THE PALEOZOIC CRATER AT FLYNN CREEK, TENNESSEE

Thesis by

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ABSTRACT

Flynn Creek crater, approximately 330 feet deep and 11,500 feet in diameter, was formed in north central Tennessee in Middle or Late Devonian time. Impact of a large meteorite or comet probably produced the crater, which later became filled with Upper Devonian shale and covered by Lower Mississippian chert. Major structural elements include a zone of highly deformed rim strata surrounding a crater-shaped depression. A large central uplift occurs in the middle of the crater.

Flat-lying Middle and Upper Ordovician limestones surrounding the crater have been irregularly uplifted 30 to 150 feet in the rim and are moderately to tightly folded producing radial shortening as great as 35 percent. Types of rim deformation include normal faults, thrust faults and asymmetric anticlines, synclines and monoclines, all approximately concentric to the crater walls. Part of the southeastern rim has been thrust up and away from the crater and partly overrides a large tilted and folded graben. A chaotic limestone breccia ejected from the crater during its formation now overlies the graben and covers part of the ground surface that was present when the crater was formed.

The crater floor is underlain by a chaotic limestone breccia with fragments derived from the same rock units now exposed in the rim. Fragments range from less than a fraction of an inch to blocks 300 feet in length. In the center of the crater a sequence of highly deformed Middle Ordovician limestone and dolomite of the Stones River Group and Lower Ordovician limestone and dolomite of the Knox Group rises nearly 300 feet above the crater floor. Knox strata are raised as much as 1000 feet above their normal position and locally contain shatter cones.

Breccia contacts with folded rim strata are sharp in some parts of the rim but are jumbled and gradational in other parts. Intense twinning in calcite is common in an irregular zone a few feet to

several hundred feet wide adjacent to the crater wall in the deformed rim. Abundant microtwinned lamellae are common in the deformed calcite, and kink bands occur in some crystals.

A thin sequence of marine bedded breccias and dolomite was deposited in the crater during early Late Devonian time and was immediately overlain by Chattanooga Shale, whose lower unit filled the crater with nearly 300 feet of sediments. Lower Mississippian chert and limestone later covered the area.

A search for high-pressure polymorphs and for volcanic or meteoritic material was unsuccessful. A detailed gravity study indicates no gravity anomaly on the level of one milligal is associated with the crater at Flynn Creek. Magnetic studies also show that there are no large magnetic anomalies associated with the structure.

Structural comparisons between Flynn Creek crater and maars and diatremes show little or no similarity in types of deformation. Consideration of volcanic gas-phreatic eruption processes suggests that brittle fracture should accompany cratering with relatively little folding in the rim strata, unlike the deformation at Flynn Creek. Structural comparisons between Flynn Creek crater and meteorite impact, nuclear explosion and chemical-explosion craters show good agreement in nearly all types of deformation. A recently formed, large chemical explosion crater in Canada has both a central uplift and deformed rim very similar to Flynn Creek crater. Similarities in structural deformation between shock-produced craters and Flynn Creek crater suggest an origin by meteorite or comet impact.

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Statement of Problem

In north central Tennessee a crater approximately 330 feet deep and 11,500 feet in diameter is filled by Upper Devonian shale and Lower Mississippian chert. In the rim of the crater limestones of Middle and Upper Ordovician age are folded, faulted, and brecciated in an irregular zone several hundred feet wide. Strata in parts of the rim are lifted as much as 150 feet and tilted away from the crater. In other parts of the rim strata have been moved radially away from the crater in tight anticlinal and synclinal folds with axial trends concentric to the crater wall. Elsewhere in the rim a large thrust block and a large down-dropped block are bounded by fault zones concentric to the crater wall. A large mass of limestone breccia, apparently ejected from the crater, overlies the down-dropped block. Immediately outside of the deformed zone in the rim, the strata return to their normal flat-lying attitude.

The crater floor is underlain by a chaotic limestone breccia with fragments ranging in size from less than a fraction of an inch to blocks 300 feet in length. The crater breccia is made up of fragments of the same rock units that occur in the crater rim. A few fragments also occur in the breccia from horizons slightly deeper than the levels now exposed in the rim.

In the central part of the crater a sequence of steeply-dipping, folded, faulted and brecciated limestone and dolomite of the Stones River Group of Middle Ordovician age and limestone and dolomite of the Knox Group of lower Ordovician age rise nearly 300 feet above the crater floor. Knox strata in this central uplift are raised over 1000 feet above their normal stratigraphic level and locally contain breccia with shatter cones.

A thin marine deposit of bedded breccia and cross-bedded dolomite of early Late Devonian age overlies the breccia of the crater floor and wedges out against the crater walls. Outside the crater Chattanooga Shale of early Late Devonian age averages 27 feet in thickness but abruptly thickens to nearly 200 feet within the crater. Chert and cherty limestone of Lower Mississippian age conformably overlie the Chattanooga Shale. The crater and its filling strata are now well-exposed along the walls and floors of Flynn Creek Valley and its numerous tributary valleys.

The origin of this unusual structure has been the subject of controversy for nearly a century. Of the various origins proposed, impact and volcanic gas-phreatic explosions have been suggested as the most likely causes, but only one short inconclusive study has been actually directed toward this problem (Wilson and Born, 1936). Most of the specific information presented in the above description was gathered during the recent study by the author, and it is now apparent that the structural deformation is both quite intense and restricted to the area occupied by the crater and the surrounding strata in the rim. The deformation and chaotic mixing of fragments in the breccia, and the presence of a large ejected mass of breccia on the rim imply the occurrence of at least one dynamic event, presumably violent in nature. It is also possible to make an argument for the observed deformational features to have occurred at or very near the ground surface during middle Paleozoic time, and for only a moderate amount of erosion to have occurred before the crater was buried. It is also clear from reconnaissance studies of several hundred square miles surrounding the Flynn Creek area that the normal regional attitude of the strata is undeformed and nearly flat-lying. These conditions appear to be necessary but not sufficient arguments for either impact or gas-phreatic explosions. Until now no synthesis of this recent information with other available data has been made, and arguments for different origins have been left to speculation.

The purpose of this current study then is to attempt to determine the most likely mode of origin of the crater at Flynn Creek. The arguments are based on the author's recent geological and laboratory studies and on the published and unpublished studies of a number of other workers. A second aim is to present as complete a post-crater history as possible.

Although the crater is now filled and only partly exposed by erosion, the single term "crater" will be used throughout this study to avoid the constant use of such terms as partly buried crater, partly exhumed crater, or partly exposed crater.

Review of "Cryptovolcanic" Studies

In earlier papers the crater at Flynn Creek has been variously referred to as a "cryptovolcanic" structure (Wilson and Born, 1936, p. 815), a "cryptoexplosion" structure (Dietz, 1946a, p. 466), and an "astrobleme" (Dietz, 1960, p. 1781). A brief review of the usage of these names reveals that: (a) the crater at Flynn Creek is not unique, but is one of a class of many such structures which are scattered throughout the world, (b) the types of structural deformation are remarkably similar, but the ages of formation are quite different, (c) both impact and volcanic origins have been proposed for nearly all of the structures, and (d) as yet, the origin of none of the structures has been conclusively demonstrated. To further demonstrate the broader nature of the problem concerning the origin of the Flynn Creek crater, it is convenient to give a brief history of the work on "cryptovolcanic" or "cryptoexplosion" structures.

In 1905 Branca and Fraas described the unusual structure of the Steinheim Basin in southern Germany. Although no volcanic material was found, they felt that the origin was related to buried igneous activity and called the basin a "cryptovolcanic" structure. Kranz (1924, 1936, 1938) described the Steinheim Basin as a crater about 330 feet deep, 9,500 feet in diameter, and formed in flat-lying limestone. The walls of the crater contain "disturbed and shattered breccia" of limestone. Ring faults and radial faults are present in parts of the rim. Deformation of the strata elsewhere in the rim consists of intense folding and brecciation, but these structures have not been examined in detail because of poor exposures (Brinkman, personal communication, 1965).

The Klosterberg-Steinhirt, a central uplift, is present in the crater and rises 130 feet above the present floor of the basin. In describing this hill, Bucher (1963, p. 615) states "...the limestone horizons lie in wild confusion of disordered blocks between which the shale zones appear plastically squeezed and kneaded together." The limestones have been raised on the order of 500 feet above their normal positions and locally contain shatter cones.

Drilling in the basin floor has penetrated more than 300 feet of freshwater sediments. Bucher (1963, p. 615) states, "Freshwater limestone fringes the basin and caps the central hill which was an island in the lake. The calcareous tufa deposits are rather dolomitic, approximating a ratio of 3 Ca CO_3: 2 Mg CO_3. Associated with them is opaline silica which locally can be shown to have been deposited simultaneously with aragonitic sinter, suggesting hot springs action." Freshwater and land mollousks (and mammals) date the bulk of the freshwater deposits of the lake as upper Upper Miocene (Bucher, 1963, p. 616).

Some important similarities between the Flynn Creek crater and the Steinheim Basin are that both structures are circular craters of nearly the same size, and both were formed in flat-lying limestone. Deformation of rim strata, including faulting, folding, brecciation, and shattering, is also common to both craters. Central uplifts at both structures are of comparable size and have nearly identical types of internal deformation. Strata in the central uplifts of both structures have been raised 500 to 1000 feet, and each locally contains shatter cones in fine-grained limestone. Finally, both craters contain bedded deposits which are marine at Flynn Creek and freshwater at the Steinheim Basin. The only major difference between the structures is that the crater in Tennessee is older by some 350 million years. Also deposits from hot springs are reported at the Steinheim Basin, but their occurrence is common throughout this part of southern Germany, and their genetic relation to the formation of the basin has not been demonstrated.

Although Kranz (1922, 1924, 1936, 1938) continued his studies of the Steinheim Basin in Germany, little attention was given to "cryptovolcanic" structures in the United States until W. Bucher (1925, 1933a, 1933b) published a series of papers on the subject. Bucher (1936) then published an important summary of three U. S. structures he had mapped: Jeptha Knob in Kentucky, Serpent Mound in Ohio, and Wells Creek Basin in Tennessee. He also discussed several other structures that he considered of the same class, including the Kentland structure in Indiana, the Decaturville structure in Missouri, and Upheaval Dome in Utah. Wilson and Born's study (1936) of the Flynn Creek area had just been published, and Bucher agreed that this was another "cryptovolcanic" structure.

Included in Bucher's summary (1936, p. 1074) were the features he considered necessary for a "cryptovolcanic" structure:

> Comparison of the six definitely identified American examples shows that they have the following properties in common:
>
> 1. They show a tendency toward a circular outline.
>
> 2. A central uplift is surrounded by a ring-shaped depression, with or without well developed marginal folds beyond it.
>
> 3. In the larger disturbances the area of the uplifted central part is small compared to the areas that sank.
>
> 4. Where the nature of the rock materials permits any judgment, evidence is found of violent action, such as seems explicable only as the result of sudden release of pressure--that is, of an explosive force.
>
> 5. Except in the Decaturville structure, no volcanic materials or signs of thermal action have been observed.
>
> The evidence of explosive action in the center of these structures is sufficiently convincing to exclude the possibilities of a nonvolcanic origin.

Bucher (1936, p. 1074-1075) clearly felt that a volcanic origin was the only possible choice for the "cryptovolcanic" structures, and, in describing his concept of the process, stated:

> Violent explosions are usually regarded as phenomena characteristic of the last stages of volcanism, blowing away the volcanic mountains that had piled up above the orifice in the early stages. But similar effects are to be expected where ascending columns of lava failed to break through to the surface. If in such circumstances the magmas are highly charged with gases, especially with water vapor, the gases may dissipate through joints and other fractures. Occasionally, however, such an escape may be prevented by the texture of the rocks, and the gases may accumulate near the surface. Then the pressure will rise to the point where it lifts the overlying rock columns. Mere lifting will allow the gas to escape, chiefly through fractures in the center, causing the characteristic disruption and jumbling of blocks and the upward movement recorded in cryptovolcanic structures. If enough pressure is accumulated, however, the overlying column is blown out, producing explosion funnels at the surface such as the "maars" of the Eifel region of Germany or of the French Auvergne. In fact, the largest known explosion crater, the Ries Basin of Germany (24, 25), was formed in precisely this way.

Bucher also suggested that a second weaker explosion was necessary to form the central uplift. Bucher (1936, p. 1075-1076) then offered the following general classification:

> It appears, then, that the cryptovolcanic structures here described form part of 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 here described.
>
> (b) The explosion, shallow and strong enough, blows out a shallow more or less circular explosion basin filled with a jumble of disordered blocks and surrounded by a zone of materials blown or pushed out from it. The Ries Basin is an extreme example of this type. The Steinheim Basin is probably of similar origin.
>
> 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. Here belong the simple explosion funnels, the maars of the Eifel, the Auvergne, Italy, Mexico, etc.; the 125 "Vulkanembryonen" of the Schwabishe Alb in southern Germany (the same region in which lie the Steinheim and Ries Basins) the several hundred diamond-bearing funnels of South Africa; and the "chimneys" (many of them ore-bearing), filled with volcanic and bedrock breccias, which have been described from western mining camps in the United States (Colorado, Utah, etc.).

In his 1936 paper Bucher thus laid the foundation for the "cryptovolcanic" interpretation for the next 30 years. However, an alternative point of view was being offered at the same time in a series of papers by J. D. Boon, a physicist and C. C. Albritton, a geologist. Boon and Albritton (1936a, 1936b, 1937a, 1937b, 1938a, 1938b, 1938c, 1942) argued that many of the "cryptovolcanic" structures were due to the impacts of large meteorites. The crater at Flynn Creek was considered as a possible example of an impact structure because it has a central uplift. Although Wilson and Born (1936) had interpreted the central uplift as clear evidence against an impact, Boon and Albritton (1937, p. 58) stated:

> It seems this argument overlooks the fact that elasticity of rocks would cause a strong rebound following intense compression produced by impact and explosion. It is not unreasonable to suppose that the height of this rebound would be directly proportional to the diameter of the crater, with a ratio as shown in the ideal section, of about one to ten. A rebound of this amplitude would be quantitatively adequate to explain the elevation of the rock in Flynn Creek and other structures.

They then suggested that (Boon and Albritton, 1937, p. 62):

> The following features can be explained by the meteoritic hypothesis.
>
> 1. The abrupt central uplift.
> 2. The fracturing and jointing of rocks in the center.
> 3. The radial tear-faults.
> 4. Flanking, arcuate folds resembling damped waves.
> 5. Bilaterally symmetrical pattern of faults and folds about a line trending north-northwest.
> 6. Absence of volcanic materials.

In 1938 Boon and Albritton listed as "questionable meteorite structures" all of the structures considered as "cryptovolcanic" by Bucher. Boon and Albritton (1938) agreed that a "cryptovolcanic" explosion could have produced the different "crypto-" structures, but they felt that the "nature of the explosions which formed them still remains doubtful." They postulated that since large meteorites are known in space, some of these bodies must have struck the earth, and that for the present, it was justifiable to regard these "ancient explosion structures as questionable meteorite scars."

During the period from about 1940 to 1960 only a few studies were devoted to the "cryptovolcanic" problem with limited modifications of the earlier arguments of Bucher and Boon and Albritton. In 1944, the A. A. P. G. and the U. S. Geological Survey with Longwell and King as editors published the "Tectonic Map of the United States" and listed seven structures, including the crater at Flynn Creek, as "cryptovolcanic structure or similar disturbance." Although no origin was specified for the structures, the map served to expose a much larger number of geologists to the problem.

Dietz (1946a, p. 466) then proposed that the Flynn Creek structure and similar features be referred to as "cryptoexplosion" structures until their origins could be determined. The term never achieved wide use, mainly because most workers accepted the volcanic origin or preferred to use the already established term, "cryptovolcanic." In the same paper and in several subsequent papers Dietz (1946a, 1947, 1959, 1960, 1961a, 1961b, 1962, 1963a, 1963b, 1963c, 1964, 1965, 1966) pointed out that shatter cones occur in nearly all of the "cryptoexplosion" structures and are "indicative of explosive shock." Dietz visited many of the "cryptoexplosion" structures and was responsible for finding shatter cones at a number of the structures.

In 1949 Baldwin published his book <u>The Face of the Moon</u> and presented the first review of "cryptovolcanic" structures since Bucher's 1936 paper. He argued at length for an impact origin, but presented no new geologic field evidence. His book also treated the problem of lunar craters and presented a semi- quantitative approach to predicting certain impact crater parameters, such as diameter, depth and height of rim. At that time there was no widespread interest in the lunar craters, and the book received little attention.

In his catalogue of meteorites and craters, Prior (1953) listed many of the "cryptoexplosion" structures, including the crater at Flynn Creek, as possible impacts. In the same year, while studying the Wells Creek Basin, Wilson (1953) revised his earlier opinions on the Flynn Creek crater and suggested that both structures were the result of impact. In one of the few field studies on the U. S. structures Hendricks (1954) suggested that an impact best explains the features at the Crooked Creek structure in Missouri. Billing's (1954) textbook on structural geology presented a brief statement of the "cryptovolcanic" problem and offered both impact and volcanic origins as possibilities. DeSitter's text on structural geology, even in the second edition (1964), offers only a volcanic origin.

In 1955 C. S. Beals, an astrophysicist at the Dominion Observatory in Canada, initiated a systematic search for circular structures using aerial photos available from the Canadian Air Photo Library. The effort was extremely fruitful, and ten circular structures previously unreported in Canada were noted on the photos. Primarily through the efforts of Beals, extensive drilling and field programs have been carried on at nearly all of the Canadian structures. These studies have shown a wide variety of types of structural deformation in craters ranging from two miles to 45 miles in diameter. The drilling program has greatly aided in the interpretation of the structures at depth and has penetrated the bottom of the crater breccia at the Brent Crater (Dence, 1966). A variety of mineralogical and crystal structure variations have also been reported. Complete reviews of the Canadian work have been given by Beals, et. al. (1963), Dence (1964, 1965), and Innes (1964). Each of these writers argues for an impact as the most likely origin. Currie (1964, 1965) presents the most extensive discussion favoring a "cryptovolcanic" origin for the Canadian structures.

Dietz (1960, p. 1781) proposed the most recent change in nomenclature and suggested that the "cryptoexplosion" structures with shatter cones be called "astrobleme(s)" from the Greek words for star and wound. Dietz (1961a, 1961b) also published further accounts of his findings on shatter cones and listed eight structures, including the Flynn Creek crater, as "astroblemes" based on the occurrence of shatter cones.

The "Tectonic Map of the United States " published by the A. A. P. G. and U. S. Geological Survey under the direction of Cohee, et. al. (1961), again showed the same structures as the earlier edition, but listed them as "intensely disturbed, localized uplift(s)" rather than "cryptovolcanic." The new "Tectonic Map of North America," now in preparation under the direction of P. B. King of the U. S. Geological Survey, lists both the U. S. and Canadian structures, previously called "cryptovolcanic," as "astroblemes."

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 a number of important papers have been published in the last five years. A discussion of the basic theory of impact by Shoemaker (1960) provided the basis for understanding certain types of deformation during an impact. Rim folding, intense brecciation, and high pressure silica polymorphs were some of the logical consequences of impact in Shoemaker's treatment (1960, 1962, 1963). Shoemaker and Eggleton (1961) also published the first account of the structural variations to be expected in impact craters eroded to different levels. A number of studies have been directed toward understanding the rate of cratering. A study by Shoemaker, Hackman, and Eggleton (1962) examined this problem and argued for the application of cratering rates to aid in interplanetary correlation of geologic time, such as on the surface of the Moon or Mars.

In 1963 Baldwin revised and greatly expanded his earlier book on the Moon and again reviewed both impact and "cryptovolcanic" structures. He repeated the descriptions of each of the structures from the original papers and presented essentially the same arguments for impact as he gave in his 1949 book. The new book, however, presented a more complete mathematical treatment of crater physical dimensions. Baldwin also treated a variety of lunar problems, particularly lunar craters, in greater detail.

In the same year Bucher (1963) presented his most comprehensive treatment of the "cryptoexplosion" origin for three of the largest such structures, namely the Ries Basin in Germany, the Vredefort Dome in South Africa, and the Wells Creek Basin in Tennessee. In each case Bucher argued that these structures were not randomly distributed but had a systematic relation to areas of tectonic or volcanic activity. Bucher felt that the spatial relationship of these structures to normal volcanic and tectonic features was sufficient to rule out impact and implied that coesite found in the Ries Basin and shatter cones found in the Vredefort Dome and Wells Creek Basin, therefore, are not proof of an impact. The presence of nickeliferous iron in crater breccias and remoteness from centers of volcanic activity were both rejected as arguments for impact. Bucher also included both the Flynn Creek crater and the Steinheim Basin as products of terrestrial volcanism. Bucher (1963, p. 642) restated his concept of the mechanism as follows:

> If water-rich portions of magma were supercooled at great depth and then spurred to sudden crystallization, say, by earthquake shocks, enormous pressures would build up, penetrating into all fissures above the initial point of crystallization, crushing and partly pulverizing the rock in gouging out irregularly shaped pathways toward the surface, along which the comminuted rock fragments are driven upward as a highly fluid powder. This is what is meant by "fluidization". This explosive action may ultimately exhaust itself at depth, or end in an unsuccessful attempt to eject the rock material (a "cryptoexplosion structure"), or in a successful blowout, an explosion crater.

Bucher (1963, p. 597) accepted Dietz's term cryptoexplosion as the most useful because "it leaves the cause unspecified".

In 1965 the conference proceedings on "Geological Problems in Lunar Research" were published, and a large collection of papers were given presenting only the impact and volcanic arguments. More recently, in 1966, the first conference was held on "Shock Metamorphism of Natural Material", and was devoted partly to impact craters and to cryptoexplosion structures. The one conclusion that can be drawn from these most recent collective studies of the "crypto-" problem is that <u>no</u> definitive argument for either impact or volcanic origin is yet available.

At the outset of the current Flynn Creek study, the state of knowledge on "cryptoexplosion" structures could be summarized as follows:

a. The Flynn Creek crater is one of a class of structures which are widely distributed in time and space.

b. Structural deformation includes folded, faulted, brecciated and shattered strata in the rims. The details and ranges in types of deformation were mostly unknown.

c. Central uplifts of folded, faulted, brecciated and shattered strata are common and usually contain shatter cones. The details and ranges in types of deformation were mostly unknown.

d. Neither volcanic nor meteoritic material had been reported from most of the smaller structures, but systematic laboratory and field studies had not been made for such material. In the larger structures, such as the Ries Basin and the Vredefort Dome, the genetic relationships of the volcanic materials to the origin of the structures was still in debate. Coesite had been definitely found at one of the large "cryptoexplosion" structures (Ries Basin), but its reported occurrence in two smaller structures (Kentland, Indiana and Serpent Mound, Ohio) was debatable.

e. Most of the smaller structures in the U. S. were located in regions little effected by observed tectonic or volcanic activity.

f. The Steinheim Basin in Germany was the only cryptoexplosion structure studied in great detail, and this study was restricted mainly to the surface geology.

Figure 1.--Index map of "Cryptoexplosion" Structures in Eastern United States and Southeastern Canada.

1. Brent Crater, Ontario, Canada
2. Crooked Creek Disturbance, Missouri
3. Decaturville Dome, Missouri
4. Desplaines Disturbance, Illinois
5. Dycus Structure, Tennessee
6. Flynn Creek Crater, Tennessee
7. Glasford Structure, Illinois
8. Glover Bluff, Wisconsin
9. Holleford Crater, Ontario, Canada
10. Howell Structure, Tennessee
11. Jeptha Knob, Kentucky
12. Kentland Structure, Indiana
13. Kilmichael Structure, Mississippi
14. Manson Structure, Iowa
15. Middlesboro Basin, Kentucky
16. Serpent Mound, Ohio
17. Versailles Structure, Kentucky
18. Wells Creek Basin, Tennessee

g. Except for the Steinheim Basin none of the structures had been shown to have formed at the surface.

h. No ejecta deposits had been reported for any of the smaller structures the size of the Flynn Creek crater, and an "explosion" origin was inferred for all structures only from the degree of brecciation and deformation.

i. Neither a volcanic nor an impact origin had been conclusively demonstrated for any of the "cryptoexplosion" structures.

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 both a detailed regional and local geologic study combined with a laboratory examination of the rocks would give a better insight into the origin of the Flynn Creek crater.

Previous Work

The first reference to the unusual structural relationships in the Flynn Creek area was made by Safford in 1869 when he suggested an origin that involved folding and faulting. Safford (1869, p. 148) stated:

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

During the summer of 1926 Lusk mapped the geology of the Gainesboro quadrangle as an oil and gas resources project for the Tennessee Division of Geology. Apparently Lusk was not aware of Safford's earlier reference to the deformation in the Flynn Creek area, and in 1927 he reported "An interesting result of the summer's work was the discovery of an extraordinary local thickness of the Chattanooga shale." Lusk (1927, p. 579-580) considered several hypotheses to account for the structural relationships including slump, post-Chattanooga diastrophism, "sub-surface volcanism," and cavern collapse. Lusk rejected slump of the black shale into the crater after locating continuous exposures from the ridges to valley floors, and he discounted post-Chattanooga diastrophism when he found no deformation in the shale. Lusk further stated, "...the absence of veins or dikes of possible igneous origin discourages the view of sub-surface volcanism." Collapse of the roof of an irregular branching cavern or series of caverns was offered as the most likely origin. Lusk repeated his conclusions in an unpublished paper on the Gainesboro Quadrangle (Lusk, 1935).

Bassler (1932, p. 143), referring to Lusk's work, noted, "On three sides of this area the dips suggest that the region may be another example of cryptovolcanic structure such as that described by Bucher for Adams County, Ohio." Bassler later identified fossils from the Flynn Creek area for Wilson and Born (1936, p. 817), but apparently did not confirm Lusk's studies by actual field work.

The study by Wilson and Born (1936) was the first work devoted exclusively to the Flynn Creek structure. A generalized geologic map of the crater was completed (fig. 2), and a brief description was given of the local stratigraphy. At that time the contacts of the different stratigraphic units were not well-known and could only be generalized on the geologic map. Origins considered by Wilson and Born (1936, p. 828-829) included: "(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) cryptovolcanic (gas and steam) explosion."

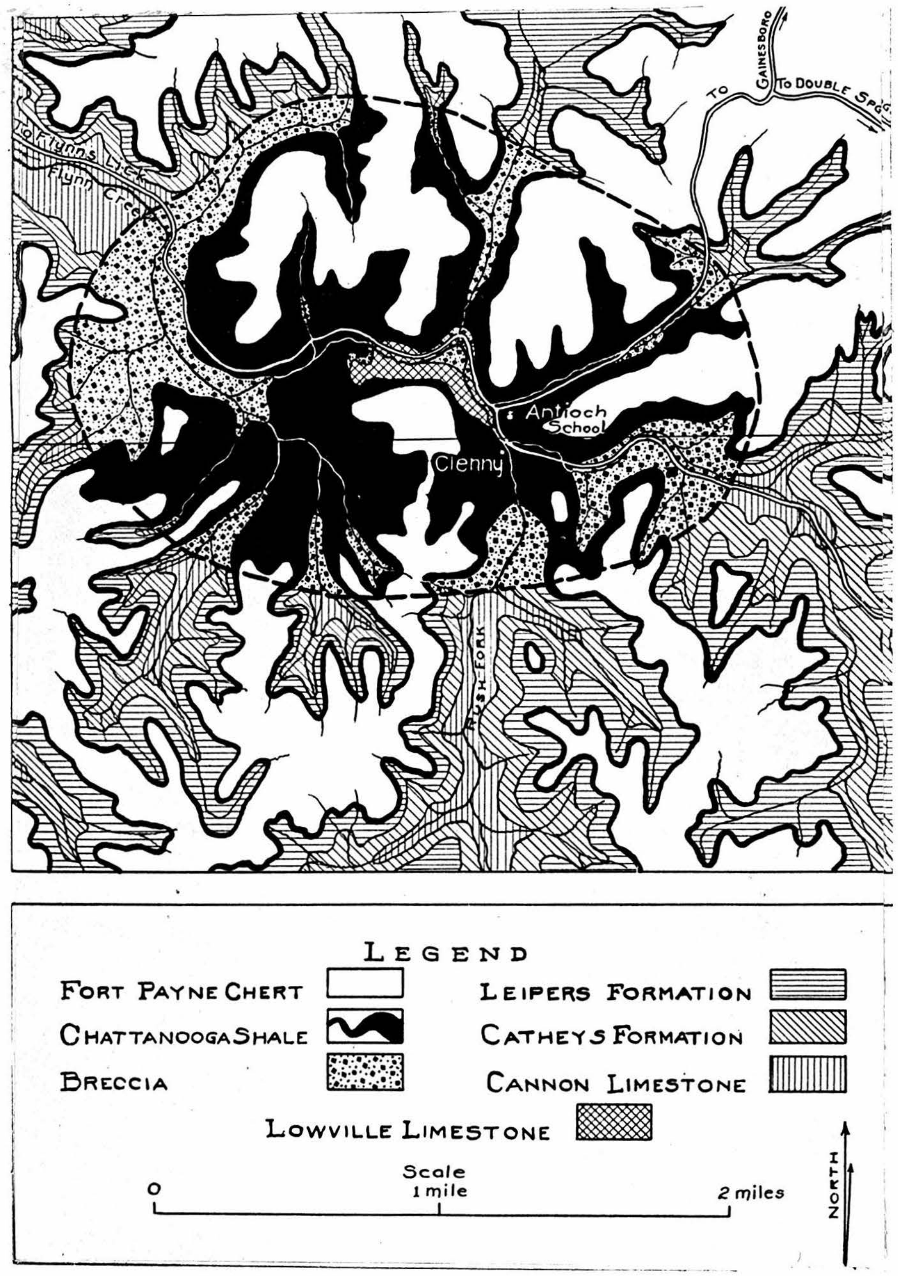

Figure 2 .--Areal geologic map of the Flynn Creek area. The heavy broken line indicates the approximate border of the circular area of intense brecciation. From Wilson and Born (1936, p. 818).

Wilson and Born rejected meteorite impact and cavern collapse because of the central uplift of "Lowville limestone" (later renamed the Carters limestone). The absence of salt, anhydrite deposits and large concentrations of natural gas in this region suggested the improbability of such causes. Wilson and Born (1936, p. 830) concluded that a "Cryptovolcanic explosion is the only possible origin amount those listed that cannot be readily eliminated." They interpreted the structural deformation as the result of a near-surface volcanic explosion that blew out a crater two miles in diameter and 300 feet deep shortly before the deposition of the Chattanooga Shale in Late Devonian time. The bedded breccias in the crater were considered as fresh-water lake deposits that accumulated before Chattanooga time. The rims of the crater were interpreted as cut by concentric vertical faults (fig.3). A closed magnetic high was also described four miles south-southwest of the crater and was postulated as caused by a "buried plug of igneous material responsible for the Flynn Creek disturbance." A recent geophysical survey has shown that this magnetic anomaly is actually an elongated closed magnetic low (Biehler and Roddy in Roddy, 1964).

On the basis of the study by Wilson and Born, Bucher (1936, p. 1074) stated that, "Wilson and Born have proved the cryptovolcanic nature of a structure on Flynn Creek...", but despite his great interest in the problem, he apparently never visited the area.

During the study of the Howell structure in south central Tennessee, Born and Wilson (1939, p. 378-379, 385, 387) reaffirmed their belief that the Flynn Creek structure had a "cryptovolcanic" origin. Wilson in 1948 and in 1949 again referred to Flynn Creek and its "cryptovolcanic" origins but did not amplify on his earlier work. In an unpublished master's thesis Mitchum (1951) described the small Dycus structure in northwestern Jackson County, Tennessee, and compared it with the Flynn Creek structure, but he could only suggest that both structures appeared consistent with an impact origin. While studying the Wells Creek Basin, Wilson (1953, p. 764) revised his opinion on

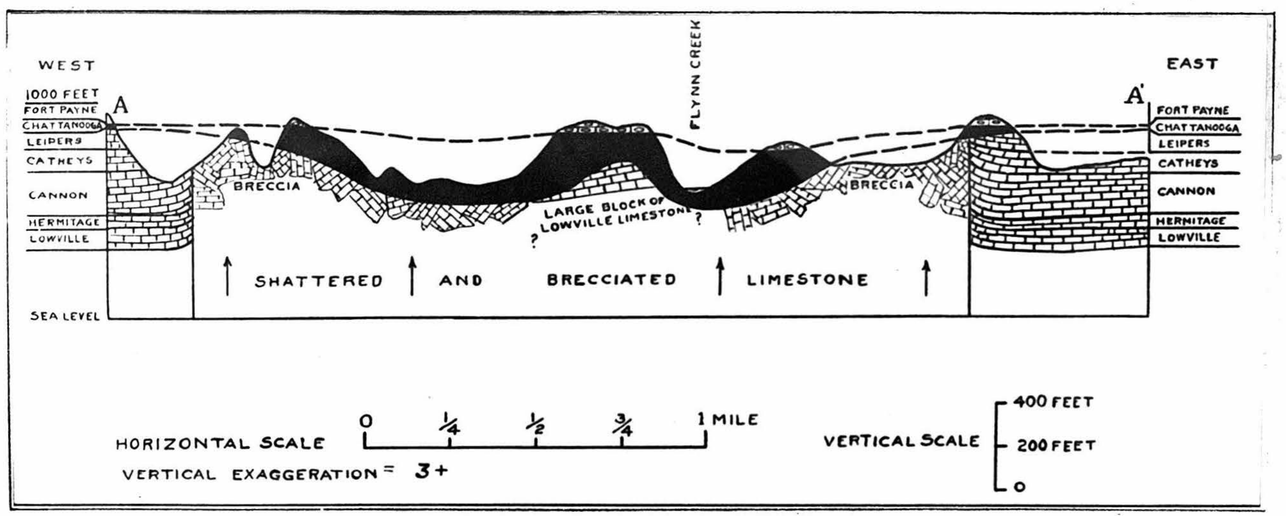

Figure 3 .--East-west structure cross section along the line A A' on Figure 2 . From Wilson and Born (1936, p. 824).

"cryptovolcanic" origins and suggested that both the Wells Creek and Flynn Creek structures were produced by meteorite impact. His new interpretation was based mainly on the highly brecciated character of the drill core taken from the central part of the Wells Creek Basin. Wilson (1953, p. 767) states:

> This core presents three significant features. (1) Deformation was instantaneous, and did not result from normal tectonic stresses; (2) progressive downward dying out of deformation may be traced, in spite of the brecciation between 1743 and 1930 feet, (3) in the top 200 feet of the core, the shatter cones are all horizontal, except for some that point obliquely upward. The greatest concentration of horizontal cones is at a depth of 100 feet. Below 200 feet, shatter cones are rare, incomplete, and poorly defined...

Conrad, Elmore and Maher (1957) briefly described the stratigraphy of the Chattanooga shale in the Flynn Creek area and stated that they believe that the Flynn Creek structure represents a pre-Chattanooga basin with at least 200 feet of relief. They noted that only the lower member of the black shale appears to be overthickened such that it partly fills the crater and suggested that "...a relatively level surface was present on which normal upper Chattanooga sedimentation took place." No arguments were presented for the origin of the crater. Stockdale and Klepser (1959, p. 15-16, 66-69, 135-137) reported many additional descriptions and thickness measurements of the Chattanooga Shale in the Flynn Creek area. They stated that the uranium content in the overthickened black shales in the crater is essentially the same as in the normal black shales outside of the crater. They interpreted this as an indication that the black muds gained their uranium content while being deposited elsewhere on the surrounding sea bottom and were then swept into the crater.

Shatter cones were discovered in the central uplift by Dietz, Stearns and Wilson in 1959 during a field trip to the Flynn Creek area, and in 1960 Dietz (p. 1783) reported eight different "cryptoexplosion" structures containing shatter cones. Dietz asserted that at Flynn Creek the orientation of the cones is upward, but they were later found to have several different orientations (Roddy, 1964).

In 1961 Conant and Swanson published their comprehensive study of the Chattanooga Shale in Tennessee and in the surrounding states and described the black shales in the Flynn Creek area. They agreed with Conrad and others (1957, p. 9-18) that the increased thickness of the Chattanooga Shale is almost wholly in its lowest unit. Conant and Swanson noted dips of 20° in the basal unit of the black shale where it overlies the flanks of the central uplift and concluded, "It is highly unlikely that the fine muds could have accumulated on the steep slopes to thicknesses of many tens of feet without slumping towards the deeper areas." They suggested that the "...disturbed area and the surrounding region had been reduced by erosion to a uniform level and the fragmental material in the structure subsided gradually during the accumulation of the black muds." They pointed out that the "bedded breccia" of Wilson and Born or "fresh-water" limestone of Conrad and others is a marine basal facies of the Chattanooga Shale according to the conodont studies reported by Hass. They tacitly assumed an impact origin was probably, and Conant (personal communication 1965) still holds that opinion.

Huddle (1963) reviewed Hass' unpublished notes on the Flynn Creek area and re-studied the conodont collection Hass had prepared from the bedded breccia in the crater. In this study Huddle assigned an early Late Devonian age to the bedded breccia and bedded dolomite in the crater. The only other microfossils reported are conodonts of Ordovician age that were present in the breccia fragments or eroded from the crater walls.

More recently various aspects of the stratigraphy and structure have been described in a series of preliminary reports for the U. S. Geological Survey (Roddy, 1962, 1963, 1964, 1965).

Field Methods

Geologic field work in the Flynn Creek area was started by the author in the summer of 1962, and approximately eight months of field work were completed during the summer of 1962, the summer and fall of 1963, and the spring of 1964 and of 1965. During this time approximately 17 1/2 square miles were mapped in detail at a scale of 1:6000 (one inch = 500 feet). The detailed map area includes the crater, the folded and faulted rim and the undeformed area immediately outside the rim (Plate 1). A larger area of about 100 square miles surrounding the boundaries of the crater map was mapped partly in detail at 1:6000 and partly in reconnaissance at 1:24,000 and 1:62,500.

The geologic mapping was completed on enlarged aerial photographs of the U. S. Department of Agriculture (flown in November 1958; enlarged to 1:4000) and the U. S. Geological Survey (flown in March 1963; enlarged to 1:5000). To aid in this mapping, several hundred accurately located control points were established in the field and their elevations and locations determined by a third-order alidade survey or by Kelsh stereophotogrammetric techniques. Elevations determined by hand leveling and locations measured by tape were then referred to these control points. All geologic contacts were walked, and continuous elevation control was carried by hand leveling along each individual contact. Selected points along contacts were measured by tape from the nearest control points to maintain horizontal accuracy in areas where photo location was difficult to establish because of dense vegetation. In areas where distance could not be taped, a Brunton compass was used to obtain bearing lines to at least two control points. Thickly wooded sections and dense undergrowth required much of the detailed mapping be completed in the fall and spring.

After the contacts were mapped, a closely spaced grid pattern was walked on most of the hillsides to ensure that all available outcrops would be utilized in the mapping. In the areas mapped in detail, it was usually necessary to locate outcrops of several or more beds since individual beds were generally not diagnostic for separation of the different map units. Although there are areas where continuous outcrops cover large parts of a hillside, approximately 85 percent of the area has a thin cover of colluvium. Where necessary, areas that were covered by colluvium were excavated by shovel. In nearly all of the map area the contacts between units could be determined in the field; however, in some of the more structurally complicated parts of the rim, samples were examined in thin section before contacts were assigned.

The choice of formational contacts in the strata of Ordovician age is based on the stratigraphic divisions established mainly by Wilson (1949; personal communication, 1963) in central Tennessee. C.W. Wilson of Vanderbilt University and R. Barnes of the Tennessee Division of Geology field checked several of the author's column sections in the Flynn Creek area and confirmed that the formational contacts are equivalent to those being mapped by the Tennessee Division of Geology elsewhere in central Tennessee.

The formations of Upper Devonian and Lower Mississippian age that were mapped in the Flynn Creek area follow the nomenclature and stratigraphic divisions of Conant and Swanson (1961) and Marcher (1962).

Individual stratigraphic units within the formations were chosen for their local persistence and mapped because of their use in delineating the structure. These units, however, were not traced in sufficient detail outside of the Flynn Creek area to allow their classification as members of the different formations. Most of the stratigraphic units which are restricted to the crater had not been mapped in any of the earlier work and are described on the basis of the author's current study.

A detailed soil survey is presently underway by the U. S. Department of Agriculture, and the different types of soil cover, except for stream alluvium, were not mapped in this study.

The topographic base map was specially prepared to meet the requirements of the detailed geologic mapping. Field control was completed by J. D. Alderman, U. S. Geological Survey in January of

1964 using U. S Coast and Geodetic Survey and U. S. Geological Survey bench marks and triangulation stations. An area of about 35.5 square miles was compiled by Alderman using the Kelsh stereophotogrammetric system with the November, 1958 photography (diapositives) of the U. S Department of Agriculture. Scaling of the base was done at 1:6000 using U. S Coast and Geodetic Survey primary control. A ten foot contour interval was used, and the base was referenced to the Tennessee State Grid System (Lambert plane coordinate system).

Transfer of the geologic contacts from the aerial photos to the base map was completed using combinations of the Kelsh system, elevations determined by hand leveling, distances measured by tape and bearing lines to control points or landmarks. In wooded and dense undergrowth areas transfer of points along contacts was completed using a minimum of two bearing lines from landmarks, hand level elevations and distances measured by tape to photo-identified points. The detail and accuracy of the base map has allowed transfer of the exposed geologic contact with approximately a two foot maximum vertical error and 10 foot maximum horizontal error.

Physiography

Tennessee spans part of five major physiographic provinces, including the Gulf Coastal Plain, the Interior Low Plateau, the Appalachian Plateau, the Valley and Ridge and the Blue Ridge Provinces (Fenneman, 1938). Of these five provinces only the Interior Low Plateau, which occupies the central part of the state, contains the state's three "cryptoexplosion" structures. In Tennessee the Interior Low Plateau is divided into the Nashville Basin and the surrounding Highland Rim (fig. 4).

The Flynn Creek area described in this study is located in the north central part of the state at the indefinite boundary between the Nashville Basin and the Highland Rim (fig. 4). This part of Tennessee is a highly dissected region of steep-sided valleys (locally

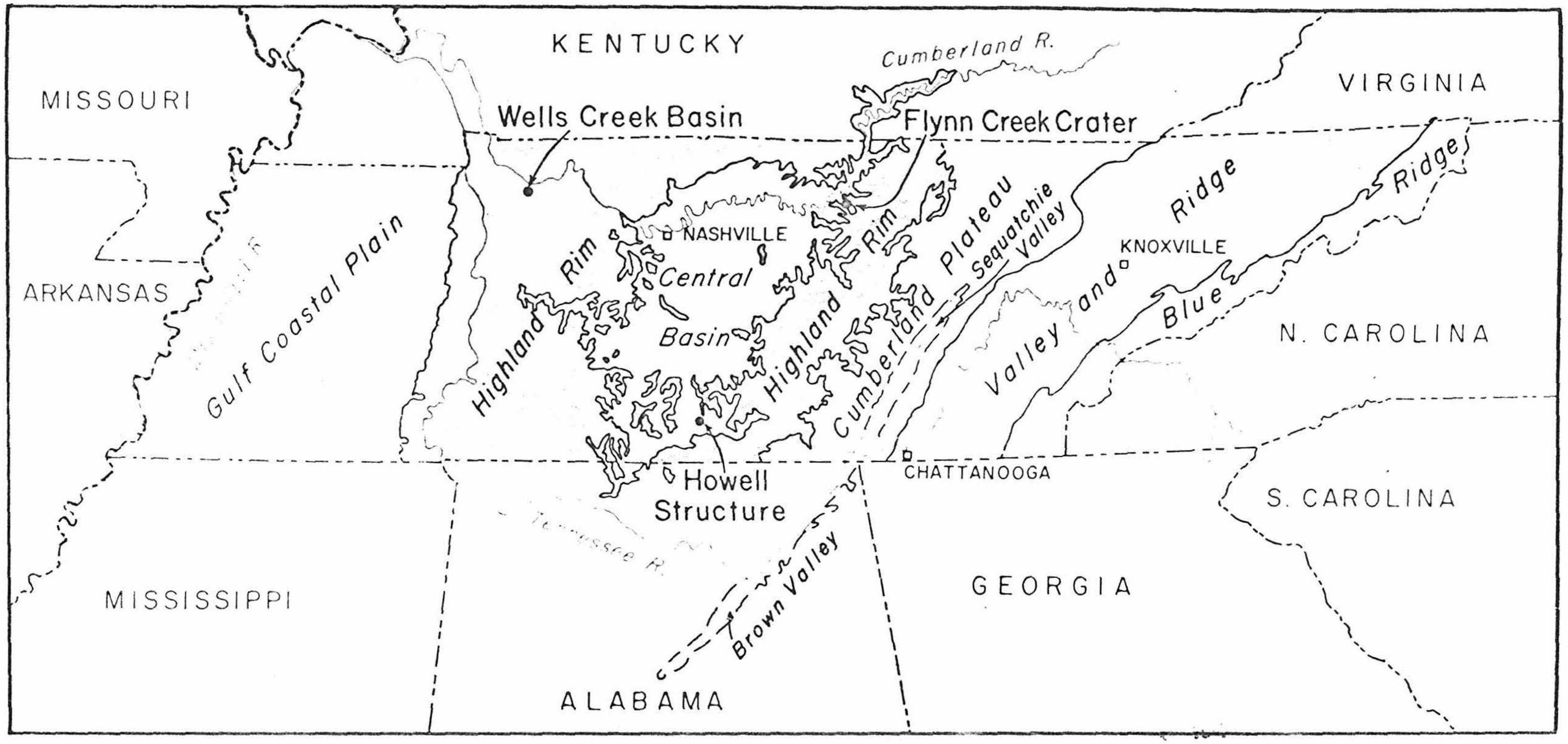

Figure 4 .--Index Map of the Flynn Creek Crater in Tennessee. Solid heavy lines show boundaries of physiographic provinces. Highland Rim Province is shown in dark relief.

called hollows) separated by narrow, winding ridges with numerous small spurs (fig.5). Throughout the area mapped in this study and for many hundreds of miles surrounding the Flynn Creek area, the ridge tops lie at a nearly uniform level of about 1000 feet above sea level (fig.6). The lowest elevations in the map area, averaging 520 feet above sea level, are in the western part of the Flynn Creek Valley. In the eastern part of the map area the streams are currently eroding into the edge of the Highland Rim. The average relief over the whole area mapped is about 450 feet. Hill slopes of 35° are common in the upper parts of all the valleys, but generally decrease to about 15° to 20° at the mouths of the main valleys. The slopes are often nearly equal on both sides of the valleys and terminate abruptly with the flat valley floors. The heads of all the smaller valleys are more nearly V-shaped.

The crater at Flynn Creek does not greatly affect the present topography except along the northwest rim. In this area one of the larger tributaries to Flynn Creek follows the approximate outline of the rim as it erodes into the less resistant, overthickened Chattanooga Shale (fig.5). The majority of the streams apparently established their drainage patterns on the strata that covered the crater and were not affected as they eroded into the deformed rocks.

The Cumberland River and its many tributaries, including Flynn Creek, are mainly responsible for the present complicated drainage pattern. Immediately northeast of the Flynn Creek area the Cumberland River has eroded into the Highland Rim in a wide, flat incised stream valley. West and southwest of the Flynn Creek area the Cumberland River flows west across the rolling lowlands of the northern end of the Nashville Basin. The best exposures of the stratigraphic section are present along the high vertical cliffs on the banks of the river.

Flynn Creek is the largest stream in the map area and empties directly into the Cumberland River about five miles northwest of the crater. A large spring at the eastern edge of the crater rim provides Flynn Creek with its source of perennial water. During the dry season the water in the gravel bed of Flynn Creek drains underground at the

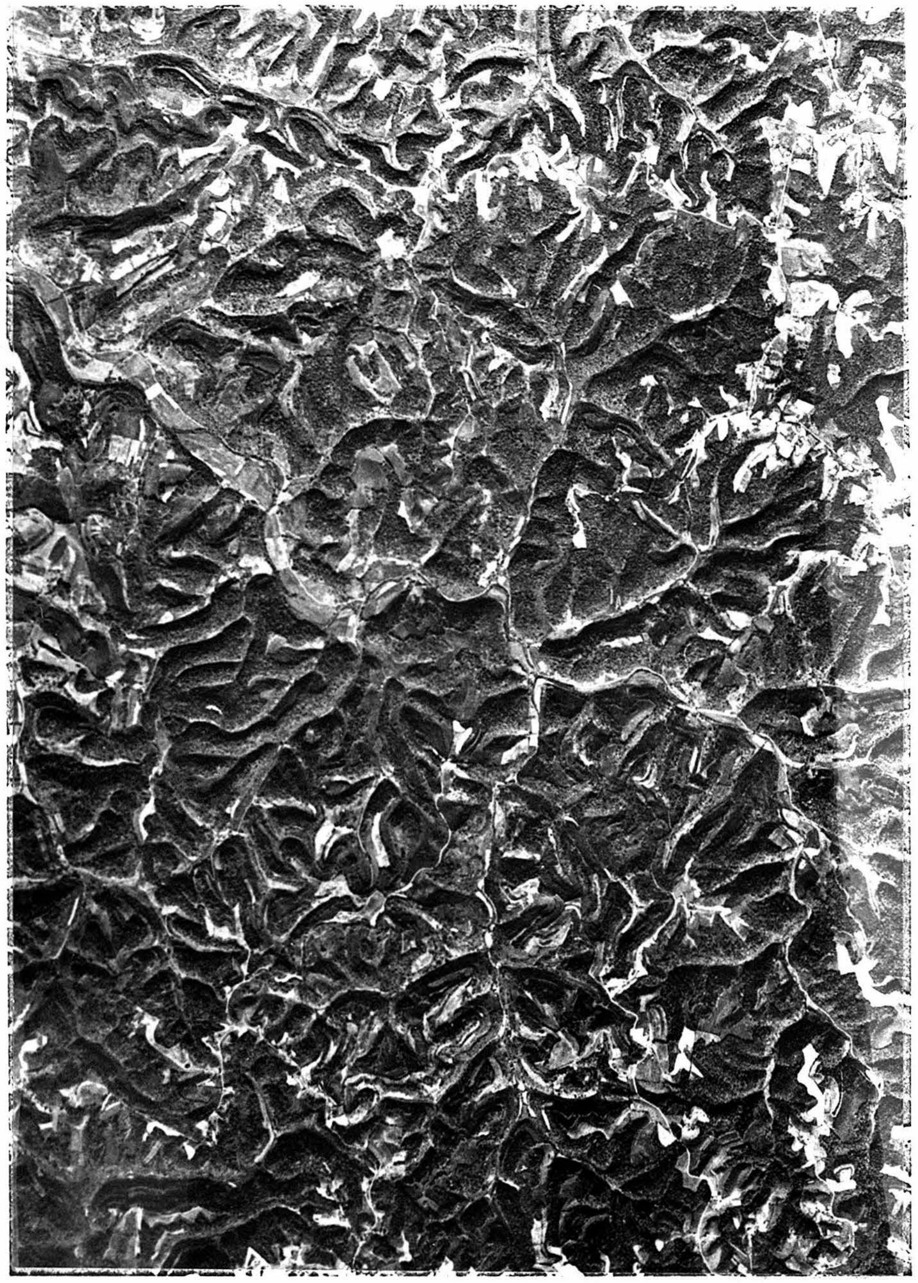

Figure 5 .--Aerial photograph of the Flynn Creek area. Center of crater is in center of photograph. Compare with Figure 2.

Figure 6 .--Flat-topped ridges in part of the highly dissected outer Nashville Basin. View North from northeast side of Flynn Creek Crater, Tennessee.

western edge of the map area. One mile northwest of this location the water flow reappears from a cave immediately east of Route 53. All other tributary streams are intermittent except where an occasional high flow of water issues from one of the small springs at the top of the Chattanooga Shale. The porous cherts of the overlying Fort Payne Formation provide the source of this spring water.

The Highland Rim, which entirely surrounds the Nashville Basin, is well-defined about three miles east of the crater (fig.4). In this area the Rim is a rolling plateau fifteen to eighteen miles wide lying in an east-west direction and ranging between 950 to 1100 feet above sea level. The western part of the Rim is bounded by the highly dissected outer Nashville Basin. The eastern part of the Rim is bounded by the edge of the dissected Cumberland Plateau.

Location

The Flynn Creek structure is located in southern Jackson County, Tennessee in the north central part of the state (fig.4). The center of the structure lies at approximately 85° 39' 45'' W longitude and 36° 16' 45'' N latitude and is about 8.5 kilometers south of Gainesboro, Tennessee and 105 kilometers east-northeast of Nashville, Tennessee.

The area is easily accessible on the west by State Route 53 and on the east by State Route 56, both hard surfaced. The recently surfaced Flynn Creek Road passes east-west through the middle of the structure, while graded roads in Cub Hollow and Rush Fork provide access to the northern and southern parts of the structure. Numerous other graded and a few hard surfaced roads provide access to within approximately two kilometers of any part of the area.

Vegetation

Jackson County and the surrounding region are located in the Central Forest Region of eastern North America (Society of American Foresters, 1954). Most of the southern part of Jackson County was originally covered by forests of the oak-hickory and oak-pine groups (Hogan, personal communication, 1963). Approximately 70 percent of the Flynn Creek area is woodland with only parts of the ridge crests and main valleys cleared for agricultural use.

During the summer a lush, very dense ground cover of great variety blankets the lower parts of the valley walls and all cleared areas. Certain plants in poorly drained areas grow in profusion six to eight feet tall, making passage extremely difficult and outcrops nearly impossible to find (fig.7). The southern valley slopes, which locally support large stands of redcedar, commonly have the most extensive outcrops.

Nearly all of the clearing for agriculture and timber was completed between the late 1700's and the early 1900's, but most of these areas are now re-grown with thick, mature woodlands often with dense underbrush. Clearings on upper hillsides left untended for a few years have re-grown with large impassable patches of blackberry bushes and underbrush. In the larger valleys irregular clearings extend only up to the base of the Chattanooga Shale where a steep increase in slope occurs (fig.8). The upper and lower edges of the clearings often approximately follow the underlying stratigraphic units. Open to dense stands of woodlands cover the interval from the base of the Chattanooga Shale to the tops of the ridges where clearings may be present on the wider, flat areas. Most of the smaller valleys and heads of the larger valleys are rarely cleared and occasionally have a dense undergrowth (from previous clearings) associated with the normal woodlands.

A

B

Figure 7 --Valley on the northeastern side of Flynn Creek crater showing typical relief of area and winter vegetation, A, and summer vegetation, B. Photographed from same location.

Figure 8 --Near western crater wall in Flynn Creek Valley. View toward west shows clearing up to top of Leipers Formation. Base of tree line at top of ridge is at the base of Chattanooga Shale. Ridge stands 400 feet above Flynn Creek in left-foreground of photograph.

A

B

Figure 9 --Typical relief on western side of Flynn Creek Crater. Flynn Creek Valley in foreground of A and B.

Acknowledgments

I wish to express my appreciation to Dr. Eugene Shoemaker for his suggestion of this thesis problem and his constant support and encouragement throughout the study. I also gratefully acknowledge the interest and continued assistance in this study given by Dr. Clarence Allen. I would further like to express my appreciation to Dr. Harrison Brown for his interest in this work.

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REGIONAL GEOLOGIC SETTING

Regional Stratigraphy

The sedimentary rocks exposed throughout central Tennessee consist mainly of limestone with lesser amounts of shale and sandstone (fig.10). The majority of these rocks are Paleozoic in age and are typical of the nearly flat-lying strata throughout the Interior Low Plateau of the central United States. Mesozoic strata are absent except for a few sedimentary rocks of Cretaceous age in west central Tennessee. Other younger rocks scattered throughout central Tennessee include flood plains, terraces, and a few surficial deposits of gravel, sand and clay which range in age from Tertiary to Quaternary.

The oldest rocks exposed in central Tennessee are dolomite and limestone of the Knox Group and range in age from Upper Cambrian to Lower Ordovician. These strata are found at the surface only in the faulted, folded and brecciated central parts of the Wells Creek and Flynn Creek structures. Normally the Knox strata occur as nearly flat-lying beds about 1000 feet below the ground surface throughout this part of the state. The Knox Group is about 5000 feet thick in central Tennessee and may rest directly on the crystalline basement.

The Stones River Group overlies a major unconformity on top of the Knox strata in the Valley and Ridge province, and presumably lies unconformably on the Knox Group in central Tennessee. The Stones River Group consists of nearly flat-lying limestone and dolomite of Middle Ordovician age and averages between 800 and 1500 feet in thickness. The upper Stones River strata are exposed throughout the inner Nashville Basin and dip gently away from the Nashville Dome. Faulted, folded and brecciated rocks of the Stones River Group also occur in the central parts of the Wells Creek and Flynn Creek structures.

During Middle Ordovician time sediments of the Hermitage Formation were deposited disconformably on the Stones River strata. Shales, silty limestones and dolomitic limestones dominate the Hermitage lithology in central Tennessee and average 70 to 100 feet in thickness.

The Cannon limestone of Middle Ordovician age conformably overlies the Hermitage Formation and averages about 100 feet in thickness. The overlying silty limestones of the Catheys Formation of Middle Ordovician age average about 170 feet in thickness and are apparently conformable with the Cannon limestone. The Catheys Formation in turn is overlain disconformably by the silty, dolomitic limestones of the Leipers Formation of Upper Ordovician age. The Leipers strata averages about 100 feet in thickness. Each of these formations are well-exposed in the dissected parts of the outer Nashville Basin.

Limestones and shales of Silurian and Lower and Middle Devonian age are present along the western and northern parts of the Nashville Basin but are absent in the Flynn Creek area. Throughout Tennessee and the surrounding states a pronounced erosional break is present at the base of the Upper Devonian strata. At Flynn Creek and in the surrounding area the Leipers strata are disconformably overlain by the regionally extensive Chattanooga Shale of early Late Devonian age. The black shales are in turn overlain, apparently conformably, by the very thin but continuous Maury Formation of early Late Devonian and early Mississippian age. Several hundred feet of chert and cherty limestone of the Fort Payne Formation overly the Maury Formation throughout central Tennessee. Younger Mississippian and Pennsylvanian sediments are present in the Cumberland Plateau area to the east. The youngest deposits are the terrace gravels, flood plain, colluvial and alluvial deposits along the hillsides and valley floors.

Regional Structure

The Nashville Dome is the dominant structural feature in central Tennessee and occurs as a very broad, flat, elliptical dome trending northeast in north central Tennessee and swinging gently to the west in south central part of the state. The crest of the dome is located in south central Rutherford County and in northwestern Bedford County.

From this location the axis plunges about ten feet per mile to the northeast and can be traced through Wilson and Smith Counties and the extreme western parts of Jackson and Clay Counties (fig.11, 12). The southwestern part of the dome is discussed by Wilson (1949, p. 326).

The distribution of several lower Paleozoic formations has been affected by repeated uplifts of the dome according to Wilson (1935, 1949, p. 328, 330, 1962). Conant and Swanson (1961, p. 9) also note that the uplifts of the dome "more recently have warped the erosion surfaces, notably the remnants of the Highland Rim surface. The pre-Chattanooga paleogeologic map [in Wilson, 1949; Conant and Swanson, 1961] shows the effects of the earlier uplifts."

Throughout most of central Tennessee the strata dip gently away from the crest of the Nashville Dome at an average rate of 10 to 20 feet per mile. Superimposed on this gentle regional dip are many small folds, such as plunging anticlines and synclines, domes and basins. Local dips on the flanks of these minor structures rarely exceed five degrees and more commonly average two to three degrees. Broad, flat plunging anticlines and synclines that cover many square miles are also common along the flanks of the Nashville Dome, but surface and subsurface mapping in this part of the state is not yet sufficiently complete to determine the exact position and shape of these folds (fig.11, 12). On the northeastern side of the dome in the Flynn Creek area several broad, flat anticlines and synclines plunge gently to the east and northeast with dips and plunges comparable to the shallow regional dip.

A prominent joint set trends northeast on the northeast flank of the Nashville Dome and is parallel to the axis of the Dome in north central Tennessee. The direction of a second, more poorly developed regional joint set trends approximately northwest.

Faults and fault zones are rare in central Tennessee, but have been reported in a few areas, mainly on the eastern flanks of the Nashville Dome (Jewell, 1939, p. 16-18). The few fault zones described usually range from a few feet up to twenty feet in width and trend northeast. The zones cannot be traced for more than a few tens of feet. Displacements on the faults appear to be mainly horizontal. The fault zones are often accompanied by well-polished walls and rubble breccia or badly cracked zones up to twenty feet across; the breccia is rarely greater than five feet wide (Jewell, 1939, p. 17).

The northeast-trending faults are locally mineralized with calcite, barite, fluorite, galena and sphalerite (fig.13). Jewell (1939, p. 17) suggests that the northeast faults were formed and mineralized before the development of the northwest faults, and that faulting and mineralization are related to the formation of the Nashville Dome. Jewell (1939, p. 17-18) also states that most mineralized veins in central Tennessee occur in association with the northeast fault zones. The trend of the larger veins is N 40° E to N 45° E but varies from N-S to N 70° E. Most veins are vertical with some mineralized zones up to three miles long. Prospecting has proved mineralization extends at least 200 feet below the present ground surface in some of the veins.

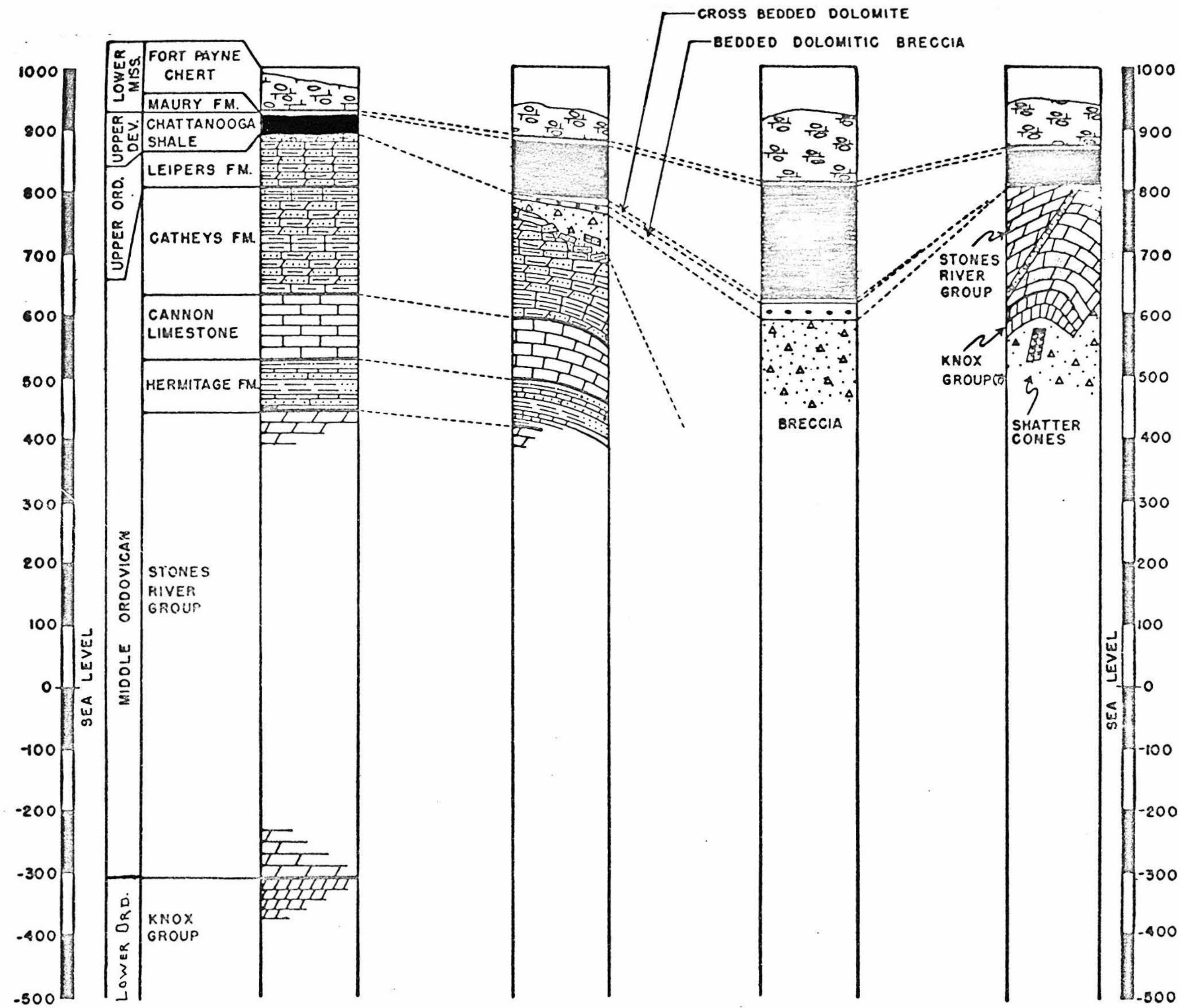


Figure 10.--Generalized columnar sections from the Western Rim to the Central Uplift of the Flynn Creek Crater, Tennessee.

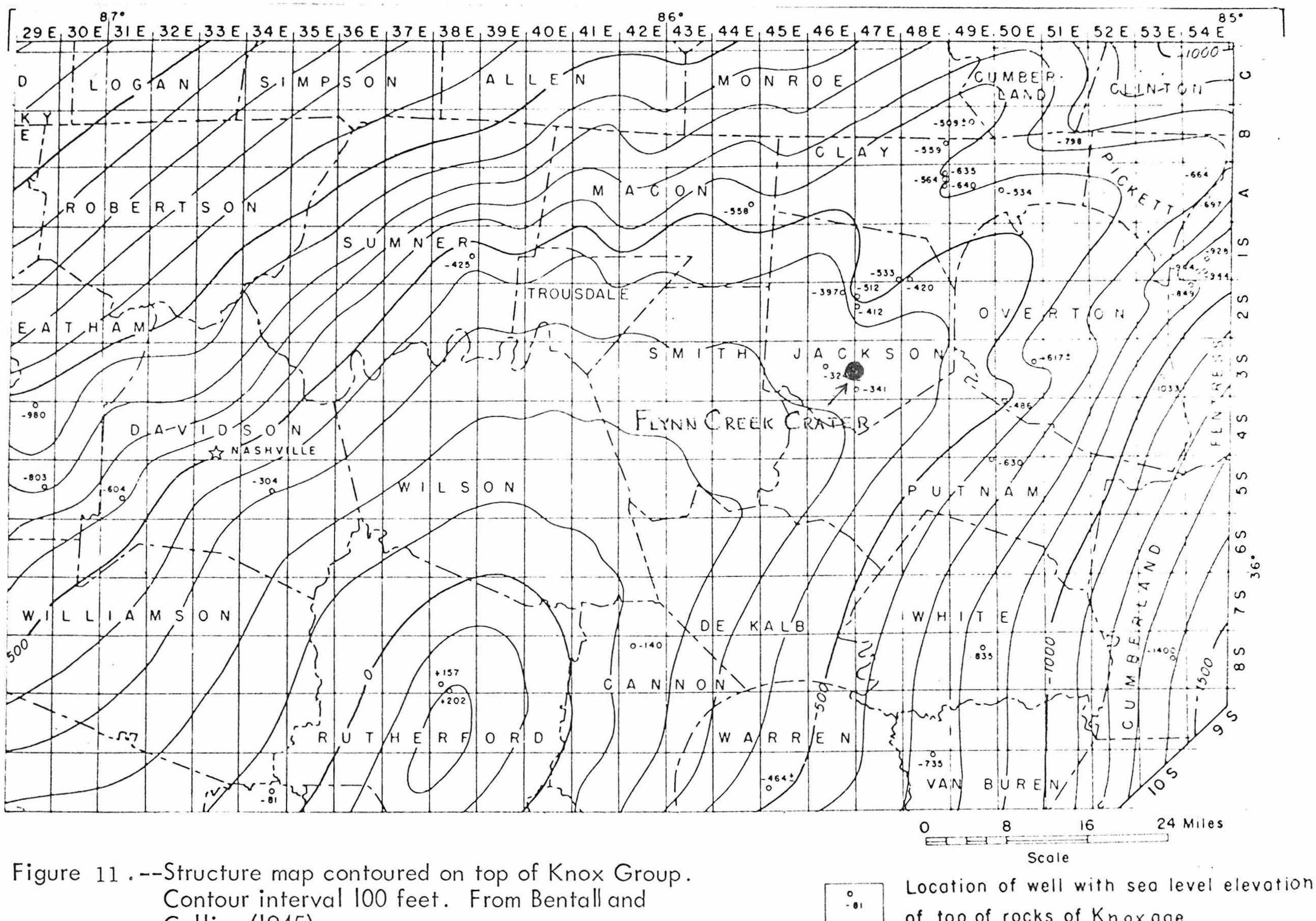


Figure 11.--Structure map contoured on top of Knox Group. Contour interval 100 feet. From Bentall and Collins (1945).

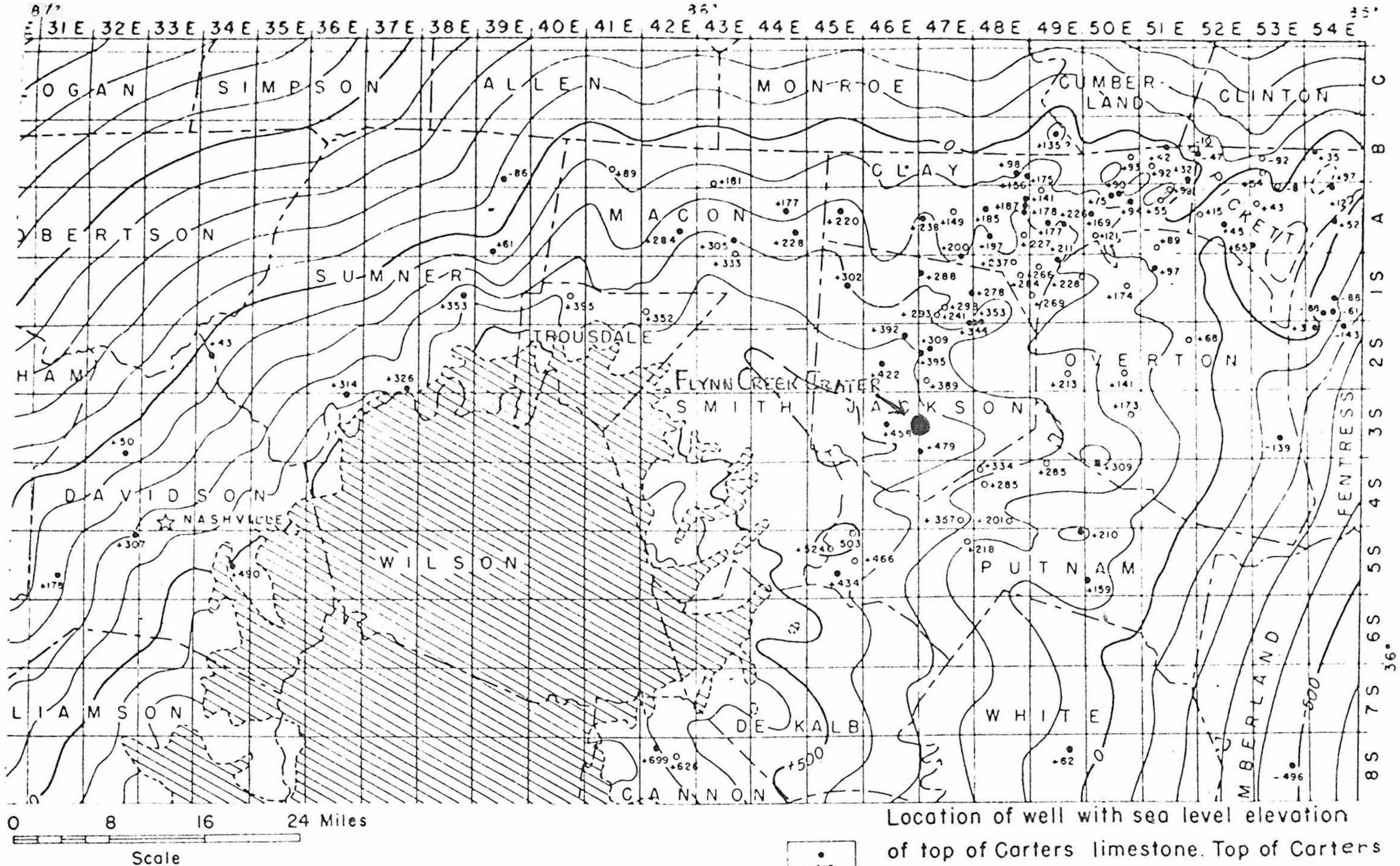


Figure 12. --Structure Map contoured on top of Carters Limestone. Contour interval 100 feet. From Bentall and Collins (1945).

Location of well with sea level elevation of top of Carters limestone. Top of Carters stone determined from sample study.

Top of Carters limestone determined from log.

Area in which Carters limestone is exposed

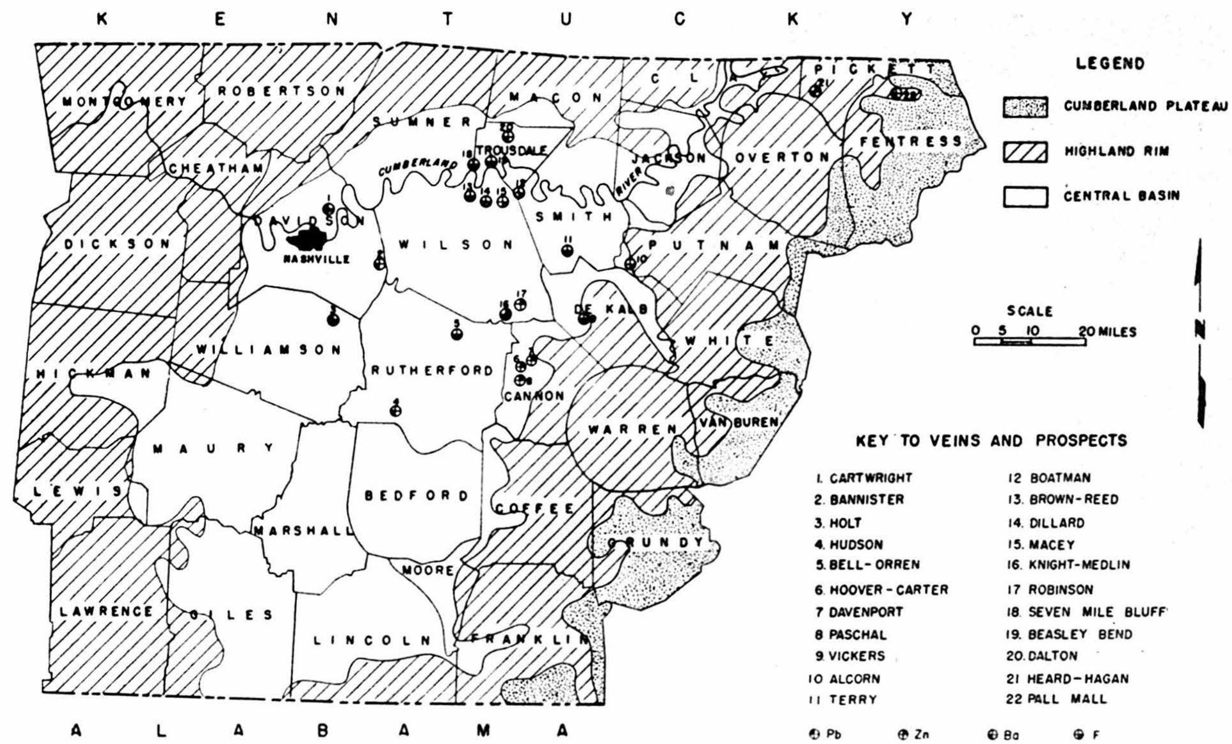


Figure 13 .--Location of known veins and prospects in central Tennessee. Red dot is Flynn Creek Crater. From Jewell (1947, p. 4).

STRATIGRAPHY OF THE FLYNN CREEK AREA

Introduction

The oldest rocks exposed in the Flynn Creek area are dolomites from the upper part of the Knox Group of Lower Ordovician age (fig. 10). The Wells Creek dolomite disconformably overlies the Knox strata and in turn is conformably overlain by the Stones River Group of limestone and dolomite. The Wells Creek and Stones River strata are Lower to Middle Ordovician in age. The Knox, Wells Creek and Stones River rocks occur as a folded, faulted and brecciated sequence only in the central uplift of the Flynn Creek crater.

The Hermitage Formation, Cannon limestone and Catheys Formation form the Nashville Group of Middle Ordovician age in the Flynn Creek area. The Hermitage strata are composed mainly of interbedded silty limestone, thin irregular calcareous shale and dolomitic limestone. The Cannon limestone and lower part of the Catheys Formation consist of dense, fossiliferous limestone. An increase in the silt content occurs in the lower part of the Catheys strata and becomes pronounced in the upper part in silty limestone and shaly limestone beds.

The Leipers Formation of Upper Ordovician age is the only representative of the Maysville Group in the Flynn Creek area. The lower part of the Leipers strata is very similar to the upper part of the Catheys beds and is composed of silty limestone with variable amounts of dolomite. The upper part of the Leipers Formation consists of a sequence of thick-bedded dolomite.

Rocks of the Hermitage Formation occur only in the faulted southern rim of the crater and in breccia within the crater. The Cannon, Catheys and Leipers strata are exposed along the valley walls throughout the Flynn Creek area, in the deformed rim strata surrounding the crater and in the breccias within the crater.

Thin-bedded breccia and dolomite of Upper Devonian age unconformably overlie the lower parts of the crater walls and the breccia of the crater floor. The crater is partly filled by the regionally extensive Chattanooga Shale of Upper Devonian age. The thin shale of the Maury Formation of Upper Devonian-Lower Mississippian age and Fort Payne Formation of Lower Mississippian age conformably overlie the Chattanooga Shale. The Fort Payne strata are mainly chert and cherty limestones. The Chattanooga Shale and Maury Formation lie in a thin zone about 30 feet thick along the upper parts of all the valley walls. The resistant Fort Payne rocks form the upper parts of ridges throughout the area.

Cherty soils formed from weathering of the Fort Payne Formation cap all the ridges and make up part of the colluvium on the steep hillsides. Lower on the hillsides limestones weathered from the Ordovician strata dominate the colluvium as a mixture of fine and coarse rock fragments associated with organic soil materials. A continuous deposit of alluvium occurs in the major stream valleys, but is present only as discontinuous strips in many of the smaller tributary valleys. Terrace gravels occur as scattered patches along the lower parts of a few hillsides in the main stream valleys.

The basis of the stratigraphic and geologic age assignments of the different formations was not re-examined except where it had a bearing on the Flynn Creek structure. Comprehensive stratigraphic studies by Wilson (1949, 1962) in the Nashville Basin have necessitated several revisions by the author in the stratigraphy in the Flynn Creek structure and surrounding area. The most important of these revisions involves re-definition of the contacts between the Cannon, Catheys and Leipers strata. Identification of a part of the Hermitage Formation and breccia of probable Sequatchie strata has further modified earlier stratigraphic work in the area. A revision has also been made of the strata in the central uplift of the crater to include parts of all of the Stones River Group and part of the Knox Group.

The revisions involving the Hermitage, Cannon, Catheys and Leipers strata have been based mainly on the writer's lithologic comparisons with rocks in the Nashville Basin where complete descriptions exist and where stratigraphic assignments have already been established by Wilson (1949). It has been possible to carry contacts as far as 30 miles on regional reconnaissance traverses from well-described or mapped localities into the Flynn Creek area. The choice of contacts and correlation of the formations with the Nashville Basin strata has been further confirmed by field checking with C. W. Wilson in 1962 and 1963 and R. Barnes in 1964. The occurrence of strata of the Stone River and Knox Groups in the central part of the structure was privately suggested by Wilson (personal communication, 1962). Examination of the equivalent strata in east Tennessee and in well cuttings from three wells south of the crater and review of the descriptions in the literature have provided reasonable lithologic correlations of the Knox and Stones River Groups and Hermitage Formation with the equivalent strata in other parts of Tennessee. The identification of breccia of probable Sequatchie age is based on the writers lithologic correlation with Sequatchie strata in southeast and north central Tennessee and published descriptions.

The detailed study of the stratigraphy has been necessary mainly for mapping and for certain laboratory studies. Since this is primarily a structural problem, the stratigraphy will be described only in sufficient detail to substantiate the aspects which bear directly on the Flynn Creek structure. The bulk of the normal stratigraphy and the petrologic conclusions must of necessity be reported elsewhere.

Cambrian and Ordovician Systems

Upper Cambrian and Lower Ordovician Series

Knox Group

Safford (1869, p. 204) originally proposed the names Knox dolomite, Knox shale (now the Conasauga Group) and Knox sandstone (now the Rome Formation) for exposures in east Tennessee along Second Creek in the city of Knoxville. For the three divisions he suggested, "...the Knoxville, or the Knox Group." In Tennessee the most extensive exposures of the Knox Group occur in the Sequatchie Valley and the Valley and Ridge province in the eastern part of the state. The only exposures of Knox strata in central Tennessee are found in two of the "cryptoexplosion" structures, the Wells Creek structure and the Flynn Creek structure. In both areas the Knox strata are restricted to the center of the structure and consist of faulted, folded, and highly brecciated units.

Rogers (in Bridge and Rodgers, 1956, p. 21-24) has summarized the history of the stratigraphic terminology which has led to the present usage of the Knox Group and has described the different subdivisions in detail. Swingle (1954, 1959) has also published recent descriptions. The present classification in order of ascending stratigraphy is: the Copper Ridge dolomite of Upper Cambrian age, and the Chepultepec dolomite, the Longview dolomite, the Kingsport Formation, and the Mascot dolomite, all of Lower Ordovician age (Bridge and Rodgers, 1956). Swingle lists thicknesses in the Cleveland area in the Valley and Ridge province in southeastern Tennessee (1959) and in northeastern Tennessee in the same province (1954) as follows:

Name	Southeast Tennessee	Northeast Tennessee
Mascot dolomite	about 500 feet	between 900 and 1000 feet
Kingsport Formation	about 225 feet	between 600 and 700 feet
Longview dolomite	about 300 feet	about 200 feet
Chepultepec dolomite	about 700 feet	between 200 and 400 feet
Copper Ridge dolomite	about 1000 feet	between 400 and 600 feet

Unfortunately, subsurface studies in central Tennessee are insufficient to define the Knox subdivisions in well cores or cuttings, mainly because drilling has not been carried deeper than the upper 2000 feet and also because of the current lack of subsurface petrographic studies. For these reasons it is common in subsurface studies to refer to the strata below the Wells Creek dolomite only as upper Knox Group, although preliminary lithologic correlations strongly suggest that it is equivalent to the strata exposed in east Tennessee. This comparison will be discussed in the section on breccias.

The Knox strata are composed mainly of dolomite with some interbedded limestone. Large, coarse chert masses are common in the upper few tens of feet of the Knox beds. The rocks are usually very fine to fine-grained, but some beds are coarse-grained. In exposed sections the color ranges from light tan and gray to dark brownish-gray. Local silty zones are present, and widespread sandy dolomites and sandstones are present in the lower part of the Knox strata. The thickness in the Flynn Creek area is probably about 3000 feet.

In the Flynn Creek area the Knox Group is exposed only in the central uplift of the crater as a steeply dipping, folded, faulted and locally brecciated sequence of rocks. The part of the uplift that is faulted and folded is considered megabreccia in that the rocks have been detached and moved several hundred feet. For this reason the outcrops of the Knox Group at Flynn Creek are described in the section on the breccia.

Ordovician System

Lower and Middle Ordovician Series

Stones River Group and Wells Creek Dolomite

The first complete classification using the name Stones River Group was given by Safford in 1851 (p. 352-361) for exposures along the Stones River in central Tennessee. Since that time numerous changes have been proposed by many workers in their attempts to correlate rocks of Ordovician age over long distances, mainly with the Ordovician stratigraphy in the New York area. Wilson (1949, p. 1-5, 23-75) has summarized the diverse history of the Stones River classification and given the stratigraphic reasons for the following nomenclature of the Stones River Group (in descending order):

Carters Limestone
Lebanon Limestone
Ridley Limestone
Pierce Limestone
Murfreesboro Limestone.

Inasmuch as these formations are now widely accepted as mappable units in the Nashville Basin and surrounding area, they are also used for the stratigraphic divisions mapped in the Flynn Creek area.

The most extensive exposures of the Stones River Group occur in the inner Nashville Basin. The only other exposures of importance of this group in central Tennessee, including the Wells Creek dolomite, are found in the Wells Creek Basin and the Flynn Creek structure.

The Wells Creek dolomite is also described in this section mainly because its distribution is the same as the Stones River Group, and because it immediately underlies the Murfreesboro limestone. Lusk (1927, p. 908) first placed it on a columnar section with a Lower Ordovician age and noted that it is exposed only in the uplifted center of the Wells Creek Basin. Bucher (1936), in describing the same part of the Wells Creek Basin, gave this strata no age assignment other than Ordovician. Wilson (1949, p. 2) first listed the currently used name of Wells Creek dolomite as the lowest unit of the Stone River Group, presumably only in the Wells Creek Basin, and again in 1952 made reference to exposures in the center of the Wells Creek strata in the Stones River Group in his detailed stratigraphic description for surface exposures in central Tennessee. For descriptive purposes the Wells Creek dolomite is informally included in the Stones River Group in this study.

The contact between the Knox Group and overlying strata in east Tennessee has been shown to be a major unconformity (Laurence, 1966; Rodgers, 1953; Swingle, 1959; Oder, 1954). Strata overlying the Knox Group in the Valley and Ridge province have been placed in the Middle Ordovician Series and at the present time this assignment is not in debate. Unfortunately little successful correlation work has been done on the Stones River Group in central Tennessee, leaving the lower boundary in this part of the state in doubt as to its Lower or Middle Ordovician age. Many workers in Tennessee have assumed that the top of the Knox Group is the Lower-Middle Ordovician boundary, but until regional stratigraphic and paleontologic studies are available, the exact age of this erosional period must remain in question.

The Stones River Group in the Nashville Basin is predominately dark-gray to light-gray, very fine- to medium-grained, thin- to thick-bedded limestone with variable amounts of interbedded dolomite. Some zones are fossiliferous and often fucoidal, while other scattered horizons contain persistant fine chert. Thin, gray calcarious shales are occasionally interbedded with the limestone and dolomites (Wilson, 1949, p. 24, 54). A minor unconformity occurs between the Lebanon and Carters limestone, but the other contacts between the formations within the Stones River Group are conformable. Descriptions of the Stones River Group in the Sequatchie Valley in East Tennessee by Milici (1963, p. 11-17) are essentially the same as given above for central Tennessee. Unfortunately, Stones River strata examined in studies of well cuttings by Collins and Bentall (1945) and the author are not easily correlated directly with each of the formational contacts exposed at the surface. This is primarily because the surface exposures exhibit different erosional and weathering characteristics which do not occur in the subsurface, and the formational nomenclature is based on surface studies. The writer's studies on well cuttings used chert, bentonite, pellet, and other lithologic horizons to correlate the three test wells south of the Flynn Creek structure. One of the results of this work was an accurate determination of the thickness of the Stones River Group, which is 820 $\pm$ 5 feet including the Wells Creek dolomite.

In the Flynn Creek area the Stones River Group is exposed only in the central uplift of the crater as a steeply dipping, folded, faulted and locally brecciated sequence of rocks. The part of the central uplift that is faulted and folded is considered megabreccia in that the strata have been detached and moved several hundred feet from the original position. For this reason the outcrops of the Stones River Group at Flynn Creek are described in the section on the breccia.

Middle Ordovician Series

Nashville Group

Hermitage Formation

The Hermitage Formation was named by Hayes and Ulrich (1903, p. 2) for exposures near Hermitage Station, Davidson County, Tennessee, and consists of limestone, shale, and shaly limestone. A description of the different facies and their extent in Tennessee has been given by Wilson (1949, p. 81-107; 1962, p. 483-487). The distribution of the Hermitage Formation in Central Tennessee is similar to that of the Stones River Group. Until the current work on the Flynn Creek structure, exposures of Hermitage rocks were not reported east of Granville along the Cumberland River. This location is approximately eight miles west of the Flynn Creek area. However, Hermitage strata are now recognized by the writer in a major fault block in the southeastern part of the Flynn Creek area (Plate 1). The Hermitage strata are considered as Middle Ordovician in age (Wilson, 1949, 1962).

Only four of the facies described by Wilson (1949, p. 81-107; 1962, p. 483-487) are recognized in the Carthage area which is about 15 miles west of the Flynn Creek structure. In descending order, using Wilson's terminology, these facies are:

	Average Thickness
silty nodular limestone member	about 15 feet
blue clay-shale member	about 10 feet
granular phosphatic member	about 6 feet
laminated argillaceous limestone member	about 48 feet
total thickness	about 79 feet

A thin bentonite bed 1 to 4 feet thick is present about five feet above the base of the formation. Outcrops of the upper 10 to 20 feet of the Hermitage strata are also present along the Cumberland River eight miles west of Flynn Creek, but only the silty nodular limestone is exposed.

The exposures of the Hermitage strata in the Flynn Creek area are restricted to a fault block on the southeastern rim of the crater and several very large breccia blocks within the crater. Good exposures of the fault block are present on the east side of Rush Fork approximately 1500 feet north of the abandoned Chaffin No. 1 test well. The Hermitage units can be traced east and up hill in Rush Fork Valley for several hundred feet but are then lost under thick colluvium. The continuation of the same strata is found in the first valley northeast of Rush Fork but is not present further north. Normally the top of the Hermitage Formation is about 110 feet below the valley floor of Rush Fork, but in this part of the valley the Hermitage strata have been thrust upward with dips ranging from 20° to 50° N.

The rocks on the east side of Rush Fork consist of light-brownish to medium-gray, fine to coarse-grained, thin to medium-bedded, often nodular limestones and dolomitic limestones. The beds are fossiliferous and generally slightly porous. Thin calcareous shaly limestone and shaly partings are also common. Examination of well cuttings suggest a subsurface thickness of 75 ± 5 feet, but only the upper 20 to 40 feet are exposed in the fault block.

Cannon Limestone

The name Cannon limestone was first used in central Tennessee by Ulrich (1911, p. 27) without definition. The Cannon strata have been described by Wilson (1949, p. 107-136; 1962, p. 487-490) as the eastern facies of the Bigby-Cannon limestone, and the name is used in this way in this study. The Cannon limestone is exposed throughout the eastern part of the Nashville Basin and reaches thickness of 100 feet in the subsurface in eastern part of central Tennessee. The typical Cannon facies is a dark-gray, fine- to medium-grained, medium- to thick-bedded, moderately fossiliferous limestone. Occassionally thin, local variations of the Dove-colored facies of light-gray, very fine-grained, conchoidal fracturing, thin- to medium-bedded limestone are present. The Dove facies is common near Nashville in the central part of the basin. The Cannon limestone is considered as Middle Ordovician in age (Wilson, 1949, 1962).

In the Flynn Creek area the Cannon limestone is exposed in the western half of the map area along the bases of all the valleys. It had originally been mapped by Wilson and Born (1936) in the eastern part of the Flynn Creek valley and along the southern part of Rush Fork. The Cannon limestone in these two areas is only present in the deformed rim strata immediately adjacent to the crater (Plate 1). In the eastern part of the Flynn Creek valley the Cannon strata are restricted to a limited number of outcrops along the southern side of the stream and in the deformed rim of the crater. In the Rush Fork area the Cannon limestone overlies the Hermitage Formation as part of the upthrust fault block and dips 20° to 65° N.

The characteristic lithology of the Cannon strata in the Flynn Creek area is medium-light to dark-gray, cryptocrystalline to medium-grained, sparcely to highly fossiliferous, thin- to thick-bedded limestone. Thin, wavy, calcareous shale partings and scattered gray to black chert nodules are common in the upper third of the formation. Freshly broken rock yields a bituminous odor common throughout the

Cannon strata. The total thickness from well cuttings from two test wells south of the crater is about 90 $\pm$ 5 feet. Only the upper one-third of the Cannon limestone is exposed in the western part of the area, but the lower two-thirds is exposed in the fault block on Rush Fork.

Solution channels, locally forming inter-connected caverns, are common along the larger stream valleys. The channels are found in the base of the valley walls and at or within a few feet of the present valley floors. The openings locally allow large scale slumps as seen along western Flynn Creek Valley. The chaotic nature of these outcrops had led some observers to suggest they were part of the deformed rim, but undisturbed units can be traced immediately above these outcrops. Also thick dripstone deposits can be found on the recent fresh road cut exposures. The lack of deformation on either side of these outcrops and the dripstone is satisfactory evidence to demonstrate their cave-slump origin.

Catheys Formation

The Catheys Formation was named by Hayes and Ulrich (1903, p. 2) for exposures along Cathey's Creek in southwest central Tennessee. The distribution of this formation in central Tennessee is the same as that of the underlying conformable Bigby-Cannon limestone. The major changes between these two formations are the introduction of several new lithologic types, an increase in the amount of silt, particularly in the upper half of the Catheys strata and a different faunal assemblage (see Wilson, 1949, p. 136-157 for fossil descriptions) In 1962 Wilson (p. 489-491) summarized the different rock types or facies of the Catheys formation in the Nashville Basin. In the eastern part of the basin Wilson (1962) simply referred to the "normal eastern Cathey's limestone" of shaly facies, laminated siltstone facies and nodular facies. The strata are described as gray, thin to medium-bedded, very fine to medium-grained, and nodular to uniformly bedded with shale partings. The Catheys Formation is considered as Middle Ordovician in age (Wilson, 1949, 1962).

In the Flynn Creek area the Catheys Formation occupies the lower and middle parts of the hillsides and is present throughout the map area. The formation is divided into three units for structural mapping and consists of the following units in descending order:

Upper Catheys Unit, limestone: medium light to medium gray; increase in light brownish gray, grayish orange, and olive gray in upper half; cryptocrystalline to coarse grained; sparsely to highly fossiliferous; thin to thick bedded; increasing silt content and thin irregular argillaceous silty zones and partings in upper half. Base includes 3 foot argillaceous, silty, highly fossiliferous, persistent ledge-forming bed with scattered siliceous nodules at the top. Thickness averages 100 feet.

Middle Catheys Unit, limestone: upper half is light to medium gray with slight increase in argillaceous and silt content over lower half. Lower half is medium light to dark gray; cryptocrystalline to medium grained; sparsely to highly fossiliferous; thin to thick bedded; thin calcareous shale in middle of unit; occassional scattered brown to gray, small siliceous nodules throughout unit. Base includes 3 foot argillaceous, silty, highly fossiliferous, persistent ledge-forming bed with siliceous nodules at top. Thickness averages 70 feet.

Lower Catheys Unit, limestone: medium light to dark gray; cryptocrystalline to medium grained; fossiliferous; scattered elongated gray chert nodules; thin to thick bedded. Thickness averages 10 to 15 feet.

The choice of these units was based mainly on their persistence throughout the area and their nearly constant thicknesses. These two factors served to provide the accuracy necessary for the structural mapping. The writer was also able to recognize the equivalents of these units at least as far as 10 miles from the Flynn Creek area. The massive ledge-forming units at the base of the middle and upper Catheys units appear as continuous beds over many hundreds of square miles of the northeastern inner Nashville Basin-dissected Highland Rim. The writer's experience suggests, however, that correlation of facies within the Catheys formation cannot be accomplished without very close-spaced columnar sections, or, more probably continuous mapping from one area to another.

Figure 14.--Typical outcrops of the lower ledge unit of the Catheys Formation. Approximately 1 mile west of western rim of Flynn Creek Crater on the Flynn Creek Road.

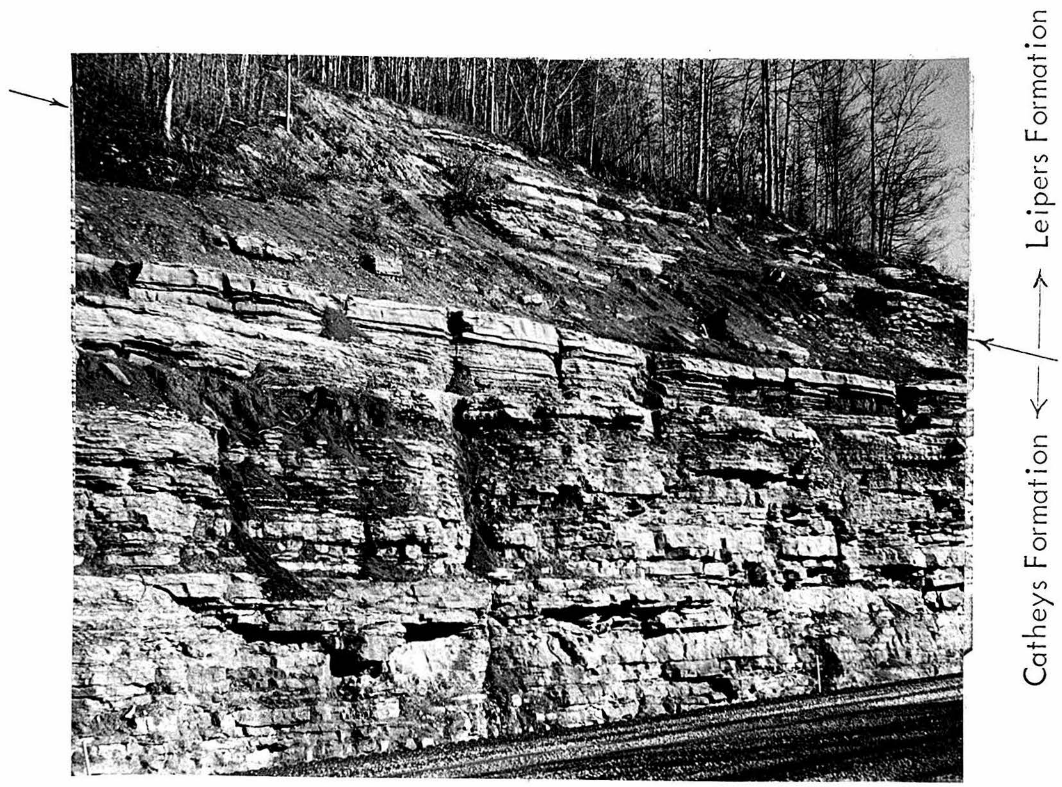


Figure 15.--Upper unit of the Catheys Formation in a recent road cut 2 miles south of Gainesboro, Tennessee, and 3 miles southeast of Flynn Creek Crater. Upper quarter of outcrop is lower Leipers Formation. Exposure is about 60 feet high. Note massive beds in middle of photograph which are typical of upper Catheys-lower Leipers strata.

Upper Ordovician Series

Maysville Group

Leipers Formation

Safford, during his work in the late 1800's, included the Leipers strata in his Nashville Group but did not actually use the name Leipers. In 1903 Hayes and Ulrich published the Columbia Folio and named the Leipers Formation from exposures along Leipers Creek, Maury County, Tennessee. Wilson (1949, p. 179-201; 1962, p. 491-493) has described the different facies and their faunal groups for the Leipers strata in central Tennessee. Wilson's descriptions, however, refer to the strata in the eastern part of Nashville Basin and Highland Rim only as normal eastern Leipers Formation consisting of a variety of argillaceous limestones. The Leipers strata are considered Maysville in age (Wilson, 1949, 1962).

Wilson (1962, p. 490-491) has described a regional unconformity between the Catheys and Leipers Formations based upon marked faunal differences between the two formations and subtle truncation of the Catheys strata in the central parts of the Nashville Basin. In south central Tennessee the Inman Formation of Eden age is present between the Catheys and Leipers strata. The Inman strata are not present in the northwestern part of the Basin nor is any obvious truncation of the Catheys rocks present. Faunal changes do occur but have not been studied in sufficient detail to solve this problem. Until the current mapping no direct field evidence had been presented to demonstrate a period of erosion between the Catheys and Leipers Formation except the absence of Inman rocks. It is common practice for the mapping done by the Tennessee Division of Geology to include both the Leipers and Catheys rocks together because of the difficulty of identifying the contact on weathered exposures.

A recent road cut was made along Doe Creek-Haile Hollow Road about 3.5 miles south of Gainesboro and 2 miles northeast of the Flynn Creek structure. Extensive fresh exposures exhibit an irregular low-relief contact which is parallel to the bedding of the overlying and underlying strata and is at the approximate level of the Catheys-Leipers contact. The relief of the contact is about 2 feet. The contact is more appropriately called a contact zone where it locally contains abundant thin shaly limestone and thin, irregular shale lenses. When this contact is traced into weathered outcrops, it is nearly indistinguishable as an erosion surface. The fanual breaks described by Wilson (1949, p. 179-201) in the central Nashville Basin are also reasonably consistent with this choice of a contact between Catheys and Leipers strata. A careful study of this contact and adjacent rocks would probably help establish the actual erosional break between these formations.

In the Flynn Creek area the Leipers Formation occupies the middle parts of the hillsides and is present throughout the area. For structural mapping the writer divided the formation into three units, of which only the lower two units are present throughout all of the area. These units are described in descending order in the following:

Upper Leipers Platystrophia Ponderosa Unit, dolomite: grayish orange to brownish gray; fine to coarse grained, irregular argillaceous and silty zones, large siliceous brachiopod fragments, large Platystrophia ponderosa. Occurs in faulted southeast rim of crater.

Upper Leipers Unit, argillaceous dolomite to dolomitic claystone: medium gray to grayish orange; very fine to fine grained; silty, moderately to highly argillaceous; locally non- to irregular to blocky bedded; locally thin to very thick bedded; locally thin, shaly dolomitic beds. Lower blocky to non-bedded part of this unit may be equivalent to the "Centerville Mudstone." Thickness averages 35 feet.

Lower Leipers Unit, limestone: medium light to medium dark gray; increase of light brownish gray to grayish orange to olive gray in upper half, fine to coarse grained; argillaceous and silty content increases toward top; local, calcareous shaly horizons; sparsely phosphatic in some beds; moderately to highly fossiliferous; thin to thick bedded; irregular to poorly bedded, locally discontinuous lateral zones in upper one third; cross bedded in some horizons, locally dolomitic in upper half. Thickness, 70-80 feet.

The choice of these units was based on the mappable differences in lithology between the lower and upper Leipers units, on their presence throughout the area and on their nearly constant thicknesses. The upper Leipers Platystrophia Ponderosa unit is restricted to the southern faulted rim and possibly a few exposures in the extreme southern part of the map area. The writer was able to trace the lower and upper Leipers units in most outcrops in the northeastern inner Nashville Basin-dissected Highland Rim, except that the upper Leipers was quite variable in thickness. Subtle facies changes appear present in the lower Leipers unit, and close-spaced columnar sections or continuous mapping will be necessary to describe its regional lithology.

Richmond Group

Sequatchie Formation

Wilson (1949, p. 201-239) has suggested the following classification of Richmond age strata in central Tennessee:

Nashville Basin		Sequatchie Valley
West side of basin	North side of basin	
Mannie shale Fernvale limestone Western tongue of Sequatchie Fm. Arnheim Formation	Sequatchie Fm.	Sequatchie Fm.

At the present time only the Sequatchie Formation of the Richmond group has been recognized along the northeastern part of the Nashville Basin at a distance of about 14 miles northwest of the Flynn Creek structure. Thicknesses in southern Clay County range between 5 and 15 feet (Born and Burwell, 1939, p. 47). Born and Lockwood (1945) also report about 40 feet of Sequatchie strata in test wells 36 miles east of the Flynn Creek area.

The Sequatchie Formation consists of greenish-gray to green massive calcareous and dolomitic mudstone and "sugary" dolomitic argillaceous limestones that occassionally have fine-grained sand, shale and silty limestone (Wilson, 1949, p. 219-221; Born and Burwell, 1939, p. 46-47). The limestone may be locally bluish gray in color. Both the mudstone and limestone are characteristically laminated, although the limestone in places is irregularly bedded. The Sequatchie Formation, particularly the green laminated dolomite, is distinctive in outcrop and not likely to be confused with other formations in the Silurian and Devonian strata to the west along the northern edge of the Nashville Basin.

Until the present work on the Flynn Creek structure, Richmond strata had not been recognized in the area. However, breccia fragments have been found in the southeastern part of the Flynn Creek structure which are very similar in lithology to the green laminated dolomite of the Sequatchie strata 15 miles north of Flynn Creek in southwestern Clay County. The fragments which occur south of the crater in the ejected breccia and in the southern-most fault zone (Plate 1) consist of pale-green to grayish-green, fine-grained and laminated to medium-grained and non-laminated (usually light tan) silty, argillaceous, shaly- to medium-bedded, limy dolomite to dolomite. No fossils were observed in either the fragments located in greatest concentration in the southern-most fault zone, or in the few fragments located along the base of the ejected breccia on the southern-most fault block (fig.16). Breccia of the upper Leipers Platystrophia Ponderosa unit is mixed with the green laminated dolomite breccia high in the fault zone, while the lower part of the fault zone has mainly green laminated dolomite. The fragments occur as blocks up to several feet in size, often tightly folded. Smaller fragments are present in the rest of the ejected breccia immediately north of the fault zone but are restricted mainly to the base of the breccia. The lithologic similarity of these green fragments to the outcrops of Sequatchie formation to the north in Clay County is so striking that there seems little doubt of their correlation. Also there are no other stratigraphic units in the Silurian or Devonian strata of northern Tennessee that bear as close a resemblance to the breccia at Flynn Creek as does the Sequatchie strata. Microfossil studies are necessary before the age is completely substantiated.

Figure 16 .--Typical outcrop of brecciated Sequatchie claystone in fault zone in southern rim.

Devonian System

Middle to Upper Devonian Series

Non-Bedded Breccias

Introduction

The non-bedded breccias within the crater consist of a chaotic mixture of fragments of Knox, Stones River, Hermitage, Cannon, Catheys, and Leipers strata ranging in size from very fine microbreccia to blocks several hundreds of feet in length. Based on matrix lithology, two main types of non-bedded breccia are recognized, but they have such an irregular gradational relationship that no contact was mapped. The two types consist of dolomitic breccia with a limy dolomite matrix overlying breccia with a predominately limestone matrix. Of the two types, the underlying breccia with the limestone matrix occurs in much greater volume than does the overlying dolomitic breccia. A variation of these breccias occurs in the central uplift where breccias of only Knox and Stones River strata are present.

Dolomitic Breccia

The dolomitic breccia is not present everywhere in the crater and makes up only a small percentage of the non-bedded breccias. It mainly occurs in areas where the overlying bedded breccias are thickest, suggesting that the dolomitic breccias may be the basal non-bedded parts of the sequence. A typical outcrop consists of yellowish to dark-gray, commonly non-bedded, unsorted, angular microbreccia to blocks several feet in length. The matrix is a yellowish-gray to yellowish-brown, argillaceous limy dolomite very similar to the matrix in the overlying bedded dolomitic breccias. Breccia fragments consist mainly of Cannon, Catheys and Leipers strata with sparse small Hermitage fragments. Knox and Stones River Group fragments form a major part of this unit along the northern flank of the central uplift but are rarely found more than a few hundred feet from this area. The upper contact is gradational in areas where the overlying unit is a poorly bedded breccia, but is usually sharp in areas where the overlying unit is well-bedded. The lower contact is nearly always so gradational and irregular that it can only be approximately located in the available exposures. The dolomitic breccia rarely exceeds 50 feet in thickness.

Breccia

The breccia which underlies the dolomitic breccia forms the major proportion of all the breccias exposed in the crater. A typical exposure in the crater consists of medium-light- to dark-gray, unsorted, chaotic, angular, very fine microbreccia to blocks several feet in length. The matrix is a light- to medium-dark-gray, locally argillaceous, dolomitic limestone. Breccia fragments consist mainly of Cannon, Catheys and Leipers strata with occasional Hermitage fragments. The total thickness is unknown except where it overlies the folded rim strata on the crater walls. Some exposures near the western rim reveal a minimum thickness of 250 feet for the breccia.

The most extensive exposures of the breccia occur where Flynn Creek Valley cuts through the eastern and western rims. Other areas of good exposures of the breccia are found where Lacy Branch cuts the northern rim and where Rush Fork cuts the southern rim. Excellent outcrop of breccia are also present in the southern rim in Steam Mill Hollow and in the second stream valley east of Steam Mill Hollow.

It is common for the largest breccia blocks, up to 300 feet in length, to be restricted to a band less than 1000 feet wide and adjacent to the crater wall. Cannon and Hermitage megabreccias are commonly restricted to this band. A large block of Hermitage strata approximately 120 feet in length and 50 feet wide is present adjacent to the western crater wall. In this part of the rim the block is 60 to 100 feet above its normal stratigraphic position.

Where exposures are reasonably complete, blocks larger than about 10 feet in length have been mapped and referred to as megabreccia elements, usually with the lithology identified. In many cases the unit of the formation from which the megabreccia element was derived is also noted on the map. In other areas the chaotic nature of the large breccia blocks and their extremely irregular contacts made it too difficult to map individual blocks, and it was necessary simply to refer to the area as megabreccia. Lithologies and formational names are still applied. Other exposures which have smaller sized fragments often have concentrations of breccia from a single formation and can be mapped as such. It is also common to have mixtures of formations in the breccia such that the outcrop could only be designated as to the lithology without specifying the formation. In some areas breccia could be correlated with specific horizons outside the crater.

Breccias with blocks large enough to contain several beds usually can be identified in the field. Smaller fragments which might be confused with a number of different source beds were identified by petrographic and laboratory studies. Although not all of the breccia outcrops were studied in such detail to identify all the fragments, the writer at no place observed other than Knox, Stones River, Hermitage, Cannon Catheys and Leipers fragments within the crater.

Central Uplift Breccia

In the center of the crater, Stones River and Knox strata occur 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. The local descriptions of these rocks are reported in this section because the central uplift consists entirely of breccia and megabreccia. The faulted and folded part of the central uplift are considered megabreccia in that the strata have been detached and moved several hundred feet from their original positions. In the following description the Knox strata will be discussed first, and the Stones River discussed second.

Breccia and Megabreccia of the Knox Group: The top of the Knox strata, now located in the central uplift of the Flynn Creek structure, normally lies at about 1000 feet below the level of the present valley floors. The best exposures of the strata in the central uplift are along the north side of Flynn Creek Road immediately west of the mouth of Lacy Branch. The eastern 500 feet of the outcrops are very poorly exposed because of colluvium and vegetation. However, the outcrops that are exposed or excavated consist of breccias with fragments ranging in length from a fraction of an inch to nearly 65 feet. Some of the breccia in this area probably belongs in the Stones River group; however, difficulty in identifying some breccia fragments and the presence of obvious Knox types suggest that their description be placed with the Knox Group.

Outcrops of breccia near the eastern end of the exposures are composed of light-gray, thin-bedded to laminated limestone. The laminations consists of yellowish-gray, very fine-grained, argillaceous limestone. The large fragments exhibit many small faults which increase in number in irregular zones until the rock is completely brecciated with all fragments rotated and separated from their original position. The breccia matrix is mainly a yellowish-gray, very fine-grained, argillaceous limestone apparently derived from the argillaceous laminations. The finely laminated limestones often exhibit such intense folding and brecciation that the tops or bottoms of beds are folded over upon themselves. In a few outcrops the laminated limestones exhibit a concentration of fracturing and brecciation with the surrounding beds only moderately disturbed.

Other outcrops in the eastern exposure consist of an extensive megabreccia block of thin- to medium-bedded limestone at least 65 feet in length and dipping 22° to 42° NE with a N 40° W strike. Contacts with the finer breccias are sharp on the west and east sides of this block.

Scattered outcrops west of the megabreccia block have many breccia blocks up to 3 feet in length and consist of intensely fractured and brecciated dolomite. The fractured parts of the breccia blocks have no relative rotation of individual fractured segments (fig.17); however, these parts of the rock usually grade laterally into irregular zones of monolithologic breccia where the fragments are rotated. The enclosing matrix consists of finely pulverized host rock. Fractures in the rock are actually very irregular, branching micro-fault zones when seen in thin section and have a very fine microbreccia fill. On weathered surfaces this fill is removed to depths of several tenths of an inch, enhancing the fractures.

Shatter cones are present in the breccia west of the megabreccia block and occur in three vertically orientated, yellowish-gray, fine-grained dolomite beds. The shatter cones are never observed on weathered surfaces and are seen only when the rock is broken open, although all fresh surfaces do not have cones. Where cones are present, they generally consist of many cones pointing in a common direction and range in length from a few tenths of an inch to at least 3 inches (parallel to the cone axis). Smaller cones occasionally have surface striations which are curved through nearly 90°. Apical angles range between 80° and 100°. 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 cone axes were seen to point in several different directions. Sawed surfaces allow one to trace the larger cone surfaces as fractures or micro-fault zones into the rock, but many of the adjacent and overlapping smaller cones do not show such a trace into the rock. Also many cross-cutting fractures or micro-fault zones are present and identical to those described in the shattered limestone breccia. In thin section the shatter cones exhibit irregular, branching fractures or micro-fault zones with a micro-breccia fill of cryptocrystalline dolomite and large dolomite crystals from the host rock (fig.19).

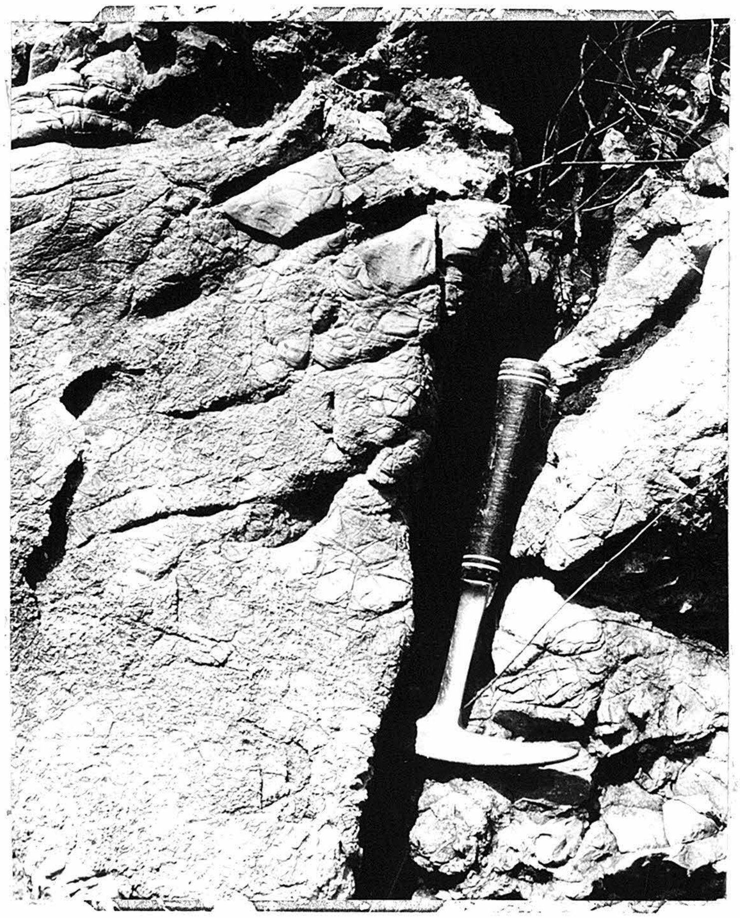
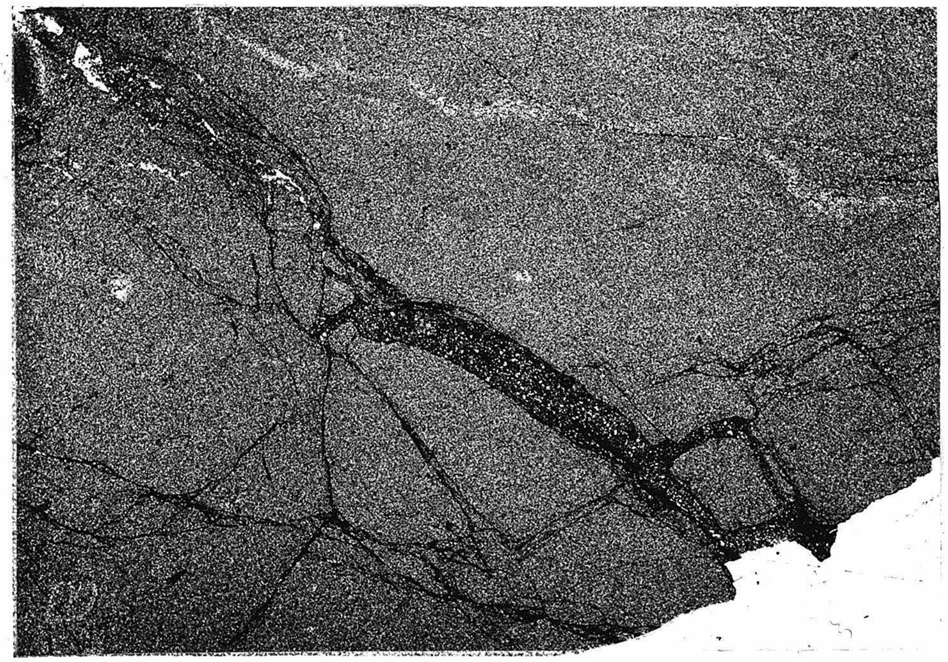


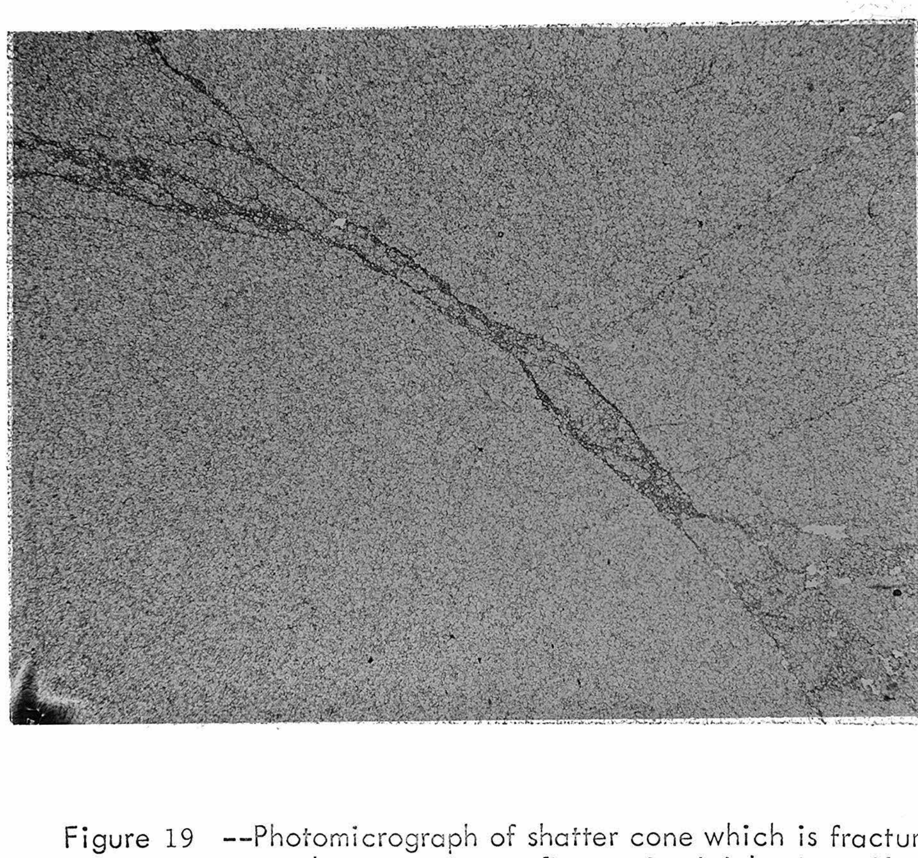
Figure 17 --Shattered Knox strata in central uplift.

Beds containing shatter cones

Figure 18 --Vertical megabreccia beds of Knox strata containing shatter cones in the northeastern part of central uplift.



A



B

Figure 19 --Photomicrograph of shatter cone which is fractured and brecciated very fine grained dolomite. Knox breccia from central uplift. A is cut normal to shatter cone axis and B is cut parallel to axis.

Movement along the breccia zones cannot be determined because no linear markers are present in the rock. The beds containing shatter cones contain very fine-grained detrial quartz that averages about 40 microns in diameter. The quartz is present between 0.05 and 0.3 percent by volume and occurs as clear, angular grains. Several bulk rock samples were treated using 100-gram samples and using Fahey's (1964) method for identifying coesite, but all x-ray examinations produced negative results. The beds containing the shatter cones are surrounded on the sides and top by other limestone and dolomite breccias without shatter cones.

The remainder of outcrops to the west are nearly continuous outcrops exposed by a recent road cut. About 800 feet west of the point where Lacy Branch empties into Flynn Creek, the first continuous, folded, non-brecciated units of Knox strata are present. The beds consist of light-olive-gray to medium-dark-gray, very fine- to fine-grained, thin- to thick-bedded dolomite locally containing irregular gray to white siliceous nodules. The dolomite is composed of 0.05- to 0.1-mm hazy, inclusion-filled crystals forming an anhedral mosaic. Cross-cutting irregular fracture surfaces and micro-breccia zones are filled with cryptocrystalline dolomite, larger clear dolomite and calcite, and some host-rock dolomite crystals. The beds dip up to 65° to the west with a variable northwest strike. The beds form a broad anticline truncated on the east by extensive breccia deposits (Plate 1).

The lithology and texture of the folded and brecciated Knox strata in the central uplift, except for the fractures and micro-breccia zones, are identical to the upper Mascot dolomite of the Knox Group in both the Sequatchie Valley in southeast Tennessee and the western Valley and Ridge province in northeast Tennessee. In both areas the writer was able to recognize similar chert horizons in the upper part of the Mascot strata which are very similar in color and texture to the chert in the upper Knox Group at the Flynn Creek crater. These chert horizons were also recognized in a study of the well cuttings from test wells located south and southwest of the crater. Test wells in other parts of central and east Tennessee also have penetrated strata at similar depths which have the same lithology (including the chert), and presumably are all of the upper Knox Group.

The earliest identification of these rocks as Lowville limestone (now Carters limestone of upper Stones River Group) was made by Wilson and Born (1936), but Wilson (personal communication 1962 and 1963) has told the writer that he now feels these rocks clearly include all of the Stones River and part of the Knox Groups. Other workers, including Swingle, Maher, and Laurence, who have examined these outcrops at Flynn Creek and are intimately familiar with the Knox Group, also are convinced of both the Knox and Stones River correlations. No published accounts have been given except by the writer (1963, 1964, 1965). The similarities in lithology, textures, chert types, and stratigraphic position (subsurface information from local test wells) appear adequate for reasonable preliminary correlation of the Knox Group until micro-fossil studies can be made.

Breccia and Megabreccia of the Stones River Group: The exposures of Stones River strata in the Flynn Creek structure are limited to the central part of the crater, with the best outcrops present along a recent road cut on the north side of Flynn Creek Road and about 900 feet west of the intersection of Lacy Branch and Flynn Creek. The top of the Stones River Group normally lies about 200 feet below the level of the present valley floors, while the base of the strata is normally 1000 feet below the valley floors. In this area the Stones River Group, including the Wells Creek dolomite, occurs in the central uplift as a sequence of steeply dipping, faulted, folded and locally brecciated rocks (fig.20 ; Plate 1). Only about 70 percent of the Stones River Group appears to be present, the remainder apparently omitted because of the faulting. Bedding plane faults may be important in all of these exposures as evidenced by occasional slickensides on bedding surfaces.

A

B

Figure 20 .--Faulted Stones River strata in the central uplift of the Flynn Creek Crater.

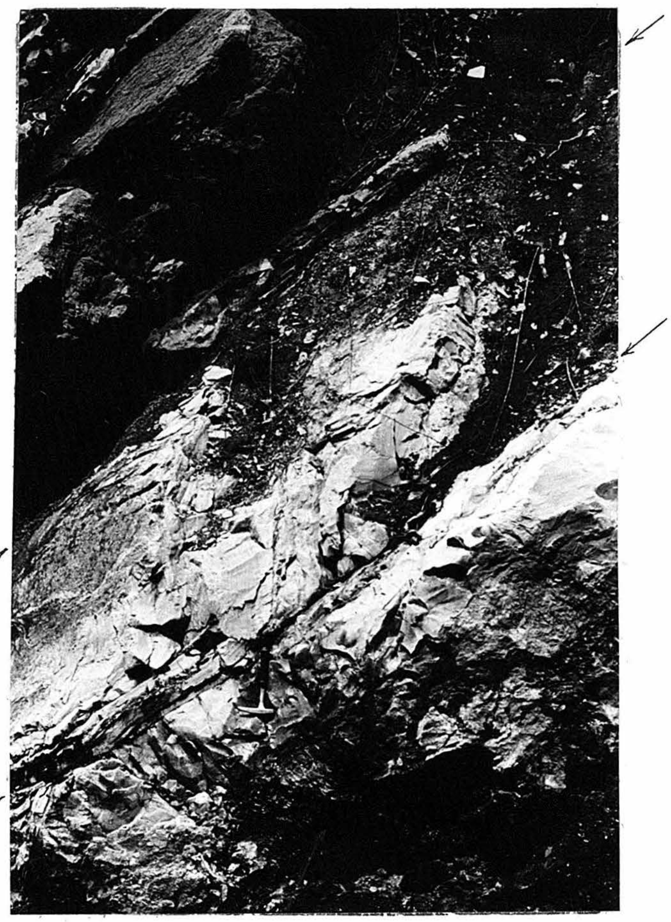


Figure 21 --Stones River, Wells Creek and Knox contact in the central uplift.

In these exposures the Wells Creek dolomite lies with apparent conformity on the Knox strata with a moderately folded contact dipping steeply to the west. The strata consist of light-greenish to yellowish-gray bands of microcrystalline to very fine-grained dolomite. The color bands occur mostly as discontinuous stringers irregularly truncated by a low angle fault, thus preventing an accurate location of the upper contact. Well cuttings give a thickness of about 8 feet for the undisturbed Wells Creek strata. An isopach of the Wells Creek dolomite in central Tennessee shows a thickness of 10 feet in the Flynn Creek area (Smith, 1959).

Wilson (personal communications, 1962) originally suggested the possible presence of Wells Creek dolomite in the central uplift at Flynn Creek. There is no question in the writer's opinion that the exposed lithology of this strata in the Flynn Creek Structure compares only with the thin interval between the Knox Group and basal Murfreesboro limestone. Furthermore, the Wells Creek strata in the type locality of the Wells Creek Basin include units identical in lithology and texture to these rocks in the central uplift in Flynn Creek. Collins and Bentall (1945) also have noted a "basal silty unit" from wells that extends from the western to the eastern part of central Tennessee. This same unit has been examined by the writer in two sets of well cuttings from wells south of the crater, and the rock has the same lithology as the proposed Wells Creek strata in the Flynn Creek crater. The conclusion from these lines of evidence strongly suggests that the strata at Flynn Creek are the equivalent to the Wells Creek dolomite in the Wells Creek Basin and probably represent the same formation.

A similar approach was used in correlating the Stones River Group in the Nashville Basin and in east Tennessee with the strata in the central uplift at Flynn Creek. These strata are well exposed throughout the Nashville Basin and can be traced to within 20 miles west of the Flynn Creek area and present less of a long range correlation problem. Wilson (1949, p. 24-53), Milici (1963), and Born (1939) have described the Stones River Group in the Nashville Basin, Sequatchie Valley, and Clay County (north of Jackson County) respectively. A generalized lithologic description of the group based mainly on the writer's observations at Flynn Creek and on Wilson's extensive studies (1949, p. 24-53) in the Nashville Basin is given in the following:

Carters limestone: light gray to light olive gray; very fine to coarse grained; thin to medium bedded; some beds dolomitic; three bentonite beds in upper part, fossiliferous. Bentonite beds not identified at Flynn Creek.

Lebanon limestone: medium to dark gray, very fine to fine grained to occasional thick bedded units in middle; fossiliferous; some dolomitic beds.

Ridley limestone: medium light to medium bluish gray; very fine to coarse grained; thin to thick bedded; thin discontinuous dark gray shale partings; irregular argillaceous content; some beds dolomitic; fossiliferous.

Pierce limestone: medium light to medium bluish gray; very fine to coarse grained; mainly thin to medium bedded; gray calcareous shale parting and thin lines of shale; some units high in clay and silt; some beds dolomitic; fossiliferous.

Murfreesboro limestone: dark gray to dark bluish gray; very fine to fine grained; medium to mainly thick bedded; low silt and a clay content; some dolomitic beds; fossiliferous.

Examination of these units in the Nashville Basin and in the Sequatchie Valley, studies of well cuttings in the Flynn Creek area, and field checks with Wilson (personal communication, 1962, 1963), Barnes (personal communication, 1963) and Sterns (personal communication, 1964) strongly suggest that all of the formations of the Stones River Group are present in the central part of the Flynn Creek crater. The writer was able to locate representatives of each of the formations in their appropriate stratigraphic sequence, but in most cases faults appear to truncate the strata too pervasively to locate the contacts without further detailed study. There is also the problem that these exposures are relatively fresh, and the Stones River Group can normally be divided only on weathered outcrop. From present field measurements the writer believes that more than 600 to 700 feet of the total 820 $\pm$ 5 feet of Stones River Group plus Wells Creek dolomite are present in the central uplift center of the Flynn Creek crater.

Age of the Breccias

The youngest fragments identified in the non-bedded breccias are from the Sequatchie Formation of Upper Ordovician (Richmond) age. The bedded breccias and bedded dolomite that overlie the non-bedded breccias in the crater have been identified as early Late Devonian in age. Strata of Silurian and Lower and Middle Devonian age are present 25 miles northwest of the Flynn Creek area (Wilson, 1949) , but are absent between the bedded breccia and the underlying non-bedded breccia in the crater. These age relationships and the possibility of non-deposition of Silurian and Lower and Middle Devonian sediments in the present Flynn Creek area suggests a maximum age range for the non-bedded breccia of Upper Ordovician (Richmond) to early Late Devonian.

Wilson (1949, p. 334-347), however, has described stratigraphic evidence for several periods of erosion and sedimentation during Silurian and Lower and Middle Devonian time. Part of the area discussed by Wilson lies at the northern end of the Nashville Dome and immediately northwest of Flynn Creek. Assuming the depositional conditions described by Wilson existed in the present Flynn Creek area, and if the crater was formed before or during this time, then it should have received sediments from the time of formation until it was filled. Instead, the first bedded rocks in the crater are early Late Devonian in age. Based on this evidence alone, it can be tentatively concluded that the non-bedded breccias are probably of Middle or Upper Devonian age.

A second argument can be made for the Middle or Upper Devonian age of the non-bedded breccia based on the expected resistance of the crater to erosion. It seems extremely unlikely that a crater formed in limestone could exist more than a few million years before being filled by erosion of the surrounding strata in the crater walls. It also seems improbable that the central uplift, which was a hill on the crater floor, would have survived extended exposure to erosion. For the sake of demonstrating the rate of erosion of the central uplift, one could assume a rate of erosion of 0.02 inches of material removed from the flanks of the hill per year. If this rate was constant, then in approximately one million years the hill would be removed. Another point which argues for the Middle or Upper Devonian age is the absence of lake deposits in the crater. Instead, the bedded deposits are marine and of the same age as the Chattanooga Shale that fills the crater. The implication from these lines of evidence suggests that the non-bedded breccia in the crater probably was formed shortly before early Late Devonian time.

Upper Devonian Series

Bedded Breccia

A sequence of bedded breccias consisting of several different lithologies overlies the non-bedded breccias within the crater. The most common type consists of a bedded dolomitic breccia that is present throughout the crater and thins out high on the crater walls and flanks of the central uplift. The unit consists of yellowish-gray to yellowish-brown, coarse to poorly-sorted, poorly-graded bedded breccia. The breccia is made up mainly of angular to poorly-rounded fragments which are predominately of upper Leipers dolomite and enclosed in an argillaceous dolomitic matrix very similar to the overlying bedded dolomite. This unit locally develops into poorly-bedded, very coarse breccia with poorly-sorted fragments. The upper contact with the overlying bedded dolomite is gradational over a few inches in some outcrops, while in other exposures the contact is sharp on the order of a fraction of an inch. The lower contact is irregular but sharp where in contact with the non-bedded crater breccia. Where the unit overlies other variations of bedded breccia, the lower contact is gradational over a few inches to several feet.

The only other bedded breccias of importance consist of a bedded limestone breccia with local variations of poorly-bedded limestone breccia, and bedded breccia with local variations of poorly-bedded breccia. The description of these units is as follows:

Bedded limestone breccia: medium light to medium dark gray, poorly sorted, coarsely bedded, angular to poorly rounded fragments predominately of limestone of lower Leipers, Catheys and Cannon strata in an argillaceous dolomitic limestone matrix. Only occurs locally.

Poorly bedded limestone breccia: same as bedded limestone breccia except poorly bedded with very coarse and poorly sorted fragments. Only occurs locally.

Bedded breccia: yellowish gray to dark gray, poorly sorted, coarsely bedded, angular to poorly rounded fragments of Leipers, Catheys and Cannon strata in an argillaceous dolomitic limestone to limy dolomite matrix. Only occurs locally.

Poorly bedded breccia: same as bedded breccia except very poorly bedded with very coarse and poorly sorted fragments. Only occurs locally.

The poorly-bedded breccia, if present, is always the basal unit and is overlain by the bedded breccia. The bedded limestone breccia is present only locally as is its basal variation of poorly-bedded limestone breccia. The bedded dolomitic breccia with its local development of poorly-bedded dolomitic breccia is the highest stratigraphic unit of the bedded breccia sequence. The bedded breccias are a minimum of 40 feet thick near the central part of the crater and around the flanks of the central uplift. In this part of the crater the bulk of the fragments are from the Stones River and Knox Groups.

Huddle (1963) has reported conodonts of early Late Devonian age in the bedded breccia and overlying bedded dolomite at three localities within the crater. Wilson and Born (1936) had called these units freshwater limestones, and Conrad, et. al. (1957, p. 16) concurred with this interpretation. As pointed out by Conant and Swanson (1961, p. 11), the conodonts are marine microfossils and indicate a marine environment of deposition.

Bedded Dolomite

The bedded breccias are overlain by a single bed of massive dolomite which averages about 3 feet in thickness throughout the crater, with local increases of up to 25 feet. The dolomite also overlies the bedded breccia high on the crater walls and central uplift, but usually thins out somewhat lower in elevation than do the underlying bedded breccias. The bedded dolomite is locally absent in a few parts of the crater allowing the Chattanooga Shale to lie in direct contact on the bedded breccia, or in some cases on the non-bedded breccia.

Typical exposures of the bedded dolomite are present on the western rim immediately north of the Flynn Creek Road and on the west side of Fox Hollow. In this area the bedded dolomite consists of yellowish-gray to yellowish-brown, slightly argillaceous, fine-grained dolomite. Thin laminations which appear to represent variations in the clay content are common throughout the unit. Cross-bedding is locally present as are thin lenses of breccia in the lower few inches of the dolomite. In some exposures the lower contact is gradational over several inches with the bedded dolomitic breccia, while in other exposures this contact is very sharp. In a few exposures the thin lenses of breccia in the base can be traced into the underlying bedded breccia. Conodont fragments, phoshphatic remains, and coarse dolomite crystals which may be clastic give a coarse-grained appearance to some exposures near the eastern and western rims.

The upper contact with the Chattanooga Shale is always very sharp, although locally there are usually several feet of relief on the upper surface of the bedded dolomite. Immediately west of Flatt Cemetary in the west central part of the crater and several feet north of Flynn Creek Road, exposures of the bedded dolomite exhibit pre-Chattanooga channeling with relief on the order of three feet. Basal Chattanooga Shale can be seen in contact with some of the vertical channel walls occuring as a soft, weathered, silty carbonaceous claystone (fig. 24). This outcrop is on the western edge of a small mount of breccia.

The early Late Devonian age of this dolomite and the argument for a marine origin were given in the previous section on the bedded breccia.

Basal Claystone

The basal claystone is probably a local variation of the basal Chattanooga Shale within parts of the crater. It occurs in at least three localities, the central part of Fox Hollow, the western part of the mouth of Fox Hollow, and the western flanks of the central uplift (Plate 1). This thin unit is similar to the interbedded

Figure 22 --Weathered outcrop of bedded breccia overlain by bedded dolomite. Immediately west of central uplift.

Figure 23 --Fresh outcrop of bedded breccia overlain by bedded dolomite. Note lens of breccia in bottom of bedded dolomite. Immediately west of central uplift.

Figure 24.--Pre-Chattanooga Shale channeling in top of bedded dolomite. Immediately west of central uplift.

claystones in the middle part of the Chattanooga Shale and consists of brownish-black to medium- to dark-gray, calcareous to dolomitic, carbonaceous, silty claystone. Locally calcite and siliceous nodules are present, the silica often replacing the calcite. In a few locations where this unit is present, it has a thickness of a few inches to 3 feet. The upper and lower contacts are usually sharp.

Conodonts of early Late Devonian age have been identified from the underlying bedded dolomite and from the overlying basal Chattanooga Shale (Huddle, 1963). The basal claystone was not present in the conodont collecting sites, but its occurrence in other parts of the crater between the bedded dolomite and the base of the Chattanooga Shale, and its strong lithologic similarity to the black shale leaves little doubt that this is another local variation of the shale.

Chattanooga Shale

Although the Chattanooga Shale was recognized as early as 1835 by Troost (p. 6-8), it was not named until 1891 by Hayes (p. 142-143) for exposures in the city of Chattanooga, Tennessee. Since that time a great deal of study has been devoted to the Chattanooga strata, and is best summarized in the recent comprehensive study by Conant and Swanson (1961). The Chattanooga Shale forms a thin but remarkably persistent formation of black shales of early Late Devonian (and possibly late Middle Devonian) to Early Mississippian age over much of the interior lowlands of North America.

In the northeastern part of the Nashville Basin the Chattanooga Shale averages 25 feet in thickness with variations rarely over three feet. The Flynn Creek structure is the one major exception where the Chattanooga Shale thickens to a minimum of at least 180 feet in a closed depression. Normally the Chattanooga strata are found along the upper parts of the valley walls where a slight steepening occurs in the slope. Exposures are usually restricted to the heads of the smaller valleys and to occasional road cuts. In the Flynn Creek structure, however, the black shale occupies most of the interval between the floor of the stream valleys and the Fort Payne Formation high on the hillside. Indeed, had it not been for the presence of such a distinct lithologic marker as the black shale, it is doubtful if the Flynn Creek structure could have been examined in any reasonable amount of detail. The presence of the black shale at stream level, instead of along the ridges, was one of the reasons the structure was first noticed by Safford in 1869.

Hass (1956) in an early study and as a personnel communication to Conant and Swanson provided the most reliable age assignments by his work on the conodonts in the Chattanooga Shale. The stratigraphic nomenclature and age assignments described by Conant and Swanson (1961) are applicable to the Chattanooga Shale throughout the Flynn Creek area (fig. 25). This five-fold division, with the Dowelltown member and its lower and upper divisions, and overlying Gassaway member including its lower, middle and upper divisions, is also recognizable in all of the overthickened part of the Chattanooga strata in the crater. Where exposures are reasonably good, such as at the heads of small valleys, the two members can always be separated. The five divisions are also usually recognizable. The lithology of the Chattanooga Shale for both the Flynn Creek structure and surrounding area is as follows:

Chattanooga Shale (general), shale and claystone: Grayish-black, calcareous, highly carbonaceous shale; unweathered massive, weathers fissile; local pyrite, marcasite and fine silt partings; lesser amounts of medium light-gray silty, calcareous, carbonaceous claystone interbedded with black shale. Formation undivided on most of the map because of poor exposures. Thickness averages 27 feet, except within crater where maximum thickness is about 200 feet.

Gassaway member, shale and claystone: Upper and lower parts are grayish-black to black, fissile, calcareous, highly carbonaceous shale; unweathered massive, weathers into blocky, fissile slabs in upper part; local pyrite marcasite and fine siltstone partings. Middle part medium light- to medium-gray, silty, calcareous, carbonaceous claystone interbedded with black shale. Thickness averages 17 feet except within crater where maximum thickness is about 25 feet.

Dowelltown member, shale and claystone: Upper part is medium light-gray, silty, calcareous, carbonaceous claystone interbedded with black shale; thin bentonite bed in upper 2 feet. Lower part is grayish- black to black fisile, calcareous, highly carbonaceous shale; unweathered massive, weathers fissile; local pyrite, marcasite and fine silt partings. Basal contact with Leipers Formation sharp with less than 0.02 foot basal calcareous, poorly carbonaceous siltstone which is also present within the crater. Thickness averages 10 feet except within crater where maximum thickness is about 170 feet.

The thickened part of the black shale occurs mainly in the lower unit of the Dowelltown member. This has been noted by Conrad, et. al, (1957), Stockdale and Kepser (1959), and Conant and Swanson (1961); however, no detailed studies or mapping were carried out. During the current study the writer observed changes in thickness over a linear distance of about 500 feet from 27 feet over the rim to nearly 120 feet within the crater. Immediately over the eroded crater wall, the shale has dips as great as 18° towards the crater, but the dips rapidly flatten to very gentle inward dips in distances of 100 to 300 feet. Dips of 23° maximum are present along the flanks of the central uplift but also flatten to zero and then reverse in dip direction (dip towards central uplift) in linear distances averaging about 20 feet. Without exception, the shale in the crater always exhibits gentle dips towards the deeper parts.

The Chattanooga Shale is clearly unconformable in central Tennessee, lying on 23 different formations (Wilson, 1949); however, this is not apparent in the Flynn Creek area where the black shale is in contact with the Leipers Formation. Bedding in both formations

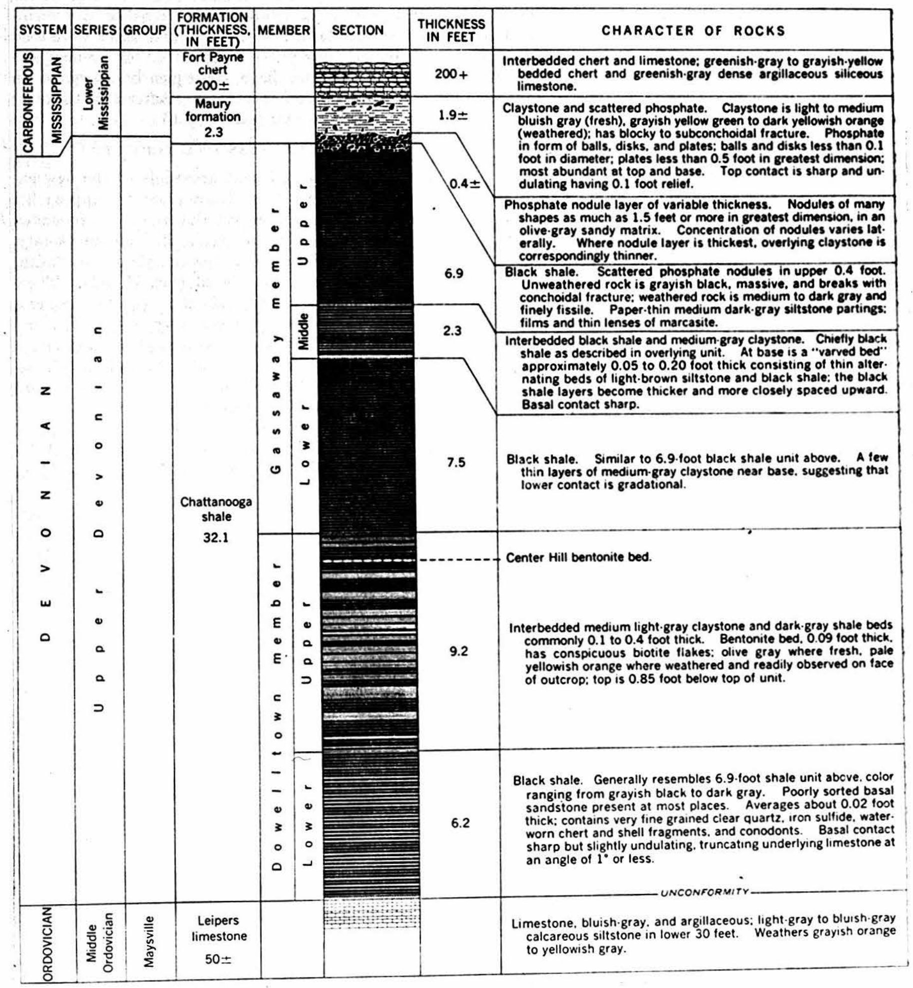


Figure 25 --Standard section of the Dowelltown and Gassaway members of the Chattanooga Shale. Vertical cut along east approach to Siligo bridge on State Route 26, about 7 miles east of Smithville, DeKalb County, Tennessee. From Conant and Swanson (1961, p. 24).

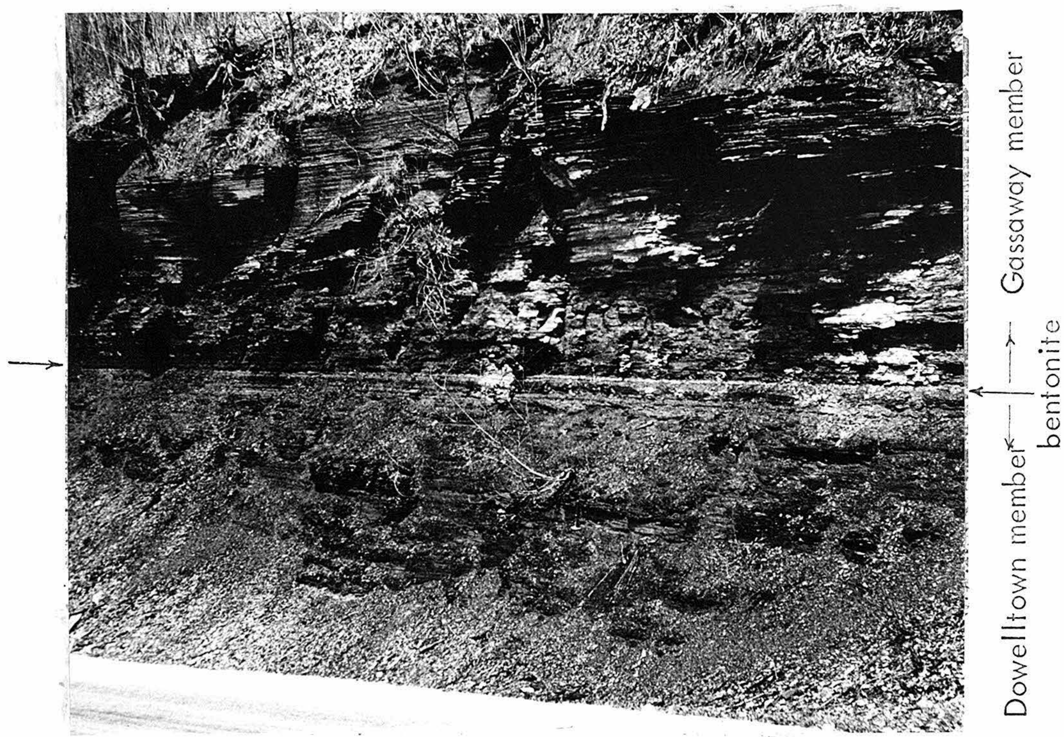


Figure 26 --Typical exposure in road cut of Chattanooga Shale. Upper half of outcrop is Gassaway member and lower half is Dowelltown member. Thin white band in center of photograph is bentonite bed. Location is about 2 miles west of Chestnut Mound, Tennessee.

is parallel, and only a discontinuous, silty black shale horizon less than 1/2 inch thick is present at the base of the Chattanooga Shale. Both the top and bottom contacts of the Chattanooga strata are without exception extremely sharp.

Within the crater the basal few inches to a few feet contain a slightly higher percent of silt than the rest of the formation. Small siliceous nodules are also locally present at the base of the shale within the crater. These two variations are the only ones noted in the Chattanooga strata within the crater relative to the surrounding area except for the pronounced thickening. The basal, locally discontinuous, calcareous, carbonaceous siltstone to silty shale is present throughout the area, including the crater.

Devonian and Mississipppian Systems

Upper Devonian-Lower Mississippian Series

Maury Formation

The Maury Formation was named by Safford and Killebrew (1900, p. 104, 141-143) for exposures in Maury County in south central Tennessee. Poor exposures in this area later led Hass (1956, p. 23) and Conant and Swanson (1961, p. 63) to designate an area near Cross Key, Williamson County, Tennessee as the standard section.

Throughout Tennessee, Kentucky and Alabama the Maury Formation consists of variable proportions of greenish claystone, shaly claystone, shale, poorly-shaly siltstone and fine-grained glauconitic sandstone. The average thickness is commonly 1 to 4 feet but in some localities it ranges from a few inches to nearly 7 feet. Claystone in the lower part of the formation is often shaly with an olive-gray to dark-greenish gray color. Dense phosphate nodules are common in the lower part, often tightly packed and of many shapes and sizes up to 1 foot in length. Kellberg and Maher (1959,

p. 136-138) and others have reported studies by Hass on conodonts and by Dunkle on rare vertebrate fragments in a few of the phosphate nodules in east Tennessee. Both Hass and Dunkle consider these fossil fragments as indicative but not definitive of Late Devonian or Early Mississippian age. The upper part of the formation usually consists of a greenish-gray claystone to shaly claystone. Smaller phosphate nodules are scattered throughout the upper part. A grayish-blue green claystone is often present in the upper few inches. The upper part of the formation tends to be greenish-gray when rare fresh exposures are found. Weathered surfaces have a light to dark-olive green or blue green color.

Exposures are usually restricted to areas where cliffs are formed by the underlying resistant Chattanooga Shale in the heads of the narrowest valleys. At these exposures the Maury Formation commonly weathers as a shallow depression beneath the resistant cherts of the Fort Payne Formation.

Conant and Swanson (1961, p. 62-69) have discussed the regional aspects of the Maury Formation and have demonstrated that the top and bottom contacts appear conformable with their underlying and overlying strata. Hass (1956, p. 23-24) concluded from conodont studies that in most areas the entire Maury Formation is of Kinderhook (Early Mississippian) age, but a small area in north central Tennessee has a few basal beds of very Late Devonian age, while other places have uppermost beds of probable Early Osage age. Conant and Swanson (1961, p. 68-69) suggest that at the end of Devonian time the epicontinental sea expanded greatly over its peneplained margins with the result that land sources of sediments were greatly separated. The result was a shallow sea with wide coverage and little sediment for deposition.

The regional lithologic descriptions given in this section are also valid for the Flynn Creek area including the beds above the crater In so far as the writer could determine, there is no change in the character of the Maury strata inside the crater area relative to the surrounding area. Sizes and distribution of phosphate nodules are unchanged, and thicknesses range between a few inches and three feet. Other than a very broad gentle structural depression or sag over the crater, no structural anomalies are present.

It may be noted that in exposed sections and in excavations by the writer, the basal contact of the Maury strata with the Chattanooga Shale was usually sharp on a wavy irregular surface with relief up to 1 inch. The top contact with the cherts of the Fort Payne Formation is almost always very sharp with no measurable relief over short distances on the order of 100 feet.

There are scattered areas where the Maury Formation is overlain by a greenish, calcareous, poorly-silty shale to shaly claystone. This unit invariably has scattered, broken silicified crinoid stems up to 1/2 inch in length, and in some exposures irregular thin chert beds are present. The upper Maury contact is more difficult to locate when it is overlain by this type of shaly strata, but it can nearly always be found by locating the lowest crinoid stem fragments in the green shale. The crinoid stems in the shaly strata are identical to ones found in the cherts and limestones of the immediately overlying Fort Payne Formation.

Mississippian System

Lower Mississippian Series

Fort Payne Formation

Smith (1890, p. 155-156) proposed the name Fort Payne chert for Fort Payne, De Kalb County, Alabama. Current mapping by the U. S. Geological Survey describes the equivalent strata in Kentucky as the Fort Payne Formation. Fort Payne strata are present throughout Tennessee in the Lower Mississippian interval and exhibit a highly varied lithology of siliceous limestone and dolomite, chert and siliceous calcareous shales. Lateral variations occur over such short distances in the Flynn Creek area that no attempt was made to map separate units or facies. Rodgers (1953, p. 108) states that fossils of this formation in east Tennessee demonstrate a correlation with the Osage group of the Upper Mississippi Valley States, but there is a possibility of a Kinderhook age for the basal beds.

In parts of the Flynn Creek area a basal greenish-gray shale is present with scattered silicified crinoid stems up to 1/2 inch in diameter. This is common throughout east Tennessee according to Milici (1963, p. 25) and Rodgers (1953, p. 107-108). In the Flynn Creek area the green basal shale appears restricted to the northern, eastern and southern parts of the map area. Northwest, west, and southwest of the crater, cherts immediately overlie the Maury Formation. The basal shale varies in thickness from a few feet to at least 20 feet and is commonly replaced in short distances in a lateral direction by cherts, although no exposures were seen where the shale graded directly into the chert. The greenish, calcareous, poorly-silty shale to shaly claystone commonly has scattered thin chert beds, usually lenticular. Occasionally a few shaly chert beds are present at the base, but more commonly the shale is in contact with the underlying Maury Formation. The contact can generally be found within an inch by locating the lowest crinoid stem fragment and the lowest calcareous, non-glauconitic beds. Thin lenticular chert beds are also definitive for an approximate location of the lower contact.

Several other basal shale outcrops are present between the Flynn Creek structure and Gainesboro, 5 miles to the north. Outcrops on State Route 53 and 0.75 miles west of Gainesboro consist of a minimum of 30 feet of mottled reddish-brown to green fissile shale with thin interbedded cherts containing silicified crinoid stems. There is a possibility that these various irregular distributed basal shales may be part of the New Providence formation as suggested by Hass (1956, p. 28) and Wilson (1962). Until adequate paleontological studies are undertaken, the green shales are considered as a basal unit of the Fort Payne Formation.

Another variation in the basal lithology of the Fort Payne strata consists of massive, poorly-bedded to non-bedded biostroms made of siliceous limestone with abundant crinoid stems. These units occur as lenticular bodies up to several hundred feet in length, are 10 to 20 feet thick and are irregularly distributed throughout the area. In one area about 0.15 miles northeast of the Flynn Creek structure, crinoid stems and fossil fragments form a small biostrom with a flat base about 200 feet long and 26 feet in height. Marcher (1962) and Hass (1956) have discussed similar biohermal structures in central Tennessee and southern Kentucky. Petrographic studies of this bioherm have shown very fine breccia zones accompanied by highly twinned calcite crystals. The intense twinning occurs both in the mica-breccia fragments and in the calcite immediately adjacent to the breccia zone. Lowenstam (personal communication, 1966) suggested to the writer that this intensity of twinning was quite atypical of most bioherms. The writer tentatively interprets the twinning as a result of the brecciation, probably caused by overburden collapse of the bioherm while it was in more porous condition.

Another type of basal lithology envolves a variation in the ratio of siliceous limestone to chert. This type of variation is common throughout the entire Fort Payne Formation, and in the western part of the Flynn Creek area the basal Fort Payne strata consist exclusively of medium-bedded cherts.

The changes in lithology from one location to the next within the Fort Payne Formation preclude a standard section in the Flynn Creek area. This is also true in Clay County to the north (Born and Burwell, 1939, p.50) and surrounding counties to the east, south and west according to the writer's reconnaisance work. Lithologic types include cherty limestone, shaly siltstone, siliceous and calcareous shale, and chert, often all within a few hundred feet of each other. In the Flynn Creek area chert is the dominate lithology and is commonly white to brown to dark gray, thin to thick-bedded with local non-bedded to irregular-bedded zones. All of the different lithologic types in the Flynn Creek area are poorly to highly fossilferous with local concentrations of crinoid stems. The Fort Payne strata are normally overlain by the Warsaw Formation of Lower Mississippian age in the Highland Rim area, but no strata of Warsaw age were identified in the Flynn Creek area. The Fort Payne rocks show no effects from the underlying crater, except for a gentle downbending over the thicker parts of the Chattanooga Shale (Plate 2). The thickness of the Fort Payne formation is between 100 and 150 feet.

The cherts are resistant and serve as ridge formers with dark brown to red, deeply weathered zones. Nearly all of the hill slopes have a colluvial cover which includes weathered chert blocks. The residual materials weathered on top of the Fort Payne strata varies from a few inches to over 20 feet deep on some ridges.

Quaternary System

Unconsolidated materials of Quaternary and possibly Tertiary age are present throughout the Flynn Creek area and consist of residium, colluvium, alluvium, landslides and slumps. Patches of gravels of possible Tertiary age have been reported on the Highland Rim northeast of Gainesboro (Lusk, 1928, p. 164-170), but none have been observed in the Flynn Creek area.

The residium consists of deeply weathered Fort Payne strata that caps all the ridges in depths from a few inches to over 20 feet. The lithology of the fragments in the residum strongly suggests that this unconsolidated and partly weathered material is derived in situ from the Fort Payne rocks. Jackson (1961), Rogers (1953), Swingle

(1959) and others have also advanced this viewpoint for the thick residium in east Tennessee.

The upper hillslopes commonly have a thin cover a few inches to several feet thick of weathered material consisting of cherty colluvium and soil developed on the underlying weathered limestone. The lower hillslopes have a variable thickness of colluvium of limestone and chert fragments mixed with coarse to fine soil material, often up to 30 feet thick in the smaller stream valleys. Landslides of colluvium are common in the steeper valleys, and in some cases bedrock is exposed above the slides. In some areas the weathered surface material forms a landslide made up mainly of material weathered from one part of a formation, and is mapped separately. Large slumps are also common along the main stream valleys and are generally associated with solution caverns. The slumped material can usually be mapped showing the lithology of the formation in which the slump occurred.

The alluvial deposits consist of clay, silt, sand and boulder-sized materials forming unconsolidated stream deposits. The materials are mainly angular chert and rounded limestone fragments with occasional plate-like clasts of Chattanooga Shale. The main stream valleys have flat transverse profiles which terminate abruptly against the steep valley walls. Flynn Creek Valley is the only valley wide enough to have appreciable flood plain deposits. Hogan (personal communication, 1963) suggests that alluvial deposits in the main stream valleys are probably less than 50 feet in thickness. Judging from recent water-well drilling information, thicknesses of less than 20 feet are more likely in the Flynn Creek area. Many of the smaller tributary stream beds have exposed bedrock with only scattered, thin patches of colluvium.

Unconsolidated to semi-consolidated alluvial terrace gravels are present along the main stream valleys at a few locations, but were mapped as part of the main stream alluvium.

STRUCTURAL GEOLOGY

Introduction

The crater at Flynn Creek is located in an area of normally flat-lying, undeformed sedimentary strata that dip gently east away from the Nashville Dome. The crater averages about 2.2 miles in diameter and was about 330 feet deep before being filled later by shale and cherty limestone. The floor of the crater is underlain by a chaotic breccia of limestone derived from the same strata now exposed in the rim. Before the crater was filled, a central uplift of older deformed limestone and dolomite formed a hill rising about 300 feet above the crater floor. The limestones in the rim surrounding the crater have been moderately to intensely folded, faulted and locally brecciated. Deformation in the rim is restricted to an irregular zone adjacent to the crater and varies in width from a few hundred feet to nearly 3000 feet. These major structural elements are shown in Figure 27 and were delineated during the present field study.

Structural Geology of the Flynn Creek Area

Structural contour maps have been prepared for the top of the middle Catheys unit and for the post-crater pre-Chattanooga surface. The top of the middle Catheys unit is exposed in the western half of the map area and in several places along the deformed rim. In other areas the contour information was taken from higher horizons with known stratigraphic intervals to the upper Catheys unit. Elevation information for the pre-Chattanooga post-crater time surface was taken directly from exposed contacts at the surface. The six cross-sections (Plate 4, 5,fig 29) are constructed from the geologic map (Plate 1) and, structure contour maps (Plate 2, 3) are plotted with the vertical scale equal to the horizontal scale. The locations of the cross-sections are based mainly on availability of long continuous exposures and on the ability to exhibit the basic types of different rim deformation. The structural features in the Flynn Creek area are described in the following order: Local Structure Surrounding the Deformed Rim Strata, Structure of the Crater Rim, Post-Crater Pre-Chattanooga Surface, and the Structure of the Central Uplift.

Local Structure Surrounding the Deformed Rim Strata

Newcome (1954) and Wilson (1949) suggested that most of southern Jackson County, including the Flynn Creek area, is situated on one of the many broad eastward-plunging anticlines which are present on the flanks of the Nashville Dome. These structures are so large and have such gentle dips that regional studies are necessary to delineate the exact trends. In contrast to the deformation at the Flynn Creek structure, the surrounding area exhibits a pattern of only very gentle folds superimposed upon a shallow regional dip to the east and southeast. Within the map area (Plate 1) the average regional dip is about 0.25 degrees, with a maximum change in elevation from west to east on a typical structural horizon (top of middle Catheys unit, Plate 2) of 130 feet. Within the surrounding area the folding is usually localized as gentle anticlines and synclines with dips on the flanks rarely exceeding 5° and averaging about 2°. The folds usually are closed such that anticlines form domes, and synclines form basins; however, the shapes of these minor structures are generally quite irregular and asymmetric. Although there may be a common trend of axes, it was not noted in the current field work.

A broad structural high is present about one-half mile west of the western rim of the crater and trends generally west to west-southwest. Structural relief in this area on the top of the Cannon limestone averages about 50 feet (Plate 2). This structural high is also reflected in the pre-Chattanooga surface on the upper Leipers strata and has about the same relief as the top of the middle Catheys unit (Plate 2, 3).

A closed basin in the southwest corner of the map area (Plate 2) has a structural relief of about 60 feet. This basin is also reflected in a closed basin with relief of about 40 feet on the pre-Chattanooga surface on the upper Leipers erosion surface (Plate 3). Structure contours on both horizons have a poorly defined northwest-southeast long axis. Another elongate basin is present in the extreme south central part of the map area and has a north-south axis. Structural relief on the top of the middle Catheys unit is about 30 feet, but relief on the pre-Chattanooga surface on the upper Leipers erosion surface is ten feet or less and does not exhibit a closed basin.

The pre-Chattanooga strata in other parts of the area surrounding the deformed rim have very gentle dips away from the crater. In general, the northwest, northeast and southeast parts of the area surrounding the crater exhibit only broad, very gentle folds superimposed on an overall shallow regional dip to the east and southeast (Plate 2, 3).

Structure of the Crater Rim

General Statement

The deformed strata in the rim exhibit several different types of deformation, including rim tilting and uplift, folding, faulting and local brecciation. The major part of the deformation averages about 2000 feet in width, but is very irregular and in some parts can extend out to nearly 3000 feet. The main structural features

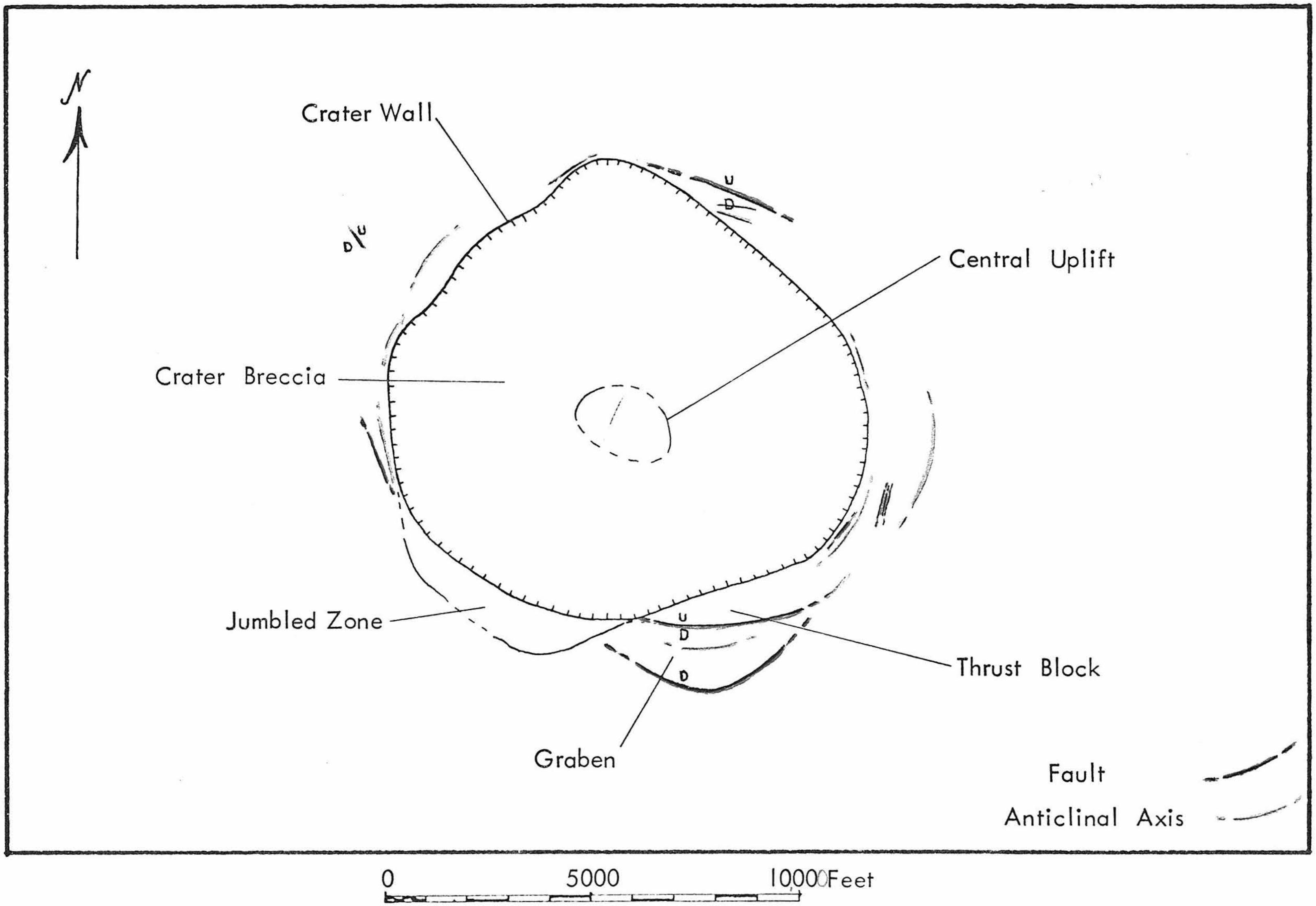
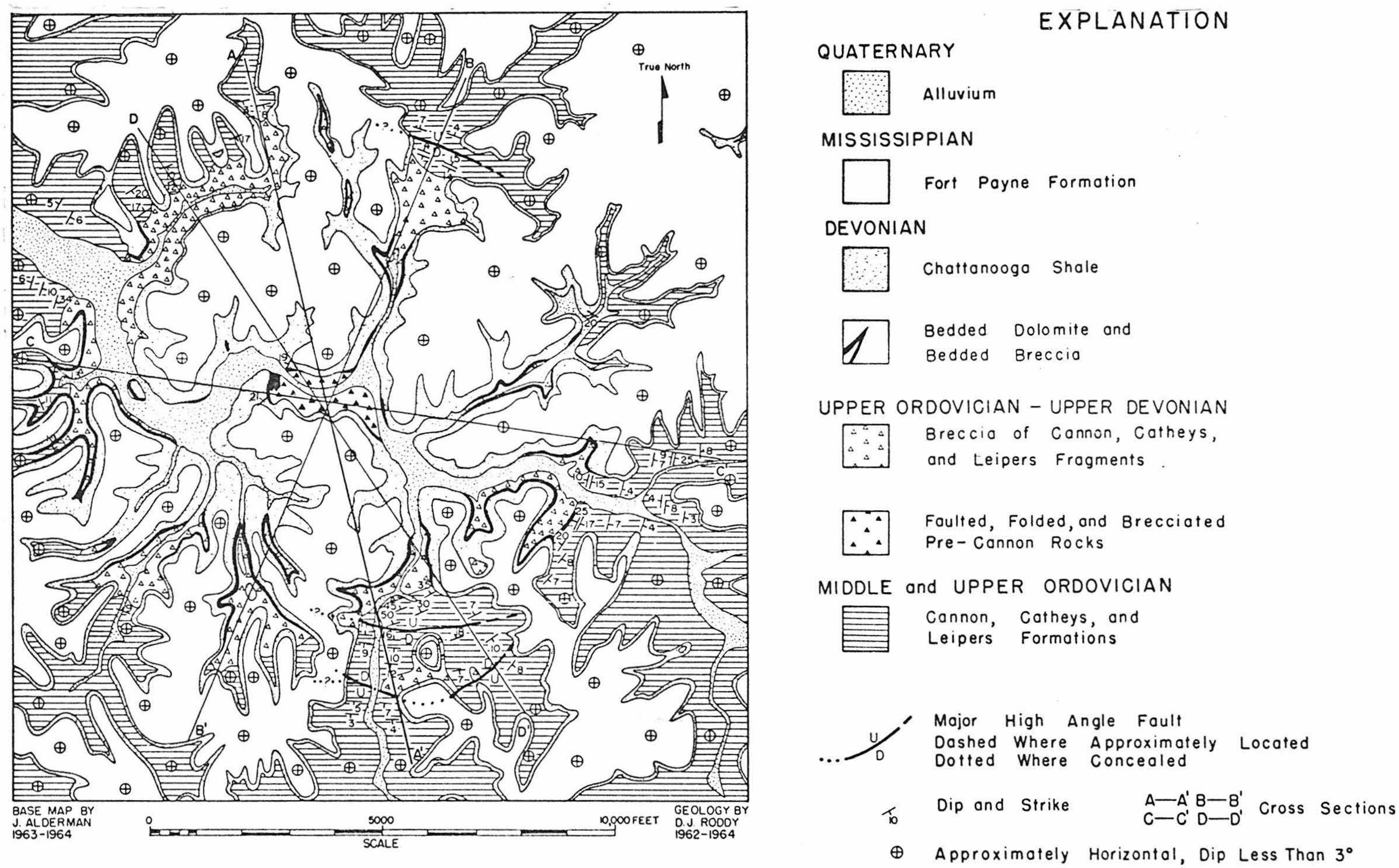


Figure 27 :--Schematic map of major structural elements at the Flynn Creek Crater, Tennessee



GENERALIZED GEOLOGIC MAP of the FLYNN CREEK STRUCTURE, TENNESSEE

Figure 28

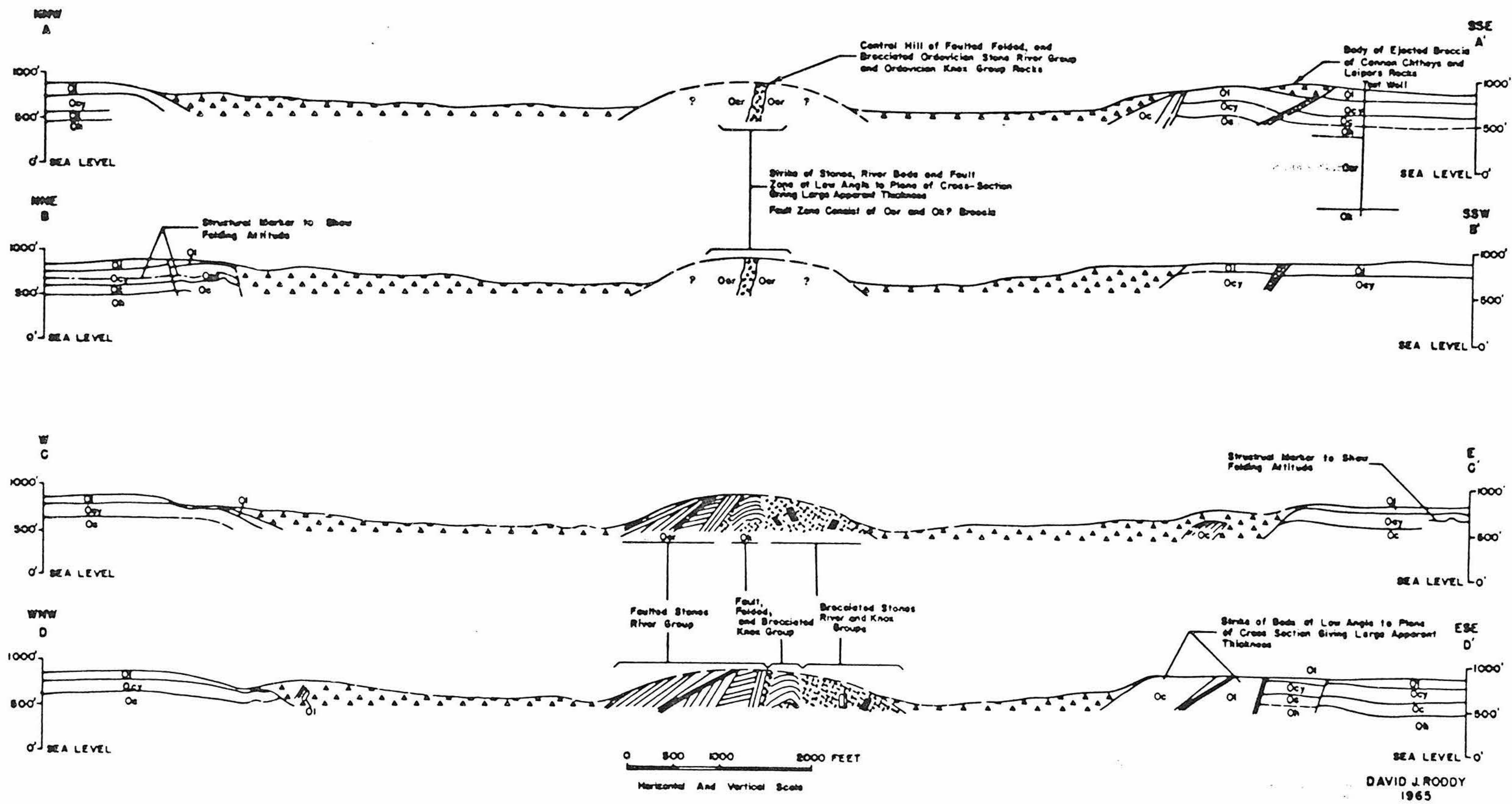


Fig. 29 Generalized geologic cross sections of the Flynn Creek structure. Sections show structure shortly before deposition of Chattanooga Shale in early Late Devonian time.

are best exhibited by the structure contours on the top of the middle Catheys unit (Plate 2). Many smaller structural features, such as minor folds and breccia contacts at the crater wall, are not shown in the diagrams but are of sufficient importance to require separate description. The structure in the crater rim is described in order of the western rim, northern rim, eastern rim and southern rim. The crater wall and crater non-bedded breccia are also described in these sections where significant features are present.

Western Rim

In general, the western and northwestern parts of the rim are raised by an anticlinal high whose axis is approximately concentric with the crater (Plate 2, 4). The axis ranges from a few hundred feet to 2000 feet from the breccia contact at the crater wall. On the western rim, the anticline has a north-trending axis and is highly asymmetric with a shallow west-dipping limb and a very steep east-dipping limb. In areas where the anticline is broad and flat, the limb on the crater side has the appearance more of a monoclinal fold. Western dips average 2^{o} to 4^{o}, while eastern dips are as great as 34^{o} immediately adjacent to the breccia contact. The anticline plunges shallowly to the north with a sharp bend to the northwest, and then bends back to the northeast in the area of the Flynn Creek valley. The anticline then broadens out into a very flat structural high trending northeast and finally bends 90^{o} to the northwest or intersects another northwest-trending elongate dome.

Along the northwest rim the anticline has a dip of 1^{o} to 2^{o} on the northwestern limb and a variable dip on the southeastern limb from 2^{o} to 21^{o} (Plate 2). The dips on the limb next to the crater, without exception, begin very abruptly, going from nearly horizontal to 20^{o} to 30^{o} in 100 feet or less (Plate 2, 4).

Exposures along the western crater wall exhibit relatively sharp contacts of folded strata with the crater breccia, as well as the more common gradational jumbled contacts. For example, the breccia contact is well-exposed on the western rim approximately 600 feet southwest of the area where Fox Hollow empties into Flynn Creek. High on the hillside in this area the contact is between Catheys and Leipers strata and dips gently into the crater and chaotic crater breccia of Cannon, Catheys and Leipers rocks. The contact is somewhat irregular, but can be located to within three feet. In a few exposures brecciation in the rim strata in the crater wall occurs as an irregular zone several feet wide, and in this case it consists solely of breccia from the local horizon, a type of authigenic breccia (fig. 30).

Low on these same hillsides at least two outcrops are deeply enough eroded to expose the tightly folded lower rim strata where dips of 20° to 30° are common (Plate 4). In these exposures the brecciation in the rim strata is usually more intense, and the contact with the actual rim rock and the crater breccia is more difficult to locate.

Approximately 3000 feet south-southeast of the area where Fox Hollow opens into the Flynn Creek valley, the rim structure becomes much more complicated. The crater extends back to a very steep crater wall nearly 150 feet high. A mass of breccia extends out from the base of this crater wall towards the crater. The Chattanooga Shale drops very rapidly over this ancient cliff area, increasing from about 27 feet thick to nearly 100 feet in less than 800 feet linear distance. The contact of the crater breccia and the rim strata along the steep crater wall is very poorly exposed and can be located only approximately. The remainder of the exposures suggests that the area within the crater and adjacent to the cliffs consists of very large megabreccia blocks several hundreds of feet in size, partly brecciated, and probably highly faulted and folded.

Figure 30.--Authigenic breccia in upper ledge unit of Catheys Formation on the western crater wall.

The contact of the crater breccia and the crater wall in this part of the structure is commonly a gradational, jumbled zone that may extend over a hundred feet. Even where complete exposures are available, it is difficult to locate the contact between the jumbled strata which still retain their stratigraphic relationship, and the strata which become increasingly disorientated and deformed toward the chaotic crater breccia. For this reason a special contact symbol has been used to indicate a jumbled contact that extends over several tens of feet. For the most part, the jumbled contact dips into the crater at shallow angles ranging from 20° to 40°.

A different type of rim structure is present slightly south of the western center of the rim. In this area the rim anticline becomes very tightly folded with a poorly-defined, high-angle fault cutting the southern limb (Plate 2,). Dips on the crater side of the anticline average 24°, but dips near the fault are as great as 34°. The northeastern side of the fault is dropped between 20 and 40 feet relative to the southwestern side. Colluvial cover is too great in the area to expose the actual fault surface, but the exposures available suggest a very high-angle fault plane, at least at the level of the Catheys and Leipers strata. The fault crosses a structural basin immediately southwest of the tight anticline which is next to the crater. Presumably the fault is a result of the sharp synclinal or down-bending associated with the anticlinal folding in the rim. If this fault is similar in nature to others along the rim, then displacement at both ends of the fault should decrease in the manner of a hinge fault.

Northern Rim

Deformation along the extreme northwestern rim is the least complex of the whole crater (Plate 2,). In this area the rim strata 1000 feet from the crater wall are raised 20 to 30 feet above the local level and dip gently into the crater at 1° to 2°. Within 250 feet of the crater breccia the dips increase as a monoclinal fold to 7° to 10°, and the folded rim strata develop a jumbled aspect that increases in intensity towards the crater. The jumbled zone occurs as a downward-thickening wedge with a maximum horizontal thickness of about 50 feet at stream level. The entire jumbled zone dips shallowly into the crater at an angle varying from 25° to 35°.

Several examples of small folds with axes trending radially to the crater are present along the northwestern rim. Several of these folds are present in faulted blocks in the northwestern rim about 1000 feet north of the mouth of Fox Hollow (Plate 2). The folds consist of adjacent anticlines and synclines with limbs dipping up to 25°. The plunges of these structures appear to reverse several times toward the crater, presenting a complicated three-dimensional fluted appearance. Another similar fold is present in the northern rim near the head of Fox Hollow. Here only monoclinal dips up to 14° are exposed, but structure contours (Plate 2) suggest a broad syncline plunging gently toward the crater.

Only limited exposures are available of the northeastern rim and are confined mainly to Lacy Branch Hollow and its tributaries. In this area a complex set of tight folds trends approximately parallel to the rim and is cut by two faults which also parallel the rim (Plate 2). The rim strata begin to rise toward the crater starting at a distance of about 2500 feet out from the crater wall. The total rise is nearly 110 feet measured to the crest of the anticline nearest the crater. The rim uplift, although irregularly shaped, continues for at least 4000 feet around the rim to the east and affects strata away from the crater for a minimum of 2500 feet.

The most intense folding in this area is best exposed in the valley walls of Lacy Branch Hollow. Here two well-defined, closed anticlines are separated by a tightly folded eastward-plunging syncline (Plate 2). Both anticlines have near vertical axial planes, are approximately concentric with the rim, and form elongate domes. Horizontal shortening of the beds is on the order of 35 percent. An important change in folding attitudes occurs less than 100 feet higher in the strata over the dome nearest the crater, where beds rapidly flatten and exhibit little of the folding shown by the lower strata. Considerable bedding-plane slippage must be common in these folded strata because no thickening or thinning of individual beds was noted. The cross-section of this fold is seen in Plate 5 and in Figure 29 .

Two northwest-trending normal faults are present immediately north of the two domes seen in Lacy Branch Hollow and dip steeply towards the crater. Displacement on the fault nearest the crater is about 25 feet with the dropped side nearest the crater. The other normal fault has a displacement of only 5 feet with the dropped side nearest the crater. Both faults roughly parallel the crater wall and die out rapidly as hinge faults.

The contact of the crater breccia with the rim strata in this area consists of an irregular jumbled zone which is poorly exposed, but which varies in dip from nearly vertical to about 50° towards the crater. The crater breccia extends up to the base of the Chattanooga Shale and continues at a relatively high elevation out into the crater. Many large megabreccia blocks up to at least 100 feet in length are common in this mass of breccia, particularly near the rim (Plate 2).

No other exposures of the northeastern rim are available except for those at the head of Cub Hollow. Unfortunately, the valley floor is so high in this area that only a very small part of the folded and eroded rim is exposed. Structure contours in the area suggest a rim uplift of between 30 and 50 feet at the level of the top of the middle Catheys unit (Plate 2). One exposure available in Cub Hollow and another in a small east-trending tributary show a tight monoclinal fold towards the crater, but less than 50 feet of folded strata are exposed. The monocline occurs in a horizontal distance of less than 50 feet and has dips toward the crater as great as 33^{o}. This fold is very similar to the monoclinal fold present along the western and northwestern rim. The breccia contact is not exposed in this area except for the presence of a thin wedge of dolomitic breccia in the eastern tributary (Plate 1). The dolomitic breccia lies in direct contact on the monoclinal fold and develops a very poorly bedded character as the contact rises in elevation. The exposures are too high in elevation to expose normal chaotic crater breccia in the upper part of Cub Hollow.

Eastern Rim

Exposures farther south along the northeastern rim and along the eastern side of Cub Hollow exhibit chaotic crater breccia which includes many large megabreccia blocks. Structure contours in this area on the base of the Chattanooga Shale also indicate a very large mass of breccia parallel to the rim (Plate 2). Large megabreccia blocks at least 150 feet long and 50 feet thick dip at various angles toward the center of the crater. From the available exposures these megabreccia blocks appear to be completely enclosed in breccia. The top of the breccia drops rapidly and irregularly into the crater in this area.

The eastern rim has excellent exposures showing rim uplift and tilting away from the crater as well as a variety of different types of folds and faults (Plate 2, 4). Rim uplift near the breccia contact is as great as 150 feet, occurring in a horizontal distance of 2500 feet. The initial rim deformation begins approximately 2500 feet east of the breccia contact as a very gentle upbend from nearly horizontal beds. At 1100 feet 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 again dip to the east. Beds 100 feet above this anticline are nearly flat-lying, a most remarkable change in attitude considering the very sharp folding in the adjacent lower beds. The nature of folding in this area is very similar to the folding in the northern rim in Lacy Branch Hollow. On the western flank of this anticline the strata continue to rise toward the crater and steepen until dips of 15° away from the crater are common 100 feet east of the breccia contact. At 50 to 100 feet from the breccia contact a sharp downbend occurs toward the crater with dips as high as 30°. This sharp fold near the breccia contact is analogous to the monoclinal fold described elsewhere along the rim.

Structure contours of the eastern rim on the top of the middle Catheys unit show even better than do the cross-sections, the broad uplift and eastward tilt of the eastern rim (Plate 2, 4). They also present another example of very tight anticlinal folding immediately adjacent to the breccia contact (Plate 2). Approximately 1000 feet south of the area where the eastern crater wall crosses the Flynn Creek Road, a tightly folded, closed anticline or dome occurs. Excellent exposures of the crest of this structure are found along the south-trending tributary to Flynn Creek and provide excellent control for the structure contour map (Plate 2). The axis of the dome is approximately concentric to the crater wall. Tighter folding on the crater side gives an asymmetrical pattern to the structure, with dips up to 46° towards the crater and 10° to 15° away from the crater. The structural rise to the crest of the dome

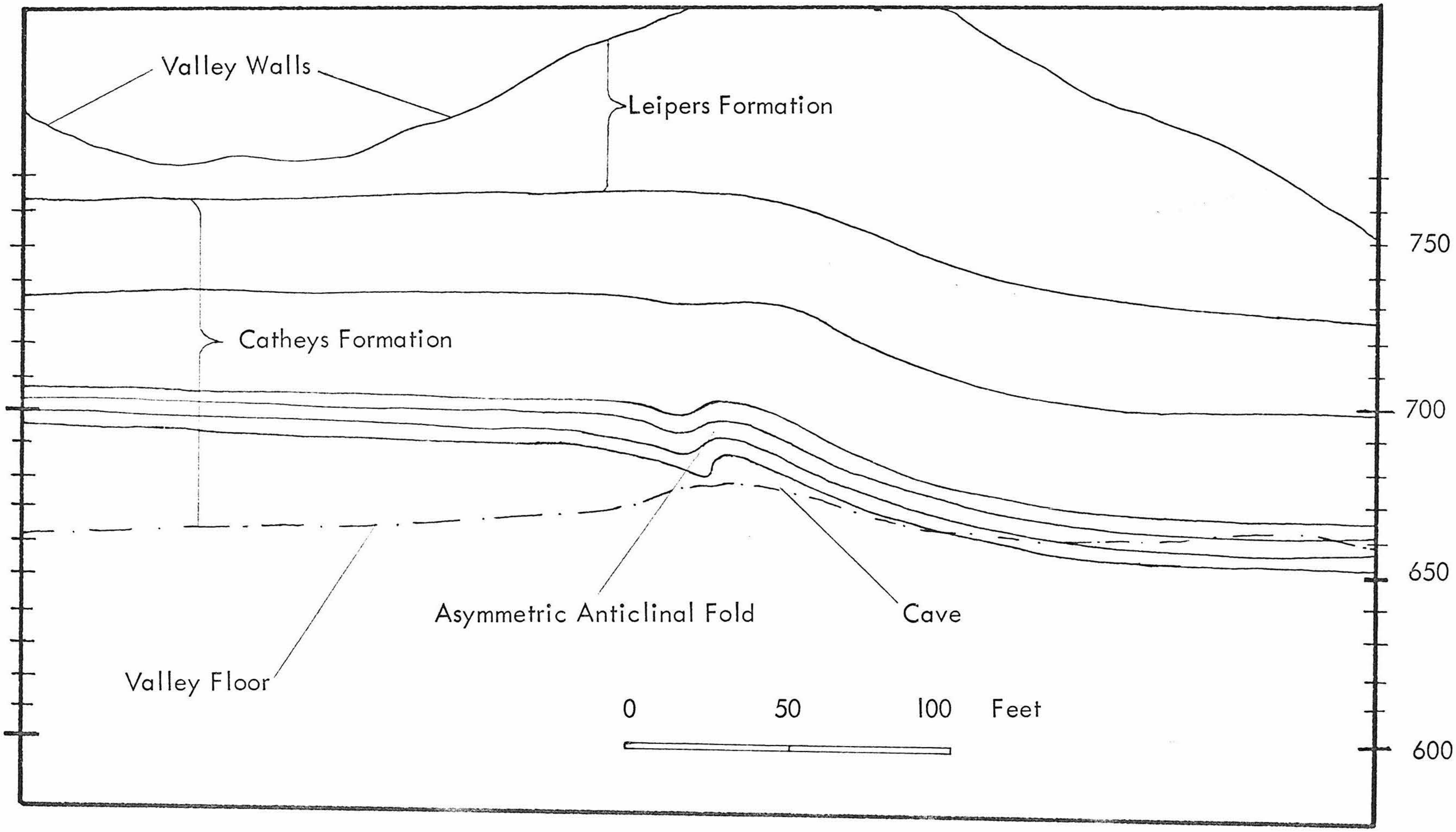
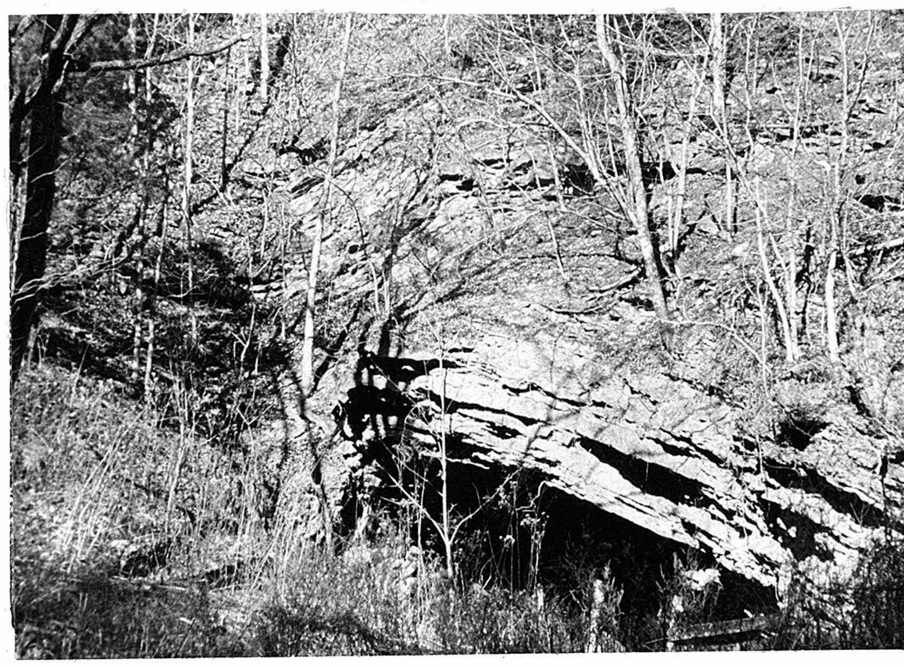


Figure 31.--Folding in Western End of Peters Hollow on East Side of Flynn Creek Crater, Tennessee. Tightly folded asymmetric anticline overlain by progressively more open folds. An elongated cavern now replaces the rocks in the core of the anticline.

A



B

Figure 32 --A, moderately folded Catheys strata overlying asymmetric anticlinal fold. B, tightly folded asymmetric anticlinal fold below A and showing cave in core of anticline.

is 50 feet in a horizontal distance of about 150 feet from the crater wall, and total rise of 170 feet measured from the eastern undeformed strata (Plate 2). Available exposures indicate that the dome parallels the crater wall for at least 2000 feet, plunging gently to the north and steeply to the south.

In the same area two small thrust faults and one small normal fault are exposed on the north side of the Flynn Creek Road and about 500 feet east of the crater wall. Figure 33 is a sketch of these structures with displacements and attitudes taken from a photograph. An interesting point concerning these structures is that they are only observable in the exposures in the road cut north of the Flynn Creek Road. It is extremely difficult to trace the faults up the hill side to the north where they appear to die out within a distance of a few hundred feet. If the road cut had not been located precisely where it is, it is extremely doubtful if these small faults would have been noted. Indeed, it is most likely that many more such structures are present along the rim, but simply are too poorly exposed to be seen.

The breccia contact along the east rim consists of an irregular jumbled zone a few feet to nearly 100 feet in width. Large megabreccia blocks are scattered in a disordered array along the rim in such a manner that separation of the folded rim strata and megabreccia is very difficult. Usually shallow excavations will show that the megabreccia blocks are surrounded by finer chaotic breccia of the crater. Also the lithologic differences between the rim strata and the crater breccia are useful, but not always definitive.

An example of extremely tight folding in a very large megabreccia block near the east rim can be seen approximately 400 feet west of the area where the crater wall crosses Flynn Creek Valley. Although this megabreccia block is larger than the average blocks along the rim, it demonstrates the problem of differentiating between folded rim strata and folded megabreccia. Where exposures are poor, these

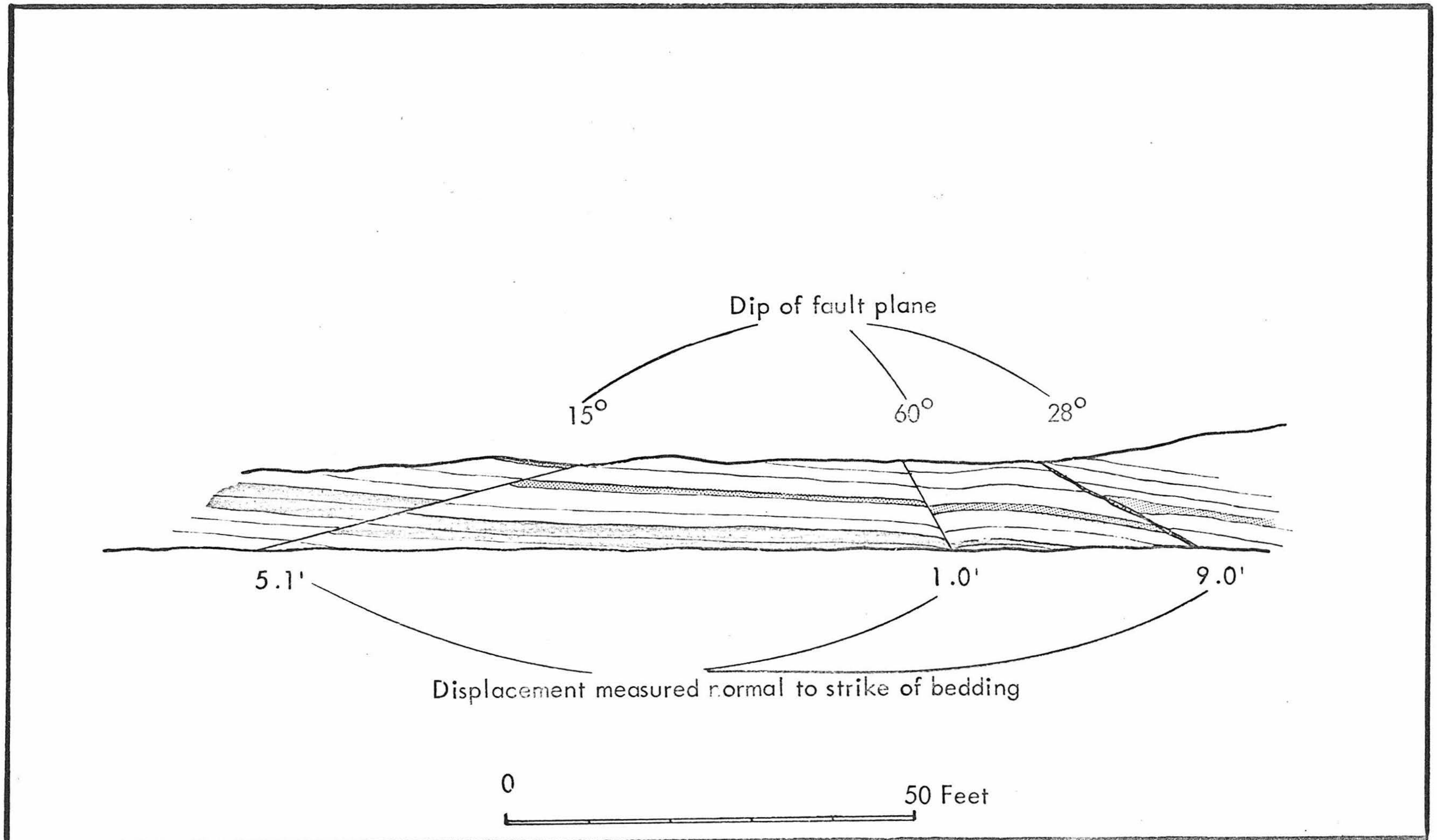
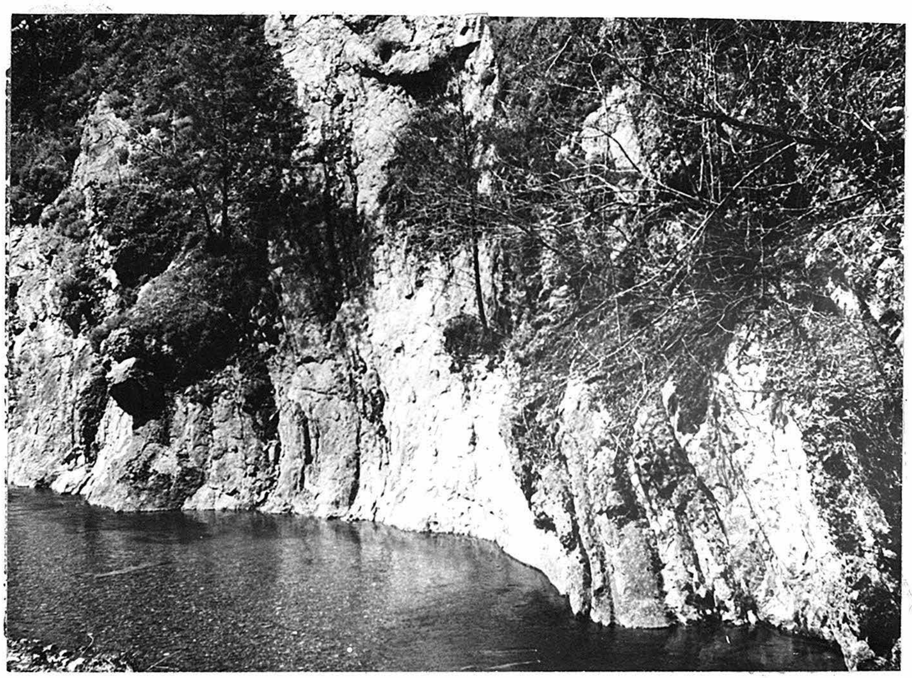


Figure 33 -- Field sketch of thrust faults and normal fault exposed on north side of Flynn Creek Road approximately 300 feet east of eastern crater wall. Outcrops are of lower and middle Catheys units.



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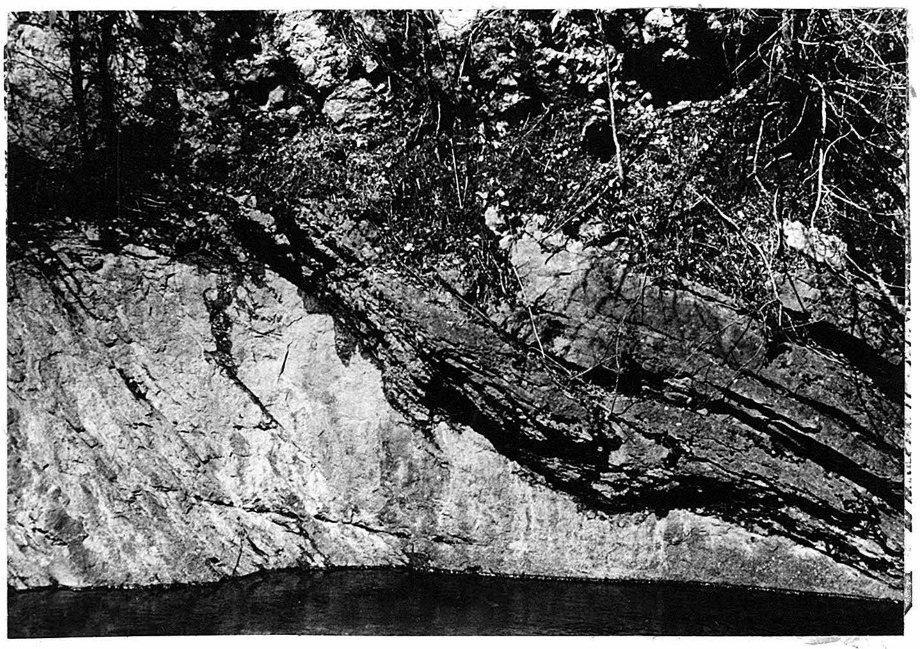
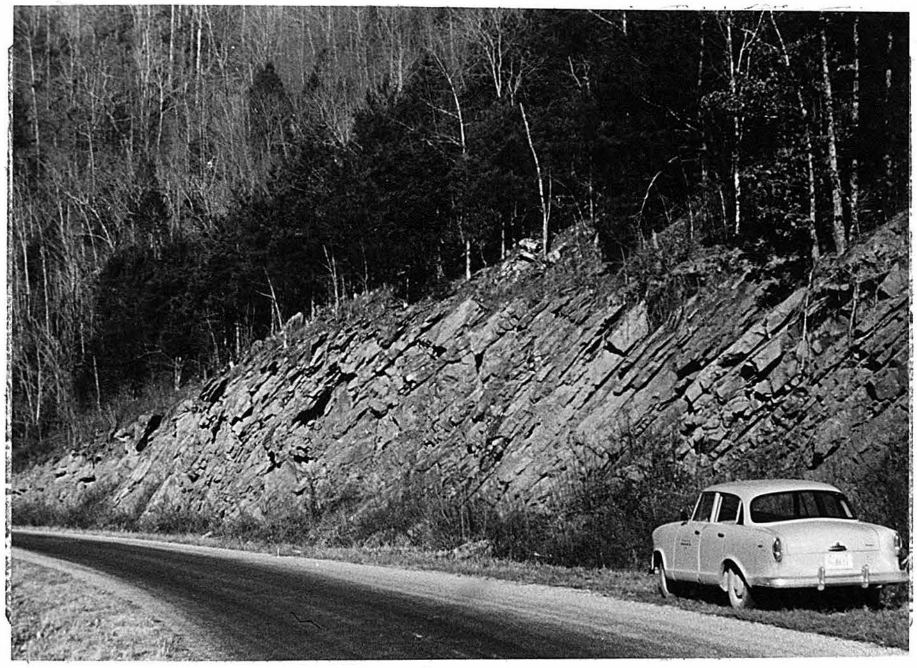
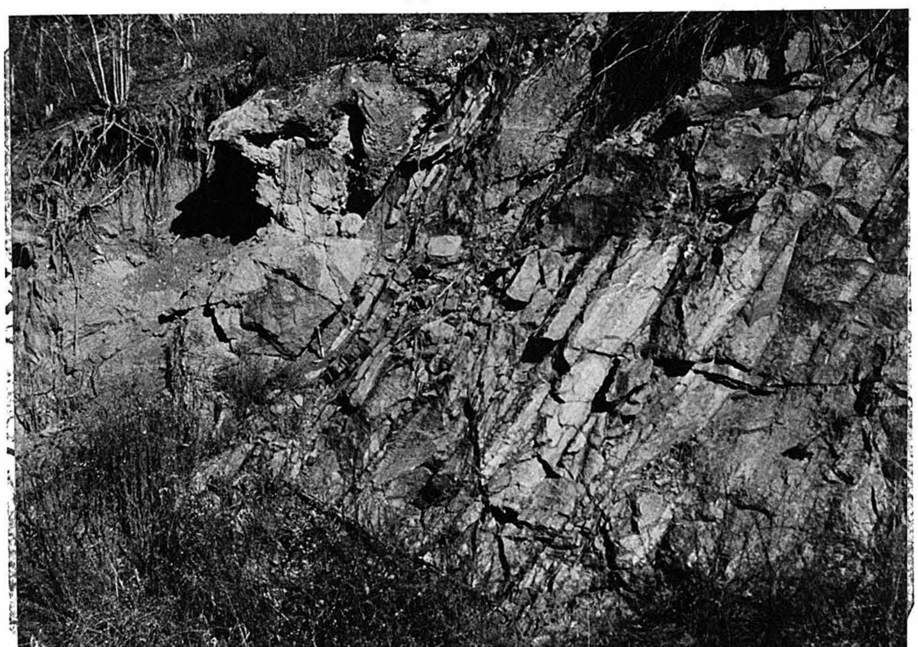


B

Figure 34 .--Typical megabreccia blocks of folded, faulted and brecciated Catheys Formation in Flynn Creek Crater near eastern side of crater.



A



B

Figure 35 --A, outcrop of megabreccia block of Cannon limestone in Flynn Creek Crater near eastern side of crater. B, western end of megabreccia block in photograph A.

types of large megabreccia are very difficult to properly identify. Another example of a large megabreccia block can be seen in the extensive road cut north of Flynn Creek Road and 700 feet west of the eastern crater wall (Plate 2, 4, fig. 35). In this area between 50 and 70 feet of Cannon limestone are exposed as a large megabreccia element dipping about 50 degrees west into the crater. In this block, however, the deformation is very slight and restricted to broad gentle folding. Coarse crater breccia can be observed surrounding the megabreccia element on all sides except beneath the block where it dips below the valley floor.

Southern Rim

The southeastern and southern rim contain the most complicated structures exposed in the entire rim. Within this part of the rim major faulting occurs with displacements on the order of 300 feet. Also located in this structurally complex sequence is a part of the pre-crater ground surface that was present immediately before the formation of the Flynn Creek structure.

Approximately 4000 feet south of the southeastern contact between the crater breccia and the deformed rim strata, the Catheys and Leipers strata occur at their normal elevations (fig.36). At 2600 feet south of the breccia contact the equivalent stratigraphic horizons are raised about 30 to 50 feet accompanied by a gentle tilting to the south. Except for the slight uplift, a 1150-foot-deep test well showed no deformation of the subsurface strata 2150 feet south of the crater (fig. 36). At about 2000 feet south of the crater a major fault zone is approximately concentric to the southeastern crater wall (Plate 1). The northern side of this normal fault zone has a minimum downward displacement of 300 feet and dips north at angles varying from 30° to 70° (fig. 36). The displacement dies out as

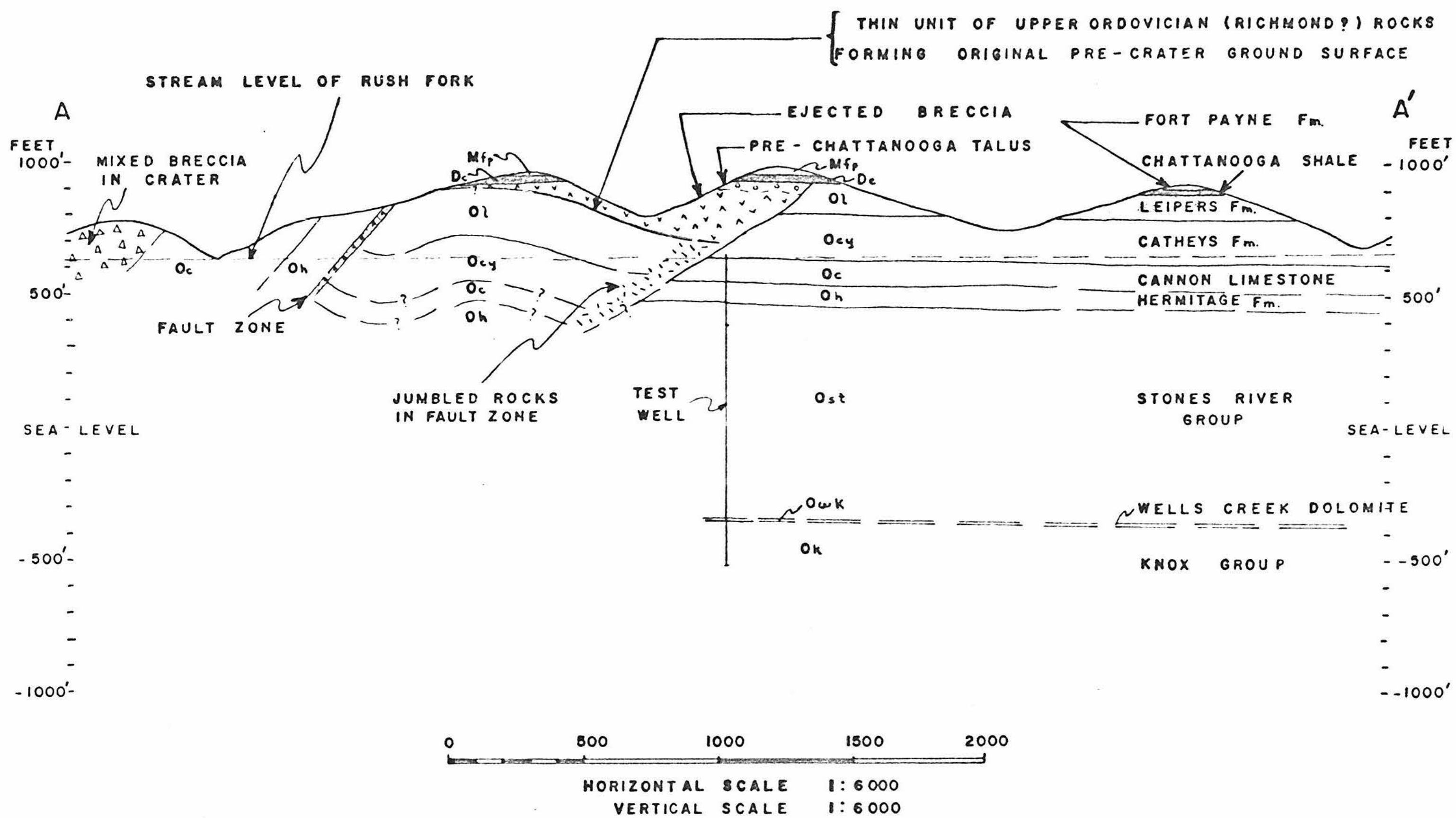


Figure 36 Geologic Cross-Section of the Southeastern Rim of the Flynn Creek Structure, Tennessee.

a hinge fault to the northeast, and within 2000 feet is reduced to only 20 feet displacement. The fault zone is very poorly exposed to the west, but appears to grade into a fractured and brecciated zone at about 2600 feet.

The strata on the northern side of the fault zone are composed of down-faulted Catheys and Leipers strata. Beds preserved in the upper part of the Leipers Formation in this down-faulted section are stratigraphically higher in the section than any Upper Ordovician beds observed in the area surrounding Flynn Creek (compare fig. 10 and fig. 36). At the top of this section of Leipers rocks are a few thin patches of pale green, argillaceous, dolomitic limestone. Although only a few feet of these non-fossiliferous beds are present, their gross lithology bears a resemblance to rocks of the Richmond Group (Upper Ordovician) located elsewhere in central Tennessee. As discussed in the section on Stratigraphy (p. 58) these rocks are probably part of the Sequatchie Formation of Richmond age.

These beds of probable Richmond age are immediately overlain by a thick unit of non-bedded breccia (fig. 36), with lithologies and gross textures that are very similar to those of the breccia in the crater. In the lower part of this breccia sparse angular fragments of the probable Richmond age rocks are mixed with angular fragments from the upper part of the Leipers Formation. Higher in the breccia the percentage of probable Richmond age rocks decreases, while the percentage of rocks older than Richmond age increases. This amounts to a very crude inversion of the ages of the breccia fragments with respect to the normal stratigraphic sequence of rocks outside of the deformed area. Fragments from the upper part of the Catheys Formation and lower part of the Leipers Formation become increasingly abundant in the upper two-thirds of the breccia. In this part of the breccia the lithologies of the fragments and the gross textures are markedly similar to many exposures of the breccia in the crater. The top of the breccia near the normal fault zone is overlain by a few feet of breccia that consist solely of fragments from the upper Leipers Platystrophia Ponderosa unit. This breccia appears to be a talus deposit that formed shortly after the mixed breccia was placed in the present position (fig. 36).

The entire sequence of the upper Leipers strata and the breccia are truncated by another major fault zone approximately 500 feet south of the crater wall. Beds on the north side of this east-trending, nearly vertical fault zone are raised about 300 feet and tilted steeply to the north with dips of up to 65°. The beds immediately north of the fault zone have been tentatively identified as part of the Hermitage Formation which in turn are overlain by the Cannon limestone. Approximately 650 feet north of the fault zone, the Cannon limestone is intensely deformed and forms a very irregular contact with the breccia of the crater.

The structural relief across the valley of Rush Fork is as great as 200 feet in an east-west horizontal distance of about 500 feet. The strike of all the beds in this part of the valley is also east, implying a north-trending fault between the two east-west faults and concealed beneath the alluvial floor of Rush Fork. Until subsurface studies are available, the attitude of this fault cannot be determined.

The two main east-west fault zones previously described can be traced west from Rush Fork for about 2500 feet. Farther west the few exposures available indicate a very large-scale jumbling of the entire sequence of strata between these fault zones. Some breccia zones are present but cannot be traced more than a few feet. The general appearance in this area is of a highly fractured, jumbled sequence about 1000 feet wide and 2000 to 3000 feet long. The western end narrows to a wedge where it appears to merge into the crater breccia at the crater wall in Steam Mill Hollow.

The contacts of the crater breccia with the rim strata in the few valleys between Rush Fork and Steam Mill Hollow are poorly exposed but have the same jumbled nature as the contacts in Rush Fork.

Figure 37 --Typical outcrop of folded and fractured ejected breccia overlying the graben in the southern rim.

Figure 38 .--Part of thrust block on southern rim exposing Cannon limestone.

In Steam Mill Hollow the rim strata, rather than being lifted, are folded into a shallow syncline plunging towards the crater. Beds immediately south of the southern jumbled contact dip up to 36° toward the crater in a steep monocline. Over a distance of a few feet the disorientation in the jumbling becomes so intense that individual units cannot be traced. The next several hundred feet toward the crater have great megabreccia blocks surrounded by chaotic crater breccia. The jumbled zone from the east cannot be traced into this area and appears to have merged with the crater breccia. The chaotic breccia overlies the megabreccia, rising up to the original rim level, and continues as a great mass of breccia well out into the crater.

Post-Crater Pre-Chattanooga Surface

The post-crater pre-Chattanooga surface has the same gross regional structure as that of the lower Ordovician horizons (Plate 2, 3). except for the area of the crater. There are, however, certain differences in this surface surrounding the crater when compared with the lower Ordovician horizons. The most notable of these are structural highs along the rim and the irregular valleys which were eroded into the rim. The normal local relief on the pre-Chattanooga surface is about 30 feet with dips averaging 1 to 3 degrees. There are areas where present structural relief in basins is as great as 90 feet, but lack of thickening of the Chattanooga Shale over the low suggests gentle post-Chattanooga deformation.

The most prominent structural high along the crater rim is centered about 2000 feet southeast of the southeast rim where it is underlain by the extensive mass of ejected breccia and the southern fault block. This is also an area which is structurally high on the Ordovician strata because of rim uplift. In this area the high drops about 50 feet to the south in a distance of 2000 feet, and drops 110 feet to the east in 5000 feet. This high is continuous for nearly one-fifth of the way around the southeast rim. Several other broad, flat highs are also present along the eastern, northern and western parts of the rim and are prominent features on the structure contour map of the post-crater pre-Chattanooga surface (Plate 3). The other structural highs average about 50 feet of relief with the surrounding flatter area.

The crater rim was moderately eroded in pre-early Late Devonian time in at least two localities, one on the north central part of the rim and the other on the southwest part. 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 (Plate 3). Other parts of the rim have short shallow valleys and gulleys which produce numerous minor irregularities in an otherwise relatively smooth crater wall. The Chattanooga Shale thickens from 27 feet to 38 feet in the northern rim valley. In the southern rim valley the thickness of the Chattanooga beds increases from about 28 feet to 31 feet. Occasional increases of the Chattanooga strata of a few feet are also present in a few of the other shallow valleys along the eroded rim. Thickness measurements along the eastern and southeastern rim indicate a thinning over the rim highs. The Chattanooga strata commonly decrease to about 25 feet over the highs and thicken to 27 to 30 feet to the east and southeast.

The outer parts of the crater present a very complicated surface on top of the breccia, as seen in Plate 3. Near the northwestern and western crater wall a continuous mass of breccia stands very high within the crater. Most of the breccia, if not all, is underlain by great megabreccia blocks for nearly 3000 feet. 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. In one case a closed high (nearly 70 feet high) of breccia and megabreccia is located nearly 2500 feet from the crater rim in the northeastern part of the crater (Plate 3). This is the only large isolated high of breccia found in the crater, but many smaller mounds of breccia are scattered throughout the crater floor.

Differential erosion has further modified the top of the breccia masses within the crater and along the crater wall to produce a complicated set of curving valleys and ridges. The valleys and smaller depressions all empty into the low area around the base of the central uplift. The deepest low is about 300 feet below the high on the western rim and 340 feet below the high area on the southeastern rim. Surface exposures are not adequate to define the exact location of the low that surrounds the central uplift, but present measurements indicate a low divide is present on the south and north sides of the central uplift which separate the western low from an eastern low (Plate 3). The eastern low is only about 15 feet shallower than its western counterpart. Considering both lows together, they extend about 75 percent around the base of the central uplift. Before the crater was filled, the central uplift stood as a steep-sided hill in the center of the crater.

In general the crater walls are relatively straight along the northeastern and northwestern rims for several hundreds of feet (Plate 3). The northeast crater wall trends N 45° W and the northwest crater wall is about N 45° E. The major rotated fault in the southeast rim dies out to the east with a general trend of N 50° E. The south-southwestern crater wall trends approximately N 50° W for several hundred feet.

Jewel (1949) stated that the dominant joint system and major fault zones and veins lie in a northeast direction on the northeastern and northern part of the Nashville Basin. He also described a set of minor joints and a fault system which lie in a northwest direction, but no bearing was specified for either direction. It would appear that the rough polygonal shape formed by the crater walls is the result of pre-Chattanooga erosion which was active along the original joint directions.

Structure of the Central Uplift

The internal structure of the central uplift has been partly described in the section on the stratigraphy of the Knox and Stones River Groups and need only briefly be mentioned again. The central uplift consists of a faulted, folded, and brecciated sequence of limestones and dolomite. The top of the Knox strata has been raised about 1000 feet. The overlying Stones River Group appears to be a continuous sequence, with several omissions of parts of the section caused by faulting, both low and high angle. The entire sequence in the western half of the uplift dips from 24^{o} to 60^{o} to the west. Large breccia zones cut the sequence at various angles and trend generally north. Exposures of the eastern half of the uplift are too poor to determine the exact nature of the structure. The shape of the central uplift can only be approximately defined by the present surface exposures (Plate 3), although the base of the structure appears roughly circular and measures about 3000 feet in diameter. There are no exposures on the southern side of the central uplift and its true shape may be more elliptically elongated northwest-southeast than circular. In either case the general outline is not greatly altered.

An elevation of 905 feet was measured at the top of the central uplift giving a maximum relief of 325 feet to the top of the crater breccia. The top of the central uplift is about 15 feet above the average rim height and about 15 feet below the maximum high on the southeastern rim. The flanks of the central uplift have an average dip between 10^{o} and 15^{o} but local increases in slope are as great as 30^{o}.

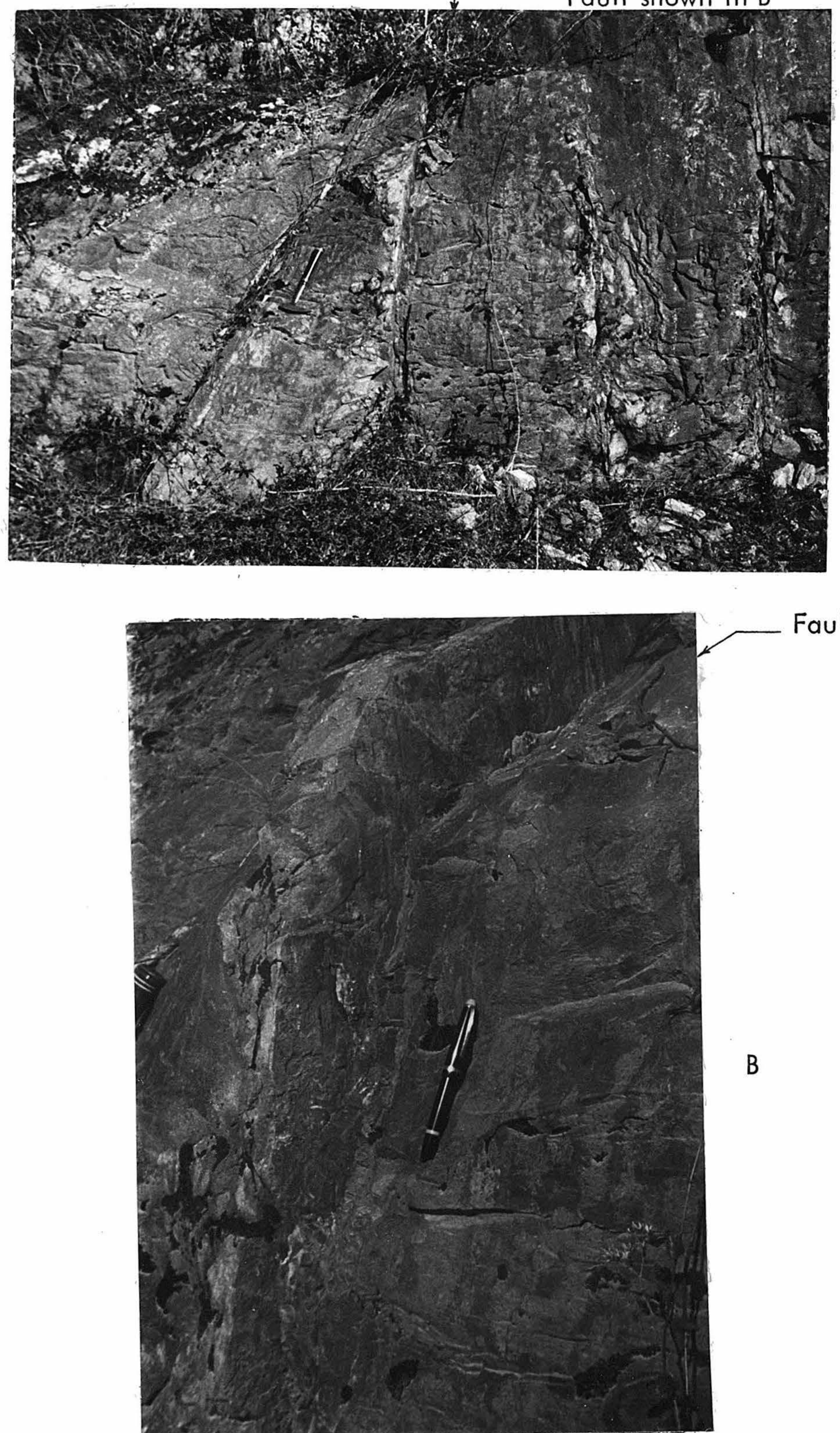


Figure 39 --A, faulted megabreccia block of Cannon limestone near southern side of the Flynn Creek Crater. B, fault plane in photograph A showing slickensides.

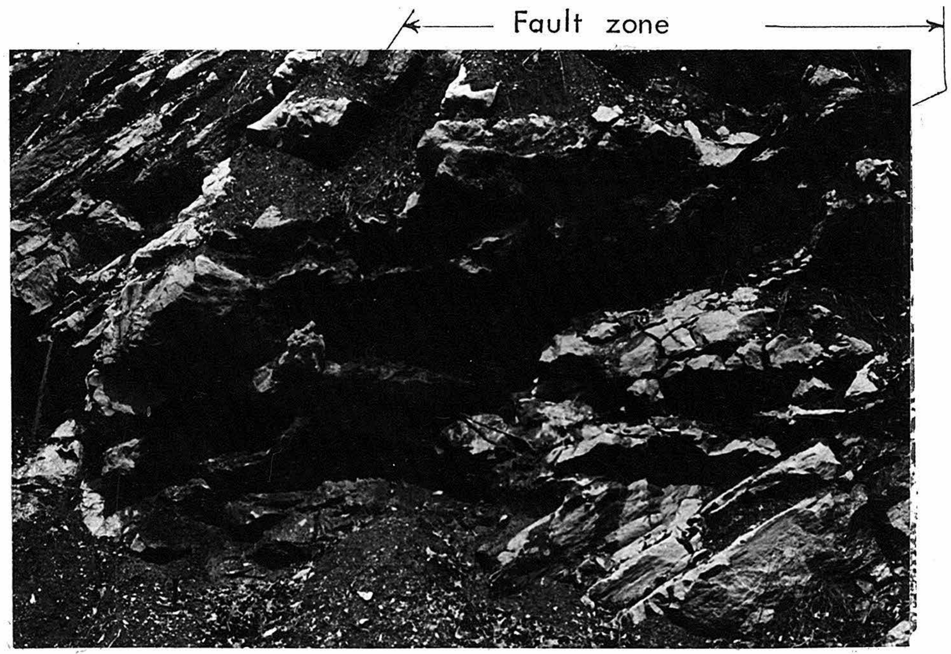


Figure 40 --Fault zone in Stones River strata in the uplift of the Flynn Creek Crater.

LABORATORY STUDIES

Introduction

Laboratory examinations were completed on the rocks of the Flynn Creek structure and surrounding area to look for possible volcanic and meteoritic material and for evidence of possible high pressure or high temperature modifications. The most significant results are the presence of an irregular band of highly twinned calcite in the deformed rim of the crater and the absence of mineral and chemical variations in the breccias. The laboratory studies are discussed in the following order: Petrography, Geochemical Search for Volcanic or Meteoritic Material, Search for High Pressure Polymorphs, and Thermoluminescence.

Petrography

General Statement

Approximately 250 thin sections were examined, with 90 of the sections prepared from the undeformed rocks surrounding the Flynn Creek structure to provide a comparison with the deformed rim strata and provide a standard for identification of the smaller breccia fragments in the crater. As a result about 80 percent of all breccia fragments could be assigned to specific stratigraphic units. The remaining 20 percent of breccia fragments could only be assigned to ranges which covered two or more stratigraphic units.

Mineral variations were specifically looked for, such as low temperature carbonate metamorphism in the beds high in clay content, but none were found. Breccias were examined in thin section for chemical or thermal alteration of the fragments or of non-carbonate materials in the matrix. In many cases insoluble residues were also prepared and examined by microscope and x-rayed when necessary.

The result was that nearly all materials recognized in the breccias and deformed rim were also recognized in the strata outside the deformed area. An exception to this is the matrix of the bedded breccia sequence which locally contained very finely divided "iron compounds" usually less than 100 microns in diameter and less than 0.1 percent by volume. When these particles were separated and concentrated, they were found to be mainly limonite, with occasional hematite, magnetite, and pyrite also identified near the Chattanooga Shale contact. One x-ray pattern showed poorly-ordered lepidocrocite. Goethite is also probably present, particularly in the limonitic masses, but was only tentatively identified by microscope. Two samples from breccia fragments with noticeable surface iron stains were examined for trace-element abundances, but no anomalous percentages or elements were present relative to the undisturbed strata (see section on Geochemical Search for Volcanic or Meteoritic Material).

Petrographic studies confirmed field observations that physical deformation, including coarse brittle fracturing, microfracturing, and moderate to intense twinning, was much more pronounced than mineralogical variations. The brittle fracturing has been partly described in the sections on stratigraphy and structure, and occurs mainly in the jumbled gradational zones forming the transitions between the rim strata and crater breccia. Petrographic examination of the fractures indicates that they were commonly filled by a microbreccia apparently derived from the walls of the fracture. Movement of a minimum of a few tenths of an inch is common along some of the fractures.

Microfracturing

Microfractures are usually apparent only in thin section and consist of several different types. A common type occurs at the ends of the larger brittle fractures where the width of the fracture has decreased to less than 100 microns. Usually this type of microfracture is filled by cryptocrystalline calcite with occasional large fragments from the walls of the fracture. Another type of microfracture consists of "bundles" of irregular fracture zones such as those described for the rocks containing shatter cones (fig. 19). The wider microfracture zones commonly contain microbreccia derived from the wall rock. There is some differential movement of the walls of the microfracture zones, but it appears to be on the order of a few tenths of an inch or less in most cases. The microfracturing is abundant in the strata of the central uplift, in many of the breccia fragments in the crater, and in an irregular, discontinuous narrow band around the deformed rim strata adjacent to the crater wall. Another type of microfracture appears to be a recrystallized or "healed" fracture common in the fine-grained dolomites of the central uplift. 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 (fig.41).

Twinning

Rocks containing moderately to intensely twinned calcite have a distribution similar to the strata containing microfractures. An exception is that the fine-grained dolomites of the central uplift and other deformed strata containing very fine-grained rocks do not exhibit noticable twinning. The most intense twinning in calcite is common in an irregular zone a few feet to several hundred feet wide in the deformed rim strata adjacent to the crater wall and in some of the breccia fragments in the crater. The more intense twinning consists of one to three sets of closely spaced non-twinned or microtwinned lamellae (Conel, 1962, p. 174 ff) and one to three sets of normal twin lamellae.

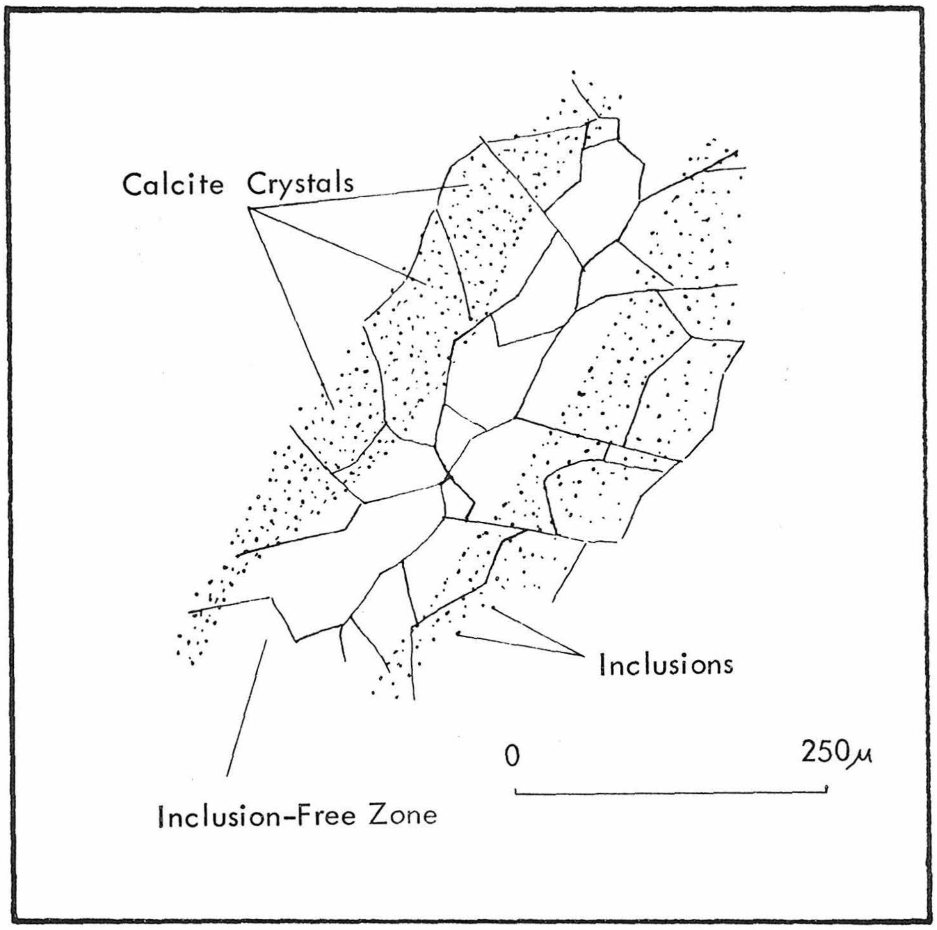


Figure 41.--Calcite crystals with abundant inclusions cut by a zone free of inclusions.

The normal twin lamellae are common in calcite both in the Flynn Creek structure and in the surrounding undeformed strata, but several important differences are present. In the undeformed strata calcite exhibits twin lamellae only in crystals larger than approximately 100 microns. In these crystals twinning consists of one to two, rarely three sets of lamellae ranging between 50 and 100 microns in width. Each crystal rarely contains more than 10 lamellae, usually spaced 150 microns or more apart. A few microtwinned lamellae are also present in these crystals and are usually parallel to the normal twin lamellae.

A pronounced difference in the number and relative abundance of both types of twin lamellae occurs in an irregular zone a few feet to several hundred feet wide in the deformed rim strata and adjacent to the crater wall. The normal twin lamellae increase in number from two to three times the number found in the same size crystals outside of the deformed area. Also it is more common to find two or more sets of normal twin lamellae and to have twinning in crystals as small as 20 microns. The most striking difference, however, is the very large increase in microtwinned lamellae in the deformed rim strata and in some of the breccia fragments (fig.42). Microtwinning is also prominent in some crystals as small as 20 microns (fig.43A). Kink bands occur in some larger crystals (fig.43B) and offsets of lamellae along microfractures are present in a few crystals.

Single crystals and groups of crystals which have a low percentage of twin lamellae occur irregularly through the zone of high twinning. Unfortunately petrofabric studies have not been completed on these rocks, but it is likely that a part of the low percentage of twinning is due to original crystal orientation and its low response to deformation in that position. This is certainly true under normal circumstances in deformed limestones. This explanation is probably not valid for individual rocks which contain groups of crystals with a low percentage of twinning associated with groups of crystals with a very high percentage of twinning. In this case about the

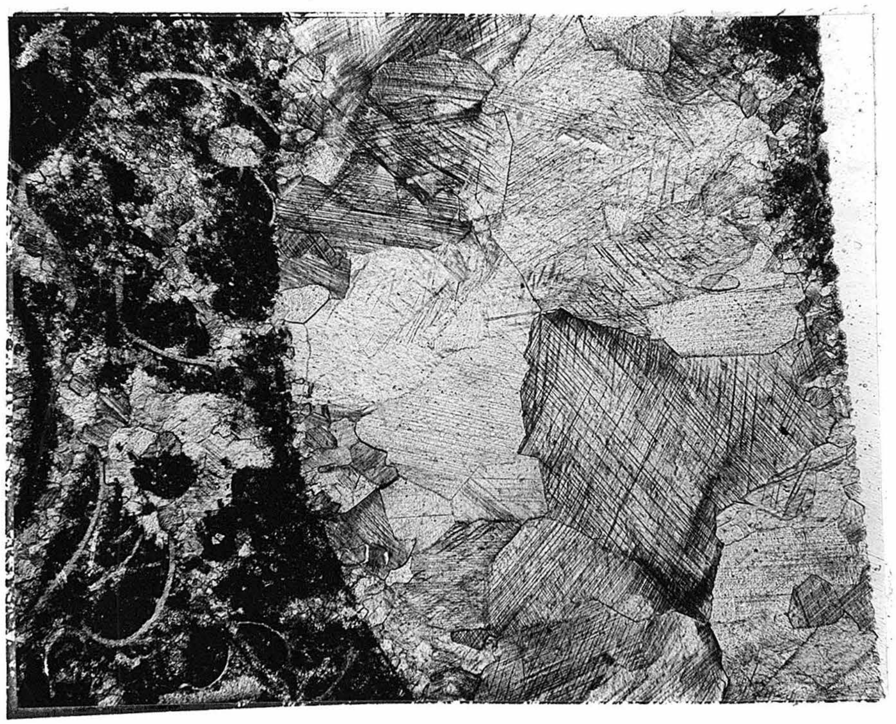
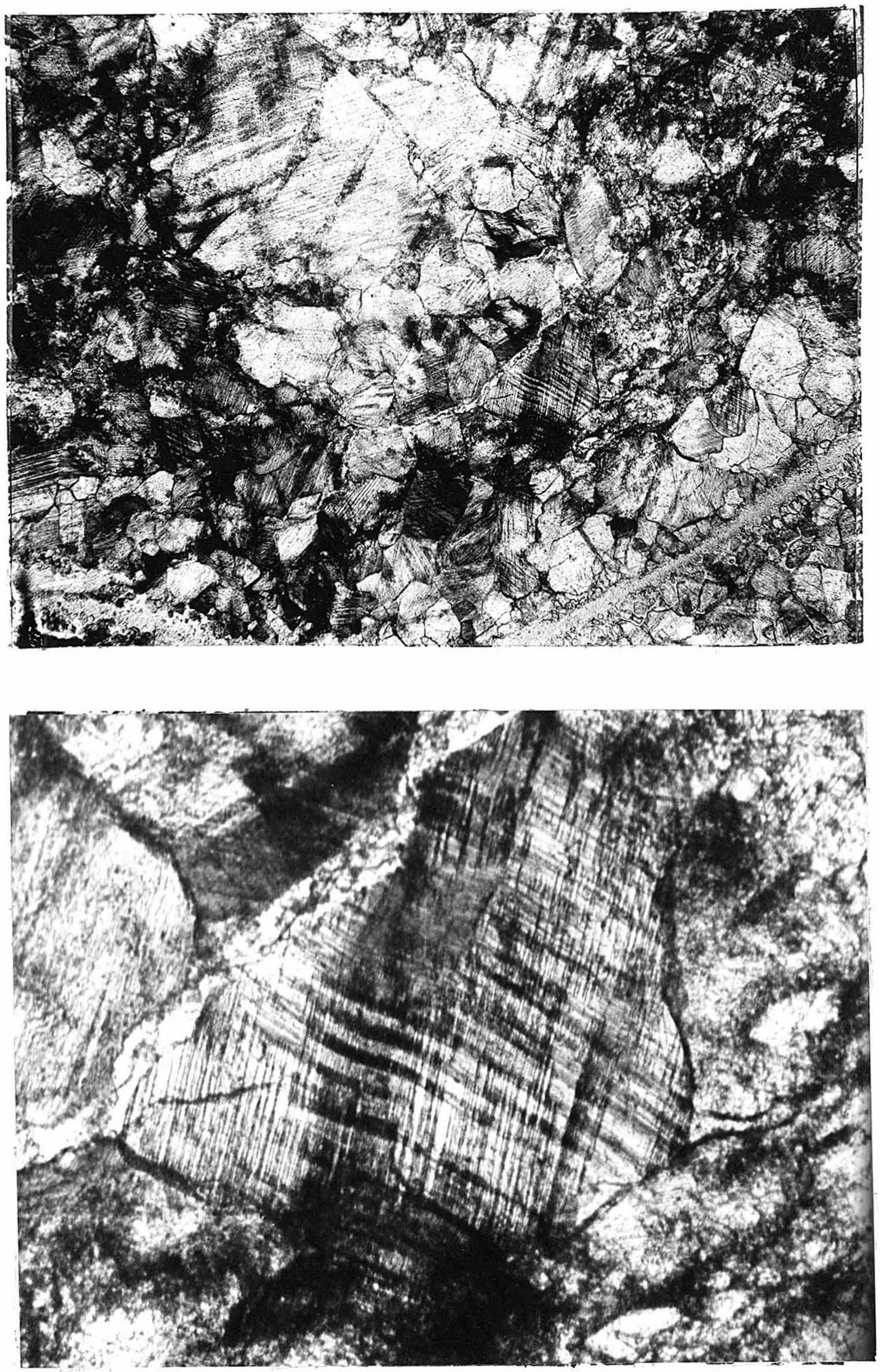


Figure 42 --Photomicrograph of intense to moderate microtwinning in coarse calcite from breccia fragment of Cannon limestone in Flynn Creek Crater. Note microtwinning in very small crystals in dark calcite matrix.



A

B

Figure 43 .--A, photomicrograph of coarse calcite crystals with twinning and moderate to intense microtwinning. Breccia fragment from Cannon limestone in western crater wall. B, kink band in calcite crystal in A.

Figure 44.--Photomicrograph of microtwinning in pre-crater clear spar in a fine grained pellet limestone. Note broken fossil at top cut by later calcite.

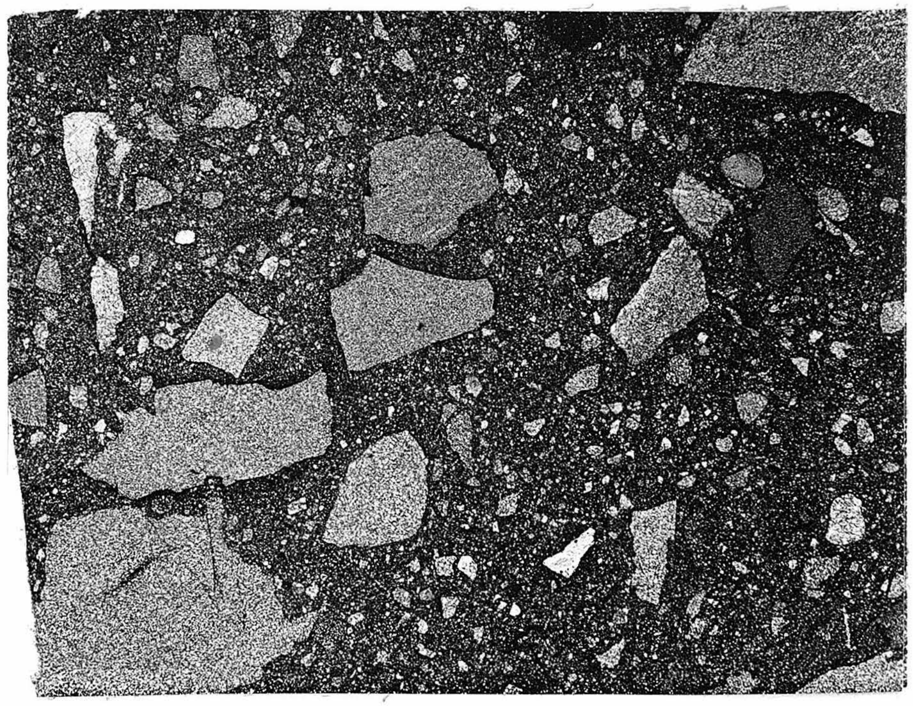


Figure 45 .--Photomicrograph of breccia from west side of central uplift containing fragments of Stones River strata in very fine grained dolomitic calcite matrix.

same number of crystals (5 to 20) and the same size of crystals occur in both groups, and it is reasonable to expect the same degree of random orientation in both groups. Considering the irregular trends of the fracturing and microfracturing it these rocks, it appears likely that the response to twinning could be equally irregular. Quite different intensities of deformation in different parts of the rock would be expected, depending on the time duration and nature of the deforming stress system. Gold (personal communication, 1966) independently suggested this effect is also true in his petrofabric examinations of deformed silicates from several of the Canadian "cryptoexplosion" craters. The unequal distribution of different intensities of twinning with single thin sections is shown in Figures 42,43.

The only exception to the low percentage of twin lamallae outside of the immediate crater strata was found in two isolated small bioherms of cherty limestone in the Fort Payne Formation. In these rocks thin, discontinuous breccia zones a few tenths of an inch wide were bordered by calcite with moderate to high percentages of twin lamellae. Field and petrographic relations suggest that these bioherms experienced collapse and compaction after formation, and that the thin breccia zones and accompanying twinning apparently resulted at this time. Discussions with H. A. Lowenstam (personal communication, 1966) suggests this is a likely mechanism.

Study of Well Cuttings

Well cuttings from three dry test wells located south and southwest of the Flynn Creek structure were examined for the possibility of: (a) subsurface deformation, (b) subsurface mineralization or chemical or thermal alterations, (c) identification and correlation of subsurface units with their equivalent formations exposed in the crater and rim, (d) correlation of subsurface units, (e) determination of thicknesses of subsurface units, and (f) determination of depths to different critical horizons.

The writer was given permission by W. D. Hardeman, Head of the Tennessee Division of Geology, to remove half splits of well cuttings of the Chaffin No. 1, McNabb No. 1, and Wheeler No. 1 wells (Plate 1).

The Chaffin No. 1 well is located in Rush Fork approximately 2,100 feet south of the crater and 330 feet south of the southernmost fault zone. The McNabb No. 1 well is located in a small valley west of Rush Fork and approximately 3,300 feet south of the crater. The Wheeler No. 1 well is located approximately 6,600 feet southwest of the crater. None of the wells showed any evidence of subsurface deformation, mineralization, chemical or thermal alteration. Occasional horizons of very fine pyrite and chalcopyrite were noted, but this is common for all subsurface samples in central Tennessee. Fine anhedral to subhedral barite crystals were noted in trace amounts in many of the horizons, but this is also common for the subsurface and surface limestones of Tennessee. The studies of the well cuttings provided the best lithologic correlations of the Stones River and Knox Groups in the subsurface at Flynn Creek with exposures in the central uplift and in east Tennessee. All of the surface exposures of these rocks in the central uplift of the crater could be matched with lithologic units in the well cuttings.

Correlation of subsurface units was accomplished mainly using lithologic changes, such as pellet horizons and high dolomite horizons, pyrite and chalcopyrite horizons, different types of chert, and thin bentonite beds. Correlations with surface outcrops of the Hermitage, Stones River and Knox strata were based mainly on lithology and chert horizons. The results of the subsurface correlation together with thicknesses and depth determination are shown in Figure 46 .

Geochemical Search for Volcanic or Meteoritic Material

A trace-element study was completed for selected rocks in the Flynn Creek structure and in the surrounding area to examine the possibility of low-level abundances of volcanic or meteoritic materials.

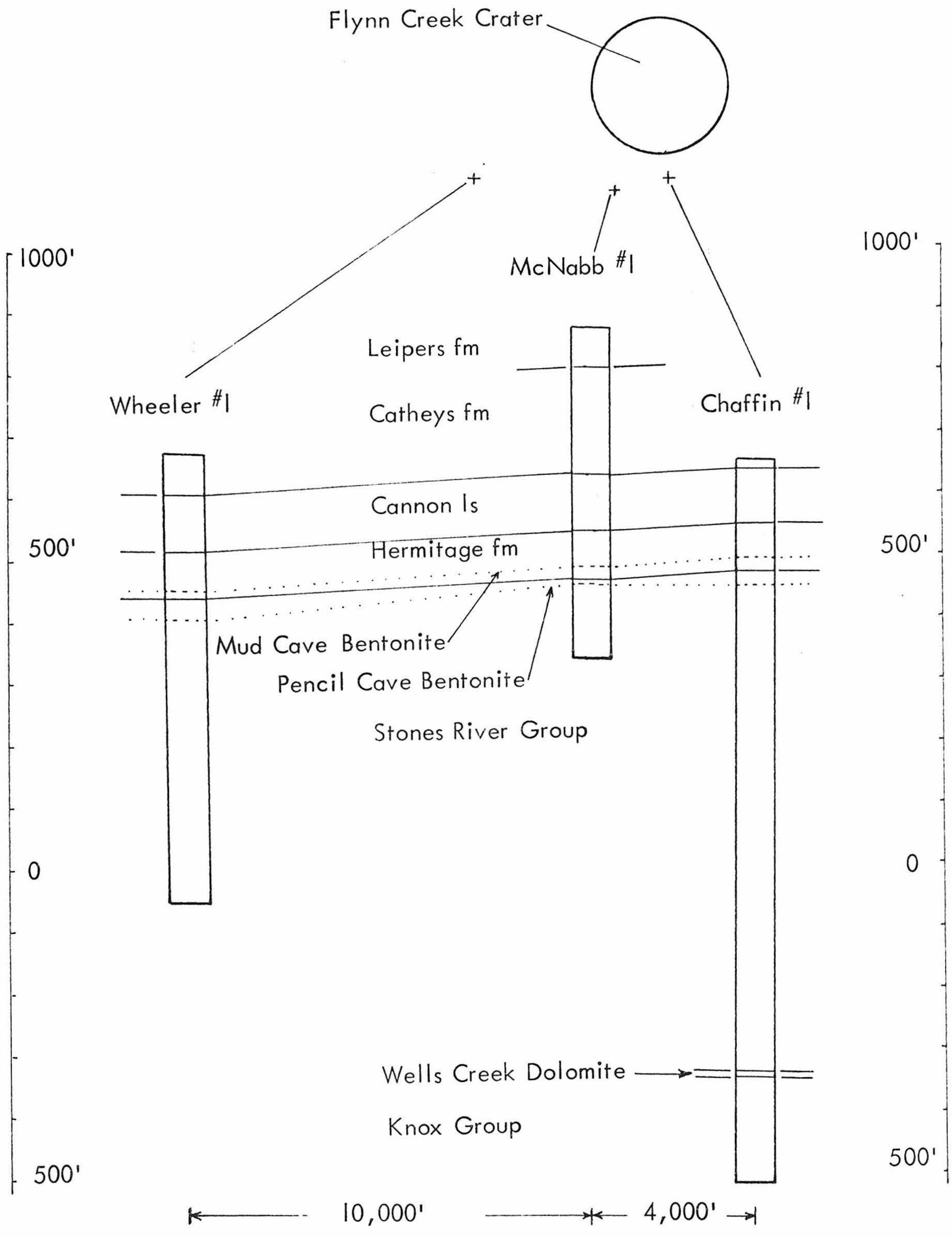


Figure 46 .--Correlation of Wheeler No. 1, McNabb No. 1, and Chaffin No. 1 Test Wells in Flynn Creek Area.

The results indicate trace-element abundances are quite constant throughout the area, including the crater, and all are within the limits given by Graf (1960) in his extensive collection of analyses for carbonate rocks. Figures 47 and 48 show the trace-element abundances and locations of the samples respectively.

The Flynn Creek analyses were made on total rock samples collected from ten horizons outside of the crater, three fragments in the breccia, and eight breccia-matrix samples. Natural variations in one bed outside the crater were determined by examining three samples separated by several thousand feet along the same horizon, the lower ledge unit in the Catheys Formation. The trace element abundances for these samples from the same horizon were nearly identical, indicating only natural low percentage variations, at least for this bed.

The breccia fragments that were selected for analyses are from the upper Leipers unit. These fragments were selected in particular so that direct comparisons could be made with the same undisturbed beds outside the crater. The trace element abundances of these breccia fragments are consistent with the abundances observed in the parent rock in the deformed rim strata.

The trace-element abundances in the breccia matrix are different from the preceding analyzed rocks only in that they occasionally have lower abundances for some of the elements (fig. 47). The most important aspect is that there were no trace element enhancements in either the breccia fragments or the breccia matrix.

It should be kept in mind that these results are valid only for the upper 100 feet of the exposed breccia, and the possibility remains that samples taken at depth will exhibit differences not seen in the near surface breccia. For example, if the crater was produced by an impact, then a "fall-out layer" (Shoemaker, 1960) should be present below the breccia that later washed back into the crater. If the crater was produced by a volcanic gas-phreatic mechanism, then traces of volcanic materials might be present deep in the breccia.

FIELD NUMBERS

	26	55	56	319	265	266	327	328	415	414	333	32	44f	44m	71	48	346	351	28b	46	50
Al	7000	7000	7000	15000	10000	20000	50000	50000	20000	50000	30000	30000	30000	20000	10000	10000	10000	7000	15000	10000	15000
Fe	3000	3000	5000	7000	20000	20000	20000	30000	10000	15000	15000	15000	15000	10000	15000	7000	7000	7000	10000	7000	10000
Mg	30000	10000	7000	5000	M	M	70000	M	M	70000	M	70000	M	M	M	M	M	M	M	M	M
Ca	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
K	0	0	0	0	0	2000	30000	30000	0	30000	30000	30000	30000	0	0	0	0	0	0	0	0
Ti	200	500	200	500	300	700	2000	2000	500	1500	1500	1500	1500	700	500	200	300	300	500	500	700
Mn	200	200	150	300	5000	1500	1000	3000	700	500	700	700	1000	1000	2000	1000	700	1000	700	700	2000
B	0	0	0	0	0	0	50	70	0	70	50	50	55	0	0	0	0	0	0	0	0
Ba	20	30	30	50	30	70	200	300	70	200	150	150	150	100	30	30	30	30	30	30	50
Cr	7	7	7	10	10	15	30	50	10	50	30	30	30	20	30	10	10	20	10	7	15
Cu	20	30	30	30	30	50	70	50	70	50	70	20	30	50	30	50	50	50	50	50	30
Ga	0	0	0	0	0	0	10	15	0	10	0	0	0	0	0	0	0	0	0	0	0
Ni	0	7	10	15	15	30	30	50	20	30	20	20	30	15	20	15	20	50	30	15	20
Pb	0	0	0	0	0	0	0	150	0	0	0	0	0	0	0	0	0	0	0	0	0
Sc	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0
Sr	700	700	1000	1000	200	200	150	150	200	150	200	300	150	200	150	150	150	100	150	150	200
V	0	0	0	0	0	30	50	70	20	50	50	50	50	0	0	0	0	0	0	0	0
Zr	0	0	0	0	0	0	70	50	0	70	30	0	0	0	0	0	20	0	0	0	0
Li	1	1	2	2	3	5	9	9	7	24	5	6	9	4	3	4	2	2	4	2	4
Rb	20	20	10	20	20	40	80	120	50	120	90	100	70	50	30	20	20	20	20	20	30
Cs	<5																				

Figure 47a.-- Spectrographic trace element analysis of rock samples taken from the Flynn Creek Crater and surrounding area. Semiquantitative analysis by U.S. Geological Survey, Denver, in ppm.

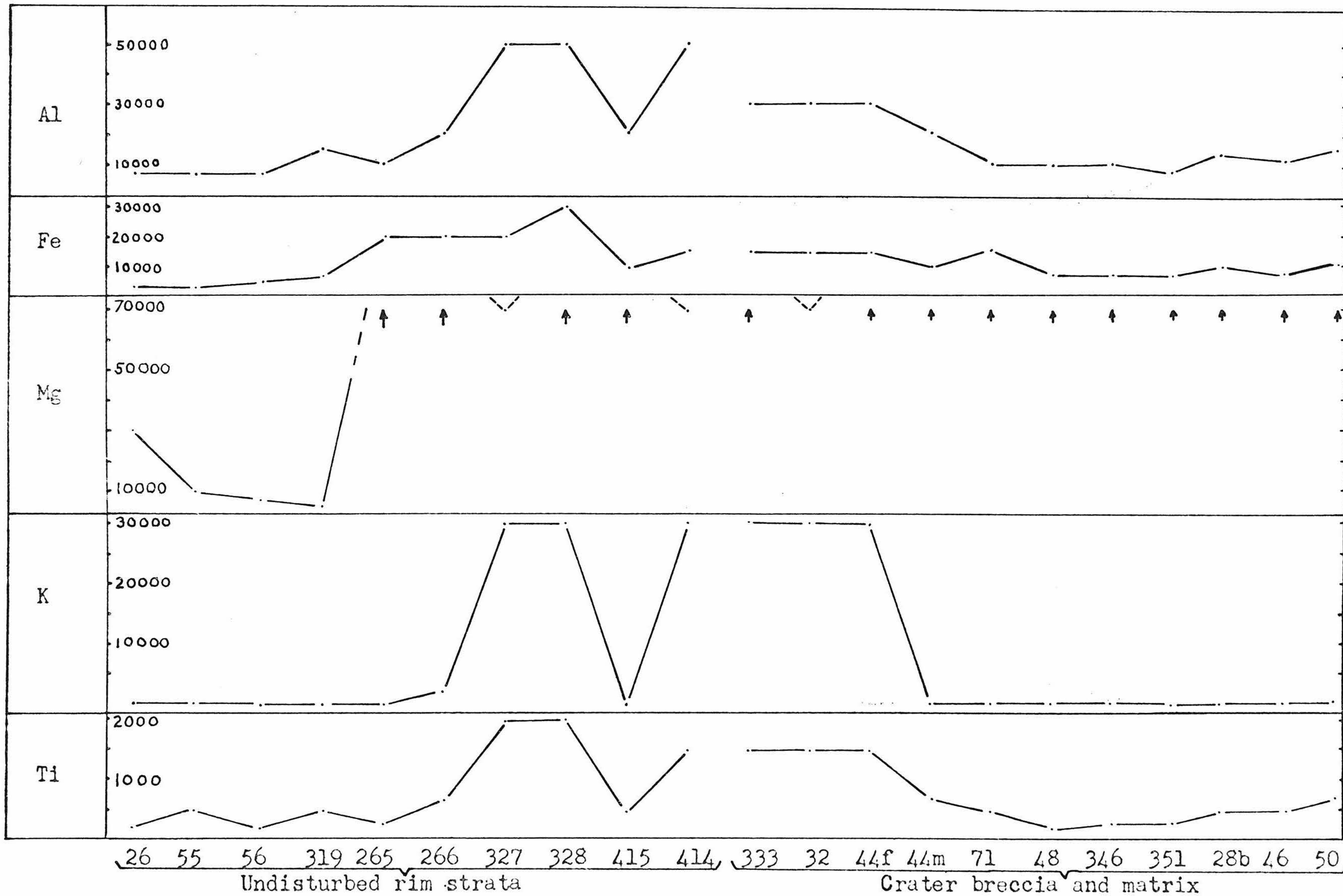


Figure 47b.-- Spectrographic trace element abundances of rock samples taken from Flynn Creek area.

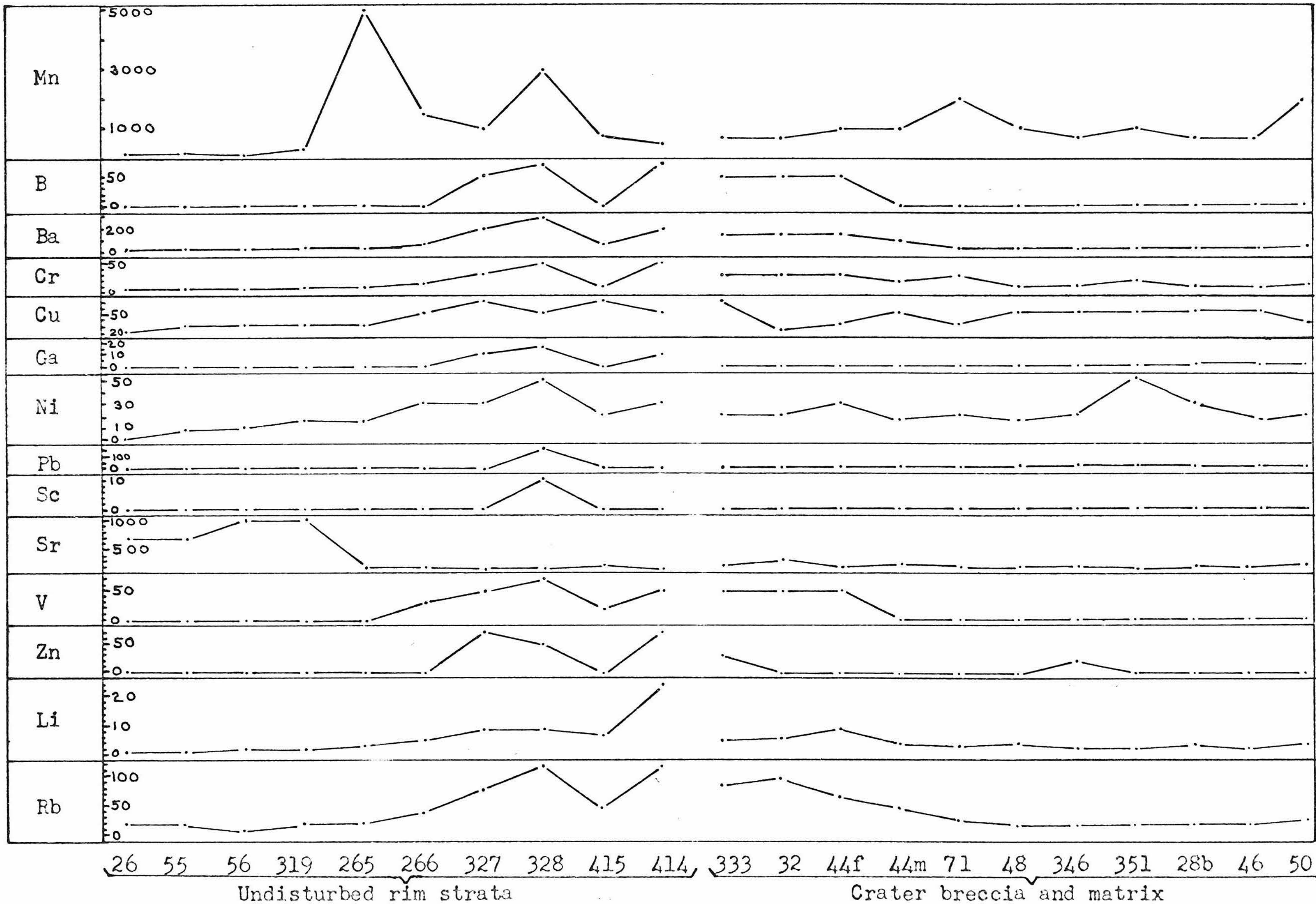


Figure 47c.-- Spectrographic trace element abundances of rock samples taken from Flynn Creek area.

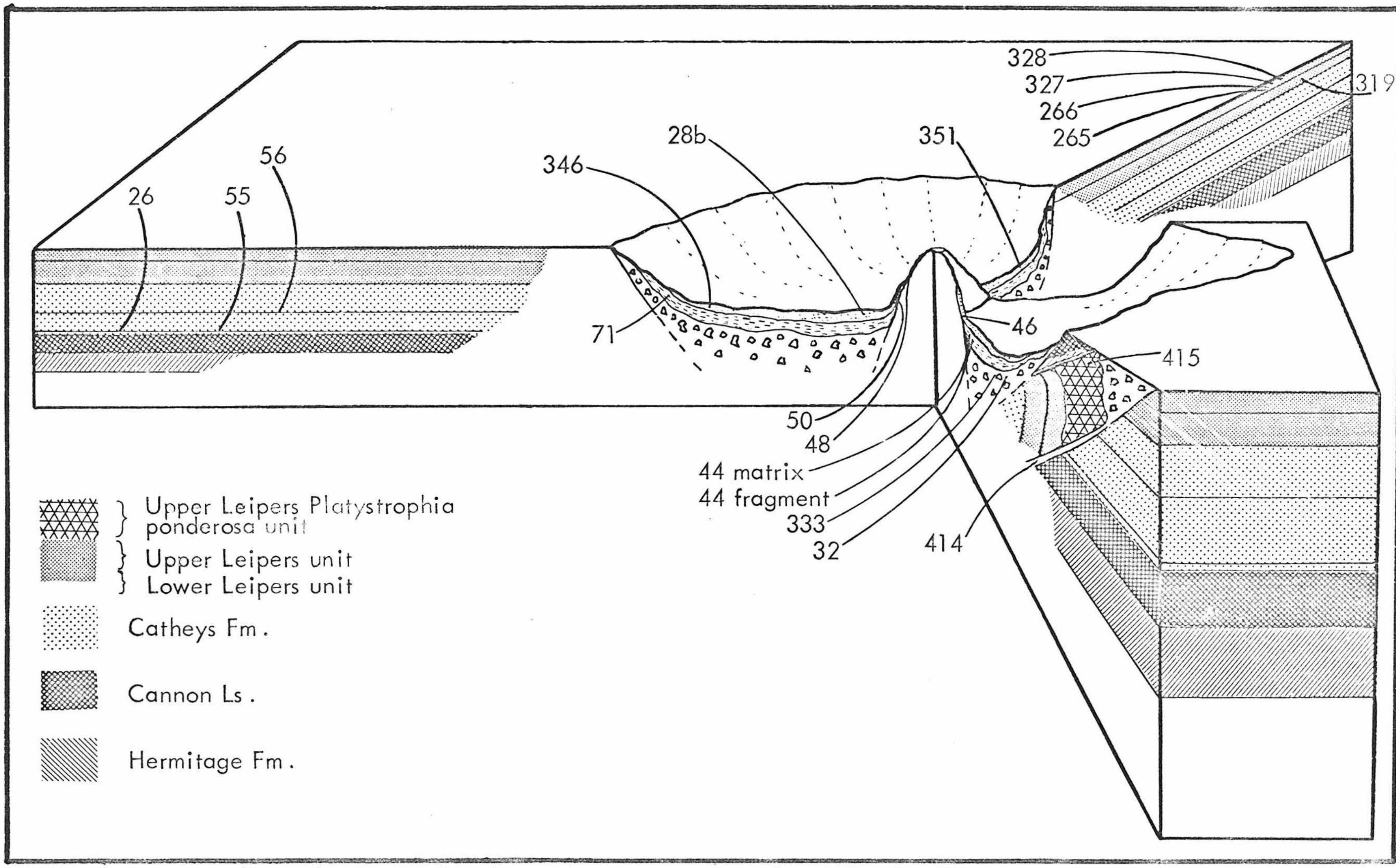


Figure 48 .-- Relative locations of rock samples used in trace element study of Flynn Creek Crater, Tennessee.

Search for High-Pressure Polymorphs

Rock samples were selected from the breccias and central uplift within the Flynn Creek structure and examined by x-ray diffraction techniques for possible high-pressure polymorphs, including coesite, stishovite, and aragonite. Four of the rock samples were taken from a group of beds in the shattered central uplift which contain an abundance of shatter cones and consist of fine-grained, equigranular dolomite. Very fine-grained, angular, detrital quartz grains are scattered throughout the rocks in concentrations averaging 0.2 to 0.7 percent. The other rock samples studied consist of intensely fractured limestone fragments located in the chaotic breccia near the eastern, northwestern, and southern rims of the structure. These samples are composed of intensely fractured, very fine-grained limestone, locally containing scattered chert concretions, chert fragments and fine detrital quartz grains. The total detrital quartz and chert content averages about 1.0 percent in these rocks.

Each of the rock samples were examined by x-ray diffraction for the presence of aragonite, but it was not found in any of the diffraction patterns.

All samples were then treated using 1000 grams in a 10 percent hydrochloric acid solution until all carbonate minerals were dissolved. The argillaceous part of the insoluble residues was removed and examined by x-ray diffraction, and the remaining material was then examined by x-ray diffraction. No trace of coesite or stishovite was noted in any of the diffraction patterns. Electron diffraction patterns of the shatter cone samples also showed no trace of coesite or stishovite.

All of the samples were then treated using the hydrofluoric acid procedure described by Fahey (1964). The maximum amount of residue remaining after 48 hours was usually less than a milligram, and no trace of coesite or stishovite diffraction lines occurred in any of the samples. Quartz was still present in small amounts.

The low concentration of quartz in these rocks and its irregular distribution pose a serious problem in the search for possible high-pressure polymorphs at Flynn Creek. Fahey (1964) has shown, for example, that coesite cannot be detected if less than 0.2 percent by volume of the total rock, even when it is a highly shocked pure sandstone. The limestones at Flynn Creek contain only one to two percent quartz. If one makes the unrealistic assumption that coesite was produced in the same percentages (by volume of total rock) as in shocked sandstone, then at least 1000 grams of limestone would have to be examined. If coesite occurred in very low abundances, as would be expected, then several kilograms as a minimum should be tested. Further work on this problem will be necessary before these tests are definitive for limestones bearing very small amounts of possible high-pressure polymorphs.

Thermoluminescence

Experimental impact studies on rocks in the laboratory have shown that certain parts of the thermoluminescence emission curve are increased in intensity after passage of a shock wave (Roach, 1961). Calcite is particularly susceptible to an increase of the emission peak, which lies between 240° and 280°C, and to a lesser extent an increase of the higher temperature peaks. Roach (1962, p. D98) states that, "Two characteristics of thermoluminescence of rocks shocked under laboratory conditions vary with the strength of the shock: (a) the total amount of thermoluminescence (area under the glow curve) decreases systematically with distance from the shock origin and, therefore, with decreasing peak shock pressure; and (b) in some rock types strong shock causes the low-temperature peak to have a greater amplitude than the high-temperature peak." Roach (1962, p. D 103) concluded that thermoluminescence techniques might be useful in the study of "cryptovolcanic" structures.

A set of samples were selected from the lower ledge unit of the Catheys Formation on the western side of the crater at Flynn Creek and examined for thermoluminescence. The samples were selected from the middle of the bed at distances ranging from 500 feet to 10,000 feet from the crater. A smaller number of samples were also taken from the upper ledge unit of the Cathey Formation and examined.

The thermoluminescence of each of the samples was determined, and results are presented as the ratio of the height of the low-temperature peak to the high-temperature peak and the ratio of the areas under the respective curves. Both ratios indicate a slight increase in intensity of the lower temperature peak in the ledge units very near the crater. One sample (F C 20), collected from the lower ledge unit approximately 9000 feet west of the crater, had values near those of samples in the deformed rim. This sample, however, was collected from a road cut which had several blast cores within 50 feet that possibly could have effected the low-temperature emission curves. This rock also has several percent of very thin vein calcite which increases the low-temperature peak.

Samples of the breccia fragments were also examined and had values comparable to the deformed rim strata. It is important to note that the highest values for the low-temperature curve are invariably found in the zone with the most intense twinning in the calcite.

Possible alteration effects of sample crushing were examined by the author on limestones from the Flynn Creek area by testing small uncrushed fragments of limestone and intensely crushed fragments. No modification of the emission curves were noted until the sample was both crushed and ground with a strong shearing motion. Only then did the low temperature peak noticeably decrease, presumably because of heating during the grinding. The author was unable to increase the low temperature peak by intense crushing in the samples studied.

The results suggest that the intensity of the low temperature curve does increase slightly in the deformed strata in the rim. It is possible that natural variations in other samples will alter the simple picture of increasing intensity of the low-temperature emission peak toward the crater. Further study will be necessary before this present data can be clearly related to the stress history of the crater.

GRAVITY AND MAGNETIC SURVEY

Introduction

A gravity and magnetic survey was made to complement the geologic studies and to try to provide additional information on the subsurface structure of the Flynn Creek crater. The measurements were based on one mile spacing along roads outside of the structure and a 0.2 mile spacing across the deformed rims and within the crater. Neither the gravity nor the magnetics studies indicate any large anomalies directly associated with the structure. The data reductions for this study were completed by Dr. S. Biehler of the California Institute of Technology.

Gravity

The gravity studies were made using a Worden gravimeter with a reading accuracy of 0.07 mgal. The gravity observations were corrected for terrain effects through Hammer's zone G and reduced to complete Bouguer anomalies assuming a near surface density of 2.67 gm/cc. The elevation of the gravity stations were determined by third order leveling, U.S.G.S. and U.S.C. and G.S. elevations at road intersections, and Kelsh photogrammetric elevations from air photos. Most elevations are accurate to 2 feet. A complex drainage pattern of deeply dissected valleys with steep hill slopes produce inner zone (C to G) corrections between 0.2 and 3 mgals. Terrain corrections are accurate to about 15 to 20% of the total correction, and errors from meter reading and elevation reduction give the complete Bouguer map in Figure 48 about ±0.6 mgal. maximum error.

No gravity anomaly of the level of 1 mgal. is associated with the Flynn Creek crater (fig. 49), and indicates only that there is no anomalous mass associated with the geologic structure sufficient to produce a 1 mgal gravity anomaly. A broad gravity minimum forms a trough trending north-south on Figure 49. This is probably associated with basement or intracrustal topography or lithology and is only a small portion of a much larger gravity feature as shown on the gravity map of the United States (1965).

Magnetics

Total intensity magnetic field measurements were made with a Varian nuclear precession magnetometer with an accuracy of 20 gammas. The total intensity magnetic map (fig. 50) shows that there is no large magnetic anomaly associated with the structure. Three small magnetic lows of less than 40 gammas exist near the center of the crater in areas where the Chattanooga Shale is thickest. These small magnetic lows may be related to the local thickening of the shale, but each low is based on only a single measurement and occurs in areas where contamination from man-made disturbances are high. Without further investigation little emphasis should be placed on these three points.

A north-trending magnetic trough extends across the southern part of the map (fig. 50), and a closed magnetic low of about 100 gammas 4 miles southwest of the Flynn Creek crater forms the lower end of the magnetic trough. This 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 that it is not associated with the Flynn Creek structure but more closely allied with the broad gravity minimum and its source. The absence of a large magnetic anomaly within the Flynn Creek structure indicates that there is little or no susceptibility contrast associated with the structure.

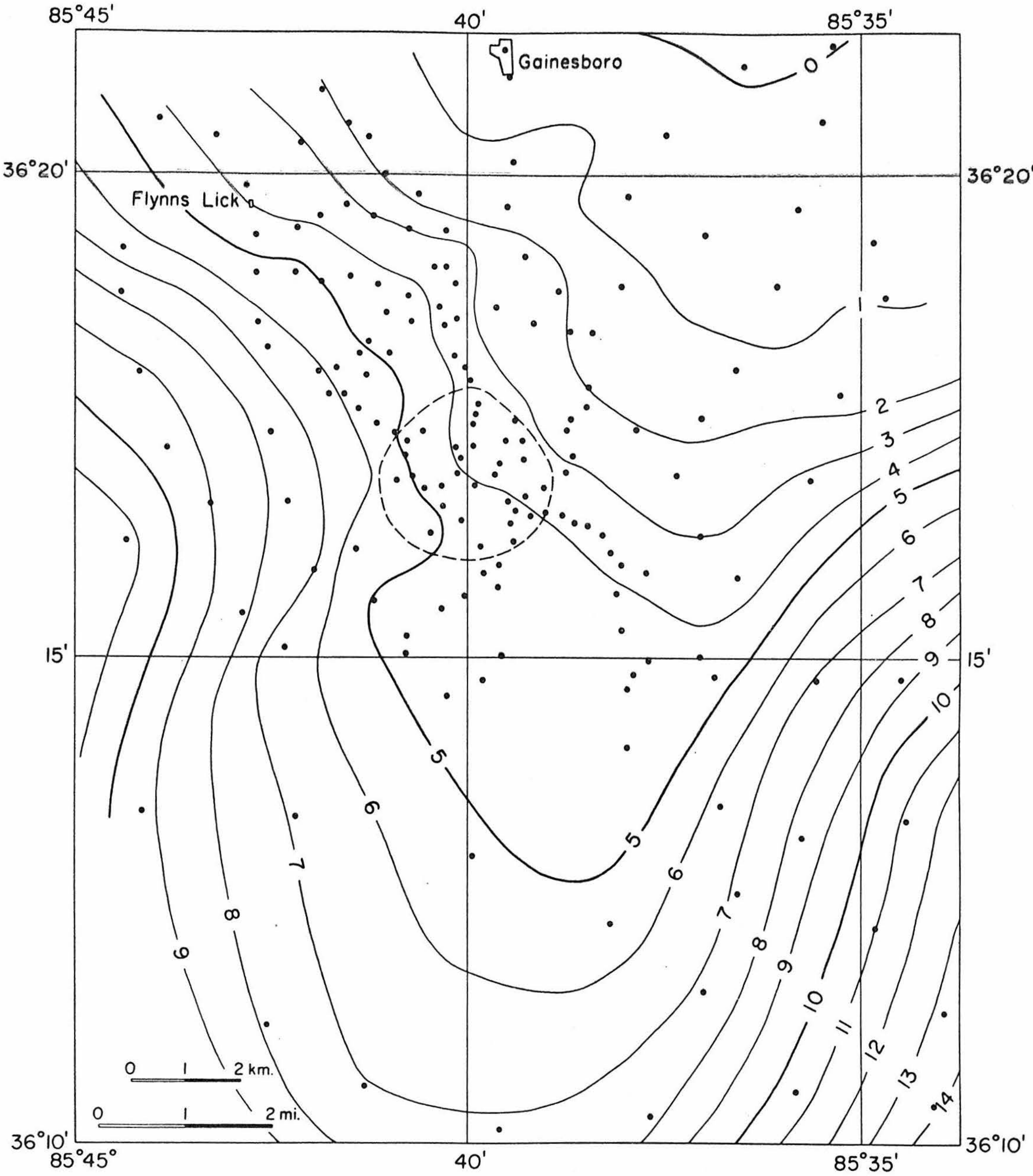


Figure 49. -- Complete Bouguer anomaly map of the Flynn Creek area, Tennessee. Contour interval = 1 mgal. Gravity station locations indicated by dots. Approximate location of Flynn Creek structure shown by dashed circle.

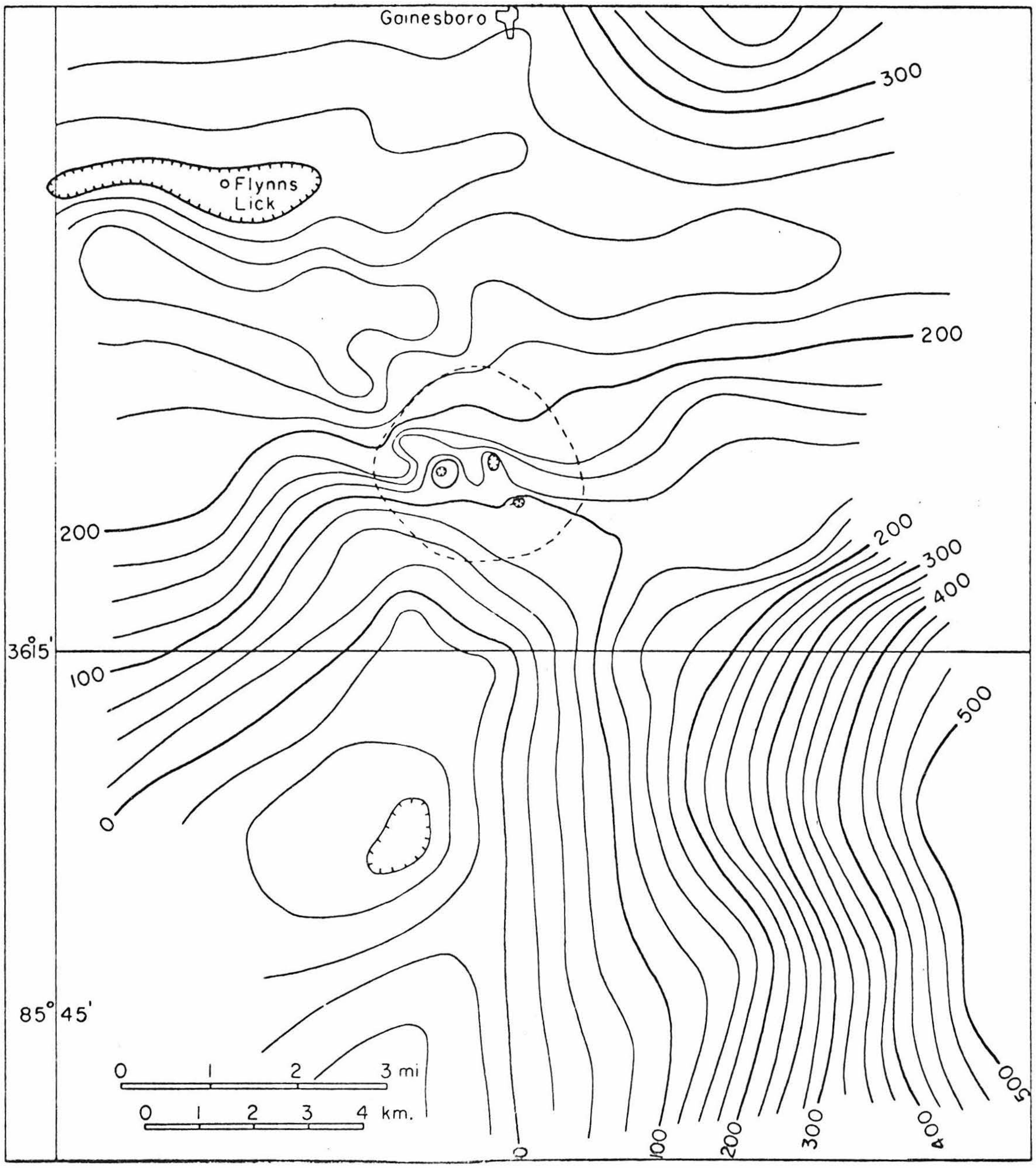


Figure 50.--Total intensity magnetic anomalies of the Flynn Creek area, Tennessee. Contour interval = 25 gammas. Approximate location of Flynn Creek structure shown by dashed circle.

ORIGIN AND HISTORY OF THE FLYNN CREEK CRATER

Introduction

The origin and history of the unusual structure at Flynn Creek have been the subject of a controversy for nearly a century. Different hypotheses advanced to explain the origin include: (1) cavern collapse, (2) salt dome or anhydrite expansion, (3) natural gas blowout, (4) tectonic folding, (5) hydraulic fracture, (6) volcanic gas explosion, and (7) meteorite impact. Cavern collapse is rejected because rocks within the crater have been recognized that are raised several hundred feet above their normal level. Origins involving a salt dome, an anhydrite expansion or a natural gas blowout are considered unlikely because evaporites and high pressure gas deposits have not been found in central Tennessee. The types of structures they produce are also unlike those of the crater at Flynn Creek. The type of tectonic folding necessary for such an origin is not present in the Flynn Creek area. Hydraulic fracture by water is also considered unlikely because it would not produce the type of structure seen at Flynn Creek, and there does not appear to be any way to get sufficient water pressures. The volcanic gas explosion and meteorite impact hypothesis require more detailed examinations. Each of these hypotheses is treated separately and in more detail in the following section.

Bucher (1963, p. 642) included the Flynn Creek crater as a "cryptoexplosion" feature and suggested that the structure was not consistent with an impact origin. Shoemaker and Eggleton (1961), on the other hand, classified this same structure as a "buried crater with the form and structure of a meteorite crater." The central point of the argument has resolved basically to comparison of the deformation at Flynn Creek with the structures observed in volcanic, impact and other shock-produced craters. If good structural comparisons can be established with craters produced by one mechanism, and if poor comparisons exist with other types of craters, then this will at least provide a specific model to test with further studies. Other criteria which might indicate an origin, such as the presence or absence of volcanic or meteoritic material or the presence of shatter cones, are also discussed. The geologic history of the crater is then presented in terms of what is known about the origin and the post-deformational sequence of events.

Summary of the Important Geological, Geophysical and Laboratory Data

The information in the earlier parts of this paper has been described without offering comments on what bearing the data have on the origin of the crater at Flynn Creek. To facilitate comparisons of the Flynn Creek crater with the other structures, the following summary is given of the geological, geophysical and laboratory data:

A. Geological Data

1. Regional

(a) Strata of Middle and Upper Ordovician age surrounding the crater are flat-lying and undeformed except for very gentle anticlinal and synclinal folding which is typical of the region. Dips on the flanks of these folds rarely exceed 2°. Faulting has not been observed in the several hundred square miles surrounding the Flynn Creek area.

(b) Mineralized breccia zones along what appear to be poorly exposed faults are present in central Tennessee, but none are closer than 12 miles to the Flynn Creek structure. Mineralization includes calcite, barite, fluorite, galena and sphalerite.

(c) The nearest deformed areas in Tennessee which are similar to the Flynn Creek structure are the Howell structure in the south central part of the state, the Wells Creek structure in the northwestern part of the state, and the Dycus structure approximately 12 miles northwest of the Flynn Creek area.

2. Crater

   (a) A nearly circular crater was formed in the flat-lying limestones with a diameter of about 11,500 feet.

   (b) The original topographic form was a crater with moderately to steeply dipping walls.

   (c) The average depth of crater measured from the top of the crater walls to the lowest point on the crater floor is about 330 feet. This is the depth after an unknown amount of breccia washed back over the earliest crater floor.

   (d) A chaotic non-bedded breccia forms the floor of the crater and is composed of angular fragments ranging in size from a fraction of an inch to megabreccia blocks 300 feet in length. The megabreccia is located along the outside of the crater. The breccia is composed of the same Middle and Upper Ordovician limestones that were present in the area where the crater was formed. The breccia is cemented by a fine-grained calcite to dolomitic calcite matrix.

3. Central Uplift

   (a) A sequence of steeply-dipping, folded, faulted and brecciated limestone and dolomite of Middle-Lower Ordovician age has been uplifted in the center of the crater. Before the crater was filled the central uplift represented a hill which rose about 300 feet above the crater floor and was nearly 2500 feet in diameter at its base.

   (b) The oldest strata in the central uplift have been raised about 1000 feet and contain the only shatter cones found.

   (c) Strata of the Knox Group of Lower Ordovician age and of the Stones River Group of Middle Ordovician age are now recognized as forming the central uplift.

4. Crater Rim

   (a) The strata in the rim are commonly uplifted and tilted away from the crater. The width of the deformation band in the rim strata varies from a few hundred feet to nearly 3000 feet.

(b) Anticlines and synclines are common in the rim strata and become more pronounced near the crater. The trends of most of the axes of these folds are concentric with the crater wall, but some fold axes are radial to the crater. Tight folding in parts of the rim produces radial shortening as great as 35 percent. Tight folds in the northern and eastern rims grade upward in less than 100 feet into progressively more open folding.

(c) A sharp anticlinal to monoclinal downfold is common in the rim strata adjacent to the crater wall. The width of this fold is commonly less than 100 feet.

(d) A large fault zone is present in the southern and southeastern rim with dips up to 50° toward the crater. The upper part of the Hermitage Formation of Middle Ordovician age, unexposed elsewhere in the area, is present in the lower part of the thrust plate. Displacement along the fault zone is at least 500 feet.

(e) The fault zone in (d) forms the northern boundary of a tilted graben in the southern rim. The southern part of the graben is bounded by a brecciated zone dipping 30° to 50° toward the crater. Displacement along this fault zone is about 300 feet. Units of Upper Leipers Platystrophia ponderosa strata that have been removed from the surrounding area are preserved in the graben.

(f) The fault zones of (d) and (e) die out as sharp anticlinal folds in the eastern rim strata and grade westward into jumbled strata of the southern rim.

(g) Breccia of Sequatchie strata of Richmond age (Upper Ordovician) is present in the fault zone south of the graben.

(h) Breccia with a very crude inversion in the stratigraphy overlies the graben mentioned in (e) and has a lithology identical to the crater breccia, except for the presence of fragments of the upper Leipers Platystrophia ponderosa unit and possible Sequatchie strata.

(i) Minor low angle thrust faults are present in the eastern rim, and minor high-angle normal faults are present in the northern and southwestern rim. All faulting is roughly concentric with the crater and restricted to the more tightly folded parts of the rim.

(j) The contact between the rim strata in the crater wall and the breccia in the crater is sharp and well-defined in some areas and gradational in other parts.

5. Crater Filling Deposits

(a) A bedded breccia, locally poorly bedded, wedges out high on the crater walls and thickens to at least 50 feet near the center of the crater around the flanks of the central uplift. Fragments in the breccia consist of the same rock types found in the underlying crater breccia and in the crater walls. An abundance of fragments from the upper Leipers unit is present.

(b) The bedded breccia of (a) is overlain by a single bed of dolomite, locally cross-bedded, that averages three feet in thickness and thins out high on the crater walls. The dolomite locally thickens to 25 feet in some parts of the crater floor.

(c) The Chattanooga Shale lies unconformable on a relatively flat surface with low relief surrounding the crater. The lower unit of the shale thickens from about 10 feet to about 170 feet in the crater. The rest of the overlying units of the black shale are nearly constant in thickness in the crater.

(d) Conodont studies indicate an early Late Devonian age for the bedded breccia of (a), the bedded dolomite of (b) and the basal Chattanooga Shale of (c).

(e) Strata of Mississippian age cover the area and sag gently over the crater.

6. Exposures

The area is now highly dissected by Flynn Creek and its tributaries. Good exposures of the rim structure, crater walls and central uplift are now present on the valley walls. The original crater floor is exposed on the floors and lower walls of some of the present deeper valleys.

B. Geophysical Data

1. Gravity

A detailed gravity study indicates no gravity anomaly on the level of one milligal is associated with the Flynn Creek crater.

2. Magnetics

A detailed magnetic study indicates no large magnetic anomalies are associated with the structure. Several small magnetic lows located within the crater appear to be associated with man-made disturbances and probably are not related to the structure.

C. Laboratory Data

1. Petrography

(a) No meteoritic or volcanic materials were found in the breccia fragments or in the breccia matrix. No chemical or mineral alterations involving high temperatures or metasomatic-hydrothermal processes were recognized.

(b) Fracturing and microfracturing is common in an irregular zone several tens to hundreds of feet wide in the rim strata adjacent to the crater wall.

(c) Twinning and abundant to intense microtwinning are present in calcite in the irregular zone of (b). The distribution of the most intense twinning and microtwinning is irregular, even on the scale of inches, but is generally confined to the rocks immediately adjacent to the crater wall. Some of the fragments in the crater breccia also have highly twinned and microtwinned calcite.

(d) Studies of well cuttings from three wells immediately south and southwest of the crater show no mineralization or deformation in the rocks down to a depth of 1150 feet, the deepest level of the wells.

2. Geochemical Search for Volcanic or Meteoritic Material

   (a) Trace element abundances appear to be relatively constant within individual horizons outside the crater.

   (b) Trace element abundances of rocks in the breccia are nearly identical with the values found for the parent rocks in the rim.

   (c) The trace element abundances in the breccia matrix are very nearly identical with the levels seen in the rim strata, and no anomalous values were found in the trace element studies inside or outside the crater.

3. Search For High-Pressure Polymorphs

   (a) An x-ray search for aragonite, coesite and stishovite in the more intensely deformed breccia fragments was not successful.

4. Thermoluminescence

   (a) Thermoluminescence studies indicate the possibility of a modification of the 270°C emission peak in the deformed rim strata, but the results are inconclusive.

Although a large amount of other field and laboratory data have been described earlier in this paper, the preceding summary lists the more important information that is necessary in a discussion of the proposed hypotheses on the origin of the Flynn Creek crater.

Cavern Collapse Hypothesis

In 1926 Lusk mapped the areal geology and structure of the Gainesboro quadrangle for the State Geological Survey of Tennessee. Lusk (1927) was apparently unaware of the reference by Safford (1869) to the Flynn Creek area, and he reported "the discovery of an extraordinary local thickness of the Chattanooga shale." Lusk recognized that the thickened part of the shale was localized in what he thought was "an irregular closed depression or series of depressions in a limestone conglomerate-breccia which is at the same attitude as Leipers, Catheys and Cannon strata. The actual contact of the breccia with formations other than the shale was not seen."

Lusk considered several hypotheses for the depression, but rejected each for different reasons (see p.15 of this study). He then concluded that at the beginning of the deposition of the Chattanooga shale, there must nave been a depression with an irregular outline and an uneven floor. Lusk considered that:

> 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.

Lusk, however, did not recognize the Stones River and Knox strata in the central uplift where rocks have been raised nearly 1000 feet. Wilson (1936, p.829) rejected cavern collapse when he mapped what he called "Lowville limestone" (now Carters limestone) in the central uplift. During the study by the author many other blocks in the crater breccia were found tens of feet above their normal stratigraphic level. These raised blocks, including the uplifted Stones River and Knox strata, clearly eliminate an origin by cavern collapse.

Salt Dome and Anhydrite Hypothesis

Wilson (1936, p. 829) suggested the intrusion of a salt dome or an anhydrite expansion as possible origins of the Flynn Creek crater, but he rejected both because of the absence of evaporite deposits in the strata of central Tennessee. The writer assumes that solution of the salt or anhydrite was part of the proposed mechanism to account for collapse of the breccia into the crater. The subsurface information that has become available over the last 30 years has tended to substantiate the objection offered by Wilson. Information obtained from deep drilling in southern Kentucky and in Tennessee indicates that it is unlikely that conditions in these regions were ever suitable for the formation of evaporites in Cambrian or Ordovician time. In this part of the Interior Lowlands evaporites apparently did not occur until upper Paleozoic time. A further objection to a salt dome origin at Flynn Creek is that no similar structure has yet been recorded in the many hundreds of salt domes investigated throughout the world.

Bucher (1936) considered Upheaval Dome in Utah as a typical example of the "cryptovolcanic" structure although it had been described earlier by Harrison (1927) as a salt dome. Bucher drew mainly upon the unpublished work of E. T. McKnight and described the structure as having a circular outline about 3 miles in diameter and a "central uplift" surrounded by a ring depression (syncline) about half a mile wide. Some of the strata in the "central uplift" have been raised about 1,200 feet. The less competent sandstones are highly folded in parts of the syncline and center of the structure. Faulting is very rare, and shattering or brecciation is absent except for the disordered, chaotic blocks in the center of the structure. No volcanic material has been found in the area. McKnight (1940) studied the area in some detail and stated, "The rock in the center of the dome is greatly broken, mashed, and squeezed, as if it had been plastically kneaded, but...can in no way be described as a breccia."

Bucher was aware of the great thicknesses of salt and gypsum in the underlying Paradox Formation, but he argued that the ring depression of Upheaval Dome made the structure significantly different from salt domes. Bucher (1936, p. 1066) concluded that the origin must be "cryptovolcanic" and has resulted from a buried igneous plug, presumably having a high gas pressure.

McKnight (1940, p. 126-128) later opposed Bucher's view and pointed out that the ring syncline is not an atypical structure to develop on the flanks of an intruding salt dome. He quoted the studies of Nettleton (1934), which predicted this behavior of an intruding salt mass, and concluded that Upheaval Dome is probably the top of a salt-dome structure. A cross-section of the dome (Nettleton, 1940) is consistent with some of the cross-sections of Gulf Coast salt domes shown by Murray (1961). From the present information it appears that Upheaval Dome is not typical of the "cryptoexplosion" structures, and it certainly bears little resemblence to the Flynn Creek crater. It should be noted also that shatter cones, regardless of their origin, have not been found in the rocks in the "central uplift" of Upheaval Dome. On the other hand, shatter cones are present in each of the other "cryptoexplosion" structures described by Bucher (1936). Although the origin of shatter cones has not yet been firmly established, their occurrence in most of these structures and their absence in Upheaval Dome implies a different mechanism of deformation.

Natural Gas Blowout Hypothesis

Wilson (1936, p. 829) suggested the possibility of a natural-gas blowout but felt it unlikely because, "The stratigraphic horizon (Lower Ordovician) makes it improbable that sufficient natural gas occurred deep enough below the pre-Chattanooga to have blown out a crater." It is now known that Knox strata are involved in the central uplift. This places an upper limit on the level at which a possible gas concentration would have had to exist. This level would have been about 1500 feet below the pre-crater surface and in the upper part of the Knox strata. Subsurface information accumulated over the past 30 years has proven this is not a productive part of the section for oil and gas, and a review of the drilling data has shown that only small amounts of oil and gas have been found locally in the upper Knox Group.

Natural gas under very high pressure has been known to cause collapse craters under special conditions. C. H. Dix (personal communication, 1965, 1966) described a collapse crater produced during a gas blowout which occurred in 1935 over a small structural dome about 4 miles northeast of the city of Maturin in northeastern Venezuela. The small dome was located approximately over the deepest part of a very large east-northeast trending syncline. The southern limb of the syncline rises gently to the south toward the Brazilian Shield. The northern limb of the syncline rises very steeply 10 to 20 miles north of Maturin. Dix stated that the sedimentary strata in the deeper parts of the syncline had a thickness in excess of 15,000 feet according to seismic reflection studies.

A test well was drilled over the crest of the small dome, and the well was cased to about 900 feet. The upper several hundred feet of the well was in poorly consolidated sandstones. At about 800 to 1000 feet the drilling penetrated a limestone of unknown thickness. At this level gas began to flow up along the outside of the casing carrying small fragments. Apparently the casing was weak and deteriorated at this level. The ground surface around the top of the casing began to cave-in along the side of the well as a violent flow of gas issued from the sides of the test hole. The drill rig collapsed into the rapidly forming crater, and the one man operating the equipment was barely able to "outrun" the collapsing ground. The large drill rig was lost in the crater, and an enormous amount of gas, crude oil and fine debris was blown into the air. After several hours the crater was several hundreds of feet wide, and after several weeks the crater was from 1500 to 3000 feet in diameter. Most of the later widening was caused by slumping of the poorly consolidated rim strata.

The gas ignited very early in the collapse and burned several hundred feet in the air for nearly 3 months. The fire was finally put out only to have to be started again to prevent excessive accumulation of gas in the air. A lake later formed in the crater.

No other such collapse craters have been reported in the Venezuelan oil fields. The only other types of "eruptive" structures are the line of mud volcanoes that also are situated over the deepest part of the trough of the syncline and extend from near the collapse crater northeast to Trinadad.

Although gas blowouts with associated collapse craters are known, Dix suggested that the rim strata are apparently not disturbed beyond the crater wall. He also knew of no crater breccia comparable to the "cryptoexplosion" type, and certainly no central uplift is present. Dix also noted that such blowouts are known only in areas of major gas and oil accumulation, a condition certainly atypical of Tennessee. Such structures as these collapse craters bear little resemblance to the structure at the Flynn Creek crater.

Tectonic Hypothesis

Kelberg (1965) proposed that the Wells Creek structure in northwest Tennessee may be the result of two major anticlines crossing at nearly right angles. He suggested that the result would be an intense brecciation at the intersection of the anticlines, and that concentric folds and faults would surround the brecciated area. The details of the mechanics were not discussed, but the origin of the forces producing the folding was thought to be related to the deep-seated shifts of the crust along the Kentucky fault zone and possibly to the Mississippi Embayment faulting.

Kelberg suggested that other "cryptoexplosion" structures could originate in similar ways, but he did not attempt to relate regional tectonic movements to the others. The mechanism proposed by Kelberg seems unlikely for the origins of either the Wells Creek structure or the Flynn Creek crater. The available subsurface information shows that the Wells Creek area is situated over a gently plunging syncline on the flank of the Nashville Dome. The Flynn Creek area appears to overlie one of the many gently plunging, very broad anticlines that are present on the eastern side of the Nashville Dome. There is certainly no subsurface evidence of crossing anticlines either at the Wells Creek structure or at the Flynn Creek crater. The recent detailed surface mapping of the Wells Creek area by Stearns, et. al. (1966) and the current study by the author at Flynn Creek have also confirmed the absence of any surface expression of regional folding in the respective areas that might be interpreted as cross-anticlines.

Hydraulic Fracture Hypothesis

Goguel (1963) has proposed that the "cryptovolcanic structures of the central platform of North America" might have been formed by a very large hydraulic pressure lifting a column of strata until fracture occurred with subsequent collapse into a crater. Goguel (1963, p. 665) objected to a volcanic-gas origin because "...no volcanic activity is known elsewhere in the region...". He apparently felt that the basis of the impact hypothesis was dependent on the significance of shatter cones as interpreted by Dietz. After noting at the Kentland structure in Indiana that shatter cones are present in some beds and not present in adjacent beds, Goguel (1963, p. 665) concluded that this "...appears to exclude the possibility of exterior impact." He considered the shatter cones as "allied" to cone-in-cone structures and postulated "...a mechanical origin resulting from stress with a minimum pressure along the axis of the cone."

Hubbert and Rubey (1959) had pointed out that water in some deep permeable rocks can be at a pressure approaching lithostatic pressure. Goguel(1963, p. 667) stated: "There seems to be no reason why such phenomena should not sometimes produce a hydraulic pressure greater than the lithostatic pressure. If so, then the impermeable cover should be uplifted." The lower flanks of large domes or uplift were suggested as likely sites to produce a large hydraulic head. Goguel felt that such a "gigantesque bubble of water" would not last very long and would be accompanied by piecemeal breakdown of the arch and fracture (fig. 51). The collapse of the water-domed structure was thought to result in a crater such as the "cryptovolcanic structures" now seen in North America. Goguel also felt that, "The evidence of some drastic mechanical event, such as shatter cones, is likewise explained by the shock of the different layers falling against one another during the collapse of the arch." He stated that this mechanism would leave no trace of the water which caused the arch and better explains the absence of the volcanic "fluids" of Bucher.

It seems unlikely that this process could be applied to the Flynn Creek structure for several reasons. One objection is that the Flynn Creek crater is situated close to the crest of the Nashville Dome and no highly porous aquifier is present in the underlying limestones. Even if such an aquifier did exist and a maximum difference in elevation of 500 feet is considered, then the maximum hydraulic head would be less than about 60 bars at the deepest known level of brecciation, the top of the Knox Group. This is well below the weight of the overlying column of Knox and Stones River rock and could not have lifted it. A greater elevation difference than 500 feet in Paleozoic time is unlikely, considering that there is no evidence of depositional thickening in the sedimentary column in the Flynn Creek area.

A more serious objection to the hydraulic-fracturing hypothesis can be seen in Figure 51 of Goguel. The mechanism proposed does not produce folding with radial movement away from the crater, as is present in the rim strata of Flynn Creek crater. An equally serious

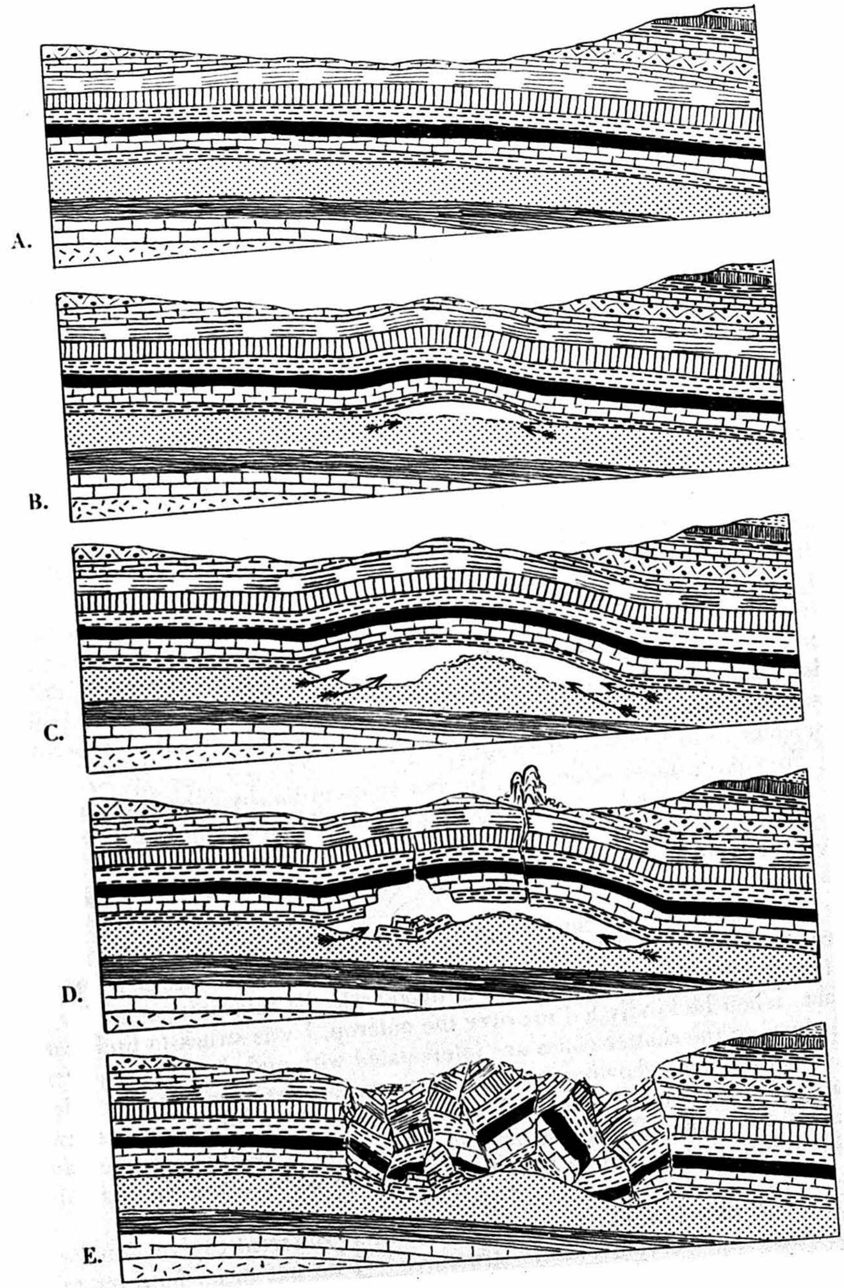


Figure 51 --Formation of "cryptovolcanic structure" by fluid explosion and subsequent collapse.

A. Original situation: permeable layer (dots) overlain by impermeable layers.

B. Uplift produced where fluid pressure in permeable layer is locally greater than the lithostatic pressure.

C. Erosion of permeable layer by fluid moving toward center of uplift.

D. Escape of fluid to surface.

E. Collapse of uplift.

From Goguel (1963, p. 666).

drawback is that shatter cones have never been observed in an environment where simple collapse occurred. The experimental studies which have produced shatter cones were done using hypervelocity impact (Shoemaker, et. al, 1963). The pressure field in the laboratory experiment was far in excess of any stress that would occur in simple collapse as suggested by Goguel.

The central uplift is also difficult to interpret in Goguel's model. Assuming water pressure sufficient to lift such a large mass (contrary to the hydraulic head calculation), no explanation is readily apparent from Figure 51 to explain the intense folding and wide fault zones seen in the Flynn Creek central uplift.

"Cryptovolcanic" Explosion Hypothesis

Introduction

The "cryptovolcanic" or volcanic gas explosion hypothesis has been most strongly advocated by Bucher (1936, 1963). In his discussion of the problem he noted that "cryptovolcanic" structures have several distinctive features which include a circular outline, a central uplift surrounded by a ring-shaped depression, concentric marginal folds, rock deformation which indicates an "explosive force", and no signs of volcanic material or "thermal action" (Bucher, 1936, p. 1074). However, his concept of the deforming process was less definitive, and he referred to it simply as a "subterranean blast." Bucher (1963, p. 642) speculated that enormous pressures from a rapidly crystallizing, water-rich magma would penetrate the overlying strata, "...crushing and partly pulverizing the rock in gouging out irregularly shaped pathways to the surface..." He stated that the "explosive action" may exhaust itself at depth, or end in an unsuccessful attempt to eject the rock and thereby produce a "cryptoexplosion" structure. This general description of the proposed "crypto"-mechanism has been accepted by many workers to explain the "cryptoexplosion" structures located in various parts of the world. Other workers, such as Amstutz (1965), Currie (1965) and Snyder and Gerdemann (1965), have restated Bucher's general hypothesis but have not added to it in any significant way.

More recently Bucher (1963, p. 600) agreed that certain features of the "cryptoexplosion" structures could also be accounted for by meteorite impact and listed the following:

> The highly disordered structure of the central uplift consisting of rocks carried above their original positions (and the limitation of the shatter cones to these central uplifts).
>
> The corresponding downward displacement of a ring-shaped belt of rock concentric with the central uplift.
>
> In some cases, the development of a seemingly wave-like up-and-down movement in one or two rings surrounding the first rim syncline.
>
> The relatively shallow depth to which these cryptoexplosion structures seem to extend, judging from the few drill holes the results of which have become available.

Bucher then stated that if meteorite impact had produced the cryptoexplosion structures they must be:

(1) Randomly distributed, e. g., not demonstrably related to structures of purely terrestrial origin;

(2) Independent of magmatic activity in the region;

(3) Structurally of a nature that is comprehensible in terms of instantaneous impact and its immediate consequences.

Based mainly on points (1) and (2), Bucher (1963, 1965) presented reasonable arguments for the non-meteoritic "cryptovolcanic" origin of the Ries structure in Germany, the Vredefort Dome in South Africa, and the Wells Creek structure in Tennessee. The main argument offered for each structure was that it lay on or within some volcanic or tectonic lineament or zone. Although this type of reasoning can be most convincing, it still falls short of demonstrating a true genetic relationship to the regional volcanic or tectonic activity.

Perhaps one of the best arguments made for the association of a structure with widespread volcanism and tectonic activity was the discussion given by Hager (1953, 1954) for Meteor Crater in Arizona. Meteor Crater is situated directly over a large monoclinal fold and lies in an area of extensive extrusive activity (Shoemaker, 1960). The extensive field of explosive volcanic vents of the Hopi Buttes lies less than 50 miles to the north. It would be difficult to find a more suitable location to refute randomness and to argue for a relationship to regional volcanic and tectonic activity. Yet there is no doubt that Meteor Crater is actually an impact crater (Shoemaker, 1960).

One of the serious problems in applying Bucher's points (1) and (2) as the test for an origin is that it is difficult to locate any place in the Interior Lowlands that does not have some regional tectonic or volcanic feature nearby. On the other hand, impact craters would be expected to be random in their location, and could just as easily be located on or near a regional tectonic or volcanic feature. The writer fully agrees with Bucher that the first step in examining the "cryptoexplosion" structure is to establish its position in the regional tectonic and volcanic framework. The writer disagrees that this approach alone will establish any single origin.

Bucher (1963, p. 600) listed a third point which he did not pursue at length, but it in effect stated that the structure of each feature must be consistent with the proposed origin. This important step has not been followed until now, mainly because there was very little structural data available for the "cryptoexplosion" features. Structural comparisons appear to be a reasonable approach to examining the possible origin of the Flynn Creek crater, now that structural studies have been completed.

Regional Tectonic and Volcanic Setting

The regional tectonic and volcanic setting of the Flynn Creek crater was discussed earlier in this paper in the section on Regional Structure (p. 35) and is only briefly reviewed here. The Flynn Creek area is located on the eastern flank of the Nashville Dome. The crest of the dome in this area trends northeast and lies about 30 miles west of the crater at Flynn Creek. The regional attitude of that strata surrounding the crater is nearly flat-lying with a gentle dip towards the east. Many small folds are present throughout the region. Local dips on the flanks of these minor structures rarely exceed five degrees. Broad, flat plunging anticlines and synclines that cover many square miles are also present. The Flynn Creek area appears to be situated on one of the broad eastward-plunging anticlines. The dips on the limbs of these structures and their plunges are only about one to two degrees (fig. 11,12).

Faults are rare in central Tennessee and in the Flynn Creek area. The breccia in the existing fault zones is locally mineralized with various combinations of calcite, barite, fluorite, galena, and sphalerite. The nearest mineralized zone is a small limestone breccia with fluorite located about 15 miles south of the Flynn Creek crater.

No volcanic rocks are present in central Tennessee. The nearest extrusive rock is a small dike of mica peridotite in the Valley and Ridge province in east Tennessee.

Present knowledge of the regional geologic setting indicates that no volcanic or tectonic lineaments or zones appear to be genetically related to the Flynn Creek crater (Plate 6).

Description of Maar and Diatreme Structures

The most likely volcanic structures to compare with the Flynn Creek crater are those produced by violent gas eruptions, such as maars and diatremes. This excludes the very large gas eruptions such as Krakatoa in Indonesia and Katmai in Alaska, which have occurred in large, previously established volcanoes and, according to Williams (1941) and Shoemaker (1961), occur for reasons different than those for maars and diatremes.

The term maar is a German word applied to the volcanic craters occupied by lakes in the Eifel region of Germany. The term has been used more generally for any volcanic crater of moderate size (less than about five kilometers) that was produced by a violent gas eruption. The term diatreme refers to the pipe or vent exposed below a maar after the crater has been eroded away. Although the exact mechanisms which produce these structures are subject to debate, there is general agreement that they are the result of volcanic gas pressures with or without associated violent surface eruptions (Shoemaker, personal communication, 1966). This type of mechanism is apparently what Bucher (1963, p. 642) had in mind, except that in "cryptoexplosion" structures the eruption fails to continue after the initial gas break-through to the surface. Heated ground water accompanied by a phreatic "explosion" is also considered a possible part of some maar forming processes (McBirney, 1959).

The best descriptionsof a number of maars and diatremes are summarized below. Volcanic structures with sizes comparable to the Flynn Creek have been stressed. Descriptions have also been limited to volcanic structures which have penetrated sedimentary strata. The most important maar and diatreme fields that have been described in detail include the following areas: Eastern Fife in Scotland, Swabian Alb in Germany, Eifel District in Germany, Hopi Buttes in the Navaho areas in Arizona, Pinacate Craters in Sonora, Mexico, and the Kimberlite District in South Africa. Other important but smaller maar and diatreme fields include those of central Chile, eastern Australia and northern Death Valley, California. There is a great similarity in all these volcanic structures and their associated deformation in the surrounding strata, and it is necessary to summarize only the more important structural features of these maar-diatreme fields which bear upon the structure of the Flynn Creek crater.

Maars commonly range from a few tens of feet to nearly 2 miles in diameter and are usually circular to elliptical in shape with funnel-shaped craters over 600 feet deep. Maars which have suffered little erosion have ash and agglomerate ejecta forming ejecta rims with heights of up to nearly 250 feet at the largest craters. When the crater vent (diatreme) is exposed, as in Eastern Fife, it is seen to contain mainly tuff and agglomerate (Geikie, 1902). The agglomerate can have great amounts of the local sedimentary strata in the vent as breccia. Alteration effects in the vent breccia and rim strata are generally small and restricted to a narrow band of induration and bleaching. The diatreme walls in Eastern Fife (Geikie, 1902) and in the Swabian Alb (Cloos, 1941) appear to have a thin shattered or fractured zone a few feet thick, regardless of the rock type. Brecciation and irregular mixing of the vent tuffs and agglomerates are also present in some maar walls. Deformation is not reported beyond the immediate few feet of the vent, but exposures are rarely good enough to allow further examination at the crater level. Where extensive excavations have been made at the Kimberlite pipes in Africa, no report is made of rim deformation other than that described above.

The classic area of Eastern Fife in Scotland has been described by Giekie (1902) from many excellent exposures. This area is underlain by folded and faulted carboniferous sandstones, shales and limestones averaging about 10,000 feet in thickness. In an area of about 60 square miles at least 80 volcanic vents or diatremes are present ranging in size from a few tens of feet to nearly 2 miles in diameter. The diatremes contain tuff and agglomerate in varying proportions. The agglomerate consists of volcanic breccia of basalt, tuff and finely comminuted volcanic rock and sedimentary breccia derived from the surrounding strata. The fragments range in size from very finely comminuted powder to blocks 150 feet long.

In some cases the sedimentary rock in the vent is highly altered, with sandstones converted to quartzite, shales to "porcellanitic substances" and limestones converted to marble. In other vents the sedimentary rock is little altered except for minor induration. Heddle (in Giekie, 1902, p. 278) has estimated temperatures from studies of coal fragments to be between 300° and $500^{\circ}C$.

The vent walls are commonly vertical over the range of exposures. The wall rocks are often locally shattered, "plicated" (folded), dislocated, and jumbled over a distance of up to a few feet away from the vent wall. An increase in the size of the vents does not appear to proportionately increase the width of the deformed zone. The "plication" is without exception a moderate to sharp downbend of the strata immediately adjacent to the vent wall, and in one case the monoclinal axis is up to 30 feet away from the vent wall. The monoclinal downfold at the vent wall is commonly in sandstones and shales; the shales usually have a "crumpling" shown by many minor small folds. The stratigraphic downdrop of the monoclinal fold is less than 30 feet. Limestone forming the vent walls is rarely downfolded, but tends to shatter, jumble and brecciate for a distance of about 5 feet from the vent wall. In places the limestone is converted to marble for a distance of 3 feet from the vent wall. Sandstones locally are converted to quartzite, and shales to "porcellanitic substances" in the monoclinal downfold.

One unusual vent was reported containing only sedimentary breccia with no volcanic material. It probably overlies the top of a normal diatreme. The vent is about 150 feet by 40 feet and has no deformation in the sandstone walls except for fracturing and induration.

The relatively small thermal alteration of the shattered and fractured wall accompanied by great amounts of tuff and agglomerate including much local strata implies a gas pressure mechanism instead of a volcanic intrusive process (Giekie, 1902). The important point is that the vents have formed mainly by brecciation of a column of strata with very little, if any, lateral compression of the vent walls.

Only the shales exhibit minor compression which appears to amount to less than a few percent shortening occurring in a very narrow band. No accepted theory has been offered for the narrow monoclinal downbend, but Giekie believes it is the result of post-vent collapse. Another aspect is that large and small craters had approximately the same size narrow monoclinal downfolded zone. Giekie (1902, p. 280) further suggests that the volcanism occurred in Permian time, and the present structures were near the original ground level.

Appledorn and Wright (1957, p. 462-463) have noted shallow inward dips in sandstone at the Roof Butte diatremes in the Chuska Mountains, Arizona, and state that "the marked funnel shape of the crater fillings show that erosion has not removed much material since the time of volcanism." They consider "phreatic explosions" (explosions produced by steam from heated ground water) to have been the dominate cratering process. Bucking (1904, p. 267-308) has also reported inward dips adjacent to the diatreme of the Rhongebrige in South Germany.

The Navaho-Hopi Buttes diatremes also have little or no deformation reported in the rim sandstones and shales (Williams 1936, p. 118). Shoemaker (1962, p. 346, personal communication, 1966) reports only local shattering and brecciation immediately adjacent to the vent walls of these diatremes.

Published descriptions of the maars in the Eifel District in Germany, the diatremes in the Kimberlite District in South Africa, the recently active Nilahue Maar in southern Chile, and Ubehebe Crater maar in northern Death Valley in California also suggest little or no deformation of the rim sedimentary strata. What deformation is present usually consists of the narrow band of fractured and locally brecciated strata with no reported folding. In his detailed study of the diatremes of the Swabian Alb, Cloos (1941, p. 709-800) reports no folding in the vent walls and only minor fracturing and brecciation in the rim strata, usually only a few feet or less in thickness.

Gevers (1929) reports a gentle "upward arching" of adjacent strata around one diatreme in the Western Stromberg area in South Africa, but it is apparently small and close to the vent. Jahns (1959) shows outward dips of 10° to 20° in basalts on the rim of Crater Elegante maar in the Pinacates in northern Sonora, Mexico. In this case the basalt flows forming the rim are mixed with pyroclastics and obviously were extruded on a previously outward dipping ejecta rim.

McGetchin (personal communication, 1966) has described gentle outward dips which occur locally along the southern edge of Moses Rock diatreme in southern Utah, a part of the Navaho diatremes. The gentle outward dips occur in sandstones and siltstones and extend only about 200 feet out from the vent wall. Dips are at shallow angles of a few degrees away from the diatreme. One set of well-defined fractures are parallel to the vent wall, while a secondary set dips at about 20° towards the diatreme. McGetchin (1966) has also described a circular collapse several hundred feet in diameter in sandstones southwest of Moses Rock diatreme. Steep dips occur at the circular hinge line but return to about the normal regional dip within the collapse except for jumbled and brecciated beds. Rim deformation is restricted to the narrow hinge line 20 to 30 feet wide. Apparently this structure is over the top of a diatreme.

The writer is aware of only one area where moderate to intense deformation appears in diatreme rims. Wilshire (1961, p. 474) described four diatremes in eastern Australia near Sydney, New South Wales, and states that, "At the southwest margin of the Erskine Park diatreme, breccia dips (from 20° to 55°) under Wianmatta sandstone and shale, and the country rock is strongly folded and faulted for about 100 feet from exposed contacts." The diatreme is about 1800 feet by 800 feet and contains a multi-layered agglomerate consisting of a wide variety of rock fragments, including shale, sandstone, siltstone, coal, basalt, granite, gabbro, and ultrabasic rocks. Wilshire (1961, p. 743) states that, "All inclusions in the breccia are intensely altered by hydrothermal processes, and induration was effected by compaction of abundant interstitial clay and by sporadic carbonate cementation...." A subsurface connection of several miles between two of the diatremes

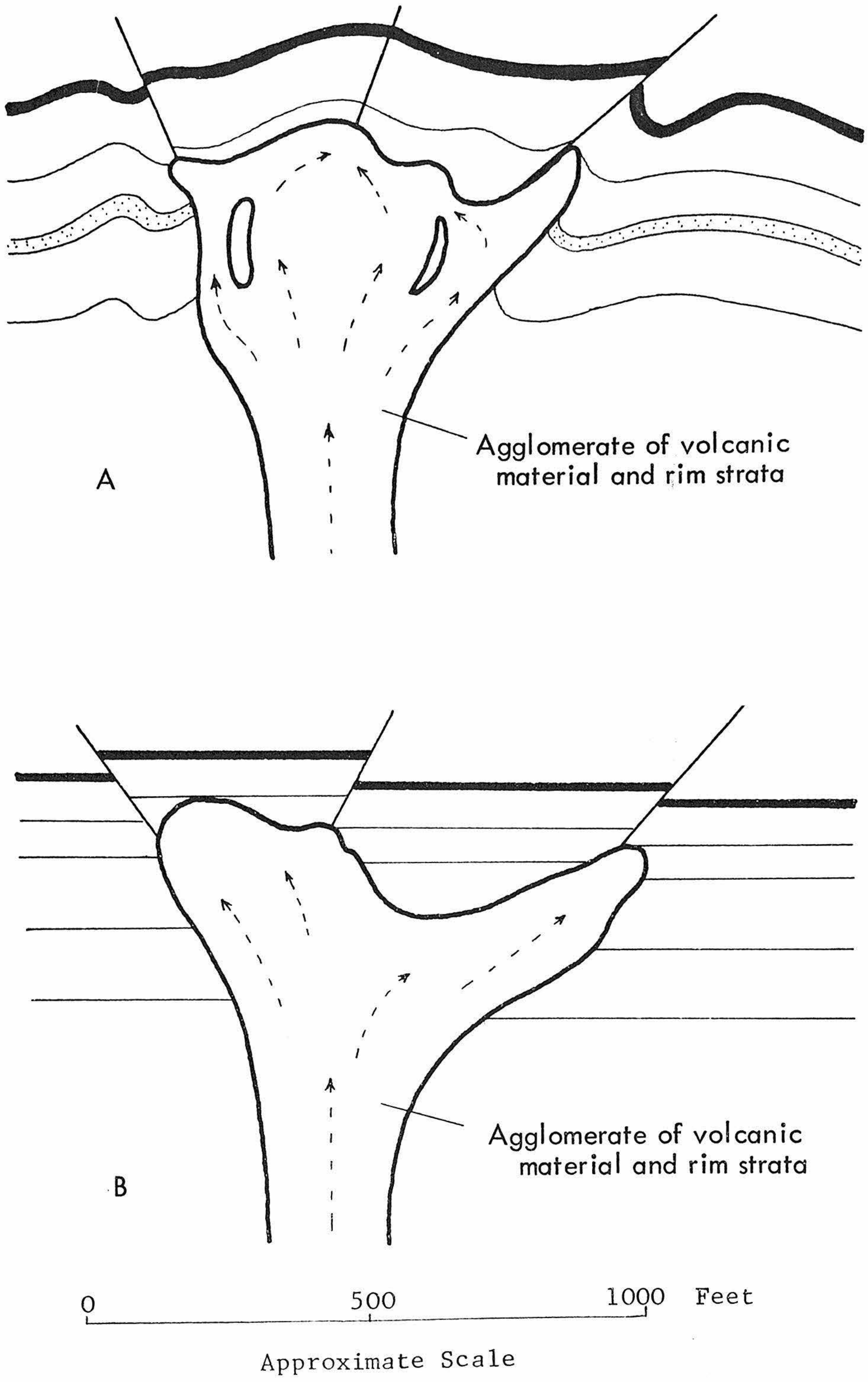


Figure52 --A, Folded rim strata in diatreme walls;
B, Unfolded rim strata in diatreme walls.
Flow directions indicated by arrows.
From Wilshire (1961, p. 482).

is suggested by shallow drilling which intersects breccias. Wilshire gives an extensive treatment of the field data which strongly suggests emplacement of the breccia in the diatreme by wedging and lifting of country rock. Figures 52A and 52B are from Wilshire (1961, p. 482) and demonstrate his proposed mechanism. This type of diatreme, of course, does not reach the surface to form maar craters as in most of the previous cases. There is also a large room problem created by intruding extensive amounts of breccia from depth even when lifting of the overlying strata occurs. It is logical to expect some rim compression under such circumstances, particularly if the rim strata consist partly of shale. It will be recalled that the small amount of rim folding in the Eastern Fife diatremes was prominent mainly in the shales. Wilshire (personal communication, 1964) states that probably less than 500 feet of strata covered the area during the intrusion and would have provided a relatively small overburden.

Comparison of the Flynn Creek Crater with Maars and Diatremes

Comparisons of the structure of the Flynn Creek crater with the structures of maars and diatremes are listed in the following:

1. The Flynn Creek crater is roughly circular with a partly polygonal outline. Maars and diatremes of similar size may be circular to elliptical, but rarely exhibit a well-defined polygonal outline.
2. Both maars and the Flynn Creek structure are craters formed in a pre-existing terrain, with moderate to steep crater walls.
3. Maars and diatremes usually exist in groups. The Flynn Creek structure is an isolated crater.
4. Maar craters have an ash and agglomerate ejecta blanket on the rim. The Flynn Creek structure presumably had an ejecta blanket of sedimentary rock thrown out of the crater. A crude inversion of the ejecta stratigraphy is preserved in the fault block.

Volcanic material is common in the breccia and rim ejecta of maars. No volcanic material is observed at the Flynn Creek crater.

5. The Flynn Creek crater has a large central hill or central uplift of older strata, with some units raised nearly 1000 feet and containing shatter cones. Maars may occasionally have central or non-central small volcanic cones in the crater, but large blocks such as the central uplift at the Flynn Creek structure are unknown. Shatter cones have not been found in maar or diatreme breccias.
6. The breccias in the crater of the Flynn Creek structure were formed from the same rocks as are exposed in the surrounding sedimentary section. Deformation in the individual breccia blocks is often severe and includes fractures, folds and intense deformation such as twinning. The agglomerates in maars and diatremes, particularly in those the size of the Flynn Creek structure, consist of a variable assemblage of volcanic tuff and breccia and occasional irregular intrusive and extrusive igneous dikes. The breccias of maars and diatremes usually contain igneous and occasionally metamorphic rocks from deeper horizons. If these structures penetrate sedimentary columns, abundant breccia from the sedimentary rocks is also common in the agglomerate. Deformation in these sedimentary blocks consists of moderate brecciation, fracturing and occasional folding and induration.
7. Slumping within the crater and concentric normal faulting in the rim are present in both maars and the Flynn Creek structure. Thrust faulting is present only in the Flynn Creek structure.
8. When structural deformation is present in the rims of maars and diatremes, it is commonly restricted to a narrow band a few feet wide. Some diatremes have a steep inward dip adjacent to the vent wall, but the fold is rarely wider than 30 feet and averages 5 feet. Most maars and diatremes have sharp boundaries with the surrounding strata and no folding. A narrow band of fracturing

with occasional brecciation is also present in some of the vent walls. The size of the structure does not appear to affect the width of the inward-dipping fold or fracture zone. The same zone which is fractured is commonly indurated to some extent, and mineralization may be present.

In contrast with the maar and diatreme rims, the rim of the Flynn Creek structure is uplifted and generally tilted away from the crater, with many doubly plunging asymmetric anticlines and synclines. Most axes of folds in the rim are concentric with the crater wall, but some folds have axes radial to the crater wall. Tight folding in parts of the rim produces radial shortening as great as 35 percent. Tight folds in the northern and eastern rim are overlain by progressively more open folding. A sharp anticlinal to monoclinal downbend is common in the rim adjacent to the rim-breccia contact. A large thrust fault and a rotated fault block which forms a tilted graben are present in the southern rim. Deformation is present along much of the crater wall and consists of fractured and folded limestones containing an irregular zone of intensely twinned calcites. Microfractures are common in much of the folded rim strata near the crater wall. At other locations along the rim the contact is jumbled and gradational. Mineralization related to hydrothermal or volcanic processes has not been recognized in the Flynn Creek area.

From the preceding outline it is clear that few structural comparisons can be drawn between the Flynn Creek structure and the structure of maars and diatremes. It also seems unlikely that a crater as large as the Flynn Creek structure with its extensive brecciation does not contain even a trace of volcanic material or mineralization if it had a volcanic origin related to maar-diatreme type activity. This is particularly true since fault breccias within 12 miles of the Flynn Creek area are highly mineralized with materials which probably had their source in hydrothermal solutions.

The point must be made that the lack of comparison between structural deformation at Flynn Creek and at maars and diatremes does not uniquely rule out some unusual type of volcanic gas origin (with or without ground water steam) whose mechanism of eruption is foreign to current understanding. This is considered in the following section.

Volcanic Gas or Steam "Explosion" Processes

The lack of structural similarities between the Flynn Creek crater and maar and diatreme structures was discussed in the previous section. Maar craters and their pipes (diatremes), however, are not the only volcanic features that must be considered. In fact, Bucher (1936, p. 1076) considered maar craters as end products of the volcanic gas "explosion" process. Wilson and Born (1936, p. 832) also described the structure at Flynn Creek as the product of a "relatively rapid, deep seated volcanic explosion accompanied by a gas explosion near the surface." Apparently Bucher (1936, p. 1025; 1963) considered this a distinct possibility when he said that "the explosion [from volcanic gases], shallow and strong enough, blows out a shallow, more or less circular explosion basin filled with a jumble of disordered blocks and surrounded by a zone of materials blown or pushed out from it." Currie (1965), Snyder and Gerdemann (1965), Amstutz (1965) and others have agreed in part with this view.

In the earlier papers of Branca and Frass (1905), Bucher (1936), Wilson and Born (1936) and others, the meaning or physical concept of a "buried volcanic explosion" and how it could occur was never made clear. Bucher (1963, p. 642) restated the process in terms of very high gas pressures derived from rapidly crystallizing, water-rich magmas. He also equated "fluidization" and comminution of the rock to an "explosion." More recently, Snyder and Gerdemann (1965) have also discussed high volcanic gas pressures accompanied by fracturing and structural disordering as the process which produces "cryptoexplosion" structures. They suggest that when the sedimentary cover is thin, as at the Crooked Creek structure in Missouri, gas pressure domes the rocks until an "explosion" occurs and the strata collapses as a breccia into the crater.

It would seem unlikely that the process offered by Snyder and Gerdemann would produce the particular types of folding observed in the rim strata and parts of the breccia at the Flynn Creek crater. This can be examined in at least a semi-quanitative way by considering the minimum mechanical energy necessary to form the crater and relating this energy to gas pressures that might accompany the process. The gas pressures and their relationship to the folding in the rim strata can then be discussed.

If a cylindrical shape is assumed for the Flynn Creek structure at depth with a diameter equal to 11,500 feet and a depth of 1,500 feet (depth to lowest brecciated horizon known), a volume can be calculated of 4.55×10^{15} cc. Assuming a density of 2.7 g/cc., the mass will equal 1.23×10^{16} gm. A conservative estimate of the mass raised in the central uplift, plus the estimated mass of all blocks in the breccia raised above their normal stratigraphic position, plus the mass of the thrust fault in the southern rim is about 0.6×10^{16} gm. with an average increase in elevation of 100 meters. The work necessary to raise this mass is approximately 6×10^{22} ergs. This is a minimum estimate of work done in lifting material, because the rim ejecta is neglected.

An estimate of the amount of energy needed to fracture the total mass of rock can be made using comminution surface energy from the extensive work of Bergstrom (1963, p. 168). The fracture energy is about $1.6 \times 10^{23 \pm 1}$ ergs. The uncertainty is primarily because a mean fragment size must be assumed for the breccia to use Bergstrom's values. A volume of 15 cc. was assumed for the mean size of the breccia fragments on the basis of estimates made from surface observations of the breccia.

It is also necessary to make an estimate of the energy needed to eject the mass which occupied the crater. Using a diameter of 11,500 feet and a depth of 330 feet, the volume is equal to 9.6×10^{14} cc., and the mass (assuming density equal to 2.7 g/cc.) is equal to 2.6×10^{15} gm. The work necessary to lift this mass to the level of the original rim is about 2.6×10^{22} ergs. If one assumes a value of 30 meters/sec. for the acceleration of the ejected material, the total work involved will be about $7.8 \times 10^{23 \pm 1}$ ergs. This value does not include the energy necessary to overcome the friction between breccia fragments during movement.

To estimate the minimum volume of gas (volcanic gas or steam from ground water) that would provide energies on the order of 10^{23} ergs if allowed to expand adiabatically, assume a 10 percent porosity in the limestone. Considering the limestone to have a total volume of 4.55×10^{15} cc, this gives a pore space for the gas of about 0.5×10^{15} cc. Also assume that this gas is steam at 250°C and take Goguel's (1951, p. 30) value of approximately 2.5×10^{9} erg/cc for an adiabatic expansion. This gas will have approximately 1.25×10^{24} ergs available for expansion work. A pressure computed for gas under these P-T-V conditions is on the order of 1000 to 2000 bars, which is at least 100 times the pressure necessary to produce tension fracturing in limestone. Considering the uncertainties in such calculations, it still seems clear that even modest amounts of volcanic gas or steam (from ground water heated by a volcanic source) have sufficient energy to move the masses under consideration at Flynn Creek when one compares the 10^{24} ergs available for work versus the 10^{22-23} ergs of work necessary to be done. It is also important to note that this is at a pressure high enough to easily produce tensile fracturing.

The relationship that these gas pressures have to the folding in the rim strata of the Flynn Creek crater can be discussed only in a qualitative way. It is known that mechanical properties of rocks are greatly affected by confining pressure, temperature, interstitial solutions, time factor, and previous physical history. Fortunately, several of these factors can be reasonably approximated for the Flynn Creek rocks before the deformation.

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. Using this field information, lithostatic pressures or confining pressures have been calculated for different levels known to be brecciated (Table 1). Later in this section these confining pressures are related to laboratory investigations on rock deformation and comparisons made between brittle and plastic failure of limestone.

No thermal metamorphic effects have been noted either in the field or in petrographic studies, and temperatures were probably below 200°C, considering there are no indications of even the lowest temperature carbonate metamorphic reactions. The low porosity of the rocks in the Flynn Creek area suggests that interstitial solutions probably were well below ten percent by volume.

The time factor and previous physical history would probably be of minor importance if rapid deformation occurred. This is true for all of the origins that have been offered for the crater. It is recognized that the varying roles these factors play in rock deformation allow, at the present time, only a qualitative application to natural systems, but some comments can be made concerning the nature of the deforming process and the low, near-surface confining pressures that existed before the formation of the Flynn Creek structure.

Lithostatic pressures existing just before the deformation in the Flynn Creek area probably did not exceed about 150 bars at the lowest known depth of brecciation (top of the Knox Group) (Table 1). At the present level of the exposed folded, tilted and faulted rim strata the pre-deformation lithostatic pressure probably did not exceed about 50 bars (Table 1). Laboratory investigations (Robertson, 1955; Handin and Hager, 1957, 1958; Handin, et al , 1963) on the deformation of limestones and dolomites have shown that both rock types exhibit varying degrees of ductile behavior under the confining pressures calculated for the Flynn Creek structure. For a number of limestones tested, the range in ductility varied from about two percent to nearly ten percent strain before rupture at confining pressures of 150 bars (Handin and Hager, 1957). Rupture occurred at about 1000 to 1500 bars compression under these conditions. Studies on the effects of temperature and confining pressure by Handin and Hager (1958) have shown that certain limestones will not deform more than five percent before rupture under 2800 bars compression at 75^{o}C and 500 bars confining pressure.

In general, previous work has shown that the brittle-ductile transition in limestones at room temperatures occurs at an effective confining pressure of about 1000 bars (Robertson, 1955; Handin and Hager, 1957). Under the low confining pressures calculated for the Flynn Creek area, it is reasonable to expect the limestones to behave as nearly brittle material, or more appropriately as semi-ductile material (Robertson, 1955) under differential compression or extension pressures of a few thousand bars. When tensile stresses are considered, failure commonly occurs at values 50 to 100 times lower than for compressional stresses. Also if compressional stresses of 1000 to 5000 bars are applied rapidly, limestone invariably fails by brittle fracture.

Without other complicating factors it seems logical not to expect large scale folding to occur from compression effects alone, whereas fracturing and small amounts of plastic flow should be common. Nevertheless, large scale folding, which appears to have had the major stress component in the horizontal direction, is present in much of the rim strata of the Flynn Creek crater. Intense fracturing and minor plastic deformation are equally present.

Formation	Maximum original pre-crater depth from ground surface to base of formation		Pressure (bars)		
			Densities g/cc		
	Feet	Meters	2.50	2.70	3.00
Leipers	300	91	22.9	24.7	27.5
Catheys	475	145	36.3	39.2	43.5
Cannon	574	175	43.8	47.3	52.5
Hermitage	675	206	51.5	55.6	61.8
Stones River Group	1476	450	112.5	121.5	135.0
Lowest known depth of brecciation	1500	475	114.2	123.4	137.1
Knox Group-basement	6000	1829	457.3	493.8	548.7

Table 1. Lithostatic pressures calculated in bars for rock densities of 2.50, 2.70, 3.00 g/cc for selected stratigraphic horizons just before the formation of the Flynn Creek crater. The original ground surface described in this paper as Sequatchie Formation (Upper Ordovician) is used as the zero pressure surface. The lowest level of known brecciation is in the top of the Knox Group and was located at a depth of about 457 meters.

If a gas is introduced under high pressure near the surface, one might expect that under low confining pressures (as in the Flynn Creek area) the rocks would exhibit a small amount of flow followed by extensive fracturing. This of course does not explain the major folding present in various parts of the rim. If the laboratory investigations of rock deformation can be extrapolated to the Flynn Creek structure in the manner described, one would expect fracturing to occur before large plastic folding is completed under the condition of low confining pressure. Arcuate faulting and subsidence at depth conceivably could explain some of the folding, but it can not account for other rim folds that definitely appear to have had the major stress component in the horizontal direction. Consequently, the simple build up of gas pressure near the surface, as proposed by Snyder and Gerdemann (1965) and Bucher (1963), would not appear to explain this part of the structure at Flynn Creek.

Meteorite Impact Hypothesis

Introduction

The crater at Flynn Creek was first proposed as a possible meteorite impact structure by Wilson and Born (1936), but they rejected the idea because of the raised strata in the central uplift. Boon and Albritton (1937) suggested that the argument of Wilson and Born overlooked the fact "...that elasticity of rocks would cause a strong rebound following intense compression produced by impact and explosion." During a study of the deformation at the Wells Creek structure Wilson (1953) revised his opinion on the origin of the Flynn Creek crater and referred to it as a possible impact crater. Dietz (1960) reported shatter cones from the central uplift at Flynn Creek and thereby argued for an impact origin.

No attempt was made in the earlier work to compare the crater at Flynn Creek with either impact or volcanic craters, partly because detailed structural studies had not yet been undertaken. Shoemaker (1960, 1961, 1962, 1963) described in detail the structural similarities between different impact craters and nuclear explosion craters, and developed a model for the penetration mechanics of a meteorite based on observation of nuclear cratering and the resulting structural deformation. One of the important contributions of Shoemaker's study was that it demonstrated that plastic folding is a normal consequence of impact. His study also showed that the type of deformation in the rim strata is dependent on the depth of penetration of the meteorite. One of the long-standing objections of many workers to an impact origin had been the failure to recognize the wide variety of different types of structural deformation which result from impact. For example, the tectonic hypothesis of Kelberg (1965) was proposed for "cryptoexplosion" structures mainly because he was unaware of plastic folding at impact craters.

Shoemaker (1960) drew his structural comparisons between Meteor Crater, Arizona and nuclear craters because of the obvious similarities in deformation. The comparison was strengthened because it was known that shock effects played a dominant role in the formation of both impact and nuclear craters. The study at the Flynn Creek crater has now provided sufficient information to see close structural similarities with several of the different "shock-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.

Although direct evidence of shock effects cannot yet be demonstrated in the Flynn Creek rocks, excellent comparisons can be made between the types of deformation at Flynn Creek and those seen in impact, nuclear and chemical explosion craters. Structures of comparable size are chosen ,where possible,for comparisons to lessen complications that may occur in scaling.

Meteorite Impact Craters

Although a number of impact craters are known, only Meteor Crater in Arizona, the Henbury Craters in Australia and the Odessa Craters in Texas have been described in sufficient detail for structural comparisons with the Flynn Creek crater.

Meteor Crater, Arizona

Meteor Crater is located in the southern part of the Colorado Plateau in nearly flat-lying sandstone, shale, and dolomite and has been described in detail by Shoemaker (1963). The crater is a bowl-shaped depression about 4000 feet in diameter and 600 feet deep. The rim strata are overlain by ejecta from the crater that rise 80 feet to 200 feet above the surrounding flat plateau. The ejecta overlying the rim display a crude inversion of the stratigraphy and consist of fragments ranging from microbreccia to blocks 100 feet across. Shoemaker (1962, p. 308) states that the surface of the surrounding Colorado Plateau and crater rim have been eroded about 50 feet since the crater was formed.

The deformation of the rim strata has been examined in detail and is shown in Figure 53. Beds of the older formations exposed in the lower parts of the crater walls dip gently away from the crater. Higher in the crater walls the outward dip becomes greater,and in the northeast part of the rim, the uppermost beds can be traced in an overturned fold with the upper limb folded back and away from the crater.

Small vertical faults with scissor-type displacements and small thrust faults are common in parts of the rim. Shoemaker (1963, p. 311) states that a majority of the scissor-type faults are parallel with the northwesterly regional joint set, and a smaller number are parallel with the northeast joint set. Regional jointing has also controlled the shape of the crater to some extent and gives it a square-like outline with the diagonals of the square parallel to the two main sets of joints. A few normal faults are present in parts of the rim and are concentric with the crater wall. Some of the faults locally have authigenic breccia forming zones rather than well-defined fault planes. On all the thrust faults the lower plate moved away from the crater.

Rock exposed in the crater walls is locally intensely fractured to brecciated, while adjacent exposures a few tens of feet away may exhibit relatively little visible deformation. Irregular zones of authigenic breccia several feet to tens of feet wide are also locally present in the rim.

The floor of the crater is underlain by alluvium and talus. Lake beds nearly 100 feet thick cover the central part of the crater floor and interfinger with the talus and alluvium along the edges of the crater wall. Below the lake beds a layer of mixed debris about 30 feet thick forms part of a fallout layer of ejecta (Shoemaker, 1963, p. 312). A lens of breccia about 650 feet thick underlies the fallout layer. Along the outer margins of this lens are large blocks of limestone and dolomite, while only finer breccia is present in the inner parts of the lens. Meteoritic iron is present as finely divided fragments and microscopic spheres throughout most of the breccia and in the crater walls.

Coesite has been reported from the breccia, fallout layer and alluvium by Chao, Shoemaker and Madsen (1960). Stishovite was later reported by Chao, Fahey, Littler, and Milton (1962).

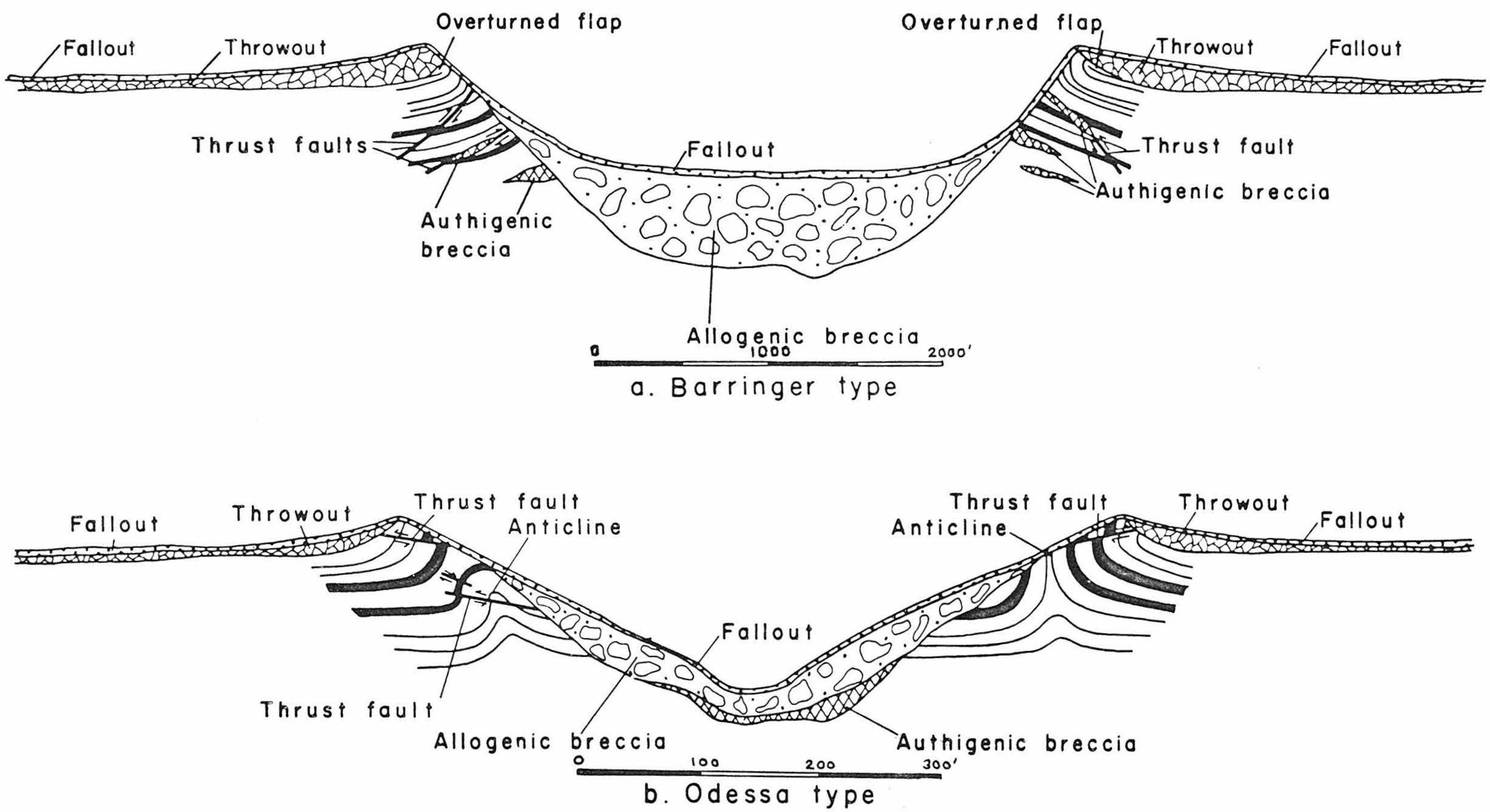


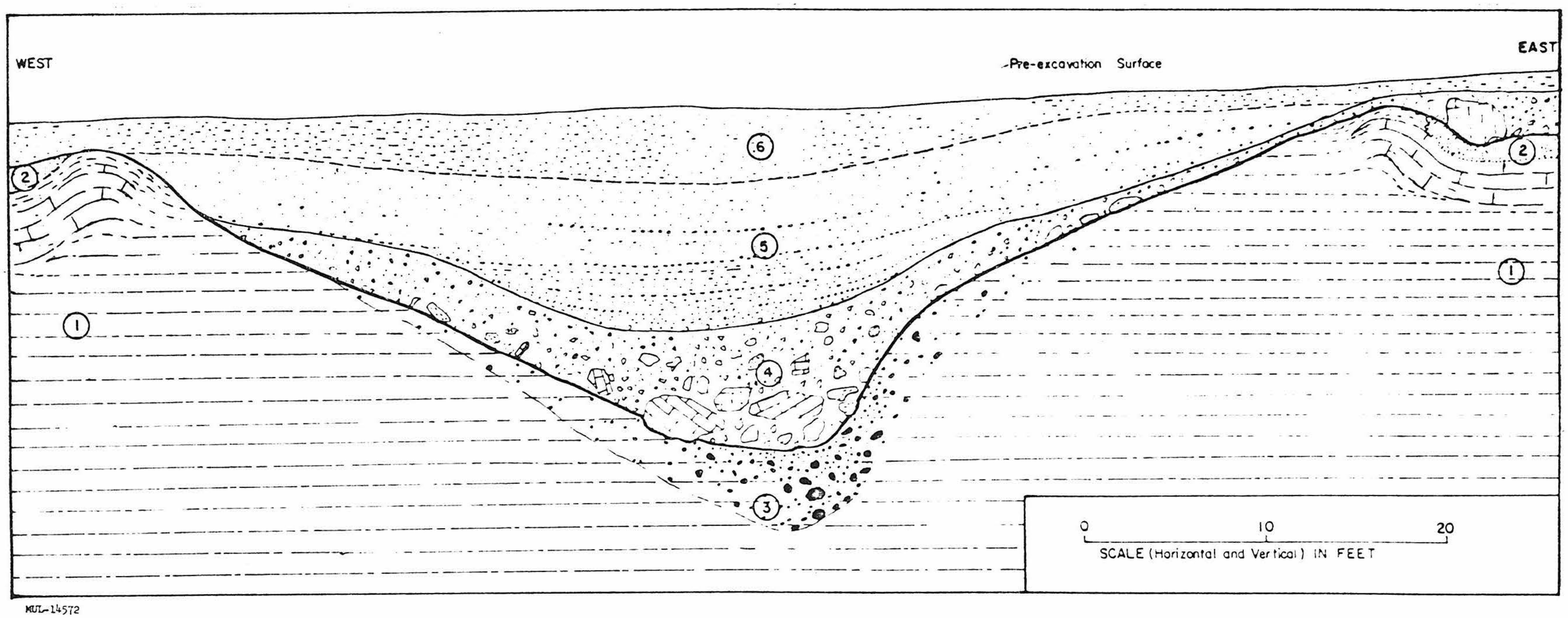
Figure 53.--Schematic cross sections illustrating the structure of Meteor Crater in Arizona and the largest Odessa Crater in Texas shortly after their formation by meteorite impacts. From Shoemaker and Eggleton (1961, p. A-9).

Odessa Craters, Texas

A group of small impact craters near Odessa, Texas exhibit a variety of structural features which, in part, are not found at Meteor Crater, Arizona. Evans (1961) described the main crater as about 650 feet in diameter with a maximum depth of about 100 feet. A smaller crater approximately 650 feet west of the main crater is about 73 feet in diameter and 16 feet deep. All the craters are filled or partly filled by Pleistocene and recent sediments. Although the craters were formed in late Pleistocene time, Evans reports,"The mass which produced the main crater evidently suffered extreme fragmentation, and perhaps partial decomposition, and was mostly or entirely expelled with ejected earth materials." The mass which produced the smaller crater was less severly broken up,and fragments are still present in small amounts in the craters. Evans notes that the rim deformation is markedly different between the craters (fig. 53; 54). The rim of the largest crater consists of a strongly folded, distorted and thrust-faulted sequence of limestones. The oldest strata in the "overthrust rim folds" have been uplifted as much as 50 feet from their original position, a distance equal to one half the depth of the crater. A tightly folded and deformed asymmetric anticline is present on one side of the rim and is cut by a thrust fault with the upper plate moved out from the crater. An inward dip is present in other parts of the rim resulting from more open-folded asymmetric anticlines (fig. 53). The upper plate of at least one thrust fault moved towards the crater, as in the Meteor Crater, Arizona thrust faults.

The smaller crater exhibits much simpler rim deformation involving only a ring anticline (fig.54). Evans (1961, p. D-11) shows the strata in the upper part of the rim with a gradational transition into breccia.

Fallback and underlying breccia lenses are present in the Odessa Craters, similar to those described at Meteor Crater, Arizona.



Cross section through crater No. 2. The circled numbers refer to different rock units, as follows: (1) Compact, calcareous sands and sandy clays with hard, platy caliche in upper part. Except for compressional folding on the crater rim, this unit was not perceptibly affected by the meteorite impact. (2) Reddish-brown surface soil of impact time. (3) Zone of meteorites. The bedrock of this zone shows some distortion and incipient shearing, but it was not actually displaced from its original position. (4) Zone of fallback. Large limestone boulders and much of the other coarse material in this zone were ejected from deeper levels in the main crater, while blocks of reddish-brown soil and caliche appear to be fallback from crater No. 2. (5) Post-impact ponded deposits. (6) Recent sands and soil.

Figure 54.--Cross section of one of the smaller Odessa Craters in Texas. From Evans (1961, p. D-11).

Henbury Craters, Australia

Milton (1965) has recently described the Henbury Craters in Australia. The craters are located on the flank of a broad anticline in bedrock consisting of siltstones and shales and a few thin sandstones. Bedding near the crater field has a regional dip of about 35° south. A major thrust fault is exposed a few thousand feet to the south, but no other faults and only a few minor folds are present within the crater field.

The main Henbury Crater is apparently a double crater with the larger end about 500 feet in diameter and on the average of 30 feet in depth. The original pre-impact ground surface has been lowered very little by erosion, but the crater floors and much of the walls are now covered by extensive alluvium. Deformation in the walls of the larger craters is not continuous, but consists of "mosaics formed by the reorientation of fracture-bounded blocks that are themselves little deformed. The fractures are so closely spaced... commonly on the order of an inch or inches...that the appearance of continuous smooth folds is produced." (Milton, 1965, p. 30-33). This is very similar to the jumbling in the rim at the Flynn Creek structure (Milton, personal communication, 1966).

Irregular, open to tight synclinal, anticlinal and monoclinal folds are present in the crater walls with numerous curving low- to high-angle thrust sheets (fig. 55). The upper plates of the thrusts are commonly displaced away from the craters.

Milton's cross-sections indicate that rim deformation decreases outward and is absent 30 to 70 feet from the crater wall. Overturned units are accompanied by "thin slices that formed by strong shearing parallel to the bedding and [were] active simultaneously with the outward rotation."

Milton (1965, p. 44-45) noted that most of the ejecta on the rims and that exposed in the crater walls exhibit no gross indication of

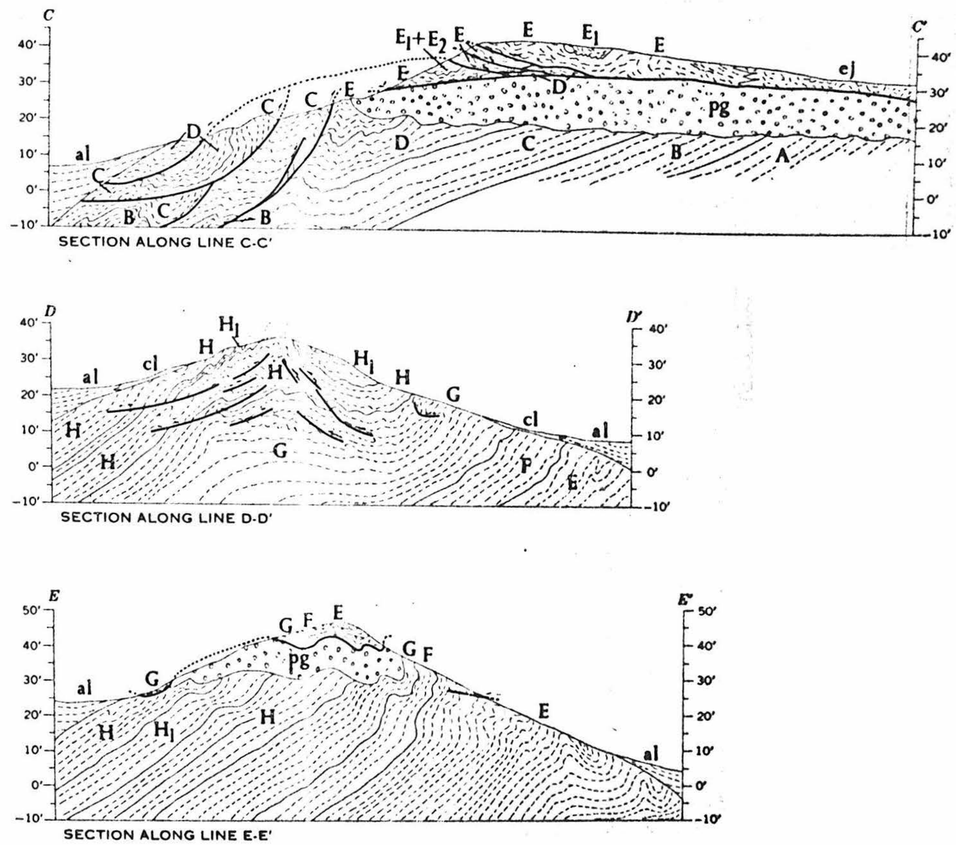


Figure 55 .--Cross sections of the Henbury Craters, Australia, showing types of folding in rim strata. From Milton (1966).

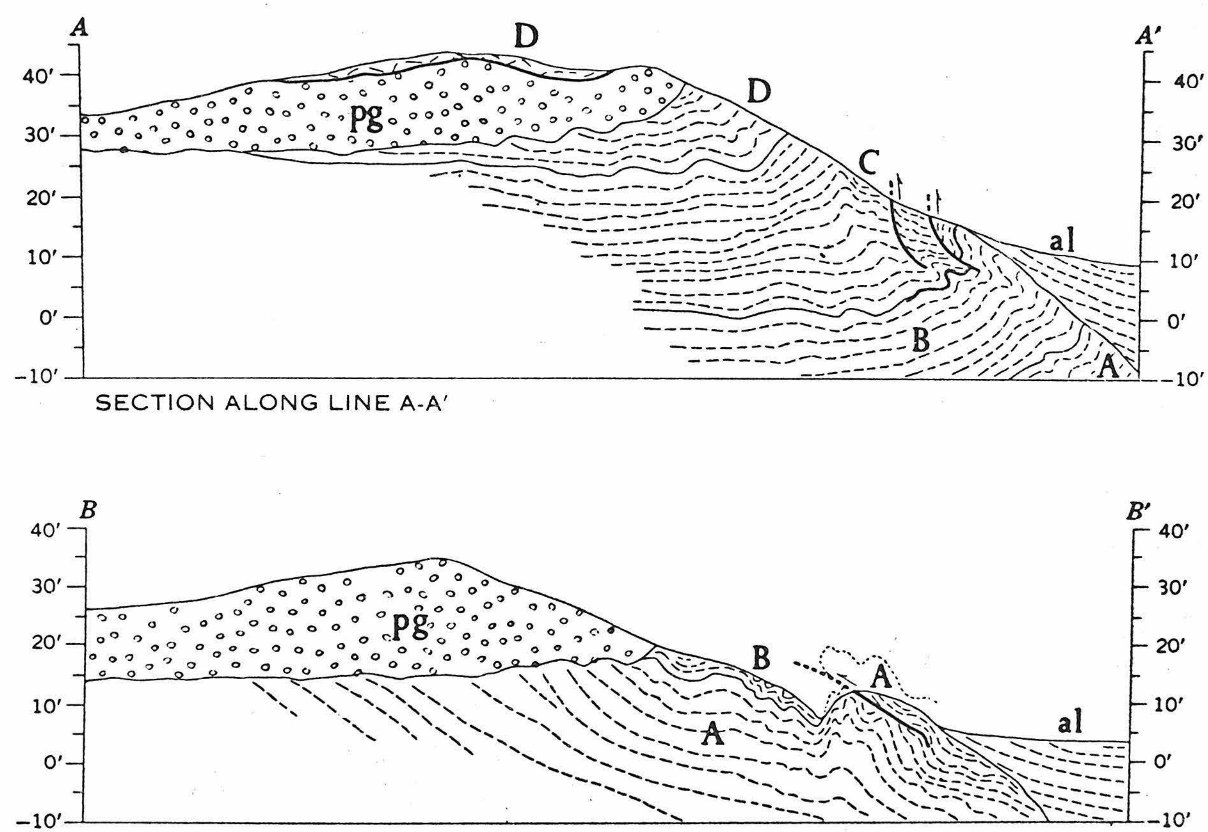


Figure 56.--Cross sections of the Henbury Craters, Australia, showing types of folding in rim strata. From Milton (1966).

impact metamorphism. One exception is a small amount of sandstone ejecta which has quartz grains transformed to glass. Milton states that the Henbury Craters exhibit all the types of structural deformation found at Meteor Crater in Arizona, Odessa Craters in Texas, and the Ries Basin in Germany.

Nuclear Explosion Craters

The structures of only four nuclear explosion craters have been described in detail in the unclassified literature. However, many of the structural features of the Flynn Creek crater are reproduced in these four craters, and each of the four nuclear explosion craters will be briefly described.

The Sedan crater is the largest known nuclear-produced crater, and was formed at the Nevada Test Site by detonation in alluvium of a 100 kiloton thermonuclear device, 635 feet below the surface. The crater measures about 1200 feet in diameter and is about 320 feet deep (fig. 57). The rim strata have been uplifted 10 to 20 feet adjacent to the crater wall. The upper 10 to 15 feet of strata in one part of the rim are overturned (fig. 59) and are cut by a thrust fault with the upper plate moved away from the crater. Complex folding is present in other parts of the rim but has not been described. Below the surface the strata are upturned but not extensively folded (Short, 1965, p. 582). Other details of the structure have not been reported.

The Danny Boy nuclear crater was formed at the Nevada Test Site by detonation of 0.4-kiloton shot in basalt 105 feet below the surface. This produced a crater 210 feet in diameter and about 55 feet deep (fig. 58). Uplift of rim strata averages about 15 feet at the crater wall, but no evidence of overturning is present on the rim. Blocks of basalt up to 20 feet were ejected onto the rim. Deformation in the rim of the massive basalt was controlled mainly by differential slip and rotation along joints and newly created fracture surfaces

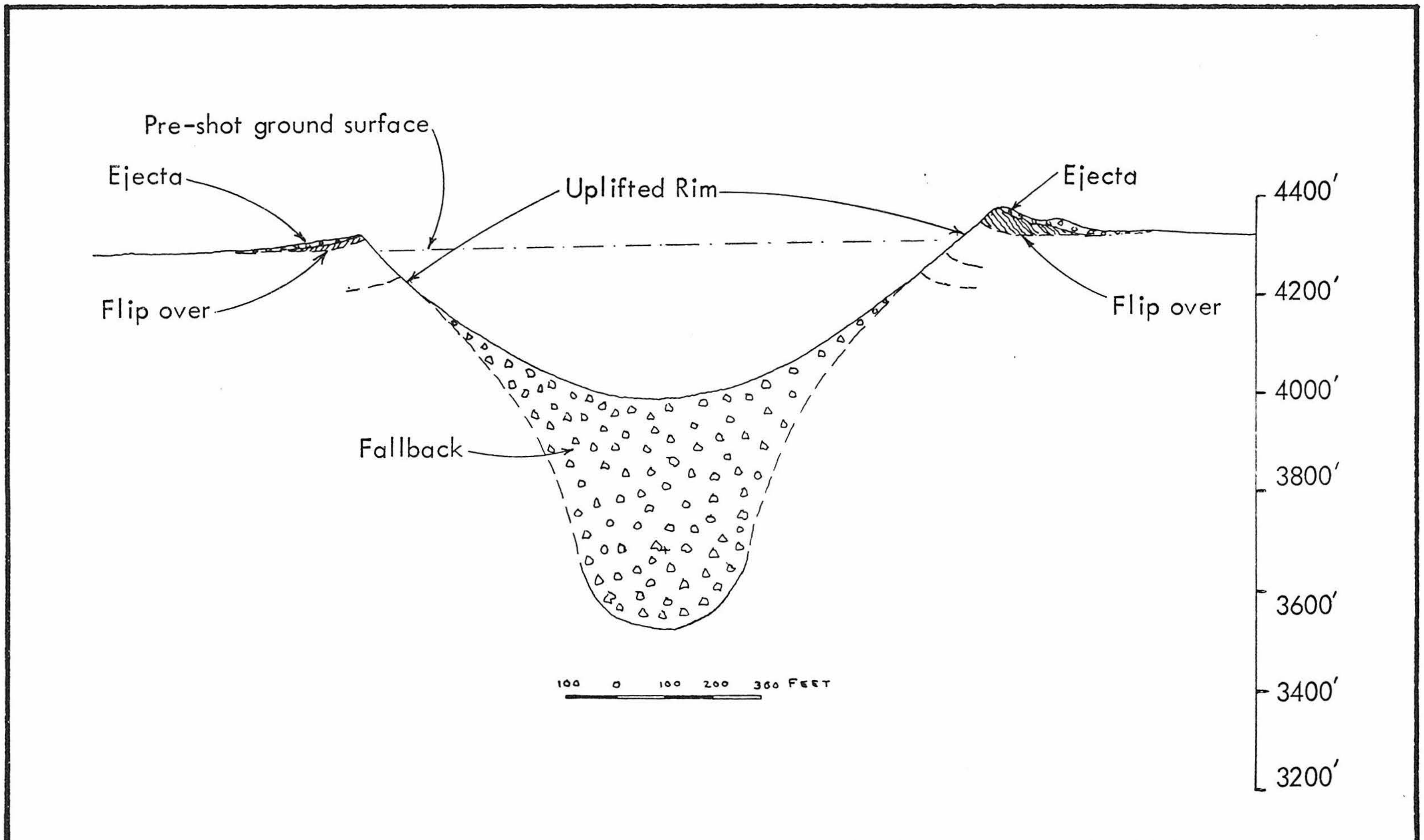


Figure 57 --Cross section through the Sedan Nuclear Crater at the Nevada Test Site. From Short (1965, p. 583).

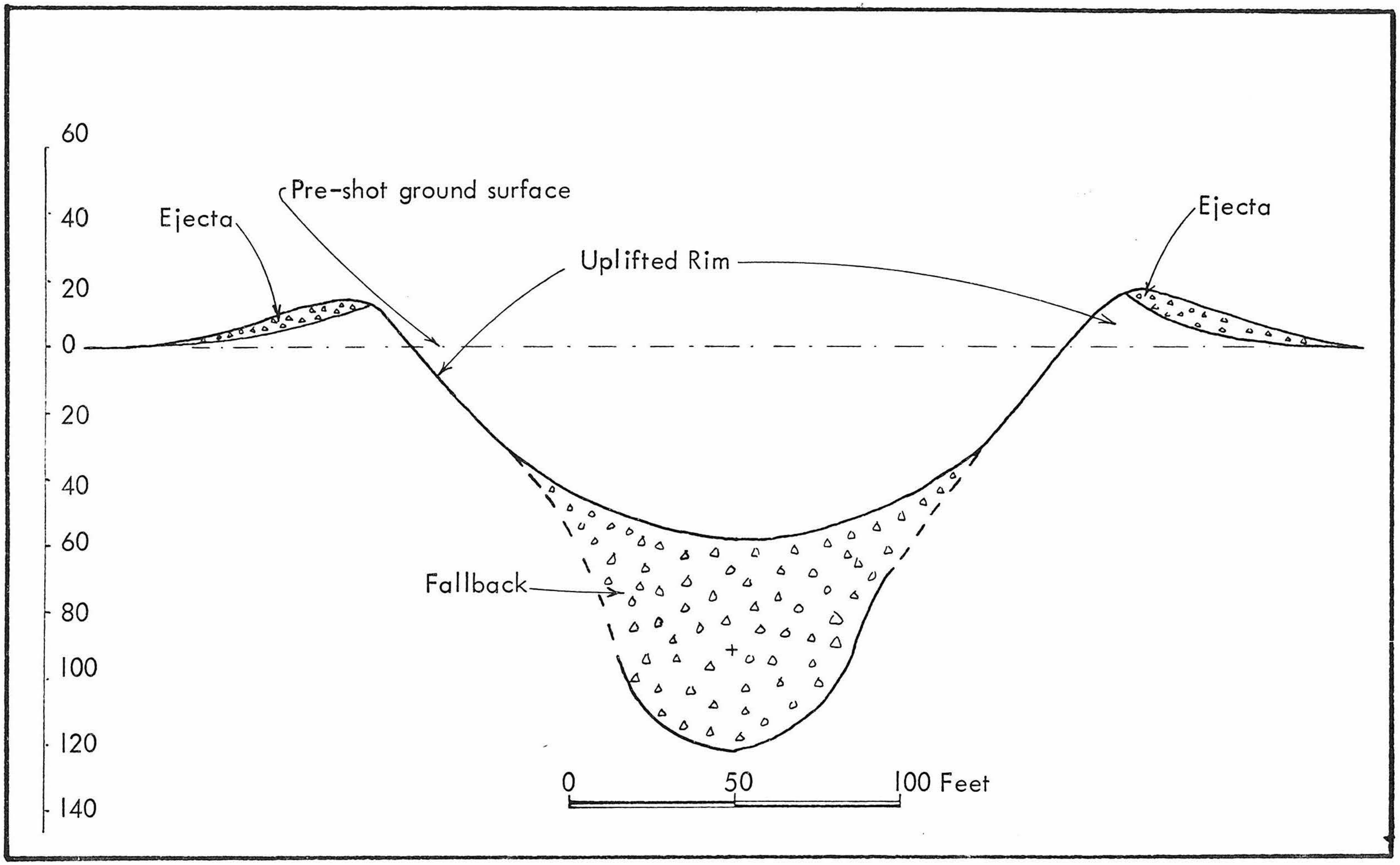


Figure 58 --Cross section through the Danny Boy Nuclear Crater at the Nevada Test Site. From Short (1965, p. 584).

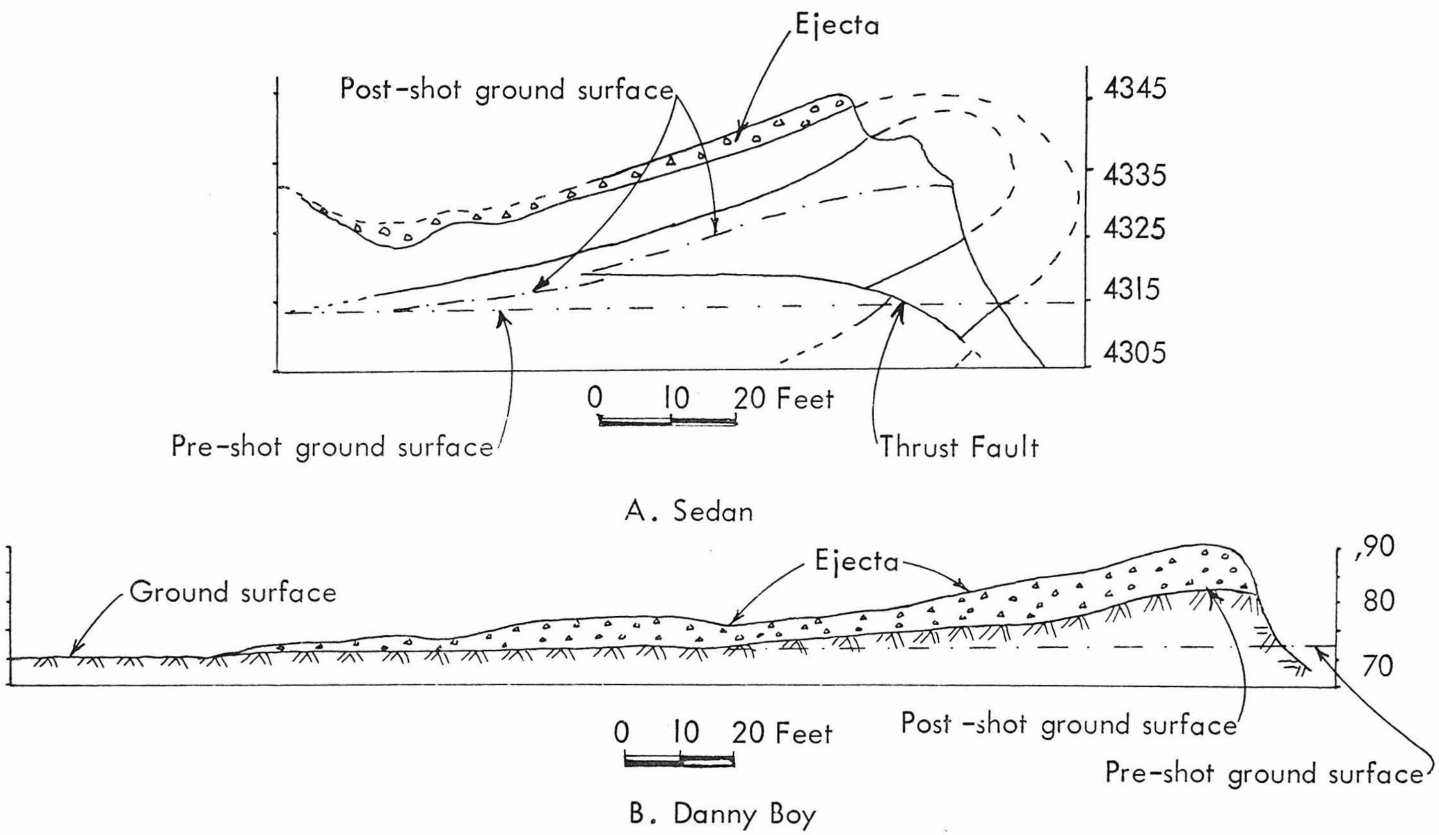


Figure 59 --Generalized cross sections of the rims of the Sedan and Danny Boy Nuclear Craters. From Short (1965, p. 585).

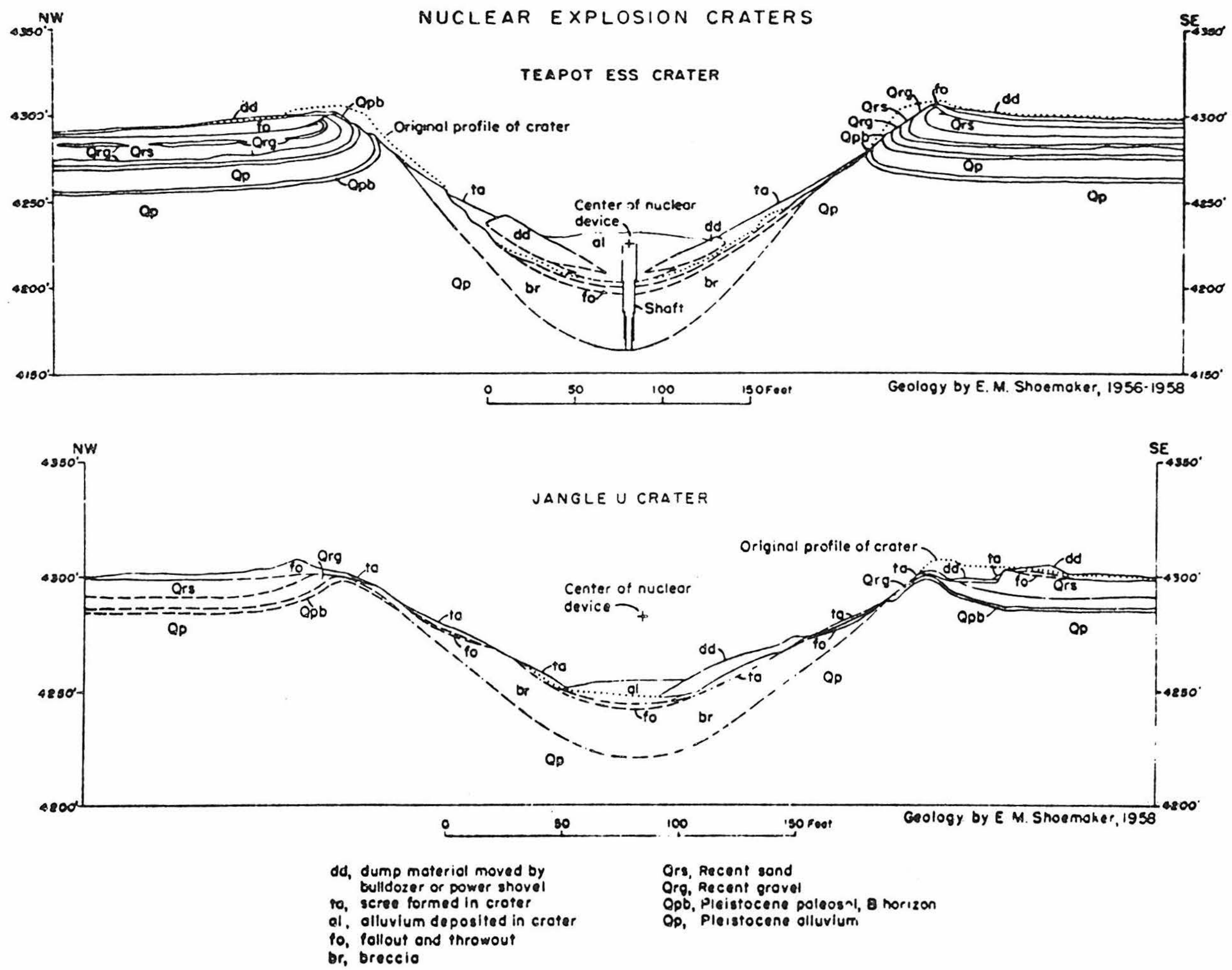


Figure 60 --Geologic cross sections of Teapot Ess and Jangle U Nuclear Craters. From Shoemaker (1960, p. 422).

(Short, 1965, p. 582). Further details of the structure have not yet been reported.

Shoemaker (1963, p. 313) has described the Teapot Ess nuclear crater shown in Figure 60 . This crater was produced in alluvium by a 1.2 kiloton shot detonated 67 feet below the surface. The crater produced was about 300 feet across and originally about 100 feet deep. Beds of alluvium in the rim are overturned as they are at Meteor Crater, Arizona, and at the Sedan and Danny Boy nuclear craters. Shoemaker (1963, p. 313) states, "The upper limb of the fold is overlain and locally passes outward into debris that roughly preserves, inverted, the original alluvial stratigraphy." The crater floor is underlain by a thick lens of breccia composed of fragments of the original alluvium which is sheared and compressed plus dispersed glass made from the alluvium. Shoemaker (1963, p. 312) reports that, "Nearly all the major structural features of Meteor Crater, Arizona are reproduced in the Teapot Ess crater."

The Jangle U crater was formed in alluvium several thousand feet from the Teapot Ess crater by 1.3 kiloton shot detonated 18 feet below the surface. The crater produced was 60 feet deep and 240 feet in diameter (fig.60). Instead of overturning in the rim strata, a pronounced anticline with rim uplift has developed similar to that at Odessa Crater and the Flynn Creek structure. A lens of breccia underlies the crater floor as in the other nuclear explosion craters. Other details of the crater have not been reported.

Chemical Explosion Crater

In June, 1964, the Suffield Experimental Station in Alberta, Canada, detonated a 500 ton TNT charge on the surface. The crater that resulted had such pronounced structural similarities to the Flynn Creek crater that a visit was arranged for the author by the U. S. Geological Survey and the Canadian Government.

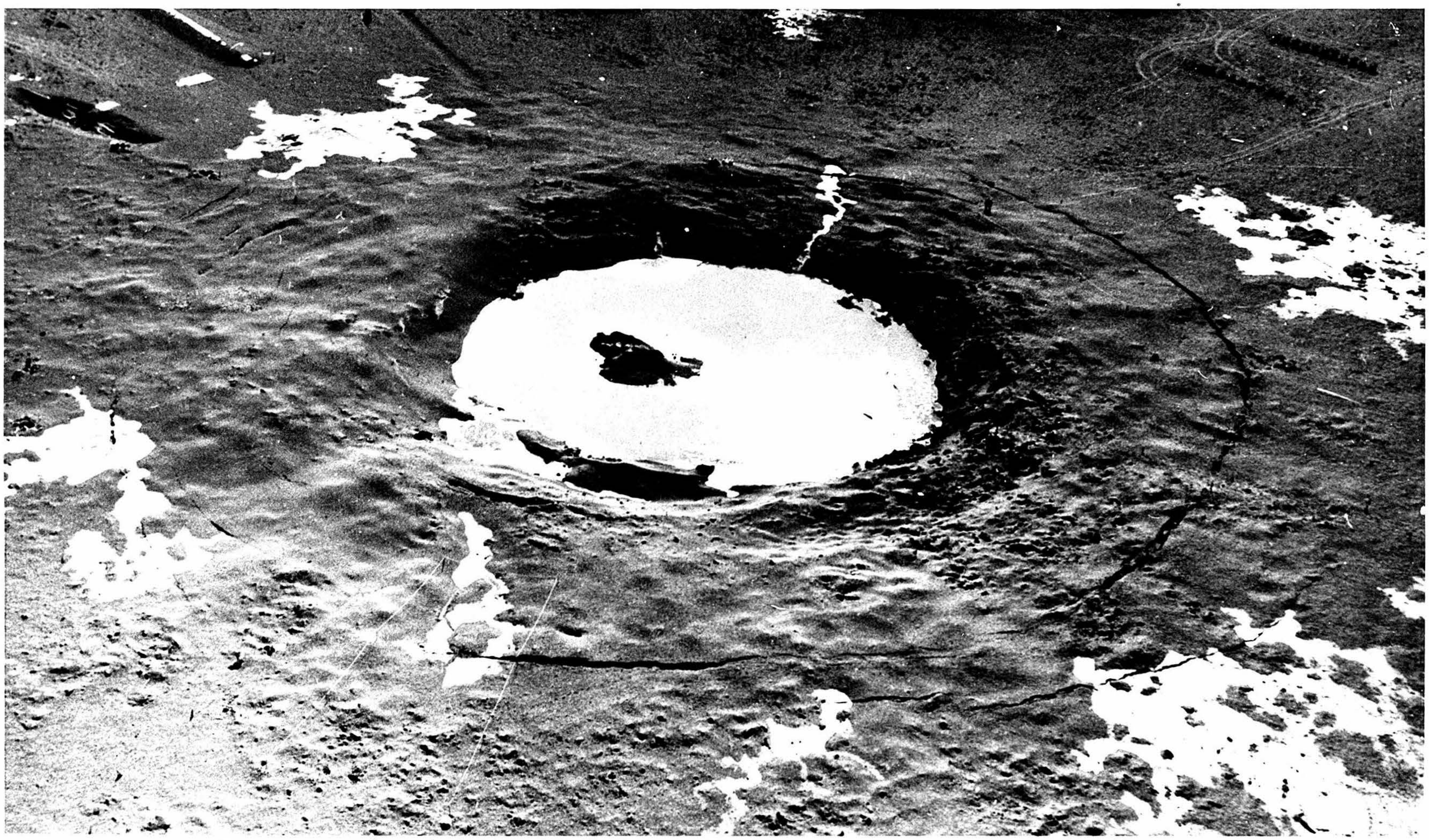


Figure 61 -- Aerial photograph of 500 ton TNT crater at the Suffield Experimental Station, Alberta, Canada. Note concentric fractures and central uplift in lake. Light colored sand issued from fractures during water flow after explosion. Courtesy of G.H.S. Jones, Suffield Experimental Station, Alberta, Canada.

Access to the crater was granted by the Suffield Experimental Station, and the following account is taken from the information supplied by Dr. G. H. S. Jones and C. Diehl and from the writer's observations at the crater during part of its excavation.

The upper 25 feet of the strata at the test site consist of unconsolidated alluvium and lake beds of clays, silty clays, silts, and sands. The coarser material appears lenticular. At a depth of about 20 feet a dense yellowish-brown clay is present, and at about 25 feet a dense blue-gray clay is at least five feet thick in places. A red sand a few feet thick underlies the blue-gray clay. The water table is about 34 feet below the surface.

The explosive was stacked in a hemispherical shape measuring about 30 feet in diameter and 15 feet 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 in diameter at the original ground level, and was about 15 feet in final depth after 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.

C. Diehl stated that he was able to reach the crater and began survey operations about five minutes after the detonation. He described the ground as hot enough to make it uncomfortable to walk upon, and observed that a large mound had formed in the center of the crater. Tension fractures began to open and continued to open for several days after the event. Less than five 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 distances of about 210 feet and 260 feet from the crater wall also continued to open for several days after the detonation (fig. 61). Sand pipes or dikes were formed in many of the fractures during water flow.

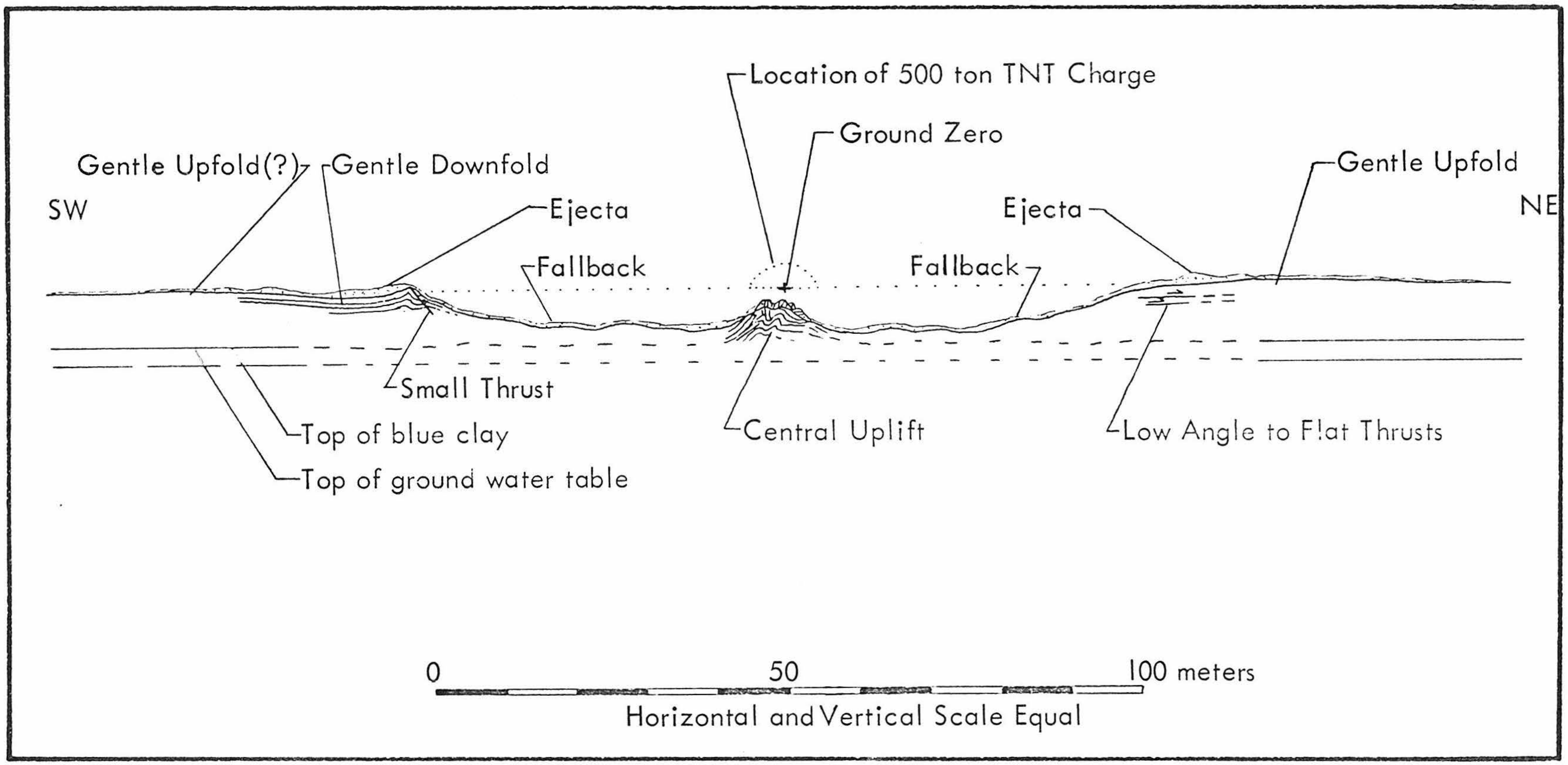


Figure 62.--Schematic cross section of the 500 Ton TNT Crater at the Suffield Experimental Station, Alberta, Canada.

The bedding planes of the clays and silty clays are slightly more fractured near the pipes but are otherwise undisturbed as seen in the excavated rims.

Excavations of the southwestern rim are shown in Figure 62 from sketches made in the field. Diehl states that a gentle depression is generally present beyond the deformed rim strata adjacent to the crater wall. A few feet from the original crater wall the slightly depressed rim rises abruptly into a tightly folded and distorted anticline (fig.62). Parts of some beds are sheared off along the crest of the anticline, and 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. The rims also exhibit intense differential shearing at low angles to the ground surface (fig. 62).

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. Careful measurements by Diehl indicated a minimum folded uplift of ~~15 to 25~~ 35 DJR feet of the blue clay horizon (fig. 62). The top of the mound is mainly a breccia of folded clay fragments. Sand injected by the water flow along fractures made it difficult to determine details of the rest of the central mound in the early stages of excavation, but 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 positions after the detonation. The down warping beyond the crater wall, and the central uplift are confirmed by these markers. Diehl and Jones (1965, p. 305-309) described this technique and demonstrated its immense usefulness with a 20 ton TNT detonation. The displacement of the alluvium in the 20 ton crater is shown in Figure 63. Diehl and Jones pointed out the relationship to the theoretical velocity and particle study of Brode and Bjork (1960).

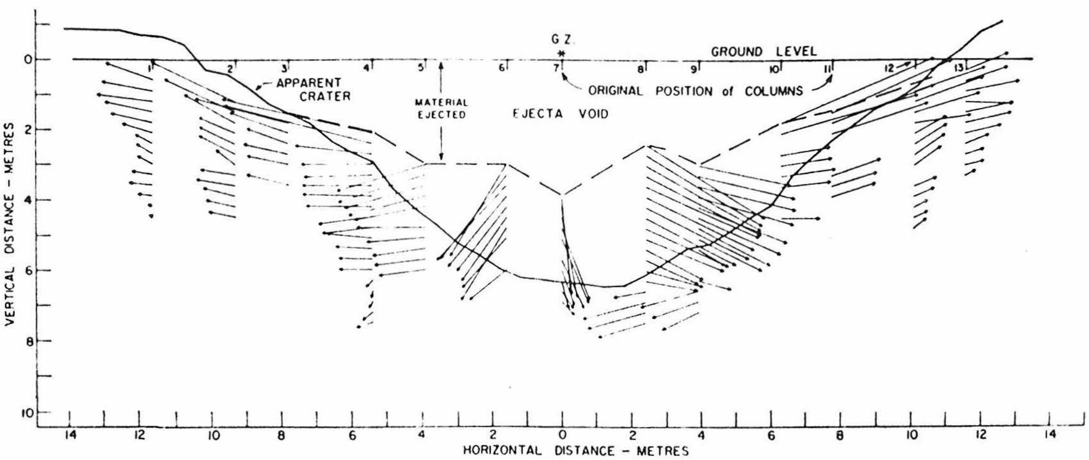


Figure 63 -- Displacement of alluvium below explosion of 20 ton TNT hemispherical charge at the Suffield Experimental Station. Marker cans were buried in sand columns located on radial lines from ground zero. The post-shot positions of the marker cans were used to determine the direction and displacement of the ground. From Diehl and Jones (1965, p306).

A significant result in the 20 ton TNT experiment is the reversal in displacement direction below ground zero. A velocity reversal was predicted in the study by Brode and Bjork and is qualitatively similar to the reverse displacement found by Diehl and Jones. 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. In fact, this particular surface burst produced nearly every structural feature found in the Flynn Creek crater. Publication of Jones' and Diehl's studies will undoubtedly shed further light on this relationship but this information will not be available before completion of the excavation in 1966.

Comparison of the Flynn Creek Crater with Meteorite Impact, Nuclear Explosion, and Chemical Explosion Craters

Comparison of Flynn Creek Crater with Meteor Crater

The crater at Flynn Creek has a number of features which are also present at Meteor Crater. Both structures were formed in flat-lying sedimentary rocks and both are craters. Meteor Crater is bowl-shaped, but at Flynn Creek the crater has a flat floor because of depositional fill. An ejecta blanket is present on the rim of Meteor Crater and at one time was present at Flynn Creek. Both ejecta blankets contain a crude inversion in the stratigraphy.

The strata in the rims of both craters are raised and dip away from the crater walls. Strata exposed in the crater walls at Meteor Crater dip steeply away and in one case are overturned. At Flynn Creek the strata in parts of the crater walls dip steeply away from the crater; in other parts it is more common to have an anticline concentric to the crater wall with the limb on the crater side dipping steeply towards the crater.

Small thrust faults are present at both craters and appear to be approximately parallel with the regional joint systems. Normal faults are present at both craters and are approximately concentric with the crater walls, with authigenic breccia zones present along some of the faults at both craters. Thrust faults at Meteor Crater have upper plates moved toward the crater where as at Flynn Creek all large thrust faults have upper plates moved away from the crater. One smaller thrust, comparable in size to those at Meteor Crater, has its upper plate moved toward the crater.

Rocks in the crater walls at both craters are intensely fractured to brecciated. At Flynn Creek a jumbled zone is developed in some parts of the crater walls. In either crater, strata in the rim a few tens of feet from the crater wall commonly exhibit little deformation. Irregular zones of authigenic breccia are locally present in the rims of both craters.

The floors of Meteor Crater and Flynn Creek crater are both underlain by a chaotic breccia of fragments derived from the local strata. The largest blocks are restricted to near the crater walls.

Comparison of Flynn Creek Crater with Odessa Craters

The structures at Flynn Creek and at Odessa are both craters formed in flat-lying limestones. Rim strata have been uplifted and locally folded in rim anticlines adjacent to the crater walls of both structures. The limbs of the rim anticlines dip toward the craters. Thrust faults have upper plates moved away from the crater. One small thrust fault at Flynn Creek and one at Odessa has the upper plate moved toward the crater. Jumbled strata are present in the crater wall in one of the smaller craters at Odessa, but are common at Flynn Creek.

Comparison of Flynn Creek Crater with Henbury Craters

The Henbury Craters are located in dipping siltstones and shales, whereas the Flynn Creek crater is located in flat-lying limestones. Both are craters which have received varying amounts of washed-in material. Deformation in parts of the walls of both craters is characterized by jumbled strata with no sharp break between the crater breccia and rim strata.

Folding in the rims of both craters is composed of synclines, anticlines and monoclines, locally cut by low to high-angle thrust faults. The upper plate is commonly thrust away at both Flynn Creek and Henbury. Deformation decreases rapidly away from the crater walls.

Comparisons of Flynn Creek Crater with Nuclear Explosion Craters

The crater at Flynn Creek and each of the nuclear explosion craters are located in flat-lying strata. Uplifted strata in the rims are common to all the nuclear craters, with strata dipping away from the crater. The rim strata at Flynn Creek are also raised and commonly dip away from the crater.

Thrust faulting is present in several of the nuclear craters, and commonly the upper plate has moved away from the crater as at Flynn Creek. Shoemaker (personal communication, 1966) states that there are other details of rim deformation and brecciation present at the nuclear craters which compare with deformation at the Flynn Creek crater, but this has not as yet been published.

Locally an anticline is concentric and adjacent to the crater wall at Flynn Creek and has the limb on the crater side dipping steeply toward the crater. This is also present in the rim of the Jangle U nuclear crater and is identical to the fold in the rim of the largest Odessa crater. A shallow depth of burial of the nuclear device at Jangle U crater produced a crater most like that at Flynn Creek. A deeper burial of the nuclear device at Teapot Ess Crater produced a crater most like Meteor Crater.

Comparison of Flynn Creek Crater with Chemical Explosion Crater

The Flynn Creek crater and the 500 Ton TNT crater are both flat-bottomed craters formed in flat-lying strata,and both have a pronounced central uplift. Both structures have uplifted strata in the rim and local anticlinal folding in the rims adjacent to the crater wall. The anticlinal folds are identical to those at the larger Odessa Crater and the Jangle U nuclear crater. A thrust fault cuts the top of the fold as at the Odessa Crater. An ejecta blanket is present.

Tension fractures formed in the rim strata at the 500 Ton crater and very slight subsidence of the blocks occurred. A similar structural feature is present at Flynn Creek in the southern rim, except that the block dropped considerably.

Deformation in other parts of the rim strata of the 500 Ton crater is intense but limited to a zone very close to the crater walls. Jumbling is also common in a few places in the rim. Both of these features are present at the Flynn Creek crater.

The structure of the central uplift at both craters bears a close resemblance. Faulting and brecciation are more common in the strata of the central uplift at Flynn Creek, while folding is more common in the central uplift of the 500 Ton crater.

Conclusions

The crater at Flynn Creek exhibits nearly all the types of structural deformation found at Meteor Crater, Odessa Crater and the Henbury Craters. Comparisons with four nuclear explosion craters have indicated that the structure at the Flynn Creek crater is nearly identical with the Jangle U nuclear crater and has pronounced similarities with parts of the other nuclear craters. The 500 Ton TNT explosion crater has nearly identical structural deformation in all respects with the Flynn Creek crater. On the basis of these structural comparisons it is concluded that the crater at Flynn Creek is also produced by a shock-mechanism, in this case an impact.

Other approaches to the problem of the origin of the Flynn Creek crater have been less definitive,but none contradict the concept of an impact.

The petrographic studies of the zone of intense twinning also indicate a very high pressure environment during the formation of the crater. In so far as is known, this type of deformation has not been shown for maars or diatremes.

High pressure phases, such as coesite and stishovite, are absent at Flynn Creek, as one would expect in such a low silica environment. The maximum percent of detrital quartz in the limestones does not exceed one percent. Thus far the high pressure phases have been found only in rocks which are entirely silicates. Detrital quartz grains would probably be little affected in a matrix which deforms as easily as calcite. It must be emphasized that the exposed horizons at the Flynn Creek structure are not ideal for finding the most intensely deformed material if an impact had occurred. Most of the breccias exposed on the crater floor are reworked and washed into the crater and would cover any fallout layer if one were present. The fallout layer,according to Shoemaker (1960),contains the most highly shocked material in an impact crater.

The trace element results were also negative in finding volcanic or meteoritic materials. The absence of volcanic materials would be difficult to explain by weathering processes,considering they have remained in other sites for similar lengths of time. If a nickel-iron meteorite or even a stoney meteorite had caused the crater, one could suggest that the impact so highly fragmented the body that it was easily weathered and removed by solution. Certainly the amount of meteoritic material in the largest Odessa crater is small and not easily found. This is even true for the surface at Meteor Crater, Arizona. Until drilling has been done at the Flynn Creek structure, this question will not be answered.

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. This is consistent with the 500 Ton TNT surface explosion and the Jangle U nuclear crater. 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. This would explain the absence of meteoritic iron or stoney iron materials, if comets are "frozen gases" as postulated. Shoemaker (1966) has suggested the possibility of comets actually being carbonaceous chondrites which, of course, would not leave any trace after even a short period of erosion following impact.

Shatter cones have not been found in any proven impact craters, although Shoemaker, et. al. (1963) has made them under laboratory hypervelocity impact conditions. Johnson and Talbert (1964) have published a short theoretical treatment which suggests that a very high stress environment is necessary.

Both gravity and magnetic studies were unsuccessful in locating a buried igneous source for the speculated volcanic gases. Either an igneous plug is not present, or the density and magnetic susceptibility of the intrusive body are very close to those of the surrounding sedimentary rocks.

Field studies have shown that the level of the pre-crater surface allows an argument favorable to very low confining pressures. Comparison of the low pressures necessary to fracture limestones under these confining pressures indicates that a high pressure cannot account for the plastic folding. Large meteorite impacts, on the other hand, can generate pressures that are adequate to cause the rim folding as well as brecciation.

Simple scaling laws from nuclear explosion craters and the 500 Ton TNT explosion crater suggest that between 10^{24} and 10^{25} ergs were necessary to form the Flynn Creek crater. Comminution energy calculations also give 10^{24} ergs to fracture the volume of rock in the crater. For illustrative purposes, if a comet of density 3.33 g/cc produced the Flynn Creek structure, one can calculate the size of body using an average impact velocity of 18 miles/second. The diameter of the mass would be approximately 280 feet.

The writer's suggestion that the evidence indicates an impact origin can be uniquely tested by a drilling program. The depth of the lowest brecciated horizon from nuclear scaling suggests it should be less than 3000 feet. This is at least 2000 feet above basement rock. If a lower limit of brecciation is at the approximate predicted level, it would not only help solve the Flynn Creek problem, but would also aid in the solution of many other similar cryptoexplosion structures. Unless subsurface information later provides information to the contrary, the impact origin of the Flynn Creek crater is considered the most likely hypothesis.

Geologic History of the Flynn Creek Crater

The geologic history of the crater at Flynn Creek is important for two reasons: (1) to help determine the most probable origin of the crater, and (2) to establish the time of formation. A thorough understanding of geologic history has been necessary to show that the crater has experienced only moderate erosion. This information has helped establish that the observed structural deformation at Flynn Creek is at or near the original level of the crater. Without this knowledge, structural comparisons could not be made between the Flynn Creek crater and other craters known to have formed at the ground surface, such as meteorite impact and maar craters. The time of formation of the structure is important to an understanding of the rates of erosion and of depositional filling of the crater. The age of the crater also is of particular interest to studies of the rate of terrestrial impact cratering.

The geologic environment of the Interior Lowlands during Lower Paleozoic time has been discussed at length by King (1959), Freeman (1953, 1959), Wilson and many others. It has been generally accepted that regionally extensive shallow seas periodically covered most of the Interior Lowlands during Cambrian and Ordovician time. Wilson (1962) has described conditions in central Tennessee as characterized by shallow seas with periodic uplifts exposing the Nashville Dome to areal erosion. Wilson (1962, p. 504) states that during Late Ordovician time the Nashville and Ozark swells were uplifted, and Leipers strata (Maysville time) were eroded from the higher parts of the Nashville Dome. Immediately north of the Flynn Creek area only the upper 25 to 50 feet of Leipers strata were eroded from the area. This was probably also true in the Flynn Creek area, except the level of erosion was slightly lower.

Near the end of Ordovician time the Richmond sea covered central Tennessee including the Nashville Dome and the Flynn Creek area. The Sequatchie sediments were deposited as a calcareous ooze in silt-free water over a large part of the state (Wilson, 1949, p. 343). Several changes in depositional conditions occurred during late Richmond time, and limestones, shales and silts were deposited as interbedded units north and west of the Flynn Creek area. During the end of the Ordovician and possibly at the beginning of Silurian time, central Tennessee was exposed to a period of erosion, and unknown amounts of older strata were eroded from different areas. Erosion in the Flynn Creek area did not go below the Sequatchie strata.

During the Silurian Period several advances and withdrawals of shallow seas occurred accompanied by the deposition of a series of limestones, shales and siltstones. Marine carbonates and shales of Silurian age are present along the extreme northern and northwestern part of the Nashville Basin in central Tennessee (Wilson, 1949, p. 239-279). The Silurian strata are restricted to the western side of the present Nashville Dome, a distance of nearly 30 miles from the Flynn Creek area. The nearest probable Silurian strata to the east is suggested by Born and Lockwood (1945) from test wells, a distance of nearly 50 miles from the Flynn Creek.

During Early and Middle Devonian time several incursions of shallow seas again occurred and were accompanied by periods of extensive erosion. Middle Devonian strata are absent on the eastern side of the Nashville Dome except for a small isolated deposit of Pegram Formation in west-central Jackson County about 12 miles northwest of the Flynn Creek area. Only a rubble of weathered Pegram sandstone blocks covering a few thousand square feet are present in this area representing the only remains of what was once probably a continuous shoreline deposit. The sandstone blocks lie directly upon the Leipers formation in a manner suggesting they have been let down from an earlier erosional surface. The nearest Pegram strata, lying in their normal stratigraphic position,are located along the western flanks of the Nashville Dome, a distance of 30 miles from the Flynn Creek area. Lower and Middle Devonian strata have not been described in the subsurface from east of the Flynn Creek area to the Valley and Ridge province of east Tennessee.

It is not yet possible to say if Middle Devonian seas covered the Flynn Creek area. The distribution of the Pegram strata, according to Wilson (1949, p. 346), suggests that a Middle Devonian sea rose very high on the eastern flank of the Nashville Dome. If this is true, then the Flynn Creek area was almost certainly covered.

A major interval of erosion followed the withdrawal of the Pegram sea, and the newly-deposited sandstone and limestone were widely removed from much of central Tennessee. During Middle Devonian time the area immediately north of Flynn Creek was reduced to a rolling lowland with less than 100 feet of relief and with gentle slopes (Barnes, personal communication, 1964; Maher, personal communication, 1964). In some localities the Sequatchie rocks are removed, and part of the top of the Leipers strata is also eroded away.

In the Flynn Creek area the Leipers strata were eroded 50 to 100 feet below the level of the highest Leipers horizons exposed 15 miles to the north. Most of the Sequatchie strata and the upper Leipers units of Platystrophia ponderosa limestone were probably eroded from the area. The down-faulted blocks on the southeastern rim of the crater, however, preserves 75 to 150 feet of upper Leipers unit of Platystrophia ponderosa limestone and brecciated fragments of Sequatchie dolomite.

It would appear likely that the crater was formed within this interval in Middle Devonian time, possibly during a period of extensive regional erosion. The presence of Sequatchie fragments in the breccia clearly indicates a post-Richmond age for the crater. 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 Devonain 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.

Fragments from the upper Leipers unit of Platystrophia ponderosa limestone age are rare in the crater breccia, and Sequatchie fragments have not been found in the crater, yet both these rocks are present in the down-faulted block in the southern rim. It seems likely that the area may have been a rolling lowland with the low hills capped with Sequatchie rocks which were underlain by 75 to 150 feet of upper Leipers unit of Platystrophia ponderosa limestone. If a complete cover of these rocks had been present when the crater was formed, then more fragments should be present in the breccia of the crater, both from the initial deformation and from later erosion of the crater wall. It is possible that the region may have been in a coastal plane environment if the Middle Devonian sea was still in the immediate area.

It would seem unlikely that the crater could have existed for any great length of time before being destroyed by erosional and depositional processes. Instead, crater walls are still present as steep cliffs in parts of the crater, and the central uplift still remains with little obvious erosional destruction. An age of late Middle Devonian to early Late Devonian seems most consistent with the available evidence.

The crater appears to have been formed during the impact of either a comet or a meteorite, and a large amount of rock ejected and fell as an ejecta blanket surrounding the crater. A crude inversion of the strata occurred during the ejection and was later preserved on the southern rim. Presumably the central uplift and the intense folding and faulting in the rim occurred during the brief period of cratering. The large thrusts on the southeastern rim were probably formed during the impact, but other fault blocks, such as the down-faulted block on the southeastern rim, may have subsided for some time after the event. It seems most likely that the southern-most fault zone was an open fracture at one period of time. Sequatchie breccia fills most of the fault zone and is present at the base of the overlying ejected breccia (fig. 36). The Sequatchie rocks, which were ejected and scattered at the base of the ejecta blanket, probably dropped into the opening fault zone as the block slowly subsided. The block probably continued to slump toward the crater until it formed a depression in the rim which preserved part of the ejecta blanket.

Erosion began to act immediately upon the ejecta and crater, and the entire ejecta blanket was eventually removed, except for that part preserved in the down-faulted block. Ejecta breccia over the block settled enough to allow a small talus deposit of upper Leipers

Platystrophia ponderosa rocks (fig. 36) to develop. Some of the ejecta and rim strata must have been eroded and deposited at the base of the crater walls and spread out over the crater floor. A very crude lineation in the long direction of some breccia fragments can be seen in a few of the breccia outcrops near the crater walls, suggesting that these breccias were washed or deposited over the crater slopes with a very crude bedding.

Slumping is evident along some of the crater walls where large megabreccia blocks are nearly at their original stratigraphic levels but are now tilted and separated a few hundred feet from the rim strata. Subsidence probably occurred over all of the crater floor as solution removed finer breccia fragments from lower levels.

Lake beds and alluvium may have formed on the crater floor, but they would now be covered by breccia washed in from the rim strata and ejecta blanket. Erosion proceeded to form small valleys and gulleys in the crater walls, but it does not appear that the rim was ever breached and opened to outside drainage. Erosional cliffs are present in parts of the crater walls. An internal drainage system developed in the crater, and much of the ejecta blanket that washed over the rim was carried to the low areas surrounding the flanks of the central uplift.

Apparently the Chattanooga Sea had begun to cover the area by this time, or possibly it was present slightly earlier. If a high ejecta blanket surrounded the crater, it could have prevented a shallow sea from initially flooding the crater. However the unconsolidated nature of the ejecta would suggest that any surrounding body of water would quickly remove any standing mass of breccia. On the other hand, much, if not all of the breccia may have been removed by pre-Chattanooga erosion.

The first clearly bedded deposits in the crater appear to be poorly-bedded breccias composed of reworked crater breccia. These poorly-bedded breccias cover the crater floor and wedge out low on the crater walls. Apparently these breccias were reworked and distributed over the crater floor and were then overlain by well-bedded breccia derived mainly from the highest horizons in the crater walls. A single massive bed of dolomite was then deposited on the well-bedded breccia throughout the crater.

The bedded breccias and dolomite were apparently deposited in a marine environment, because conodonts of early Late Devonian age are present in these rocks; they form the local, basal units of the Chattanooga Shale within the crater. No trace of ejecta or bedded breccia is present outside the crater.

During early Late Devonian time sediments of the Chattanooga Shale filled the crater and prevented further erosion of the structure. Nearly 300 feet of the lower unit of the black shale filled the crater to a level about equal with the surrounding rim surface. Younger units of the shale then covered the nearly level area over the crater.

Deposition appears to have been continuous into Early Mississippian time with the Maury and Fort Payne Formations. The shale in the crater continued to compact until it had decreased in thickness to about 200 feet and produced a broad sag in all of the filling sediments. Pennsylvanian sediments later covered the area but were removed during more recent erosion. During Quaternary and Tertiary time drainage patterns were established, probably contemperaneous with a gentle uplift of the Nashville Dome and surrounding region. The Cumberland River and its many tributaries, including Flynn Creek, continued their downward-cutting to form a complicated drainage pattern of incised stream valleys. The heads of the many stream valleys are slowly eroding into the flat uplands of the Highland Rim to the east and northeast of the Flynn Creek area. To the west the streams empty into the Cumberland River where it flows across the rolling lowlands of the northern end of the Nashville Basin. The once deeply-buried crater at Flynn Creek is now exposed in the walls and floors of the many valleys that have more recently been incised into the older rocks.

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