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 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.

Table 4.1: Wells Creek Basin, Tennessee, and its satellite craters (after O"Connell, 1965: 126).

Feature	Diameter	Depth
W ells 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 4.18 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. Comparing the diameters given in O'Connell's table above with Wilson and Stearn's map shown in Figure 4.18, 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.

Starting from the main Wells Creek structure, the first 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 the main structure's northern rim is the Cave Spring Hollow basin, the true extent of which is unknown. Almost five kilometers further 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 indicates that the Indian Mound basin has 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.

In 1953, Wilson indicated that he believed 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 were first reported by Safford (1869: 349). Bucher showed Wilson these deposits sometime around 1933.

The Indian Mound satellite crater was originally 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 in 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.

However, another explanation may be found in the fact 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 4.18 map, which includes Indian Mound and Austin, is enlarged in the geological map shown in Figure 4.19.

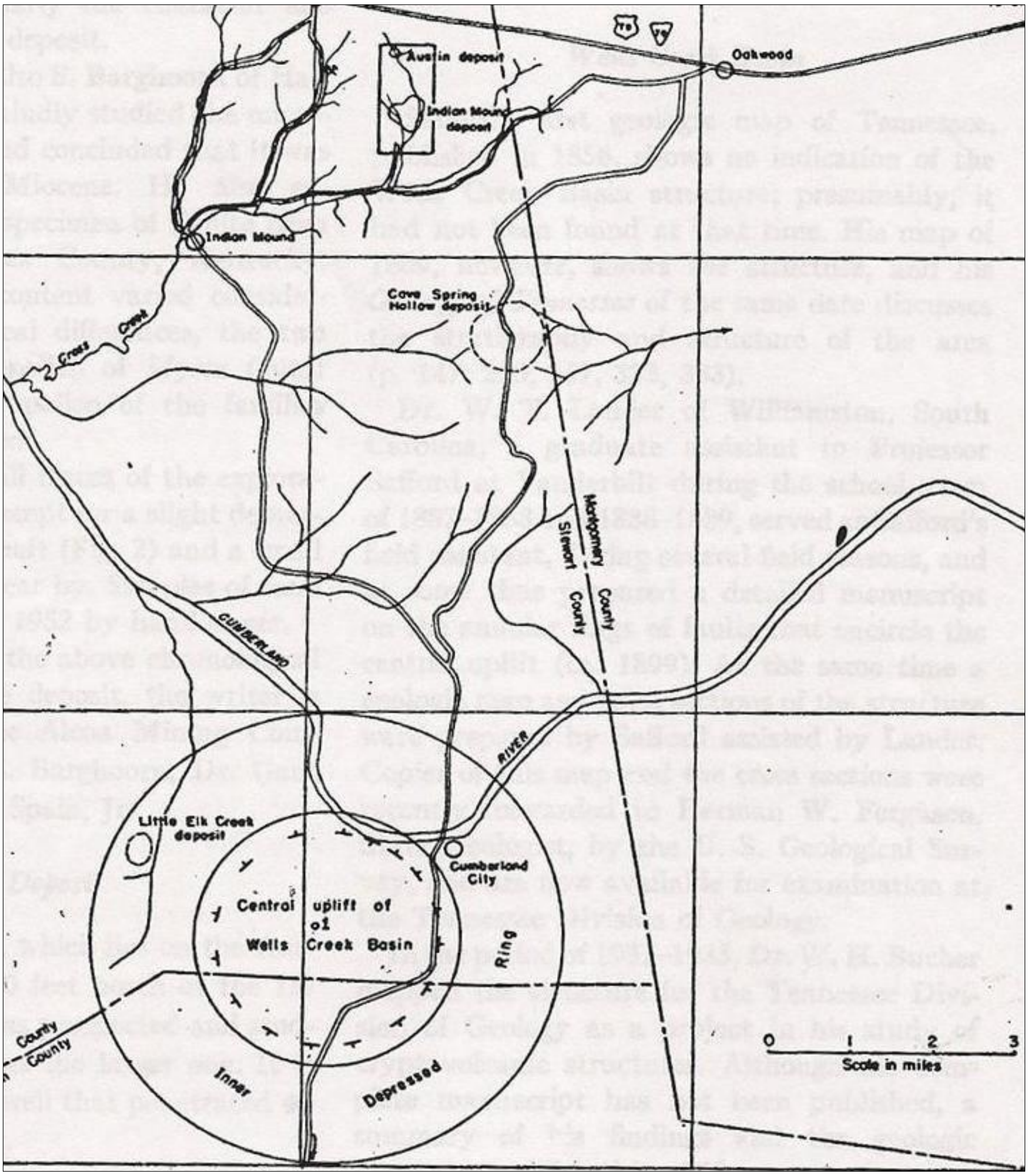


Figure 4.18: Map showing the locations of the Wells Creek Structure and the Little Elk Creek, Cave Spring Hollow, Indian Mound, and Austin 'satellite craters' (after Wilson, 1953: 754).

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, points 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 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 craters 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.

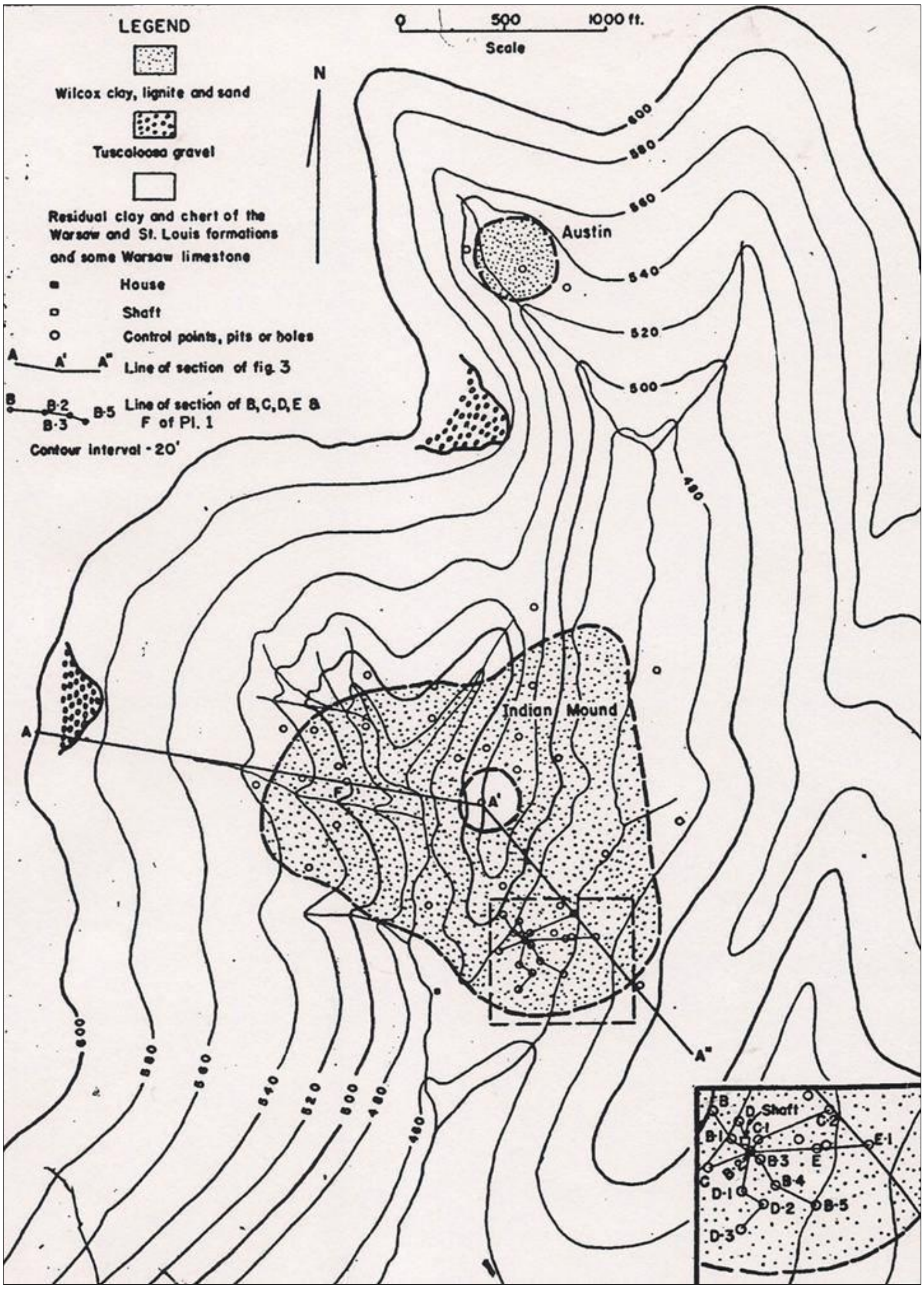


Figure 4.19: Geological map showing the presumed areal extent of the Indian Mound and Austin structures, based on shafts, pits and holes. The inset shows in detail the investigation of the southeastern section of the Indian Mound site (after Wilson, 1953: 759).

The son of D.M. Barringer recognized several small craters at Odessa, Texas, in 1922 (e.g. see Figure 4.17b) 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 satellite structures found at Wells Creek is striking.

However, due to their distances from the Wells Creek structure, one has to wonder 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 since 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).

McCall (1979: 279-281) then 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 objections:

> 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 crypto-explosion 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). In this context, it is interesting that in 1963 Alvin J. Cohen included Indian Mound on a map showing US impact sites (see Figure 4.20).

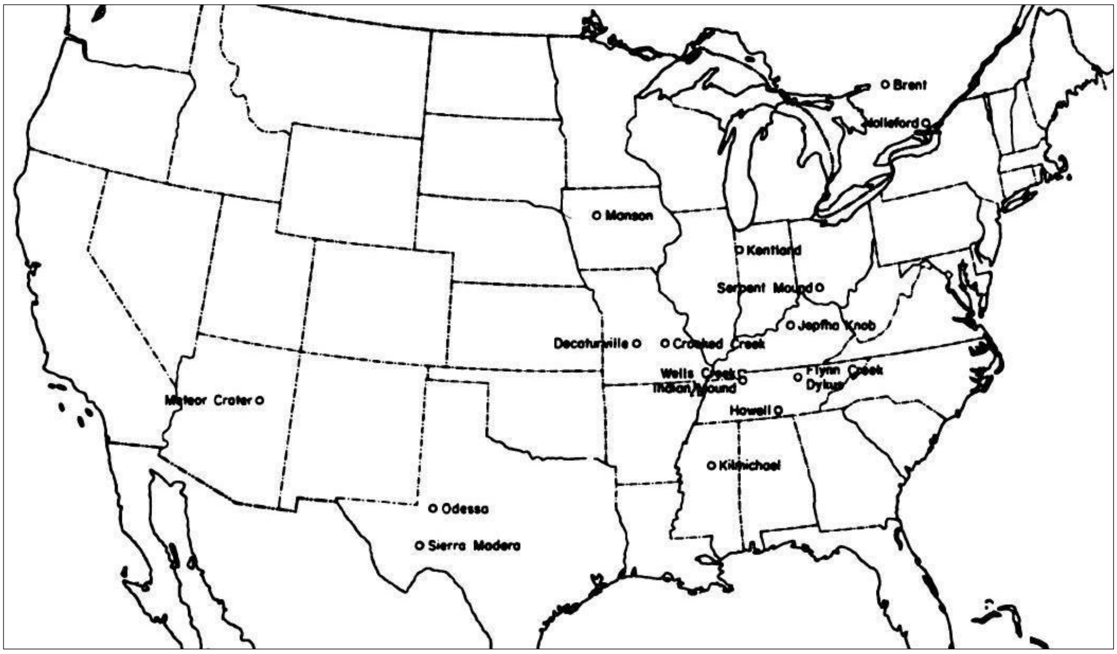


Figure 4.20: A paper prepared by Alvin J. Cohen for a conference on Nuclear Geophyics included this map of US impact crater sites. Indian Mound is included in the map next to Wells Creek. (Cohen, 1963: 237).

In their 1968 interpretation of the origin of the Wells Creek structure Wilson and Stearns now 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 supposed ‘satellite craters’ may never be determined as Wilson and Stearns note 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.

4.2.9 Conclusion

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 recognized 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 nuclei 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).

4.3 The Flynn Creek Structure

4.3.1 Introduction

The Wells Creek Structure played a major role in furthering our understanding of the nature of terrestrial impact cratering (see Ford et al., 2012), but Tennessee‘s second confirmed impact site, Flynn Creek, has also made a significant contribution, especially to our knowledge of shallow marine impact events and the formation of cave systems associated with impact sites. In addition, from the 1940s the Flynn Creek site was regarded as more closely resembling a typical lunar crater than any other known terrestrial crater, and this would later prompt its intense investigation in the era leading up to the first American Moon landing. In this paper we review the accumulating evidence that has been provided by the Flynn Creek impact site.

According to Dietz (1959: 498), "An event, if there is any possibility of its happening, becomes a commonplace occurrence within the enormous span of geologic time …" We see a myriad of craters on our nearby neighbor, the Moon, so similar impacts should have occurred and be evident on the surface of our own Earth. Koeberl (2009: 14) explains the distinction between an "impact crater" and an "impact structure":

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

In late Devonian or early Mississippian times, a nearly circular crater, about 3.6 km in diameter, formed at the location that is known today as Flynn Creek in Jackson County, Tennessee, and was soon after filled with and preserved by sediments from the Chattanooga Sea (Baldwin, 1963; Schieber and Over, 2005). Today the Highland Rim entirely surrounds the Nashville Basin in central Tennessee, and the Flynn Creek Structure is located on the northern section of the Eastern Highland Rim escarpment (Roddy, 1966c) where the strata are essentially horizontal and dips >5° are rare (Roddy, 1963, Wilson and Born, 1936). In fact,

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

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

> … fault zones are present in the region of the innermost rim, crater wall, and outermost crater floor region, and are continuous around at least the western, northern, and eastern sides of the crater … (Roddy, 1980: 941).

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

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

4.3.2 Historical Context

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

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

Although Safford considered the Wells Creek Basin of sufficient importance to be included on his map of the State of Tennessee which accompanied the geology report (see Ford et al., 2012), the Flynn Creek structure was not even noted on the map. Figure 4.21 is a close up view of the Flynn Creek area as depicted on Safford's 1869 map.

Figure 4.21: View of the Flynn Creek area on Safford"s 1869 geological map of Tennessee (adapted from: http://alabamamaps.ua.edu/historicalmaps/us_states/tennessee/index2_1851-1900.htm). No indication whatsoever is shown of the Flynn Creek Structure.

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

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

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

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

Roddy (1965: 50) stated that as a result of this strong resemblance to lunar craters, the Flynn Creek structure "… has been under study as part of a larger program of crater investigations by the Branch of Astrogeology …" It was one of only two impact structures located in the United States selected for this study (Astrogeologic Studies, 1967). A series of *Astrogeologic Studies Annual Progress Reports* from the 1960s and 1970s describe this research as it was conducted by the United States Geological Survey on behalf of the National Aeronautics and Space Administration. The long-range objectives of this project were

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

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

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

Figure 4.22: Dave Roddy (1932–2002) spent around forty years researching the Flynn Creek Structure (adapted from Chapman, 2002).

We have to thank the late Dave Roddy (Figure 4.22) for much of what we now know about the Flynn Creek Structure. David John Roddy

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

Roddy was a graduate student at CALTECH when he first investigated the Flynn Creek site and began publishing papers about it in the *Astrogeologic Studies Annual Progress Reports* for the U.S. Geological Survey. These early reports were followed by many more papers on Flynn Creek that Roddy wrote throughout the rest of his career. Roddy's research and field work associated with his Ph.D. thesis was supported by the U.S. Geological Survey's Branch of Astrogeology, as well as by a National Aeronautics and Space Administration (NASA) grant from 1963 to 1965

(Roddy, 1966c: 33). His thesis involved a comprehensive study of the Flynn Creek Structure, and he noted that "Since 1961 increased interest in the lunar craters has been stimulated by the efforts directed toward manned lunar exploration. This interest in lunar craters in turn revived an interest in terrestrial crater studies …" (Roddy, 1966c, 10). Unfortunately this interest did not spread very far, as noted by Denson (2008: 15), a native of the Flynn Creek area:

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

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

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

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

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

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

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

4.3.3 Structural Features and Age

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

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

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

Figure 4.23 shows a composite stratigraphic section for Middle Tennessee by Miller (1974: 59) as a reference for discussing the Flynn Creek structure. Referring to Upper Devonian units, Roddy (1966c: 59) writes that "Until the present work on the Flynn Creek structure, Richmond strata had not been recognized in the area." According to the United States Geological Survey, the Upper Ordovician units in Tennessee include the Richmond Group (name not shown in Figure 4.23), which is composed of the Mannie Shale, Fernvale Limestone, Sequatchie Formation, and the Arnheim Formation; the Maysville Group, which includes the Leipers Formation; the Eden Group, which includes the Inman Formation; the Middle Ordovician with the Nashville Group, which includes the Catheys Formation, Cannon Limestone, and Hermitage Formation; and then the Stones River Group, which includes the Pond Spring Formation. In Tennessee usage, the Pond Spring Formation is equivalent to the Wells Creek Formation (Brahana and Bradley, 1985).

The oldest rocks in central Tennessee are dolomite and limestone of the Knox Group, which range in age from Upper Cambrian to Lower Ordovician, and these are found exposed "… at the surface only in the faulted, folded and brecciated central parts of the Wells Creek and Flynn Creek structures …" (Roddy, 1966c: 34; cf. Miller, 1974). Roddy (1966c: 46) states that "… it is common in subsurface studies to refer to the strata below the Wells Creek dolomite only as upper Knox Group." Normally, the Knox strata are over 300 meters below the middle Tennessee surface in flat-lying beds (ibid.). The Knox Group in central Tennessee is around 1.5 km thick and may rest directly on the crystalline basement. As can be seen in Figure 4.23, a major unconformity exists in central Tennessee between the Stones River Group and the Knox strata.

It is interesting to compare and note the similarities in Miller's stratigraphic section for Middle Tennessee, shown in Figure 4.23, and Figure 4.24, the "Generalized columnar sections from the Western Rim to the Central Uplift of the

Flynn Creek Crater" by Roddy (1966c: 38). Outside of the Flynn Creek area of deformation, rocks range from the Cannon Limestone of the Middle Ordovician to the Fort Payne Formation of Early Mississippian age (Roddy, 1968b). Inside of the crater, however, rocks from the upper Knox Group of Early Ordovician age through the Stones River Group and Hermitage Formation of the Middle Ordovician age are exposed (ibid.). Beds of Cannon Limestone up to the Leipers Limestone are exposed in the crater rim and walls. The only rocks found to be involved in the structural deformation of the crater are of pre-early Late Devonian age. Roddy (ibid.) also points out that no Silurian or Lower or Middle Devonian strata have been recognized in the area of the Flynn Creek impact site.

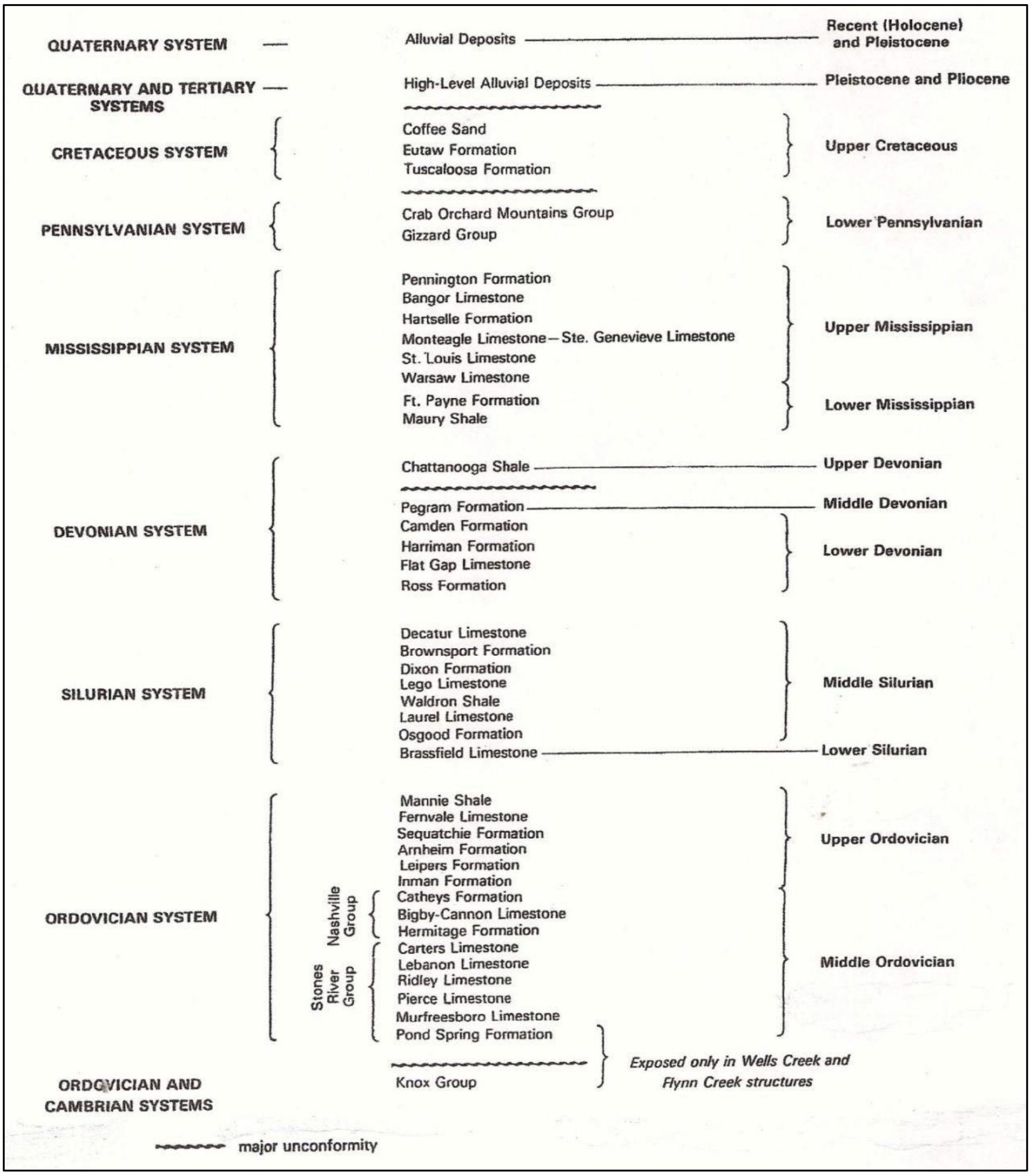


Figure 4.23: Composite stratigraphic section for Middle Tennessee (after Miller 1974: 59).

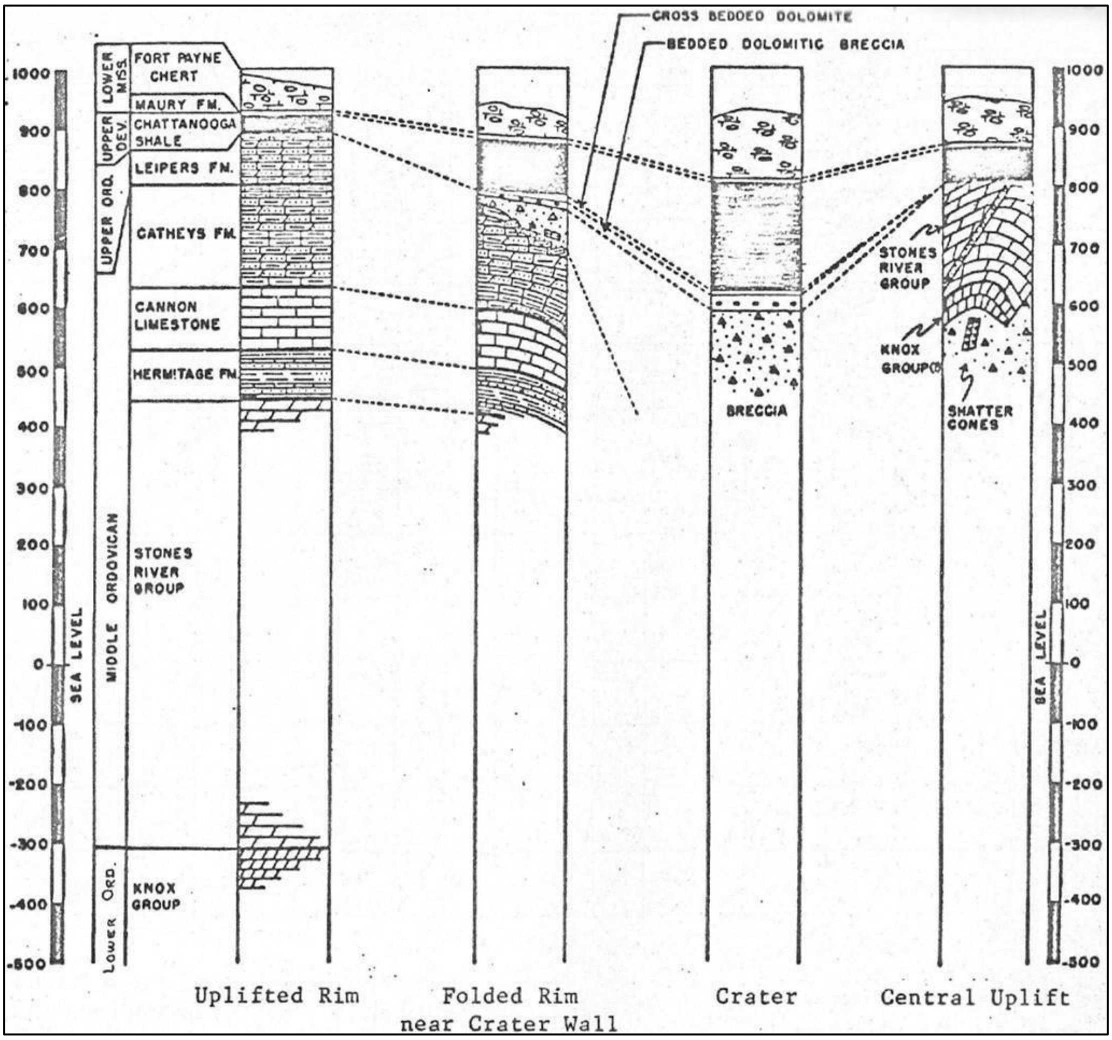


Figure 4.24: Generalized columnar sections from Flynn Creek Western Rim to Central Uplift (after Roddy, 1966c: 38).

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

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

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

As an overview, the Flynn Creek Structure's primary features are its central uplift, which consists of limestone blocks raised over 150 meters, and a depressed ring of breccias that surrounds the uplift and contains blocks of all the rock layers involved in the disturbance (Baldwin, 1963). Breccia overlying a graben in the southern rim is still preserved and this "… is the first indication from any of the cryptoexplosion structures that an ejection of crater breccia definitely occurred …" (Roddy, 1968b:

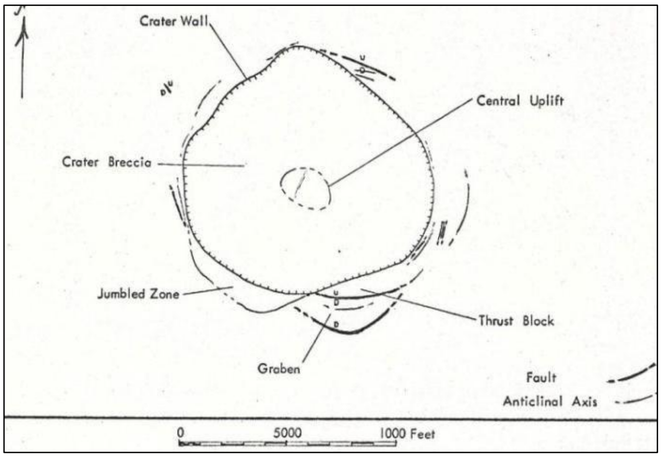
297). The breccia layers are covered by Chattanooga Shale which apparently filled the crater when a lake occupied the crater during pre-Chattanooga times. Strata dip away from the central uplift on the western, northern, and eastern sides of the Structure; however, to the south of the uplift the rock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

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

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

Flynn Creek falls into category (d).

Figure 4.25 is a schematic map of the Flynn Creek Crater by Roddy which shows its basic structural similarity to lunar craters, with terraced walls and central uplift. Figure 4.26 is a much more detailed contour map of the Flynn Creek Crater by Roddy (1968b: 302; cf. 1977b: 280). Note that though the crater is basically circular in shape, sections of the crater walls, specifically the northeastern and northwestern rims, are relatively straight for around 1500 meters (ibid.). Roddy (1968b: 303) utilized this particular contour map to construct the 3-D model shown in Figure 4.27.



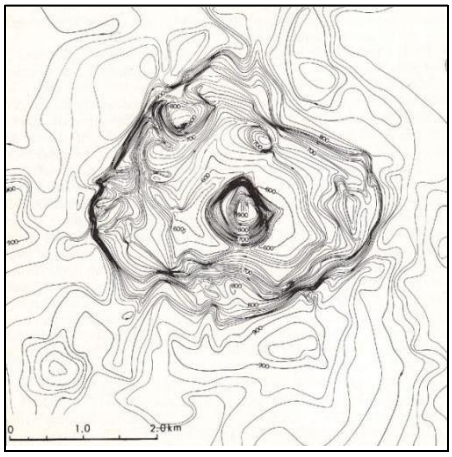


Figure 4.25 (left): Schematic map of major structural elements at Flynn Creek (after Roddy, 1966c: 98).
Figure 4.26 (right): Contour map of the Flynn Creek Crater (after Roddy 1977b: 280).

In this model, Figure 4.27, Flynn Creek is seen to be flat-floored with a single central uplift and terraced walls, and the dotted line "… indicates the position of the top of the crater wall in areas where large volumes of ejecta have washed back into the crater, modifying the original crater shape …" (ibid.). The terraces are not prominent due to this erosional redistribution of ejecta on the crater rim (Roddy, 1979b). Large hills visible near the outer sections of the crater are underlain by megabreccia blocks, derived from the crater walls, which also washed back into the crater along with the ejecta and formed "… a terraced effect along the crater walls …" (Roddy, 1968b: 302). Note that the Flynn Creek model, with its central uplift, shallow flat floor, and terraced walls, bears a remarkable similarity to the lunar crater Pythagoras, as seen by comparing Figures 4.27 and 4.28.

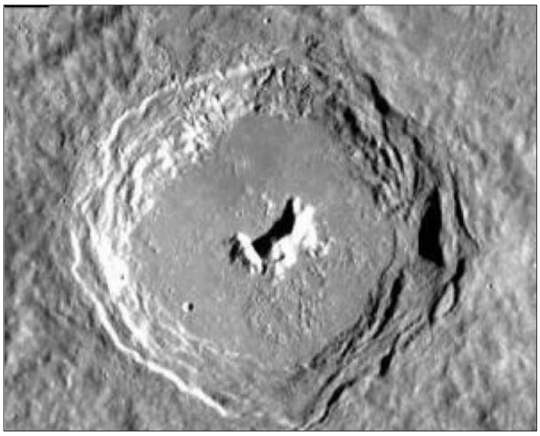



Figure 4.27 (left): The 3-D model of the Flynn Creek Crater made by Roddy (1968b: 303; courtesy: Planetary and Space Science Centre, University of New Brunswick, Fredericton, New Brunswick, Canada). Figure 4.28 (right): The lunar crater Pythagoras (courtesy: European Space Agency).

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

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

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

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

> The history of this disturbed area is interpreted as follows: Shortly preceding Chattanooga deposition an explosion took place near the surface, blowing out a crater 2 miles [3.2 km] in diameter and 300 feet [90 meters] deep. The Ordovician limestones forming the floor and walls of this crater were shattered into breccia composed of angular fragments of varying sizes

imbedded in a matrix of smaller fragments and “rock flour.” The deeper parts of the crater were filled with redeposited breccia, either as talus breccia or as bedded breccia deposited in a fresh-water lake that occupied the crater at one time. The Chattanooga sea invaded central Tennessee and filled the crater with black mud, now represented by about 250 feet [75 meters] of black shale. Fort Payne chert was later deposited upon the relatively smooth surface of the black shale.

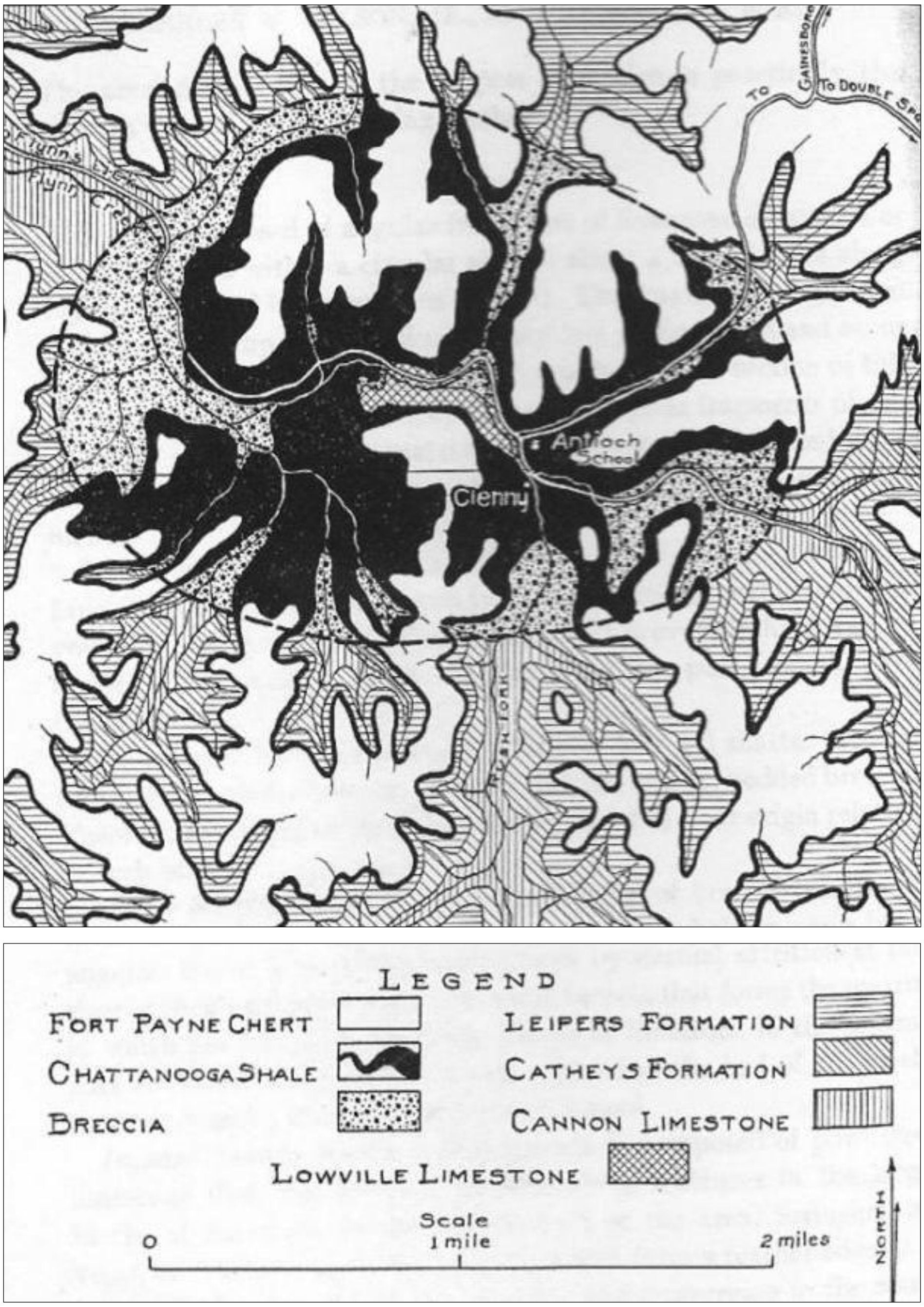


Figure 4.29: Areal geologic map of the Flynn Creek area (Wilson and Born, 1936: 818).

The consolidated rocks in the area were found to range in age from Ordovician to Mississippian, the oldest rock being dense Lowville Limestone which was found in “… the center of the disturbed area and is composed of many large, disconnected blocks, some of which are several acres in size …” (Wilson and Born, 1936: 817). Figure 4.29 is a geological map of the Flynn Creek area by Wilson and Born which shows that this area of intense brecciation is somewhat elliptical in shape. They note an interesting fact concerning the Hermitage Formation at Flynn Creek:

> In the normal stratigraphic succession along the eastern edge of the Central Basin, the Hermitage formation overlies the Lowville limestone; but this formation was not found in the Flynn Creek area. It is believed that the Hermitage formation was originally deposited in this region but that during the local deformation and subsequent erosion all traces of it were removed. (Wilson and Born, 1936: 819).

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

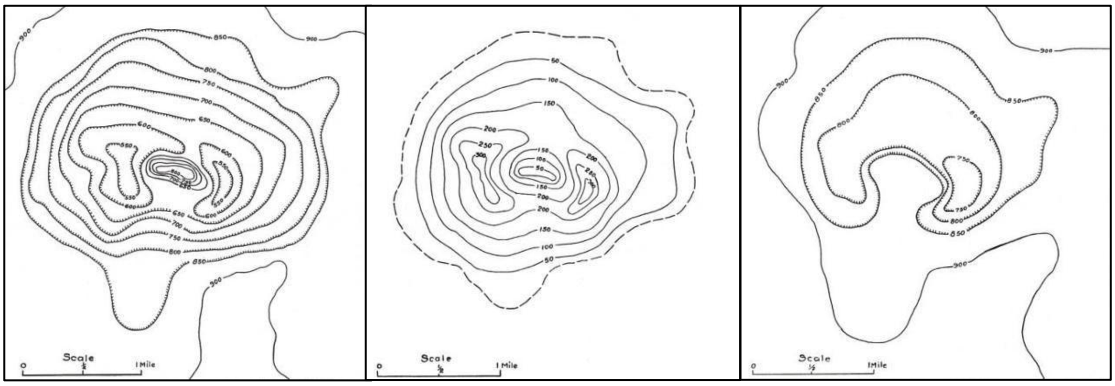


Figure 4.30 (left): Contour map of the pre-Chattanooga topographic surface (after Wilson and Born, 1936: 827).
Figure 4.31 (centre): Isopach map showing thickness of Chattanooga shale (after Wilson and Born, 1936: 828).
Figure 4.32 (right): Contour map showing the post-Chattanooga structure (after Wilson and Born, 1936: 829).

At the Flynn Creek site the Chattanooga Shale had "… its characteristic lithology, being a black, fissile, highly carbonaceous shale." (Wilson and Born, 1936: 822). Figure 4.30 is a contour map by Wilson and Born showing the topographic surface on which the Chattanooga Shale was deposited and Figure 4.31 is a map by Wilson and Born which shows the thickness of the black shale in the Flynn Creek structure. Around the structure, the shale has its normal thickness for the region, which is around 6 meters, but within the structure, the shale attains a thickness of more than 75 meters. Wilson and Born (1936: 826) explain that "Such variations in thickness indicate that the black shale filled a pre-existing topographic basin …" which would have been some 90 meters deep at the time. Figure 4.32, after Wilson and Born, is a contour map showing the post-Chattanooga Flynn Creek structure to be a closed, synclinal basin. Wilson and Born (1936: 826) note that "The overlying Fort Payne chert was deposited upon a relatively level surface of black shale …" and unlike the Chattanooga Shale, does not show any abnormal areas of thickness within the structure. The Fort Payne Chert does gently dip toward the center of the basin "… paralleling the slightly greater dips of the underlying black shale …" (ibid.).

Figure 4.33 is an east-west structural cross section, as mapped by Wilson and Born, which shows the thick black Chattanooga Shale overlying the shattered and brecciated Ordovician limestone. These two series of strata were found by these researchers to be separated by a marked unconformity with a maximum differential relief of around 90 meters within 0.8 kilometers. Wilson and Born (ibid.) give the following description:

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

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

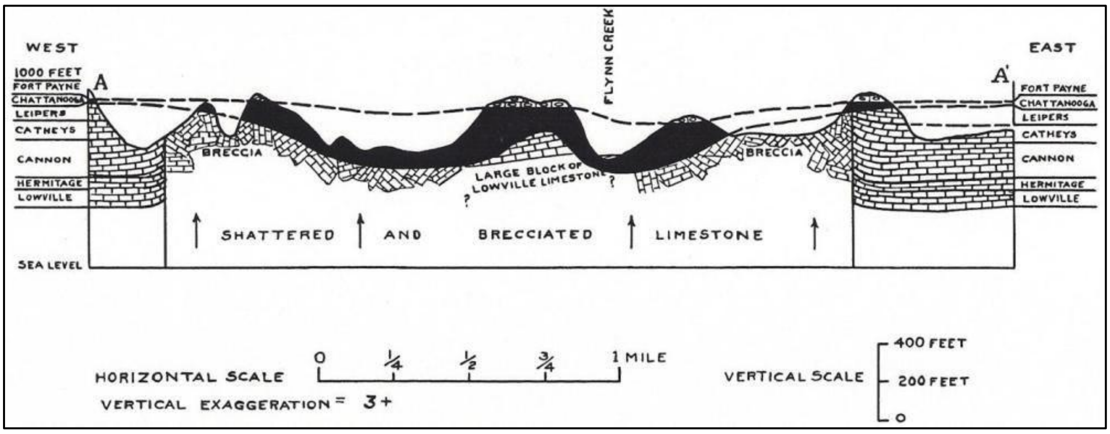


Figure 4.33: East-west structural cross section of the Flynn Creek site (after Wilson and Born, 1936: 824).

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

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

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

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

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

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

Figure 4.34 is a "Diagrammatic restoration of a section across the Flynn Creek disturbance‖ by Wilson and Born (1936). The diagrams show Wilson and Born's interpretation of the structure shortly after the Flynn Creek event in diagram A, after a period of erosion and pre-Chattanooga deposition in diagram B, and after the compaction of the Chattanooga Shale in diagram C (ibid.). In their opinion, the Flynn Creek explosion blew limestone blocks out of the crater, with some of the debris falling back into the crater and the rest scattering around the rim within a radius of several kilometers (ibid.).

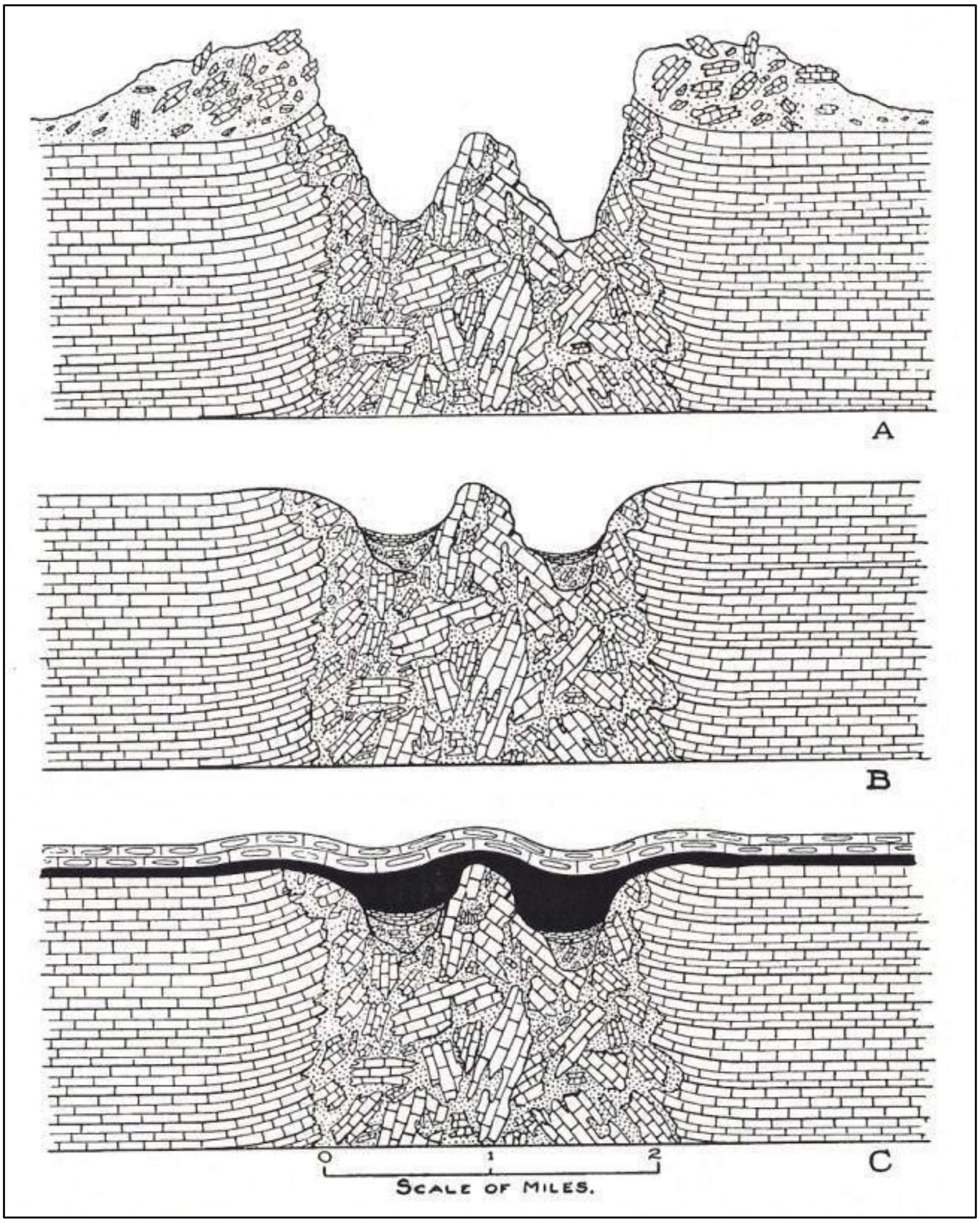


Figure 4.34: Diagrammatic restorations of a section across the Flynn Creek Structure (after Wilson and Born, 1936: 834).

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

In diagram C in Figure 4.34, the abnormal thickness of the Chattanooga Shale is seen, which can be attribute to the filling of the crater during the deposition of this formation. According to Wilson and Born (1936), the gentle dips, also shown in diagram C, are a result of the following:

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

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

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

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

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

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

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

Roddy's (1963: 121) diagram of the stratigraphic succession he found in the western section of the Flynn Creek Structure and the geological cross-section of the western rim of the Structure is shown in Figure 4.35. He notes in his description that the valleys surrounding the structure have as their lowest exposed stratigraphic unit Cannon Limestone which is conformably overlain by the Catheys Limestone, both from the Middle Ordovician. The Catheys Limestone is in turn overlain by the Late Ordovician Leipers Limestone. The next youngest stratigraphic unit is a breccia mass that "… occurs in a nearly circular area slightly more than 2 miles [3.2 km] in diameter …" (Roddy, 1963: 120). This breccia unit contains fragments of the Cannon, Catheys and Leipers Limestones as well as the even older Stones River rocks from the Middle Ordovician, all of which range in size from under a millimeter to blocks measuring up to hundreds of meters. In exposures, fragments of these different formations appear to be unsorted and set in a matrix of very fine crystalline and dolomitic limestone (ibid.).

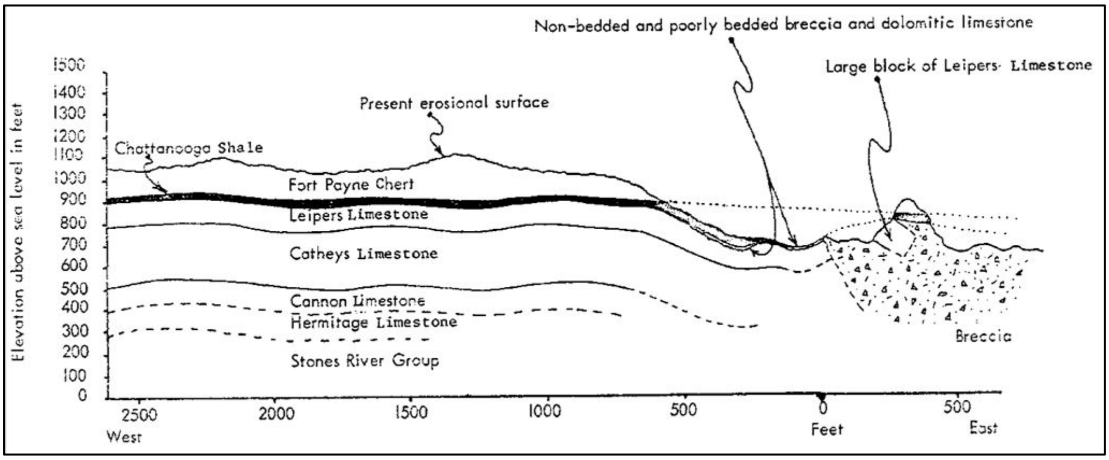


Figure 4.35: Cross-section of the western rim of the Flynn Creek Structure (after Roddy, 1963: 121).

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

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

Roddy (1963) noted that in this region of Tennessee the Chattanooga Shale was an extensive black shale unit with a nearly uniform thickness of some 8 meters. He also pointed out that outside of the Flynn Creek structure the Chattanooga Shale overlies the Upper Ordovician Leipers Limestone and that the contact does not contain breccia. Within the Flynn Creek Structure the Chattanooga Shale increases abruptly to over 35 meters above the depressed and deformed rim and to some 60 meters above the main breccia mass; however, it is only the lower member of the Chattanooga Shale that appears to increase in thickness (ibid.). In addition, away from the Flynn Creek Structure the Chattanooga Shale is nearly flat-lying, although in the Structure it dips as much as 21º and "All of the relatively high dips are inclined toward the thicker parts of the shale, which overlies the breccia …" (Roddy, 1963: 123).

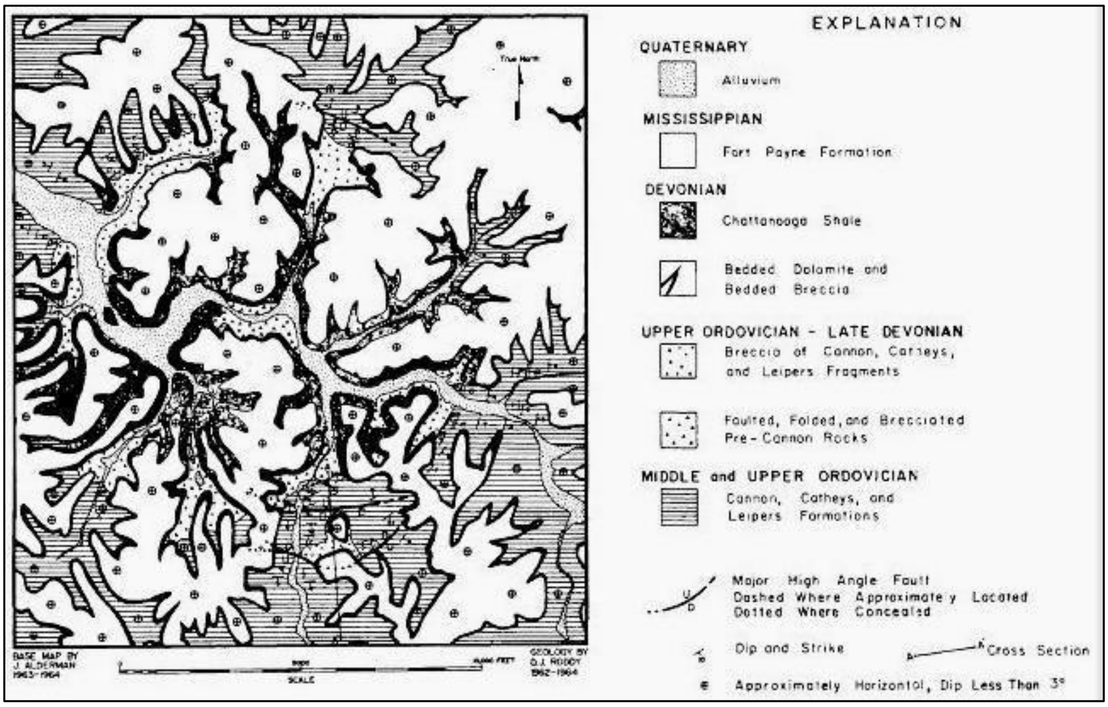


Figure 4.36: Generalized geological map of the Flynn Creek Structure (after Roddy, 1964: 166).

Figure 4.36 is a 1964 generalized geological map of the Flynn Creek Structure by Roddy. During the Late Devonian to the Early Mississippian time the structure was buried under hundreds of meters of rock, much of which was later removed by erosion. The crater floor is underlain by a mixed breccia except at the center where the partly-buried central hill rises around 100 meters above the crater floor. Roddy (1964: 164-165) describes this central uplift:

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

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

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

The eastern rim of the Flynn Creek Structure includes "… chaotic crater breccia which includes many large megabreccia blocks …" (Roddy, 1966c: 107). These blocks are around 45m long and 15m thick and dip toward the crater center at various angles. Here the rim tilts away from the crater and observed uplift near the breccia contact is some 45 meters over a horizontal distance of 760 meters. Roddy (1966c: 108) notes an unusual find in the eastern side of the Flynn Creek structure:

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

Roddy (1964: 163-164) states that his previous Flynn Creek field studies left some unanswered questions and did not address "… the geologic history of the southeastern rim and its bearing on the origin of the Flynn Creek structure." Breccia overlying the graben in the south-eastern rim are 50 meters above the crater floor, and yet are essentially identical to the breccia on the floor, "… except for a crude inversion of stratigraphy, and is interpreted as ejecta," (Roddy, 1968b: 297). Roddy (ibid.) determined that a section of the original, pre-crater ground surface is located at the base of the ejecta, and he noted that "The southeastern and southern rim contains the most complicated structures exposed in the entire rim …" (Roddy, 1966c: 115). Figure 4.37 is the geological cross-section of the southeastern rim of the Flynn Creek Structure by Roddy (1964: 167). Roddy points out that although the entire rim surrounding the Flynn Creek crater is tilted, folded and locally faulted, it is this southeastern section that is most intensely deformed; in this section "… there are faults with displacements on the order of 100 meters …" (ibid.).

Starting from 1200 meters south of the point where the crater breccia makes contact with the southeastern deformed rim, the Middle and Upper Ordovician beds are found to be in their normal sequence (Roddy, 1964). Going 400 meters north, these beds are found to be 10 to 15 meters higher. Another 150 meters north, "… a

300 meter deep test well showed no deformation of the subsurface strata …" except for the slight 10 to 15 meter uplift previously noted in the beds (Roddy, 1964: 168). About 50 meters north of the test well is a major, curved fault that is approximately concentric with the contact of the crater breccia, and the north side of this fault is displaced a minimum of 100 meters downward and dips north at angles that vary from 30º to 70º. Roddy (ibid.) reports that "… the displacement dies out to the northeast, and within 600 meters is only 10 meters …" The fault grades into a fractured, brecciated zone around some 800 meters to the west.

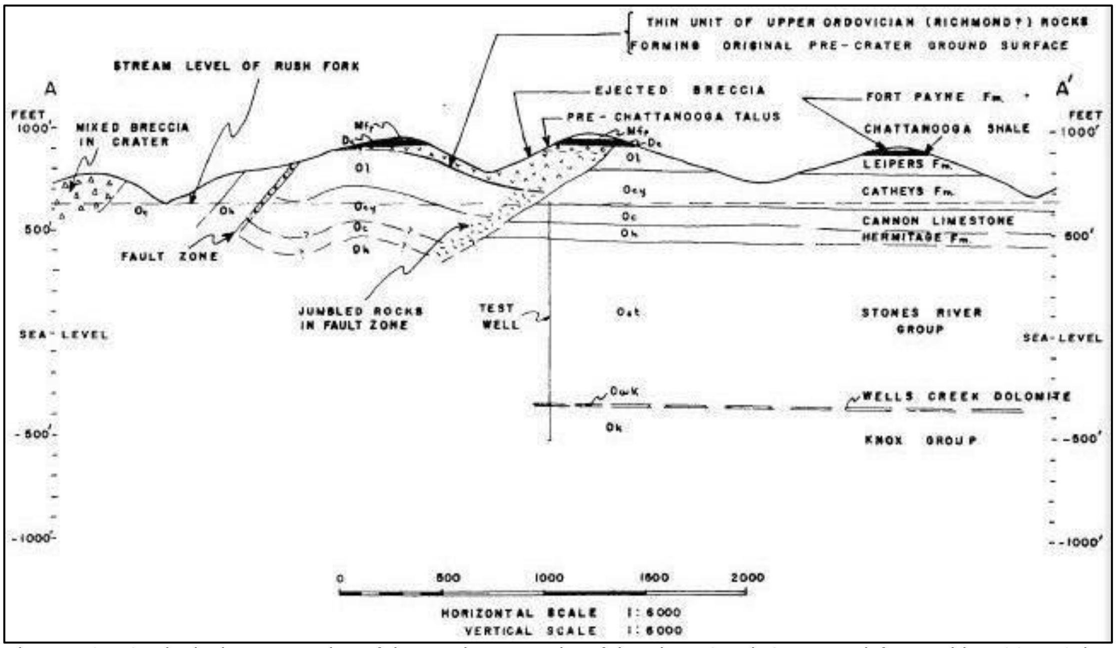


Figure 4.37: Geological cross-section of the southeastern rim of the Flynn Creek Structure (after Roddy, 1964: 167).

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Figure 4.38 shows generalized geological cross-sections of the Flynn Creek Structure prepared by Roddy "… shortly before deposition of Chattanooga Shale in early Late Devonian time." He points out an unusual type of fold shown in cross sections B-B' (northeast rim) and in C-C' (east rim) that suggests strong horizontal compression. These two folds "… have vertical axial planes, approximately concentric with the rim and with horizontal shortening on the order of 35 percent …" (Roddy, 1965: 59). The rock beds below the folds are not exposed, but the beds above flatten rapidly which suggests that considerable bedding plane slippage took place within the tightly folded strata, and "The beds forming these folds were less than 100 meters below the ground surface when the Flynn Creek deformation occurred …" (ibid.).

The cross-sections in Figure 4.38 show "… a major body of continuous breccia within the crater; a localized body of probable forcefully ejected breccia; and a central uplift of faulted, folded, and brecciated rocks." (Roddy, 1965: 58). Analysis of the breccia indicated that it was derived from the upper quarter of the rim‘s deformed strata. The breccias in the structure were all formed from the same rocks that are exposed in the surrounding sedimentary section, but do not contain any igneous or metamorphic rocks from depth, and “Deposition of the bedded breccia and crossbedded dolomite probably occurred in a coastal plain environment in the shallow waters of the slowly advancing Chattanooga sea …” (Roddy, 1965: 54). Roddy (1965) believed that for some time after the crater formed, the area consisted only of very low hills ranging from a few meters to perhaps as much as 20 meters with slopes less than 4 degrees.

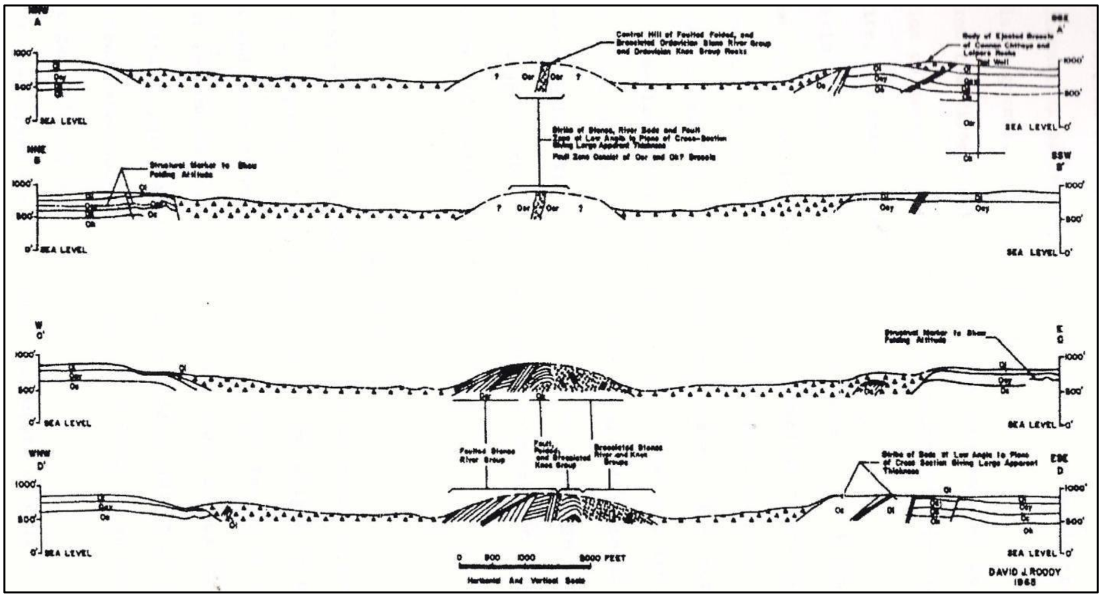


Figure 4.38: Generalized geological cross sections of the Flynn Creek Structure (after Roddy, 1965: 57).

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

According to Roddy (1966c: 157) "… the most intense twinning and microtwinning … is generally confined to the rocks immediately adjacent to the crater wall." Normal twin lamellae were common in the calcite found both within the Structure and in the surrounding undeformed strata. In the undeformed strata, however, twin lamellae were seen only in calcite crystals that were larger than ~100 microns. Twinning in these crystals consisted of one, two, or occasionally three sets of lamellae which ranged from 50 to 100 microns in width. These crystals rarely contained more than 10 lamellae and these were usually spaced at least 150 microns apart. Roddy (1966c) found two to three times the normal twin lamellae in the same size crystals outside of the deformed area and these were more likely to have two or more sets of normal twin lamellae as well as twinning in crystals as small as 20 microns. He also found a large increase in microtwinned lamellae in the deformed rim strata and some of the breccia fragments. In addition to highly-twinned calcite found in the crater rim, Roddy (1966c: 127, 129) found microfractures to be common in the fine-grained dolomites of the central uplift that appeared to be recrystallized or 'healed' fractures. Figure 4.39 is a sketch by Roddy of some of these calcite crystals. Roddy (1966c: 129) states that in these rocks, "… thin, irregular, clear bands up to 50 microns wide cut across grain boundaries without visibly disturbing each individual crystal, except that all inclusions are absent from the band."

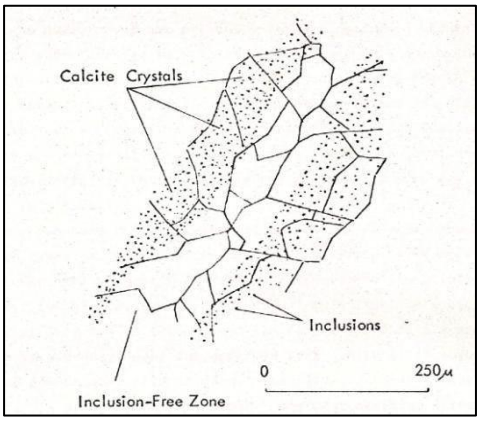


Figure 4.39: Calcite crystals with abundant inclusions cut by a zone free of inclusions (after Roddy, 1966c: 130).

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

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

> undisturbed below about 100 m beneath the breccia lens … Folding immediately below the base of the breccia lens extends 30 to 40 m deeper on the eastern side of the crater than on the western wide [side].
>
> The absence of lake deposits and a fallback zone and the occurrence of the bedded dolomitic breccia containing marine conodonts suggest that the shallow waters of the initial Chattanooga Sea occupied the area when the crater formed, probably in early late Devonian time. (Astrogeologic Studies, 1967: 29).

In his research for the Branch of Astrogeologic Studies, Roddy‘s (1968a: 272) final conclusion was that the Flynn Creek crater "… was formed in flat-lying limestones in northern Tennessee approximately 360×10^6 years ago."

Roddy noted that most of the structural elements he found at Flynn Creek, "… including a central uplift, occur in two craters formed by a 500-ton TNT hemisphere and a 100-ton TNT sphere detonated on alluvial surfaces at the Defense Research Establishment, Alberta, Canada …" (ibid.). The structural similarities between Flynn Creek and these chemical explosion craters indicated that a shock-wave process was responsible for the formation of the structure at Flynn Creek and that the deformational energy was concentrated in only the upper 300 meters of rock strata. This was confirmed to be the case by the six drill cores which also indicated that a surface-generated energy source was responsible for the cratering event:

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

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

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

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

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

> are observed are marine breccias derived locally within the crater and which are of early Late Devonian age.

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

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

> This crater, approximately 360 million years old, was initially ~3.8 km in avg. rim crest diameter (~3.5 km apparent) and ~180 m in avg. rim crest depth (~80 m apparent). Previous core drilling of six holes (762 m total) in the crater floor showed limestone and dolomite beds immediately below the base of the breccia lens (35 m avg. thickness) are intensely faulted and locally folded and brecciated, however deformation decreases downward and the strata is nearly flat-lying at depths of about 100 m below the base of the breccia lens.
>
> Core drilling completed in the outer crater floor area shows the strata underlying the breccia lens to be nearly 50 m lower than that in the adjacent inner rim and that the rocks are extensively faulted and locally brecciated. At depths of 350 m to 400 m in the same drill cores the relative displacement between the sub-crater floor and inner rim strata decreases to less than 30 m ...
>
> Preliminary reduction of the drill data from the central uplift indicates an abrupt transition from limited deformation in the rocks underlying the breccia lens on the crater floor to very complex deformed rocks beneath the central uplift. Uplift, including extensive faulting and brecciation, beneath the flanks of the central uplift is over 130 m at a depth of 50 m below the level of the original crater floor. Uplift in this same region decreases to only 15 m at depths of 340 to 360 m below the original floor. Exposures in the top of the central uplift show a maximum uplift of Knox strata of about 450 m. The drill data confirm uplift is due, in part, to extensive faulting and brecciation beneath the uplift region creating a locally decreased mass/volume relationship. The ring fault and clear-cut inward movement of sub-crater floor strata also contribute to sustained uplift. The drill data completed to date suggest that the central uplift formed so rapidly that the large sequence of exposed Knox strata was violently uplifted over 450 m to form a massive detached block underlain by previously higher strata. (Roddy, 1979a: 1031).

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

Figure 4.40 is a map by Roddy (1980: 942) showing the locations of the 1967 and 1978-1979 drill holes at Flynn Creek. Drill hole numbers 1 through 6 were drilled in 1967 along an approximate east-west diameter of the crater in order to investigate the thickness of the breccia lens and determine the nature of the underlying formation. The second phase of core drilling at Flynn Creek occurred from November 1978 to

November 1979 and consisted of 12 holes that were 3.5 cm in diameter and totaled 3064 meters:

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

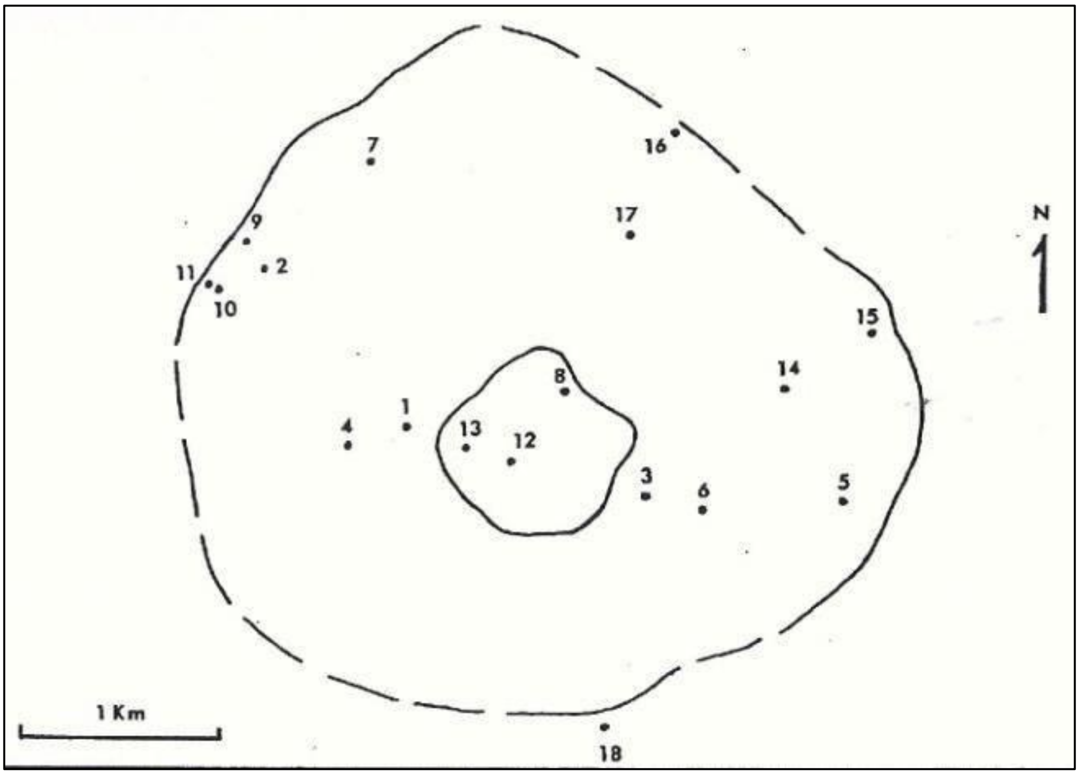


Figure 4.40: Location of 1967 and 1978-1979 drill holes at Flynn Creek (after Roddy, 1980: 942).

The "… shallow depth of excavation and deformation underlying essentially all the crater floor, except for the central uplift region …" was absolutely confirmed (ibid.). The crater floor averaged around 80 to 98 meters in depth below the pre-impact crater surface, the breccia lens was only 35 to 50 meters in thickness, and the strata underlying the breccia were undeformed, continuous, and flat-lying around 100 meters below the base of the lens which was around 200 meters below the pre-impact ground surface. The crater was the result of a broad, but shallow excavation cavity, with "… the crater diameter/ depth of cavity ~1/23 …" associated with a deep, but narrow central cavity containing the uplifted strata in the center (ibid.). The new 216 meter drill core from the southern graben indicated that the strata were basically flat-lying at depths of 50 to 75 meters below the pre-impact ground surface which led Roddy (1980: 942) to conclude that "… the graben or terrace block moved downward and slid towards the crater with relatively little secondary deformation or tilting."

Figure 4.41 is a cross-section of the Flynn Creek impact crater based upon surface geological and core drilling studies. Deformation in the eastern rim was primarily due to simple uplift. The western and northern rims were relatively flat except for some limited folding immediately outside the walls which caused the rock to dip into the crater. It was the southern rim that was home to the most developed terraces and the most complex deformation of Flynn Creek including "… a major rim graben partly overlain by a large thrust sheet …" (Roddy, 1979b: 2524).

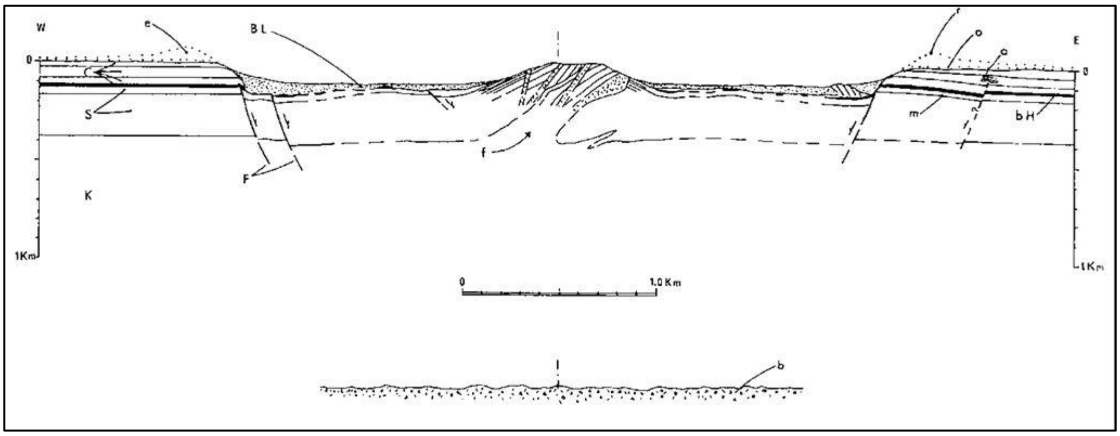


Figure 4.41: Schematic geological cross-section of Flynn Creek (after Roddy, 1979b: 2523).

Surface mapping and drill data indicated that the folded strata in the inner rim, crater wall, and outer crater floor were underlain by one or more concentric ring faults on the western, northern, and eastern sides of the crater. The down-dropped sides of these faults were towards the crater and maximum displacement appeared to have been no more than around 40 meters. "These faults appear to be relatively high-angle normal faults immediately below the folded strata …" as is shown in Figure 4.41 (Roddy, 1979b: 2527). The net effect of the concentric faulting served to lower the outer part of the crater floor from a few meters up to some 40 meters and tilt the subcrater floor strata away from the crater center. Roddy (ibid.) states that "… the drill data indicate that the total vertical displacement across the rim to the outer crater floor strata commonly takes place in a horizontal distance of 50 m or less …"

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

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

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

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

> Both the extensive surface exposures through the middle of the central peak above the crater floor level and the deep drill data indicate a westward plunge of this zone of subsurface deformation. The continuation of the dipping geologic contacts in the exposed rocks with the deep subsurface data on Knox and Stones River contacts indicates that the source of the uplifted Knox lies under the western flanks of the central peak and that it was uplifted and displaced strongly to the east.

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

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

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

Roddy (1979b: 2532) summarized his interpretation of the sequence of cratering events at Flynn Creek as follows:

> (1) oblique impact of a low density body such as a comet nucleus or carbonaceous chondrite … (2) oblique penetration into the rocks, including a possible very shallow body of water, to depths on the order of 100 to 200 m; (3) vaporization and melting of carbonate rocks and impacting body along penetration cavity; (4) total brecciation and ejection of a small bowl- to conical-shaped region which had a diameter of less than ~900 m and a very approximate depth of 200 to 250 m; (5) intensive bulking and disruption of the rock surrounding the central impact area and violent expansion and uplift into the partly opened central transient cavity; (6) broad anticlinal folding and faulting of sub-crater floor region caused by shock compression and initial outward expansion and relaxation; (7) continuous brecciation and excavation of the strata over the present crater floor area to a depth no greater than 150 m and out to approximately the present crater walls. This stage is probably continuous with the ends of stages (5) and (6); (8) continuous ejection of rocks from crater floor region to form an ejecta blanket with crudely-inverted stratigraphy surrounding the crater; (9) formation of concentric ring fault zones, probably as early as the end of state (6), with down-dropping and inward movement of sub-crater floor strata completing final reposition of deeper rocks.

Terrace formation probably continued to occur during this time. Final inward movements in the lower disrupted central uplift zone probably continued to close the deepest part of the partly opened transient cavity and sustain the uplifted strata. Elsewhere in this paper Roddy (ibid.) points out that these suggested stages most likely overlap and are transitional in time with each other.

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

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

Recent research has led to the recognition that some of the Flynn Creek breccias primarily consist of black shale clasts that are most likely derived from the Upper Devonian Chattanooga Shale and apparently do not contain limestone or dolomite clasts derived from the Nashville, Stones River, or Knox Groups which are

Ordovician in age, which "… suggests an early syn-depositional impact event rather than Ordovician or pre-Chattanooga Shale impact …" (Evenick et al., 2004: 1). Thin sections prepared from Flynn Creek breccia have been found to display rare flow textures and minor spot melt at grain boundaries. "The presence of spot melt and flow textures further confirm the structure's impact origin …" (ibid.).

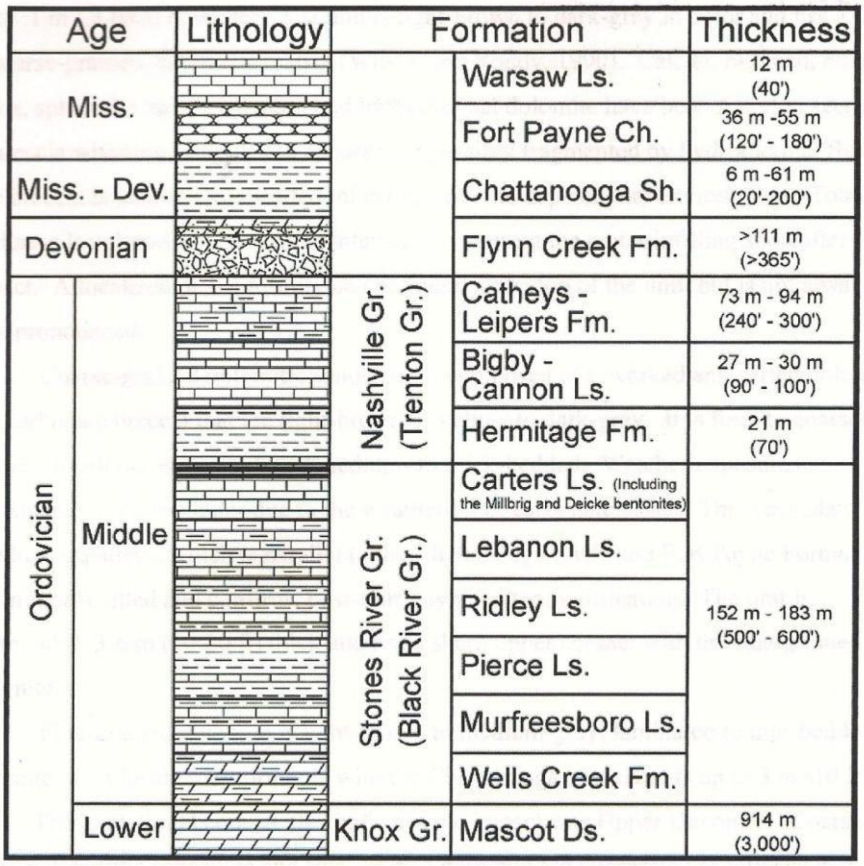


Figure 4.42: Stratigraphic column of Gainesboro quadrangle (after Evenick, 2006: 3).

The Flynn Creek crater fill in relatively recently has been "… separated into four categories (called the Flynn Creek Formation): non-bedded breccia, bedded breccia, course-grained dolomitic sandstone, and fine-grained dolomite. This Formation is found only within the crater …" (Evenick, 2006: 1). Drilling data indicate that the Flynn Creek Formation is over 111 meters thick, as is shown in Figure 4.42, a stratigraphic column of rock exposed in the Gainesboro quadrangle, which includes the Flynn Creek area (cf. Evenick et al., 2005). The basal breccia unit in the Flynn Creek structure is the non-bedded breccia, predominately composed of angular and unsorted limestone along with minor dolomite and chert clasts that are up to 0.3 meters in diameter.

The bedded breccia overlies the non-bedded breccia and is composed of angular and unsorted limestone, minor dolomite, chert and shale clasts up to 0.1 meters in diameter. "The breccia is locally crossbedded inferring a marine depositional environment … This unit is inferred to represent the crater infilling soon after impact …" (Evenick, 2006: 4). The coarse-grained dolomitic sandstone is around 3 to 6 meters thick and composed of reworked and sorted dolomite and carbonate breccia. It has a sharp upper contact with the fine-grained dolomite which is light-brown to medium-gray and laminated to thin-bedded dolomite. This unit is up to 3 meters thick and locally conformable with the Chattanooga Shale. The gradational contact also indicates the impact was upper Devonian. "Course-grained dolomitic sandstone and fine-grained dolomite are interpreted as fallback and ejecta that washed into the crater following impact …" (ibid.).

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

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

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

Schieber and Over (2005: 64) state that

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

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

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

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

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

4.3.4 Cratering Mechanics

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

According to Roddy (1977b: 296) a basic effect of the very high shock pressures during an impact event is that the impactor and the target rock "… respond hydrodynamically, temporarily exhibiting a fluid behavior." This is because the strength of the impactor and the target rock would be exceeded by factors of 10-cubed or more, literally causing them to flow. Following is Roddy's (1977b: 297) description of the excavation of a crater such as Flynn Creek:

> The basic mechanism for pressure release lies in the interaction of the shock waves with all free surfaces. Stated simply, material semi- infinitely deep in a shocked zone moves only in the direction induced by the shock wave. Near a free surface, however, material experiences a different unloading path due to the fact that an unconfined free surface cannot support stress across that surface, i.e., continuity conditions require an instant equilibration of the stress field. Consequently, the high pressure zones created in the target and projectile, together with very low surface pressures, define a decreasing stress gradient along which material can be accelerated and ejected. The practical result is that the free surface moves. The point is that impact craters, at least in hard rock systems, are *not* formed during the very high pressure compression stage. Instead, they form as a response to the later dynamic rarefaction fields developed along all free surfaces.

Roddy (1976: 121) describes Flynn Creek as a "… large, flat-floored crater, 3.6 km in diameter and over 200 m deep …" resulting from an impact that violently fragmented over 2.0 cubic km of flat-lying Middle and Upper Paleozoic limestone and dolomite.

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

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

Milam and Deane (2005: 2) give the following description of the probable sequence of events for formation of the central uplift of a complex crater such as Flynn Creek. Pre-impact deposition of target rock and its subsequent lithification and diagenesis may have involved the generation of some microfractures. However, the passage of the compressional front of the shock wave due to impact results first in the production of shatter cones and shocked minerals and then, due to subsequent decompression, the generation of microfractures (ibid.). The result of such deformation is the weakening of target rock material which in turn allows for "… potential pathways for subsequent movement of large blocks of material from the centers of craters …" (Milan and Deane, 2005: 1). During the rise of the central uplift, microfault movement and microbreccia generation take place which is immediately followed by major fault movement and fault breccia generation. Major faults are likely responsible for and represent the final stages of central uplift formation. Roddy (1977b: 302-303) estimates that the entire cratering process and sequence of events, including the rise of the Flynn Creek central uplift, took only 20 to 60 seconds. Fracturing due to weathering has and will continue to occur as part of the structure's overall, long-term modification process (see Milam and Deane, 2005).

4.3.5 Crypto-Controversies

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

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

Lusk (ibid.) pointed out that "Bucher has described a circular area of intense folding and faulting … [and referred to it as a] crypto-volcanic … [structure].

However … the conglomeratic nature of the breccia and the absence of veins or dikes of possible igneous origin discourages the view that sub-surface vulcanism may have been the cause …" (ibid.). After considering all of the observed facts discussed above, Lusk (1927: 580) concluded:

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

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

Although Lusk (1927) did come to consider, with some reservations, the Flynn Creek structure to be a ~60 meter deep pre-Chattanooga sinkhole resulting from a cavern collapse, Wilson and Born (1936: 832-833) considered the evidence and disagreed with his conclusions as to the cause and the depth:

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

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

> The present writers did not find sufficient evidence of rounding, or "conglomeratic nature," of the breccia, and hence believe that all breccia but that designated as talus breccia resulted from the mechanical fragmentation of limestone and subsequent cementation. Also, they cannot accept the absence of veins or dikes of igneous origin at the surface as sufficient to eliminate a possible volcanic origin.

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

1. Disturbances produced by the explosive release of gases under high tension, without the extrusion of any original magmatic material, at points where there had previously been no volcanic activity ("abortive volcanism"): Cryptovolcanic structures.

(a) The explosion, too deep-seated, too weak, or too unconcentrated ("muffled"), results merely in the more or less circular dome and ring structure …

(b) The explosion, shallow and strong enough, blows out a shallow more or less circular explosion basin filled with a jumble of distorted blocks and surrounded by a zone of materials blown or pushed out from it …

2. Features produced largely by the explosive release of gases under high tension, with magmatic materials more or less subordinate to fragments of the overlying rocks, at points where there had previously been no volcanic activity ("embryonic volcanism"): "Funnels," "chimneys," "pipes" filled with volcanic breccias or tuffs …

The explanation of the cryptovolcanic structures here presupposes that in plateau regions seemingly devoid of volcanic activity magma is at times working its way locally upward through the crystalline basement complex into the sediments above, without actually breaking through. The few examples in which erosion has cut low enough to expose such places are of unusual interest.

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

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

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

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

Wilson and Born (1936: 828) considered each of these possible origins for the Flynn Creek Structure, taking into account the fact that any theory of origin for the structural features in the Flynn Creek area must explain the following:

(1) a central uplift of approximately 500 feet [150 meters], bringing relatively old beds (Lowville) up to the level of younger beds (Leipers); (2) the intense brecciation of the Ordovician limestone, and the grinding, or pulverizing, of much of the limestone into 'rock flour'; (3) the striking ability of breccia to actually force its way into fractures in unbrecciated limestone in a way suggesting dike intrusion; (4) the shattering of the Ordovician limestone into large blocks, and the irregular jumbling of these blocks; (5) the dip away from the central uplift on the northern, eastern, and western flanks; (6) the dip into the central uplift on the

> southern flank, and the thrusting away from the center of uplift on that side; (7) a closed, irregular topographic depression with 300 feet [90 meters] relief on the pre-Chattanooga surface, the deformation being post-Leipers, pre-Chattanooga in age; (8) the abnormal thickness of the black shale (250 feet) [75 meters]; (9) the closed synclinal basin in the black shale and overlying Fort Payne chert, centered over what was originally an uplift (this is rather unusual in a region where anticlines and synclines were formed early in the Paleozoic, and all subsequent diastrophic movements rejuvenated these earlier structures as anticlines and synclines, respectively); (10) a well-developed magnetic high centered about 4 miles south-southwest of the disturbed area. (This magnetic high is believed to be the surface expression of the postulated buried plug of igneous material responsible for the Flynn Creek disturbance. The offset of 4 miles [6.4 km] to the south-southwest is the result of the high-angle dip to the north of magnetic lines of force in the earth's surface.)

Figure 4.43 is a map showing magnetic intensity found in and around the Flynn Creek structure, as well as the location of the crater in relation to the magnetic high mentioned above.

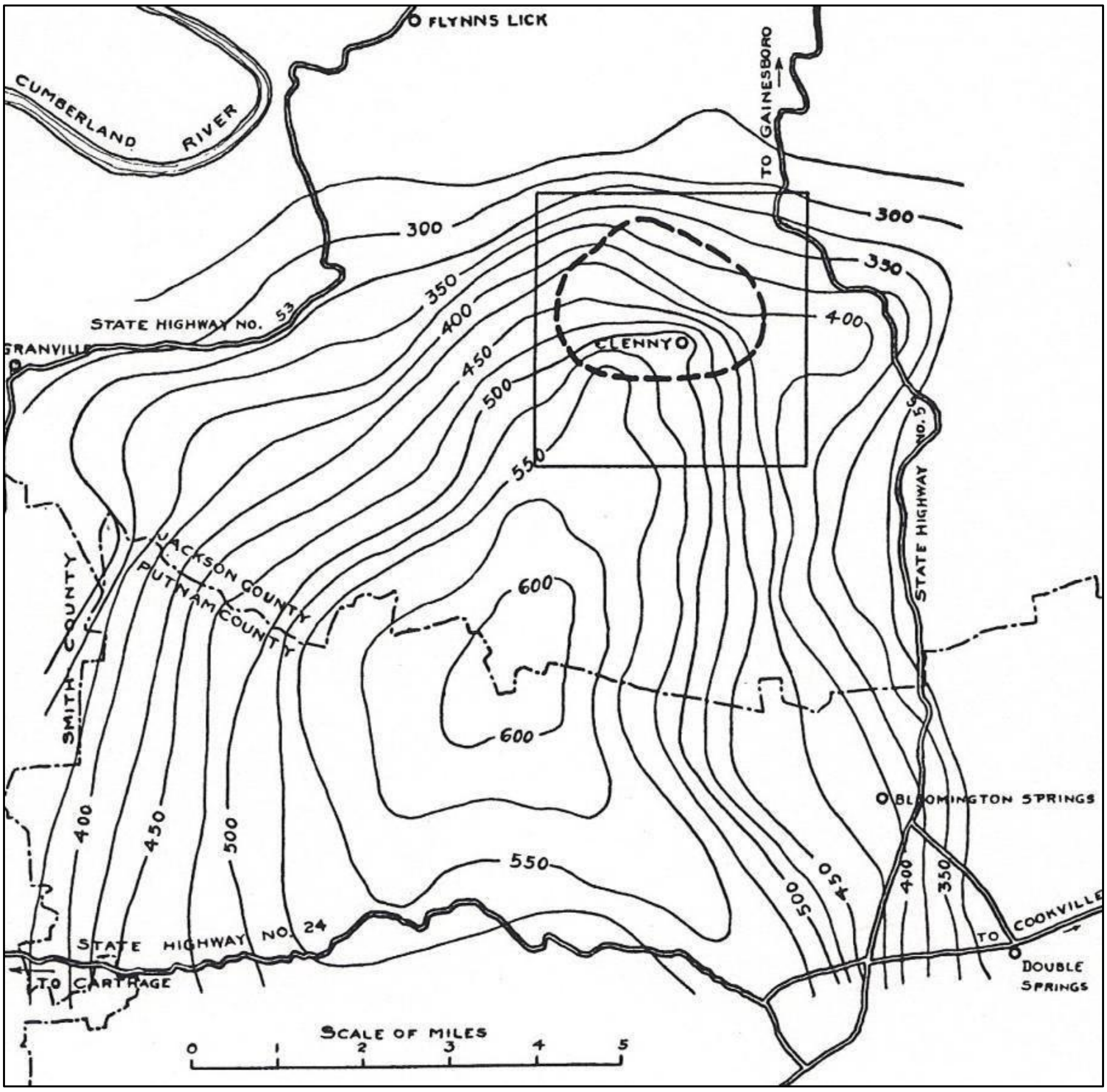


Figure 4.43: Isogammal map showing magnetic intensity in the Flynn Creek area (after Wilson and Born, 1936: 830).

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

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

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

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

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

> 1. Deposition of the Lowville, Hermitage, Catheys, Cannon, and Leipers formations. If younger Ordovician or Silurian formations were deposited, they were removed by pre-explosion erosion, as the Leipers is the youngest formation involved in the explosion.
>
> 2. A volcanic explosion, blowing out a crater 300 feet [90 meters] deep and 2 miles [3.2 km] in diameter, and piling up limestone debris in the vicinity of the crater at some time between the deposition of the Leipers and Chattanooga formations [see Figure 4.34-A]. This explosion preceded the deposition of the Chattanooga shale sufficiently to permit removal of all blocks of limestone around the crater [see Figure 4.34-B].
>
> 3. Accumulation of talus in the deeper part of the crater, resulting from gravity rolling and slope wash of rock debris into the crater [see Figure 4.34-B].
>
> 4. Formation of a fresh-water, ring-shaped lake that occupied the crater and surrounded the central hill leaving it an island. In this lake was deposited as much as 12 feet [3.7 meters] of bedded breccia [see Figure 4.34-B].
>
> 5. Transgression of Chattanooga sea, which filled the crater with 250-300 feet [75-90 meters] of black mud and covered the surrounding region with 20 feet [6 meters] of similar sediments [see Figure 4.34-C].
>
> 6. Deposition of Fort Payne chert.
>
> 7. Subsequent local synclinal sagging caused by compaction of the underlying Chattanooga shale and by subsurface readjustment following explosion.

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

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

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

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

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

Dietz (1959: 498) believed that the most remarkable aspect of a cryptoexplosion structure is the central uplift, surrounded by a ring syncline, which gives the structure a remarkable resemblance to that of a damped wave. Dietz (1959: 499) explained that according to the meteorite hypothesis, a central uplift may be formed by an elastic rebound of the highly-compressed target rock following an explosive impact, and it "… is likely that giant meteorites strike the earth's surface at hypervelocities, defining this term here to mean velocities in excess of the speed of sound in average rock, i.e., in excess of 5 km/sec …" (ibid.). The target rock would be subjected to an intense shock wave which would greatly compress a cylinder of rock beneath the meteorite. Following the impact explosion, "… compressed rocks might elastically recoil past the zero position into a dome. This dome would be damped or 'frozen' by the formation of tension cracks …" (ibid.).

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

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

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

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

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

> According to the meteorite-impact hypothesis, cryptoexplosion structures are explosion-percussion deformations produced by the hyper-velocity and explosive impact of crater-forming meteorites of asteroidal dimensions – a concept developed by J.D. Boon and C.C. Albritton … [These] meteorite-impact scars … [are] ephemeral geologic features which are rapidly eroded away, but the jumbled mass of shattered rock which must extend for several thousand feet beneath an impact crater stands an excellent chance of geologic preservation. (Dietz: 1959: 497498).

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

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

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

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

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

Roddy‘s 1964 report on the Flynn Creek Structure included a magnetic field study performed in order to obtain information on the subsurface structure. The result of the magnetic measurements "… shows there is no large magnetic anomaly associated with the structure …" (Roddy, 1964: 175). Roddy did note a northeast-southwest trending magnetic trough extending across the area, though, as is shown in Figure 4.44. This map shows that a closed magnetic low around 6.5 kilometers southwest of the crater forms the lower end of the magnetic trough.

Based on this map, Roddy (1964: 175, 177) made the following observations:

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

Neither gravity nor magnetic studies indicated any large anomalies directly associated with the Flynn Creek structure (Roddy, 1966c). Figure 4.45 is a complete Bouguer anomaly map of the Flynn Creek area (after Roddy, 1968b: 305), which shows the location of the Flynn Creek crater in relation to the locations of the gravity stations utilized in the geophysical study.

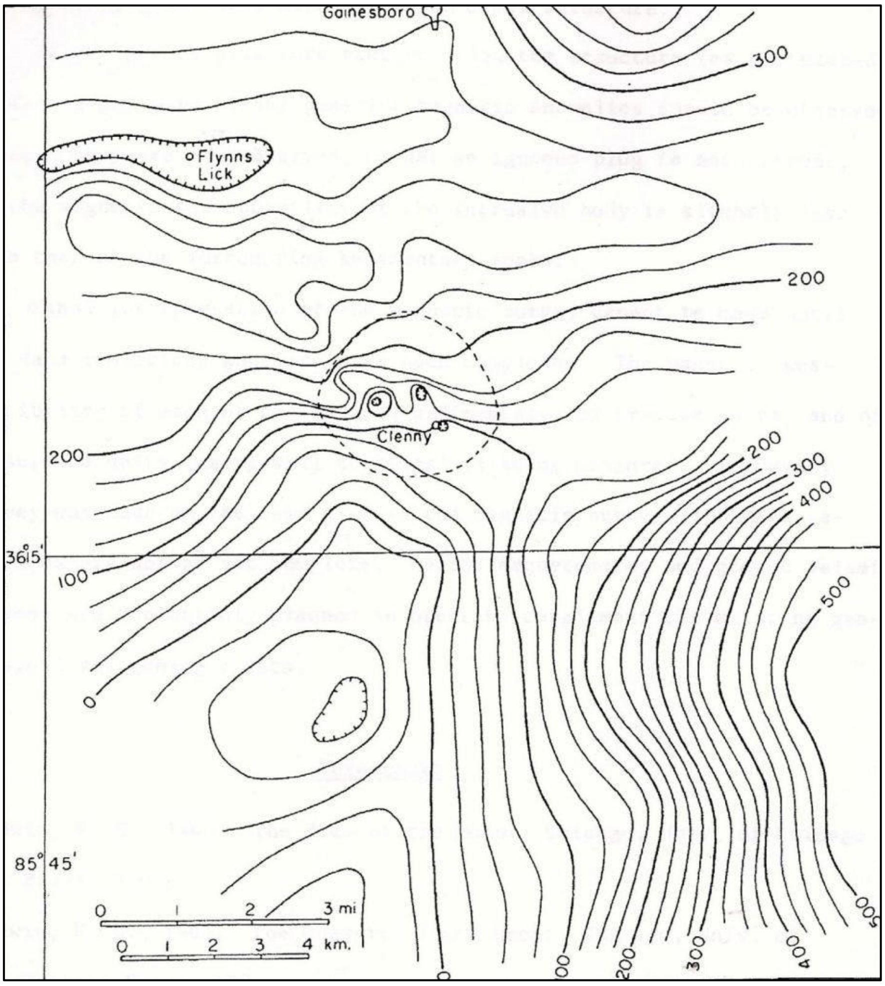


Figure 4.44: Total intensity magnetic anomalies in the Flynn Creek area (after Roddy, 1964: 176).
The Flynn Creek Structure is shown by the dashed outline.

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

Miller (1974: 58) also reported that neither volcanic nor meteoritic material has ever been found at Flynn Creek and that "… studies show no magnetic anomalies which might be associated with buried meteoritic material." He concludes that "Comparison with other craters of known meteorite impact origin shows similarities, therefore, it is assumed that either a meteorite or comet impact formed this structure

…" (ibid.). Milam and Deane (2007: 1) also examined Flynn Creek breccias, and their preliminary results suggest "… a lack of chondritic or iron meteoritic component remaining in the breccias or post-impact fill of the Flynn Creek impact structure …"

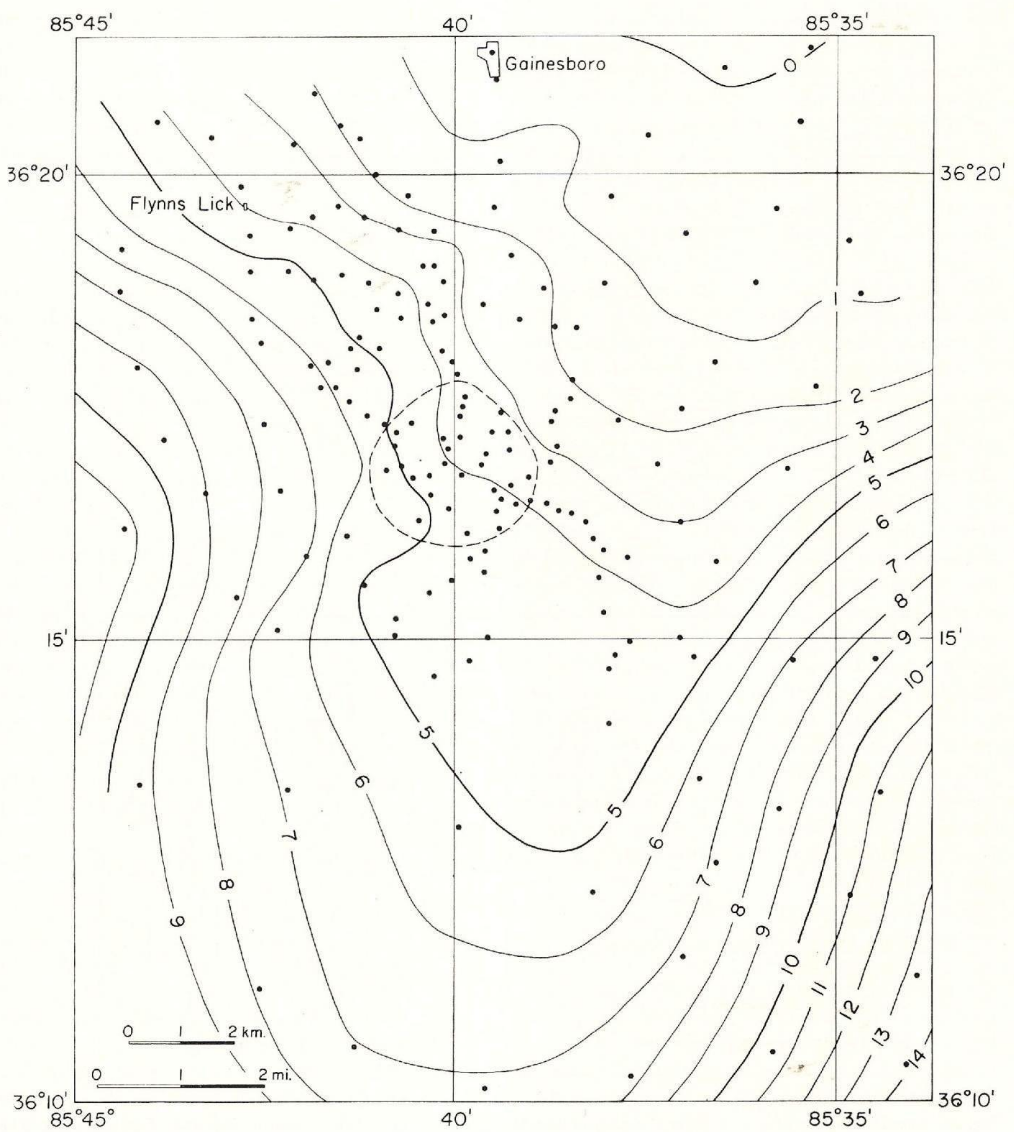


Figure 4.45: Complete Bouguer anomaly map of the Flynn Creek area (after Roddy, 1968b: 305). Gravity stations are indicated by dots. The Flynn Creek Structure is shown by the dashed outline.

In his Ph.D. thesis Roddy (1966c: 152) addressed various origins suggested for the Flynn Creek structure. He rejected the possibility of a cavern collapse because rocks in the crater were raised far above their normal stratagraphic level. The possibility that Flynn Creek was a salt dome or the result of anhydrite expansion or a natural gas blowout was rejected, primarily because neither evaporites nor high pressure gas deposits had ever been found in central Tennessee, nor did Flynn Creek resemble the types of structures these would produce. He ruled out tectonic folding, stating that the type necessary to form a structure such as Flynn Creek was not present in the area. Hydraulic fracture by water was not considered to be likely because there was no known way for sufficient water pressure to build up; nor would this method produce a structure that resembled Flynn Creek. He also noted that "Mineralization related to hydrothermal or volcanic processes has not been recognized in the Flynn Creek area …" (Roddy, 1966c: 179), and "No thermal metamorphic effects have been noted either in the field or in petrographic studies …" (Roddy, 1966c: 183). He further pointed out that in the Flynn Creek rim strata, large-scale folding appears to have had the major stress component in the horizontal direction. Roddy (1966c: 186) therefore concludes that the simple build up of gas pressure near the surface, in other words, a volcanic gas or steam explosion, would not explain the Flynn Creek rim folds having their major stress component in the horizontal direction.

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

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

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

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

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

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

Researchers at the Suffield Experimental Station in Alberta, Canada, had detonated a 500 ton TNT charge on the ground surface in June 1964 which produced a chemical explosion crater with "… such pronounced structural similarities to the Flynn Creek crater that a visit was arranged for the author [Roddy] by the U.S. Geological Survey and the Canadian Government." (Roddy, 1966c: 201). The resulting crater was shallow, flat-floored, around 100 meters in diameter, and originally 6.5 meters deep with a 5.5 meter high central uplift (Roddy, 1968b). Material thrown out of the crater formed an ejecta blanket that was continuous to around 130 meters from the crater walls (ibid.). This crater is still visible today and can be seen on Google maps at the location given by Roddy (1977a). The following quotation is taken from Roddy's (1966b: 203, 205) Ph.D. thesis, and is based on his observations and on interviews with Suffield Experimental Station personnel, including Dr. G.H.S. Jones, who was in charge of the large-scale explosion experiment (see Schaber 2005: Appendix A, page 256):

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

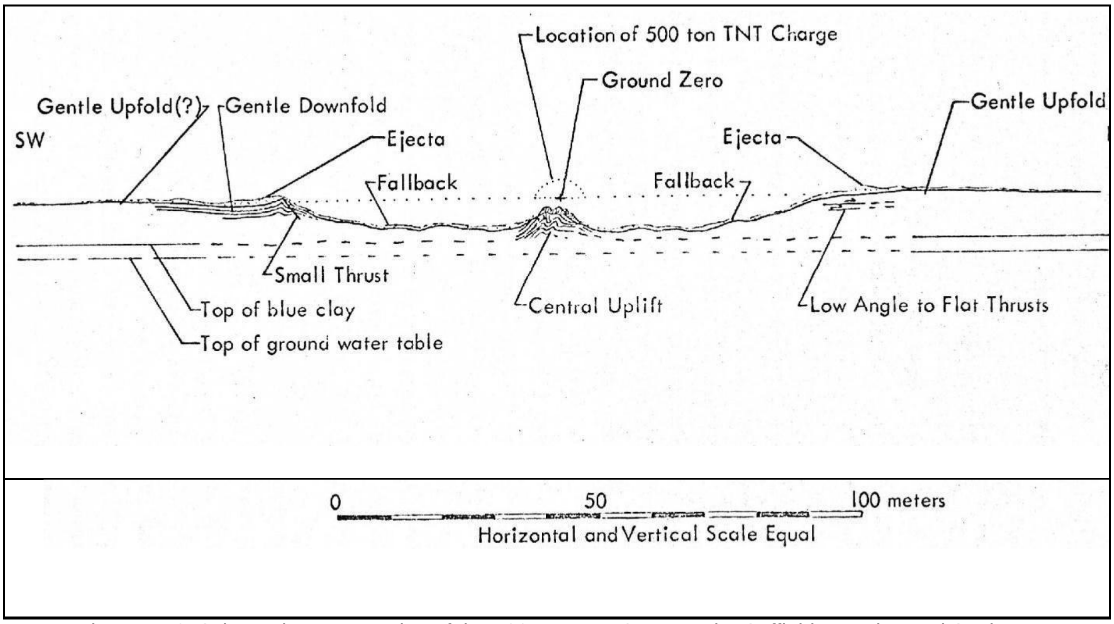
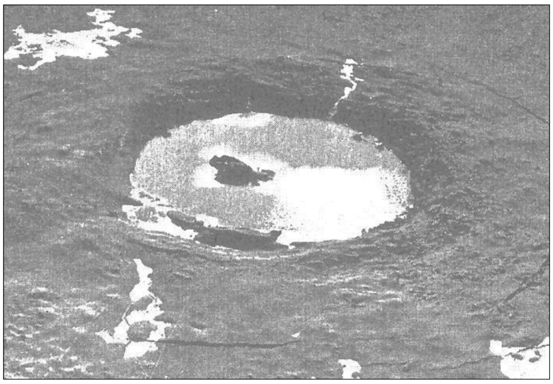


Figure 4.46: Schematic cross section of the 500-ton TNT Crater at the Suffield Experimental Station, Alberta, Canada (after Roddy, 1966c: 204).

Figure 4.46 is a schematic cross section of the 500-ton TNT Crater at the Suffield Experimental Station based on sketches Roddy (1966c: 204) made in the field. Affectionately known as the ‘Snowball Explosion Crater’, this “… has nearly identical structural deformation in all respects with the Flynn Creek crater … In fact, this particular surface burst produced nearly every structural feature found in the Flynn Creek crater …" (Roddy, 1966c: 207, 210), and "The three ratios of diameters vs. shear strengths, diameters vs. distances to concentric fracture zones, and diameter vs. depth to deepest horizons exposed in the central uplifts, are nearly identical for both the Flynn Creek crater and the 500-ton TNT crater …" (Roddy, 1968b: 318).



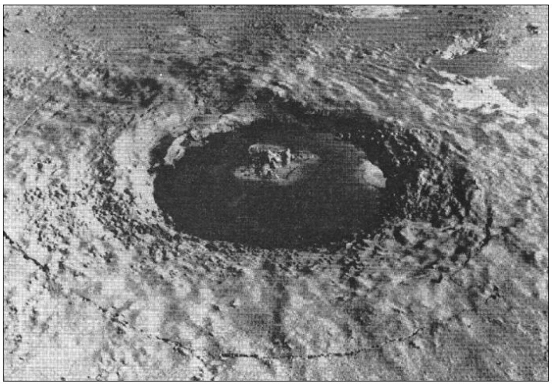


Figure 4.47 (above): An aerial view of the 500-ton TNT Crater one day after formation, showing concentric fractures and the central hill. The light-colored areas are sands deposited during water flow from the fractures and the lake in the crater was formed by water flow from fractures within the crater (after Jones, 1977: 164; cf. Roddy, 1968b: 314).

Figure 4.48 (top right): Another aerial view of the 500-ton TNT Crater one day after formation, showing concentric fractures, the central hill, structural terraces on the crater walls and the irregular distribution of eject blocks (courtesy: Dr G.H.S. Jones; after Roddy, 1968b: 315).

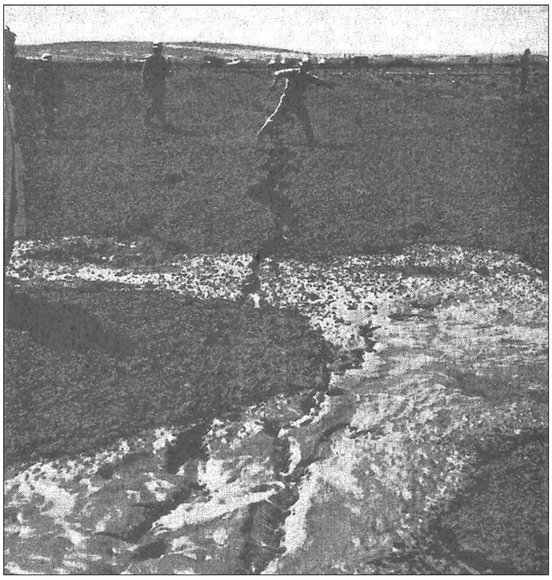


Figure 4.49 (right): A close-up view of one of the concentric fractures at the 500-ton TNT Crater (after Roddy: 1968b: 317). Note light-colored sand deposited during water flow from the fracture and people in background for size comparison.

Figure 4.47 is a view of the 'Snowball Explosion Crater' one day after its formation. The photograph shows the central uplift as an island, in addition to the concentric fractures which formed around the crater. Figure 4.48 is another view of the Snowball crater from a different angle on the same day, allowing a better view of the terraced wall. Jones (1977) states that the terracing was produced by late stage slumping.

Figure 4.49 is a ground view of the crater showing a close up of the concentric fracture that developed around 110 meters from ground zero and the sand that was deposited when water flowed from the fractures. Jones (1977: 182) stated that "… the ejecta blanket consisted of a coherently overturned, stratigraphically inverted expression of the pre-existing stratigraphy." Jones also pointed out that "This overturning is clearly not due to sequential fall-out of the ejected material, but is a coherent roll-back of the strata …" (ibid.). Taking into consideration the close structural similarities between Flynn Creek and the 500-ton TNT Snowball crater, Roddy (1966c: 201) concluded that the Flynn Creek crater was "… also produced by a shock-mechanism, in this case an impact …"

The morphological and structural features of the Flynn Creek Crater, the 500-ton TNT 'Snowball Crater' and the lunar crater Copernicus are compared by Roddy (1977a: 205). The terrestrial, the chemical explosion, and the lunar crater all display a flat floor, central uplift region, and terraced walls, as does the lunar crater Pythagoras, which is also shown in Figure 4.50 with the other three craters. Roddy (1977b: 302) concluded that all of the terraces resulted from late-stage slumping.

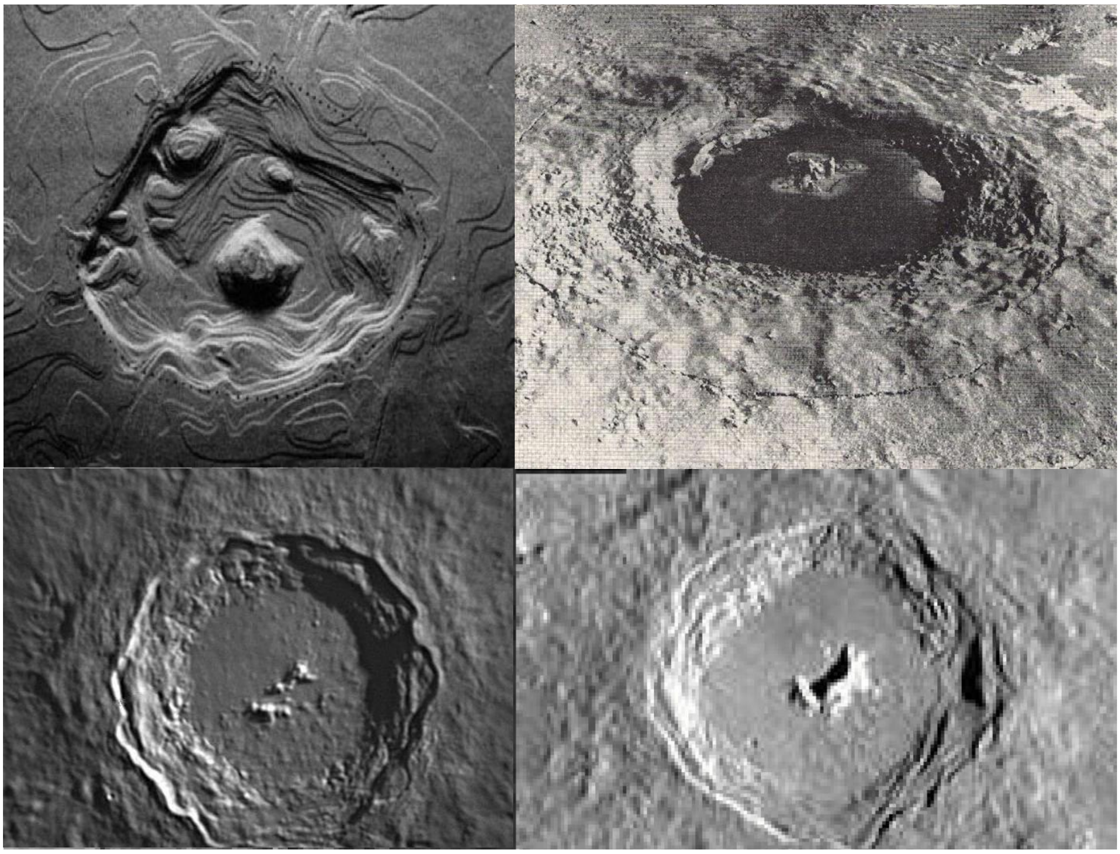


Figure 4.50: Crater comparisons. Left top: The Flynn Creek model (Roddy, 1977b: 206); right top: the 500-ton TNT 'Snowball Crater' (Roddy, 1977b: 206); bottom left: the lunar crater Copernicus (www.footootjes.nl/Astro photography_Lunar); and bottom right: the lunar crater Pythagoras (European Space Agency).

The similarities in the above images are striking indeed. Figure 4.51 further explores their similarities by comparing the geological cross-sections of the Flynn Creek crater, the 'Snowball' 500-ton TNT explosion crater, and lastly, a "… schematic of the lunar crater, Copernicus, drawn with the actual lunar curvature …" (Roddy, 1977a: 209). Roddy (1977a: 193) now points out another interesting similarity that these three craters share: estimating the immediate post-crater diameter, *D*, and depth, *d*, based on their rim crests, he found *D*/*d* to be 3830m/198m = 19 for Flynn Creek, 108.5m/7.5m = 15 for 'Snowball', and 79km/4km = 20 for Copernicus.

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

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

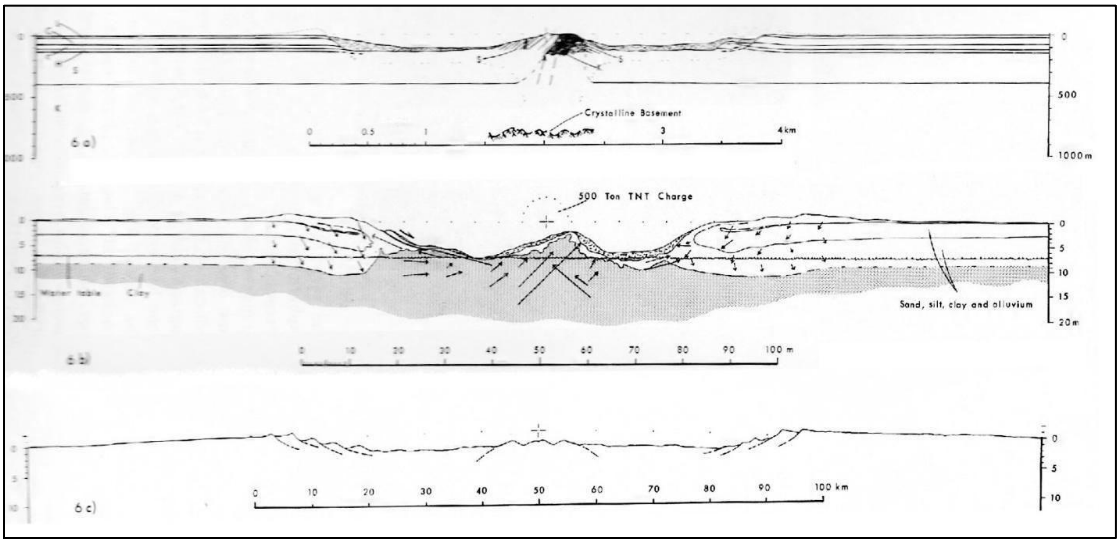


Figure 4.51: Geological cross-sections of the Flynn Creek (top), Snowball (middle), and Copernicus (bottom) craters (after Roddy, 1977a: 208209).

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

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

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

Later Roddy et al. (1980: 943) argued that low-density impactors such as cometary nuclei or carbonaceous chondrites would form flat-floored craters with central uplifts because "… the impacting bodies act as distributed energy sources that never produce deep transient cavities … [and that Flynn Creek] is quite shallow with an aspect ratio of crater diameter/crater depth ~ 1/35 …" In addition, excluding the central uplift, the depth of the breccia lens underlying the crater floor plus the depth to the bottom of the deformed strata underlying the breccia lens is around 250 meters below the pre-impact ground surface, which indicates a crater diameter/deformation depth ~1/14.

Figure 4.52 shows "… calculation profiles of two impact craters at end of numerical solutions in graphite target …" (Roddy et al., 1980: 945); Figure 4.52a shows "… a water sphere (ρ = 1.0 g/cm^3) impacting a graphitic solid at ~4 km/sec …" which results in a bowl-shaped crater (Roddy et al., 1980: 944); and Figure 4.52b shows a comparison impact produced by "… a *very low density* (0.05 g/cm^3) porous water sphere onto the same graphite …" also traveling at 4 km/sec, and producing "… a very broad, shallow, flat-floored crater with an aspect ratio of *only* ~1/14," (ibid.; his italics). Roddy (ibid.) points out that the theoretical calculations of such a cratering event indicated that a low-density impactor was at least capable of producing a flat, shallow crater, with the sub-surface deformation limited to very shallow layers and to a small central section, as is seen at Flynn Creek.

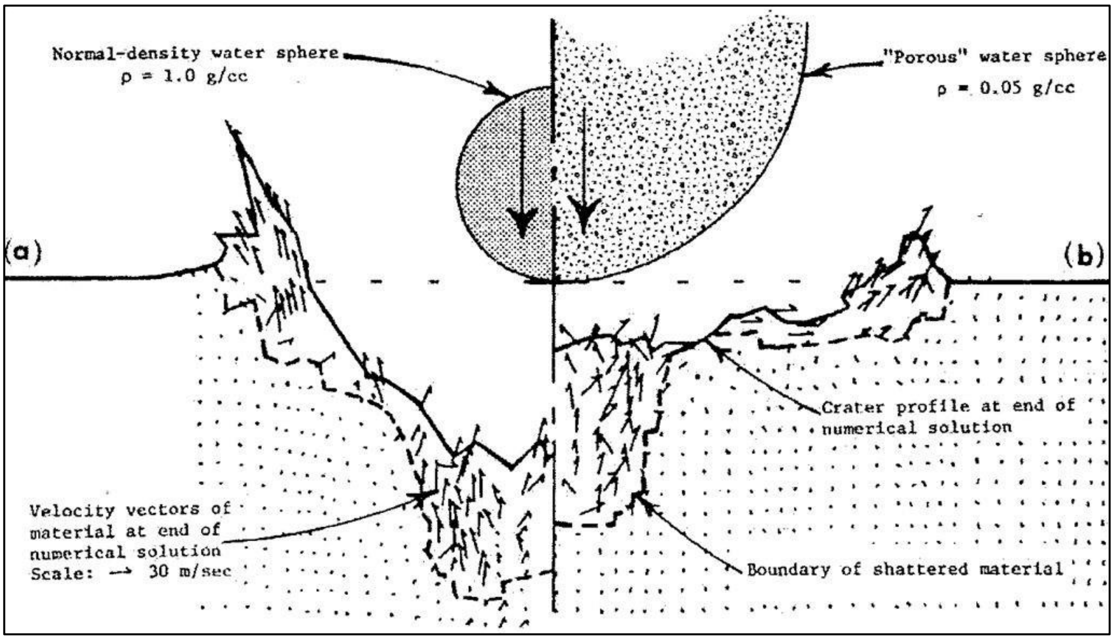


Figure 4.52: Calculated profiles of craters formed by impactors having densities of ρ = 1.0 grams per cubic centimeter and ρ = 0.05 grams per cubic centimeter (after Roddy et al., 1980: 945).

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

$D_1 = D_2 (E_1/E_2)^{1/3}$ Eq. 4.1

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

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

$$KE = (½)MV^2 \qquad \text{Eq. 4.2}$$

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

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

$$\rho = M / vol \qquad \text{Eq. 4.3}$$

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

An icy comet would have a density less than that of water, but for simplicity, a density, ρ, of 1000 kg/m^3 is assumed. Using Equation 4.3 gives a volume of 2×10^6 m^3, and thus a diameter of 156 meters. But Roddy (1977b: 292) reminds us that such low density bodies "… may not survive the atmospheric passage, as with Tunguska."

A second chemical explosion crater was produced at the Suffield Experimental Station with a 20-ton TNT detonation (see Roddy, 1966c). Figure 4.53 shows the alluvium displacement patterns below the 20-ton TNT hemispherical charge, as determined by marker cans that were buried in sand columns located on radial lines from ground zero. The post-shot positions of the marker cans shown in this figure "… were used to determine the direction and displacement of the ground …" (Roddy, 1966c: 206). The major horizontal component of displacement is easily seen.

Another interesting find from the study of this chemical explosion crater is visible in this figure and is described by Roddy (1966c: 207):

> A significant result in the 20 ton TNT experiment is the reversal in displacement direction below ground zero … Possibly under higher energy explosions, such as the 500 ton experiment which has a central uplift, the reversal in particle displacement aids in the formation of an

> uplifted zone. It is not known as yet what specific conditions are necessary to form the central uplift, but it is now clear that shock mechanisms from a surface burst can produce such a structure.

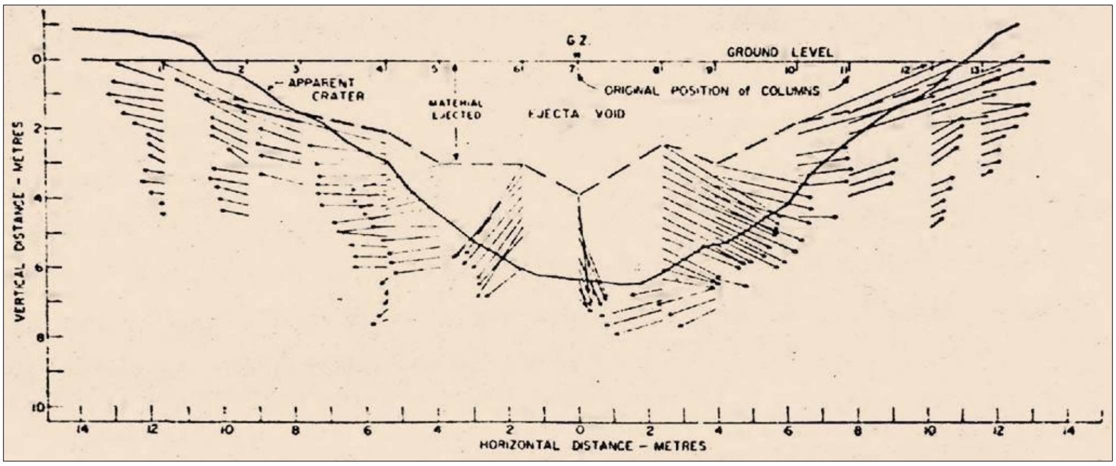


Figure 4.53: Alluvium displacement below the 20-ton TNT Crater at the Suffield Experimental Station, Alberta, Canada (after Roddy, 1966c: 206).

Roddy (1968b: 316) reports that another confirmation in support of an impact origin for Flynn Creek came in July 1967 when "… the Defence Research Establishment, Suffield, Canada, detonated 100 tons of TNT in the shape of a sphere lying tangential to the ground surface …" there-by producing a third chemical explosion crater for comparison. The resulting crater was 30 meters across, ~5.5 meters deep and also included a "… large, well-developed central uplift …" (ibid.). Beds in the central uplift were raised 3 to 5 meters and formed a "… tightly folded and faulted dome …" (Roddy, 1968b: 317). The 100-ton TNT crater displayed "… low-angle thrust zones and high-angle faults and folds that are concentric to the crater walls … [plus] pronounced structural similarities to the Flynn Creek crater …" (Roddy, 1968b: 318).

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

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

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

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

Dietz (1960: 1783) notes that the Flynn Creek structure was studied by Wilson and Born, “… who [originally] considered that it was created by a cryptovolcanic explosion. Wilson now has revised this opinion, attributing the origin of the structure to a meteorite impact …” This was in part due to the fact that he, Wilson, and Stearns found shatter cones along a new road cutting near the Structure‘s center in November 1959 (Dietz, 1960: 1783; cf. Baldwin, 1963: 89). Whereas the dolomite shatter cones from the Wells Creek site are described by Dietz (1968) as ‘excellent’, the limestone shatter cones from Flynn Creek were “… poorly developed … [but] the identification is unquestionable.” (Dietz, 1960: 1783). Dietz (1968: 271) describes the Flynn Creek shatter cones in more detail:

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

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

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

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

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

4.3.6 Bilateral Symmetry

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

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

In 1967, Roddy (*Astrogeologic Studies,* 1967: 29) stated that the asymmetry he noted in the structure's surface and subsurface deformation indicates that the Flynn Creek impactor traveled from southeast to northwest. More than a decade later Roddy (1979b) concluded from a second round of drilling that the basic shape of the Flynn Creek transient cavity was that of a very shallow, flat-floored crater with a deep and narrow central core of disruption dipping to the west, as shown in Figure 4.54. He determined that the depth of total disruption and uplift in the center of the crater extended to around 450 meters and then continued downward with decreasing deformation to around 770 meters, again dipping to the west. "The implication is that the impacting body has an oblique angle of entry tentatively interpreted here to be from the east or southeast …" (Roddy, 1979b: 2531). Roddy (ibid.) states that the "… pervasive westerly to northwesterly dips [of the exposed rocks in the central peak] … are consistent with such an entry angle …" Although other researchers agree that Flynn Creek's bilateral symmetry indicates an oblique impact, not all agree with Roddy on the azimuthal impact direction.

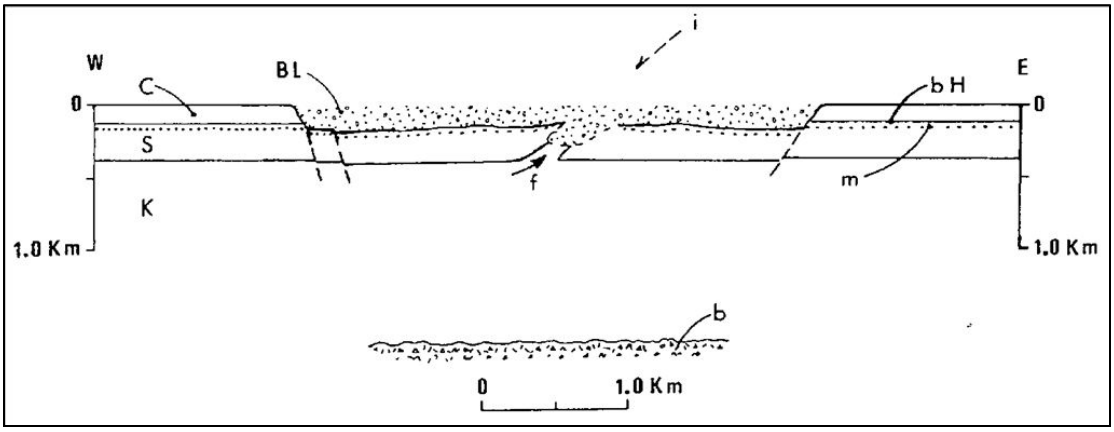


Figure 4.54: Schematic cross-section showing the Flynn Creek cratered region, where **'i'** is the inferred direction of the impactor. The „b" region immediately above the scale is the crystalline basement beneath the crater; there is no vertical exaggeration (after Roddy, 1979b: 2531).

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

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

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

On the other hand, the oblong lunar crater Messier is thought by Gault and Wedekind to be the result of a grazing impact event with θ < 5°. Gault and Wedekind (1978: 3843) note that "Impacts at shallow incidence, which are not uncommon, lead to ricochet of the impacting object … at velocities only slightly reduced from the pre-impact value." Gault and Wedekind (1978: 3873) state that "Lunar crater Messier is, of course, the prime type-example of an oblique impact along a grazing trajectory …" Herrick and Forsberg-Taylor (2003: 1556) support this interpretation: "Messier A appears to have resulted from a ricochet down-range from Messier, the original point of impact …" The shape of Messier A resembles shapes formed by experimental impacts with impact angles of 5° (Herrick and Forsberg-Taylor, 2003: 1557). Messier and Messier A, shown close up and with their ejecta patterns in Figure 4.55, may be the result of a single impactor first creating Messier and its butterfly ejecta pattern and then ricocheting to form Messier A with its forward ejecta rays.

In addition, ricochet may occur with the projectile remaining intact, rupturing into two or more large fragments, or shattering into a myriad of small fragments (Gault and Wedekind, 1978). Herrick and Forsberg-Taylor (2003: 1557-1558) note that "Messier A also bears some resemblance to experimental clustered impacts … [which] are more shallow than similar diameter craters resulting from a single impactor "‖ Interestingly, Roddy et al. (1980) considered Flynn Creek to be a shallow impact crater. Of course, Flynn Creek and Dycus could simply be the result of a binary impact. "Doublet craters are a product of binary asteroid impact, and the amount of asteroid separation determines whether overlapping or separated craters form … [around] 16% of the near-Earth asteroid population are doublets …‖ (Herrick and Forsberg-Taylor, 2003: 1558; cf. Bottke and Melosh, 1996).

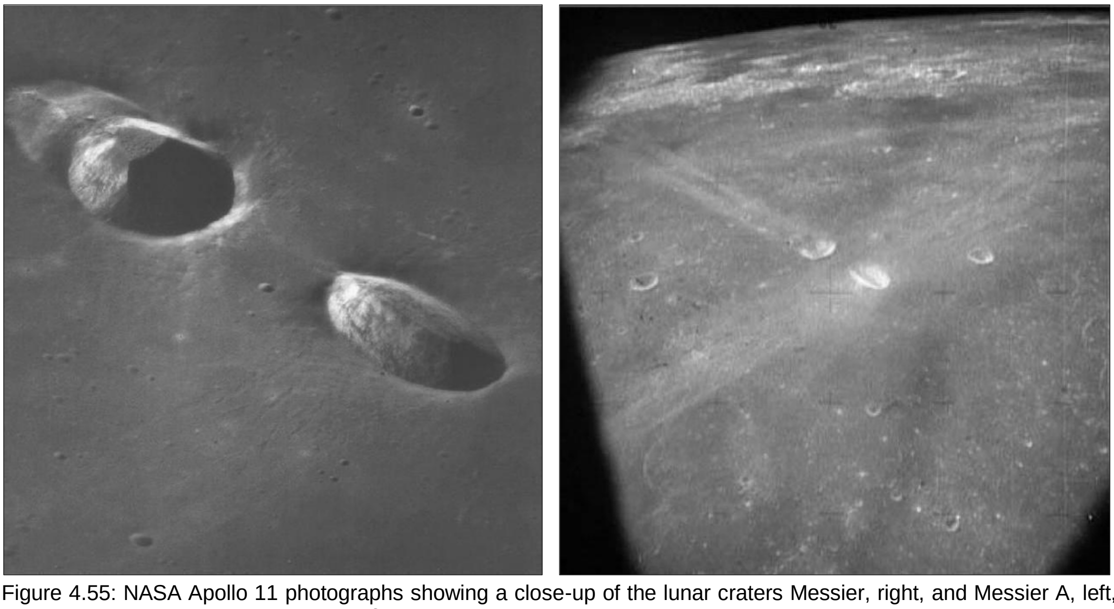


Figure 4.55: NASA Apollo 11 photographs showing a close-up of the lunar craters Messier, right, and Messier A, left, and long-range with Messier"s butterfly ejecta and Messier A"s two prominent downrange ejecta streaks (after Forsberg et al., 1998: 1).

4.3.7 Marine Impact

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

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

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

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

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

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

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

Jansa (2003: 332), though, steam expels more ejecta than would be generated by an equivalent dry impact.

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

This indicates that whereas most terrestrial impact craters have been subject to long periods of erosion and only their basement structures have survived, Flynn Creek was basically cocooned in mud, and thus its form has been preserved. As such, it is one of the few ancient terrestrial impact structures that can be reasonably referred to today as a 'crater'. Mitchum (1951: 29) notes that one reason the Flynn Creek Structure is especially interesting is that the actual explosion crater has been preserved. Shoemaker and Eggleton (1961) describe Flynn Creek as a buried crater with the form and structure of a meteorite crater.

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

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

widespread black muds of the Chattanooga Sea were not introduced immediately onto the floor of the crater since other deposits have been identified, yet the same marine conodonts in the basal Chattanooga *were* included, at least, in the earliest bedded dolomitic breccia on the crater floor. This suggests the waters of the Chattanooga Sea were in the immediate area at the time of impact but were not deep enough to flow directly over the crater rim and ejecta blanket. Instead, it appears that the marine waters carrying the microscopic conodonts fragments flowed or were initially filtered through the ejecta blanket and rim into the crater at a reduced rate such that the coarser black silty muds were initially deposited outside the crater … Immediately thereafter, the black silty muds of the Chattanooga Shale appear to have spilled over the crater rim to eventually fill the crater over the next few million years. The conclusion one draws is that of a shallow sea with abundant black silty muds … that did not immediately flood the crater, perhaps because of the barrier of the uplifted rim and the 100 m or so thickness of ejecta blanket. After a limited period of probable wave and other types of erosion, the ejecta was removed and the black silty muds were rapidly deposited over the crater floor, walls, and rim …

Another line of evidence regarding the *depth* of the Chattanooga Sea at the time of impact lies in an explanation of *talus-like* deposits at the base of a cliff formed by the rim graben. This ancient talus has the character and composition of subareal deposits with no apparent marine influence of its matrix chemistry and no black, silty, mud additions. Since the presence of the Chattanooga Sea in the immediate area has been established, it would appear that the evidence of no direct communication of the talus with the sea indicates that it was formed above the local water level … This shallow sea depth would still allow local wave action to remove the ejecta, flow over the stripped rim, and deposit marine sediments on the crater floor. In any case, the overall impression remains that of a very shallow sea, a few meters or so in depth, in this area *at* the time of impact …

The actual impact event may have occurred *in* these very shallow waters, but the depths were apparently only on the order of approximately 10 m.

Figure 2.16 on page 22 is a painting by artist Jerry Armstrong showing the Wetumpka impact crater in Alabama, a coastal state bordering Tennessee to the south. The painting is based on the research of Professor D.T. King (King et al., 1999; King et al., 2002), Department of Geology, Auburn University, Alabama, and depicts Wetumpka, a confirmed marine impact crater, during the Late Cretaceous. The process depicted is similar to that described by Roddy for Flynn Creek. After impact, the crater rim is thought to have stood above sea level, excluding the sea water, but eventually, the weaker south-western rim of Wetumpka was breached, allowing sea water to flood across the interior.

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

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

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

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

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

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

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

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

In addition, Schieber and Over (2005: 53) state that sedimentological and petrographic examination of the Flynn Creek Crater fill gives conclusive evidence of a shallow marine impact. These researchers determined that the Chattanooga Shale only comprises a small part of the black shale fill inside of the crater and that "… the bulk of the black shale is part of an earlier deposited member of the Chattanooga Shale, largely absent elsewhere, that extends the record of Devonian black shale deposition in central Tennessee …" (ibid.). They propose the name 'Flynn Creek Member' "… for the portion of the crater fill that underlies the Dowelltown Member of the Chattanooga Shale …", which consists of three distinct units that in ascending order are the basal breccia, bedded breccia and black shale sub-members (ibid.). The distribution of these litho-stratigraphic units in the Flynn Creek crater is shown in Figure 4.56, along with the locations where drill cores 3, 6, 12 and 13 (see Figure 4.40) were obtained (ibid.). Meanwhile, Figure 4.57 shows the black shale stratigraphy based on information from drill cores 12 and 13, obtained from the western flank of the Flynn Creek central uplift (after Schieber and Over, 2005: 62).

Roddy obtained a total of 18 drill cores (see Figure 4.40) for the US Geological Survey through a drilling program conducted at Flynn Creek in 1967 and 1978-1979. The project produced more than 3.8 km of nearly continuous core from 18 bore holes

(Hagerty et al., 2013). After Roddy's death in 2002, the cores were basically forgotten. However, they were relocated and are now contained in 1,271 standard core storage boxes, as shown in Figure 4.58, and archived at the USGS in Flagstaff, Arizona where they are all available for scientific study (Hagerty et al., 2013).

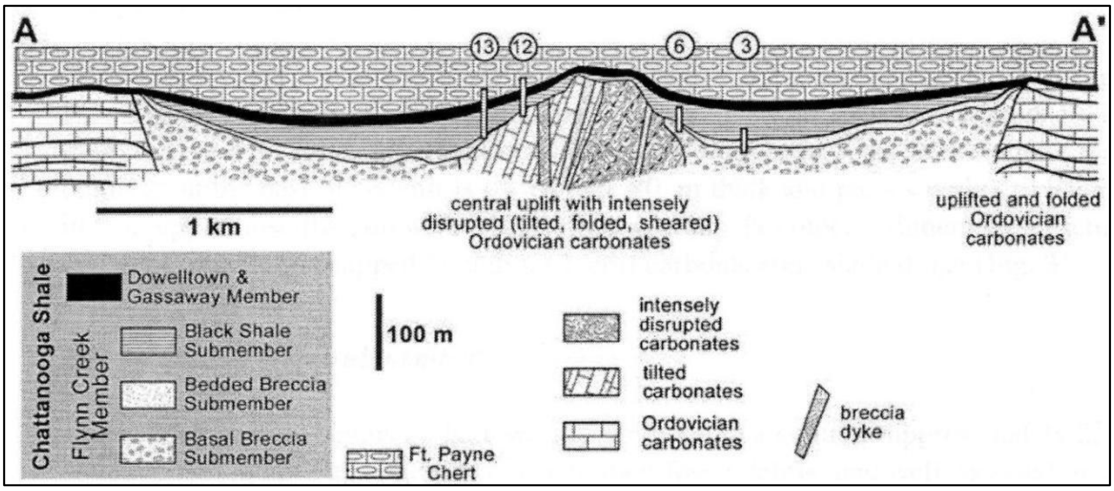


Figure 4.56: Schematic presentation of the Flynn Creek crater stratigraphic relationships showing locations where drill cores 3, 6, 12, 13 were obtained (after Schieber and Over, 2005: 53).

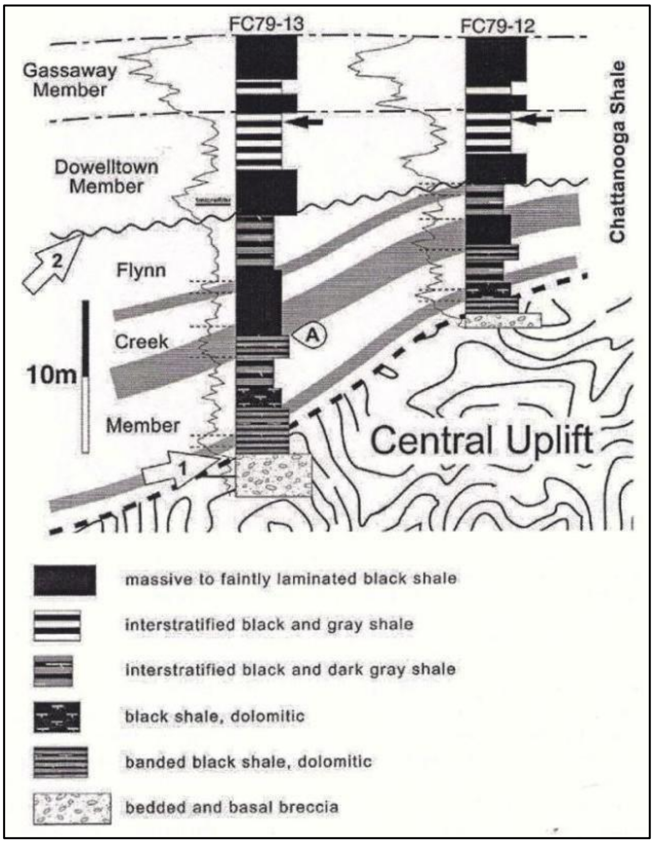


Figure 4.57: Black Shale stratigraphy from central uplift western flank drill cores (after Schieber and Over, 2005: 62)

Results of the drill core study indicate that the basal breccia averages 40 meters in thickness and consists of a poorly sorted, chaotic mix of angular carbonate clasts which range from granule to boulder size and were derived from the underlying strata. This unit is capped by a 2 cm carbonaceous shale drape. The bedded breccia unit starts at the lowest shale drape and contains "… around 25% carbonate clasts, quartz and chert grains, silicified fossil debris, and well-rounded phosphate granules in a fine-grained matrix of organic matter, dolomicrite, and clays …" (Schieber and Over, 2005: 54). The shale is overlain by beds of gravel, granule, sand, and silt-size carbonate debris ranging in thickness from 0.5 to 1.5 meters and cemented by dolomite. These beds vary in number depending on their location in the crater, but are each separated by shale drapes. They "… are massive to crudely wavy-parallel bedded …" on a centimeter to decimeter scale, and in places, fine upwards (ibid.).

Figure 4.58 Sample of drill cores from the USGS Flynn Creek Crater Drill Core Collection in Flagstaff, AZ. (after Hagerty et al., 2013).

The poorly-bedded breccia is primarily located along the crater margins, while the bedded dolomitic breccia and bedded dolomite is prominent in the crater interior. "Within bedded dolomite layers occur thinner (2-5 cm), graded dolomite beds that have horizontal lamination, water escape structures, and fading ripples … in the basal portions …" (ibid.). Dolomite beds that are overlain by a shale drape have "… an irregular bumpy surface, probably a result of water escape …" (ibid.).

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

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

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

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

Dypvik and Jansa (2003: 309) state that in subaerial impacts, the target rock is generally hard igneous or metamorphic rock, but in submarine impacts, the target rock is primarily composed of "… unconsolidated or poorly lithified sediments, or sedimentary rocks, with high volumes of pore water." They point out that the lack of an elevated rim in a shallow-water marine impact is thought to result from current reworking and resurge of the water back into the excavated crater as the water in the crater is vaporized during impact. Another characteristic they noted of marine impact sites is the presence of resurge gullies that cut across the rim: "Such erosional features result from submarine erosion which bevels off the crater rim, causing lower, more subtle rims or almost complete removal of a rim …" (Dypvik and Jansa, 2003: 332; cf. Dalwigk and Ormo, 2001). Schieber and Over (2005: 64) point out that Flynn Creek, in contrast, possessed "… an uplifted rim that was not significantly beveled by post-impact erosion and was not dissected by resurge gullies." This fact indicates that the Ordovician target rock was already lithified by the time of the Flynn Creek impact (ibid.). In fact, the Flynn Creek Crater's morphology was " … a close match to that expected of a sub-aerially produced crater …" (ibid.), but Dypvik and Jansa (2003) do point out that in shallow submarine impacts, the top of the central uplift is usually flat as a result of waves and shallow currents scouring and reworking the impact deposits. As can be seen in Figure 4.27, Flynn Creek possesses a flattened central peak in contrast to the sharp central peaks most complex impact craters display, suggesting that post-depositional modification by wave action associated with the shallow water at this site may have altered the crater's morphology to an extent (Schieber and Over, 2005).

The Wetumpka impact crater in Alabama is a confirmed *shallow* marine impact that took place 83.5 million years ago in 30 to 100 meters of sea-water (King and Petruny, 2003; King et al., 2002; 2008). Field work completed by Roddy, Schieber, and Over indicates that Flynn Creek is the result of an *extremely shallow* (~10 meters deep) marine impact. At the outset of this study, it was hoped that comparisons between known shallow marine impact sites such as Wetumpka, and extremely shallow marine impacts sites such as Flynn Creek, might provide an understanding on a macroscopic level of the similarities and differences in shallow and extremely shallow impacts that could then be applied to impact craters on other Solar System bodies. Unfortunately, this has not proven to be possible since the basic morphology of the Flynn Creek crater so closely resembles that of subaerial impact craters.

4.3.8 Cave Development

Caves have formed in the Flynn Creek Structure where slightly acidic groundwater has leaked through cracks and crevices in the limestone gradually dissolving it and thereby creating passages and caverns. Caves form by dissolution along zones of weakness "… such as bedding planes, fractures, and faults …" (Milam and Deane, 2006a: 82). Milam and Deane (ibid.) have discovered that "… impact cratering, one of the dominant surface-modifying forces on Mars and elsewhere in the Solar System, can also exert control over cave passage development …"

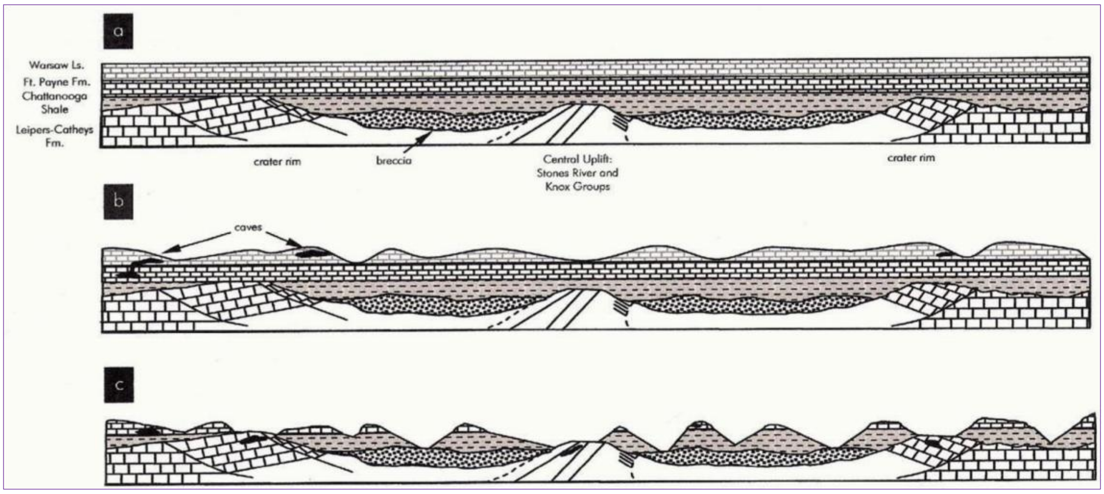


Figure 4.59: Generalized model for the speleogenetic modification of the Flynn Creek Structure; Jackson County, Tennessee. For details see the associated text (after Milam, Deane and Oeser, 2005b: 34).

Regional uplift due to the formation of the Nashville Dome in what is now central Tennessee caused the uplifted strata to have higher potential erosive energy. The overlying Pennsylvanian rocks were eventually breached and erosion exposed the underlying Upper Mississippian Warsaw Limestone and Lower Mississippian Fort Payne Formation. "It was in these geologic units (and once overlying Upper Mississippian rocks) that a first generation karst landscape developed …" (Milam et al., 2005b: 30). Cave passages first developed in Flynn Creek along strike and/or dip and/or joint orientations and continued erosion exposed the underlying Chattanooga Shale and below that the Ordovician carbonates. As a result, "… a second generation karst landscape was formed locally in the Leipers-Catheys, Bigby-Cannon, and Hermitage Formations, as well the underlying Stones River and Knox Groups …" (ibid.). Figure 4.59 shows Milam, Deane and Oeser's (2005b) generalized model for the speleogenetic modification of the Flynn Creek Structure. Figure 4.59a shows the buried crater with only the Knox Group through the Warsaw Limestone sediments depicted (ibid.). Figure 4.59b shows the first generation karst development, and Figure 4.59c, the second generation karst development along the rim of the crater and in the central uplift.

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

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

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

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

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

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

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

Wave Cave "… is located in the outermost concentric fault that defines the modified crater …" (Evenick, 2006: 7), and was formed in a tightly-folded asymmetric anticline on the east side of Flynn Creek (Roddy, 1966c: 109). The fragmented rock in the anticline core has been replaced by the cave (ibid.). A lack of tectonic deformation in this area indicates that this anticline formed as a result of the Flynn Creek impact (Evenick, 2006). The main passageway is around 43 meters long and near its end, two side crawls lead to a ~6×12 meter room, and "An unusual inverted breakout dome [that] is forming on the western side of this room due to gravitational collapse along bedding planes …" (Evenick, 2006: 7).

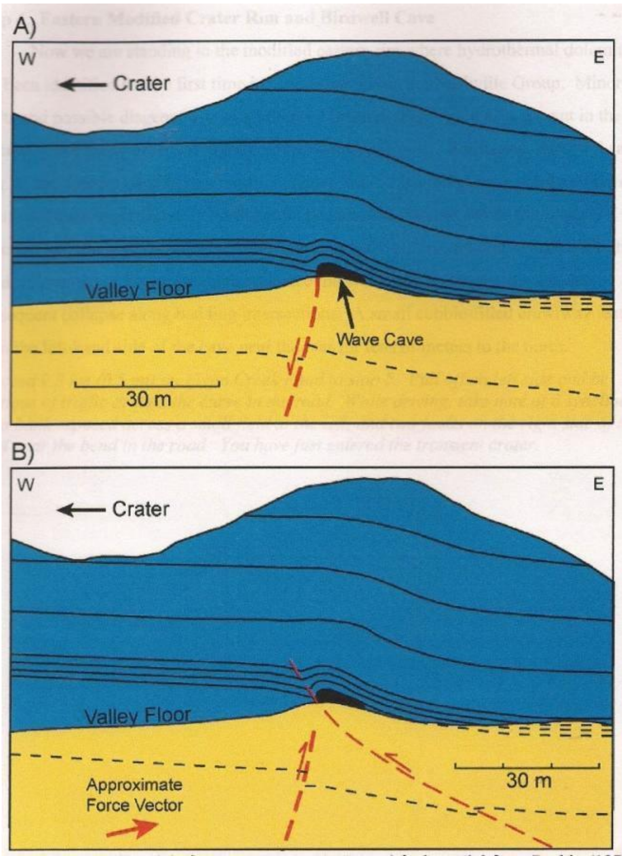


Figure 4.60: Two different structural models for Wave Cave (after Evenick, 2006: 9).

Figure 4.60 shows two structural models for Wave Cave. Model A shows that Roddy‘s “Normal fault model … does not balance nor take asymmetry into account …” (Evenick, 2006: 9), while Model B is a new interpretation of Wave cave:

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

Figure 4.61: Jana Ruth Ford (foreground) and Larry Knox (to her left) examine the entrance to Wave Cave (courtesy: Jessica Tischler).

Figure 4.61 shows the entrance area of Wave Cave and Figure 4.62 an interior view just inside the cave entrance. Figure 4.63 is a map of Wave Cave (after Milam, Deane and Oeser, 2005a: 43).

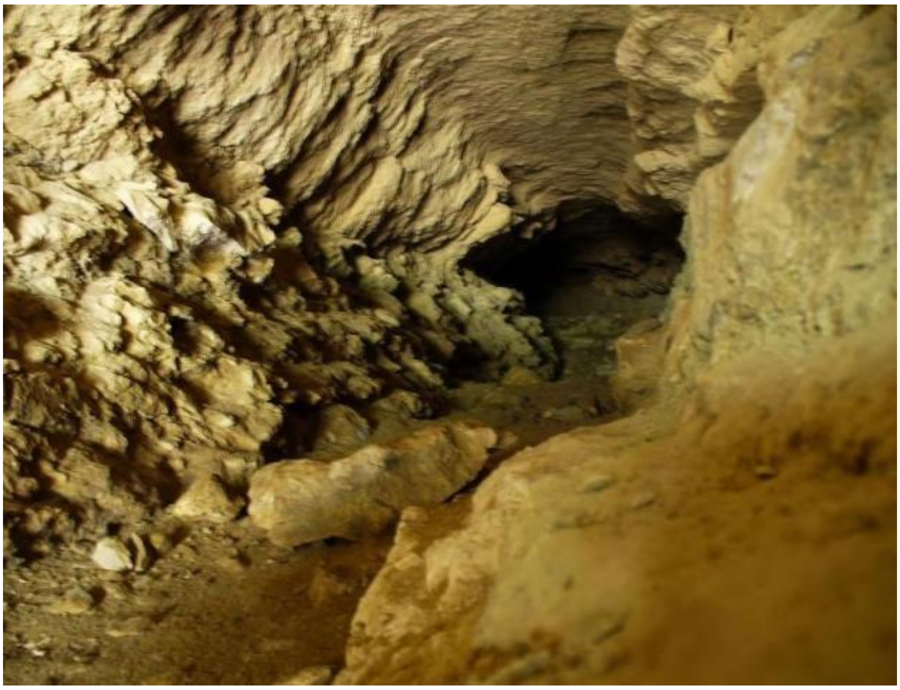


Figure 4.62: A view within the Wave Cave Anticline Room (courtesy: Rebecca Tischler).

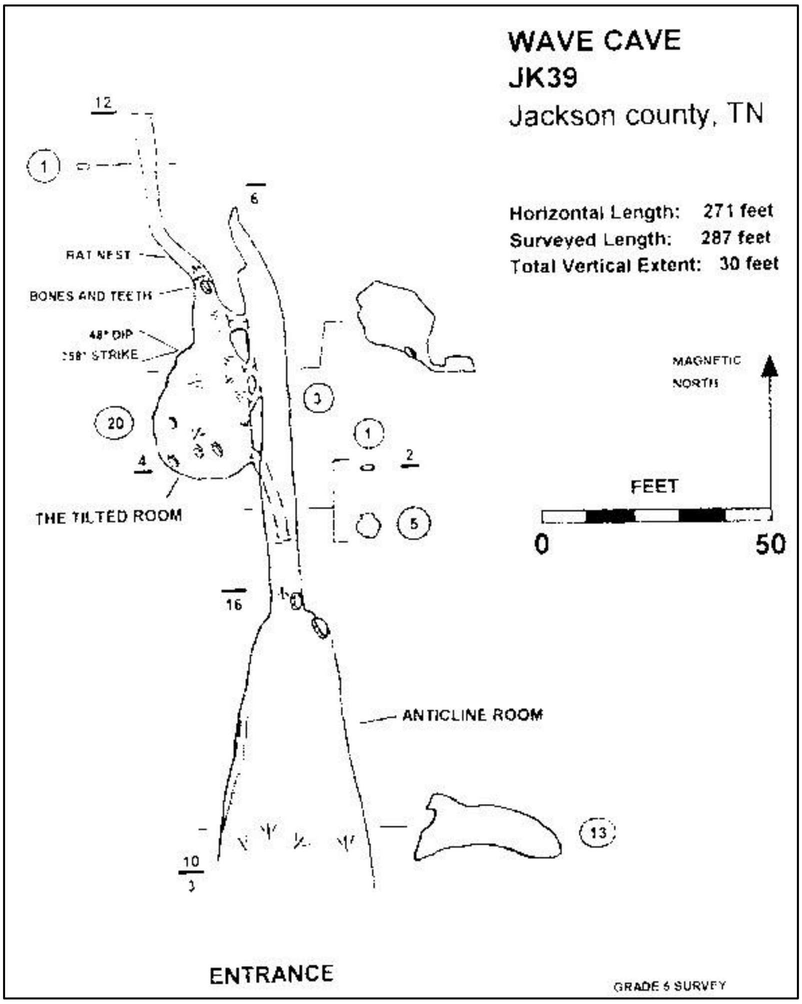


Figure 4.63: A map of Wave Cave (after Milam, Deane and Oeser, 2005a: 43)

The Tilted Room in Wave Cave shown on the left side of the Figure 4.63 map "… developed along the strike of steeply-dipping (61°) beds of the western limb of the anticline …" (Milam, Deane and Oeser, 2005b: 33).

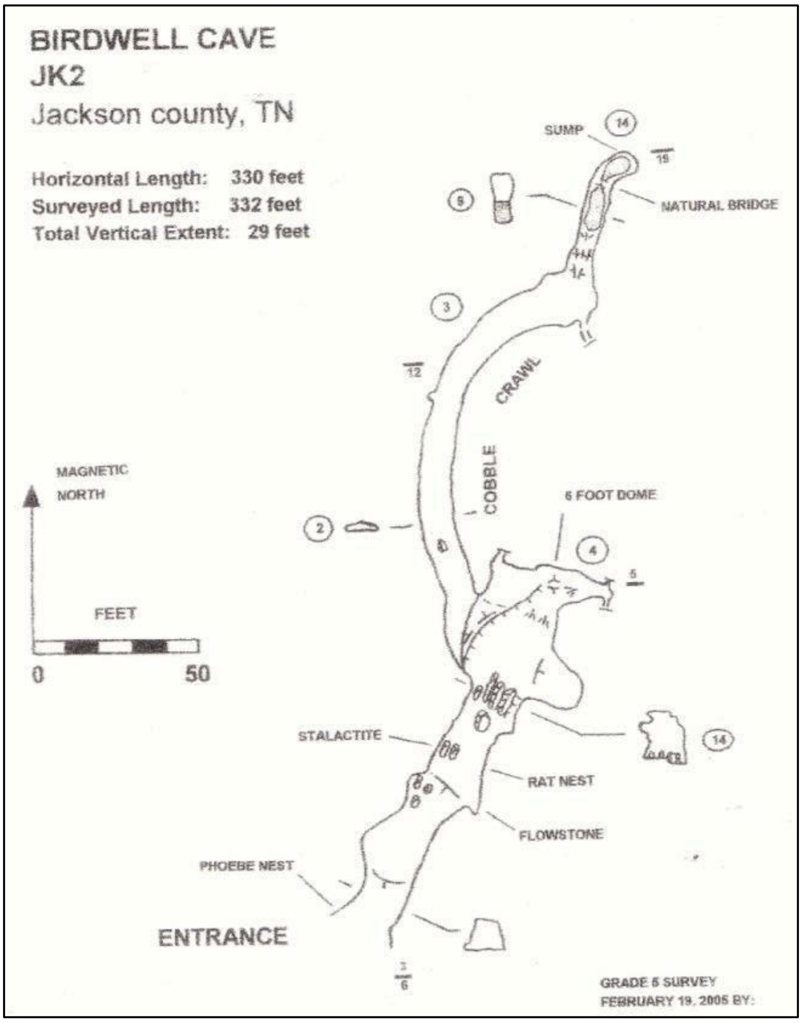


Figure 4.64: Map of Birdwell Cave (after Milam, Deane and Oeser, 2005a: 44).

Another Flynn Creek cave is Birdwell Cave (Figure 4.64), which formed in the eastern modified crater rim parallel to a modified crater fault (Milam, Deane and Oeser, 2005a). Both Birdwell and Wave Cave are oriented approximately northsouth, which is perpendicular to the center of the crater and probably perpendicular to the maximum stress of impact (ibid.). Birdwell Cave is at least 116 meters in length with a 3 meter-high entrance (ibid.). A passageway continues from the entrance for some 30 meters, and then splits. A short climb up to the right leads to a small passage that lies 2.5 meters above the entrance elevation. The left branch is a crawlway, only 30-40 cm high in some places, which developed along bedding planes. This crawlway in turn opens to a passage which is in places filled with pools of water. A blue hole, located around 100 to 150 meters to the south, is split by a north-south trending natural rock bridge as shown in the upper right of Figure 4.64. Milam, Deane and Oeser (2005a: 37) suggested that "Based on the proximity of Birdwell Cave to this blue hole and their similar structural patterns, it is possible that these two karst features may be connected hydrologically …" A small cobble-filled crawlway leads from the left, rear side of Birdwell Cave northward for some tens of meters (Milam, Deane and Oeser, 2005a).

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

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

Forks Creek Cave is about 172 meters above sea level and was exposed in a road cut along the southern bank of the Flynn Creek. This cave has four entrances that lead to tight and interconnected crawlways (Milam, Deane and Oeser, 2005a).

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

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

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

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

In addition to these known caves in the Flynn Creek structure, collapsed caves can be seen along road cuts in the crater, such as one along Flynn Creek Road shown in Figure 4.65. The rock layer at the very top of the photograph is relatively horizontal however, the lower rock layers on the left and right all dip toward the center of the photograph. These collapsed caves serve as indicators of fault or fracture systems associated with the western modified crater rim (Evenick, 2006).

Figure 4.65 shows a collapsed cave on the side of Flynn Creek Road (photograph: Jana Ruth Ford).

Of special interest is Hawkins Impact Cave, "… the only known cave in the world developed in a central uplift of a complex crater …" (Milam and Deane, 2006b: 81). The central peak, ~0.75 km in diameter, "… was buried by Devonian/Mississippian-aged marine sediment that later became the Chattanooga Shale, Fort Payne, and other formations …" (Milam et al., 2006: 1). Milam and Deane (2006b: 81) believe that the Hawkins Impact Cave exposures "… provide a unique perspective into processes of central uplift formation …" This cave was discovered by the landowner, Michael Hawkins, in 1989 and was subsequently mapped in 2003 and found to be 277 meters in length (ibid.). Figure 4.66 is a map of the Hawkins Impact Cave (after Milam, Deane and Oeser, 2005a: 45).

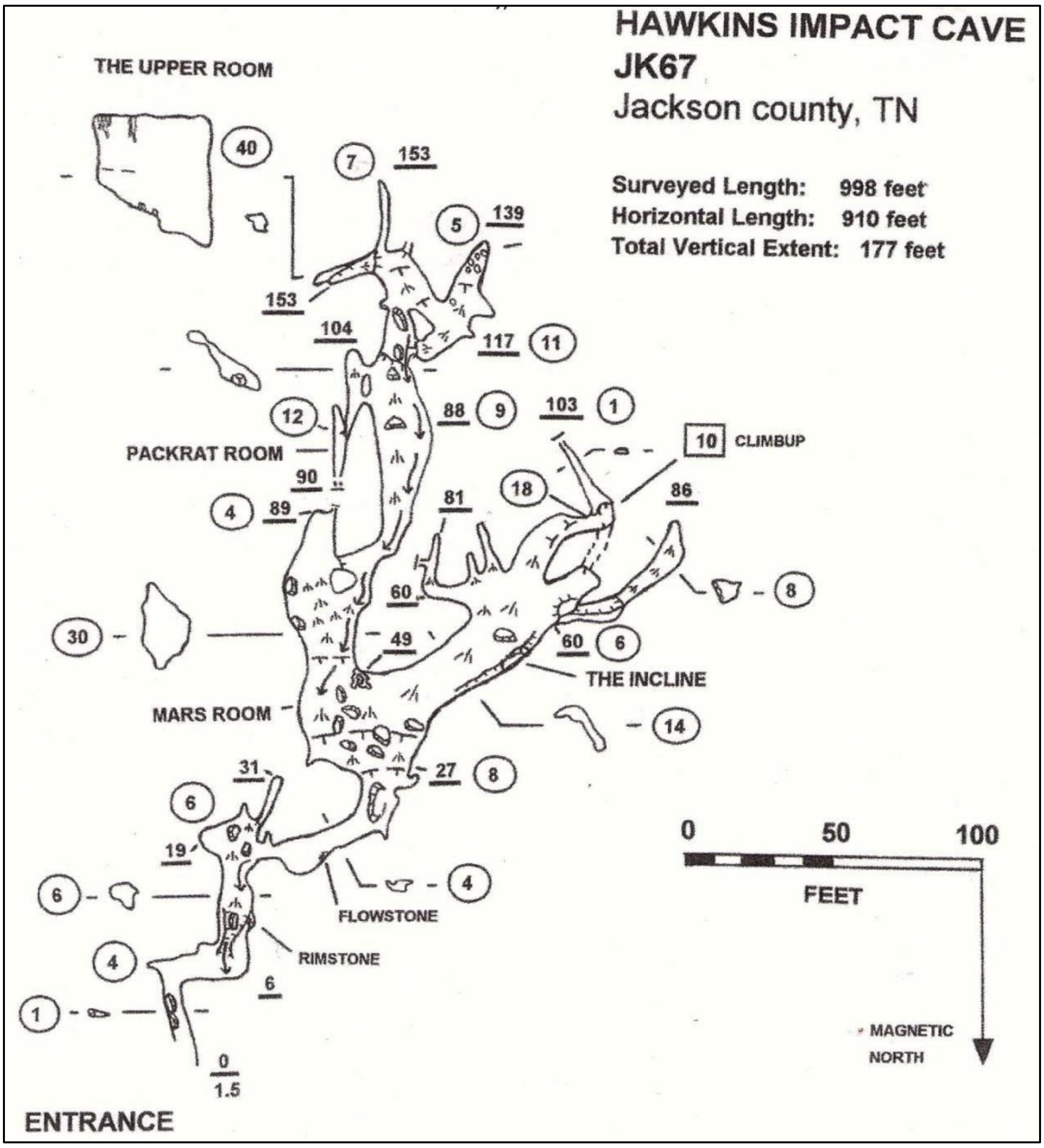


Figure 4.66: Map of Hawkins Impact Cave (after Milam et al., 2005a: 45).

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

Based on their exploration of the Hawkins Impact Cave, Milam et al. (2006) conclude that the initial microfractures were generated after compression due to the Flynn Creek impact. Cross-cutting relationships show that this first generation of microfractures was subsequently cut by microfaults and both terminate at major fault boundaries. Microfault movement followed with the subsequent generation of more microfractures and microfaults followed in turn by the rise of the central uplift, and "This is expressed by major fault movement along megablock boundaries, which truncate all of the above features …" (Milam et al., 2006: 2). "Two large rooms (the Mars and Upper rooms shown in Figure 46) were formed by dissolution and subsequent collapse at the intersection of several major faults …" (Milam, Deane and Oeser, 2005a: 33).

4.3.9 Conclusion

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

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

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

Flynn Creek did prove valuable, however, to the National Aeronautics and Space Administration (NASA). Unlike most terrestrial impact structures, rapid burial by sediment that would later become Tennessee‘s Chattanooga Shale preserved the form of this crater, which is strikingly similar to lunar craters such as Pythagoras and Copernicus. As such, a detailed study of the Flynn Creek Structure was supported by

NASA and the United States Geological Survey's Branch of Astrogeologic Studies in preparation for the Apollo Program which resulted in astronauts walking on the lunar surface.

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

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

4.4 The Dycus Structure

4.4.1 Introduction

Although Flynn Creek is a confirmed impact crater (Evenick et al., 2004; Ford et al., 2013b; Milam and Deane, 2005; Milam et al., 2006; Roddy, 1997a; 1977b; Schieber and Over, 2005), the nearby Dycus Disturbance has received little attention from researchers and is only considered to be a suspected site of impact (Deane et al., 2006; Schedl et al., 2010). These sites are both 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, in the northern section of the Eastern Highland Rim Escarpment.

Although the Dycus Disturbance 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 Disturbance 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 Structure 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 Disturbance is in an unpublished M.Sc. thesis submitted to Vanderbilt University in 1951 by Robert M. Mitchum. This structure was still not well known afterwards and 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).

4.4.2 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 4.67 is a view of the area. The most intensely-disturbed section is located in the forested area in the center of the photograph. The structure does not extend beyond the ridge. Wilson considered this structural disturbance interesting enough to warrant further investigation and wanted to determine whether or not it should be included in the growing list of cryptovolcanic structures (ibid.).

Figure 4.67: A view of the Dycus Disturbance 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).

Although the Dycus Disturbance had been known for a few years before his field work commenced, Mitchum (ibid.) stated that no research had previously 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 4.68. Based on his study of the structure, Mitchum (1951: 2) concluded that the disturbance was the result of a meteorite impact.

4.4.3 Structural Features and Age

The Dycus Disturbance is located in the northern part of middle Tennessee on the edge of the Nashville Central Basin in the northern section of the Eastern Highland Rim Escarpment. The structure stands out from 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).

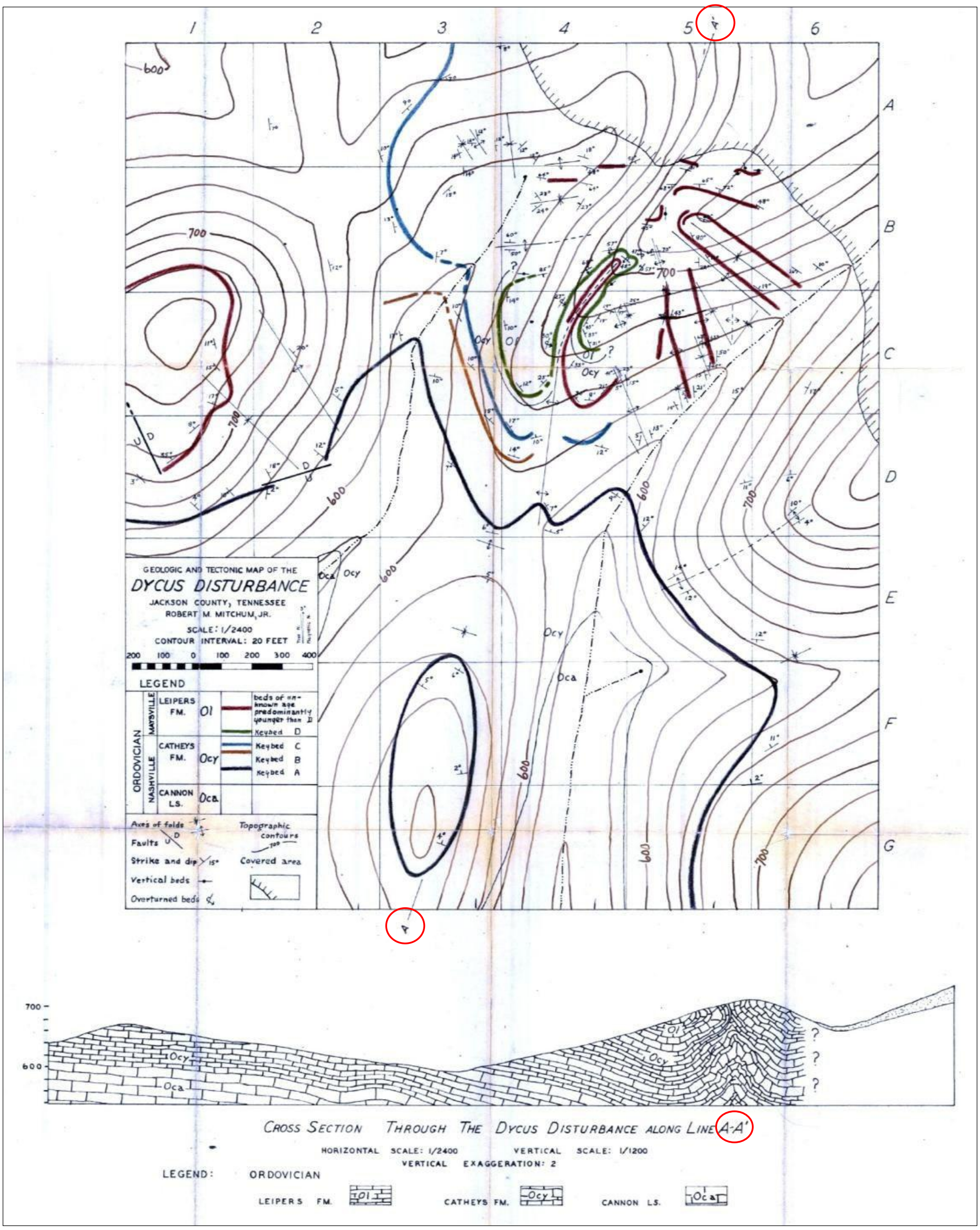


Figure 4.68: Mitchum"s geological map of the Dycus Disturbance. A cross-section through the disturbance along line A-A" is included at the bottom of the figure (after Mitchum, 1951). A and A' are circled in red on the above map.

Later investigators agree 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) states that the Dycus Disturbance is Ordovician in age. Rock exposures in the disturbed area are primarily limestone that range from Ordovician to Mississippian (Mitchum, 1951). The Chattanooga Shale, so prominent in the nearby Flynn Creek impact site, occurs near the tops of high hills in the region of the Disturbance, but it is not present in the area mapped by Mitchum. The northern and north-eastern sections of the disturbed area are covered by rubble containing the Mississippian chert that is usually found to cap high hills in the surrounding area. The chert is not found to occur in place within the intensely-deformed part of the structure (ibid.).

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

> 1. A small, relatively subordinate central uplift occupies the approximate center of the disturbance and marks the area of most intense deformation.
> 2. Surrounding and subordinating the uplift is an annular depressed area that is accompanied by buckling and tight folding. The axes of the folds are roughly radial from the central uplift. The down-bowing has greater magnitude than the uplift, both vertically and horizontally, so that the center of the structure, although higher than the surrounding depressed area, is still lower than its normal altitude in this vicinity.
> 3. A gentle ring-shaped anticline occurs on the outer periphery of the down-warped area. This peripheral fold surrounds the central area for at least three-fourths of the circumference of the exposed half-circle.
> 4. At least two normal faults occur outside the ring-shaped anticline.
> 5. Outside the area of intense disturbance the rocks dip gently toward the center of deformation. This dip dies out with increasing distance from the center.

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

Mitchum (ibid.) considers the intense folding to be the most important feature of the Dycus Disturbance, 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 Disturbance rather than at the 190 meter altitude the same facies were 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) notes that the zone of greatest deformation in the Dycus Disturbance is apparently 20 to 35 meters higher than the depressed area surrounding it. This area is considered an annular depression thought to have been lowered by at least 42 meters below its normal position and surrounding what Mitchum refers to as the central uplift. In addition, Mitchum (ibid.) notes that the basal granular facies of the Leipers Formation is at least 43 meters below its normal position found just to the east of this 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 is 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.) notes the increasing deformation and radial folds that are superimposed on the structure from the depressed area to the uplift area.

A short distance to the north the beds are vertical and then remain nearly vertical for some distance. Overturned beds are also seen along some of the folds. As an example, an anticline in the east-central section of the disturbance is overturned to the west and an anticline striking northeast-southwest is overturned to the northwest (ibid.). Figure 4.69 (after Mitchum, 1951: 21) 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) states that "The disturbed attitude of the rocks precludes a complete understanding of the folding …" He notes that it is only as the zone of most intense deformation is approached that the beds are 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.).

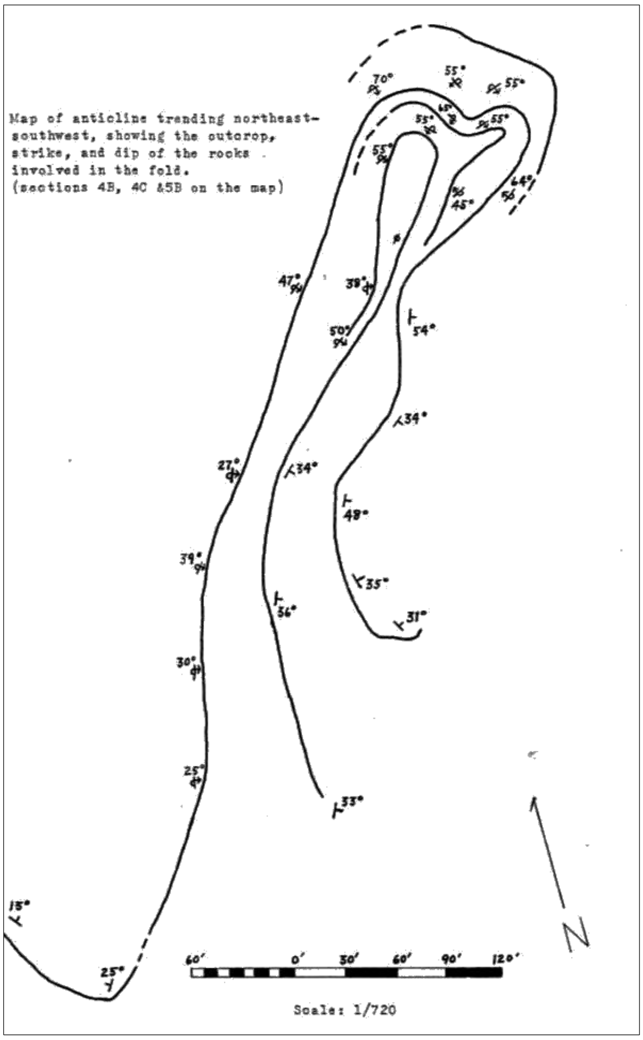


Figure 4.69: Map of anticline trending northeast-southwest, showing the outcrop, strike, and dip of the rocks involved in the fold (after Mitchum, 1951: 21).This map includes sections 4B, 4C & 5B from the 1951 geological map shown in Figure 4.68.

Rock layers are found throughout the Dycus Disturbance to be tilted at all angles, some vertical, others overturned. Figure 4.70 includes two photographs of moss-covered rock layers standing vertically or nearly so in the disturbed area.

The general fold pattern in the Dycus Disturbance is radial, and (Mitchum, 1951: 22) notes 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 has a radius from 365 to just over 425 meters and the limbs of this ring-shaped anticline show gentle dips which never exceed 14 degrees in the central and eastern exposures and never exceed 20 degrees in the rest of the structure. Although the dips here are somewhat steeper and the vertical movement has been greater than elsewhere in the structure, the intensity of deformation is less than in the central zone (ibid.).

Figure 4.70: Two views of rows of moss-covered rocks standing on edge in the Dycus Disturbance. 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).

. Mitchum (1951) notes that there is 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 is concentrically parallel to that of the anticline, and just over 90 meters from it. Two faults are located on the outer periphery of the ring fold which Mitchum interprets as being medium- to high-angle normal faults. Though he was unable to determine the displacement of one of these faults, he notes that a key bed is offset from the fault by at least 6 meters vertically and over 60 meters horizontally. He construes that pre-existing joint planes influenced the orientation of the two faults by offering the least amount of resistance to readjustment, 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 are significant in Mitchell‘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 are found along the fault planes imbedded in a limestone matrix.

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

4.4.4 Crypto-Controversies

Bucher (1963: 1242) describes 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) suggests 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) states that these cryptoexplosive structures are characterized by:

> (1) a roughly circular outline and a radial symmetry which, in some cases, is 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 contains sheared, shattered, and powdered rock and, in some cases, 'shatter-cones' which are indicative of explosive shock; (5) volcanic, plutonic, or hydrothermally-altered rock is not found.

According to Dietz (ibid.), "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 …" Mitchum (1951: 26-27) argues that the Dycus Disturbance 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) points out that there are striking similarities between the Dycus Disturbance and the general description given above of a cryptovolcanic, or cryptoexplosive, 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 notes a similarity between "… the ring-shaped folds of the Dycus structure … [and] a series of marginal ring-shaped concentric folds …" that surround the central uplift of the Wells Creek Basin. He points out that they differ only in size and intensity (ibid.).

However, there also are differences between the Dycus Disturbance and most other recognized cryptoexplosive structures: (1) Most of the disturbance seems to be the result of folding rather than faulting. (2) As a result, there is correspondingly less breccia. (3) The intensity of deformation is not as great as is usually found in other structures. (4) The radial folds are more distinct than in most other structures. (5) The central uplift is 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, cryptovolcanic or cryptoexplosive structures have been attributed to a variety of causes, most of which are refuted by Mitchum (1951: 30; my 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 addresses 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) points 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 notes (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 surrounds 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.). If the erosion is sufficient, Mitchum (ibid.) concludes that not only would the crater not be preserved today, but the existing surface would be below the original level where the most intense faulting and brecciation took place (ibid.). The current surface, therefore, shows deformation predominately caused by folding, so if the Dycus Disturbance is a heavily-eroded impact site, then the fact that the deformation found there is 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) concludes that the Dycus Disturbance “… may serve as an example of a deeply eroded explosion structure and afford some knowledge of the mechanics of the deformational stress at depth …”

4.4.5 Cratering Mechanics

Although the majority of suggested origins of the Dycus Disturbance 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 4.68) shows that the Dycus Disturbance 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 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 and 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). On the Earth the transition from a simple to a complex crater occurs around a diameter of 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 indicates 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 Disturbance shown at the bottom of Figure 4.68, is not centrally located. Later investigators concluded that the uplifted area is not located at the center of the structure:

> 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 of hundred meters farther north with the discovery of bedding dipping 8° radially away from the structure … (Deane et al., 2006: 2).

Although the Dycus Disturbance is slightly larger than Mitchum realized (Deane et al. 2006: 2), it is oval in shape rather than circular and the uplifted area is not centrally located. The similarity of this structure to the unusual lunar crater Schiller is striking.

4.4.6 Comparisons with Lunar and Oblique Craters

Kenkmann and Poelchau (2008: 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° … Here we use the term "oblique" for craters formed at angles between 35° and 15° from the horizontal, and as "highly oblique" or "acute-angled" impacts below 15° incidence … At highly oblique angles, "butterfly‖ ejecta blankets form …

> [but] ejecta blankets are rarely preserved on Earth … The crater outline is insensitive to the impact trajectory and remains circular with the exception of highly oblique impacts … [However] 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, 2008: 2).

Other researchers agree. Ekholm (1999) finds no empirical evidence that there exists a systematic uprange offset of the central peak in oblique impact craters; Ekholm and Melosh (2001) found the central peak offset distribution to be random and very similar to that for high-angle impacts; and Shuvalov (2003) substantiates the conclusion of Ekholm and Melosh that an uprange offset of the central uplift cannot be used as a criterion of obliquity. In another study of lunar craters that are considered to be the result of oblique impacts, however, preliminary results show that in these craters the central peak is located away from the geometrical center (Goeritz et al., 2009).

The lunar crater Schiller is an example of an elliptical crater, however, in which the uplifted area is a central ridge that is not centrally located, but is quite near the northern end of the structure, as can be seen in see Figure 4.71.

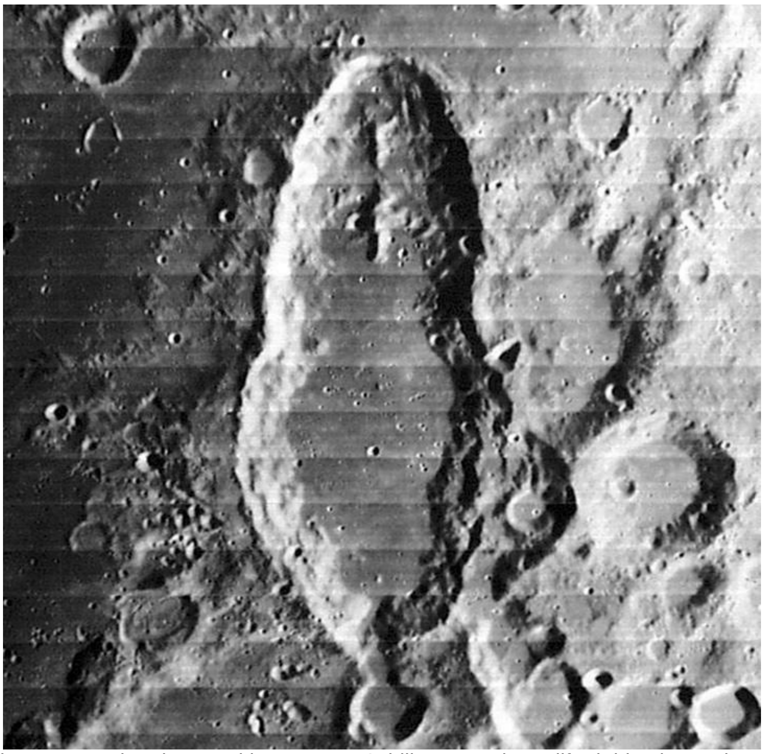


Figure 4.71: The elongated lunar crater Schiller. Note the uplifted ridge located near the crater's edge in the top of the photograph (Lunar Orbiter IV image IV-155-H1).

Schultz (1992) considers oblong 'Schiller-like' craters to be 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° … [and] the crater becomes highly elongated in the downrange direction … In some cases, the low point of the rim for an oblique impact is at the level of the surrounding terrain …

Some researchers have posed the question, "Is Dycus a secondary of Flynn?" (see Deane et al., 2006: 2). Or perhaps the relationship between the Dycus Disturbance and Flynn Creek is that they are two 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), the only known example of a low angle ricochet crater on the lunar surface (Melosh, 2002: 1039).

In laboratory experiments, failed projectiles with impact angles less than 20 degrees from the horizontal can create what appears to be a double impact. Re-impacting, decapitated fragments sheared off the projectile travel at speeds close to initial impact speed resulting in the extension and modification of the downrange crater rim. Computational studies by Schultz and Stickle (2011) showed a failed projectile impacting 10 degrees from horizontal resulted in a downrange crater before excavation of the primary crater, thus forming a double impact. This occurred early in the impact process, so the excavation stage could overprint or mask these surface features. Since oblique impacts can also result in offset and elongated central peaks (Schultz and Stickle, 2011), the origin of the oblong lunar crater Schiller, with its notably offset central ridge, could be the oblique impact of a decapitated projectile.

The Dycus Disturbance is just 13km from Flynn Creek, and Stratford (2004: 22) believes that they may be the result of an actual 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 population 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 on Earth during the Paleozoic.

4.4.7 Conclusion

Although first investigated decades ago, the Dycus Disturbance has received little attention from those researching meteorite 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 and easy-identified feature of craters caused by meteorite 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 Disturbance or by Dr Larry Knox, Marvin Berwind, and the author of this thesis when we visited the site in March 2012. Nonetheless, Mitchum (1951: 38) believes that the accumulated evidence "… adds weight to the meteoritic hypothesis of origin …" Until more compelling evidence is assembled, the enigmatic Dycus Structure must remain a suspected impact crater, but it may be that even if it was indeed caused by a meteorite impact the relics of such an event have been so heavily eroded that no positive proof can now be found. Nevertheless, if the Dycus Disturbance is in fact a relic impact crater, it may be related to the nearby confirmed impact site at Flynn Creek. Its formation may have been the result of an oblique impact, with the uplift at one end of the major axis of its elliptical boundary—just as can be seen in the photograph of the lunar crater Schiller.

Dycus is an enigma. Overall, the evidence is not conclusive but indicates that Dycus had a *probable* oblique impact origin with a *possible* connection to the Flynn Creek impact event. Unfortunately, interest in the Dycus Disturbance has waned over time and only sporadic field work has taken place in the decades since its recognition as a site of interest. Hopefully in the near future, though, the Dycus Disturbance will be shown to be an impact site or else its terrestrial origin will be established.

4.5 The Howell Structure

4.5.1 Introduction

Although three confirmed or suspected of impact sites are found on the Highland Rim or the Highland Rim escarpment which surrounds the Nashville Central Basin in middle Tennessee (e.g. see Berwind, 2006; 2007; Deane et al., 2004; 2006; Evenick, 2006; Evenick et al., 2004; Ford et al., 2012; 2013; Milam et al., 2006; Mitchum, 1951; Price, 1991; Roddy, 1977a; 1977b; Schedl et al., 2010; Schieber and Over, 2005; Stearns et al., 1968; Wilson, 1953; Wilson and Stearns, 1966; 1968; and Woodruff, 1968), the fourth site of interest, the Howell Structure, is located on one of the numerous isolated Highland Rim residual areas that lie within the Central Basin, near its south-eastern boundary. Even though meteorite impacts most certainly also occurred in the eastern and western sections of the state, Woodruff (1968: 20) notes that there may have been impact structures to the east of the Highland Rim "… in the deformed rocks of the Appalachians but the structural features there may be obliterated." Meanwhile, impact craters in the western part of the state would have been covered by coastal plain marine and transitional sediments during the Mississippian Embayment and are now unrecognizable (Miller, 1974). In this section an historical review of investigations that have been carried out at the Howell Structure is presented.

The Howell Structure is "… a circular, intensely deformed area …" located in the Highland Rim of south-central Tennessee (Born and Wilson, 1939: 371). It "… is a roughly circular feature about 2.5 km in diameter, comprising brecciated, deformed, and disturbed sedimentary strata … centered on the unincorporated village of Howell …" (Deane et al., 2004: 1). The regional dip in this area "… is to the south and is at an average angle of considerably less than 1° …" (Born and Wilson, 1939: 375). Large creeks, such as Cane and Norris, have eroded valleys in this section of the Highland Rim to almost the level of the Nashville Central Basin (Born and Wilson, 1939). Although "No large creeks flow across the [Howell] structure proper … Cane Creek borders the western and southern limits, and Buchanan Creek borders the easternmost areas. The tributaries of Cane Creek dissect a large percent of the deformed area …" (Woodruff, 1968: 4). Narrow ridges between the creeks and streams are remnants of the Highland Rim with an average elevation of some 100 meters above the eroded valleys and the Howell Structure, for the most part, is some 16 meters above these valley floors (Born and Wilson, 1939; Woodruff, 1968). Deane et al., (2004: 1) note that "The western two-thirds of the Howell Structure occurs in rolling, grass-covered pastureland, while the eastern one-third consists of forested hills rising 130 m above the surrounding terrain. Exposures are limited …"

4.5.2 Historical Context

Mr J.W. Young, of Fayetteville, Tennessee, around 10 km from Howell, was the first to notice this interesting, but "… small area of intricate structure …" (Born and Wilson, 1939: 371). He showed the structure to several geologists and discussed it with others, including Wilson and Born, sometime around 1934. As a result, the first known detailed map of the structure and surrounding area was completed in 1937 by Born and Wilson. They did not come to a conclusion as to its origin, stating that

> While no conclusive evidence has been observed to support either the cryptovolcanic or the meteoritic hypothesis of origin of the Howell structure is considered tentatively as an example of the cryptovolcanic structures as interpreted by Bucher … (ibid.).

Detailed geological mapping of this "… small area of intricate structure …" was undertaken again from 1964 to 1965 by Wilson and R.H. Barnes, of the Tennessee Division of Geology, assisted by R.A. Miller and C.E.L. McCary (Deane et al., 2004; Woodruff, 1968). Figure 4.72 is the "Geologic map of the Howell Area" as prepared by Wilson and Barnes, with additions by C.M. Woodruff (1968). The next serious study of the Howell Structure was undertaken in 1967 by Woodruff and supervised by R.G. Stearns, in order "… to map in detail the limits of deformation …" (Woodruff, 1968: 1). Woodruff (ibid.) noted that "At the same time, geologists of the National Aeronautics and Space Administration began to do field reconnaissance work in preparation for core drilling to determine the nature of the structure at depth …" The lead geologist was J. Bensko, from NASA‘s Marshall Space Center in Huntsville, Alabama. The last major study of the Howell Structure, which included an aerial survey, was undertaken by B. Deane, P. Lee, K.A. Milam, J.C. Evenick, and R.L. Zawislak in late 2003 in order to search for "… evidence of shock metamorphism in local lithologies …" (Deane et al., 2004: 1-2).

4.5.3 Morphology, Stratigraphy and Age

The Howell Structure is a *suspected* site of impact because its "… original morphology has been completely obliterated by the various geologic processes that have worked on the area …" (Woodruff, 1968: 57). The stratigraphy of the Highland Rim in which the Howell Structure is located is

> … primarily composed of flat-lying limestones, dolomites, and shales, and to a much lesser extent, of cherts, siltstones, mudstones, and very fine-grained to conglomeratic sandstones. Strata range from Upper Ordovician to Lower Mississippian in age and contain several prominent unconformities … (Deane et al., 2004:1).

Woodruff (1968: 6) found similar strata, and stated that he encountered rock units at Howell including "… the Hermitage Formation of the Nashville Group of the Ordovician System, through the Fort Payne Formation of the Mississippian System."

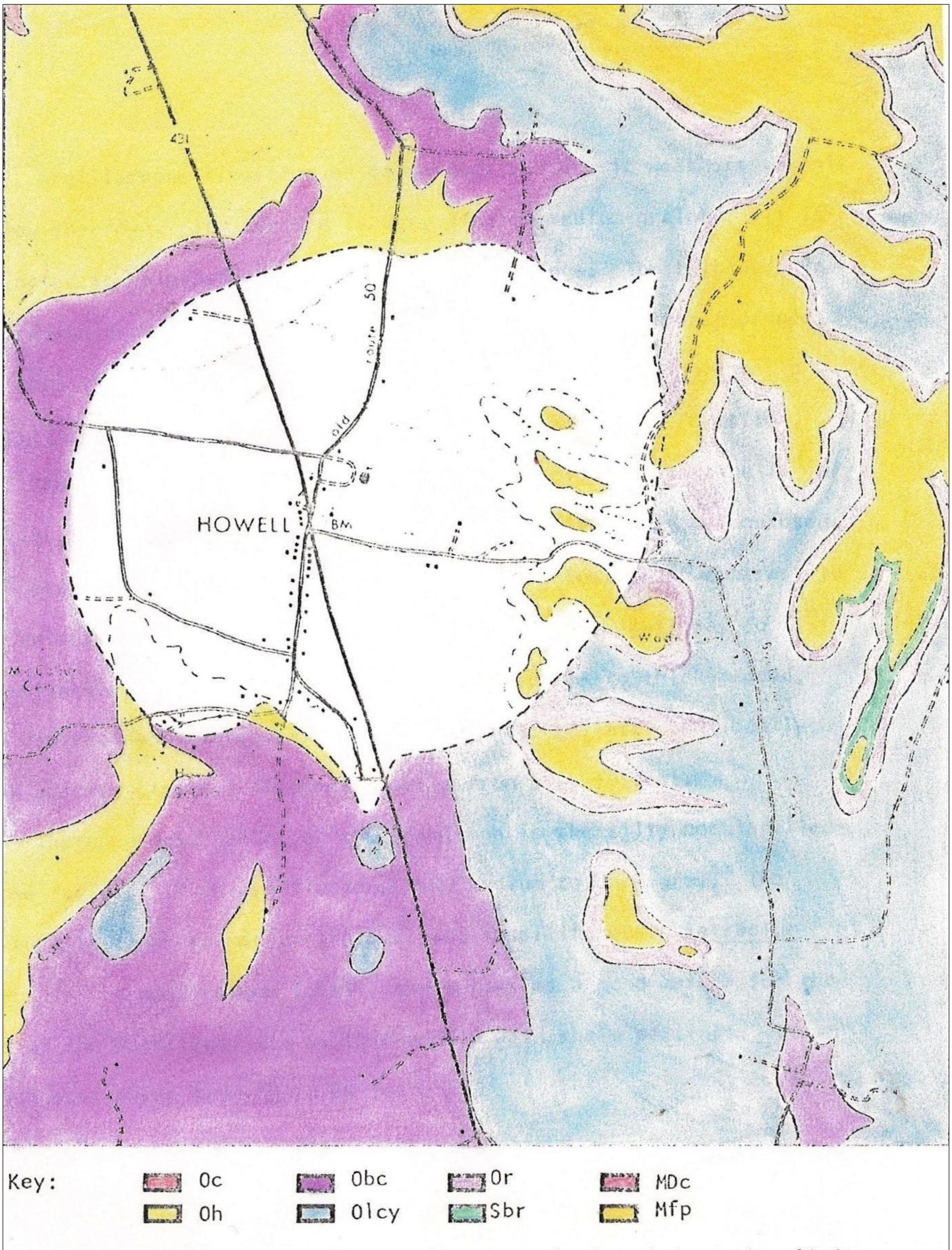


Fig. 3. Geologic map of the Howell Area, showing deformation limits. (Contacts mapped chiefly by Wilson and Barnes with additions by this writer.)
Scale 1:24000

Figure 4.72: A geological map of the Howell area as mapped by Wilson and Barnes and with additions by Woodruff. [Key: Oc = Carters Limestone (Middle Ordovician), Oh = Hermitage Formation (Middle Ordovician), Obc = Bigby-Cannon Limestone (Middle Ordovician), Olcy = Leipers Formation and Catheys Limestone (Middle and Upper Ordovician), Or = Richmond Group (Upper Ordovician), Sbr = Brassfield Limestone (Lower Silurian), MDc = Chattanooga Shale (Upper Devonian and Lower Mississippian), Mfp = Fort Payne Formation (Lower Mississippian)] (after Woodruff, 1968).

Figure 4.73 is Appendix A from Miller (1974: 59) showing the Composite Stratigraphic Section for Middle Tennessee which includes rock units essential to the understanding of the Howell Structure.

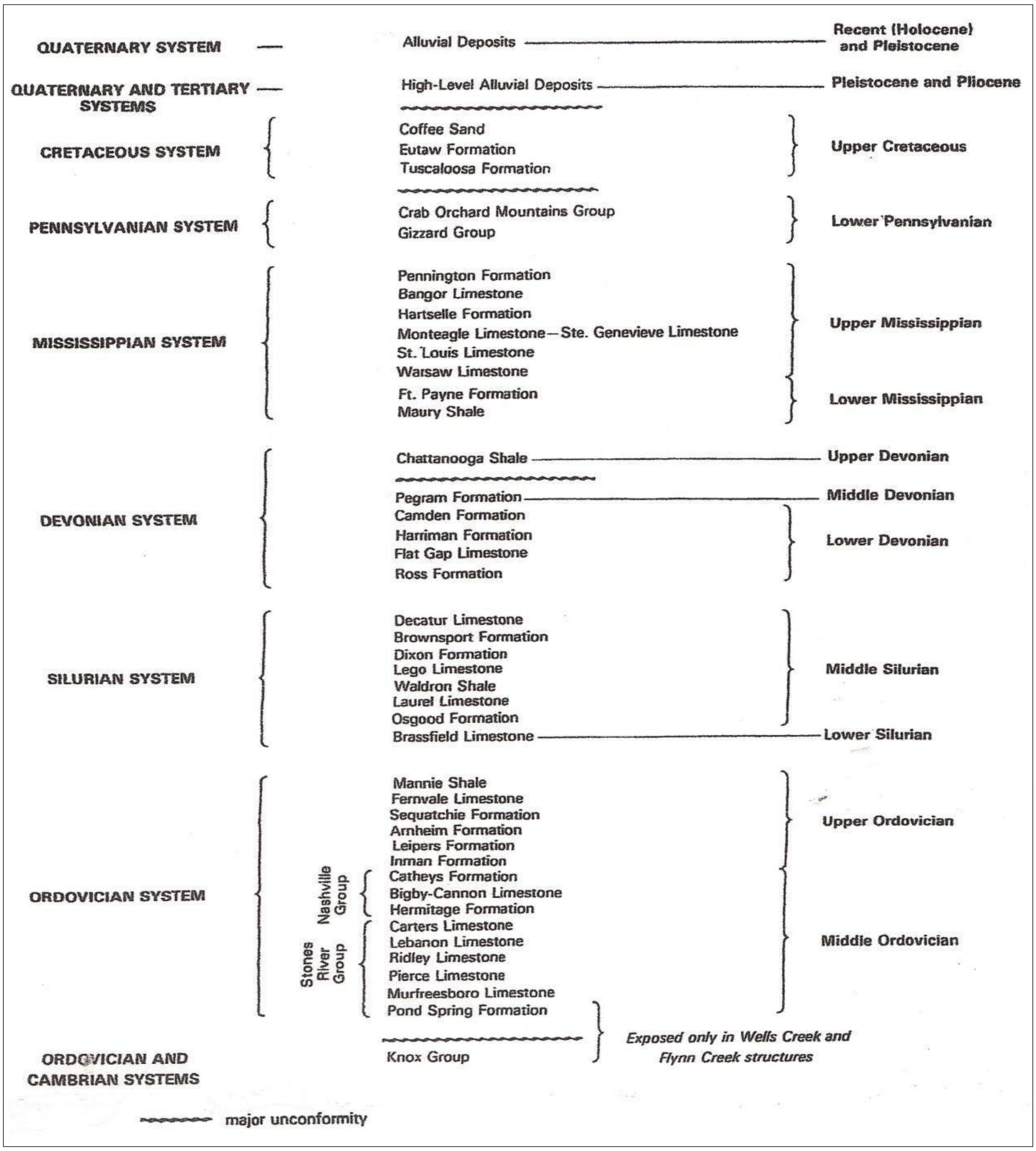


Figure 4.73: A composite stratigraphic section for Middle Tennessee (after Miller, 1974: 59).

The Stones (Black) River Group includes Carters Limestone and the Nashville (Trenton) Group, which in turn includes the Hermitage Formation, Bigby-Cannon Limestone and Catheys Formation, all from the Middle Ordovician. The Richmond Group is not specified in this particular stratigraphic section, but according to the U.S. Geological Survey is in the Upper Ordovician and includes the Arnheim Formation, Sequatchie Formation, Fernvale Limestone, and Mannie Shale. The Brassfield Limestone is Lower Silurian. Shown between the Pegram Formation of the Middle Devonian and the Chattanooga Shale of the Upper Devonian is a major unconformity found throughout Middle Tennessee. The Fort Payne Formation is Lower Mississippian. Note that in United States common usage, the Carbonifeorus

System is divided into the Mississippian (early Carboniferous) and Pennsylvanian (late Carboniferous). Unfortunately, rocks that are exposed on the surface and "… extend beneath the surface throughout Tennessee and other areas of the east-central United States … are referred to by other names elsewhere." (Miller, 1974: 19). These include the Nashville/Trenton and Stones River/Black River Groups. Woodruff (1968: 52) points out another difficult issue related to the Howell Structure: "One does not know how much of the entire stratigraphic section was actually present at the time of explosion." He states that there could have been as much as 90 additional meters of Silurian at the time of the event, which adds even greater uncertainty to our understanding of the Howell Structure (ibid.).

The Howell Structure is described by Born and Wilson (1939: 371) as "… a small area of highly disturbed, contorted, and brecciated strata." After studying and mapping the area in detail, Born and Wilson (ibid.) described the Structure:

> The salient structural feature is a circular area of intensely deformed Black River [Ordovician] and Trenton rocks, which have been uplifted approximately 100 feet [30 meters] above their normal positions. This circular area is composed of jumbled blocks of limestone imbedded in a matrix of shatter breccia. The major deformation is believed to have been Post-Trenton and pre-Fernvale in age. Overlying the shattered strata is the Fernvale Formation, the relative thickness and lithology of which point directly toward deposition in a graded crater.

During their investigation, Wilson and Born (ibid) determined that "The younger Silurian and Mississippian formations are relatively undisturbed."

Born and Wilson (1939: 375) describe the structural features of Howell in three parts: (1) the underlying, intensely-deformed rocks, which include Black River and Trenton strata; (2) the Fernvale Formation; and (3) the Chattanooga Shale and Fort Payne Chert. Their investigation indicated that the "… first series is separated from the second by a marked nonconformity with maximum differential relief of 100 feet [30 meters] within ½ mile [0.8 km] …" (Born and Wilson, 1939: 375). The plane of the nonconformity coincided with the pre-Fernvale surface. Figure 4.74 shows the structural cross-section of the Howell Structure, as determined by Born and Wilson (1939: 376).

Born and Wilson note that "The much brecciated rocks of Black River and Trenton age are limited to a circular area about 1 mile [1.6 km] in diameter …" (ibid.), and the strata of these groups occur in blocks that vary from small fragments up to 20 feet [6 meters] or more. The blocks abut against each other at greatly varying angles of strike and dip with individual blocks showing "… contortion and warping of bedding planes … [and] blocks of the Hermitage Formation have been rotated in respect to each other with resulting small-scale thrust-faulting …" (ibid.). This faulting, however, seems to be restricted to adjacent blocks that are in actual contact with each other:

> These blocks of limestone are imbedded in a matrix of shatter breccia composed of smaller fragments of limestone in a groundmass of powdered limestone. The breccia and the powdered limestone have been forced to flow around the blocks and along fractures within them, somewhat as in dike intrusion.
>
> This circular area of jumbled, brecciated, and unbrecciated limestone has been uplifted vertically in part, so that blocks of Carters Limestone are now in juxtaposition with the surrounding undisturbed Cannon Limestone outside the brecciated area. The maximum uplift was approximately 100 feet [30 meters]. Some blocks of Trenton limestone occur at the same

level, or even below, their normal horizon, but these blocks are believed to have fallen or rolled to these positions at the time of origin of the crater.

A rather definite break occurs between the jumbled and brecciated limestone within the circumference of the Howell disturbance and the surrounding normal limestone of the Cannon and Catheys formations.

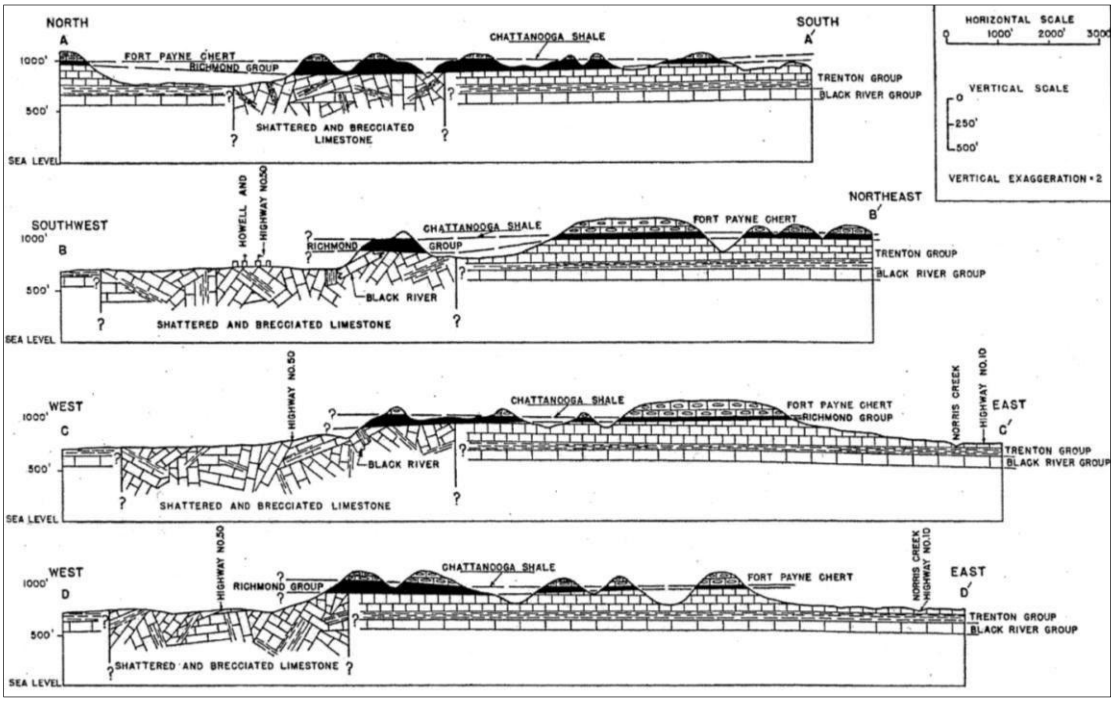


Figure 4.74: A structural cross-section of the Howell Structure (after Born and Wilson, 1939: 376).

Born and Wilson (1939: 376) note that "The Fernvale Formation rests nonconformably upon the underlying, greatly deformed Trenton and Black River strata." The Fernvale Formation, however, is only preserved in the eastern section of the Howell Structure, as well as to the east of the disturbance, so its extensive removal "… prevents conclusive determination of its former extent, thickness, and structural details …" (Born and Wilson, 1939: 377). Mapping of the region surrounding Howell Structure shows that the Fernvale Formation is noticeably absent, indicating that its preservation in the disturbed area is "… due to unusual local conditions." (ibid.). Born and Wilson (ibid.) point out that "… the rapid thickening of Fernvale from 15 to 115 feet [5 to 35 meters] toward the deformed area suggests some genetic relationship between the local abnormal thickness of Fernvale and the deformed area." They conclude that a closed crater some 30 meters deep and 1.6 km in diameter existed in pre-Fernvale times. This 30 meter depth would be that of the crater at the start of the Fernvale deposition, so it can be inferred that the crater's original, pre-erosion depth would have been greater:

> This crater must have been exposed to appreciable erosion before Fernvale deposition began, for its sides were not steep but rather were graded, as indicated by the abnormally thick Fernvale extending southeastward beyond the circumference of intense deformation that probably marked the limits of the crater. (ibid.).

The crater is thought to have filled with Fernvale sediments while flooded by the Fernvale Sea (ibid.). The lower shale unit was not deposited for a long period of time, though, as "… the sea was soon freed from silt, and the clear-water limestone unit was deposited …" (ibid.). Around 10 to 11 meters of this limestone unit were deposited before silt and quartz pebbles were subsequently brought in by the sea from a distant source. This last deposition completely filled the crater before the sea retreated.

The Fernvale limestone breccia is believed in part to have been the result of contemporary brecciation:

> One significant fact is that, even though locally brecciated, this limestone is a continuous unit that was deposited over the strongly deformed rocks. Also, the elevation of the Fernvale limestone averages lower within the circular area of deformation that outside, where it overlies normal strata, indicating that the Fernvale did not participate in the uplift that locally raised rocks of the Black River and Trenton Groups above their normal levels. (Born and Wilson, 1939: 377).

The thick shale overlying this limestone locally has dips as great as 45 degrees. Born and Wilson (1939) believe these dips are due to tilting and slumping that took place within the shale due to the settling and subsequent readjustment of the underlying deformed strata. They also state, though, that "… it may be necessary to postulate a mild post-Fernvale and pre-Chattanooga renewal of activity to account for such high dips …" (Born and Wilson, 1939: 377). It should be noted that if this subsequent activity was involved in the formation of the crater, then a meteoritic origin for the Howell Structure is not indicated. The overlying Chattanooga Shale and Fort Payne Chert formations show no brecciation, although they are warped, but Born and Wilson (1939) conclude that this warping had no relation to the pre-Fernvale crater.

Born and Wilson (1939: 377) state that the localized forces which brecciated the Black River and Trenton limestone "… obviously operated after the deposition of the Catheys Formation… [but] As the Leipers Formation is not present today in this mapped area, it is impossible to date the brecciation relative to this formation …" (ibid.). They point out, however, that since "… the Leipers Formation is believed to have covered most, or all, of central Tennessee … a post-Catheys, pre-Leipers crater should have been filled with Leipers sediments." (ibid.). Born and Wilson (1939: 377-378) conclude that the age of the Howell Structure must be determined from the following restraints:

> Even though the Fernvale limestone unit is locally brecciated and high dips occur in the Fernvale shale unit, the major deformation, when viewed from a study of all known facts as well as these anomalies, would appear to have been pre-Fernvale. There is no basis for argument for a post-Fernvale date for the maximum deformation, but there is some basis for believing in a post-Fernvale renewal of the activity, which was so great in pre-Fernvale times. If this did occur, it would have an important bearing on the problem of origin of the deformative forces; but, unfortunately, the data are not sufficient to prove that the initial strong pre-Fernvale deformation was followed by a mild post-Fernvale renewal of deformation.
>
> In summary, it is believed that the major deformation in the Howell disturbance may be dated as post-Catheys (probably post-Leipers) and pre-Fernvale, with possibly post-Fernvale and pre-Chattanooga recurrence in a mild form.

Born and Wilson (1939: 380) note that "If the Leipers formation were deposited prior to the explosion, as is believed to have been the case, it was removed by postexplosion erosion. No evidence is available for dating the explosion with regard to the Arnheim Formation."

Summarizing their findings at the Howell site, Born and Wilson state that an explosion occurred,

> … blowing out a crater at least 100 feet [30 meters] in depth and 1 mile [1.6 kilometers] in diameter, and piling up limestone debris around the crater … [Subsequent] Removal of this debris (and possibly the Leipers Formation from the surrounding area) and the grading of the crater walls by erosion … [occurred before] Deposition of the Fernvale Formation, filling the crater level with the surrounding floor of the Fernvale sea … (Born and Wilson, 1939: 380).

An item of interest was included in the 1961 United States Geological Survey, Branch of Astrogeology report:

> Field examination of the Howell disturbance, Tennessee, by E.M. Shoemaker, R.E. Eggleton, and D.J. Milton, in company with C.W. Wilson Jr. of Vanderbilt University, led to the conclusion that if this structure is of impact origin, as has been suggested by Wilson and others, the structure was probably formed at a time when the epi-continental Ordovician sea had significant depth at the site of the Howell disturbance. (Schaber, 2005: 31).

Woodruff (1968: 44-45) undertook the next major study of the area and mapped the Howell Structure‘s limits by including "… all expressions of deformation beyond an established 'norm' as being within the structure … all dips greater than those of the normal regional dip, all fracturing, folding, faulting, overturning, and brecciation." Woodruff (1968: 46) states that "The structure limits cannot be interpolated with ease from any one point to another. Interpolation is necessary, even though undesirable, in some areas because of lack of outcrops." Woodruff (1968: 46-47) determined that the Structure is roughly circular and somewhat irregular in outline, as shown in Figure 4.72. In locations where the Structure‘s boundaries seem to deviate from an idealized circular outline, Woodruff (1968: 49) surmises that the "… deviation might be due to dip of the structure at depth, which would give an irregular trace conforming to topography. Such irregularities might also be due to the vicissitudes of shock in rock layers at depth." He also determined that Howell is "… slightly elliptical with the axis of the ellipse trending slightly northeast …" (Woodruff, 1968: 47). The Structure‘s minor axis is around 1.8 km and trends north-south, while the major axis is about 2.5 km and trends approximately north 45 degrees east. Woodruff did not find an appreciable uplift between the rock units within the Howell Structure and the surrounding undisturbed strata, although he does suggest further investigation in order to verify this finding. Neither Wilson and Born nor Woodruff mention a cave located in the NE corner of the disturbance that was noted in 2003 by Deane et al. (2004).

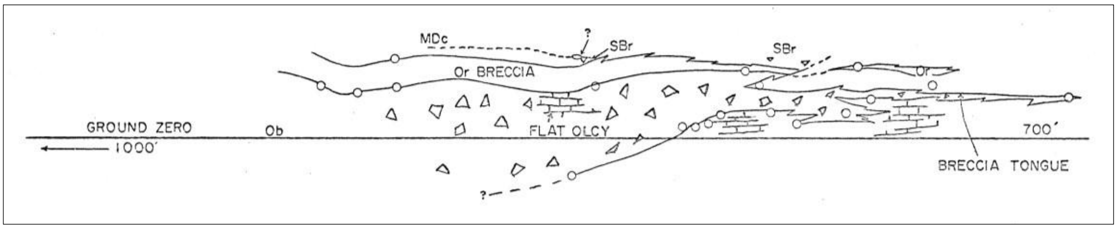


Figure 4.75: Idealized cross-section of the eastern half of the Howell Structure.
Scale: 1 inch = 500 ft.; o = points of control (after Woodruff, 1968: 51).

Woodruff (1968: 50) constructed an idealized cross-section of the Howell Structure by assuming that the Structure possesses "… basic radial symmetry …" and utilizing "… topographic elevations of the outcrops …" from his compilation map. The eastern half of his cross-section is seen in Figure 4.75 (after Woodruff, 1968: 51). He notes that as with the surface boundaries, the resulting drawing shows irregular deformation limits at depth, and he discusses the implications:

> This irregularity could be an artifact of the projection technique, but may well be real and due to a propensity of shock to be transmitted along bedding planes, or at least parallel to bedding. The irregularity may be due to the vagaries in behavior of different lithologic types when subjected to such forces … Only extensive subsurface information will demonstrate whether such boundaries actually exist. (ibid.).

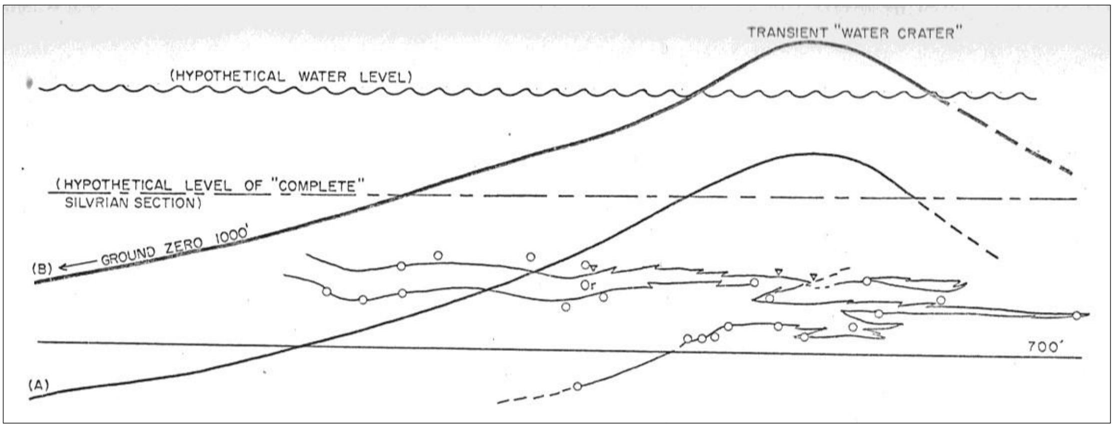


Figure 4.76: Idealized cross-section of the Howell Structure based on two superimposed half craters assuming (a) 90 meters of Silurian and (b) 90 meters of Silurian under another 120 meters of water. Scale: 1 inch = 500 ft.; O = points of control. (after Woodruff, 1968: 55).

If Woodruff's idealized cross-section is correct, then "… the zone of deformations is not as deep as would be expected …" (ibid.), but Woodruff (1968: 52) does note that "One does not know how much of the stratigraphic section was actually present at the time of explosion." Based on the complete Silurian section found in the Western Valley of Tennessee, there may have been as much as 90 meters of Silurian present at the time of the Howell event. Another possibility is that Howell "… at the time of impact (or explosion) was under water …" (ibid.). Figure 4.76 shows the eastern side of the idealized cross-section by Woodruff (1968: 55), with two superimposed half craters assuming (a) 90 meters of Silurian and (b) 90 meters of Silurian under another 120 meters of water. He continues: "… the depth of water would be equivalent to a certain amount of rock in dissipating the shock. At the same time, no indication of deformation would remain in water after the event …" (Woodruff, 1968: 57).

Woodruff noticed a 'gradation zone' from 18 to 45 or so meters between the breccias and normal, undisturbed rock as he mapped stratigraphic units from " … normal flat-lying beds into zones of intense deformation …" (Woodruff, 1968: 45). "This same relationship seems to hold true in subsurface work …" according to a personal communication between Bensko and Woodruff (1968: 3, 45) regarding the Howell core which was drilled by a crew from the National Aeronautics and Space Administration's Marshall Space Center located in nearby Huntsville, Alabama. Most all of the questions concerning the Howell Structure's limits of deformation at depth require subsurface data which Woodruff (1968: 49) points out are not extensive since such data requires "… drilling into a section of deformed rock and continuation of the drilling until undisturbed rock layers are reached … only one such NASA drill hole was available …" Bensko informed Woodruff "… that the drill hole penetrated past the breccias into undisturbed bedrock, and that there was a zone of gradation between the breccias and the normal bedding …" (Deane et al., 2004: 2; cf. Woodruff, 1968: 65).

According to Woodruff (1968: 57), "Essentially, all geomorphological indications of deformation are expressed in joint, and/or fault controlled stream lineations and joint and fault control of escarpments …", and he cites several "… striking examples of joints controlling a stream pattern …" within the Howell Structure:

> Cane Creek turns about 80 degrees, reflecting a joint pattern radiating outward from near the center of the structure. Again on Cane creek, but outside the northwestern limits of the structure, is another such elbow turn, where the joint similarly appears to radiate outward from the center of the structure. Striking joint control is further seen in the tributary of Cane Creek that cuts the northern portion of the structure … The joint pattern again appears to radiate.
>
> These features indicate an event of sufficient magnitude to give rise to a more or less radiating set of joint fractures in surrounding otherwise undisturbed rocks. (ibid.).

This finding rules out localized sedimentary processes that would have caused slumping and brecciation. Other geomorphic indications of structure according to Woodruff are also joint and/or fault controlled within the area of deformation. These are "… the apparent alignment of the dissected escarpments on the eastern ridges making up the drainage divide between Cane and Norris Creeks …" (Woodruff, 1968: 58). He notes that these features radiate from a central area in the Structure.

Woodruff (1968: 23) discusses the age of the Howell Structure based on stratigraphic relationships:

> On the western two-thirds, erosion has cut deep into the roots of the structure completely obliterating most geomorphological indications of deformation. However, on the high ground on the southern and eastern side, the structure is buried by undeformed Fort Payne chert of Mississippian age. This is valuable because it limits the structure to a pre-Fort Payne time of origin. However, certain problems have arisen in dealing with rock units older than Fort Payne.

In his discussion, Woodruff (1968: 23) notes that Born and Wilson recorded the finding of strong dips, local faults and some brecciation in the Richmond Group of rocks at Howell and "… that the geologic sequence of events was further confused by the presence of tongues of the Fayetteville channel of Richmond Age." He then explains the process by which he arrives at an age for the Howell Structure:

> Born and Wilson (1939) placed the age of the structure as being post-Leipers and preRichmond. The fact that the Richmond Group occurs as a <u>continuous</u> belt of rocks (and can be mapped as such) overlying the much more intensely brecciated older Ordovician rocks and the fact that this belt of Richmond contains <u>only</u> blocks and fragments of Richmond (never blocks of older Ordovician age) led them to this conclusion. They attributed the deformation of the Richmond to contemporaneous brecciation that occurred shortly after the partial consolidation of the Richmond as a result of readjustments in the underlying jumbled breccia of older Ordovician rocks and also to a possible mild renewal of the forces that caused the original major deformation (volcanic origin required for this).
>
> The present writer has now asserted that the age of the structure is definitely post-Richmond – indeed post-Silurian, on the strength of the discovery of brecciated lenses of chert, identified by Wilson as being in the Brassfield Formation (Silurian). Also, another zone, which may represent an intensely deformed area of still younger age, has been found by this writer. This consists of a mixed zone of chert, sand, various sulfides, and possibly even carbonaceous shale material. Petrographic study shows planar features cutting across quartz grain boundaries, and the possible presence of glass, and/or isotropized quartz. The zone has been postulated by Stearns as being a mixture of Silurian (Brassfield) and Devonian (basal

> sand of the Chattanooga Shale). The most realistic appraisal of a "normal" stratigraphic position for the so-called "mixed zone" would be in the basal sand of the Chattanooga Shale. This still gives a striking parallel in time of deformation with the Flynn Creek structure. (Woodruff, 1968: 23, 27).

Woodruff (1968: 28) concludes that the age of the Howell Structure "… may be stated with authority as being post-Brassfield, and possibly into the upper Devonian time … Also, it is safe to say that the structure is pre-Fort Payne."

A possible explanation of the 'mixed zone' discussed above "… is that it may be the fossilized crater rim, buried and thus preserved from erosion by the Fort Payne chert." (Woodruff, 1968: 27). The possibility that this 'mixed zone' may be composed of rim material is indicated by petrographic studies and based on samples that seem to be reworked rim material. Woodruff (1968: 63-64) concludes:

> It contains fragments from Brassfield chert, and basal sand of the Chattanooga Shale. The quartz grains that are deformed are probably of Devonian age, probably from the basal sand member, but it is believed that the Chattanooga Shale is post-deformation in age. This gives the outstanding age control that was hoped for from the beginning. The age can be bracketed into a time zone in the uppermost Devonian. It is known to be pre-Fort Payne (Mississippian), and is probably pre-Chattanooga (Devonian-Mississippian). This means that the Howell event could exactly coincide with the Flynn Creek structure in age, as the Flynn Creek crater is filled with material of Chattanooga age…
>
> The rock units exposed in the Howell area range from the Hermitage Formation of Ordovician age to the Fort Payne Formation of Mississippian age. The units involved in the deformation range from the Hermitage through the Brassfield of Silurian age. Another younger rock unit, considered to be a mixed zone between Silurian and Devonian and Mississippian units was found. Constituent members of that rock unit were also deformed. The geological age of the structure has been placed as certainly post-Lower Silurian and probably post-lower Devonian. It is probably pre-Chattanooga and is certainly pre-Fort Payne (Mississippian).

In another discussion of the age of the Howell Structure, Miller (1974) points out that the adjacent Fort Payne rocks, which are Lower Mississippian, are not structurally disturbed indicating that the Structure's origin is pre-Mississippian and that Silurian rocks in the Structure are brecciated, indicating it is post Silurian. Miller (1974: 56) also compares the Howell Structure's age to that of Flynn Creek noting that Flynn Creek "… formed in Middle to Late Devonian time (350-375 million years ago), for it is filled with Chattanooga Shale …" Miller (ibid.) concludes that "… the Howell Structure may be very close in age to the one at Flynn Creek, or some time in the Devonian Period, possibly just prior to deposition of the Chattanooga Shale…"

Miller also notes that Howell, unlike the larger Flynn Creek and Wells Creek impact structures in Tennessee, is only 2.1 km in diameter and that there are some dissimilarities between this and the other Tennessee impact sites. He points out that "There is no distinct central uplift, although intense brecciation and other disturbances of the rocks have possibly concealed or obliterated an otherwise more definitive uplift …" (ibid.). However, on the Earth the transition from a simple to a complex crater occurs around a diameter of 2 km in sediments and 4 km in massive crystalline rocks (French, 1998: 24). Howell might just be a simple crater and as such would not possess a central uplift.

Miller (1974: 56) also states that “Although there are faults within the Howell Structure, there are no clearly definable circular faults surrounding it …” (ibid.). This statement is in dispute, however. There are three somewhat concentric faults in the quadrant just to the southwest of Howell that are seemingly centered on the Structure, and although there is no published information that would suggest that the faults are in any way associated with the Structure, their proximity to it is interesting. The distances of the faults from the Structure, as measured on a 1:250,000 map, are approximately 6.4, 22.5, and 38.6 kilometers, but they are not *perfectly* concentric to the Structure. Since they are situated on the S-SW periphery of the Nashville Basin another possibility is that they may have formed during the uplift of the Nashville Dome and thus related to that structure. If so, their proximity to the Howell Structure may merely be a coincidence. Figure 4.77 is a generalized tectonic map of the southern interior lowlands of the United States which shows the Howell Structure, the three faults, and the Nashville Dome (after Roddy, 1968b: 293).

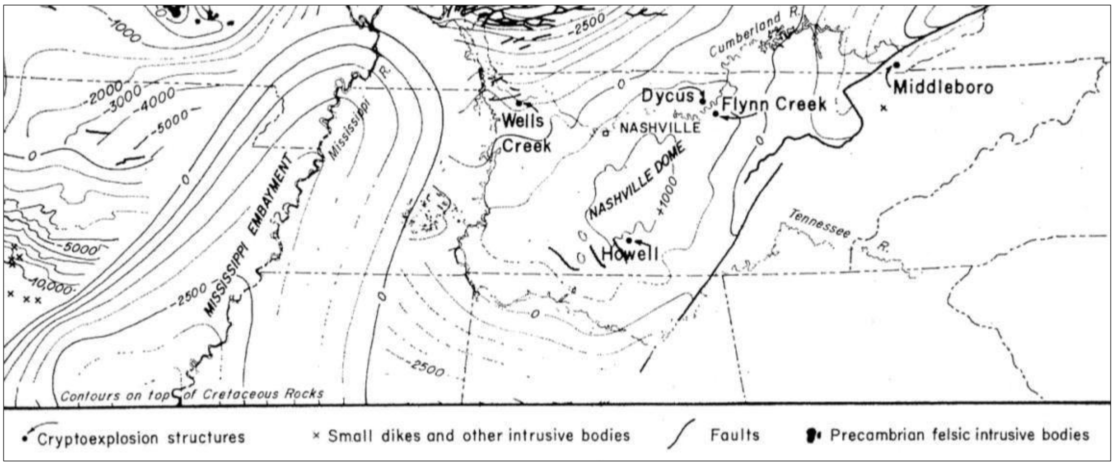


Figure 4.77: A generalized tectonic map of the southern interior lowlands of the United States which shows the locations of the Howell Structure and Nashville Dome with respect to three concentric faults (after Roddy, 1968: 293).

4.5.4 Crypto-Controversies

Fossil meteorite craters display certain characteristic features, such as circular limits of deformation, and faults and joint sets that are within a crater‘s area of deformation and to some lesser extent outside of the area of deformation, that usually “… demonstrate a striking radial symmetry …” (Woodruff, 1968: 19). Dietz (1960: 1781) points out, however, that “… the formation of a chaotic, circular structure, extensive brecciation, and intense shattering are all suggestive of meteorite impact but are hardly definitive.” Likewise, an actual impact structure may not be easily recognized due to subsequent geological processes:

> The actual crater morphology of such features may have been destroyed until only the “roots” are exposed, as is the case at Wells Creek, or the crater floor may have been preserved (but at the same time kept from view) by crater filling as is seen at Flynn Creek. (Woodruff, 1968: 18)

Cryptoexplosive structures have been attributed to various mechanisms, including salt-doming. However, salt beds are not known in this region either at the surface or in subsurface drilling records (Born and Wilson, 1939: 379). Woodruff (1968: 17) agrees, stating that “Although there are some who would attribute the deformation to such geologic processes as salt dome collapse, these ideas have been discredited because of gross lack of evidence …" Woodruff (1968: 17-18) then addresses the remaining possibilities for the origin of Howell and similar sites:

> Generally, there are two schools of thought about the origins of the roughly circular, highly deformed areas as seen at Howell, Wells Creek Basin, Flynn Creek, and many others … One school attributes the origin to meteor impact, the other attributes the origin to "cryptovolcanic explosions" yielding a breccia pipe from depth.
>
> The meteoritic hypothesis brings to bear on the subject the concept of shock metamorphism … Shock processes, unlike classical metamorphic processes, occur over time intervals of "from a few microseconds to a fraction of a minute."
>
> The problem in dealing with such areas of deformation in the field is to define characteristics that are unique to the shock processes and characteristics unique to "cryptovolcanic processes." In finding one or another of the features, the structure can then be classified as either of "terrestrial" or of "shock" origin. In reality, however, the differentiation of the structure into the two types is not so clear cut. What a geologist has to deal with usually are only remnants of structural features that have been exposed to geologic processes for millions of years. All one finds are either greatly eroded structural features, or features that have been buried during subsequent ages. After such processes as erosion, deposition of new sediments, and possibly other structural events have sufficiently clouded the issue, the differences between features caused by shock processes in a fraction of a second, and slower formed tectonic features (and even salt dome collapse structures) become insignificant, and similar features in common become striking.

Woodruff (1968: 18) believes that "The process that affected the Howell area in particular and certain other structures in general, were believed sufficiently explosive to have formed a crater." Born and Wilson (1939: 379) agree, stating that they believe "… the Flynn Creek and Howell craters, with associated injected breccias and powdered limestone, require extremely violent explosive action." They also point out that any explanation for the structural features found at the Howell site must be able to account for the following:

> (1) a circular mass of jumbled and brecciated limestone, part of which has been uplifted approximately 100 feet [30 meters] relative to surrounding strata; (2) the shattering of Black River and Trenton limestone into blocks and the irregular jostling of these blocks; (3) the pulverizing of much of the limestone into ―rock flour‖; (4) the unusual ability of breccia and rock powder to force their way into fractures; and (5) the formation of a crater 1 mile [1.6 km] in diameter and more than 100 feet [30 meters] in depth, centered over the brecciated area. (Born and Wilson, 1939: 378).

Born and Wilson (ibid.) note that the above features are characteristic of the cryprovolcanic structures described by Bucher, "… as well as the Wells Creek basin and the Flynn Creek disturbances in Tennessee …", which are both confirmed sites of meteorite impact. Born and Wilson (1939: 380) attribute the Howell Structure to "An explosion, blowing out a crater at least 100 feet [30 meters] in depth and 1 mile [1.6 km] in diameter, and piling up limestone debris around the crater …", and they conclude:

> The writers recognize difficulties in both the cryptovolcanic and the meteoritic hypotheses and for the time being, prefer to maintain as neutral a position as possible until more data are found. Unfortunately, the Howell disturbance does not present new features that will aid greatly in determining the origin of this group of structures. (ibid.).

They also note that the possibility of a "… post-Fernvale and pre-Chattanooga renewal of the same localized force that formed the pre-Fernvale crater would support the cryptovolcanic hypothesis …" (ibid.).

Woodruff (1968: 19) addresses the possible cryptovolcanic genesis of structures such as Howell:

> The presence of volcanic material may seem to be strong evidence toward the hypothesis. However, the presence of volcanic matter associated with the ―fossil crater‖ is not unequivocal for that origin. Shock processes might well cause extensive fracturing at depth, and thus cause a drastic change in pressure which in turn might affect the geothermal gradient. Partial melting might occur with ready-made fissures for access to the surface.

Woodruff (1968: 29) states: "From the other evidence available – depth of deformation, roughly circular plan view and radial symmetry of geologic features, most of the Howell breccia has been categorized by this writer as being of shock type." This would indicate that Howell is "… the ancient eroded equivalent of a meteor impact crater …" which then requires an in-depth investigation of the breccias found at Howell for confirmation (ibid.).

4.5.5 Howell Breccias

Breccia is rock that consists of angular fragments in a fine-grained matrix. Though commonly found in confirmed impact structures, breccia is not unique to impact sites: "Breccia may be formed by diverse processes, ranging from explosions of nuclear magnitude to collapse of solution cavities and including diagenetic breccias, fault breccias and volcanic breccias …" (Woodruff, 1968: 29). Woodruff (ibid.) points out that the end result of all of these processes is the same, but examination of the breccia itself does not usually give any indication of its geological origin so other evidence must be examined and considered in order to determine its genesis.

Woodruff (1968: 19) makes the interesting comment that when it comes to impact structures, breccia "… which is so prevalent that it is used (or misused) as indication of what rocks have been affected by the structural event and which rocks have not … [is utilized in determining] the limits of deformation both laterally and vertically." He continues, noting that "… the extreme case of deformation is seen as breccia, and it is this criterion that has heretofore been the determining factor as to the limits of the structural features …" (Woodruff, 1968: 22). Woodruff (1968: 23) considers "… the best criterion for deformation at Howell is the presence of breccia." Meanwhile, the actual breccias found at the Howell site provide the best way of determining which rock units were deformed by an explosive event and which rock units were not involved (Woodruff, 1968). He also notes that "… the discovery of breccia in uppermost Ordovician, Silurian, and maybe in Devonian units is of importance … mainly because of their addition to the knowledge of the extent and age of the deformation …" (ibid.).

Born and Wilson (1939: 373) found breccias composed of angular fragments of limestone to occupy a circular area 1.6 km in diameter centered on Howell. These

> … fragments range in size from shot up to large blocks many feet in dimension and occur in a matrix of powdered limestone. Much of this breccia consists of small, angular to subangular fragments the size of walnuts. Within this type of shatter breccia occur large angular blocks of limestone that may or may not be brecciated. Many of these blocks of limestone are cut by dikelike stringers, or veins, of injected powder breccias, which suggest forceful intrusion along fractures while the injected material had a "mushlike" consistency. (ibid.).

Woodruff points out, however, that even if Howell is an impact structure, not all of the breccia is necessarily due to shock processes. The various breccia types may be "… a primary feature, pre-deformation, or as a secondary feature, post-deformation. One is very likely to find fault breccias, slump breccias, or collapse breccias associated with such a structure …" (Woodruff, 1968: 29).

Woodruff (1968: 29) focuses his discussion, though, on the formation of various types of breccias in events that are sufficiently catastrophic to yield craters. Breccias can be fragmented and granulated in place or form as "… fall back – particles thrown into the air by the explosion, but resettling into the crater proper …" (Woodruff, 1968: 30). He points out that crater fill could consist of a 'hodge-podge' of fall back, in-wash or crater rim material, and he believes that if any reworked rim material is still present at the Howell site, then it is found only on the high ridges in the eastern section of the structure.

Woodruff (1968: 31) reports that in breccia formation, "The same stratigraphic unit may be found to react differently to the deforming forces in different areas, reflecting various 'zones' of deformation …" both laterally and vertically. He points out that "Zones may be seen in which bedding and other stratigraphic features are preserved with breccias injecting joints and bedding planes …" (ibid.) and he explains his interpretation of some of the breccia characteristics as follows:

> This retention of ―relict‖ features with brecciation superimposed either concordantly or discordantly has been taken to indicate the fringes of deformation, especially at depth. In other words it would be where the deformation ―dies with a whimper‖ and the forces are not sufficient to obliterate the pre-disturbance sedimentary features. (Woodruff, 1968: 31-32).

Breccia is common throughout Howell, some of which is shown in Figure 4.78. Woodruff describes the Howell breccias as generally being composed of angular to subangular fragments that grade in particle size from 'pea-size' up to blocks several meters across embedded in a matrix which most often has a sugary appearance that is gray-brown, but occasionally distinctly pink in color. He also points out that "Certain rock units may be recognized as being matrix material of certain breccias …" (ibid.). Some of the breccias found by Woodruff are homogeneous, while others are mixtures of lithogies. As an example he notes that "… the Catheys-Leipers breccias present a hodge-podge of lithogies, in which the fragments appear to be of one rock type while the matrix appears to be another" (Woodruff, 1968: 32). In contrast, "… the Fernvale Limestone yields a homogeneous breccia …" (ibid.).

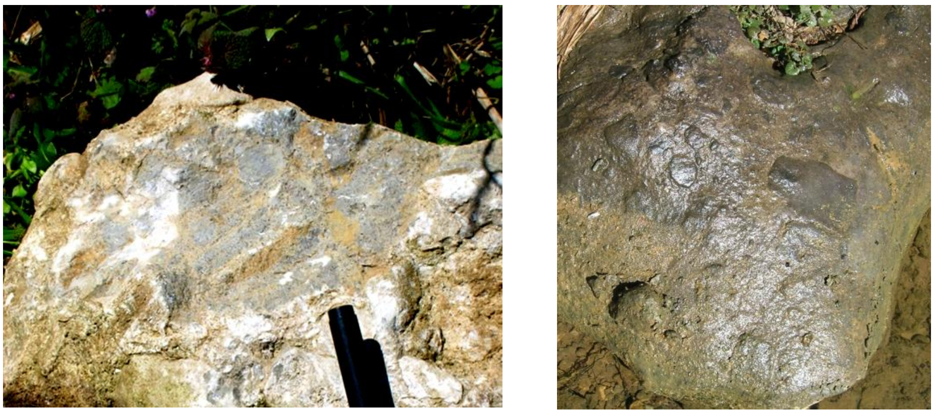


Figure 4.78: Breccia outcrops are common throughout Howell, especially along road cuts (left) and creek beds (right). (Photographs: Jana Ruth Ford).

Fossil remains were found within the brecciated rocks. A specific point of interest noted by Woodruff is that although 'fossil hash' would be expected to be preserved in breccia where fossiliferous rock units existed before the explosive event occurred, "… in at least two locations large fossils (coral heads) have been found within the breccia …" (ibid.). These coral heads are "… widely separated in stratigraphic extent …" with one sample intact within the breccia and the other with Favosites coral heads that are up to 15 cm in diameter (ibid.). Miller (1974: 22) explains that "Corals appeared for the first time in the geologic column in Tennessee during the Ordovician time and grew in abundance in what is now the Central Basin area."

There are several different breccia types that were found and photographed by Woodruff at the Howell Structure. He describes the Howell Mega Breccia as being large blocks of rock broken apart and "… disarranged at random orientations to one another … with more 'normal' fine breccias filling the interstices between the blocks." (Woodruff, 1968: 33). The mega-breccia blocks may even themselves be brecciated. Figure 4.79a is a photograph taken by Woodruff (1968: 34) at Howell of the typical 'mega-breccia' matrix he found there. Next he describes Crush Breccia or Injection Breccia by noting that "… the rocks seem to have been granulated in place without significant movement of rock material …" (ibid.). Figure 4.79b shows an example of the crush breccia Woodruff (1968, 35) located in Howell, often displaying relict bedding. Woodruff (1968: 36) notes that large quantities of vein injection breccia are seen in the crush-breccia, especially in creek beds, and that the veins cut across still-preserved bedding features. Figure 4.80 is a photograph taken by Woodruff (1968: 37) which shows a possible breccia injection vein that crosses relict bedding and Figure 4.81 shows what Woodruff (1968: 38) describes as a "Breccia vein showing flow pattern of fine-grained brecciated particles around larger fragments." Woodruff (1968: 33) interprets this finding to indicate that the crush-breccia rock units most likely experienced greater pressure and "… could only readjust on a small scale to the shock." In contrast, "… the mega-breccia may generally represent a shallower zone of the deformation, and could readjust to the shock by a bulk movement of rock material …" (Woodruff, 1968: 33, 36).

Figure 4.79a (left): A photograph of the typical Howell 'mega-breccia' matrix (after Woodruff, 1968: 34).
Figure 4.79b (right): A photograph of the Howell 'crush breccia' (after Woodruff, 1968, 35).

Figure 4.82 shows two photographs Woodruff (1968: 39) took of the 'Plum Pudding Breccia' which he only saw in the Fernvale Limestone breccias (Woodruff, 1968: 36). He states that "… this feature was attributed to slump and crater fill … [and] the rock unit consists entirely of ferruginous limestone fragments in a matrix of the same material …" (ibid.). The first photograph shows it in an outcrop, and the second is a close up which shows the fragments and matrix with identical lithologies.

Figure 4.80 (left): A photograph which shows a possible breccia injection vein that crosses relict bedding (after Woodruff, 1968: 37).

Figure 4.81 (above): A photograph of a "Breccia vein showing flow pattern of fine-grained brecciated particles around larger fragments." (after Woodruff, 1968: 38).

Figure 4.82: Photographs of 'plum-pudding breccias'; the right hand image is a close-up view that shows identical lithologies of fragments and matrix (after Woodruff, 1968: 39).

An unexpected finding by Woodruff involves the mix, or lack thereof, of breccias of various stratigraphic units involved in the Howell Structure:

> One would expect in dealing with an area which has been subjected to as severe a shock as meteor impact, that breccia formed would consist of a random mixture of all stratigraphic units involved. There should, it would seem, be no means of distinction between pre-deformation rock units. Certainly <u>contacts</u> between brecciated rock units should be virtually impossible to find. However, this writer has observed that at Howell, formation masses and even contacts are often traceable across the structure …
>
> This feature of the Howell structure is especially evident in the rocks of the Richmond Group, which were once considered post-deformation as they appear to have been deposited upon the structure proper. Even though this writer has demonstrated that the structure originated long after the Ordovician Richmond was deposited, the integrity of the mapped units in a distinct area still holds true. The same formational mass "integrity" may be generally true for the older Ordovician rock units. This has been locally observed but not fully investigated …
>
> The major problem in this assertion is the absence of a widespread zone of mixed Richmond and Nashville rocks to match the lithologic zones in brecciated older Ordovician units …

> Only in scattered localities have Fernvale fragments been found in lower "Nashville" breccias …
>
> One other zone that may be classified as a mixed zone is the rock in the area of high ground which as mentioned before, appears to have chert and sand mixed with certain sulfides, clays and carbonaceous material. This may be a mixed zone of reworked lithologies present before deformation. These lithologies might include Silurian (Brassfield), and Devonian (Hardin sandstone or basal sand of Chattanooga Shale), all of which could have lain within a few feet of each other before deformation. This would, of course, entail an unconformity in that no Silurian and Devonian would have been present between the Brassfield and the Chattanooga. (Woodruff, 1968: 36, 40-41).

Miller (1974: 25-26) also notes this unconformity in the geological history of Tennessee:

> All of the Silurian rocks in Tennessee formed in marine or near shore environments …
>
> There was uplift of the land and some erosion at the end of Silurian time … but in most places it is not possible to determine how much, for two subsequent major episodes of erosion during the Devonian in some places removed all the rocks overlying the Middle Ordovician …
>
> There was renewed uplift after the deposition of the Pegram sediments, and this new episode of erosion was to result in one of the most important unconformities in Paleozoic rocks of this region. Much of the Devonian sediments, as well as extensive areas of Silurian and Ordovician rocks, were removed by erosion.
>
> When the Late Devonian sea advanced across the land, conditions had changed dramatically compared with other invasions of the ocean, and the environment was like few others in all of the geologic history of this region. The sea eventually spread over much of the east-central United States, depositing a black, carbonaceous mud over hundreds of thousands of square miles. This black mud, containing rotted organic matter, became the Chattanooga Shale.

Woodruff (1968: 41) again notes an unusual feature of the Howell Structure: "It has been noticed in studying the Howell structure that the courser-grained rock units are more apt to be brecciated whereas the finer-grained rocks are less likely to be so deformed …" Woodruff (ibid.) noticed this phenomenon in the 'dove-like cryptocrystalline limestones' which were not often brecciated. Occasionally Woodruff came across fragments of the dove mixed with a brecciated unit and at least at one location he decided that the dove was itself the breccia matrix. "However, the dove-like zones (beds) have remained intact. The dove, therefore, has maintained its own lithologic integrity …" (ibid.). The puzzling aspect was that these seemingly undisturbed units were within the area of most intense deformation. Woodruff (1968: 41-42, 44) discusses the possible mechanisms through which this unexpected result could have occurred:

> This has led to speculation by some observers that the structure may have been caused by diagenetic processes such as slumping of unconsolidated sediments, repeated time and time again during geologic time. By this speculation, there would be periods of deposition between the times during which the breccias were formed. The rocks deposited during these interbreccia periods would be the undisturbed crypto-grained dove-like units … However, this sedimentary hypothesis cannot explain the extreme localization of deformation within a circular area and the presence of some radiating joint patterns as seen and measured in outcrops in creek beds bordering the structure. Localized solution activity is also unsatisfactory in that it would seem to call for uplift, before the process of solution could work in such a limited area. No such uplift is observed.
>
> The explanation of that phenomenon may be better dealt with in terms of the more explosive processes, which are believed to have taken place here. One such explanation would be that the undisturbed bed flat upon breccia is another example of breccia injection. Under

great pressures breccia might behave as a slurry and may cross lithologic features. It has been mentioned that "breccia injection veins" have been observed; this then would be an example of a "breccia sill …"

Another hypothesis concerning such a phenomenon would be the inconsistent behavior of shock waves in rocks of different lithologic types. Generally, the cryptograined rocks are not brecciated, although subjected to forces capable of granulating coarser rocks. Therefore, this writer postulates that there is a definite relationship between rock textures and shock transmission. Thus, the fine-grained dove-like limestones transmit the shock waves, but at the same time are not affected by the shock in a noticeable way. The coarser-grained units then receive the transmitted wave and amplify it from one grain boundary to the next, causing fragmentation. (The parallel that this writer draws is the behavior of earthquake waves in areas of sound bedrock as opposed to earthquake behavior in loose alluvial fill. The bedrock areas act as a unit in transmitting the wave, while the loosely consolidated material amplifies the "shock," causing the greatest destruction). The coarser-grained rocks do not behave as a distinct unit; the dove-like members do.

Figure 4.83 is a photograph taken by Woodruff (1968: 43) showing a breccia sill he investigated at the Howell Structure.

Figure 4.83: A photograph of a breccia sill (after Woodruff, 1968: 43).

4.5.6 Shatter Cones, Shocked Quartz and Drill Cores

According to Dietz (1960: 1781), "Volcanic explosions are steam explosions involving pressures of not more than several hundred atmospheres, so it is extremely doubtful that a shock wave can be developed in rock as a part of volcanic phenomena …" however, a meteorite impact is capable of generating a shock wave. French (1998: 36) states that "Shatter cones are the only distinctive and unique shock deformation feature that develops on a megascopic (hand specimen to outcrop) scale." Dietz (1960: 1782) searched the Howell site for shatter cones as proof of impact, but he found that "Rock outcrops at the Howell structure are too poorly developed to permit any intensive search there …" (ibid.). Miller (1974: 56), however, notes that "Some features that may be shatter cones have been found, but they are indistinct."

Shatter cones are indicators of meteoric impact, and are typically oriented so that the tips of the cones point toward the shock, or 'ground zero', of the meteorite impact. Therefore, "… shattercones are useful in determining … whether the explosion originated from above or below." (Woodruff, 1968: 23). He continues:

"Shattercones have not been previously identified in the Howell area, but this writer has found one location in which crudely formed cones may be present …" (ibid.).

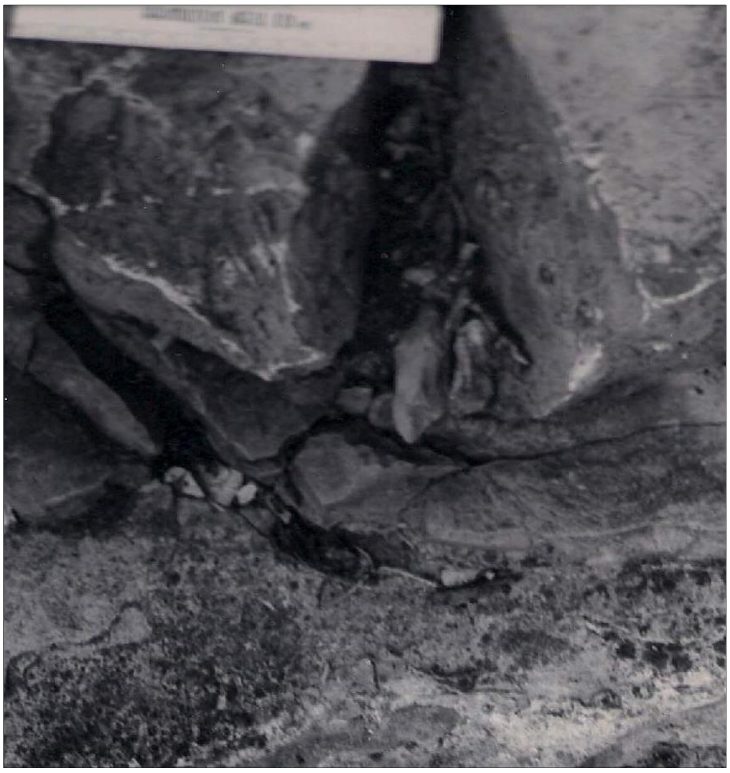


Figure 4.84: A photograph of possible shatter cones (after Woodruff, 1968: 24).

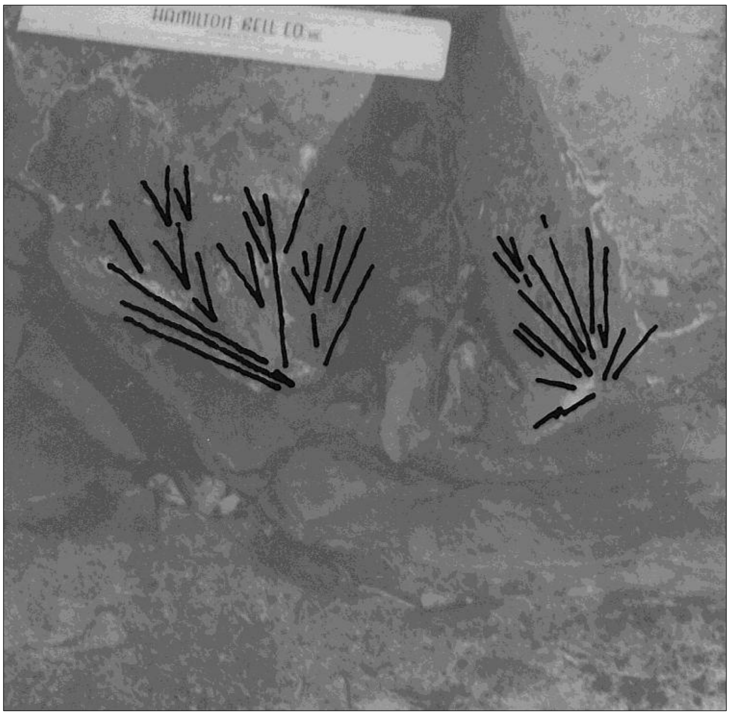


Figure 4.85: Use of an overlay to mark the features that may be shatter cones (after Woodruff, 1968: 24).

Figure 4.84 shows what Woodruff (1968: 24) calls possible shatter cones. The photographic equipment he used during the 1960s did not produce the clear images he desired, so Figure 4.85 shows this same photograph with a Mylar film overlay marked to show the features that he saw in person but did not show up well on the grainy photograph. Likewise, Figure 4.86 shows a "Poorly formed shattercone …" and Figure 4.87 shows the same photograph, again with the features he saw in person indicated by the overlay (Woodruff: 1968: 25). The fact that Woodruff considered this later example to be a poor example of a shatter cone does not preclude an impact origin since, as noted by Dietz (1960: 1783; 1968: 271), poorly formed shatter cones were also found at Flynn Creek, a confirmed site of impact.

Woodruff searched the Howell site for other evidence of shock, and noticed that the texture and mineralogy of specimens he found on the higher ground located in the northeastern section of the Howell Structure were "… so unlike anything else seen in the Howell area, that thin sections were made for further study …" (Woodruff, 1968: 59). This area is a mixed zone consisting of sand and chert, sulfides and carbonaceous material, and the outcrops here may be fossil rim material or "… a basal lens of the basal sand of the Chattanooga Shale …" which would have been deposited "… in a marsh or in deep stagnant water …" (ibid.). The thin sections studied in this petrographic investigation were found to be "… predominately quartz or other silica material, such as chert …" (Woodruff, 1968: 61).

This investigation found in some quartz grains "… a definite lineation … or sometimes sets of lineation … so prominent as to indicate one or two directions of cleavage …" (ibid.). Wilson and Stearns (1968: 153) point out that their investigation of the Wells Creek confirmed impact structure determined that "The most severe deformation noted in quartz is somewhat widely spaced fracturing." Figure 4.88 shows a thin section of a quartz grain photographed in polarized light displaying planar features (after Woodruff, 1968: 60).

Another quartz grain displayed 'patchy extinction', indicating that it was subjected to sufficient stress to granulate and then re-indurate so as to retain its original form as a single grain. Woodruff (1968: 61) also found several samples in which "Other possible indications of shock are seen where certain quartz grains, or what appear to be quartz grains are partially or entirely isotropized …", and

> In certain areas of the thin sections which macroscopically appear to be stringers of glauconite and possibly hematite, it is seen in thin section to consist of something resembling flow of finely divided quartz. The lineation of the glauconite and the flow-like trend of the smaller silicious material align with each other. (ibid.).

Woodruff states that some quartz grains were found to be "… completely fragmented in certain areas of the thin sections … usually where the section is thinner than usual, as around the edge of the section …" and believes that "This fragmentation may represent incipient fractures due to stress …" (ibid.). Figure 4.89 shows two samples found by Woodruff at the Howell site. One thin section, photographed in plain light, he calls a micro-breccia, and he states that it is a single quartz grain which displays a "… mosaic of fractures in thin section …" (Woodruff, 1968: 62). The second thin section, photographed in polarized light, shows the "… flow of finely divided particles …" (ibid.). Woodruff (1968: 63) then makes the following observation from his petrographic study:

The rocks have constituent materials that have been subjected to severe stress, but at the same time, may contain material that has not been so subjected. There, it seems most likely that the material in consideration has been reworked, possibly even reworked rim material.

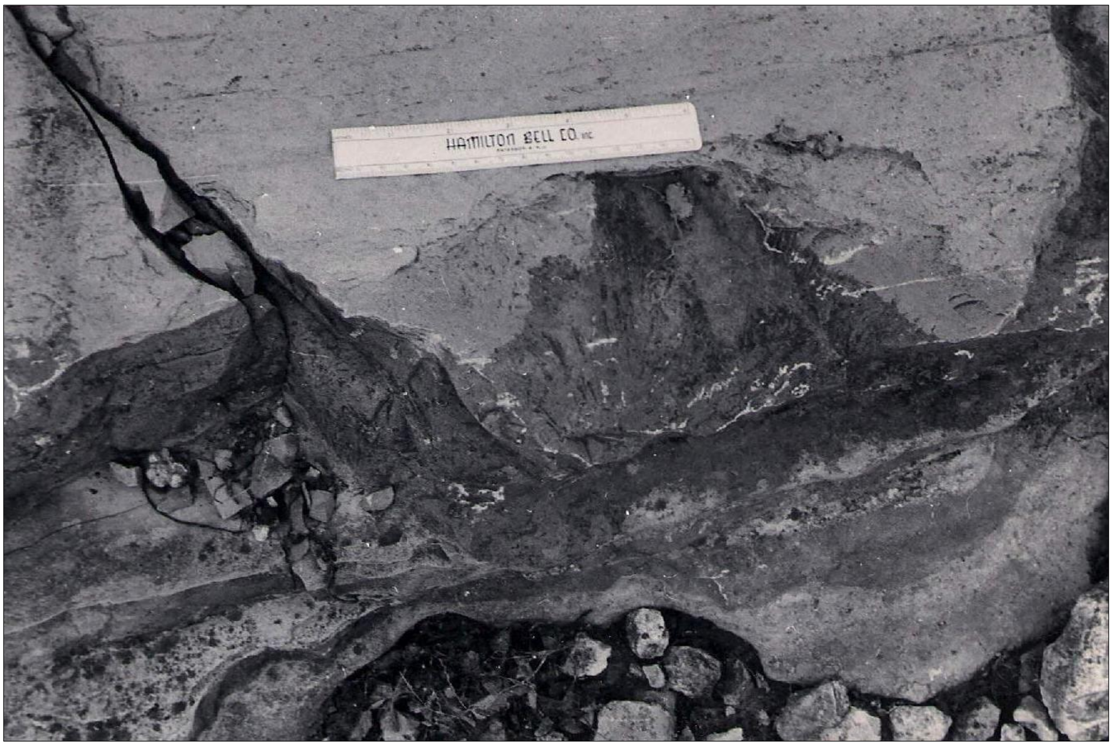


Figure 4.86: A photograph of a poorly-formed shatter cone (after Woodruff, 1968: 25).

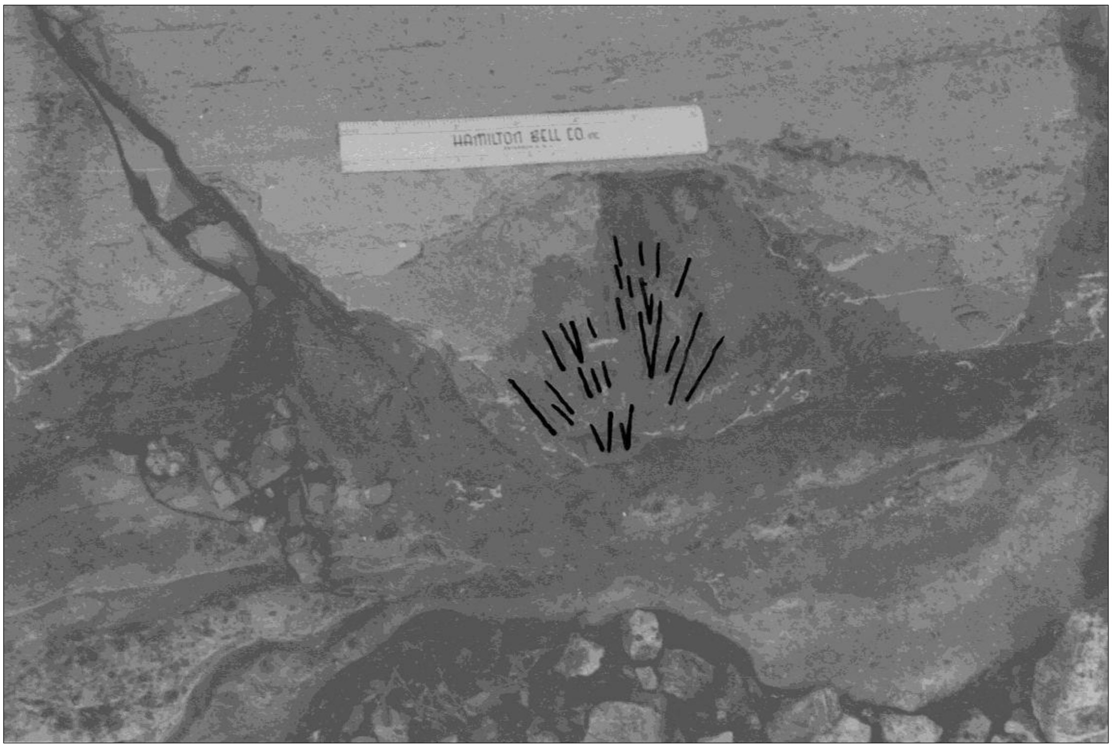


Figure 4.87: Use of an overlay to indicate the poorly-formed shatter cone (after Woodruff, 1968: 25).

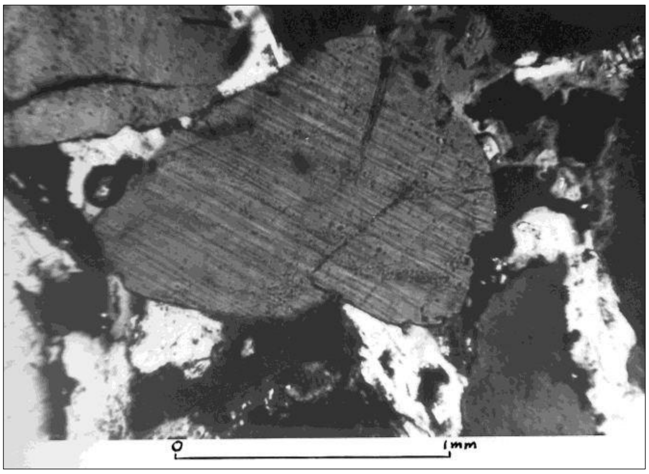


Figure 4.88 (above): A thin section showing a quartz grain with planar features (after Woodruff: 1968: 62).

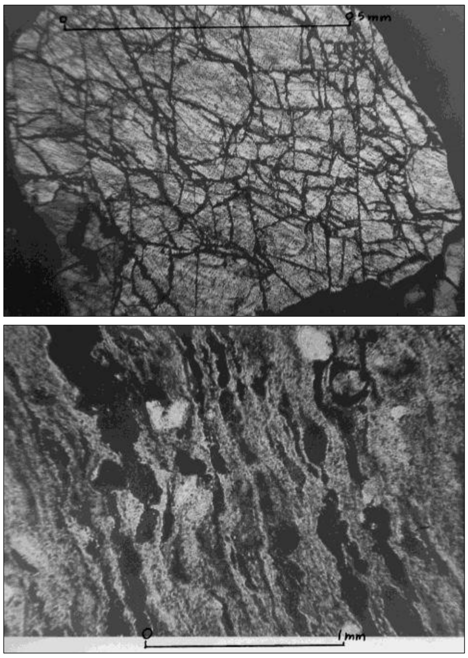


Figure 4.89 (right): Thin sections showing two quartz grain samples displaying (top) a 'micro-breccia', and (bottom) "… the flow of finely divided particles..." (after Woodruff: 1968: 63).

Woodruff (1968: 65) believes that the results of this petrographic study indicate that shock metamorphism has taken place, but unfortunately "… these thin sections did not survive the passage of 35 years of time and are lost for further study …" (Deane et al., 2004: 2). More samples from Howell are therefore required for a detailed investigation using current technology.

In 2003, Deane and Milam were members of a team that made two trips to the Howell Structure in order "… to search for evidence of shock metamorphism in local lithologies …" (Deane et al., 2004: 2). The team gathered samples of limestone breccias from creek beds in the central part of the disturbed area, as well as samples of the Leipers and Catheys Formation (a fine-grained, thin to medium-bedded Ordovician limestone exposed at the base of the hills on the eastern side of the site, but could not obtain a micro-brecciated sample similar to the one reported and photographed by Woodruff. But they did find and analyze the 'powdered limestone' breccia reported by Born and Wilson (ibid.). "Thin sections were produced for all samples. All observed quartz grains displayed substantial micro-fragmentation. However, no unequivocal evidence of shock metamorphism such as melt, flow, or planar deformation features (PDFs) was found …" (ibid.).

Woodruff (1968: 19) points out that in many structures such as Howell, geological processes have removed most of the characteristic features that are considered unequivocal indicators of shock due to impact, including coesite and stishovite, or isotropized quartz. Wilson and Stearns (1968: 152) noted that during their spectrographic study of breccias located within Wells Creek, a confirmed impact structure, no coesite or stishovite was found either, and that "Although these dense materials were not found, their absence is not considered to preclude an impact origin of the structure …" (ibid.). They concluded that the absence of coesite and stishovite at Wells Creek "… probably establishes only that if a meteor impact did occur, the zone in which shock pressures were sufficient to develop these minerals has been removed by erosion …" (Wilson and Stearns, 1968: 153).

Woodruff (1968: 19) notes that "Meteorite fragments would be conclusive evidence, but, unhappily, this is the rarest evidence." Howell is far too old for such fragments to have survived the passage of time. Woodruff (1968: 20), therefore, discusses alternate means of determining whether a structure is the result of a meteorite impact:

> Ultimately, one of the few certain means of determining whether a structure is formed by meteoric or terrestrial process is by subsurface study. If the area of deformation has a lower limit above the (igneous-metamorphic) basement complex it is then concluded to be of meteoric origin. However, this is contingent upon the size of the deformed area. Meteor impact may well yield deformation to such depths as to involve basement and be impractical to drill through.

Woodruff (1968: 65) points out that "The information gained by NASA's drilling (John Bensko, personal communication) is that the structure has a bottom in stratigraphic sequence and is thus lens-shaped at depth instead of being a breccia pipe." Similar results were noted by Wilson and Stearns (1968: 128), in the 610 meter drill core of Knox Dolomite taken from the Central Hill of the Wells Creek Structure in 1947 by the Ordman Company. Evidence of impact is "… less abundant, less complete, and more poorly defined with depth. This is consistent with the interpretation that the shock source was from above and that the intensity of shattering diminishes downward …" (ibid.). Since the drill hole at Howell went through breccias and then penetrated into undisturbed rock, an impact origin is possible.

4.5.7 Conclusion

Based on his investigation, Woodruff (1968: 29) believes that the Howell Structure is "… the ancient eroded equivalent of a meteor impact crater …", and he cites the following evidence in support of this origin:

> The criteria used in this conclusion are based on the morphology of the structure, subsurface information, and petrography. The roughly circular-elliptical appearance, and radiating joint patterns are morphological indicators of such an origin, as are breccias, but neither of these are conclusive. (Woodruff, 1968: 65).

Miller (1974: 56) also believes that "Overall, the evidence indicates the Howell Structure was formed by meteorite impact." Shoemaker and Eggleton (1961: A14A15) also state that Howell does have the form and structure of a partly-eroded meteorite crater.

Evidence of shock metamorphism was completely lacking for the Howell Structure until October 2014. Milam et al. (2014) report that samples from cores drilled at Howell in the 1960s have been recovered, courtesy of J.W. Bensko, formerly a lunar geologist from NASA's Marshall Space Flight Center located in Huntsville, Alabama. In addition, limestone breccia samples obtained from Howell surface exposures were provided by R.G. Stearns, Professor Emeritus, Vanderbilt University, Nashville, Tennessee. XRD spectral analyses of breccias from the Howell Structure were compared to unshocked, optically clear calcite in an effort to identify diffraction peak broadening that can occur in the XRD spectra of shocked carbonates. Initial results for three of seven samples are consistent with shocked calcite. Full width half maximum values for these three samples are consistent with peak broadening observed in limestone from confirmed terrestrial impact sites including Sierra Madera and Steinheim. However, this magnitude of peak broadening is also observed in some tectonically-deformed limestones. Milam et al. (2014) note that there is no evidence of tectonism in the immediate vicinity of Howell, so shock metamorphism of carbonate breccias due to impact is indicated and an impact origin of the Howell Structure is favored.

However, no indisputable shatter cones, shocked quartz or other unequivocal evidence of shock (other than breccias) have been found at the site, and although data provided by the one drill core obtained at the Howell site is suggestive of a meteorite impact, further—more compelling—evidence is required. So a continued search for shock indicators is needed to prove whether or not this site is the scar of an impact crater. Unfortunately, even if this is an impact site, it may be so heavily eroded and structurally deformed that no indisputable proof of impact will now be found. Perhaps 80-90% of the structure has been removed by erosion so that only the deepest roots of the Structure are now visible. At this time, the evidence for impact, while promising, is still insufficient to declare that the Howell Structure is a confirmed meteorite impact site.

CHAPTER 5: CONCLUSION.

Our Moon's impact scars have not suffered from the erosional processes that eventually erase terrestrial structures. Lunar craters were originally considered to be volcanic, as were terrestrial craters. This was due, in part, to a lack of understanding that the characteristic features of an impact crater are produced by an explosion, not the simple gouging of a solid surface. Terrestrial craters that showed *no* evidence of igneous origin were considered to be cryptovolcanic, later cryptoexplosive, structures that resulted from volcanic steam explosions. Decades of discussion and controversy involving notables such as Albritton, Baldwin, Barringer, Boon, Bucher, Dietz, Shoemaker, and in Tennessee, Wilson, resulted in the eventual acceptance of the fact that the Earth, like our Moon, bears the scars of ancient impacts.

Earth is a dynamic planet. If there are ancient scars of meteorite impact in west Tennessee, then they are most likely covered by marine sediments from seas that have long since advanced and retreated. If any such scars still exist in east Tennessee, they have likely been distorted by mountain building and then eroded beyond recognition. In middle Tennessee, the dominant geological feature was the Nashville Dome which began eroding during the Mesozoic Era to form the current Nashville Central Basin (Miller, 1974: 42). Any meteorite scars once located on the Dome have now been erased. However, four structures, two confirmed and two suspected sites of impact, are associated with the Highland Rim of middle Tennessee which encircles the Nashville Central Basin. Wells Creek is located in the northwestern section of the Highland Rim. Flynn Creek and the Dycus Disturbance are located in the northern part of the Eastern Highland Rim Escarpment. The Howell Structure is located on an outlier of the Southern Highland Rim.

In the early years of impact studies, Baldwin concluded that lunar craters were the result of meteoritic, not volcanic action, and Barringer became convinced that Meteor Crater, later known as Barringer Crater, was the result of a terrestrial meteorite impact; Bucher, meanwhile, advocated a cryptovolcanic origin for such terrestrial structures. Boon and Albritton published several papers in the late 1930s suggesting that structures such as Wells Creek, Tennessee, were the scars of ancient meteorite impacts. In 1936, Bucher (1936, 1070) noted the presence of shatter cones at Wells Creek, the first time they were found in an American structure, and stated that they are evidence of an "… explosive force ...", though he attributed this force to crypto-volcanic activity. In another 1936 paper, Wilson and Born (1936: 829) rejected a meteoritic origin for Flynn Creek in favor of a cryptovolcanic origin, however, in their 1939 paper concerning the Howell Structure they state:

> The writers recognize difficulties in both the cryptovolcanic and the meteoritic hypotheses, and for the time being, prefer to maintain as neutral a position as possible until more data are found. Unfortunately, the Howell disturbance does not present new features that will aid greatly in determining the origin of this group of structures. (Born and Wilson, 1939: 380).

In 1951, one of Wilson's graduate students studying at Vanderbilt University, R.M. Mitchum, investigated the Dycus Disturbance and concluded in his Master's thesis that it is a probable impact structure (Mitchum, 1951: 38). Apparently Wilson did not object to this conclusion due to his own study of a Wells Creek drill core, sometime around 1951, which caused him to again consider the origin of cryptoexplosive structures: "During this period Wilson (1953) accepted the meteor impact origin of the Wells Creek structure with its subsidiary Indian Mound craters and a similar origin for the Flynn Creek structure …" (Wilson and Stearns 1968: 165).

Dietz not only advocated a meteoritic origin for cryptoexplosion structures, but he stressed the significance of shatter cones in such structures and, in 1959, along with Wilson and Stearns, located "poor" but unquestionable shatter cones in the Flynn Creek crater (Dietz, 1960: 1783). Not everyone was convinced, however. "In 1963 the two protagonists, Bucher and Dietz, marshaled their arguments in the American Journal of Science …" (Wilson and Stearns, 1968: 165). The tide was beginning to turn, though. C.M. Woodruff (1968: ii), another Vanderbilt University graduate student, investigated the Howell Structure from 1967 to 1968 for his Master's thesis, under the guidance of Stearns and Wilson. Woodruff (1968: 64) concluded that Howell "… is believed to have resulted from meteor impact."

During the early 1960s, the National Aeronautics and Space Administration began funding the United States Geological Survey's Astrogeologic Studies headed by Eugene Shoemaker (Schaber, 2005: 23). Shoemaker suggested one of his graduate students, Dave Roddy, investigate Flynn Creek in the years leading up to the Apollo Lunar Missions (Roddy, 1966c: 33). Roddy turned in Annual Progress reports on his Flynn Creek research to the Branch of Geologic Studies throughout the Project Apollo years, and then continued his Flynn Creek research for decades after the completion of Project Apollo (Schieber and Over, 2005: 67).

The Tennessee sites were of great interest to those involved in the crypto-controversies which took place in the years before astronauts landed on the Moon. As Roddy (1966c: 8) pointed out, "During the period from about 1940 to 1960 only a few studies were devoted to the 'cryptovolcanic' problem …" However, according to Wilson and Stearns (1968: 165),

> With the advent of the Space Age and the study of the moon much work has been done and many papers published on the nature of these structural features, in large part concerning their possible genetic relationships to the craters of the moon.

Roddy (1966c: 10) concurred, noting that "… since 1961 increased interest in the lunar craters has been stimulated by the efforts directed toward manned lunar exploration. This interest in lunar craters in turn revived an interest in terrestrial crater studies …", and these studies included several sites in Tennessee.

Wilson and Stearns (1968: 1) state that within the northern part of Tennessee's Western Highland Rim, "The major topographic anomaly … is Wells Creek Basin." They describe the structure as "… a concentric series of two grabens [blocks that have dropped] and a horst [a block pushed upward] around a central uplift …" (ibid.). First recognized as an anomaly in the 1860s and described by Safford (1869: 147), Wells Creek was later classified as a cryptovolcanic or cryptoexplosive structure and its origin was debated for decades. Bucher (1963a: 1242) describes Wells Creek as "… the largest of the American cryptovolcanic structures." Dietz (1963: 650) notes that even though he and Bucher disagreed on its genesis, both agreed that "… the Wells Creek Basin structure may be usefully used as the 'syntype' for the United States …" when discussing 'cryptoexplosion structures'. Bucher (1963a: 1243) gives the following description:

> The Wells Creek Basin stands out among American cryptovolcanic areas by its size (diameter about 13.7 km = 8.5 miles) … and by the poorly developed, but distinct, anticlinal ring

> between the outer limits of the structure and the central uplift, suggestive of an elastic damped wave effect …

Safford (1869: 333) also noted the ring structure stating that "… the Black Shale … forms, by its outcrop, one of the concentric rings around the central area of the Wells Creek Basin." Wilson and Stearns (1968: 63) also described the "… structure of annular rings… " that surround the Wells Creek central uplift which cause the damped wave effect and noted that "The larger the [impact] structure, the more exterior rings relative to the central crater might be expected." (Wilson and Stearns, 1968: 171).

No microscopic evidence of shock metamorphism has been found in the Wells Creek Basin as of May 2015. Even Knox dolomite collected from the central uplift showed no evidence of impact other than numerous macroscopic shatter cones. (John C. Ayers, personal communication.) A noteworthy fact is that the central uplift of the Wells Creek Basin is home to some of the most exquisite shatter cones on Earth. Shatter cones are unambiguous shock features and, therefore, considered confirmation of impact! The age of the Wells Creek structure, however, cannot be precisely determined as explained by Miller (1974: 56):

> The time of this event can only be estimated within widely separated limits. Insofar as some Upper Mississippian rock is involved in the deformation, it is known to have occurred since that material was deposited. Because Tuscaloosa Gravel (Upper Cretaceous) is present in the deformed area, but is not itself deformed, the event was prior to Tuscaloosa time. As no rocks of any age between these two units are preserved anywhere within or adjacent to the structure, it can only be said that the event occurred somewhere between 75 and 300 million years ago.

Wilson and Stearns (1968: 17) led a team in the most detailed investigation of Wells Creek to date funded by a 1963 grant awarded to Vanderbilt University by the National Aeronautics and Space Administration (NASA). They concluded after nearly five years of study that a meteorite "… struck the earth possibly from a northnortheast direction …" and penetrated the ground some 600 meters before exploding (Wilson and Stearns, 1968: 177). The result was an explosive impact crater "… with a large central mound and exterior ring depressions …" (ibid.).

Bucher (1963a: 1243) points out that there are several small craters near Wells Creek that may have a common origin with the main structure:

> Three diminutive craterlets filled with Cretaceous sediments trend north-north-westward a short distance beyond the Wells Creek Basin … Dr. Wilson, who described them, called them impact craters, caused by small meteorite fragments … it is assumed that a giant and baby meteorites hit the ground in line …

Wilson and Stearns (1968: 88) note that if the Wells Creek structure's axis of bilateral symmetry is projected from the center of the crater, it runs north-northeastward. Wilson (1953: 764-765) points out that these "… small meteoritic pits, or craters …" lie to the north of Wells Creek "… practically in a straight north-northeast line …" and states the following:

> It is concluded that a swarm of meteors approached the earth's surface … or a single meteor fragmented into at least four pieces before striking the surface. The largest fragment struck at the present location 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.

Shoemaker suggested that Roddy (1966c: 33) investigate Flynn Creek for his thesis when he was a graduate student at the California Institute of Technology.

Roddy received a Ph.D. on the dissertation topic of "Impact-cratering mechanics of Flynn Creek, Tennessee" working under Shoemaker. During his years of study, Roddy (1964: 50; 1966c: 20) wrote a series of annual progress reports for the United States Geological Survey's Branch of Astrogeologic Studies on behalf of the National Aeronautics and Space Administration as part of a larger program of crater investigations. Roddy (1966c: 14) explains the reason Flynn Creek was chosen for study by NASA and the USGS:

> The Flynn Creek crater was chosen for the current study because the local and regional exposures are among the best of all the "cryptoexplosion" structures in the United States. The crater is buried, and it was assumed that a more complete record of its history was preserved. Consequently it was hoped that … local geologic study combined with a laboratory examination of the rocks would give a better insight into the origin of the Flynn Creek crater.

Roddy (1963: 118) points out that Flynn Creek is located in the Eastern Highland Rim Escarpment of north-central Tennessee. He wrote (Roddy, 1977b: 279) that "The Flynn Creek Crater was formed in early Late Devonian time ... [and] The entire crater and central uplift were quickly protected from any significant erosion by the rapid disposition and complete filling by marine sediments of early Late Devonian age." He evens notes that in the southern and southeastern sections of the crater rim, ejecta overlie the *original* pre-impact ground surface in a down-dropped section (ibid)., and "Limited erosion and lowering of the rim indicate that the crater, as mapped in structure contour and outcrop today, is very close to its original gross morphologic form except for the erosion of the ejecta blanket …" (Roddy, 1977b: 283). As a result, this impact structure—unlike most others—experienced limited alteration by erosion. According to Dietz (1946: 466), "… the Flynn Creek crater probably bears a closer resemblance to a typical lunar crater than any present-day terrestrial feature." In fact, it bears an uncanny resemblance to the lunar crater Pythagoras! Dietz (1960: 1783) along with Wilson and Stearns located shatter cones not far from the crater's center, giving proof of an impact origin.

Based on conodonts found within the crater that are lower Frasnian in age and overlain by Devonian black shales, Schieber and Roddy (2000: 1) and Schieber and Over (2005: 66) have determined the age of the Flynn Creek crater to be around 382 Ma, a revision from earlier estimates of around 360 Ma. They also state that the Flynn Creek impact occurred in extremely shallow water, however, except for the flat top of the central uplift that indicates some modification by wave action, "The crater morphology is a close match to that expected of a subaerially produced crater." (Schieber and Over, 2005: 64). Flynn Creek is home to at least twelve caves, nine of which are found along the crater rim while one is located in the crater's central uplift (Evenick, 2006: 15; Milam and Deane, 2006a: 1). The structural geology of Flynn Creek appears to have controlled the formation of most of these caves (Milam et al., 2005b: 34).

Roddy (1979b: 2532) concluded that Flynn Creek is the result of an "… oblique impact … [with] oblique penetration into the rocks, including a very shallow body of water." Milam and Perkins (2012: 1) also conclude from recent field work that Flynn Creek is the result of an oblique impact. The impactor traveled along "… a shallow (~5°) impact angle along an approximately NW to SE present-day trajectory …" (ibid.). Tracing this trajectory line back a few kilometers, one comes very near the Dycus Structure.

The Dycus Structure is regarded as a possible meteorite impact scar. It is a deformed area similar to Flynn Creek (Roddy 1966c), but smaller, and is only 13 km to the north-northwest of Flynn Creek, also in Jackson County. The Dycus Structure is on the Eastern Highland Rim Escarpment, as is Flynn Creek, and both sites occur in Ordovician target rock (Deane et al., 2006: 1-2). Stratford (2004: 22) also notes that “Dycus is so close to Flynn Creek … that they may be the result of a double impact.” An interesting question is: “Could these two features be related temporally, for example, were these duel impactors or is Dycus a secondary of Flynn?” (Deane et al., 2006: 2). If these structures are the result of a duel impact, they could have been formed by either binary impactors or a single impactor that fragmented in Earth’s atmosphere. Atmospheric fragmentation of an initially single impactor would result in the smaller fragment falling uprange of the main impactor that would have produced the Flynn Creek crater due to the smaller fragment having a greater area to mass ratio. This would be consistent with the incoming impactors moving *NW* to *SE* as is indicated by Flynn Creek structural evidence (Milam and Perkins, 2012). Another possibility is a ricochet. The lunar craters Messier and Messier A are thought to be the result of an oblique ricochet impact with the elongated and saddle-shaped Messier being the first impact and Messier A the ricochet (see Forsberg et al., 1998: 1). Messier A is rounder and somewhat larger than Messier. Likewise, the Dycus Structure, so near to the larger Flynn Creek, is not circular, but oval-shaped (Deane at al., 2006: 2).

It is thought that Dr C.W. Wilson either learned about or discovered the Dycus Structure during the 1940s (ibid.). He did not know of its existence in 1939 (Born and Wilson, 1939: 375). Mitchum (1951: 1), a graduate student at the time, accompanied Wilson to this disturbed area in 1950 and subsequently undertook the first investigation ever carried out on the Dycus Structure for his Master’s thesis.

Even though folding and faulting are rare in this region of middle Tennessee, Mitchum (1951: 8, 15, 16, 19, 20, 24) observed intensely-disturbed rock strata, tight folding, faults, high dips, vertical and overturned beds, as well as some breccia in a small, localized area. The fact that this small area suffered a severe disturbance in the distant past is inescapable. Mitchum (1951: 36) believes that the Dycus Structure is the deeply eroded root of an impact crater which has eroded “… below the level of more intense brecciation and faulting in the zone where deformation is predominantly by folding.” This statement may indicate that Mitchum arrived at the meteorite impact conclusion before or around the same time Wilson revised his opinion concerning cryptoexplosive structures. Wilson is known to have accepted a cryptovolcanic origin for Flynn Creek as late as 1949 (Roddy, 1966c: 17). Mitchum submitted his thesis in May of 1951, but Wilson (1953: 753, 766, 768) was apparently revising his opinion concerning cryptovolcanic structures by this time and, based in part on a Wells Creek drill core study that took place in December of 1951, became an advocate of the meteoritic hypothesis.

Mitchum (1951: 15) states that “The uncovered portion of the disturbed [Dycus] area is limited to that of an approximate half-circle … ” with a 1.2 km diameter, and he notes that the presence of “A small, relatively subordinate central uplift … marks the area of most intense deformation.” However, the entire Dycus structure had not been mapped and the boundary of the Dycus Structure was not fully defined during Mitchum’s study (Deane et al., 2006: 2). Apparently, no field research was conducted at the site from at least 1964 until 2003 (Deane et al., 2006: 1), although

Roddy was certainly aware of its existence while he was working at the nearby Flynn Creek crater (Roddy, 1966c: 17, 153). Later field work "… extended the northern boundary a couple hundred meters farther north ... [which] raises the possibility that Dycus is shaped more like an oval, rather than a D …" (Deane et al., 2006: 2). One issue that has not been resolve, though, is that central uplifts occur only in terrestrial complex craters that have a diameter of about 2 km or greater (French, 1998: 240).

A second issue is the fact that this later research shows that the uplift, "… the area of maximum deformation does not lie in the center of the structure, but rather defines the northeastern boundary …" (Deane et al., 2006: 2). It is interesting to note that the lunar crater Schiller is also elongated, probably due to an oblique impact (Melosh, 1989: 49), and displays an uplifted ridge near the crater's northwest boundary. The similarity is striking. Both Schiller and Dycus are elongated with an uplift near one end of their oval-shaped boundaries. A better understanding of the possible relationship between Flynn Creek and the Dycus Structure based on research that focuses on highly-oblique impacts may also explain other aberrant craters such as Schiller and the Messier craters. Dycus remains an enigma. Overall, the evidence is not conclusive but indicates that Dycus had a *probable* oblique impact origin with a *possible* connection to the Flynn Creek impact event.

The Howell Structure is located on a remnant of the Southern Highland Rim of Tennessee. C.W. Wilson and K.E. Born first investigated the Howell Structure in 1934, mapped the area in 1937, and published a paper in 1939 stating that they maintained a neutral position as to its origin, although indications are that they leaned toward a cryptovolcanic origin (Born and Wilson, 1939: 387). Wilson and R.H. Barnes mapped the area a second time, from 1964 to 1965, and Woodruff (1968: 1) continued the mapping in 1967 and 1968 for his Master's thesis project at Vanderbilt University. The presence of three faults to the southwest of Howell that are approximately concentric to the structure is intriguing; however, their proximity to the Howell Structure may only be a coincidence. Unfortunately, their possible relationship to Howell has never really been investigated to any great extent.

Breccia is abundant in the Howell Structure, and Woodruff (1968: 29) states that "… most of the Howell breccia has been categorized by this writer as being of shock type" and that "The structure is postulated as being the ancient eroded equivalent of a meteor impact crater." Woodruff (1968: 57) points out that "The original morphology has been completely obliterated by the various geologic processes that have worked on the area." Perhaps 80-90% of the structure has been removed by erosion and only the deepest roots remain. Howell may simply be the deeply eroded root or basement structure of an impact crater so heavily eroded that little is left to study.

"A magnetometer survey [of Howell] was undertaken by Charles R. Seeger of the National Aeronautics and Space Administration's Goddard Space Flight Center in Maryland …" around 1967 (Woodruff, 1968: 1, 3). Woodruff (1968: 3) notes that even "Further interest was given to the Howell area by NASA," when John W. Bensko, a lunar geologist from NASA's Marshall Space Flight Center in Huntsville, Alabama, oversaw core drilling in the center of the Howell Structure in 1967 (Deane et al., 2004, 2; Woodruff, 1968: 3). Woodruff (1968: 20) stated that "If the area of deformation has a lower limit above the (igneous-metamorphic) basement complex it is then concluded to be of meteoric origin." Unfortunately, the Howell drill core results were not published and are no longer at the Marshall Space Flight Center in Alabama, however, Woodruff was verbally informed and recorded that "… the drill hole penetrated past the breccias into undisturbed bedrock." (Deane et al., 2004: 2). "Information gained by NASA's drilling (John Bensko, personal communication) is that the structure has a bottom in stratigraphic sequence and is thus lens-shaped at depth instead of being a breccia pipe …" (Woodruff, 1968: 65).

Woodruff (1968: 23-25) found an outcrop in Howell where "… crudely formed [shatter] cones may be present …" and included photographs of the "Possible shattercones" and "Poorly formed shattercones" in his thesis. These could have provided conclusive evidence of impact, however, Miller (1974: 56) states that "… they are indistinct." Several subsequent attempts to relocate the outcrop where the possible shatter cones were found have not been successful due to changes in the area that have come with the passage of time (Marvin Brerwind, Tennessee Division of Geology, personal communication).

Thin sections of quartz grains found in Howell by Woodruff showed "… lineation (some with two sets of cleavage), fragmentation, micro-brecciation, and flow features." (Deane et al., 2004: 2). However, the thin sections have not survived and are lost for further study (Deane et al., 2004: 2). Subsequent studies have not found "… unequivocal evidence of shock metamorphism such as melt, flow, or planar deformation features (PDFs) …" (Deane et al., 2004: 2).

Gibson and Reimold (2010: viii) point out that research into low-level quartz deformation that results from shock due to impact may soon lead to "… diagnostic impact indicators in the structural geological characteristics of craters in the low shock-pressure range." This would allow for the confirmation of impact structures that have experienced significant erosion "… that would otherwise be impossible without having to resort to costly drilling ventures (ibid.). French (2004: 178) suggests an obvious candidate for study is cleavage in quartz which "… occurs as multiple parallel sets (also called PFs) in impact structures." French (2004: 180) states that "Cleavage in quartz is commonly observed in meteorite impact structures and only rarely (if at all?) in terrestrial rocks from non-impact settings." The questions that need to be answered are: "Can cleavage be produced naturally in quartz in non-impact (e.g., volcanic, tectonic) environments? Can the presence of multiple cleavage sets be used as an independent criterion for shock and meteorite impact?" If these questions can be answered, then highly-eroded structures such as Howell may someday be confirmed as sites of impact (French et al., 2004).

Woodruff (1968: 64) concludes that "The structure is believed to have resulted from meteor impact …", and Miller (1974: 56) states that "Overall, the evidence indicates the Howell Structure was formed by meteorite impact." Recent evidence based on X-ray diffraction of the calcite found in "shocked" Howell limestone as compared to unshocked limestone favors an impact origin for Howell (Milam et al., 2014). Strong evidence of an impact origin has been presented for the Howell Structure. Based on this evidence, Howell should be considered a *"most probable"* but not yet confirmed impact structure.

Although the pace of impact site investigation slowed in Tennessee after the lunar landings, interest in non-terrestrial sites has increased. Since the advent of the Space Age, missions to the Moon, Mercury, Mars, and the asteroid belt as well as satellites of the Jovian planets show that impact cratering is not only an important geological process, but in fact is *the* dominant process for many surfaces in our Solar System, and "Impact cratering … acquires great significance when studied in the context of planetary surfaces and planetary formation …" (Croft, 1977: 1279). Studies of terrestrial impact structures, therefore, should not cease as they will aid in our understanding of not only the planets and small bodies of our own Solar System, but someday, extrasolar planets. We should also keep in mind though, that "… impact cratering has been the most important surface process on all solid bodies in the solar system, and … it still is a process to reckon with …" (Reimold, 2003: 1889; cf. Reimold, 2007).

Finally, let us close this thesis by briefly reviewing the ways in which the four Tennessee impact or suspected impact sites have contributed to our international understanding of terrestrial impact cratering. It is noteworthy that the first detailed geological report on and map of a meteorite impact site in the United States related to Wells Creek. The research conducted at Wells Creek led to significant contributions to the impact cratering literature generated from its earliest recognition as a site of interest by Safford in the 1860s to the intense study, published in 1968, funded by NASA in preparation for the first human landing on the Moon. The first shatter cones in the United States were found in the Wells Creek structure. Bucher published a paper concerning this first recognition of shatter cones in an American 'crypto-volcanic' structure, even though he did not attribute their formation to meteoritic impact. 'Cryptovolcanic' structures show no evidence of volcanic activity, and Wells Creek was designated by both Bucher and Dietz as the 'syntype' structure for the USA, although Dietz suggested that the term 'crypto-explosive' would be more suitable in order to avoid the implication that these structures were related to volcanic activity. These two protagonists, Bucher and Dietz, stated their cases in the literature, politely rejecting the conclusion promoted by the other concerning these intriguing structures. Those suggesting a hypervelocity impact as the origin for these sites thought the shock waves would lead to a structure resembling an elastic damped wave in rock. Wells Creek provided scientists with just such a structure, with its central uplift surrounded by concentric synclines and anticlines. The central uplift also provided numerous, high-quality shatter cones in rocks that had been uplifted from a considerable depth. Importantly, it was a Wells Creek drill core that led Wilson to abandon the idea of a cryptovolcanic explanation for Wells Creek and to become a proponent of the meteorite impact hypothesis. Wilson and Stearns led the study that resulted in the Tennessee Division of Geology's Bulletin 68 devoted entirely to Wells Creek.

Flynn Creek also added to the growing knowledge and body of literature concerning meteorite impact sites. Information regarding the Tennessee impact sites is scattered and often elusive due to the fact that it is published in many different journals and monograph, reflecting the multidisciplinary nature of meteoritics and impact cratering. This is especially true of the Flynn Creek crater, and one of the primary aims of this project was to gather this information together, synthesize it, and present it in a single account. Dietz, Wilson, and Stearns located poor, but unmistakable shatter cones in the Flynn Creek crater leading to the conclusion that these were only found in sites of impact and therefore diagnostic indicators of shock requiring a meteorite impact rather than a volcanic steam explosion. Flynn Creek was chosen in 1961 to be one of two American impact craters for the Project Apollo Astrogeologic Studies resulting in publications each year concerning research on the crater. From this came Roddy's detailed mapping of outcrops which enabled him to construct a topographic model that so resembled lunar craters, which do not suffer weathering and erosion, that NASA also chose Flynn Creek as a training site for astronauts. Study of the breccia led to the understanding that this was an extremely shallow marine impact. The crater fill includes graded breccia that was deposited as waves washed ejecta back into the crater and water flowed in depositing muds from the Chattanooga Sea. The resulting Chattanooga Black Shale preserved the sedimentary record as well as the morphology of the crater with impressive detail. Although Roddy unfortunately passed away before the investigation of a marine origin for Flynn Creek was completed, others researchers are continuing the work and publishing their results.

Not much has been published on the Dycus Structure since Mitchum wrote his Vanderbilt University thesis in 1951. This site is an enigma that begs to be understood. Again, new approaches or old ones considered in new ways, such as the application of a paleostress-piezometer, may shed new light on this structure. If the Dycus Structure does prove to be a meteorite impact site then it should serve to clarify the origin of other structures that differ from the near-circular forms that usually result from hypervelocity impacts, thus adding to the body of literature concerning oblique and binary meteorite impacts. Only a few terrestrial binary sites of impact, such as Ries-Steinham, are known. Thus, further research into a possible Dycus relationship with the Flynn Creek impact site is warranted.

Even though Howell was included in 1949 list of the twelve best-known cryptovolcanic structures, interest quickly faded and information concerning the Howell Structure is not widespread in the literature. The literature that does exist indicates that it may be a deeply-eroded impact structure. The extensive brecciation, the fact that the structure dies out with depth, and the quartz grain displaying planar fractures photographed and studied by Woodruff, collectively indicate that this structure is worthy of further study. The question of its origin may be solved through an increased understanding of cleavage in quartz as a diagnostic indicator for shock metamorphism. Further searches are desirable to locate the outcrop containing the possible shatter cones reported and photographed by Woodruff and to obtain more shocked quartz samples since the earlier examples have been lost. In addition, Howell is an ideal site for further research on heavily-eroded impact structures and the development of alternative methods of confirming impact-induced shock effects, thereby adding to the body of literature on shock-metamorphic effects in quartz. Both of Tennessee's suspected sites of impact still have a valuable role to play in our overall understanding of impact cratering.

CHAPTER 6: REFERENCES

Alderman, A.R., 1932. The meteorite craters at Henbury, Central Australia. *Mineralogical Magazine*, 23, 19-32.

Alligood, L., 2007. Meteor buffs hope to make strike town's claim to fame. *The Tennessean*, February 11.

Amstutz, G.C., 1964. Introduction. *Developments in Sedimentology*, 2, 1-7.

Astrogeologic Studies Annual Progress Report, December 1967. Flagstaff, United States Geological Survey (1967).

Astrogeologic Studies Annual Progress Report, January 1970. Flagstaff, United States Geological Survey (1970).

Baldwin, R.B., 1949. *The Face of the Moon.* Chicago, University of Chicago Press.

Baldwin, R.B., 1963. *The Measure of the Moon.* Chicago, University of Chicago Press.

Baldwin, R.B., and Sheaffer, Y., 1971. Ablation and breakup of large meteoroids during atmospheric flight. *Journal of Geophysical Research*, 76, DOI: 10.1029/JA076i019p04653.

Baratoux, D., and Melosh, H.J., 2003. The formation of shatter cones by shockwave interference during impacting. *Earth and Planetary Science Letters*, 216, 43-54.

Barringer, B., 1964. Daniel Moreau Barringer (1860-1929) and his crater (The beginning of the crater branch of meteoritics). *Meteoritics*, 2, 3, 183-199.

Barringer, B., 1967. Historical notes on the Odessa Meteorite Crater. *Meteoritics*, 3, 161-168.

Barringer, D.M., 1905. Coon Mountain and its crater. *Proceedings of the Academy of Natural Sciences of Philadelphia*, 57, 861-886.

Barringer, D. M., 1914. Further Notes on Meteor Crater, Arizona. *Proceedings of the Academy of Natural Sciences of Philadelphia*, 556-565.

Barringer, D.M., 1924. Further notes on Meteor Crater in northern central Arizona (No. 2). *Proceedings of the Academy of Natural Sciences of Philadelphia*, 76, 275-278.

Bart, G.D., and Melosh, H.J., 2007. Using lunar boulders to distinguish primary from distant secondary impact craters. *Geophysical Research Letters*, 34, 7.

Bassler, R.S., 1932. Stratigraphy of the Central Basin of Tennessee. *State of Tennessee, Department of Environment and Conservation, Division of Geology, Bulletin* 38.

Beech, M., 2013. Towards an Understanding of the Fall Circumstances of the Hoba Meteorite. *Earth, Moon, and Planets*, 111, 1-2, 15-30.

Beech, M., 2014. Grazing Impacts upon Earth's Surface: Towards an Understanding of the Rio Cuarto Crater Field. *Earth, Moon, and Planets*, 113, 1-4, 53-71.

Berwind, M., 2006. Field Trip to the Wells Creek Basin Cryptoexplosive Structure, Stewart and Houston Counties. Tennessee. Tennessee Division of Geology.

Berwind, M., 2007. Meteorite impact structures in Tennessee. *The Tennessee Conservationist*, 73, 3, 15-18.

Bevan, A., and Laeter, J.R. de, 2002. *Meteorites, a Journey through Space and Time.* Sydney, University of New South Wales Press.

Bland, P.A., de Souza Filho, C.R., Jull, A.J.T., Kelley, S.P., Hough, R.M., Artemieva, N.A., Pierazzo, E., Coniglio, J., Pinotti, L., Evers, V., Kearsley, A.T., 2002. A Possible Tektite Strewn Field in the Argentinian Pampa. *Science*, 296, 5570, 1109-1111.

Boon, J.D., 1936. The Impact of Meteors. *Field and Laboratory*, 4, 2, 56-59.

Boon, J.D., and Albritton, C.C., 1936. Meteorite Craters and Their Possible Relationship to "Cryptovolcanic Structures". *Field and Laboratory*, 5, 1, 1-9.

Boon, J.D., and Albritton, C.C., 1937. Meteorite Scars in Ancient Rocks. *Field and Laboratory,* 5, 2, 53-64.

Boon, J.D., and Albritton, C.C., 1938. Established and supposed examples of meteoritic craters and structures. *Field and Laboratory*, 6, 44-56.

Born, K.E., and Wilson, C.W., 1939. The Howell Structure, Lincoln County, Tennessee. *Journal of Geology*, 47, 371-388.

Bottke Jr., W.F., and Melosh, H.J., 1996. Binary Asteroids and the Formation of Doublet Craters. *Icarus*, 124, 372-391.

Bottke Jr., W.F., Love, S.G., Tytell, D., and Glotch, T., 2000. Interpreting the elliptical crater populations on Mars, Venus, and the Moon. *Icarus*, 145, 108-121.

Brahana, J.V., and Bradley, M.W., 1985. Delineation and description of the regional aquifers of Tennessee – the Knox Aquifer in Central and West Tennessee. *United States Geological Survey, Water-Resources Investigations Report*, 83-4012.

Bryant, C., 2004. UA Museum to observe 50th anniversary of Hodges Meteorite. *University of Alabama News*, November 2004.

Bucher, W.H., 1936. Cryptovolcanic Structures in the United States. *16th International Geological Congress*, 2, 1055-1083.

Bucher, W.H., 1963a. Are Cryptovolcanic Structures due to Meteorite Impact? *Nature*, 4874, 1241-1245.

Bucher, W.H., 1963b. Cryptoexplosion Structures Caused from Without or from Within the Earth? ("Astroblemes" or Geoblemes?"). *American Journal of Science,* 261, 597-649.

Campbell, W.W., 1920. Notes on the Problem of the Origin of the Lunar Craters. *Publications of the Astronomical Society of the Pacific*, 32, 126-138.

Chao, E.C.T., Shoemaker, E.M., and Madsen, B.M., 1960. First Natural Occurrence of Coesite. *Science*, 132, 220-222.

Chapman, M., 2002. Dave Roddy. US Geological Survey, Astrogeology Science Center (http://astrogeology.usgs.gov/rpif/dave-roddy).

Classen, J., 1977. Catalog of 230 Certain, Probable, Possible, and Doubtful Impact Structures. *Meteoritics*, 12, 61-78.

Coes, L., 1953. A New Dense Crystalline Silica. *Science*, 118, 131-132.

Cohen, A.J., 1963. Fossil Meteorite Craters. In Hurley, P.M. (ed.). *Nuclear Geophysics*. Washington, National Academy of Sciences. 234-240.

Collins, G.S., Melosh, H.J., and Ivanov, B.A., 2004. Modeling Damage and Deformation in Impact Simulations. *Meteoritics and Planetary Science,* 39, 217-231.

Collins, G.S., Melosh, H.J., and Marcus, R.A., 2005. Earth Impact Effects Program: A WebBased Computer Program for Calculating the Regional Environmental Consequences of a Meteoroid Impact on Earth. *Meteoritics and Planetary Science,* 40, 817-840.

Cook, C.M., Melosh, H.J., and Bottke, W.F., 2003. Doublet Craters on Venus. *Icarus,* 165, 90100.

Croft, S.K., 1977. Energies of Formation for Ejecta Blankets of Giant Impacts. In Roddy, Pepin, and Merrill, 1279-1296.

Cushing, G.E., Titus, T.N., Wynne, J.J., and Christensen, P.R., 2007. THEMIS Observes Possible Cave Skylights on Mars. *Geophysical Research Letters*, 34, L17201.

Dalwigk, I.V., and Ormo, J., 2001. Formation of Resurge Gullies at Impacts at Sea: the Lockne Crater, Sweden. *Meteoritics and Planetary Science*, 36, 359-369.
Daly, R.A., 1946. Origin of the Moon and its Topography. *Proceedings of the American Philosophical Society*, 90, 104-119.
Davison, T.M., Collins, G.S., Elbeshausen, D., Wunnemann, K., and Kearsley, A., 2011. Numerical Modelling Of Oblique Hypervelocity Impacts on Strong Ductile Targets. *Meteoritics and Planetary Science*, 46, 1510-1524.
Deane, B., Lee, P., Milam, K. A., Evenick, J.C., and Zawislak, R.L., 2004. The Howell Structure, Lincoln County, Tennessee: A Review of Past and Current Research. *Lunar and Planetary Science*, XXXV, 1692.
Deane, B., Milam, K.A., Stockstill, K.R., and Lee, P.C., 2006. The Dycus Disturbance, a Second Impact Crater In Jackson County, Tennessee? *Lunar and Planetary Science*, XXXVII, 1358.
Denson, J.D., 2008. The Flynn Creek Impact: "The Biggest Thing to Ever Hit My Hometown." *Meteorite*, May, 13-15.
de Vet, S.J., and de Bruyn, J.R., 2007. Shape of Impact Craters in Granular Media. *Physical Review E*, 76, 4, 041306.
Dick, S.J., 1998. Observation and Interpretation of the Leonid Meteors over the Last Millennium. *Journal of Astronomical History and Heritage*, 1, 1-20.
Dietz, R.S., 1946. Geological Structures Possibly Related To Lunar Craters. *Popular Astronomy*, 54, 9, 465-467.
Dietz, R.S., 1959. Shatter Cones in Cryptoexplosion Structures (Meteorite Impact?). *Journal of Geology*, 67, 496-505.
Dietz, R.S., 1960. Meteorite Impact Suggested By Shatter Cones in Rock. *Science*, 131, 17811784.
Dietz, R.S., 1963. Cryptoexplosion Structures: A Discussion. *American Journal of Science*, 261, 650-664.
Dietz, R.S., 1968. Shatter Cones in Cryptoexplosion Structures. In French and Short, 267-285.
Dressler, B.O., and Reimold, W.U., 2001. Terrestrial Impact Melt Rocks and Glasses. *Earth-Science Reviews*, 56, 205-284.
Dypvik, H., and Jansa, L.F., 2003. Sedimentary Signatures and Processes during Marine Bolide Impacts: a Review. *Sedimentary Geology*, 161, 309-337.
Ekholm, A.G., 1999. Crater Features Diagnostic Of Oblique Impacts: The Central Peak Offset. *Lunar and Planetary Institute Science Conference Abstracts*, 30, 1706.
Ekholm, A.G., and Melosh, H.J., 2001. Crater Features Diagnostic of Oblique Impacts: The Size and Position of the Central Peak. *Geophysical Research Letters*, 28, 623-626.
Elbeshausen, D., Wünnemann, K., and Collins, G.S., 2013. Crater Formation After Shallow Impacts – How Do Elliptical Craters Form? *Lunar and Planetary Institute Contributions*, 1737, 3082.
Evenick, J.C., 2006. *Field Guide to the Flynn Creek Impact Structure*. University of Tennessee, Knoxville, Tennessee.
Evenick, J.C., Lee, P., and Deane, B., 2004. Flynn Creek Impact Structure: New Insights from Breccias, Melt Features, Shatter Cones, and Remote Sensing. *Lunar and Planetary Science*, XXXV, 1131.
Evenick, J.C., Lee, P., Deane, B., and Milam, K.A., 2005. Field Guide to the Flynn Creek Impact Structure. *69th Annual Meteoritical Society Meeting*, Gatlinburg, Tennessee.

Ferriére, L., Lubala, F.R.T., Osinski, G.R., and Kaseti, P.K., 2011. The Newly Confirmed Luizi Impact Structure, Democratic Republic Of Congo – Insights into Central Uplift Formation and Post-Impact Erosion. *Geology*, 39, 851-854.

Ferriére, L., Morrow, J.R., Amgaa, T., and Koeberl, C., 2009. Systematic Study of UniversalStage Measurements of Planar Deformation Features in Shocked Quartz: Implications for Statistical Significance and Representation of Results. *Meteoritics and Planetary Science*, 44, 925-940.

Ford, J.R.H., Orchiston, W., and Clendening, R., 2012. The Wells Creek Meteorite Impact Site and Changing Views on Impact Cratering. *Journal of Astronomical History and Heritage*, 15, 159-178.

Ford, J.R.H., Orchiston, W., and Clendening, R., 2013. The Flynn Creek Meteorite Impact Site and Changing Views on Impact Cratering. *Journal of Astronomical History and Heritage*, 16, 127-183.

Folco, L., Di Martino, M., El Barkooky, A., D'Orazio, M., Lethy, A., Urbini, S., Nicolosi, I., Hafez, M., Cordier, C., van Ginneken, M., Zeoli, A., Radwan, A.M., El Khrepy, S., El Gabry, M., Gomaa, M., Barakat, A.A., Serra, R., and El Sharkawi, M., 2011. Kamil crater (Egypt): Ground truth for small-scale meteorite impacts on Earth. *Geology*, 39, 2, 179-182.

Forsberg, N.K., Herrick, R.R., and Bussey, B., 1998. The Effects of Impact Angle on the Shape of Lunar Craters. *Lunar and Planetary Science*, XXIX, 1691.

French, B.M., 1998. *Traces of Catastrophe. A Handbook of Shock-Metamorphic Effects in Terrestrial Meteorite Impact Structures*. Houston, Lunar and Planetary Institute.

French, B.M., 2004. The Importance of Being Cratered: The New Role of Meteorite Impact as a Normal Geological Process. *Meteoritics and Planetary Science*, 39, 2, 169-197.

French, B.M., Cordua, W.S., and Plescia, J.B., 2004. The Rock Elm Meteorite Impact Structure, Wisconsin: Geology and Shock-Metamorphic Effects in Quartz. *Geological Society of America Bulletin*, 116, 1-2, 200-218.

French, B.M., and Koeberl, C., 2010. The Convincing Identification of Terrestrial Meteorite Impact Structures; What Works, What Doesn't, and Why. *Earth-Science Reviews*, 98, 1, 123-170.

French, B.M., and Short, N.M. (eds.). 1968. *Shock Metamorphism of Natural Materials*. Baltimore, Mono Book Corporation.

Gault, D.E., Quaide, W.L., and Oberbeck, V.R., 1968. Impact Cratering Mechanics and Structures. In French, And Short, 87-99.

Gault, D.E., and Wedekind, J.A., 1978. Experimental Studies of Oblique Impact. *Proceedings Lunar and Planetary Science Conference*, 9, 3843-3875.

Gibson, R.L., and Reimold, W.U., 2010. Introduction: Impact Cratering and Planetary Studies – A Fifty-Year Perspective. *Geological Society of America Special Papers*, 465, vii-xii.

Gilbert, G.K., 1892. Abstract: the Evolution of the Moon. *The American Naturalist*, 26, 10561057.

Gilbert, G.K., 1893. *The Moon's Face: A Study of Its Features.* Washington, Philosophical Society of Washington.

Gilvarry, J.J., and Hill, J.E., 1956. The Impact of Large Meteorites. *Astrophysical Journal*, 124, 610-622.

Goeritz, M., Kenkmann, T., Wunnemann, K., and van Gasselt, S., 2009. Asymmetric structure of lunar impact craters due to oblique impacts? *40th Lunar and Planetary Science Conference*, 2096.

Gounelle, M. (2006). The Meteorite Fall At l'Aigle and the Biot Report: Exploring the Cradle of Meteoritics. *Geological Society, London, Special Publications*, *256*, 1, 73-89.

Grieve, R.A.F., Dence, M.R., and Robertson, P.B., 1977. Cratering Processes: As Interpreted From The Occurrence Of Impact Melts. In Roddy, D.J., Pepin, R.O., and Merrill, R.B. (Eds). *Impact and Explosion Cratering: Planetary and Terrestrial Implications.* Flagstaff, Arizona, USA, Proceedings on the Symposium on Planetary Cratering Mechanics, 791-814.

Grieve, R.A.F. and Pilkington, M., 1996. The signature of terrestrial impacts. *AGSO Journal of Australian Geology and Geophysics*, 16, 399-420.

Hagerty, J.J., McHone, J.F., and Gaither, T.A., 2013. The Flynn Creek Crater Drill Core Collection at the USGS in Flagstaff, Arizona. *Lunar and Planetary Institute Science Conference Abstracts*, 44, 2122.

Herrick, R.R., and Forsberg-Taylor, N.K., 2003. The Shape and Appearance of Craters Formed By Oblique Impact on the Moon and Venus. *Meteoritics and Planetary Science*, 38, 15511578.

Herrick, R.R., and Hessen, K.K., 2003. Constraints on the Impact Process from Observations of Oblique Impacts on the Terrestrial Planets. *Workshop on Impact Cratering: Bridging the Gap between Modeling and Observations*, 1, 31.

Herrick, R.R., and Hessen, K.K., 2006. The Planforms of Low-Angle Impact Craters in the Northern Hemisphere of Mars. *Meteoritics and Planetary Science*, 41, 1483-1495.

Hessen, K.K., Herrick, R.R., Yamamoto, S., Barnouin-Jha, O.S., Sugita, S., and Matsui, T., 2007. Low-Velocity Oblique Impact Experiments in a Vacuum. *Lunar and Planetary Science*, XXXVIII, 2141.

Hey, M.H., 1966. Catalogue of Meteorite Craters. In *Catalogue Of Meteorites, With Special Reference To Those Represented In The Collection Of The British Museum (Natural History).* Oxford, Alden Press. Pp. 538-562.

Hodge, P.W., 1965. The Henbury Meteorite Craters. *Smithsonian Contributions to Astrophysics*, 8, 199-213.

Hodge, P.W., 1994. *Meteorite Craters and Impact Structures of the Earth*. Cambridge, Cambridge University Press.

Hoffleit, D., 1945. What Falls From Heaven. *The Scientific Monthly*, 60, 1, 30-36.

Holliday, V.T., King, D.A., Mayer, J.H., and Goble, R.J., 2005. Age and Effects of the Odessa Meteorite Impact, Western Texas, USA. *Geology*, 33, 945-948.

Hooke, R. (1961). 1665. *Micrographia. London*.

Hörz, F., Mittlefehldt, D. W., See, T. H., & Galindo, C., 2002. Petrographic studies of the impact melts from Meteor Crater, Arizona, USA. *Meteoritics & Planetary Science*, 37, 4, 501-531.

Housen, K.R., and Holsapple, K.A., 2011. Ejecta from Impact Craters. *Icarus*, 211, 856-875.

Hoyt, W.G., 1987. *Coon Mountain Controversies. Meteor Crater and the Development of Impact Theory.* Tucson, University of Arizona Press.

Ivanov, B.A., 1991. Impact Crater Processes. *Advances in Space Research*, 11, 67-75.

Ivanov B.A., And Stöffler, D., 2005. The Steinheim Impact Crater, Germany: Modeling of a Complex Crater with Central Uplift. *Lunar and Planetary Science*, XXXVI, 1443.

Ives, H.E., 1919. Some Large-Scale Experiments Imitating the Craters of the Moon. *Astrophysics Journal*, 50, 245-252.

Jenkinson, S.H., 1940. Gifford. In *New Zealanders and Science*. Wellington, Department of Internal Affairs. 125-136.

Jones, G.H.S., 1977. Complex Craters in Alluvium. In Roddy, D.J., Pepin, R.O., and Merrill, R.B. (Eds). *Impact and Explosion Cratering: Planetary and Terrestrial Implications.* Flagstaff, Arizona, USA, Proceedings on the Symposium on Planetary Cratering Mechanics, 163-184.

Kadono, T., 1999. Hypervelocity Impact into Low Density Material and Cometary Outburst. *Planetary and Space Science*, 47, 305-318.

Kadono, T., and Fujiwara, A., 2005. Cavity and Crater Depth in Hypervelocity Impact. *International Journal of Impact Engineering*, 31, 1309-1317

Kamo, S.L., Reimold, W.U., Krogh, T.E., and Colliston, W.P., 1996. A 2.023 Ga Age for the Vredefort Impact Event and a First Report of Shock Metamorphosed Zircons in Pseudo-Tachylitic Breccias and Granophyre. *Earth and Planetary Letters*, 144, 369-387.

Kashuba, J., 2013. Tissint Martian Meteorite. *Meteorite Times Magazine*, March 1. www.meteorite-times.com/micro-visions/tissint-martian-meteorite/.

Kenkmann, T., and Poelchau, M.H., 2008. The Structural Inventory of Oblique Impact Craters. *Large Meteorite Impacts and Planetary Evolution*, IV, 3057.

Kenkmann, T., Artemieva, N. A., and Poelchau, M. H., 2008. The Carancas Event on September 15, 2007: Meteorite Fall, Impact Conditions, and Crater Characteristics. *Lunar and Planetary Science Conference*, 39, 1094.

Kenkmann, T., and Poelchau, M. H., 2009. Low-angle Collision with Earth: the Elliptical Impact Crater Matt Wilson, Northern Territory, Australia. *Geology*, 37, 5, 459-462.

Kenkmann, T., Kiebach, F., Rosenau, M., Raschke, U., Pigowske, A., Mittelhaus, K., and Eue, D., 2007. Coupled Effects of Impact and Orogeny: Is the Marine Lockne Crater, Sweden, Pristine? *Meteoritics & Planetary Science*, 42, 11, 1995-2012.

Kenkmann, T., Artemieva, N. A., Wünnemann, K., Poelchau, M. H., Elbeshausen, D., and PRADO, H., 2009. The Carancas Meteorite Impact Crater, Peru: Geologic Surveying and Modeling of Crater Formation and Atmospheric Passage. *Meteoritics & Planetary Science*, 44, 7, 985-1000.

Killebrew, J.B., and Safford, J.M., 1874. *Introduction to the Resources of Tennessee.* Nashville, Tennessee, Tavel, Eastman and Howell. Cited by Wilson and Stearns in *Journal of the Tennessee Academy of Science*, 41, 37 (1966).

Killgore, M., and McHone, J.F., 1998. Small Impact Craters on Sikhote-Alin Iron Meteorite Surfaces. *Lunar and Planetary Science*, XXIX, 1839.

King-Hele, D.G., 1975. Truth and Heresy over Earth and Sky. *The Observatory*, 95, 1-12.

King Jr, D.T., Neathery, T.L., Petruny, L.W., Koeberl, C., and Hames, W.E., 1999. Evidence Confirming Meteoritic Impact at Wetumpka Crater, Alabama, USA. *Meteoritics and Planetary Science Supplement*, 34, 63.

King Jr, D.T., Neathery, T.L., Petruny, L.W., Koeberl, C., and Hames, W.E., 2002. ShallowMarine Impact Origin of the Wetumpka Structure (Alabama, USA). *Earth and Planetary Science Letters*, 202, 541-549.

King Jr, D.T., and Petruny, L.W., 2003. Alabama's Stratigraphic and Historic Record of Meteoritic Impact Events. *Geological Society of America*, Conference Paper No. 5-10.

King Jr, D.T., Petruny, L.W., and Neathery, T.L., 2008. Wetumpka Impact Effects. In King, D.T. and Petruny, L.W. (eds.). *Wetumpka Impact Crater Guidebook, 3rd Edition.* Auburn, Parsimony Press. 34-45.

Klokocnik, J., Kostelecky, J., Novak, P., and Wagner, C.A., 2010a. Detection of Earth Impact Craters aided by a Detailed Global Gravity Field Model. *Acta Geodynamica Et Geomaterialia*, 7, 71-83.

Klokocnik, J., Kostelecky, J., Pesek, I., Novak, P., Wagner, C.A., and Sebera, J., 2010b. Candidates for Multiple Impact Craters: Popigai and Chicxulub as seen by EGM08, a Global 5’ × 5’ Gravitational Model. *Solid Earth*, 2, 69-103.

Koeberl, C., 1998. Identification of Meteoritic Components in Impactites. *Geological Society, London, Special Publications*, 140, 1, 133-153.

Koeberl, C., 2001. Craters on the Moon from Galileo to Wegener: a Short History of the Impact Hypothesis, and Implications for the Study of Terrestrial Impact Craters. *Earth*, *Moon and Planets*, 85-86, 209-224.

Koeberl, C., 2009. Meteorite Impact Structures: Their Discovery, Identification, and Importance for the Development of Earth. In Gaz, S. (ed.). *Sites of Impact: Meteorite Craters around the World.* New York, Princeton Architectural Press, 8-17.

Lindström, M., Shuvalov, V. V., & Ivanov, B. A., 2004. Lockne Crater as a Result of Oblique Impact. In *Lunar and Planetary Institute Science Conference Abstracts*, 35, 1475.

Lucas, F.A., 1926. *Meteorites, Meteors, and Shooting Stars*. New York, American Museum of Natural History.

Lunar Craters. *Evening Post* (Wellington, New Zealand), 26 June, 107(150), 8 (1924).

Lusk, R.G., 1927. A pre-Chattanooga Sink Hole. *Science*, 65, 579-580.

Macdonald, F.A., and Mitchell, K., 2003. Amelia Creek, Northern Territory, Australia: a 20×12 km Oblique Impact Structure with No Central Uplift. In I*mpact Cratering: Bridging the Gap between Modeling and Observations*, 1, 47. www.lpi.usra.edu/meetings/impact2003/pdf/8006.pdf

Macdonald, F.A., Mitchell, K., and Stewart, A.J., 2005. Amelia Creek: a Proterozoic Impact Structure in the Davenport Ranges, Northern Territory. *Australian Journal of Earth Sciences*, *52*, 631-640.

Margot, J.L., Nolan, M.C., Benner, L.A.M., Ostro, S.J., Jurgens, R.F., Giorgini, J.D., Slade, M.A., and Campbell, D.B., 2002. Binary Asteroids in the Near-Earth Object Population. *Science*, 296, 1445.

Mark, K., 1987. *Meteorite Craters.* Tucson, University of Arizona Press.

Marvin, U. B. (1996). Ernst FF Chladni (1756-1827) and the Founding of Meteoritics. *Meteoritics and Planetary Science Supplement*, *31*, 82.

Masaitis, V.L., 2005. Morphological, Structural and Lithological Records of Terrestrial Impacts: an Overview. *Australian Journal of Earth Sciences*, 52, 509-528.

Masursky, H., 1977. Cratering Mechanics and Future Martian Exploration. In Roddy, D.J., Pepin, R.O., and Merrill, R.B. (Eds). *Impact and Explosion Cratering: Planetary and Terrestrial Implications.* Flagstaff, Arizona, USA, Proceedings on the Symposium on Planetary Cratering Mechanics, 635-637.

McCall, G.J.H. (ed.), 1979. *Astroblemes – Cryptoexplosion Structures.* Stroudsburg, Pennsylvania, Dowden, Hutchinson, and Ross (*Benchmark Papers in Geology*, 50).

Melosh, H.J., 1989. *Impact Cratering: A Geologic Process.* New York, Oxford University Press.

Melosh, H.J., 2002. Traces of an Unusual Impact. *Science*, 296, 1037-1038.

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

Milam, K. A., Henderson, T., and Deane, B., 2014. An Assessment of Shock Metamorphism in Breccias from the Howell Structure, Lincoln County, Tennessee, USA. *Geological Society of America Annual Meeting in Vancouver, British Columbia*, 317-5.

Milam, K.A., and Deane, B., 2005. Petrogenesis of Central Uplifts in Complex Terrestrial Impact Craters. *Lunar and Planetary Science*, XXXVI, 2161.

Milam, K.A., and Deane, B., 2006a. Flynn Creek Crater: The Birthplace of Impact Speleology. *Geological Society of America Abstracts with Programs*, 38, 3, 82.

Milam , K.A., and Deane, B., 2006b. From the Inside-Out: Central Uplift Formation from the Perspective of Hawkins Impact Cave. *Geological Society of America Abstracts with Programs*, 38, 3, 81.

Milam, K.A., and Deane, B. 2007. The Search for a Meteoritic Component in Impactites from the Flynn Creek Impact Crater. *Lunar and Planetary Science*, XXXVIII, 2320.

Milam, K.A., Deane, B., King, P.L., Lee, P.C., and Hawkins, M., 2006. From the Inside of a Central Uplift: the View from Hawkins Impact Cave. *Lunar and Planetary Science*, XXXVII, 1211.

Milam, K.A., Deane, B., and Oeser, K., 2005a. Caves of the Flynn Creek Impact Structure. In Milam, K.A., Evenick, J., and Deane, B., (Eds.). *Field Guide to the Middlesboro and Flynn Creek Impact Structures.* Impact Field Studies Group, 69th Annual Meteoritical Society Meeting, Gatlinburg, Tennessee. 36-45.

Milam, K.A., Deane, B., and Oeser, K., 2005b. Karst Modification of the Flynn Creek Impact Structure. In Milam, K.A., Evenick, J., and Deane, B., (Eds.). *Field Guide to the Middlesboro and Flynn Creek Impact Structures.* Impact Field Studies Group, 69th Annual Meteoritical Society Meeting, Gatlinburg, Tennessee. 30-35.

Milam, K.A., Evenick, J., and Deane, B., (Eds.), 2005c. *Field Guide to the Middlesboro and Flynn Creek Impact Structures.* Impact Field Studies Group, 69th Annual Meteoritical Society Meeting, Gatlinburg, Tennessee.

Milam, K.A., and Perkins, J.W., 2012. The Obliquity of the Flynn Creek Impact Event. *Lunar and Planetary Science Conference*, 43, 2294.

Miljković, K., Collins, G.S., Mannick, S., and Bland, P.A., 2013. Morphology and Population of Binary Asteroid Impact Craters. *Earth and Planetary Science Letters*, 363, 121-132.

Miller, R.A., 1974. *Geologic History of Tennessee*. State of Tennessee, Department of Environment and Conservation, Division of Geology, 74.

Milton, D.J., 1968. Structural Geology of the Henbury Meteorite Craters, Northern Territory, Australia. *United States Geological Survey Professional Paper* 599-C, C1-C17.

Milton, D.J., 1977. Shatter Cones – an Outstanding Problem in Shock Mechanics. In Roddy, D.J., Pepin, R.O., and Merrill, R.B. (Eds). *Impact and Explosion Cratering: Planetary and Terrestrial Implications.* Flagstaff, Arizona, USA, Proceedings on the Symposium on Planetary Cratering Mechanics, 703-714.

Mitchum, R.M., 1951. The Dycus Disturbance, Jackson County, Tennessee. Unpublished Thesis, Vanderbilt University.

Mulder, M.E., 1911. Cited in Hoyt, 1987.

National Space Science Data Center, http://nssdc.gsfc.nasa.gov/planetary/lunar/.

Nemchinov, I.V., Popova, O.P., and Teterev, A.V., 1999. Penetration of Large Meteoroids into the Atmosphere: Theory and Observations. *Journal of Engineering Physics and Thermodynamics*, 72, 1194-1223.

Newton, H.A., 1864a. November Star-Showers. *Reports of the British Association for the Advancement of Science*, 34, 96.

Newton, H.A., 1864b. The Original Accounts of the Displays in Former Times of the November Star-Shower; Together with a Determination of the Length of its Cycle, its Annual Period, and the Probable Orbit of the Group of Bodies around the Sun. *American Journal of Science and Arts (2^{nd} Series)*, 37, 377-389.

Newton, H.A., 1867. Shooting Stars in November, 1866. *American Journal of Science and Arts (2^{nd} Series)*, 43, 78-88.

Newton, H.A., 1868. Shooting Stars of November 14^{th}, 1867. *American Journal of Science and Arts (2^{nd} Series)*, 45, 225-239.

Nininger, H.H., 1972. *Find A Falling Star*. New York, Paul S. Eriksson.

Oberbeck, V.R., and Aoyagi, M., 1972. Martian Doublet Craters. *Journal of Geophysical Research*, 77, 2419-2432.

O'Connell, E., 1965. *A Catalog of Meteorite Craters and Related Features with a Guide to the Literature.* Santa Monica, Rand Corporation.

Officer, C.B., and Carter, N.L., 1991. A Review of the Structure, Petrology, and Dynamic Deformation Characteristics of Some Enigmatic Terrestrial Structures. *Earth Science* Review, 30, 1-49.

Olmsted, D., 1834. Observations on the Meteors of November 13^{th}, 1833. *The American Journal of Science and Arts*, 25, 363-411.

Olson, D.W., and Jasinski, L.E., 1999. Abe Lincoln and the Leonids. Southwest Texas State University Faculty Publications-Physics. https://digital.library.txstate.edu/handle/10877/4041

Öpik, E.J., 1916. Remarque sur la théorie des cirques lunaires. *Bulletin de Société Russse des amis de l´Etude de l´Univers*, 3, 125-134.

Ormö, J., and Lindström, M., 2000. When a Cosmic Impact Strikes the Sea Bed. *Geological Magazine*, 137, 1, 67-80.

Osinski, G.O., 2008. Meteorite Impact Structures: the Good and the Bad. *Geology Today*, 24, 1, 13-19.

Passey, Q.R., and Melosh, H.J., 1980. Effects of Atmospheric Breakup on Crater Field Formation. *Icarus*, 42, 211-233.

Picconi, J.E. 2003. *Guide to the Geology of the Southeastern USA*. Paleontological Research Institution, Ithaca, New York.

Pickering, W.H., 1920. The Origin of the Lunar Formation. *Publications of the Astronomical Society of the Pacific*, 32, 116-125.

Pieazzo, E., and Artemieva, N.A., 2005. Atmospheric Fragmentation of the Canyon Diablo Meteoroid. *Lunar and Planetary Science*, 36, 2325.

Pierazzo, E., and Collins, G., 2004. A Brief Introduction to Hydrocode Modeling of Impact Cratering. In *Cratering in Marine Environments and on Ice,* 323-340. Springer Berlin-Heidelberg.

Pieazzo, E., and Melosh, H.J., 2000. Understanding Oblique Impacts from Experiments, Observations and Modelling. *Annual Review of Earth and Planetary Science*, 28, 141-167.

Pilkington, M., and Grieve, R.A.F., 1992. The Geophysical Signature of Terrestrial Impact Craters. *Reviews of Geophysics,* 30, 161-181.

Popova, O., 2005. Meteoroid Ablation Models. *Earth, Moon, and Planets,* 95, 303-319.

Povenmire, H., 1995. The Sylacauga, Alabama, Meteorite: the Impact Locations, Atmospheric Trajectory, Strewn Fields, and Radiant. *Lunar and Planetary Science XXVI*, 1133-1134.

Price, B., 1991. Tennessee's Mystery Craters. *Tennessee Conservationist.* Tennessee Division of Geology, September/October issue, 22-26.

Puryear, S.M., 1968. A Study of Jointing in the Area of the Wells Creek Structure, Houston, Montgomery, Stewart, Dickson Counties, Tennessee. Unpublished M.S. Thesis, Vanderbilt University.

Rambaut, A.A., 1899. On the Orbit of the Part of the Leonid Stream which the Earth Encountered on the Morning of 1898, November 15. *Proceedings of the Royal Society of London*, 65, 321-327.

Rampino, M.R., and Volk, T., 1996. Multiple Impact Event in the Paleozoic: Collision with a String of Comets or Asteroids? *Geophysical Research Letters*, 23, 49-52.

Reimold, W.U., 2003. Impact Cratering Comes of Age. *Science*, 300, 1889-1890.

Reimold, W.U., 2007. The Impact Cratering Bandwagon (Some Problems with the Terrestrial Impact Cratering Record). *Meteoritics and Planetary Science*, 42, 1467-1472.

Reimold, W.U., and Koeberl, C., 2008. Catastrophes, Extinctions and Evolution: 50 Years of Impact Cratering Studies. In Gupta, H., and Fareeduddin, F. (eds.). *Recent Advances in Earth System Science*. Bangalore, Geological Society of India (Memoir 66), 69-110.

Robertson, P.B., and Grieve, R.A.F., 1977. Shock Attenuation at Terrestrial Impact Structures. In Roddy, D.J., Pepin, R.O., and Merrill, R.B. (Eds). *Impact and Explosion Cratering: Planetary and Terrestrial Implications.* Flagstaff, Arizona, USA, Proceedings on the Symposium on Planetary Cratering Mechanics, 687-702.

Roddy, D.J., 1963. Flynn Creek Structure. *Astrogeologic Studies: Annual Progress Report, U.S. Geological Survey*, B, 118-126.

Roddy, D.J., 1964. Recent Investigations of the Flynn Creek Structure, with a Section on Geophysical Studies by S. Biehler and D.J. Roddy. *Astrogeologic Studies: Annual Progress Report, U.S. Geological Survey*, B, 163-180.

Roddy, D.J., 1965. Recent Geologic and Laboratory Investigations of the Flynn Creek Structure, Tennessee. *Astrogeologic Studies Annual Progress Report, U.S. Geologic Survey*, B, 50-61.

Roddy, D.J., 1966a. An Unusual Dolomitic Basal Facies of the Chattanooga Shale in the Flynn Creek Structure, Tennessee. *American Mineralogist*, 51, 259.

Roddy, D.J., 1966b. Carbonate Deformation at a Probable Impact Crater at Flynn Creek, Tennessee. *Eos, Transactions, American Geophysical Union*, 47, 493-494.

Roddy, D.J., 1966c. The Paleozoic Crater at Flynn Creek, Tennessee. Unpublished Ph.D. Thesis, California Institute of Technology.

Roddy, D.J., 1968a. Comet Impact and Formation of Flynn Creek and Other Craters with Central Peaks. *American Geophysical Union Transaction*, 49, 272.

Roddy, D.J., 1968b. The Flynn Creek Crater, Tennessee. In French, B.M., and Short, N.M. (eds.). 1968. *Shock Metamorphism of Natural Materials.* Baltimore, Mono Book Corporation, 291-322.

Roddy, D.J., 1968c. Paleozoic Crater at Flynn Creek, Tennessee: a Probable Impact Structure. *Geological Society of America, Special Paper*, 101, 179.

Roddy, D.J., 1976. The Flynn Creek Crater: Structural Deformation and Cratering Processes. *Lunar and Planetary Science Institute*, 259, 121-123.

Roddy, D.J., 1977a. Large-scale Impact and Explosion Craters: Comparisons of Morphological and Structural Analogs. In Roddy, D.J., Pepin, R.O., and Merrill, R.B. (Eds). *Impact and Explosion Cratering: Planetary and Terrestrial Implications.* Flagstaff, Arizona, USA, Proceedings on the Symposium on Planetary Cratering Mechanics, 185-246.

Roddy, D.J., 1977b. Pre-impact Conditions and Cratering Processes at the Flynn Creek Crater, Tennessee. In Roddy, D.J., Pepin, R.O., and Merrill, R.B. (Eds). *Impact and Explosion Cratering: Planetary and Terrestrial Implications.* Flagstaff, Arizona, USA, Proceedings on the Symposium on Planetary Cratering Mechanics, 277-308.

Roddy, D.J., 1979a. Current Drilling and Structural Studies at the Flynn Creek Impact Crater, Tennessee. *Lunar and Planetary Science*, X, 1031-1032.

Roddy, D.J., 1979b. Structural Deformation at the Flynn Creek Impact Crater, Tennessee: a Preliminary Report on Deep Drilling. *Proceedings Lunar and Planetary Science Conference*, 10, 2519-2534.

Roddy, D.J., 1980. Completion of a Deep Drilling Program at the Flynn Creek Impact Crater, Tennessee. *Lunar and Planetary Science Conference*, 11, 941-942.

Roddy, D.J., and Davis, L.K., 1977. Shatter Cones Formed in Large-Scale Experimental Explosion Craters. In Roddy, D.J., Pepin, R.O., and Merrill, R.B. (Eds). *Impact and Explosion Cratering: Planetary and Terrestrial Implications.* Flagstaff, Arizona, USA, Proceedings on the Symposium on Planetary Cratering Mechanics, 715-750.

Roddy, D.J., Kreyen, K., Schuster, S., and Orphal, D., 1980. Theoretical and Observational Support for Formation of Flat-Floored Central Uplift Craters by Low-Density Impacting Bodies. *Lunar and Planetary Science Conference*, 11, 943-945.

Roddy, D.J., Pepin, R.O., and Merrill, R.B. (eds.), 1977. *Impact and Explosion Cratering. Planetary and Terrestrial Implications.* New York, Pergamon Press.

Safford, J.M., 1869. *Geology of Tennessee.* Nashville, General Assembly Report.

Sagy, A., Fineberg, J., and Reches, Z., 2004. Shatter Cones: Branched, rapid Fractures formed by Shock Impact. *Journal of Geophysical Research*, 109, B10209, doi:10.1029/2004JB003016, 1-20.

Sawatzky, H.B., 1977. Buried Impact Craters in the Williston Basin and Adjacent Area. In Roddy, D.J., Pepin, R.O., and Merrill, R.B. (Eds). *Impact and Explosion Cratering: Planetary and Terrestrial Implications.* Flagstaff, Arizona, USA, Proceedings on the Symposium on Planetary Cratering Mechanics, 461-480.

Schaber, G.G., 2005. The U.S. Geological Survey, Branch of Astrogeology – A Chronology of Activities from Conception through the End of Project Apollo (1960-1973). U.S. Geological Survey Open-File Report 2005-1190.

Schedl, A., Mundy, L., and Carte, K., 2010. Application of a Paleostress Piezometer to Jeptha Knob, Versailles and Dycus Structures, Are They Meteorite Impacts? *Geological Society of America, Abstracts with Programs*, 42, 5, 172.

Schieber J., and Over, J.D., 2004. Age Constraints on the Formation of the Devonian Flynn Creek Structure, Tennessee. *Geological Society of America, Abstracts with Programs*, 35, 5, 165.

Schieber, J., and Over, D.J., 2005. Sedimentary Fill of the Late Devonian Flynn Creek Crater: a Hard Target Marine Impact. In Over, D.J., Morrow, J.R., and Wignall, P.B., (eds.). *Understanding Late Devonian and Permian-Triassic Biotic and Climatic Events.* Elsevier. 51-70.

Schieber, J., and Roddy, D., 2000. The Flynn Creek Crater in Tennessee: Learning from Crater Sedimentation about Timing and Impact Condition. *Geological Society of America, Abstracts with Programs*, 32, 7, 451.

Schultz, P.H., 1992. Impactor Signatures on Venus. *Lunar and Planetary Institute*, XXIII, 12311232.

Schultz, P.H., and Gault, D.E., 1990. Prolonged Global Catastrophes from Oblique Impacts. *Geological Society of America Special Papers*, 247, 239-262.

Schultz, P.H., and Lianza, R.E., 1992. Recent Grazing Impacts on the Earth Recorded in the Rio Cuarto Crater Field, Argentina. *Nature*, 355, 234-237.

Schultz, P.H., and Lutz-Garihan, A.B., 1982. Grazing Impacts on Mars: a Record of Lost Satellites. *Journal of Geophysical Research*, 87 (supplement) A84-A96.

Schultz, P.H. and Stickle, A.M., 2011. Arrowhead Craters and Tomahawk Basins: Signatures of Oblique Impacts at Large Scales. *Lunar and Planetary Science Conference*, 42, 2611.

Schultz, P.H., Zarate, M., Hames, B., Koeberl, C., Buncj, T., Storzer, D., Renne, P., and Wittke, J., 2004. The Quaternary Impact Record from the Pampas, Argentina. *Earth and Planetary Science Letters*, 219, 221-238.

Sears, F.H., 1930. Address of the Retiring President of the Society in Awarding the Bruce Medal to Professor Max Wolf. *Publications of the Astronomical Society of the Pacific*, 42, 5-22.

Shoemaker, E.M., 1977a. Astronomically Observable Crater-Forming Projectiles. In Roddy, D.J., Pepin, R.O., and Merrill, R.B. (Eds). *Impact and Explosion Cratering: Planetary and Terrestrial Implications.* Flagstaff, Arizona, USA, Proceedings on the Symposium on Planetary Cratering Mechanics, 617-629.

Shoemaker, E.M., 1977b. Why Study Impact Craters? In Roddy, D.J., Pepin, R.O., and Merrill, R.B. (Eds). *Impact and Explosion Cratering: Planetary and Terrestrial Implications.* Flagstaff, Arizona, USA, Proceedings on the Symposium on Planetary Cratering Mechanics, 1-10.

Shoemaker, E.M., 1983. Asteroid and Comet Bombardment of the Earth. *Annual Reviews of Earth and Planetary Sciences*, 11, 461-494.

Shoemaker, E.M., and Chao, E.C.T., 1961. New Evidence for the Impact Origin of the Ries Basin, Bavaria, Germany. *Journal of Geophysical Research*, 66, 3371-3378.

Shoemaker, E.M., and Eggleton, R.E., 1961. Terrestrial Features of Impact Origin. *Proceedings of the Geophysical Laboratory/Lawrence Radiation Laboratory Cratering Symposium, Washington, D.C.*, paper A.

Shotts, R.Q., 1968. Pseudo-Volcanism and Lunar Impact Craters. *Transactions: American Geophysical Union*, 49, 457-461.

Shuvalov, V.V., 2003. Cratering Process after Oblique Impacts. *Large Meteorite Impacts*, 1, 4130.

Shuvalov, V.V., 2011. Ejecta Deposition after Oblique Impacts: an Influence of Impact Scale. *Meteoritics and Planetary Science*, 46, 1713-1718.

Silliman, B., and Kingsley, J.L., 1869. An Account of the Meteor which Burst over Weston in Connecticut, In December, 1807, and of the Falling of Stones on that Occasion. *American Journal of Science and Arts (2nd series)*, 47, 1-8.

Singer, K.N., and McKinnon, W.B., 2011. Tectonics on Iapetus: Despinning, Respinning, or Something Completely Different? *Icarus*, 216, 198-211.

Spain, E.L., 1933. An Occurrence of Pleistocene Clay near Indian Mound, Stewart County, TN. Unpublished M.S. Thesis, Geology Department, Vanderbilt University.

Stearns, R.G., 1988. Field Trip to Wells Creek Basin Meteor Impact Structure, Tennessee. Vanderbilt University, Nashville, Tennessee.

Stearns, R.G., Wilson, C.W., Tiedemann, H.A., Wilcox, J.T., and Marsh, P.S., 1968. The Wells Creek Structure, Tennessee. French, B.M., and Short, N.M. (eds.). 1968. *Shock Metamorphism of Natural Materials.* Baltimore, Mono Book Corporation, 323-338.

Stöffler, D., Artemieva, N.A., and Pierazzo, E., 2002. Modeling the Ries-Steinheim Impact Event and the Formation of the Moldavite Strewn Field. *Meteoritics and Planetary Science*, 37, 1893-1907.

Stöffler, D., and Grieve, R. A. F., 1994. Classification and Nomenclature of Impact Metamorphic Rocks: A Proposal to the IUGS Subcommission on the Systematics of Metamorphic Rocks. In *Lunar and Planetary Institute Science Conference Abstracts*, 25, 1347.

Stöffler, D., and Langenhorst, F., 1994. Shock Metamorphism of Quartz in Nature and Experiment: I. Basic Observation and Theory. *Meteoritics*, 29, 155-181.

Stokley, J., 1931. Foretasting meteors. *Science News Letter*, 20, 552, 294-303.

Stratford, R., 2004. *Bombarded Britain. A Search for British Impact Structures*. London, Imperial College Press.

Swindel, G.W., and Jones, W.B., 1954. The Sylacauga, Talladega County, Alabama, Aerolite: a Recent Meteorite Fall that Injured a Human Being. *Meteoritics*, 1, 125-132.

Thomas, J.M., 2000. *Meteoroids, Meteors, Meteorites, and Tektites*. Tampa, Museum Astronomical Resource Document, Museum of Science and Industry.

Ullmann, D., 2007. Life and Work of EFF Chladni. *The European Physical Journal-Special Topics*, *145*(1), 25-32.

United States Geological Survey Astrogeology Science Center, http://astrogeology.usgs.gov/about.

United States Naval Observatory. (1867). *Observations and Discussions on the November Meteors of 1867*. US Government Printing Office.

Wieland, F., Reimold, W. U., and Gibson, R. L., 2003. New Evidence Related to the Formation of Shatter Cones; with Special Emphasis on Structural Observations in the Collar of the Vredefort Dome, South Africa. In *Large Meteorite Impacts*, 1, 4008.

Wilson, C.W., 1953. Wilcox Deposits in Explosion Craters, Stewart County, Tennessee, and Their Relations to Origin and Age of Wells Creek Basin Structure. *Bulletin of the Geological Society of America*, 64, 753-768.

Wilson, C.W., and Born, K.E., 1936. The Flynn Creek Disturbance, Jackson County, Tennessee. *Journal of Geology*, 44, 815-835.

Wilson, C.W., and Stearns, R.G., 1966. Circumferential faulting around Wells Creek Basin, Houston and Stewart Counties, Tennessee – a Manuscript by J.M. Safford and W.T. Lander, circa 1895. *Journal of the Tennessee Academy of Science*, 41, 37-48.

Wilson, C.W., and Stearns, R.G., 1968. *Geology of the Wells Creek Structure, Tennessee*. State of Tennessee, Department of Environment and Conservation, Division of Geology, 68.

Woodruff, C.M., 1968. The Limits of Deformation of the Howell Structure, Lincoln County, Tennessee. Unpublished Thesis, Vanderbilt University.

Wünnemann, K, Collins, G.S., and Melosh, H.J., 2006. A Strain-Based Porosity Model for use in Hydrocode Simulations of Impacts and Implications for Transient Crater Growth in Porous Targets. *Icarus*, 180, 514-527.

Wünnemann, K., Weiss, R., and Hofmann, K., 2007. Characteristics of Oceanic Impact-Induced Large Water Waves—Re-Evaluation of the Tsunami Hazard. *Meteoritics & Planetary Science*, 42, 11, 1893-1903.

Xiao, Z., Strom, R. G., Chapman, C. R., Head, J. W., Klimczak, C., Ostrach, L. R., Helbert, J., D'Incecco, P., 2014. Comparisons of Fresh Complex Impact Craters on Mercury and the Moon: Implications for Controlling Factors in Impact Excavation Processes. *Icarus*, 228, 260-275.