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GEOLOGY OF THE WELLS CREEK STRUCTURE, TENNESSEE

By

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assisted by

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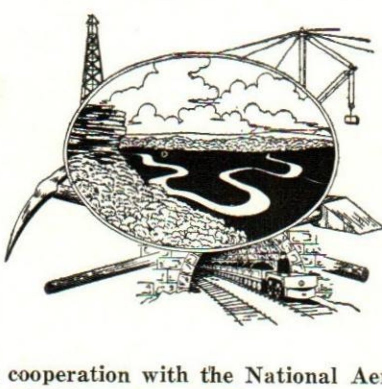

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STATE OF TENNESSEE

BUFORD ELLINGTON, Governor

DEPARTMENT OF CONSERVATION

E. BOYD GARRETT, Commissioner

DIVISION OF GEOLOGY

WILLIAM D. HARDEMAN, State Geologist

PROLOGUE

Many millions of years ago, possibly as long as 300 million years, a violent event occurred in what is now Wells Creek Basin in Stewart and Houston Counties of Central Tennessee. Probably a bright light appeared and streaked southward across the sky like a falling star. And then the foreign object struck the earth's surface with shuddering impact, accompanied by a supersonic air blast, and penetrated to a considerable depth before the tremendous downward forces together with the earth's forces of resistance resulted in an horrendous explosion. The earth shook and earthquake waves raced in all directions. A mighty fiery mushroom of masses of rock and clouds of pulverized rock dust rose high into the air, and then fell back to earth. The rock fragments landed quickly, but some of the dust stayed in the air. A great crater was formed, possibly 4 miles in diameter and half a mile in depth, rimmed by a surrounding pile of shattered rock debris. The deafening noise died out—all returned to the peace and quiet that prevailed before the catastrophe.

The earth's surface appeared to be damaged forever, but millions of years passed and erosion and vegetation softened the ugly scar. The rim of shattered rock disappeared, and the level of the region was lowered many hundreds of feet by the work of rain and running water—mass wasting, gullying, and downward and lateral cutting by streams. Because of the shattered character of the rock in the impact area, the circular scar was eroded faster and therefore deeper than the surrounding region. Thus, circular Wells Creek Basin, as we know it today, was born.

And then came Man. Perhaps 10,000 years ago, man first saw Wells Creek Basin. Indian tribes found haven in this pleasant basin that had so much to offer. Game was plentiful, and the streams yielded a variety of fish and mussels. Springs and clear streams were present. The low hill in the middle of the basin afforded an excellent place to camp and to live safely above the highest flood water. Outposts of watchers could guard the trail that entered the basin from the south along Wells Creek as well as paths that crossed the protective rim of hills surrounding the basin. The low central hill could be defended easily. Dense flint found in great abundance in the hills about 5 miles to the west could be patiently worked into arrow points and spears for war and hunting, large ceremonial flint objects, and many other useful items.

When the first white settlers came from North Carolina and Virginia, they were impressed by the relatively flat, well-drained basin. The soil was better than that of the surrounding hill country. Not only was the soil fertile and essentially free of chert blocks, but it also presented within a small area a variety of soil types formed by the weathering of the many types of rock exposed there. Here, in the basin, a highly agricultural society was developed, as is attested by the two magnificent old homes still standing as mute testimony of the proud history of the basin.

The owners, their neighbors and visitors, knew that the soil was different and that the rocks were unlike others in the region. Undoubtedly many wondered why.

As early as 1806 taverns and mills operated along Wells Creek, presumably named from Phillip Wells who had a small store on the creek in that year.

In 1852 a charter was granted to the Memphis, Clarksville, and Louisville Railroad to lay a railroad line between Paris, Tennessee, and Guthrie, Kentucky. Actual work along the line began in August 1854. And then surveyors and engineers came to the basin. As they ran their lines and figured cuts and fills, they noticed the rocks, badly deformed, standing on edge, and utterly different from other horizontal strata of the region. Either the railroad company invited Dr. James M. Safford, State Geologist of Tennessee, to come to see their unique find, probably previously unknown to professional geologists; or he came of his own volition, looking for new exposures of rock in the new railroad cuts.

And thus geologists came to the basin; and today, in 1968, they are still coming to observe, examine, and study the deformed rocks and to ponder and debate what happened in Wells Creek Basin.

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INTRODUCTION

GENERAL STATEMENT

The Wells Creek structure is a concentric series of two grabens and a horst around a central uplift. The diameter of the entire structure is about 8 miles. It is about 50 airline miles northwest of Nashville, Tennessee, in the northern part of the Western Highland Rim. The major topographic anomaly in this region is Wells Creek Basin, a circular basin about 2 miles in diameter through which Wells Creek flows toward the Cumberland River.

The origin of this structure has been of considerable interest since its discovery in about 1860. As a result of the present investigation the most plausible origin is believed to be by the impact of a large meteor. A volcanic blowout, however, is another possible explanation.

This report includes a detailed presentation of observations made on the geology of the Wells Creek area, which is included within the Needmore, Cumberland City, Erin, and Ellis Mills 7½-minute quadrangles. In the chapters on stratigraphy and structure observations are described in considerable detail so that later workers in this area will have at their disposal observations that were recorded during the field work and, also, descriptions of these observations. This also was done in the chapters on interpretation of structural data, structural fabric, shatter cones, brecciation, and geophysics, but in these chapters some analyses and interpretations are included. In the final chapter both the preferred interpretation of the origin of the structure by meteor impact and an alternative origin by volcanic blowout are presented.

Inasmuch as the presentation of observations and their interpretations are given in greater detail than some readers need, our chapter-by-chapter "abstract-summary" is presented first. Full details of observations are on file with the Tennessee Division of Geology in Nashville.

SUMMARY

Stratigraphy

The Wells Creek area is an important locality for stratigraphic studies, because almost 4,000 feet of strata can be studied here. Most of this sequence either is eroded or is buried deeply elsewhere in this region. The Highland Rim level of this region is underlain by relatively flat-lying strata of the Mississippian System—the Fort Payne, Warsaw, and St. Louis formations. Strata as old as early Ordovician Knox Dolomite are pushed up in the center of the structure; indeed, pre-Devonian strata are restricted to the central uplifted area. Faulted down in annular grabens, concentrically encircling Wells Creek Basin, are small areas of preservation of Ste. Genevieve Limestone and post-Ste. Genevieve beds as young as the Paint Creek Limestone—the youngest formation known to have been involved in the Wells Creek structure. The Tuscaloosa Formation of Late Cretaceous age occurs locally in small patches on the higher ridges in all four quadrangles. As it is not involved in the deformation that caused the Wells Creek structure, this gravel is of special significance as a delimiting dating plane. It is present at an elevation of about 600 feet in the central block, the inner graben, the horst, and the surrounding region. The date of the Wells Creek event,[1] therefore, is post-Paint Creek and pre-Tuscaloosa (preferably late Mississippian, as mid-Mississippian brecciated rock apparently was not completely lithified when deformation occurred).

[1] The term, Wells Creek event, will be used throughout this report to refer to the application of the deformative stress that produced the Wells Creek structure.

TABLE 1.—*Thickness (in feet) of formations exposed in the Wells Creek structure.*

	Representative average thickness
Mississippian System	
Post-Ste. Genevieve (including equivalents of Paint Creek)	about 180
Ste. Genevieve Limestone (including some Renault)	about 200
St. Louis Limestone	180
Warsaw Limestone	100
Fort Payne Formation and New Providence Shale	450
Maury Shale	about 2
Devonian System	
Chattanooga Shale	30
Camden and Harriman Formations	70
Ross Formation	40
Silurian System	
Decatur Limestone	70
Brownsport Formation	70
Dixon Formation	45
Laurel and Lego Limestones (and Waldron Shale)	60
Osgood Formation	30
Brassfield Limestone	20
Ordovician System	
Fernvale Limestone	30
Hermitage Formation	250
Stones River Group	1,000
Knox Dolomite	600 known
Total (best estimate of known strata)	3,427 known

Structure

The five structural subdivisions are (in order inward toward the center):

(1) the essentially undisturbed region surrounding the Wells Creek structure

(2) annular outer graben

(3) annular horst

(4) annular inner graben

(5) circular central block containing a circular core of megabreccia about 5,000 feet in diameter.

The total structural relief outside the structure is about 350 feet; the north-south trending anticlines and synclines have an average amplitude of about 100 feet. Inside the structure, total structural relief is more than 3,000 feet. Grabens have been dropped as much as 550 feet, and rock at the center is uplifted at least 2,500 feet.

TABLE 2.—*Dimensions of structural features.*

	Feet	Miles
Diameter of entire structure		
Average (approximate)	43,500	8.24
Diameter of Central Block		
Average (approximate)	16,500	3.12
Width of Inner Graben		
Average (approximate)	6,000	1.14
Width of Horst		
Average (approximate)	4,000	0.76
Width of Outer Graben		
Average (approximate)	3,500	0.66

	Square feet	Square miles
Area of entire Wells Creek Structure (planimeter)	14.76×10^8	52.9
Area of Central Block (planimeter)	2.13×10^8	7.6
Area of Inner Graben (planimeter)	4.57×10^8	16.4
Area of Horst (planimeter)	3.74×10^8	13.4
Area of Outer Graben (planimeter)	4.32×10^8	15.5

	Feet
Uplift at crest of Central Block at center	
Preferred estimate (assuming 600 ft. of Knox eroded)	2,565
Downthrow of Inner Graben	
Maximum	550
Minimum	less than 50
Average	216
Uplift of Horst	
Maximum (5 local places only)	400
Minimum (usual altitude)	0
Average	nearly 0
Downthrow of Outer Graben	
Maximum	350
Minimum	0
Average	188
Thickness of strata exposed	
A. Above Knox	
Best estimate	2,827
B. Including Knox	
Best estimate known (includes 600 feet of Knox)	3,427 plus

For the outer graben, dip of the outside fault is nearly vertical; whereas, the inside fault dips outward from 30° to 60°, so that the graben narrows as the bounding faults converge with depth.

For the inner graben, dip of the outside fault is believed to be nearly vertical; whereas, the dip of the inner fault is steeply outward probably from 45° to 70°, so that this graben also narrows as its bounding faults converge with depth. The horst widens at depth between the grabens.

The outer graben portion of the structure is broken by five major radial faults.

The central block, which is about 3 miles in diameter, contains a core of Knox Dolomite 6,000 to 7,000 feet in diameter. This core has been uplifted, or forced upward, more than 2,500 feet above its normal regional position. The central block has a circular mass of jumbled blocks of all sizes referred to as megabreccia, about 5,000 feet in diameter, at its center. Megabreccia includes both Knox and younger strata. Dipping off the core of megabreccia are Knox and post-Knox Ordovician, Silurian, Devonian, and lower Mississippian formations in concentric outcrop belts. These belts are offset by several radial faults; these are not connected with the radial faults that offset the exterior ring grabens.

Geological Interpretation of Structural Data

Although the pattern of the Wells Creek structure is basically circular, it has a north-northeast axis of bilateral symmetry. This bilateral symmetry is manifested by the linear occurrence of several structural features along this line and by the "enantiomorphic pairings" of other structural features in reference to this line. Gravity patterns also show this symmetry, which is related to trends of pre-existing joints and probably was controlled by the north-northeast joint set.

A structure map drawn by projecting contours across the structure shows that the regional north-south trending highs and lows continued across the area before the structure was formed.

As well as can be measured, the volume of rock downthrown in the two ring grabens appears to be equal to the uplifted rock in the central block. This is consistent with the geophysical evidence that there is no intrusion at depth nor uplift of basement rocks. Conclusions as to absolute movement are:

(1) The outer graben merely has dropped downward about 200 feet.

(2) The horst has moved inward about 200 feet to accommodate the downdipping "wedge" of the outer graben.

(3) The inner graben has moved 200 feet inward with the horst and 250 feet downward.

(4) The central block has moved inward about 325 feet and also upward about 2,500 feet.

(5) Lateral movement of all the structural elements is interpreted to diminish at depth.

Structural Fabric

The Wells Creek structure, from the configuration of its shape, its radial and circumferential fault patterns, and local gravity anomalies, down to such details as the tilting of beds within relatively small blocks of rock, was strongly influenced by two main pre-existing sets of joints N. 10°E. and N. 85°W. Another fabric trend, approximately northwest, is not explained by joints cutting Mississippian rocks but could be related to lower Paleozoic buried joints.

Shatter Cones

Shatter cones, abundant in some outcrops of Knox Dolomite in the central block, point obliquely to bedding at several separated localities. They are supposed to have been formed by shock waves that arrived before the beds were tilted by the Wells Creek event. Also, they are supposed to have formed pointing toward the place from which the shock waves came. If these premises are granted, the shatter cones were formed by shock waves coming from a position near the Stones River-Knox contact, which at that time was more than 2,000 feet underground.

Brecciation

Two main episodes of brecciation were (1) Ordovician karst brecciation of the Knox Dolomite and (2) formation of megabreccia and other breccias at the time of the Wells Creek event.

Knox homogeneous and heterogeneous rubble breccias and crackle breccias are similar to, and probably had the same paleokarst origin as, Knox breccias in East Tennessee. Megabreccia, a jumble of large (several feet to hundreds of feet across) clasts or fault blocks, is characteristic of the center of the structure. The fractured chert breccia in Mississippian limestone adjacent to most of the annular faults apparently formed with the Wells Creek structure, perhaps when this limestone was a partially indurated sediment. This breccia may approximately date the structure as late Mississippian or early Pennsylvanian. This dating of the structure, though tenuous, is the best that can be offered, as the structure otherwise is dated as post-Paint Creek and pre-Tuscaloosa (late Mississippian to late Cretaceous).

Geophysics

The structure is on a broad gravity promontory extending northward as an extension of a prominent east-west high. At the center is a positive 3-milligal anomaly due to uplift of dense Knox Dolomite. Outward from this central high are a concentric low and an incomplete horseshoe-shaped high that are roughly concentric with the structure. These define a north-northeast line of extension that coincides in trend with the structural symmetry axis.

Regional gravity highs have magnetic counterparts, but the central high does not. Lack of magnetic anomaly at the center is consistent with a lack of volcanic material and absence of a buried meteorite at depth, and with the idea that the basement is not uplifted beneath the structure.

Interpretation of Origin of Wells Creek Structure

The two likely hypotheses of origin for the Wells Creek structure are either by volcanic blowout or meteor impact. The meteor impact hypothesis is preferred mainly because of shatter-cone orientation and the inferred inward movement pattern.

Possibly there was a steam explosion or series of explosions that drove a plug of rock within the central block upward and created a void at depth which was filled by rocks moving inward and downward as a collapse cone—the inner graben. Under this hypothesis, the outer graben is interpreted as a conventional graben restricted to a shallow depth.

The preferred impact hypothesis is that a meteor, about 1,000 feet in diameter and traveling 10 to 25 miles per second (36,000 to 90,000 mph) hit the earth's surface, penetrated about 2,000 feet and exploded. It formed a crater about 4 miles in diameter which may have been mostly filled by the central uplift. The circular horsts and grabens exposed on the surface are mainly exterior structures that resulted from elastic rebound from shock pressures that followed the explosive meteor impact. The grabens occur where rock fell downward and outward into ring cracks; these ring cracks developed during inward movement of rock that formed the central uplift.

TOPOGRAPHY AND PHYSIOGRAPHY

The Wells Creek structure (fig. 1) is named for Wells Creek, a stream that flows northward through Wells Creek Basin. This circular basin was carved by erosion in the uplifted central zone of the circular structure.

The area described in this report is entirely within the Western Highland Rim physiographic province. This province is here essentially a relatively flat or rolling upland into which a complex drainage pattern has been incised. In general, the elevation of this upland surface ranges from 700 to 800 feet in the south, and lowers northward to 600 to 700 feet. The Cumberland River enters the Wells Creek area on the east at an elevation of about 360 feet and leaves its western edge at an elevation of about 340 feet.

In this setting Wells Creek Basin is a circular basin about 2 miles in diameter (fig. 2). The floor of the basin ranges from 360 to 450 feet in elevation. Near the center of the basin is Central Hill, which rises to about 450 feet. Surrounding Central Hill is the belt of prominent inner annular valleys, which ranges in elevation from 360 to 380 feet. This feature is surrounded, in turn, by a broken ring of annular ridges, an incomplete belt of outer annular valleys, and an outer belt of annular ridges 500 to 600 feet in elevation.

PREVIOUS INVESTIGATIONS

Safford's First Biennial Report as State Geologist, presented to the Thirty-First General Assembly of Tennessee in December 1855 (Safford, 1856), was accompanied by a geological map of Tennessee. Inasmuch as this map did not show the Wells Creek structure, Safford probably was unaware of its existence at that time. However, the structure was shown on the Geologic Map of Tennessee that accompanies his *Geology of Tennessee* (Safford, 1869). The structure was described in the text (p. 147-148, 220, 257):

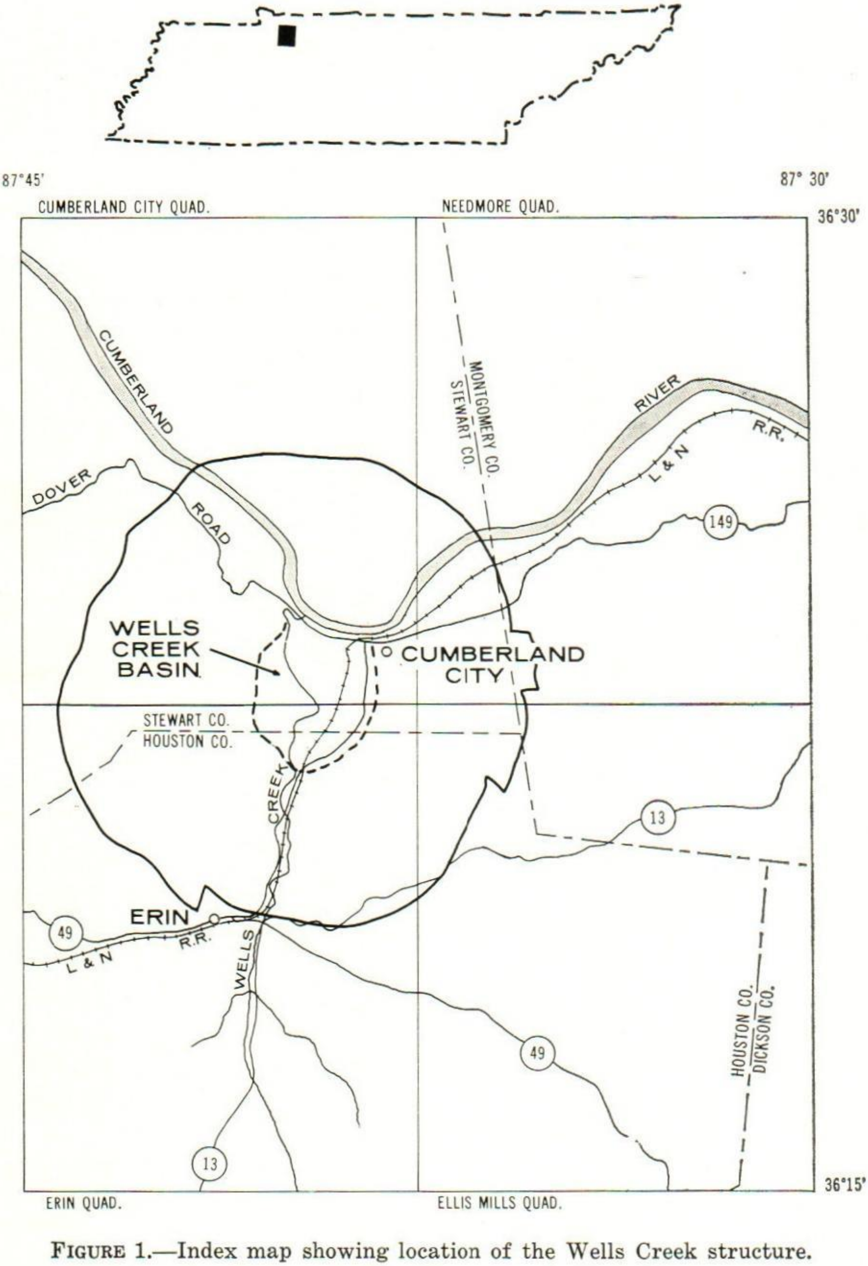


FIGURE 1.—Index map showing location of the Wells Creek structure.

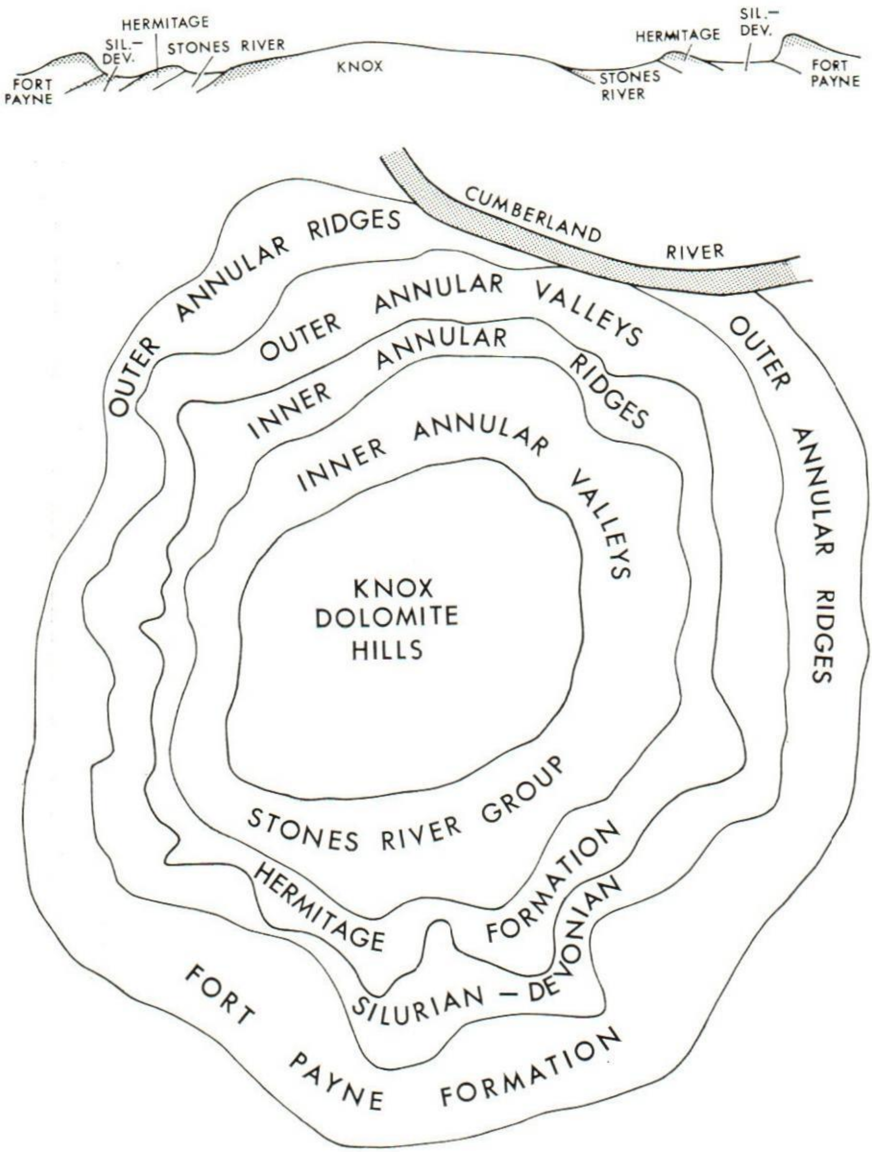


FIGURE 2.—Sketch showing relationship between annular physiographic features and major geologic units in Wells Creek Basin.

The most interesting of these localities is in the region of Cumberland City, a small town on the Cumberland River, in Stewart County. This town is on the side of an elliptical area, or basin, containing six or seven square miles, and surrounded by hills. The river cuts through the northern end of the basin. Wells Creek enters it on the south, and flows through it to the river. From this circumstance I have named it the *Wells Creek Basin*. Within this area the strata are highly inclined. We have here indeed, a very considerable upheaval of the formations. The strata were lifted in a high dome, the top of which has been worn and washed away. The elevation was so great as to bring to the light, through the subsequent denudation, certain low strata * * * no where else to be seen in Middle Tennessee.[1] These strata occupy the central part, and a large part, of the Basin. They dip at high angles and, at some points, are even vertical, forming low "hog-back" ridges. Outcropping around the strata of an older formation are those of the higher formations, each group appearing successively in order, the rocks dipping away from the centre of the Basin. The hard rocks of the *siliceous* * * * form the encircling hills, and, with the *Mountain Limestone* above * * * constitute the formation of the whole country outside.

The disturbance, however, has not been confined to the area of the Basin; it has extended to the strata beyond its limits. This is seen in the bluffs on the river, both above and below Cumberland City. In these, the strata show small and great folds, fractures, dislocations, and inclinations at all angles, all, however, so far as seen, being confined to the rocks of the Lower Carboniferous. Coming up the river, the first bluff in which these disturbances are seen to have occurred is the one several miles below Cumberland City, known to river-men as the *Checkered-house* bluff. In the upper part of this, the strata are boldly bent and faulted.

* * *

The exceptional spot, in Middle Tennessee, showing outcropping Knox Dolomite, has been noticed. It may be added, that the part of the basin holding these rocks, rises up (regarding the area generally) in a wide, low dome—a feature consistent with the ridge-making character of the same rocks in East Tennessee. The dome shows upon the surface, in isolated pieces, the characteristic chert of the division. Its agricultural features are good, and the basin in general, is highly valued as a farming region. The dome has a depression all around it—a ring of valleys, in which outcrop the Trenton, Nashville and Niagara rocks.

* * *

The only region in Tennessee, west of the Cumberland Tableland, in which I have seen the *Knox Dolomite* is the Wells Creek Basin. How thick the *Trenton and Nashville Series* may be here, I have not had the opportunity of ascertaining. There is, however, no reason for thinking that it is thicker than

[1] When I first saw these rocks I recognized them at once as East Tennessee acquaintances, but was greatly surprised to meet with them here, a point where. of all other points in Middle Tennessee, I least expected to find them, as in all this country one of the higher formations, the *Lower Carboniferous,* is brought down to the level of the Cumberland River. By the uplift the top of the Knox Group has been thrust up through the Lower Carboniferous, as well as through all the intervening beds, the elevation of the lowest strata being not less than 2,500 feet.

1,000 feet, indeed, I doubt if it reaches this. So far as can be ascertained, these rocks grow less in volume in that direction.

A more detailed geologic map of Wells Creek Basin was shown in the corner of the Geologic Map of Tennessee of 1869. All that can be inferred from known publications is that Safford became acquainted with the structure some time between 1855 and 1869.

Circumstantial evidence, however, may be used to narrow the time of Safford's first knowledge of Wells Creek Basin. Actual work of building the railroad between Bowling Green, Kentucky, and Memphis began in August 1854. Work was essentially completed by September 1860, the last rail being laid in March 1861. Through traffic started April 14, 1861, just 2 days after Fort Sumter was fired upon. Undoubtedly, surveyors and engineers directing the work noticed the rocks, badly shattered, standing on edge, and utterly different from other rocks between Bowling Green and Memphis. This was probably the first observation of the structure by professionally trained men. Either the railroad company invited Safford, then State Geologist of Tennessee, to come and see their unique find, or he came of his own volition, looking for new exposures of rocks in the new railroad cuts—in those days railroad cuts and bluffs exhibited the better exposures in the region. From this line of reasoning, it may be assumed that Safford first visited Wells Creek Basin between 1855 and 1860. The earlier date seems more likely because Safford would have been most eager to visit the new railroad cuts, particularly if he had been told of the unusual strata and structure exposed in the cuts.

In 1874 Safford (Killebrew and Safford, 1874, p. 761-762) again described the geology of Wells Creek Basin, which at that time was believed to be most of the entire structure. Safford's very interesting description of the structure is as follows:

Geology. A great portion of the country is included in the river basin, whilst a still larger portion belongs to the silicious group of the lower carboniferous. A very interesting geological phenomenon occurs in this county, in the Wells' Creek basin. This is an area, nearly circular, containing six or seven square miles, and touching the Cumberland River. Wells' Creek runs through it, the rocks in the basin dip at a very great angle, and in some places are nearly vertical. There are evidences of a terrible subterranean convulsion at one time. To explain to the unscientific reader, we will premise that the crust of the earth consists of layers which were originally deposited or formed in regular order, one above the other. Sometimes there are lapses or failures of certain formations, but a lower formation is never seen superimposed on a higher one without showing signs of great disturbance. Now, to illustrate the peculiarity of the Wells' Creek basin, we will suppose that layers of flour dough, of different colors, are placed one above another, and that from beneath, the mass is forced up in the center, so as to form a cone. Now, suppose this cone to be cut off horizontally, and on a level with the surface of the undisturbed portion, the various colors of dough would be seen in concentric rings, the lowest layer on a level with the highest. This is precisely the case with Wells' Creek basin. The center of the basin has been elevated by subterranean forces, and the elevation or cone swept away by abrasion. The surrounding rocks belong to the silicious group of the lower carboniferous formation; the other formations—the Black Shale of the Devonian, the lower Helderberg, and the limestone of the upper Silurian; the Nashville and Trenton Limestones, and lastly, the Knoxville limestones of the lower Silurian, all appear in regular succession until the center of the basin is reached. Walking across the valley, all the formations are passed over twice, except the lowest—the Knoxville. The locality, geologically and agriculturally, is interesting. Here may be tested, within a few miles, the relative capacity of the several formations for the growth of any crop, without the complicating elements of different elevations, and varying seasons. Valuable agricultural knowledge might be acquired by trying the various crops in this valley, and noting the difference in yield on the several formations.

Between 1889 and 1893 Safford, Professor at Vanderbilt University, and W. T. Lander, Graduate Fellow and Assistant in Natural History and Geology at Vanderbilt, mapped the structure in some detail. Their work revealed for the first time the full size of the structure as they concentrated on the encircling fault pattern. The culmination of their field work was the preparation of a manuscript, signed by Lander but apparently edited by Safford. The manuscript (ca. 1895) was accompanied by a geologic map and cross sections (fig. 3), the style and workmanship of which suggest the work of Safford. This manuscript with its map and drawings is the first detailed report on the Wells Creek structure. Their report with its detailed description and remarkably accurate grasp of circumferential faulting was not published until 1966 (Wilson and Stearns, 1966). The reader is referred to this long overdue publication as an example of an outstanding study, description, and analysis of complex faulting and fault dynamics in the style of 1889-1893.

In 1903 Foerste (1903a, p. 35 and 1903, p. 690-695) recognized the Chattanooga, Camden-Harriman, Birdsong, Brownsport, Dixon, Lego, Laurel, Osgood, Brassfield, and Hermitage Formations in Wells Creek Basin. Ulrich (1911, p. 418 and 671) stated that the Lebanon Limestone had not been recognized in the basin, and also

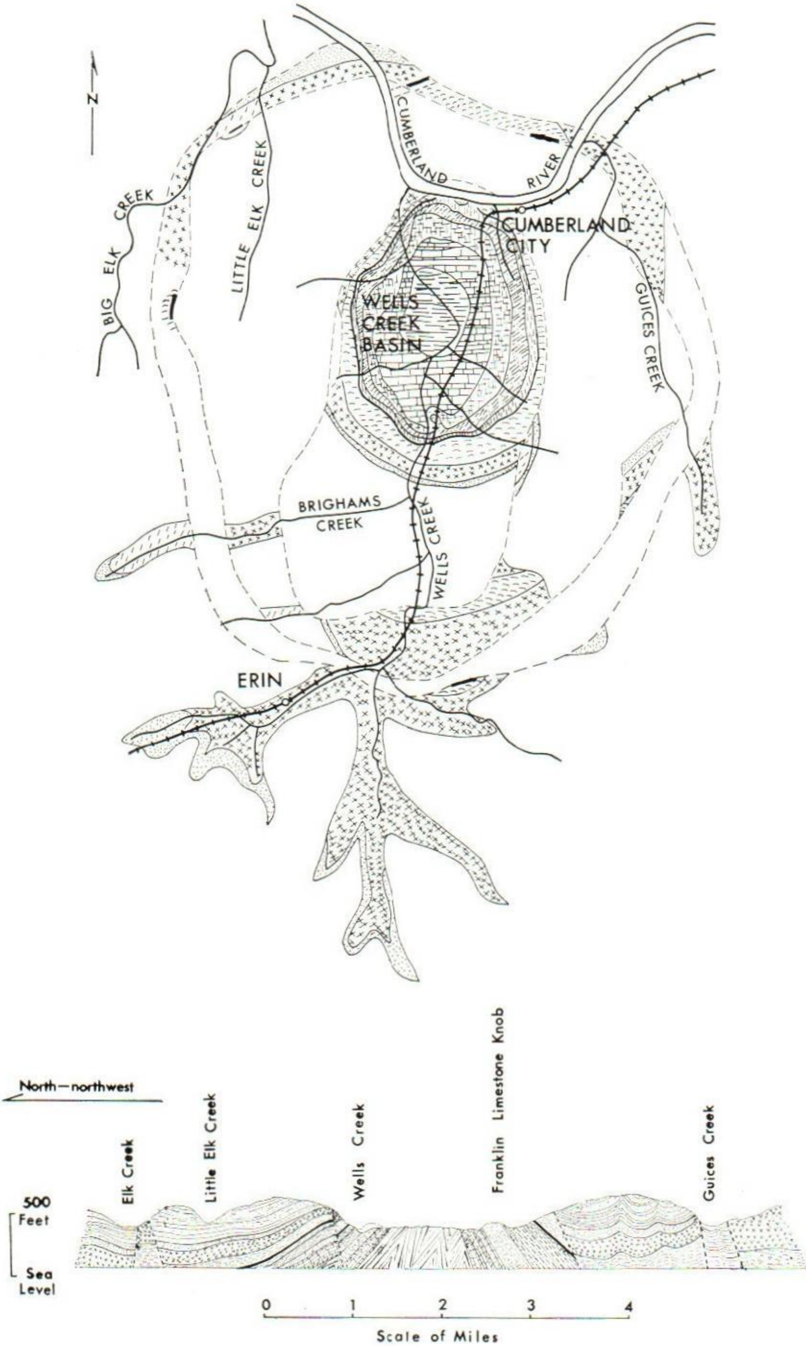


FIGURE 3.—Safford and Lander's geologic map and cross section of the Wells Creek structure, circa 1895 (Wilson and Stearns, 1966).

that the Canadian, which he named the Wells Chert, is overlain by Lowville Limestone.

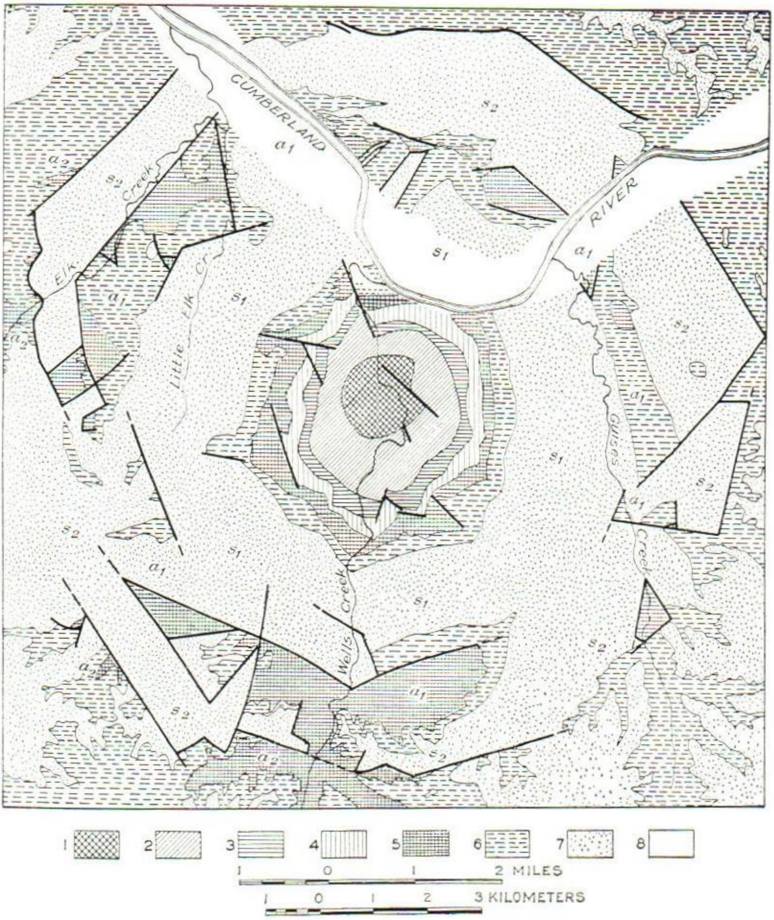
During the period from 1931 to 1933 Professor Walter H. Bucher, then of the University of Cincinnati, mapped the structure for the Tennessee Division of Geology. This was part of a project in his study of what he called "cryptovolcanic" structures after Branca and Fraas (1905). Although the results of his study never were published in full, he did publish an abstract in 1932 and a summary 4 years later (Bucher, 1932, 1936). Although the latter publication, accompanied by a geologic map (fig. 4), was only about 4 pages long, it showed his remarkable knowledge and understanding of the structure. His map is bounded approximately by 36°19′ and 36°27′ N. Latitude and by 87°35′ and 87°45′ W. Longitude. His base map was the 15-minute Erin quadrangle of 1931.

In 1932 Piper published a report on ground water in north-central Tennessee in which he referred to the general geology of the region and included a brief statement on Wells Creek Basin.

In 1940 Wilson published an abstract based on a magnetic survey he had made of the basin and its vicinity. In 1940 and 1941 he studied the pre-Chattanooga stratigraphy of Wells Creek Basin for the Tennessee Division of Geology and refined the stratigraphic section used by Bucher (Wilson, 1940, 1949).

In 1947 the Ordman Company cored Wells Creek Basin on the interpretation that it was a salt dome. The core, which was drilled to a depth of 2,000 feet, was given to the Tennessee Division of Geology and later made available for study by Vanderbilt University (Wilson, 1953).

In 1953 Wilson described three small deposits of Eocene sediments that occupy depressions in Stewart County north of Wells Creek Basin. These were not reinvestigated because they were known mainly from drilling and excavation done before or during 1934. Wilson concluded that these depressions had common origin with the Wells Creek structure by the impact of a meteor that fragmented into at least four pieces before striking the earth. Upon impact the largest of these fragments formed the Wells Creek structure. Wilson still adheres to his conclusions of 1953 with one modification made necessary by the present project—namely, that it is now believed that the Wells Creek structure is Late Mississippian



		Feet	
8.	Alluvium.		
7.	St. Louis limestone (may include higher beds locally; thickness estimated, probably more)	200	Middle Mississippian
6.	Warsaw limestone	120	
5.	Fort Payne chert	110	Lower Mississippian
	Ridgetop shale (including Maury member)	35	
	Chattanooga shale	25	
4.	Harriman chert	20	Devonian
	Birdsong formation	20	
	Limestone series	110	Silurian
	Red shales with limestone layers	130	
3.	Hermitage formation	100	Middle Ordovician
2.	Post-Beekmantown, pre-Trenton limestones (estimated, probably more)	500	
1.	Wells limestone (estimated, probably more)	200	Lower Ordovician

s_1, Inner ring depression; a_1, inner ring of the anticlinal bulges; s_2, second depressed zone; a_2, incomplete second marginal zone of anticlinal bulges.

FIGURE 4.—Bucher's geologic map of the Wells Creek structure (Bucher, 1936).

in age rather than "post-Eutaw, pre-Wilcox" (post-Late Cretaceous, pre-Eocene).

Wilson (1953, p. 764-765) also interpreted the size of the original crater and its topography as he states

> * * * the central area of uplift at the time of explosion was a central hill or 'spine' such as found in the Steinheim and Flynn Creek craters, and that the inner depressed ring formed the topographic crater proper with the central hill in the middle. Such a crater would have been 6 miles in diameter.

In 1959 Kellberg published an abstract describing 53 cores that had been drilled on a 200-foot grid covering an area 1,200 by 1,400 feet near the northern edge of the basin on the west end of Allen Ridge. These were foundation-testing holes drilled by the Tennessee Valley Authority. Later (1965) Kellberg published an abstract proposing a tectonic origin for the Wells Creek structure.

Marcher, in a joint project by the U. S. Geological Survey, the Tennessee Division of Geology, and the Tennessee Division of Water Resources, prepared a report on the Dover area immediately west of the Cumberland City quadrangle (Marcher, 1962). In addition, in a joint project between the U. S. Geological Survey and the Tennessee Division of Geology, Marcher mapped the Dover 7½-minute quadrangle west of the Cumberland City quadrangle (Marcher, 1965), the Bumpus Mills 7½-minute quadrangle northwest of the Cumberland City quadrangle (Marcher, 1965a), and the Vanleer 7½-minute quadrangle southeast of the Ellis Mills quadrangle (Marcher and Finlayson, 1965). Owen T. Marsh (1966) mapped the Slayden 7½-minute quadrangle east of the Ellis Mills quadrangle in a joint project between the U. S. Geological Survey and the Tennessee Division of Geology. Reconnaissance mapping by the U. S. Geological Survey and the Tennessee Division of Geology also was done in other quadrangles adjacent to the four quadrangles of the Wells Creek structure.

PRESENT INVESTIGATION [1] AND ACKNOWLEDGMENTS

In June 1963 the National Aeronautics and Space Administration gave Vanderbilt University a grant (Project NASA Grant NsG-465) for the study of the Wells Creek structure. Robert P.

[1] A generalized geologic map (fig. 5) based on the present investigation has been prepared and is presented here for convenient comparison with the same scale geologic maps of Safford and Lander (fig. 3) and Bucher (fig. 4).

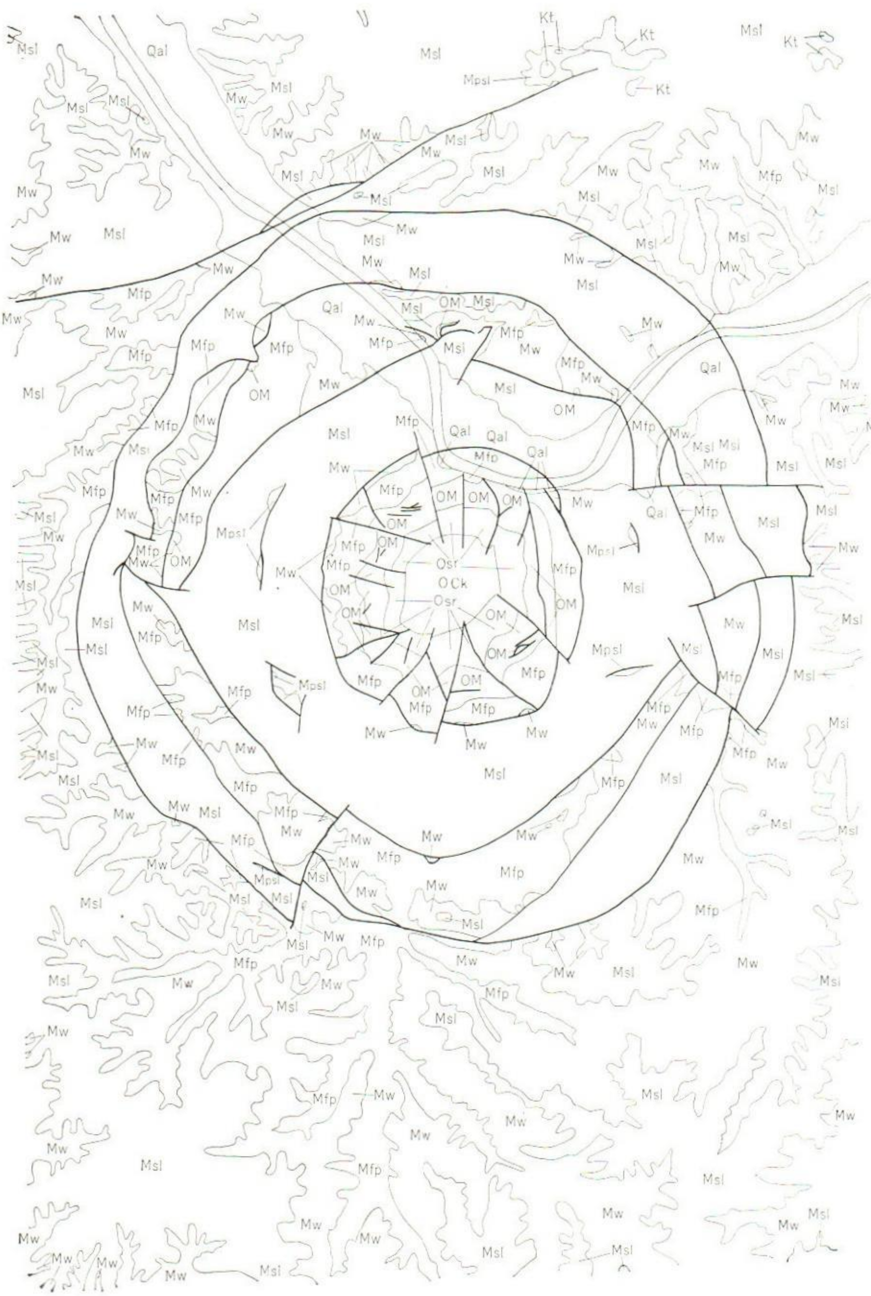


FIGURE. 5.—Generalized geologic map based on the present investigation. *Qal*—Alluvium; *Kt*—Tuscaloosa Formation; *Mpsl*—Post-St. Louis Mississippian; *Msl*—St. Louis Limestone; *Mw*—Warsaw Limestone; *Mfp*—Ft. Payne Formation; *OM*—Nashville Group through Chattanooga Shale; *Osr*—Stones River Group; *O€k*—Knox Dolomite.

Bryson, Staff Scientist of NASA, contributed much helpful advice during all stages of this project. The writers are grateful to W. D. Hardeman, State Geologist, and members of his staff for the close cooperation and assistance during all stages of this project.

At the beginning of the project highest priority was placed on topographic and geologic mapping. The U. S. Geological Survey and the Tennessee Division of Geology prepared excellent topographic maps of the Needmore, Cumberland City, Erin, and Ellis Mills quadrangles, and the Tennessee Valley Authority prepared a special highly detailed map of Wells Creek Basin proper. Geologic mapping was begun in June 1963 and was completed in June 1965. Mapping of Wells Creek Basin was done with alidade and plane table, topographic maps, and aerial photographs. In the rest of the area mapping was done primarily on topographic maps. Plate 1 (in pocket) is the geologic map of the entire structure. This map, which shows formational contacts and faults on a planimetric base at a scale of 1/48,000, is a composite of Tennessee Division of Geology Geologic Quadrangle Maps GM 38-NE, 38-NW, 38-SW, and 38-SE. Plate 2 (in pocket) is a detailed geologic map of the complex central portion of the structure drawn on a topographic base at a scale of 1/6,000. Many geographical names are given on this plate only. The Tennessee Valley Authority provided the project with cores from the 53 holes drilled in the west end of Allen Ridge. The Tennessee Division of Geology made available the 2,000-foot core drilled by the Ordman Company in 1947 in the center of Wells Creek Basin. As part of the present project this core hole was deepened an additional 500 feet in early 1965. A gravity survey (with minor magnetic surveying) of the area was begun in November 1963 and was continued until June 1964, using a gravity meter loaned by the U. S. Bureau of Mines.

Herbert A. Tiedemann (Research Assistant, Geology Department, Vanderbilt University) concentrated on geologic mapping and also prepared air photo blocks (figs. 13-23). J. T. Wilcox (Assistant Professor of Geology, Vanderbilt University) studied mineralogy and petrography of the rocks with emphasis on breccias and evidence for shock deformation. The gravity survey was made by Mrs. Phyllis S. Marsh (Research Assistant, Geology Department, Vanderbilt University), who also studied the shatter cones. Graduate students who made specific contributions are James A. Hulme, who measured stratigraphic sections; Sam M. Puryear, who made

a study of joint systems; John M. Colvin, Jr., who logged all cores available for study; and John M. Wilson, who logged drill cuttings in this region.

The writers are grateful for the professional advice and services of many other geologists, including Robert P. Bryson, John M. Kellberg, Helmuth Wedow, Delia Lavin, Robert A. Miller, and George D. Swingle. Special acknowledgments are due Robert J. Floyd for serving as editor of the manuscript.

Critical readers who made a considerable number of technical suggestions are Howard Wilshire, U. S. Geological Survey, Flagstaff, Arizona; R. C. Milici and Stuart Maher, Tennessee Division of Geology; and J. M. Kellberg and R. W. Johnson, Jr., Tennessee Valley Authority.

Students who assisted in mapping and other miscellaneous phases of the project are Roy Ewing, Michael F. Geiger, Robert C. Lagemann, and Ray G. Martin, Jr.

We are also indebted to the U. S. Department of Agriculture, Soil Conservation Service, and particularly Clarence B. Breinig, State Soil Scientist, and James L. Bilyeu, Work Unit Conservationist, who advised us and made available unpublished soil mapping data. This information was very helpful in mapping alluvium.

We are indebted to Virgil A. Rye, owner of part of Central Hill, for his cooperation, particularly in permitting us to deepen the 2,000-foot core to 2,500 feet. The friendly and helpful cooperation of Gordon Schmid is gratefully acknowledged. We also wish to express thanks and appreciation to the many landowners in the area and to Road Materials, Inc., for permitting us access to their land in pursuance of the completion of the project.

STRATIGRAPHY

INTRODUCTION

A detailed knowledge of stratigraphy is fundamental to the understanding of the geology of this (or any) region underlain by sedimentary rocks. The extent to which geologic structure may be understood is proportional to stratigraphic knowledge; that is, the thinner the units mapped, the more detailed is the map and the greater is the understanding of structure. Geologic structure also determines formational distribution.

In the Wells Creek area, strata that have been eroded away in adjacent undeformed regions are preserved in structural depressions, and more than 3,000 feet of strata deeply buried elsewhere are thrust up by vertical structural movements and are brought together, at the same approximate level on the earth's surface. This anomalous area, then, is an outpost of younger Mississippian rocks removed by erosion throughout most of the region and older rocks deeply buried elsewhere.

Deformed strata range in age (fig. 6) from early Ordovician (Knox Dolomite) to late Mississippian (Paint Creek Limestone). The only post-structural units are remnants of Cretaceous Tuscaloosa gravel and Quaternary alluvium. A list of formations present with thicknesses is given in table 1 in the summary at the beginning of this report.

Because of structural complications and less than complete exposures some questions as to the accuracy of surface measurements of thicknesses are appropriate. However, these were verified by the thicknesses observed in several drill holes in the region (logged by John M. Wilson in consultation with the writers). The stratigraphic range of these bore hole records is from Mississippian St. Louis Limestone to Cambro-Ordovician Knox Dolomite.

ORDOVICIAN SYSTEM

Knox Dolomite

Safford (1869, p. 204) proposed the name Knox Group from exposures near Knoxville, Knox County, Tennessee. In the type region the group includes formations in the upper part of the

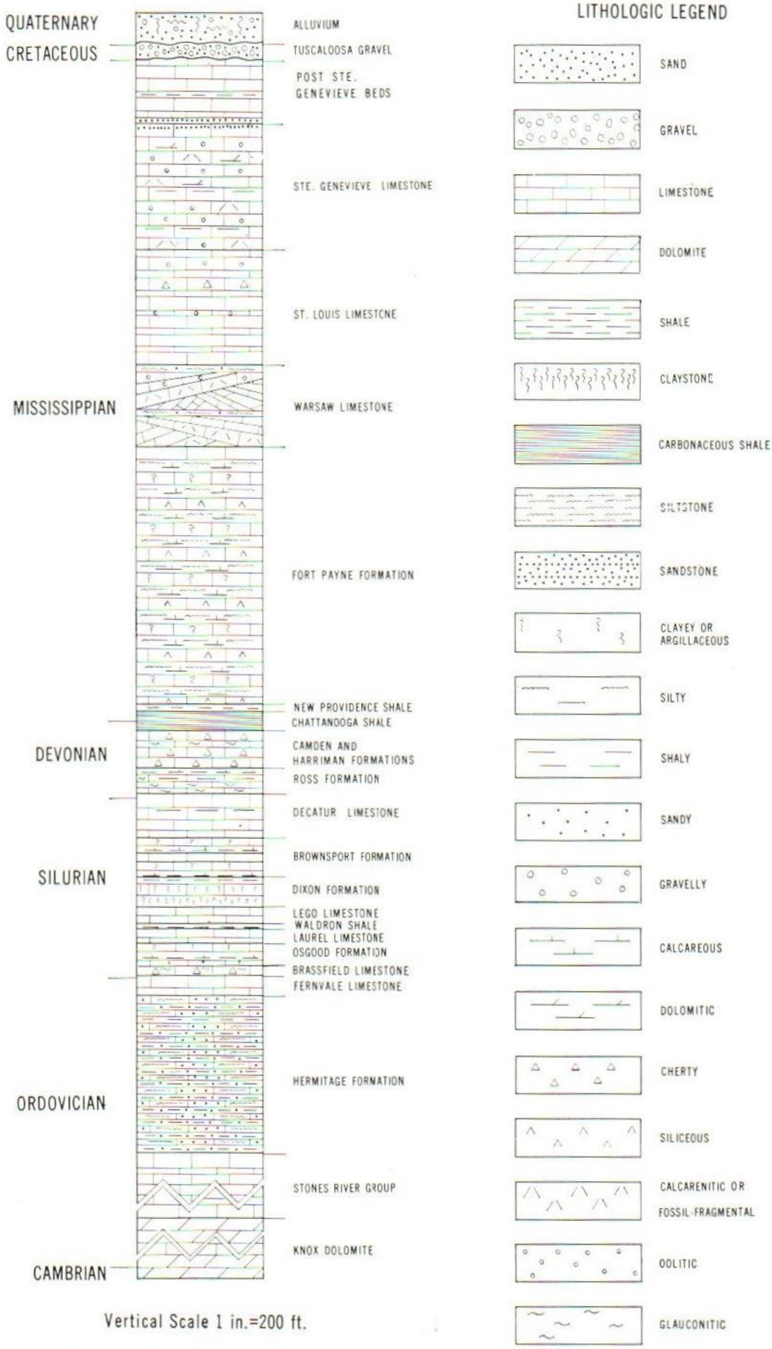


FIGURE 6.—Generalized stratigraphic column in the area of the Wells Creek structure.

Cambrian System and the lower part of the Ordovician System. As far as we know only the Ordovician part of the group is exposed at the surface in Wells Creek Basin.

Safford (1869, p. 147, 159, 220, and 257) correctly used his own name, Knox Group, for the beds exposed in the center of Wells Creek Basin. Foerste (1903, p. 557, 691, and 705) used the name "Wells limestone" for a limestone in the basin, presumably the Knox, but it was not well described and the limestone possibly is Stones River. Ulrich (1911, p. 671) listed a fauna that he interpreted as Canadian in age, naming the cherty limestone and dolomite from which it was collected, the "Wells Chert." The name "Wells" never was accepted, because it had been pre-empted. Bucher (1936, p. 1067) referred to the Knox as "the dolomitic Lower Ordovician Wells limestone," but all subsequent writers have used the name Knox.

The Knox Dolomite is restricted in distribution to Central Hill, Fairgrounds Hill, and Wickham Ridge west of the Wickham House.[1] These hills collectively are referred to as the Knox Dolomite hills. Because of slightly more resistant dolomite and its protective armour of chert blocks, Central Hill is topographically higher than the surrounding part of the basin. The best exposure is in the quarry of Road Materials, Inc., on Fairgrounds Hill (for a detailed description see Section 1, Appendix A). Figure 7 is the index map showing the locations of 15 sections that are described in Appendix A.

More than 90 percent of the Knox is limestone and dolomite, and the remainder is calcareous and dolomitic shale. The carbonate rocks range from thin- to very thick-bedded (8 inches to 10 feet, average about 2 feet). Undulated bedding planes with slight or moderate relief are abundant. Stylolites are very common.

The limestone is predominantly pale yellowish-brown but contains layers that are very pale-orange, brownish- to yellowish-gray, medium-gray, very light-gray, greenish-gray, dark-gray, and olive-gray (listed in descending order of prominence). The limestone ranges from very fine- to coarse-grained but is mostly fine-grained.

The dolomite is yellowish- and brownish-gray to light olive-gray, gray, and dusky-yellow, and ranges in texture from cryptocrystal-

[1] Locations of these geographic localities are shown on plate 2.

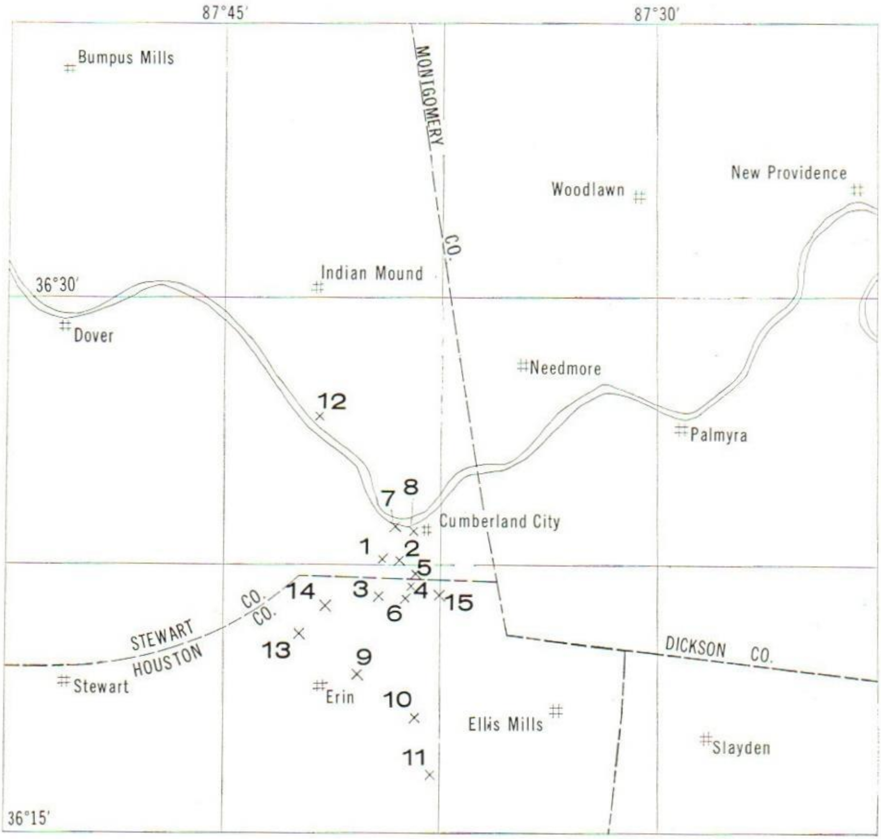


FIGURE 7.—Index map showing locations of described sections (1-15, Appendix A).

line to medium-grained; in some layers oolites are abundant. Many of the fine-grained beds have a sugary texture.

The shale ranges from isolated single laminations up to zones 18 inches thick. It is generally grayish blue-green and commonly is interbedded with beds of light olive-gray limestone.

Although individual beds appear to be massive when viewed from a distance, most are intensely fractured in many directions. The fractures are smooth-surfaced slickensided joints. Recrystallized calcite and dolomite fill many fractures. Limonite, pyrite, pyrolusite, glauconite, and grayish-green clay occur as mineral coatings.

Because breccia characterizes the Knox, and because it has been jumbled and broken into all sizes ranging from blocks perhaps as large as 500 feet across downward to silt, the stratigraphic description of Knox must include breccia. A separate later chapter will be devoted to breccia alone, most of which is Knox.

Breccia sills, breccia dikes, and crosscutting breccia masses are characteristic features in the Knox of Wells Creek Basin. Breccia sills apparently represent beds broken up in place with adjacent strata unbrecciated. They show a wide range in thickness, depending on the particular bed involved. Likewise, breccia dikes may be several feet across or may be as narrow as a fraction of an inch. Most breccias consist of dolomite fragments as much as 6 inches across within a finer grained dolomitic matrix. Limestone and chert compose 10 to 20 percent of the fragments.

The stratigraphic thickness of the Knox actually present in Wells Creek Basin is impossible to determine because of lack of continuous measurable sections, the Knox occurring in a mosaic of jumbled blocks. The beds within these blocks generally dip 65° to 90°, and the strike changes from block to block. Minor folds and faults and intense brecciation complicate the problem. The best estimate that can be made is that at least 600 feet of Knox is exposed in the quarry of Road Materials, Inc. As much as 2,000 feet possibly is present at the surface in the basin. The 2,500-foot core may have penetrated nearly 1,000 feet of Knox.

Section 1, Appendix A (fig. 7) is a detailed description of 380 feet of Knox in the quarry of Road Materials, Inc., on Fairgrounds Hill. Appendix B is a description of typical sections of the Knox in the 2,500-foot core hole drilled on Central Hill. The Knox is poorly exposed in the abandoned quarry on Central Hill.

Natural exposures of the Knox, which are stratigraphically important because they show weathering characteristics of the rock, are present on Fairgrounds Hill both north and south of the quarry. There are also exposures on Wickham Ridge, both on the western part that is surrounded by alluvium, and on the eastern, or main, part of the ridge. Exposures are present on the southeastern spur of Central Hill near the abandoned house and also are scattered on the western part of this hill.

The Knox weathers to a mass of fragments, blocks, nodules, and large irregular masses of chert in a blanket of reddish-brown soil. The concentration of chert makes the residuum of the Knox relatively resistant to erosion. Thus, Central Hill, part of Wickham Ridge, and Fairgrounds Hill, all rise above the level of the inner annular valleys that coincide with the belt of the Stones River Group.

Stones River Group

The name, Stones River Group, first used by Safford in 1851 (p. 352-361), was taken from exposures along Stones River and its tributaries in the Central Basin of Tennessee.

Safford (1869, p. 257) referred to the beds in Wells Creek Basin now comprising the Stones River Group as "Trenton and Nashville" without comment. Foerste (1903, p. 705, 706) gives a faunal list from a locality in Wells Creek Basin that he considered to be "Upper Stones River." Ulrich (1911, p. 418, 671) called the Stones River "Lowville," based on *Tetradium cellulosum* and other fossils, and also stated that the Lebanon Limestone had not been recognized in Wells Creek Basin. Wilson (1949, p. 324, 325) tentatively identified the Carters, Lebanon, Ridley, and Murfreesboro Limestones in Wells Creek Basin on the basis of lithology and fauna. Although these Central Basin formations were identified as being present, no section could be measured.

In this report the base of the Stones River Group (undifferentiated) is at the top of the Knox Dolomite, where the lithology changes from the Knox limestone-dolomite sequence to the Stones River limestone-shaly limestone sequence. The top of the Stones River Group is below the lowest beds of the Hermitage Formation, which is predominantly thin-bedded argillaceous and sandy limestones.

Physiographically, the limestone of the Stones River Group coincides with the inner annular valleys (fig. 2). Scott Branch, the lower part of Schmid Branch, and parts of Wells Creek occupy parts of, and follow portions of, these concentric valleys. Exposures of the Stones River Group are scattered and are commonly small. This would be expected in a belt of relatively nonresistant limestone dominated topographically by the adjacent Knox Dolomite and Hermitage Formation. Only one fairly complete stratigraphic section (Section 2, Appendix A) was found. It begins on the east side of the railroad tracks opposite the south end of the spur of Road Materials, Inc., and continues eastward from the tracks, north of, and parallel to, Bishops Branch. Elsewhere, the best Stones River exposures are west of the Wickham House, on Buckeye Hill, and on the north end of Broadus Ridge.

The two major rock types of this group are (1) thick-bedded limestone and (2) thin-bedded limestone with thin partings of shale. Some beds contain blebs, stringers, nodules, and thin beds of grayish-orange, dense chert. Chert also occurs as rubble and blocks near exposures.

Colors are primarily pale yellowish-brown and dark yellowish-brown with yellowish-gray, light-gray, medium-gray, light olive-gray, and very pale-orange. Almost all exposures weather to light- or medium-gray.

Texture ranges from very fine to coarse but is mostly fine. A few beds in the upper part of the group are composed of coarse fragmental calcite with well-developed, randomly oriented crystals.

Bedding ranges in thickness from 2 to 5 inches up to 2 or 3 feet.

For more detailed descriptions of the limestone of the Stones River Group, see Section 2, Appendix A.

Thicknesses for portions of the group are from three wells drilled outside Wells Creek Basin in the New Providence, Bumpus Mills, and Stewart quadrangles. These three wells and Section 2 indicate that the total thickness of the Stones River Group in this region is about 1,000 feet.

Hermitage Formation

This formation, referred to as the "Orthis bed" by Safford in 1869 because of the abundance of Orthis (later called *Dalmanella* and currently *Resserella*), was named by Hayes and Ulrich (1903, p. 2) from exposures near Hermitage Station, Davidson County, Tennessee.

In the Central Basin several facies of the Hermitage Formation have been recognized, but only the laminated argillaceous limestone facies is present in Wells Creek Basin.

In the Central Basin the Hermitage Formation is underlain by the Carters Limestone of the Stones River Group and is overlain (in sequence) by the Bigby-Cannon Limestone, the Catheys Formation, and the Leipers Formation. Westward beneath the cover of the Western Highland Rim these three formations above the Hermitage grade into laminated argillaceous limestone beds identical to those of the Hermitage (Wilson, 1962). Therefore, the Hermitage Formation of Wells Creek Basin is believed to contain equivalents of the Bigby-Cannon, Catheys, and Leipers of the Central Basin.

Safford (1869, p. 220, 257) refers to the presence of his "Nashville Series" in Wells Creek Basin, and although he does not describe the occurrence, it is assumed that he referred to the Hermitage Formation (his *Orthis* bed of the Central Basin later was named the Hermitage Formation). In 1903 Foerste (1903a, p. 33-35) named the Saltillo limestone from Saltillo, Hardin County, Tennessee. In the same year (1903, p. 691, 693) he identified the Saltillo Formation in Wells Creek Basin in which he reported the occurrence of *Dalmanella* (p. 706). The name, Saltillo, was dropped in favor of Hermitage. Bucher (1936, p. 1069) was the first to use the name, Hermitage Formation, in Wells Creek Basin.

Physiographically, the outcrop belt of the relatively resistant Hermitage Formation coincides with the inner annular ridges (fig. 2), which are prominent topographical features in the basin. Their concentric continuity is offset locally by radial faults. Exposures are relatively common in roadcuts and railroad cuts, and the outcrop belt can be traced readily by the sandy soil containing sandy and silty flakes and scattered irregular silicified masses. Incomplete sections permit no more than estimates of the total thickness, which were made directly from the geologic map.

The Hermitage Formation consists of shale and limestone, the former predominating. The shale is calcareous and sandy, light- to dark-gray, olive-black, olive-gray, and brownish-gray to brownish-black, laminated. The limestone is very fine- to medium-grained. *Resserella (Dalmanella)* is a common fossil. Well cuttings are in part pyritic.

Bedding is commonly thin, ½ inch to 3 inches (average about ½ inch). The formation weathers readily, and in most exposures studied it has a laminated, shaly appearance. This shaly weathered rock is actually pale to dark yellowish-brown siltstone and sandstone. Small to large silicified masses occur in the residuum of the formation.

The thickness of the Hermitage, as estimated directly from the geologic map and from wells drilled in the region, is between 200 and 337 feet.

Exposures are commonly small and weathered. The best exposure of fresh Hermitage is in the railroad cut at the east end of Steele Ridge in the northeastern part of the basin. Other exposures include those in the vicinity of the Scott House, along Schmid Branch Road about 1 mile northwest of State Highway 149, and on the northwest side of State Highway 149 just south of the point where this highway crosses Lickskillet Branch.

Fernvale Limestone

The Fernvale was named in 1903 by Hayes and Ulrich (p. 2) for Fernvale, Williamson County, Tennessee.

The first identification of this formation in Wells Creek Basin was made by Wilson in 1949 (p. 325). The Fernvale was found at many localities during the present project.

The Fernvale is relatively thin and occurs in a narrow concentric belt between the Hermitage Formation and the limestones of the Silurian System. Exposures are common, but only one section (Section 3, Appendix A) was measured, on the south side of Dolomite Station Hill. Here the strike is N.30°E., the dip 30°SE. The Fernvale seems to be faulted over the Brassfield in a small syncline at this locality, and the section was measured on the west limb of the syncline.

The Fernvale consists of pale yellowish-brown, yellowish-gray, and very pale-orange limestone with thin argillaceous partings. Bedding is thin to medium with wavy and irregular bedding planes. Most beds are 2 to 5 inches thick, but one bed in the lower part of the formation is about 2 feet thick. Texture is fine- to medium-grained. Some beds, particularly near the base, are coarsely crystalline. Limonite stains and specks are common.

The formation commonly ranges in thickness from 25 to 30 feet. Locally it may be thicker, as at Section 3, where it is 44 feet. (See Section 3, Appendix A.)

SILURIAN SYSTEM

Many changes in classification and nomenclature of Silurian strata in Central Tennessee [1] have established the following sequence:

Decatur Limestone
Brownsport Formation
  Lobelville Member
  Bob Limestone Member
  Beech River Member
Wayne Group
  Dixon Formation
  Lego Limestone
  Waldron Shale
  Laurel Limestone
  Osgood Formation
Brassfield Limestone

The first reference to the occurrence of Silurian strata in Wells Creek Basin was made in 1869 when Safford (p. 220) cited the presence of Niagaran beds. In 1903 Foerste (p. 690-692) identified the Clinton (later called Brassfield), Osgood, Laurel, Lego, Dixon, and Brownsport in Wells Creek Basin. Bucher (1936, p. 1069) classed Silurian strata in the basin into two units, the upper "Limestone series" and the lower "Red shales with limestone layers." Wilson (1949, p. 324-325) used the entire Silurian sequence presented above, stating that the Waldron Shale was "Not recognized, but probably present." The Waldron was identified in the basin in the present project.

Brassfield Limestone

In 1905 Foerste (p. 145) named the Brassfield Limestone from exposures along the Louisville and Atlantic Railroad between Brassfield and Panola, Madison County, Kentucky.

The Brassfield Limestone is relatively thin and occurs in a narrow concentric belt between the Fernvale Limestone and the Wayne Group. A very distinct glauconitic bed marks the base of the Brassfield, and the top was mapped at the base of the reddish-brown clayey limestones of the Osgood Formation.

Although exposures are common, they are small and scattered and only one warranted measuring and describing. This exposure

[1] See Wilson (1949) for the history of development of nomenclature of Silurian strata.

(Section 4, Appendix A) is in Bishops Branch just east of State Highway 149 between Erin and Cumberland City.

The Brassfield Limestone is chiefly light olive-gray with variations including dusky-yellow, yellowish- to brownish-gray, pale-olive, and light greenish-gray. Bedding ranges from 4 to 12 inches and averages about 4 inches. Texture ranges from fine- to coarse-grained but is commonly fine-grained with beds or scattered grains of medium to coarse calcite.

Thin partings of greenish-gray shale are common along many of the wavy bedding planes. Grains of dusky bluish-green glauconite occur in the limestone, particularly in the basal part. Dense, olive-gray to brownish-gray and gray chert occurs in nodules and thin beds.

Thicknesses of surface exposures range from 17 to 21 feet. (See Section 4, Appendix A.)

Wayne Group

The Wayne Group was named by Miser in 1914 (Drake, 1914, p. 103) for beds widely exposed and typically developed in Wayne County, Tennessee.

The formations of the Wayne Group form the inner part of the outer annular valleys. These valleys are not as pronounced as the inner annular valleys but are a persistent topographic low.

OSGOOD FORMATION

The name, Osgood, was first used by Foerste in 1896 (p. 191-192) for exposures near Osgood, Ripley County, Indiana.

The Osgood Formation occurs in a narrow concentric belt between the Brassfield Limestone and the overlying formations of the Wayne Group. Exposures are not common, and only one section warranted measuring and describing. Section 4 (Appendix A) is in Bishops Branch just east of State Highway 149 between Erin and Cumberland City and is a continuation of the Brassfield section. Another good exposure is in a roadcut of the new Cumberland City-Dover Road (500 feet south of the old Cumberland City-Dover Road) about 1 mile west of Cumberland City.

The Osgood Formation consists of argillaceous limestone with calcareous shale, grayish-red and light to dark reddish-brown with light olive-gray and yellowish-gray. The medium to dark reddish-brown limestone contains blebs and splotches of grayish-orange argillaceous limestone. It is very fine-grained and contains some fine-crystalline calcite. Bedding planes are commonly undulated. The beds are thin to medium, ranging from 4 inches to 1 foot. The formation is in part crinoidal. It weathers to reddish-brown soil that is similar to Dixon residuum.

Thicknesses of surface exposures range from 20 to 43 feet. (See Section 4, Appendix A.)

LAUREL LIMESTONE

The name, Laurel, was first used by Foerste in 1896 (p. 190-192) for exposures near Laurel, Franklin County, Indiana.

The Laurel Limestone and the closely associated Lego Limestone are very similar in appearance and are widely exposed in the outer annular valleys. One section of the Laurel has been measured and described. Section 5 (Appendix A) is on the hillside east of State Highway 149, about 0.25 mile northeast of the point where this highway crosses Bishops Branch. Another good exposure is in a roadcut on the new Cumberland City-Dover Road 1 mile west of Cumberland City.

The Laurel consists of light-brown to moderate reddish-brown limestone near the base, grading vertically into dusky-yellow to grayish-orange. Dark yellowish-orange argillaceous partings produce a characteristically crenulated surface.

Grain size is generally fine, and small amounts of medium-grained calcite crystals are present. Weathered surfaces are smooth and rounded. Bedding averages 1 foot.

Surface sections, measured or estimated, range from 20 to 40 feet. (See Section 5, Appendix A.)

WALDRON SHALE

The Waldron Shale was named by Elrod in 1883 (p. 106-111) for Waldron, Shelby County, Indiana.

The Waldron Shale was identified in a field about 2,000 feet south of the Scott House and about 200 feet east of Scott Road. It consists of greenish-gray calcareous shale with thin beds of light olive-gray and greenish-gray limestone. The actual thickness is unknown, but it is estimated to be only 2 or 3 feet. Shortly after its discovery this very small exposure was covered during cultivation of the field in which it occurred.

LEGO LIMESTONE

The Lego Limestone was named in 1903 by Foerste (p. 565) from exposures in the bluff in Perry County across the Tennessee River from Lego Landing, Decatur County, Tennessee.

Although the Lego is widely exposed, only two sections could be measured satisfactorily. Section 4 (Appendix A) is on Bishops Branch just east of State Highway 149 between Erin and Cumberland City, and Section 5 (Appendix A) is on the hill east of this highway 0.25 mile northeast of the point where the highway crosses Bishops Branch. The Lego is well exposed about 1 mile west of Cumberland City on the new Cumberland City-Dover Road.

The limestone of the Lego is very similar to that in the Laurel, and has colors ranging from moderate- to dusky-red and from reddish-brown to pale reddish-brown; it weathers to reddish-brown.

Grain size is generally fine, and small amounts of medium-grained calcite crystals are present. Zones of coarse fossil fragments occur throughout. Bedding is medium to thick, commonly between 1½ and 2 feet. Greenish-gray calcite crystals and fossil fragments weather into relief on the surface.

The Lego also contains thin partings of moderate yellowish-brown to moderate reddish-brown shale.

Surface sections, measured or estimated, range from 16 to 40 feet in thickness. (See Sections 4 and 5, Appendix A.)

DIXON FORMATION

Foerste (p. 566) named the Dixon Formation in 1903 from exposures in the vicinity of Dixon Spring, Decatur County, Tennessee.

The Dixon Formation is not as well exposed as the Laurel and Lego Limestones. The only complete section that could be measured is Section 6 (Appendix A), which is along Lickskillet Branch beginning a short distance east of State Highway 149.

The Dixon is composed mostly of splotchy argillaceous limestone, grayish-red to dark reddish-brown to light olive-gray, grayish-olive, and greenish-gray. It contains some shale and mudstone of the same colors. A shale zone commonly comprises the upper 2 to 3 feet of the formation, the upper part of the zone being light-gray, the lower part dark reddish-brown.

Although it is generally fine-grained, the formation has scattered medium- to coarse-grained calcite as fossil replacements and as isolated crystals.

Bedding is thin to medium, commonly ranging in thickness from 2 to 10 inches.

Fossils weathered into relief have produced rough surfaces. Crinoids, brachiopods, and horn corals are the three most abundant fossils.

The Dixon weathers to a characteristic reddish-brown soil that can be confused only with Osgood soil.

Surface sections, measured or estimated, range from 40 to 50 feet in thickness. (See Section 6, Appendix A.)

Various formations of the Wayne Group are exposed on the hill north of the Potter House site, west and southwest of the Scott House, and in the railroad cut at Dolomite and on Broadus Ridge east of the railroad cut.

Brownsport Formation

The "Brownsport bed" was named by Foerste in 1903 (p. 566 and 571-573) for Brownsport Furnace, Decatur County, Tennessee. Pate and Bassler (1908, p. 410-432) named and described three subdivisions of the Brownsport, the Beech River, Bob, and Lobelville formations. Miser in 1917 (p. 201-202) and in 1921 (p. 21) defined the subdivisions of the Brownsport as members.

The members of the Brownsport Formation occur in the outer annular valleys between concentric belts of the underlying Wayne Group and the overlying Decatur Limestone. Although the members of this formation are exposed at many localities, the exposures are small and scattered, and only one section warranted measuring and describing. Section 6 (Appendix A) is on Lickskillet Branch just east of State Highway 149 between Erin and Cumberland City. Here 75 feet of Brownsport was measured.

BEECH RIVER MEMBER

The Beech River Member was named from exposures along Beech River in Decatur County, Tennessee.

This member consists of alternating calcareous shales and thin beds of limestone, light olive-gray to yellowish-gray, and dusky-yellow with some grayish red-purple. The limestone is fine- to medium-grained and commonly thin-bedded. The basal part of the member is light olive-gray and greenish-gray to grayish red-purple, fine- to medium-grained, glauconitic, medium-bedded limestone.

Surface sections, measured or estimated, range from 21 to 35 feet in thickness. For detailed descriptions see Section 6, Appendix A.

BOB LIMESTONE MEMBER

The Bob Limestone Member was named from exposures in the bluff half a mile below Bobs Landing along the west bank of the Tennessee River in Decatur County, Tennessee.

The member is light olive-gray, light grayish-brown and light olive-brown to light yellowish-gray limestone with thin partings of light olive-gray argillaceous limestone and shale. The limestone is fine- to medium-grained and contains many medium-grained calcite crystals. It is medium-bedded (6 inches to 2 feet).

Surface sections, measured or estimated, range from 10 to 20 feet in thickness. For detailed descriptions, see Section 6, Appendix A.

LOBELVILLE MEMBER

The Lobelville Member was named from exposures in the vicinity of Lobelville, Perry County, Tennessee.

This member is similar to the Beech River in general appearance, being medium- to coarse-grained limestone alternating with beds of calcareous shale. Variations in thickness of the beds of limestone give them a cobbly appearance. Limestone beds range from 1 inch to 1½ feet in thickness and average 3 to 4 inches. The shale beds average no more than 1 inch in thickness. Crinoidal fragments are common.

The limestones, shaly limestones, and limy shales of the Lobelville grade from yellowish-gray, light olive-brown to light olive-gray, and light grayish-brown to light grayish-green. Argillaceous partings have the same colors.

Grain size ranges from fine to coarse but is mostly medium. The finer grained beds are near the base and the coarser ones are near the top, especially near the Lobelville-Decatur contact.

Surface sections, measured and estimated, range from 15 to 37 feet in thickness. For detailed descriptions see Section 6, Appendix A.

Decatur Limestone

The Decatur Limestone was named by Pate and Bassler (1908, p. 407-432) from exposures at Tucks Mill 1½ miles north of Decaturville, Decatur County, Tennessee.

This formation, which occurs in a circular belt on the inner slope of the outer annular ridges, is well exposed in Wells Creek Basin. Two sections were measured and described. Section 6 (Appendix A) is on Lickskillet Branch and Section 7 (Appendix A) is along the south bank of the Cumberland River 1.1 miles west of Cumberland City. The Decatur also is well exposed on the hill south of the intersection of Scott Road and Schmid Branch Road, although here the formation has been duplicated by faulting.

The limestone is generally moderate-red and pale-olive in the lower part of the formation and light olive-gray, grayish-orange, grayish yellow-green, yellowish-gray, dark yellowish-orange, and moderate yellowish-brown in the upper part. The few thin partings of shale are pale-olive, moderate yellowish-brown, dark yellowish-orange, and grayish-orange. Specks of light-brown hematite and some dusky yellowish-green grains of glauconite are also present.

Texture ranges from fine- to coarse-grained, with medium and coarse grains predominating. Coarse calcite crystals are common, and many crinoid and brachiopod fragments contain coarse calcite. Bedding is medium to thick, commonly 1 to 3 feet.

The thickness of the formation from surface exposures and from estimates is approximately 70 feet. Section 6 on Lickskillet Branch is 72 feet thick, and Section 7 on the Cumberland River is 68 feet.

DEVONIAN SYSTEM

The classification of Devonian [1] strata in Wells Creek Basin and in the northern part of the Western Valley of the Tennessee River is as follows:

Chattanooga Shale [2]
Camden Formation
Harriman Formation
Ross Formation
  Birdsong Shale Member
  Rockhouse Limestone Member

The first reference to Devonian strata in Wells Creek Basin was made by Safford (1869, p. 323 and 333), who noted the presence of Helderberg rocks and of "Black Shale." It is not known whether Safford included both the Devonian cherts (Camden and Harriman) and the Birdsong Shale Member in his Helderberg. Foerste (1903, p. 690-694) used the names Chattanooga, Camden, and Helderberg in Wells Creek Basin. Dunbar (1919, p. 58 and 74) referred to Birdsong and Harriman in the basin.

Ross Formation

Foerste (1903, p. 685) named the Ross Formation from exposures on the Ross farm on Horse Creek in Hardin County, Tennessee.

The Ross Formation occurs with the rest of the Devonian on the inner slopes of the outer annular ridges but is very poorly exposed in Wells Creek Basin. No section warranted complete description, but a thickness of 40 feet was measured in Section 7 (Appendix A) along the south bank of the Cumberland River 1.1 miles west of Cumberland City. The best exposures are in a roadcut in Allen Ridge along the new Cumberland City-Dover Road. Both members of the Ross were formerly exposed in Section 6 (Appendix A) on Lickskillet Branch but are now covered. The Rockhouse Limestone Member is present on the hill south of the intersection of Scott and Schmid Branch Roads.

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[1] See Wilson (1949) for the history of development of nomenclature of Devonian strata in Central Tennessee.

[2] The Tennessee Division of Geology has adopted the age classification "Mississippian and Devonian" for the Chattanooga Shale, and this is reflected in the use of MDc symbols for the Chattanooga in the illustrations of this report.

ROCKHOUSE LIMESTONE MEMBER

The Rockhouse Member of the Ross Formation was named by Dunbar (1918, p. 736) from an exposure at the Rockhouse (then a hunter's clubhouse) on Horse Creek, Hardin County.[1]

This limestone with its thin partings of shale is light olive- and greenish-gray to light brownish-gray and brownish-gray. Texture of the limestone is fine- to coarse-crystalline. Bedding is medium. The rock is glauconitic and fossiliferous. Estimated thickness is commonly 10 to 30 feet, although in the roadcut in Allen Ridge along the new Cumberland City-Dover Road only 2 feet was found.

BIRDSONG SHALE MEMBER

The Birdsong Shale Member was named by Dunbar (1918, p. 741) from exposures along the valley of Birdsong Creek and its tributaries in Benton County, Tennessee.

This member consists of an alternation of olive-gray to pale-olive calcareous shale and thin limestone, which is in part argillaceous. Texture is medium to coarse. The beds range in thickness from 1 to 4 inches and average 2 inches. The member is glauconitic and fossiliferous. Surface thicknesses, measured and estimated, range from 15 to 40 feet. The best exposures are in the roadcut in Allen Ridge along the new Cumberland City-Dover Road.

Camden and Harriman Formations

The Camden Formation was named by Safford and Schuchert in 1899 (p. 429-430) from exposures of residual chert near Camden, Benton County, Tennessee. The Harriman Formation was named by Dunbar (1918, p. 747) for Harriman Creek (later changed to Herron Creek), immediately east of Parsons, Decatur County, Tennessee.

Dunbar (1919) separated these two formations on their fossil content. Because of their lithologic similarity, however, they are considered together in this report.

These formations as deposited consisted of gray to light olive-gray, micrograined to fine-grained, siliceous and glauconitic, thin- to medium-bedded limestone. The limestone is exposed in the road-

[1] This member is composed mainly of shale in the southern part of the Western Valley, but to the north it is almost all limestone. Therefore, it is called the Rockhouse Limestone Member in Wells Creek Basin.

cut on State Highway 149 about 0.5 mile west of Cumberland City, just south of the intersection of this highway and the new Cumberland City-Dover Road (Section 8, Appendix A). The formations are poorly exposed on the hill south of the intersection of Scott and Schmid Branch Roads but their interval is about 95 feet.

The limestone weathers to light-gray and white chert, which has mottlings of yellowish- to grayish-brown, yellowish-orange, and yellowish-gray. The chert is bedded and blocky, ranging from 2 to 6 inches in thickness. It is dense, subnovaculitic, and breaks with conchoidal fracture. Pods of white to light-gray tripolitic clay may occur in good exposures, but the formation commonly is represented by loose blocks of chert scattered over the ground. Chert is exposed on the hill south of the intersection of Scott and Schmid Branch Roads and also in the roadcut along Allen Ridge.

Surface thicknesses range from 50 to 95 feet. The latter thickness was measured on the hill south of the intersection of Scott and Schmid Branch Roads.

Chattanooga Shale

The Chattanooga Shale was named in 1891 by Hayes (p. 143) for Chattanooga, Hamilton County, Tennessee.

Exposures of this formation are few in Wells Creek Basin and commonly are small and discontinuous. The one section that warranted measuring and describing is Section 8 (Appendix A), in the roadcut on State Highway 149 about 0.5 mile west of Cumberland City and just south of the intersection of this highway and the new Cumberland City-Dover Road.

The Chattanooga is a thinly laminated, fissile, carbonaceous, pyritic shale. It is medium-dark gray to grayish-black where fresh, weathering to pale yellowish-brown flakes and slabs from ¼ to ½ inch thick. In the roadcut along Allen Ridge it contains a 2- to 6-inch bed of sandstone.

Surface thicknesses, measured or estimated, range from 15 to 58 feet and average between 25 and 30 feet. For detailed descriptions see Section 8, Appendix A.

Other exposures of the Chattanooga Shale within Wells Creek Basin are along Lickskillet Branch, on the hill south of the intersection of Scott Road and Schmid Branch Road, in Scott Road about

1,000 feet north of this intersection, in the road along Allen Ridge, and on the east side of the railroad tracks a few hundred feet south of the point where the tracks and State Highway 149 diverge northward.

Because the Chattanooga Shale is such an excellent regional datum, exposures outside the basin proper but within the limits of the area are listed below.

In the Erin quadrangle (pl. 1) two such exposures are known. One is on the west side of State Highway 149, about 1,000 feet south of the point where the road down Spring Branch joins the highway (Section 9, Tennessee Coordinates 710,300N., 1,508,400E.[1]) Safford referred to an exposure of Chattanooga in this quadrangle which subsequently was covered in construction of State Highway 13. This locality is about 0.8 mile east of the junction with State Highway 49 (Tennessee Coordinates 705,400N., 1,511,200E.).

In the Cumberland City quadrangle (pl. 1) four exposures of Chattanooga Shale are known. These are, from southwest to east:

(1) in the head of a hollow about ½ mile east of Little Dry Elk Creek, 0.7 mile north of the south edge of the quadrangle (Tennessee Coordinates 730,000N., 1,494,000E.)

(2) on the east side of Big Elk Creek 1 mile south of the new Cumberland City-Dover Road (Tennessee Coordinates 740,500N., 1,499,400E.)

(3) in a hollow ¼ mile northeast of the Cumberland River, 1 mile southeast of the mouth of Horseford Hollow (Tennessee Coordinates 742,500N., 1,511,500E.)

(4) in the head of a hollow 1.25 miles south of Throckmorton, about 1,000 feet east of the ridge road that extends southward from Throckmorton (Tennessee Coordinates 738,500N,. 1,519,100E.)

MISSISSIPPIAN SYSTEM

Strata of the Mississippian System present in the Wells Creek Basin area are classified as follows:

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[1] The base point for the Tennessee Coordinate System (at the intersection of 86°00′ W. Longitude and 34°40′ N. Latitude near Scottsboro, Alabama) is assigned the values 2,000,000 feet east and 100,000 feet north. Reference coordinates are shown along the margins of plate 1.

Post-Ste. Genevieve
Ste. Genevieve Limestone
St. Louis Limestone
    Upper
    Lower
Warsaw Limestone
Fort Payne Formation
    Upper
    Lower
New Providence Shale
Maury Shale

Strata of the Mississippian System have long been recognized as the upland surface rocks of this part of the Western Highland Rim. Safford in 1869 (p. 147 and 338-353) referred these beds to the Lower Carboniferous, including the older "Siliceous Group" and the younger "Mountain Limestone Group." He may have included the St. Louis Limestone and the Warsaw Limestone in the Siliceous Group with the Fort Payne Formation as identified today. He described the Mountain Limestone on the Western Escarpment of the Cumberland Plateau and other localities as oolitic in the lower part. He referred to the presence of the Mountain Limestone in the Wells Creek area but did not describe it there. Therefore, it is unknown whether Safford actually recognized the oolitic basal part of the Mountain Limestone, i.e., the Ste. Genevieve.

His summary of the distribution of Mississippian strata in the Wells Creek area (1869, p. 147) states that "hard rocks of the *siliceous*" form the outer annular ridges that encircle Wells Creek Basin and that the Siliceous Group and the Mountain Limestone Group "constitute the formation of the whole country outside."

The relatively resistant and steeply dipping strata of the Fort Payne Formation form the pronounced outer annular ridges surrounding the basin. The Fort Payne, Warsaw, and St. Louis formations form the upland surface of most of the Wells Creek area. They are essentially flat-lying except where broken by the annular faults. The Ste. Genevieve Limestone was mapped in 7 small areas, 6 of which consist of steeply dipping limestone along small local faults within the grabens. The seventh occurrence is in the Cumberland City quadrangle on the north side of the Carlisle fault outside the Wells Creek structure. Post-Ste. Genevieve beds were mapped at only one locality, in the Ellis Mills quadrangle.

Mississippian rocks, particularly the Warsaw and St. Louis Limestones, are intensely brecciated adjacent to faults. This breccia is characterized by broken chert nodules and masses in a matrix of unbrecciated fine-grained limestone. Because the matrix itself is unbroken, it appears to have been only partially indurated at the time of brecciation.

Outcrops of fresh limestone are rare except along the bottoms of main stream valleys. In places small stocks or bosses of rock are exposed in gulleys and even in fields, but these occurrences are not common. Mississippian limestones yield chert upon weathering. Some types of this chert are diagnostic of a formation or subdivision of a formation; other types may occur in several formations. Therefore, it is important to be able to recognize the different types of chert, particularly in areas of poor exposures of fresh limestone.

The Fort Payne is characterized by distinctive scraggy and streaked dark chert, and the overlying Warsaw by "cinder-block" cherts. Small burrs of chert form on the surfaces of the silty dolomites of the Warsaw. In addition to "cinder-blocks" the lower unit of the St. Louis has oval-shaped bodies and streaked masses that contain some coarse layers and some dense layers. The upper unit of the St. Louis and all the Ste. Genevieve are characterized by "cannonball" cherts of various sizes as well as other types of chert. The highest St. Louis is characterized by large silicified "*Lithostrotion*" colonies and by large lumpy "balls." The chert of the overlying Ste. Genevieve in many ways is similar to that in the St. Louis. The main criteria for recognition of the Ste. Genevieve are the absence of the coral "*Lithostrotion*," the sporadic occurrence of the fenestellid-bearing "Lost River" chert (Elrod, 1899) near the base of the Ste. Genevieve, and the more abundant oolitic cherts.

Maury Shale

The Maury Shale was named in 1900 by Safford and Killebrew (p. 104, 141, and 143) for Maury County, Tennessee.

The Maury Shale consists of greenish-gray shale or mudstone that contains rounded or elliptical phosphatic nodules. Thickness is estimated to range from 1 to 4 feet.

Exposures of this formation occur on the hill south of the intersection of Scott Road and Schmid Branch Road, on the west side of State Highway 149 about 1,000 feet south of the point where the road down Spring Branch joins the highway (Section 9, Appendix

A), in the roadcut on State Highway 149 about 0.5 mile west of Cumberland City and just south of the intersection of this highway and the new Cumberland City-Dover Road (Section 8, Appendix A), and in roadcuts along the latter road where it is cut into Allen Ridge.

New Providence Shale

The New Providence Shale was named by Borden in 1874 (p. 161) for New Providence (now Borden), Indiana.

Exposures of this formation are rare in Wells Creek Basin, and no section warranted measuring and describing. The best exposure is on the hill south of the intersection of Scott Road and Schmid Branch Road.

The formation consists of medium-gray and greenish-gray shale with thin zones of reddish-brown shale. At the base of the formation is a 3-foot fine-grained limestone, mottled olive-gray and light brownish-gray. Both the shale and limestone are well exposed in a relatively large area on the hill south of the intersection of Scott Road and Schmid Branch Road.

This formation is present only in the western part of Wells Creek Basin. Its exposed thickness is estimated to be from 0 to 20 feet.

Fort Payne Formation

The Fort Payne Formation was named by Smith (1890, p.155-156) from exposures at Fort Payne, Alabama.

This formation forms the outer annular ridges surrounding Wells Creek Basin. It is exposed at many places in the horst but is exposed in the grabens at a single locality on Moccasin Branch. In the southern part of the area it occupies the valleys of the larger streams, but in the northern part it is only locally exposed.

Exposures are numerous but a complete section was not found. Three partial sections were measured and described. One, Section 6 (Appendix A), is along Lickskillet Branch and up the hill to the north. This section includes 235 feet of Fort Payne bedrock and an additional 126 feet of residuum. Another, Section 9 (Appendix A), is on State Highway 149, beginning about 1,000 feet south of the road that follows Spring Branch; it includes 245 feet of fresh rock plus about 30 feet of residuum. The third, Section 10 (Appendix

A), is on the north side of State Highway 49, about 800 feet northwest of Cedar Valley Methodist Church Cemetery; it includes only the upper 22 feet of the Fort Payne.

In general this formation is composed of argillaceous or siliceous, fine-grained limestone and calcareous siltstone, brownish-gray to light olive-gray. During early stages of weathering the color changes to yellowish-gray to pale yellowish-brown and to dark yellowish-brown, in that order. Although the fresh rock is essentially the same throughout the entire formation, some differences may be seen between the lower and upper parts of the formation. Upon mass weathering the differences between the lower and upper units become more marked. For purposes of this report, therefore, the formation is divided into lower and upper units corresponding to differences in both fresh rock and residual chert.

The lower half of the formation is predominantly thin- to medium-bedded, platy and nodular limestone, with 20 to 50 feet of shale and siltstone at the base. The limestone contains beds of dense, flintlike chert with conchoidal fracture. The chert, which is olive-gray and medium-gray to brownish-black, occurs in beds 3 to 7 inches thick. This lower unit of the formation contains few fragments of fossils.

Upon mass weathering the lower unit consists of layers of dark-gray, streaked, nonfossiliferous, bedded chert that breaks into a jumbled rubble of blocks. The basal 20 to 50 feet of this approximately 200-foot-thick unit consists of shale and siltstone with only a small amount of chert, the lowest 20 feet containing practically no chert. Upon partial weathering beds in the lowermost 20 feet weather yellowish-brown, and the thicker partially weathered beds contain a core of unleached medium-gray rock. Cores of this gray unleached rock contrast sharply with the enclosing yellowish-brown. Such "gray-core" lower Fort Payne is well exposed in a cut on the new Cumberland City-Dover Road 0.8 mile west of the point where this road leaves State Highway 149. One small block of "gray-core" lower Fort Payne on the hill south of the intersection of Scott Road and Schmid Branch Road had long been misidentified as Hermitage Formation. An almost completely weathered exposure of this zone is the basal 22 feet of Fort Payne in Section 9 (Appendix A), in the roadcut on State Highway 149 about 1,000 feet south of Spring Branch.

The upper half of the formation is thin- to thick-bedded, the thick bedding being more apparent than real. This upper unit is mottled with siliceous or cherty inclusions, layers, and nodules with grayish color streaks. It contains fragments of bryozoans, gastropods, brachiopods, and other fossils. The upper part of this unit contains several relatively thin zones of brownish-gray to yellowish-brown, fine-grained, silty dolomite that are similar to zones in the Warsaw and St. Louis Limestones.

Upon mass weathering the upper unit of the Fort Payne consists mostly of masses of banded, fine-grained, rough and porous, pale-orange and yellowish-brown scraggy chert. This scraggy chert is very distinctive, makes an extremely cherty soil with very thin soil cover, and is widely exposed. Structural attitudes can be taken in the scraggy chert, as bedding is very well preserved.

In chert sequence the gradational contact between the Fort Payne Formation and the Warsaw Limestone is marked by several changes. Scraggy chert is arbitrarily excluded from the Warsaw, and therefore all scraggy chert is mapped as Fort Payne. Interbedded with the topmost scraggy chert and above typical scraggy chert are nodules, beds, and lenses of dense, dark, streaked, fossiliferous chert, some of which has general and even detailed similarity to cherts in the St. Louis Limestone; but when seen in reasonably undisturbed residual exposures, this chert can be identified as upper Fort Payne by its position in the sequence. Above the streaked chert is a mixture of this streaked chert and the "cinder-block" porous chert typical of Warsaw residuum. The mixed chert zone is weathered rock, gradational between the Warsaw and Fort Payne formations. The Fort Payne as mapped includes this gradational zone, so that the top of this formation is placed at the top of the mixed chert zone.

The total thickness of the formation is estimated to be between 380 and 500 feet. For detailed descriptions see Sections 6, 9, and 10, Appendix A. Another good exposure is on the bluff north of the Cumberland River 0.6 mile southeast of the mouth of Horseford Hollow.

Warsaw Limestone

In 1857 Hall (p. 54-56) named the Warsaw Formation from exposures at Warsaw, Illinois.

The Warsaw Limestone is widely exposed in the Wells Creek

Basin area. It caps most of the upland interstream area to the south and occupies most of the valley walls in the north. A broken ring of Warsaw occurs along the inside of the circular Cumberland City fault. Warsaw is not exposed in the inner graben and is rarely exposed in the outer graben but is widely exposed in the intervening horst.

Exposures are numerous but a complete section was not found. Three partial sections were measured and described. The maximum thickness of bedrock measured in these sections was about 65 feet. These localities are Sections 10, 11, and 12 (Appendix A).

Warsaw Limestone is light- to dark-gray with variations of yellowish-gray and yellowish-brown to light olive-gray. The texture ranges from fine-grained, especially near the upper contact, to coarse-grained calcarenite in highly fossiliferous zones. A characteristic type of limestone has a white to light-gray, chalky, fine-grained groundmass or matrix with "floating" crystals that average 3 mm. Beds range from 6 inches to 6 feet in thickness and average 2 feet. Bedding planes are irregular, and crossbedding and stylolites are common. Fossil fragments in the calcarenitic parts of the formation include abundant bryozoans, crinoids, and brachiopods. Some oolites occur in upper beds of the formation.

The formation contains several relatively thin zones of brownish-gray to yellowish-brown, fine-grained, silty dolomite similar to zones in the Fort Payne and St. Louis Formations (particularly in the north). Warsaw is gradational into both the Fort Payne scraggy limestone and chert below and the fossiliferous St. Louis limestone above. Vertical as well as lateral changes in facies occur. Two thin zones of siltstone, containing very fine-grained sand, are present near the middle and top of the formation, respectively.

The limestone weathers to angular plates, blocks, and persistent layers of coarsely granular, porous, fossiliferous chert. The chert differs from that in the Fort Payne, being lighter in color, more fossiliferous, and more porous. Much of the chert is white with light- to dark-gray grains. Surfaces of the limestone weather dark-gray to very dark-gray and dark brownish-gray. Fossil fragments, crystals, and crossbedding weather into relief and give the limestone a rough surface.

The Warsaw is characterized by porous, fossiliferous "cinder-blocks" of chert. These may be more than a foot thick, locally almost 2 feet. The coarse-grained calcarenite of the Warsaw appears to contain little insoluble impurities, yet nevertheless it yields this very distinctive chert upon weathering. The "cinder-block" chert of the Warsaw persists well up into the St. Louis Limestone. Some layers in the Warsaw Limestone are dolomitic, silty beds that form small burrs, or rounded rough knots of chert on the surfaces after partial weathering. These do not persist with more advanced weathering.

Surface thicknesses of the Warsaw Limestone are estimated to range from 90 to 170 feet.

For detailed descriptions see Sections 10, 11, and 12 (Appendix A). Other sections include the bluff on the northeast side of Yellow Creek 0.55 mile southeast of the junction of this creek and Dry Branch, the quarry north of State Highway 49 about 1 mile west of Erin, and the bluff north of the Cumberland River about midway between the mouth of Wildcat Creek and Marshall Creek.

St. Louis Limestone

Englemann (1847, p. 119-120) named the St. Louis Limestone from exposures at St. Louis, Missouri.

The St. Louis Limestone caps only the higher upland inter-stream areas in the south but most of the upland areas in the north. It is the only formation present at the surface in the inner graben with the exception of a few small scattered areas of Ste. Genevieve and younger beds. It is rarely preserved in the horst but occupies most of the surface in the outer graben.

Exposures are numerous, but a complete section was not found. Three partial sections were measured and described. Section 14 (Appendix A), on the Schmid Branch-Erin Road 0.75 mile west of the intersection of Scott Road and Schmid Branch Road, is the most complete. The others are Sections 12 and 13 (Appendix A).

This formation is divisible into two units, referred to as lower and upper for purposes of this report.

The lower unit, which is estimated to be 50 to 60 feet thick, is medium to dark brownish-gray, fine- to medium-grained, poorly sorted, fossiliferous calcarenite. Among the fossils are bryozoans, crinoids, and brachiopods that weather into relief on the surface. Bedding is very thin to medium. The limestone has a fetid odor.

This unit is distinguished from the underlying Warsaw Limestone by brownish color, fetid odor, and in places small silicified solitary "staghorns" of the coral *"Lithostrotion."*

Upon mass weathering the chert in the lower unit is generally similar to that in the Warsaw, but slight differences in shape and texture increase upward through the unit. It contains a mixture of porous, fossiliferous, "cinder blocks" of chert, characteristic of the Warsaw, and dense (and occasional porous) oblong bodies of chert some of which have "stripes" or banded layers typical of St. Louis chert. Upward through the 50 to 60 feet of the lower unit the shapes of the chert bodies change in turn from oblong to ovoid to spherical "cannonballs." This vertical change is accompanied by the gradual disappearance of the Warsaw type of chert.

The upper unit, which is 120 to 130 feet thick, is light-gray to dark brownish-gray limestone, the texture of which is very fine- to medium-grained. Bedding is thin to medium. Many of the beds are fossiliferous, and locally large closely spaced colonies of *"Lithostrotion"* are common near the middle of this unit (or about 100 feet above the base of the formation).

Upon mass weathering the upper unit becomes a rubble of angular fragments, blocks, and rounded bodies of dense chert. The base of the upper unit of the St. Louis was drawn at the lowest occurrence of spherical balls of chert. These balls, which range in diameter from about 1 to 6 inches, occur in layers throughout the upper unit rather than scattered throughout the unit. As a general rule the balls are larger the higher in the section they occur. Within 50 to 75 feet of the top of the St. Louis are some very large ovoidal, lumpy "balls," mottled brown to very pale-orange, that may be a foot or more in one dimension and as little as 6 inches in the other.

Both the lower and upper units of the St. Louis contain several relatively thin zones of brownish-gray to yellowish-brown, fine-grained, silty dolomite similar to zones in the Fort Payne and Warsaw formations.

For detailed descriptions see Sections 12, 13, and 14 (Appendix A). Another good exposure is on the north side of Blooming Grove Road about midway between Bascomb Eldridge Creek and Cooper Creek.

Ste. Genevieve Limestone

The Ste. Genevieve Limestone was named by Shumard (1860, p. 406) from exposures in bluffs along the Mississippi River 1 to 2 miles south of Ste. Genevieve, Missouri.

Between the St. Louis Limestone and the sandstone in Section 15 (Bethel Sandstone of Kentucky ?) there is approximately 200 feet of essentially homogeneous limestone with very minor amounts of shale. The striking varicolored zone of shale and limestone in Sections 14 and 15 is considered to be the topmost zone in this 200-foot map unit. The majority of this unit is believed to be Ste. Genevieve, but some of the upper part may represent the Renault Limestone [1] of Kentucky. Where the name, Ste. Genevieve, is used in this report it may contain equivalents of the Renault; where the name, Renault, is used the reference is only to the *upper part* of the Ste. Genevieve map unit (*Msg* on the maps). The sandstone in Section 15 immediately overlying the Renault is considered to be the equivalent of the Bethel Sandstone of Kentucky. If this assumption is correct the post-Ste. Genevieve beds of this report (*Mpsg* on the maps) are therefore actually post-Renault.

In general the Ste. Genevieve map unit consists of about 200 feet of limestone, light- to dark-gray, light brownish-gray to light olive-gray, yellowish-gray and some reddish-gray. Its texture ranges from dense and fine-grained to coarse-grained. Beds are generally 1 to 2 feet thick. Some beds are calcarenitic, others oolitic. The topmost zone of this map unit is the varicolored zone of light olive-gray shale with red shale and limestone that is well exposed in Sections 14 and 15. The map unit also contains sandstone, found in residuum but never in place.

In the Needmore quadrangle the only area of preservation of this unit is on the west side of Guices Creek embayment in the southwestern corner of the quadrangle. This small area, associated with a minor fault within the inner graben, consists of limestone with chert and loose blocks of sandstone.

In the Cumberland City quadrangle there are three areas mapped as Ste. Genevieve. The largest of these caps a high hill

[1] Use of Renault and Bethel in the Wells Creek area is based solely on the position of these beds between the Ste. Genevieve as identified by the present writers and the Paint Creek Limestone as identified by Benjamin Gildersleeve and Fred R. Shawe of the U. S. Geological Survey. (See Shawe, 1967.)

southeast of the headwater area of Furnace Hollow and is north of the Carlisle fault outside the Wells Creek structure. The exposure consists of 40 feet of limestone associated with chert rubble and loose blocks of sandstone. Another area within the inner graben is on the east side of Little Elk Creek about 2,000 feet northwest of Scott Chapel, where it is associated with the Little Elk Creek fault. Here the formation consists of limestone and loose blocks of sandstone. The thickness preserved here is unknown. The third locality, on the east side of Little Elk Creek about 2,500 feet southwest of Scott Chapel, also is associated with the Little Elk Creek fault within the inner graben. Here the limestone has thin shaly zones.

In the Erin quadrangle there are also three mapped areas of Ste. Genevieve. One is in the headwater area of Booster Branch and is associated with the Booster Branch faults within the inner graben. It consists mainly of limestone. The varicolored shale and limestone zone at the top of this unit is considered to represent the top of the Renault equivalents. Section 14 (Appendix A) was measured and described at this locality. The second area is restricted to the bed of Spring Branch south of Denmark Road, where it is associated with a small fault within the outer graben. It consists of greenish-gray shale and "bouldery masses" of limestone. This exposure may actually be post-Renault. The third area mapped is on a hill south of an unnamed branch south of the Lickskillet Branch Road about 2,000 feet east of Steele Chapel. It is associated with a small east-west fault within the inner graben and is contiguous with the preservation of Ste. Genevieve and post-Ste. Genevieve beds in the Ellis Mills quadrangle on the east (Section 15). It consists of limestone and loose blocks of sandstone.

Just east along the same fault in the Ellis Mills quadrangle is the only area where post-Renault strata (*Mpsg*) were mapped separately. This is about 1,800 feet southwest of Dowdy Cemetery. At this locality the Ste. Genevieve and Renault (*Msg*) mainly consist of light-gray oolitic and fragmental limestone. Section 15 (Appendix A) was measured and described here. The 12-foot zone of light olive-gray shale and red limestone and shale in this section is believed to be equivalent to varicolored beds in the upper part of Section 14; that is, at the top of the Renault. The post-Renault strata preserved here are described later.

The Ste. Genevieve weathers to a rubble with "cannonballs" and ovoidal bodies of chert but without "*Lithostrotion*." Otherwise, residuum is similar to that of the upper unit of the St. Louis Limestone. There are also prominent silicified oolitic beds in the Ste. Genevieve. Oolitic chert is not restricted to these limestones, however, as there are some occurrences of silicified oolites in St. Louis chert residuum. The most characteristic chert in this unit is the fenestellid-bearing "Lost River" chert that occurs locally near the base of the Ste. Genevieve Limestone. Small blocks of this porous chert have been identified in the northern part of the Cumberland City quadrangle and in the Needmore quadrangle, where it is no thicker than 6 inches. A few fragments were found lying loose near the Lookout Tower on Tennessee Ridge in the southwest part of the Erin quadrangle (Tennessee Coordinates 692,000N., 1,492,000E.). Owen T. Marsh of the U. S. Geological Survey, who traced this zone from southern Kentucky to Clarksville, Tennessee, located and identified some of these occurrences.

The contact between the Ste. Genevieve and St. Louis is not readily picked on the basis of chert. The Ste. Genevieve lacks "*Lithostrotion*" but contains spherical and ovoidal chert bodies of a variety of sizes like the St. Louis. In places the Ste. Genevieve contains some "cinder blocks" similar to those in the Warsaw. Such "cinder blocks" persist in variable amounts all the way from the upper unit of the Fort Payne into the Ste. Genevieve. This type of chert is believed to form during the weathering of a calcarenite and is therefore not necessarily stratigraphically restricted.

The Ste. Genevieve Limestone contains one or two thin zones of fine- to medium-grained sandstone stained yellowish-brown. The stratigraphic position of the sandstone in the Ste. Genevieve is not known, as it has never been found in place.

Post-Ste. Genevieve Beds

The only post-Ste. Genevieve beds (actually post-Renault) that have been mapped are in the Ellis Mills quadrangle (Section 15, Appendix A) on a north-facing hillside 500 feet south of the intersection of the Cumberland City Road and the Lickskillet Branch Road from the west, this intersection being about 1,600 feet southwest of Dowdy Cemetery. Section 15 includes about 180 feet of post-Renault strata.

At this locality (Section 15) beds younger than Renault consist of limestone, sandstone and shale. Near the base a 2-foot fine- to medium-grained sandstone, stained yellowish-brown, is considered to be the equivalent of the Bethel Sandstone of Kentucky. Above this sandstone are three more thin sandstone beds separated by limestone and shale. Near the top the section consists of light olive-gray limestone and light olive-gray shale and limestone. The limestone ranges from micrograined to coarse-grained and crinoidal, and is thin- to medium-bedded. Fossils found about 35 feet below the top of this section have been identified by Benjamin Gildersleeve and Fred R. Shawe of the U. S. Geological Survey to be diagnostic of the Paint Creek Limestone of Kentucky. These are the youngest strata deformed by the Wells Creek event.

CRETACEOUS SYSTEM

Tuscaloosa Formation

This formation is present in all four quadrangles of the Wells Creek area, where it is restricted to relatively small patches on the higher ridges. The best exposure is in the large gravel pit on the east edge of the Cumberland City quadrangle, east of the headwater tributaries of Furnace Hollow and north of the headwater tributaries of Hopewell Branch.

The light-gray gravel is poorly sorted. It is subrounded to well-rounded, $\frac{1}{4}$ inch to 4 inches in diameter, and consists mainly of chert. The formation contains lenses of white sandy silt and clay. At some localities the gravel is iron stained. Maximum preserved thickness is about 50 feet.

This gravel is of special significance in determining the age of the Wells Creek structure as it was not involved in this structural deformation. The Wells Creek event, therefore, can be dated as post-Paint Creek (Late Mississippian) and pre-Tuscaloosa (Late Cretaceous).

QUATERNARY SYSTEM

Flood-plain deposits of the Cumberland River, which have surface elevations of 360 to 390 feet, consist of clay, silt, and sand, light- to medium-gray and yellowish-orange. These deposits contain lenses of quartz sand and chert sand, gray to brownish-orange, fine- to coarse-grained; and chert gravel, gray to yellowish-orange and yellowish- to reddish-brown. The thickness ranges from 0 to 90 feet.

The flood-plain deposits of the larger creeks consist of unsorted, angular to subrounded chert gravel with clay, silt, and sand. The thickness is highly variable.

Alluvium has been mapped by the U. S. Department of Agriculture, Soil Conservation Service, and their mapping was transferred to our new base maps and then field checked and adjusted along all roads and many traverses. The pattern of alluvium ultimately shown on our geologic maps remains essentially as drawn by the Soil Conservation Service, except in areas where alluvium is so thin and/or discontinuous that the underlying residuum could be mapped.

STRUCTURE

(*with* Herbert A. Tiedemann)

INTRODUCTION

Three main aspects of structure are considered. First, in conventional manner the structural geology is described in this chapter as it was mapped. In the next chapter, the geologic interpretation of structural data is presented, including general form of the structure and the nature of the structural movements. Third, structural fabric, including fault trends, bedding orientation, and jointing, are described.

GENERAL DESCRIPTION

Introduction

The 4 quadrangles that comprise the Wells Creek structure include 5 structural provinces (fig. 8) : (1) the essentially undisturbed region where the rocks have the low regional dip characteristic of the Western Highland Rim, (2) an annular outer graben, (3) an annular horst, (4) an annular inner graben, and (5) the circular central block. The latter four comprise the Wells Creek structure. The surrounding region is characterized by low dip; here, the Carlisle fault is the only fault mapped. It is not believed to be genetically associated with the Wells Creek structure. The circumferential outer and inner grabens and the intervening horst are broken by several short radial faults (the outer system). The central block also is offset by several short radial faults (the inner system). The short radial faults of these two systems do not connect with each other on the surface.

The outermost circular fault, forming the outer border of the outer graben, is named the Erin fault for the town of Erin, Houston County (fig. 9). The inside fault of the outer graben (and also the outer fault of the horst) is named the Brownsville fault for the community by that name on the Houston-Stewart County line west of Wells Creek Basin. The fault that separates the horst from the inner graben is called the Marable Hollow fault for Marable Hollow northeast of Erin. The fault between the inner graben and

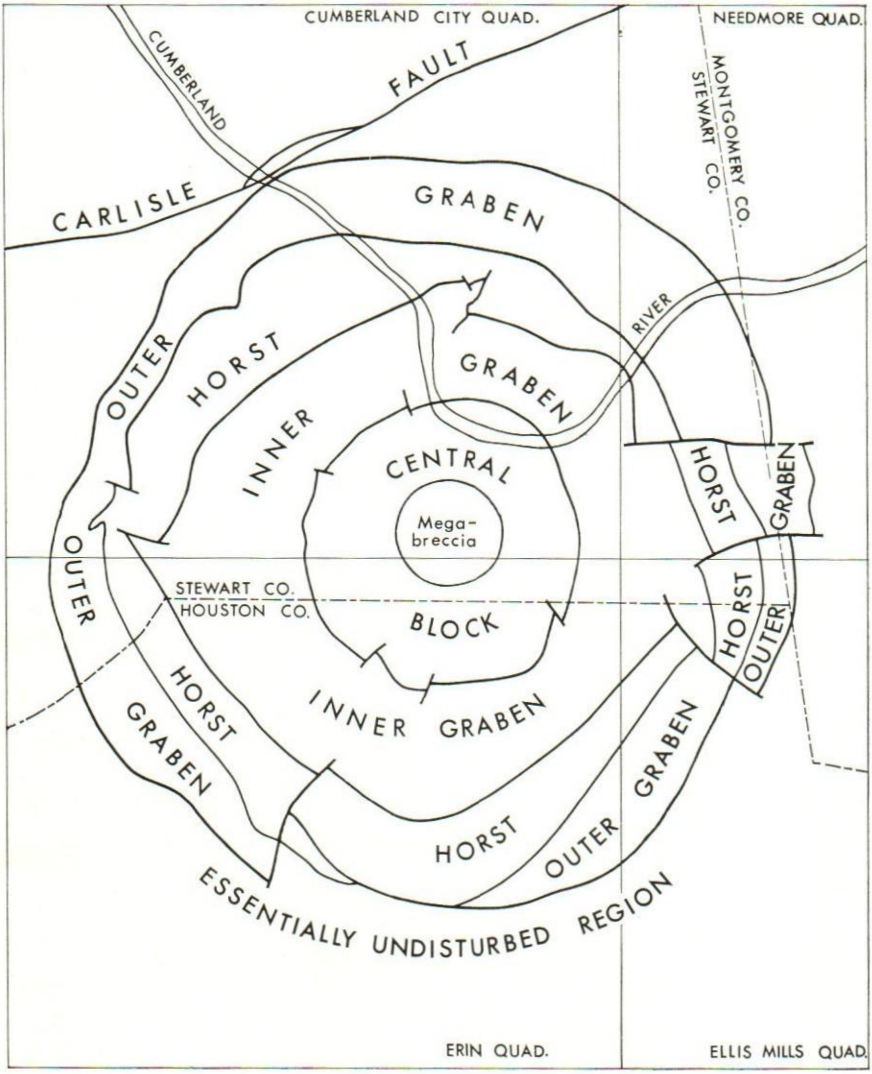

FIGURE 8.—Index map showing major structural features.

the central block is the Cumberland City fault, named after Cumberland City, Stewart County, through which the fault passes.

The major radial faults of the outer system break the two grabens and the intervening horst and are named (in clockwise

FIGURE 9.—Index map showing locations and names of faults. Shaded area in southwest is town of Erin; shaded area in northeast is town of Cumberland City.

direction from the Louisville and Nashville Railroad tracks on the south side of the structure east of Erin) the Spring Branch, Willsons Branch, Moccasin Branch, McKendree Church, and Guices Creek faults; and two minor unnamed radial faults in the west-central area. The major radial faults of the inner system offset the central block and the Cumberland City fault. These are named (in clockwise direction from the railroad tracks) the Dolomite, Carter Hollow, Schmid, Scott, Hollister Branch, North Sheep Ridge, Clements Branch, Indian Hill, Steele Ridge, Mill Spring Branch, Bishops Branch, and Lickskillet faults. The Schmid faults include three faults that converge inward toward the central block. The Scott faults include two parallel faults. The Steele Ridge fault splits outward away from the central block, and the Mill Spring fault splits inward. Beneath the alluvium a radial fault is postulated connecting the Carter Hollow and Dolomite faults.

Before the detailed descriptions of structural features are given, several general observations should be noted. First, the strike of dipping strata generally does not parallel fault planes, and faults cut across bedding at many angles. Second, many faults are associated with breccia, particularly the outer annular faults. Where weathering is deep, faults may be traced by fractured chert in the residuum. Third, structure commonly is obscured in the outer Mississippian bedrock areas because weathering is generally so deep, but structure can be followed through weathered areas by careful examination of the residuum. In areas covered by alluvium, however, the structure is buried and cannot be mapped, so the geologic maps show hypothetical fault traces but no contacts. Fourth, the central part of the structure, about 5,000 feet in diameter, is judged to be a great mass of breccia consisting of Knox Dolomite and Stones River limestone. Fifth, the main deformation is by faulting and fracturing at all scales; folds are minor, mainly restricted to subsidiary structures associated with rocks in the central part of the central block. Nearly all observed folds involve Ordovician, Silurian, and Devonian strata. Most folding was observed in Ordovician, shaly Hermitage and shaly Silurian formations, but relatively large folds occur even in rather massive Knox Dolomite (fig. 10).

FIGURE 10.—View of fold in quarry of Road Materials, Inc., on Fairgrounds Hill, view looking northeast.

Surrounding Region

Structural contour lines [1] drawn on the top of the Fort Payne Formation (fig. 11 and pl. 3) show that the beds surrounding the Wells Creek structure are gently warped. The total structural relief on this horizon between a low of about 250 feet and a high of about 600 feet is about 350 feet. Individual anticlines and synclines generally trend north-south and have average structural relief, or amplitude, of about 100 feet. These are superimposed on a gentle northward regional dip of only about 100 feet across the structure (only about 10 feet per mile).

Along the Carlisle fault, which is tangential to the northern part of the outer graben, the top of the Fort Payne has a maximum throw of approximately 250 feet down on the north. This fault,

[1] Plate 3 (in pocket) shows 20-foot-interval structure contours in full details on a planimetric base at a scale of 1/48,000. Figure 11 shows essential patterns in less detail but in relation to faults. Hereafter, reference to structure contours will be made only to figure 11, but in each case more detailed information can be obtained by examination of plate 3.

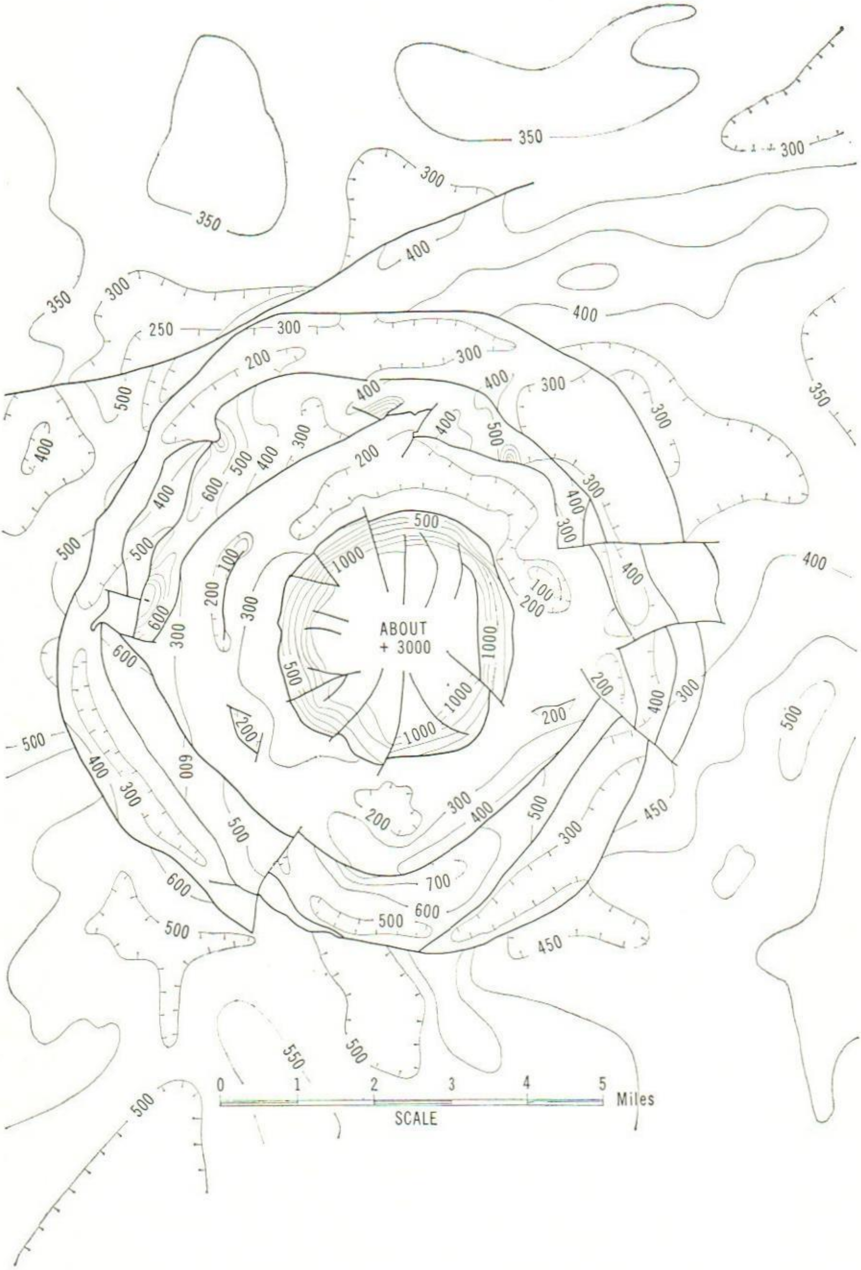

FIGURE 11.—Structural contour map on top of the Fort Payne Formation.

named and mapped in the Dover quadrangle to the east (Marcher, 1962) disappears northeastward in the Cumberland City quadrangle.

Outer Graben

In general, the top of the Fort Payne Formation forms a gently undulated surface within the limits of the outer graben (fig. 11). In most of the segments (portions bounded by radial faults) the contoured horizon is lowest in the middle of the graben and rises both inward and outward, forming elongate synclines that curve similarly to the bounding Erin and Brownsville faults. In some segments the beds rise inward toward the horst. The top of the Fort Payne in the outer graben ranges from 50 to 300 feet (averages 188 feet) lower than it is outside the Erin fault.

In the segment between the Spring Branch and Moccasin Branch radial faults the top of the Fort Payne ranges from 150 to 450 feet in elevation. In the segment between the Moccasin Branch and McKendree Church faults the structural relief averages about 250 feet. Between the McKendree Church and Guices Creek faults the top of the Fort Payne rises northward to elevations between about 250 and 350 feet. In the segment between the Guices Creek and Spring Branch faults the Erin and Brownsville faults locally merge into one fault in the south part of the circumference. Northeast of this merger the top of the Fort Payne ranges from 250 to 400 feet in elevation. West of the merger in the small wedge it is between 250 and 300 feet in elevation.

Dip of the Erin fault is steep. This fault is well exposed only near Erin, where its dip is nearly vertical. Elsewhere, though poorly exposed, its trace is nearly straight even in rough topography, and therefore the fault probably is steep throughout its length.

Horst

Within the limits of the horst, which lies between the circumferential Brownsville and Marable Hollow faults, the top of the Fort Payne Formation (fig. 11) is higher than it is in the outer graben. The contoured horizon ranges from 300 to 1,000 feet in elevation but commonly is 350 to 600 feet. The pattern is more irregular than in the outer graben. In five small major anomalies the top of the Fort Payne has been uplifted locally to elevations between 800 and 1,000 feet (fig. 11). Partly because of these anomalies it is difficult to estimate the difference in elevation between the top of the Fort Payne in the outer graben and in the horst. Except for the high anomalous areas the contoured horizon in the horst is from 100 to about 600 feet above its level in adjacent portions of the outer graben.

The west-central part of the segment between the Spring Branch fault and the Willsons Branch fault is broken by two small unnamed radial faults. Between the Spring Branch fault and the southern unnamed fault the Fort Payne is between 500 and 650 feet in elevation. Between this latter unnamed fault and the Willsons Branch fault the top of the Fort Payne is commonly 300 to 600 feet in elevation; but locally, immediately north of this unnamed radial fault and 3 miles west of the center of the entire structure, it bulges up to about 1,000 feet (first anomaly in the horst). East of the point where the Traylor Ridge fault ends and 3½ miles northwest of the center, the Fort Payne is locally above 800 feet (second anomaly in the horst). West of the Willsons Branch fault and 3 miles due north of the center, it is locally as high as 900 feet (third anomaly in the horst). North of the southern unnamed radial fault the center of the horst locally is split by the Traylor Ridge fault, which extends northward to the second "high" anomaly.

In the segment between the Willsons Branch and Moccasin Branch faults the top of the Fort Payne commonly is between 300 and 500 feet in elevation. However, in a small area in the middle of this segment and 3 miles northeast of the center the formation rises as high as 900 feet (fourth anomaly in the horst).

Between the Moccasin Branch and Guices Creek faults the contoured horizon is between 350 and 450 feet in elevation.

Within the segment of the horst between the Guices Creek and Spring Branch faults the Fort Payne is commonly 450 to 600 feet in elevation, but in a small area immediately south of the south-center of the Marable Hollow fault and 3½ miles south of the center of the entire structure the formation is as high as 700 to 800 feet (fifth anomaly in the horst).

Dip of the Brownsville fault is variable but seems to be always directed outward toward the Erin fault. It is known to dip as gently as about 30° and as steeply as about 60°. Therefore, the outer graben probably narrows at depth as the dipping Brownsville and vertical Erin faults converge.

Inner Graben

The structural position of the top of the Fort Payne Formation in this annular ring is more uniform and consistent than in the outer two rings (fig. 11). In general, the contoured horizon is lowest (100 to 200 feet) in a circular "syncline" in the middle of the inner graben. From this circular low the Fort Payne rises outward to elevations between 250 and 400 feet near the Marable Hollow fault, and rises inward to elevations between 250 and 350 feet near the Cumberland City fault. The circular "syncline" contains the Little Elk Creek and Booster Branch circumferential faults in the western part and two small unnamed faults in the eastern part.

Dip of the Marable Hollow fault is least known of any fault. It is believed to be steep mainly because its trend (mapped mainly by residual chert) is unaffected by topography, and by analogy with the Erin fault.

Central Block

Contours on the top of the Fort Payne Formation rise from elevations of 400 to 800 feet immediately inside the Cumberland City fault to elevations between 800 and 1,000 feet (fig. 11). Above these latter elevations the Fort Payne has been removed by erosion. Also, here, as the central part of the central block is approached, dips steepen so abruptly that the elevation of eroded Fort Payne cannot be projected.

Dip of the Cumberland City fault is steeply outward from the center of the structure. The fault is nowhere exposed but rock on either side crops out closely enough to show that it is steep, and at one locality in Schmid Branch it dips outward between 45° and 70°.

The central block is a circular zone characterized by steep dips and highly variable strike. Natural and excavated surface exposures showing zig-zag strike patterns reveal that this zone consists of fault blocks or extremely large breccia blocks. This disordered zone is referred to as megabreccia (fig. 8), and within this zone breccia fragments range from microscopic size to perhaps hundreds of yards across. Most of the Knox is within the megabreccia zone.

The Stones River is mainly outside the megabreccia zone, but some is inside.

DETAILED DESCRIPTION OF STRUCTURE OF ANNULAR RINGS

Needmore Quadrangle

(Northeast Quarter of Plate 1)

The southwestern corner of the Needmore quadrangle[1] is crossed by the outer graben, bounded by the Erin and Brownsville faults; the horst, bounded by the Brownsville and Marable Hollow faults; and the outer part of the inner graben.

In the outer graben north of the Moccasin Branch radial fault the St. Louis Limestone is the major surface rock, except for small areas of Warsaw and Fort Payne Formations. The largest of these areas of Warsaw is east of, and along the upthrown side of, a subsidiary fault that continues southward where the Brownsville fault curves abruptly southwestward. In the outer graben south of the Moccasin Branch fault St. Louis Limestone is the only formation at the surface. Recorded dips in the outer graben of this quadrangle range between horizontal and 60°.

In the horst north of the Moccasin Branch fault Warsaw and Fort Payne strata are exposed along the east side of Guices Creek, and Fort Payne in a small area north of the Cumberland River. Bedrock in most of this segment is veneered by alluvium. In the horst south of the Moccasin Branch fault the main surface rock is Warsaw Limestone, with a strip of Fort Payne exposed along the south side of Moccasin Branch and in two smaller areas farther south. Recorded dips range between horizontal and 50°.

In that part of the inner graben present in this quadrangle the St. Louis Limestone is the only formation present at the surface, with the single exception of a small preservation of Ste. Genevieve Limestone. Recorded dips range from horizontal to 75°.

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[1] Four 7½-minute geologic quadrangles which are separately published in the Tennessee Division of Geology Geologic Quadrangle Series are combined on plate 1 as follows: NE¼—Needmore quadrangle (Stearns, Tiedemann, and Wilson, 1968); NW¼—Cumberland City quadrangle (Tiedemann, Wilson, and Stearns, 1968); SW¼—Erin quadrangle (Stearns, Tiedemann, and Wilson, 1968); SE¼—Ellis Mills quadrangle (Wilson, Stearns, and Tiedemann, 1968).

Cross section A-A′ on plate 1 [1] shows the structure in an east-west direction across the southern part of this quadrangle. The Erin, McKendree Church, and Marable Hollow faults are shown to be nearly vertical; whereas, the Brownsville fault dips outward, or eastward, and merges with the Erin fault at depth.

A block diagram (fig. 13) is presented to give a three-dimensional view of the area where the radial Moccasin Branch fault offsets the outer annular faults. (See figure 12 for locations of block diagrams.)

Cumberland City Quadrangle

(Northwest Quarter of Plate 1)

With the exception of the western edge most of the south half of this quadrangle is crossed by the outer graben bounded by the Erin and Brownsville faults; the horst between the Brownsville and Marable Hollow faults; and the inner graben bounded by the Marable Hollow and Cumberland City faults. Structure of the central block within the circular Cumberland City fault is not considered to be part of the annular ring structure and will be described later.

In the outer graben the St. Louis Limestone is the major surface formation. Recorded dips in the outer graben range from 5° to 60°. Two small areas of Warsaw occur on the eastern edge of the quadrangle and also in two other small areas east of the Cumberland River. About ¾ mile from the south edge of the quadrangle, the Warsaw Limestone is exposed along the north side of an unnamed radial fault in the area where this fault offsets the Brownsville fault. Between this unnamed radial fault and the south edge of the quadrangle the Brownsville fault, because of its local low angle of dip, has an unusual swing in the trace of its outcrop.

In the horst east of Little Dry Elk Creek the surface rock is almost all Warsaw and Fort Payne with a narrow belt of St. Louis east of the Cumberland River and adjacent to the Brownsville fault. South of this belt of St. Louis and only a short distance east of the Cumberland River there is a small inlier of Chattanooga Shale and the Camden-Ross Formations. This inlier coincides with

[1] Section A-A′ of plate 1 contains a 2½-mile-long reduced portion of A-A′ of plate 2 at the center of the structure.

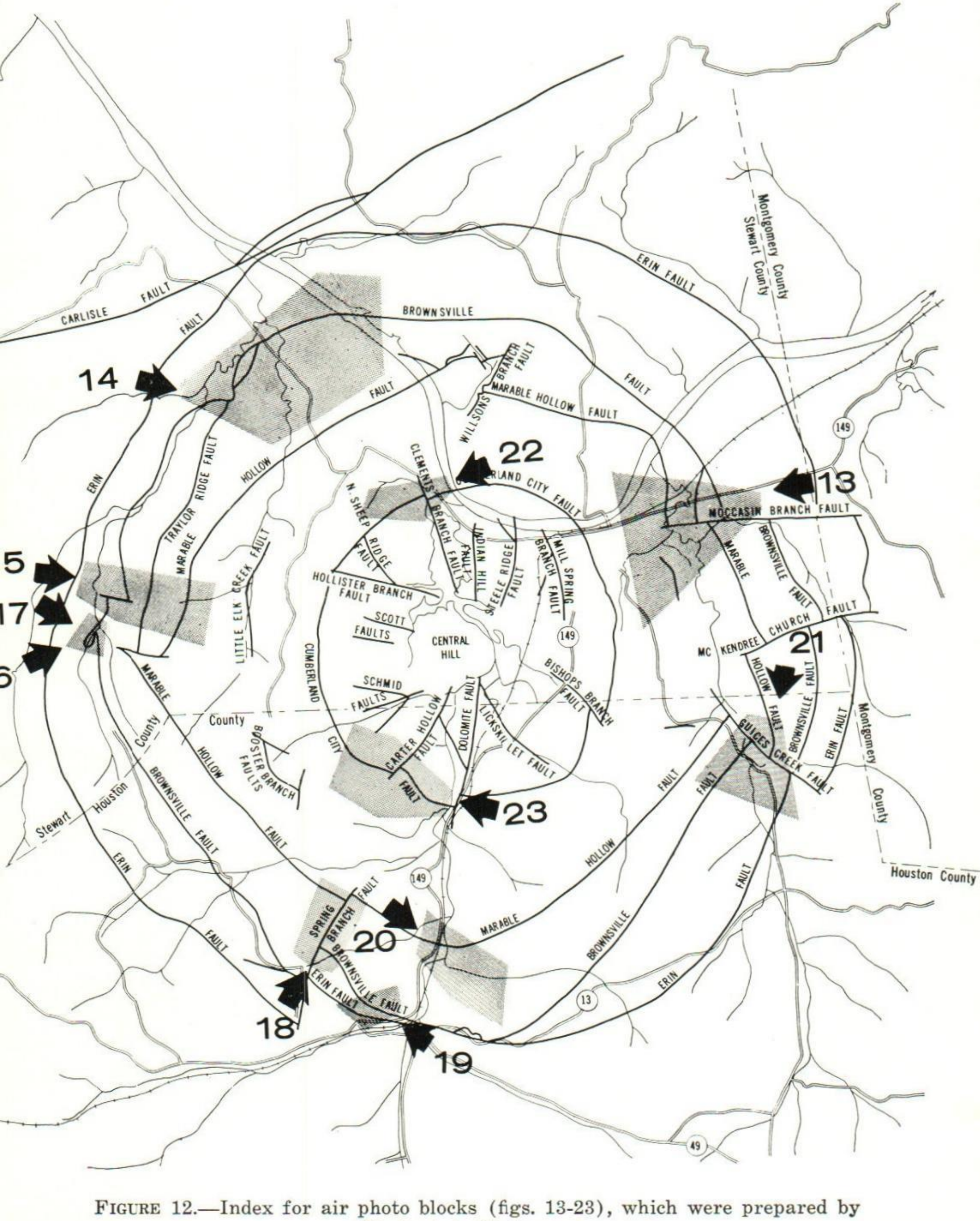

FIGURE 12.—Index for air photo blocks (figs. 13-23), which were prepared by Herbert A. Tiedemann.

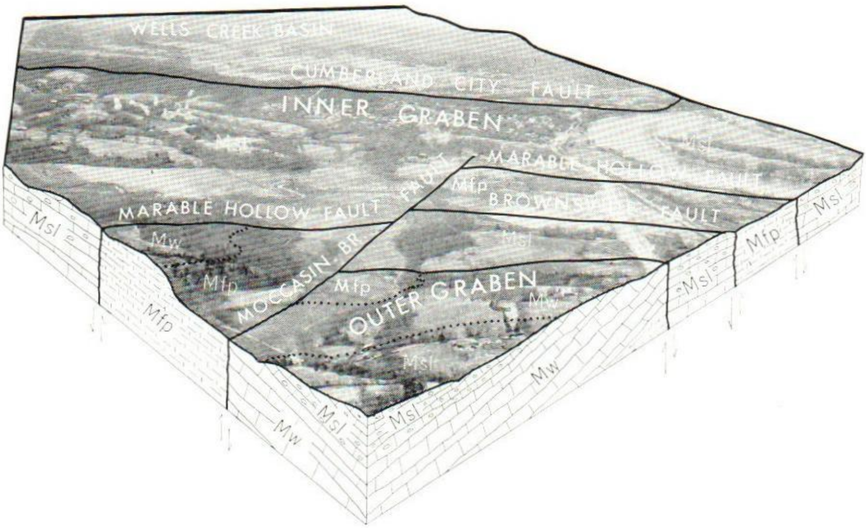

FIGURE 13.—Oblique aerial photograph with surface and subsurface geology, Moccasin Branch area, view westward.

Both inner and outer grabens are offset so that they slightly overlap (at the center of the photograph) along the Moccasin Branch fault. Outcrops along the right (north) side of the Moccasin Branch fault show Fort Payne and Warsaw Limestones brought to the surface by an unnamed local fault within the outer graben, an unusually high configuration; farther to the west the Brownsville fault borders the St. Louis limestone on the inner (east) side of the outer graben, and exposes Fort Payne limestones beside brecciated St. Louis limestone along the main road.

On the left (south) side of the Moccasin Branch fault Fort Payne and Warsaw limestones crop out on the near side of the hill, St. Louis limestones on the far side, across the Marable Hollow fault, which is offset 2,000 feet west along the Moccasin Branch fault.

The Cumberland City fault, passing through Cumberland City, and Wells Creek Basin can be seen in the background.

one of the anomalies (the third, as described previously) within the horst where the beds have been locally forced up at least 300 feet higher than their average level. About 1¾ miles east-southeast of this inlier is another exposure of Chattanooga Shale (fourth anomaly).

The horst west of Little Elk Creek is split into two slices by the circumferential Traylor Ridge fault. This fault ends abruptly to the south at a small unnamed radial fault that offsets the Marable Hollow fault. In this part of the horst, west of the Traylor Ridge fault, the surface rock is the Warsaw and Fort Payne Formations. East of the Traylor Ridge fault the surface rock is Fort Payne, with only a small area of Warsaw Limestone near the north end. In this eastern slice there is also a small inlier of Chattanooga Shale and Camden-Ross Formations near the south end and another small inlier of Chattanooga Shale near the north end, where the Traylor Ridge fault ends. These small inliers, where the beds locally have been forced up much higher than their average level, coincide respectively with the first and second anomalies within the horst.

In the inner graben, between the Marable Hollow and Cumberland City faults, the St. Louis Limestone is the surface rock. However, there are two small areas of Ste. Genevieve Limestone preserved along the east side of Little Elk Creek. Recorded dips of St. Louis Limestone in the inner graben range from 5° to 90°; recorded dips in Ste. Genevieve Limestone are 20° to 30°.

Cross section A-A′ on plate 1 [1] shows the structure in an east-west direction across the southern part of this quadrangle. The Erin and Marable Hollow faults are shown to be nearly vertical. The Brownsville fault is shown dipping to the west and converging with the Erin fault at depth. The Cumberland City fault is crossed twice by the line of section. West of the central block this fault is shown dipping to the west; east of the central block it is shown dipping to the east.

Four block diagrams are presented to give a three-dimensional view of three critical areas of the structure in this quadrangle. Figure 14 shows local relationships between the Traylor Ridge and Brownsville faults. Figure 15 shows the Marable Hollow, Traylor Ridge, and Brownsville faults, the latter being offset by an unnamed radial fault. Figure 16 shows local configuration of the surface trace of the Brownsville fault. Figure 17 is an "exploded-diagram" of the Brownsville fault at the same locality as figure 16, where it forms the contact surface between the outer graben and the horst.

Erin Quadrangle

(Southwest Quarter of Plate 1)

Most of the north half of this quadrangle, with the exception of its southwestern part, is crossed by the outer graben, bounded by

[1] Section A-A′ of plate 1 contains a 2½-mile-long reduced portion of A-A′ of plate 2 at the center of the structure.

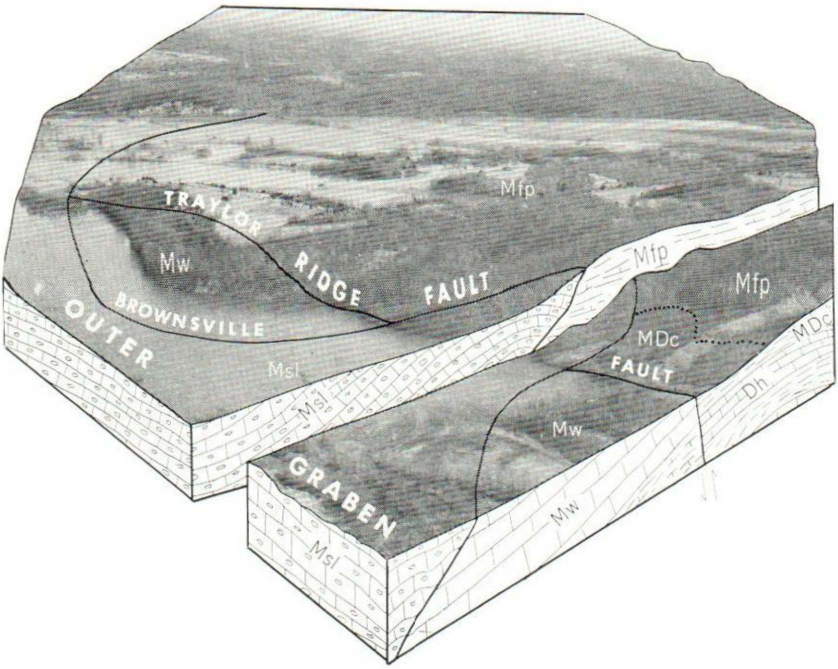

FIGURE 14.—Oblique aerial photograph with surface and subsurface geology, mouth of Big Elk Creek, view eastward.

A lobe of the outer graben overlaps the Traylor Ridge fault. Chattanooga Shale, which crops out at the base of the hill in the lower right part of the photograph, is faulted against Warsaw limestone in the right foreground (west); elsewhere along the Traylor Ridge fault residual scraggy Fort Payne chert occurs consistently eastward of, and at higher elevations than, the generally flat-lying Warsaw limestone. Here, at the mouth of Big Elk Creek, the continuity of the Traylor Ridge fault is interrupted by a lobe of dark St. Louis limestone, which crops out along the ridge to the left (north) of the Chattanooga outcrop. The trace of the Brownsville fault here indicates a gentle dip on the fault plane toward the viewer (outward).

Little Elk Creek and the Cumberland River are visible in the distance.

the Erin and Brownsville faults; the horst, between the Brownsville and Marable Hollow faults; and the inner graben, bounded by the Marable Hollow and Cumberland City faults. Structure of the central block within the circular Cumberland City fault is not considered to be part of the annular ring structure and will be described later.

In the segment of the outer graben northwest of the Spring

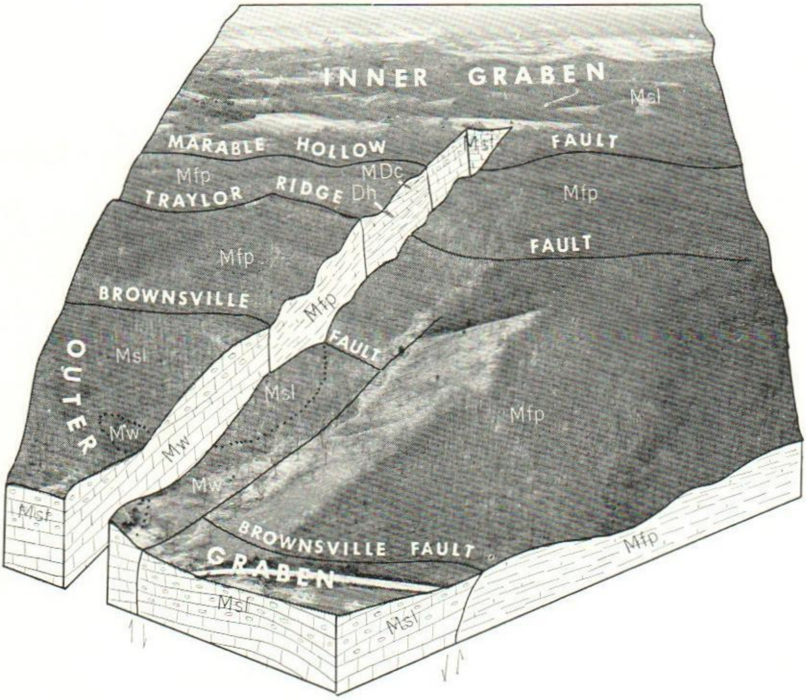

FIGURE 15.—Oblique aerial photograph with surface and subsurface geology, Little Dry Elk Creek area, view eastward.

About ½ mile north of the area of figure 16 the Brownsville fault is offset along a small unnamed fault. Outcrops along the road in the foreground indicate a jumbled mixture of St. Louis and Fort Payne along the Brownsville fault. This fault is offset about 1,000 feet away from the viewer (eastward), on the north side of the hollow, where scraggy Fort Payne limestones are adjacent to lower St. Louis and upper Warsaw limestones.

One of the "high spots" in the horst is exposed just beyond the Traylor Ridge fault, where Devonian limestone and Chattanooga shale crop out.

Branch fault the surface rock is St. Louis with the exception of a very small area of Ste. Genevieve limestone and shale in the bed of Spring Branch. Recorded dips range from 15° to 90°.

In the segment of the outer graben between Spring Branch and Wells Creek the surface rock is St. Louis Limestone, which has recorded dips of 10° to 25°. Beginning at Wells Creek on the west and extending eastward about a mile the Erin and Brownsville

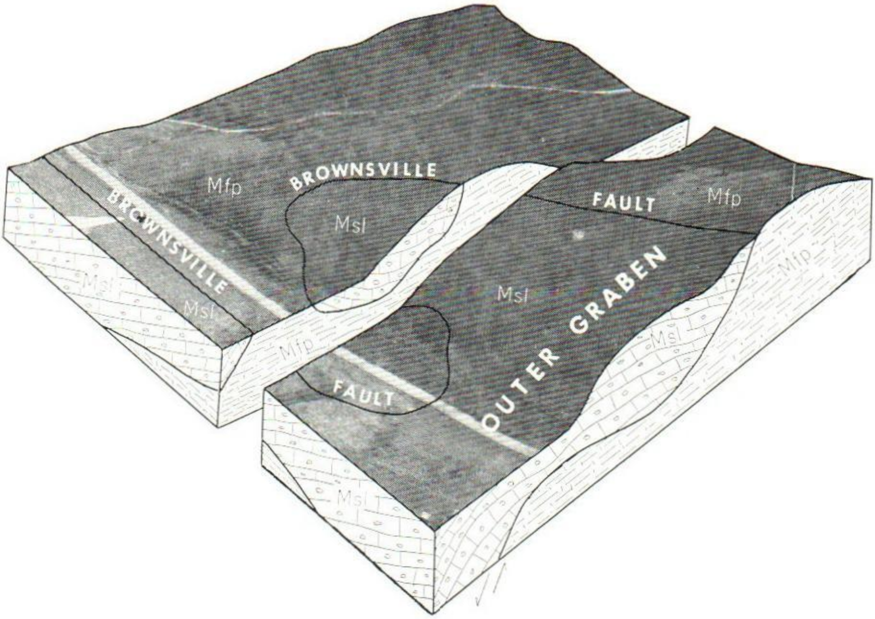

FIGURE 16.—Oblique aerial photograph with surface and subsurface geology, Little Dry Elk Creek area, view northeastward.

The Brownsville fault dips outward about 30° toward and to the left of the viewer. It makes a sinuous trace on the hillside, and St. Louis limestone can be seen lying platelike on top of scraggy Fort Payne limestone.

faults merge into a single fault, locally eliminating the outer graben at the surface in most of Tantrough Hollow. A small area of the outer graben (St. Louis) is present on the north side of this hollow and State Highway 13. The Erin and Brownsville faults diverge about a mile east of Wells Creek, and the outer graben is again present at the surface to the east edge of the quadrangle. In this segment of the graben St. Louis Limestone is the surface rock.

In the horst northwest of the Spring Branch fault Warsaw Limestone caps the upland areas, and Fort Payne Formation occupies the lower slopes and the valleys. Recorded dips range from 5° to 30° in this segment. In the horst east of the Spring Branch fault the surface formations are Warsaw and Fort Payne, essentially as they are northwest of this radial fault, with two exceptions. One is the small patch of St. Louis in the south-center of this segment. The other is on State Highway 149 about 1½ miles northeast of Erin where the Chattanooga Shale is exposed. Here the beds have been forced up locally much higher than their average level on the fifth such anomaly within the total length of the circular horst. Recorded dips range from 5° to 25° in this segment of the horst east of the Spring Branch fault.

In the inner graben, bounded by the Marable Hollow and Cumberland City faults, the St. Louis Limestone dips from 5° to 80°. It is the only surface rock with the exception of two areas of preservation of Ste. Genevieve Limestone. In both areas the Ste. Genevieve is associated with faulting. In the western part of the inner graben the Ste. Genevieve is present within the Booster Branch faults in the headwater area of Booster Branch. On the east edge of the quadrangle Ste. Genevieve is preserved on the downthrown side of a small unnamed fault.

Three block diagrams are presented to show details of structure at selected areas. Figure 18 shows the offset of the annular Brownsville fault by the radial Spring Branch fault. Figure 19 shows the eastward convergence of the annular Brownsville and Erin faults. Figure 20 shows a portion of the Marable Hollow fault where Chattanooga Shale has been uplifted locally (third anomaly).

Ellis Mills Quadrangle

(Southeast Quarter of Plate 1)

The northwestern corner of the Ellis Mills quadrangle is crossed by the outer graben, bounded by the Erin and Brownsville faults; the horst, between the Brownsville and Marable Hollow faults; and the outer part of the inner graben.

In the outer graben southwest of the Guices Creek fault the St. Louis is the only surface rock with the exception of a very small area of Warsaw on the tip of the spur between Guices Creek and Moore Branch. In the outer graben north of the Guices Creek fault the St. Louis is the surface rock.

In the horst southwest of the Guices Creek fault Warsaw is the surface rock except for a small area of Fort Payne on the west side of Guices Creek. In the horst north of the Guices Creek fault Warsaw is the surface rock except for a narrow belt of Fort Payne on the north side of Moore Branch.

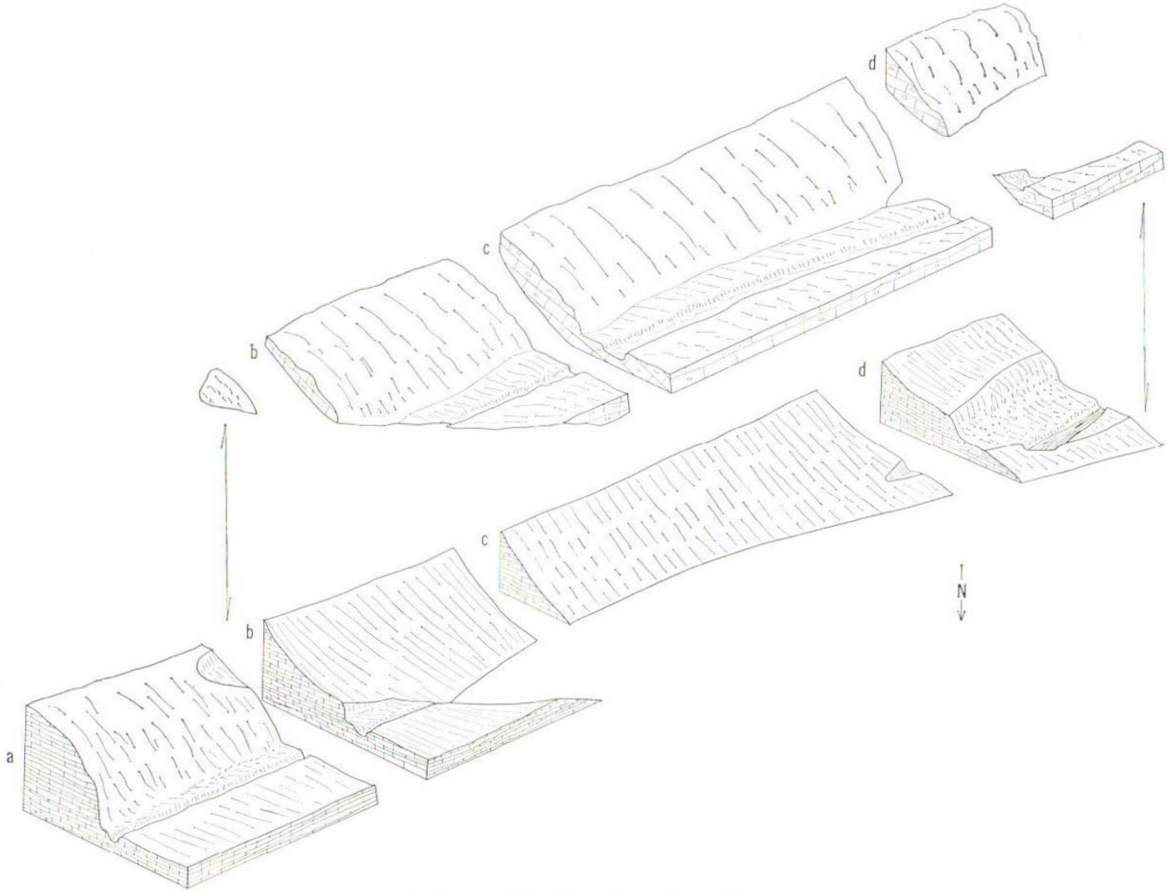

FIGURE 17.—See opposite page.

In that part of the inner graben in this quadrangle the St. Louis is the only formation present at the surface, with the exception of the preservation of a small fault-sliver of Ste. Genevieve Limestone and post-Ste. Genevieve beds on the downthrown side of a small unnamed fault on the west edge of the quadrangle. Recorded dips in the St. Louis range from 15° to 90°. Dip in the post-St. Louis beds averages 45°.

FIGURE 17.—Exploded view of the Brownsville fault on the west side of the structure, view southeastward at the east side of the valley of Little Dry Elk Creek.

This is the same area as that seen in the aerial photograph on figure 16. In this area cherty brecciated St. Louis Limestone (of the hanging wall block of the outer graben) is downfaulted over scraggy upper Fort Payne Limestone.

Four sections were measured along the bluff, beginning about 200 feet south of the north end of the bluff, at Section "a."

Section "a": Scraggy Fort Payne, which crops out in the creek bed and 20 to 25 feet up the bluff, is almost horizontal. The rest of the bluff above the outcrops is less steep and is covered. There is no evidence of faulting.

Section "b": (140 feet south of "a"): Scraggy Fort Payne, which crops out in the creek bed and about 10 to 12 feet up the bluff, is "nearly horizontal." Four or 5 feet above these outcrops is a small boulder of St. Louis limestone, cherty, brecciated, attitude indeterminate, probably dipping essentially with the bluff. Another similar, slightly larger boulder lies 5 to 6 feet higher on the bluff. These boulders appear to be isolated, "rootless" outcrops lying like klippen on the steep side of the bluff, the fault plane at a low angle to the west (20°-30°). Forty or 50 feet south along the bluff, massive outcrops of St. Louis limestone predominate, starting high on the bluff initially but dropping to creek level in a few score feet.

Section "c" (140 feet south of "b"): Massive cherty and brecciated St. Louis limestone crops out at creek level. Dip is difficult to determine but appears to be gently westward. Outcrops extend up 20 feet or more, above which is soil strewn with St. Louis chert fragments and cannonballs. Because of the attitude and position of the massive St. Louis outcrops, no Fort Payne is seen in this section and it is thought to be well below ground level.

Section "d" (220 feet south of "c"): Fault plane above ground level here, as at north end. Fort Payne scraggy limestone, which crops out along base of bluff up to about 15 feet, is nearly horizontal. Directly overlying the Fort Payne is massive St. Louis limestone, generally almost horizontal. This fault contact, which can be traced for a hundred feet or more along the bluff, rises slightly to the south and around a corner of the bluff, where it appears to rise somewhat more sharply to the east, although still probably less than 30°.

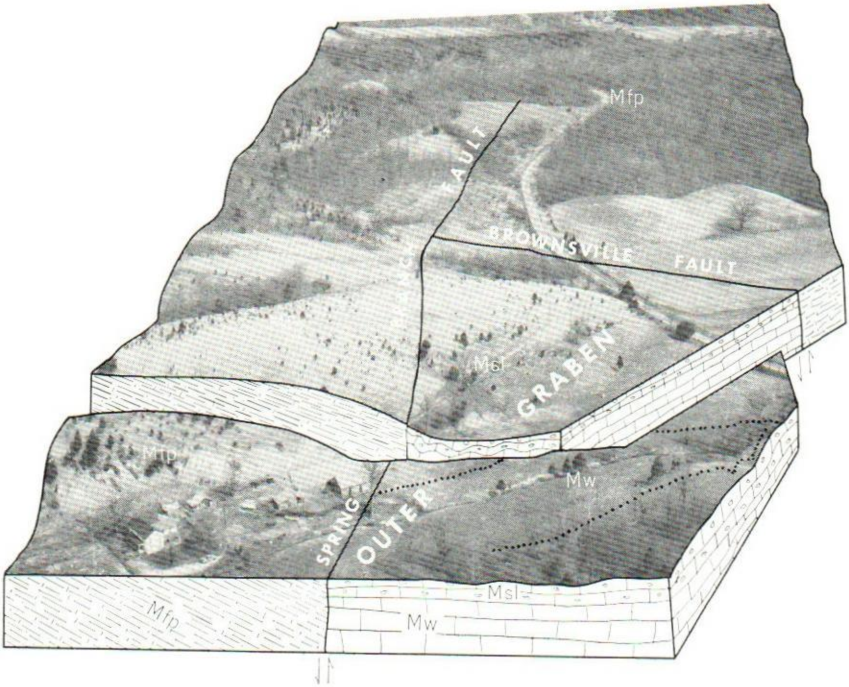

FIGURE 18.—Oblique aerial photograph with surface and subsurface geology, Spring Branch area, view northeastward.

The outer graben is offset away from the viewer toward the inside of the structure along the Spring Branch fault. Scraggy Fort Payne limestone is exposed on the hill behind the barns; the east end of the hill contains numerous exposures of St. Louis limestone. Upper Warsaw limestone is exposed in a gentle fold on the flat along Spring Creek. Along the road north of the Brownsville fault weathered chert and clay of the Fort Payne are exposed.

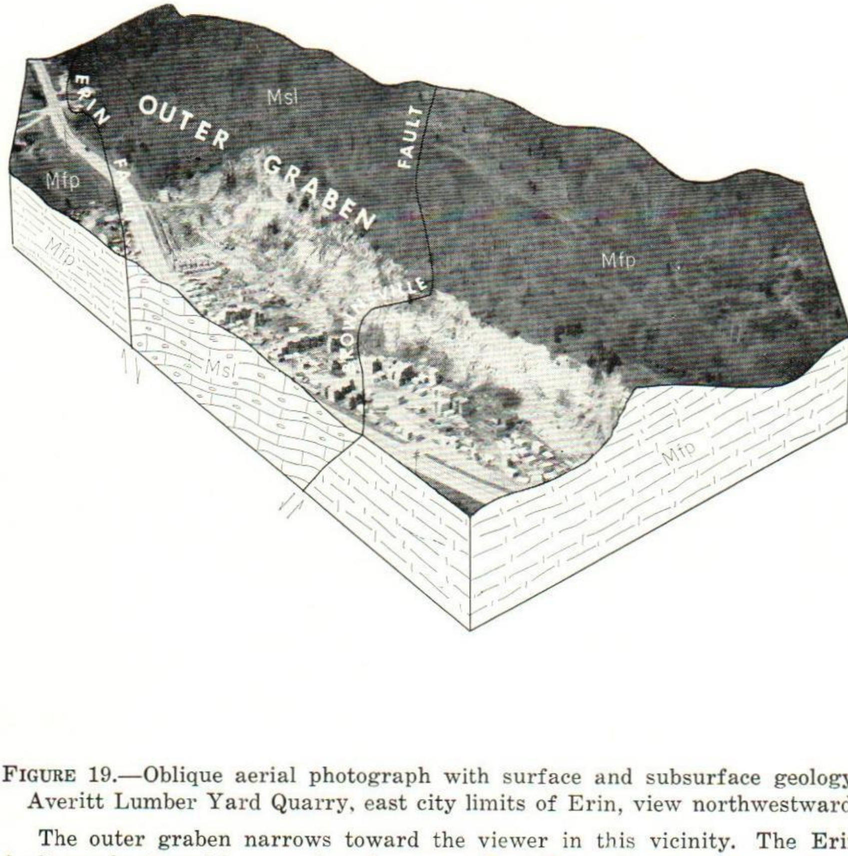

FIGURE 19.—Oblique aerial photograph with surface and subsurface geology, Averitt Lumber Yard Quarry, east city limits of Erin, view northwestward.

The outer graben narrows toward the viewer in this vicinity. The Erin fault can be traced by a series of scraggy Fort Payne limestone knobs lying against St. Louis limestone along the right (north) side of the road on the left side of the picture. The Brownsville fault is well exposed in the face of the quarry, with the Fort Payne to the right (north), or inside the structure. The fault plane is dipping generally to the left (outward), and the width of the entire outer graben here is less than 300 feet. Less than ½ mile behind the viewer (east) the two faults coalesce, and the graben pinches out entirely.

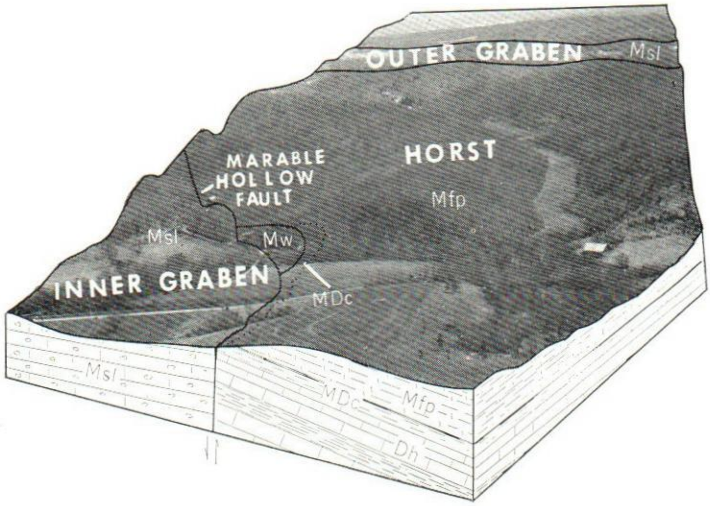

FIGURE 20.—Oblique aerial photograph with surface and subsurface geology, Marable Hollow, view southeastward.

One of the "high spots" on the horst; St. Louis limestone of the inner graben crops out on the left side of the picture (north side of the mouth of Marable Hollow). Chattanooga Shale is faulted against the St. Louis along the road in the foreground (State Highway 149) and in the base of the hill on the far side of the main valley (east side of Wells Creek). A small "horse" of Warsaw limestone is sandwiched between the Chattanooga and St. Louis units. The view extends southeastward across the horst to the outer graben.

A block diagram, figure 21, is presented to show the offset of the annular Brownsville and Marable Hollow faults by the radial Guices Creek fault.

DETAILED DESCRIPTIONS OF STRUCTURE OF THE CENTRAL BLOCK

(Cumberland City and Erin Quadrangles)

Outer Annular Ridges

The circular Cumberland City fault surrounds the structural central block and coincides with the periphery of the topographic outer annular ridges (fig. 2). These ridges are formed by outward-dipping resistant beds of the Fort Payne Formation. Recorded dips range from 6° to 80° and average 20° to 30°. The base of the outward-sloping dip slope of the Fort Payne is marked by, or coin-

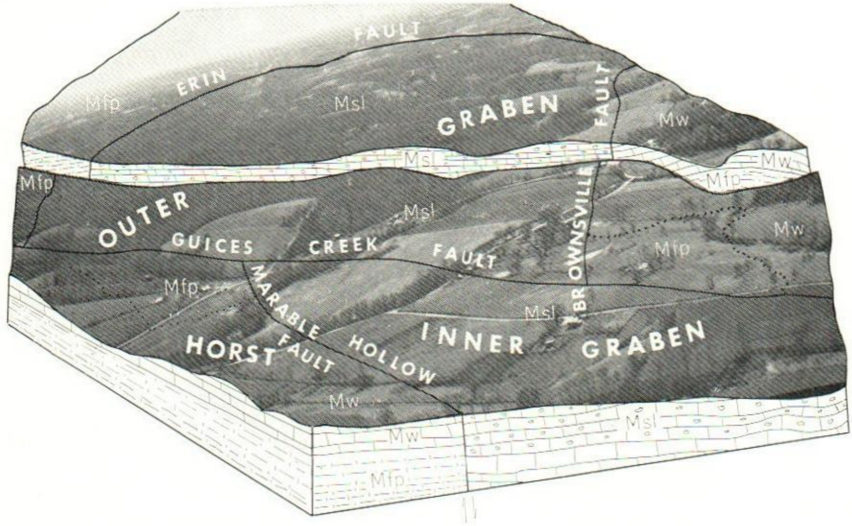

FIGURE 21.—Oblique aerial photograph with surface and subsurface geology, Guices Creek-Moore Branch area, view southwestward.

Inner and outer grabens overlap considerably along the offsetting Guices Creek fault. On the far side of the fault St. Louis limestones of the outer graben are exposed on the wooded hills. Beyond (left of) the Erin fault Fort Payne limestones are exposed along the road. To the right (west of) the Brownsville fault Fort Payne and overlying Warsaw limestones crop out along the road and in the hollow west of the road.

In the foreground St. Louis limestones of the inner graben crop out along the creek behind the barns on the right edge of the block. The horst to the left of the Marable Hollow fault is marked by Fort Payne limestone in the wooded hill on the left edge of the photograph and by Warsaw chert float on the cleared slopes in the foreground.

cides with, the Cumberland City fault. This circular belt of Fort Payne ranges in width from 750 to 3,200 feet and averages 1,500 to 1,700 feet (pl. 1). The structural contour map, figure 11, shows its dip.

"Riding up" the back of this dip slope formed by the Fort Payne are many small "flatirons" of Warsaw Limestone. They are terminated abruptly along the Cumberland City fault on the outside. These preservations of Warsaw are almost continuous on the west and northwest periphery of the central block but are only small and isolated on the northeast and south. They average less than 1,000 feet in width. (See pl. 1).

Two block diagrams are presented to give a three-dimensional view of two areas on the periphery of the central block. Figure 22 shows the offset of the annular Cumberland City fault by the radial Clements Branch fault. Figure 23 shows the offset of the Cumberland City fault by the Carter Hollow fault.

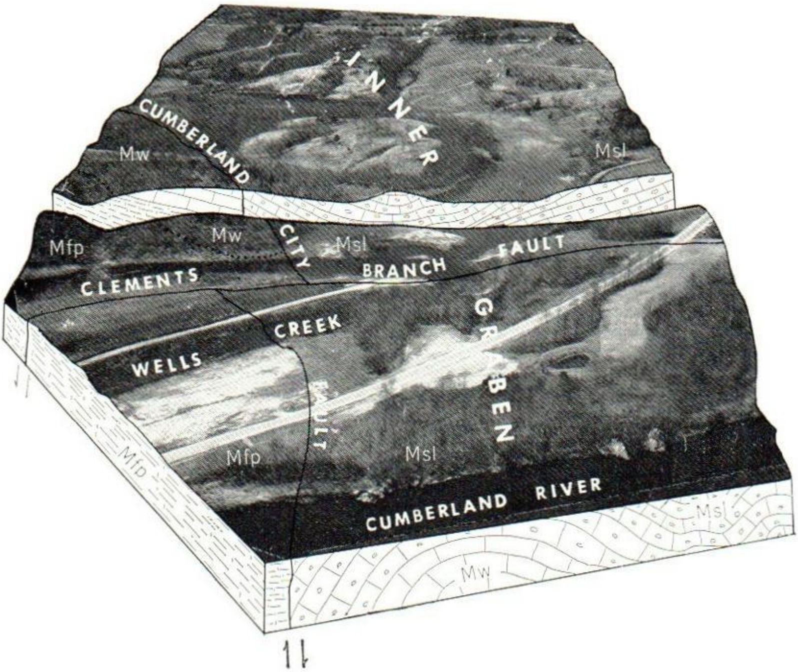

FIGURE 22.—Oblique aerial photograph with surface and subsurface geology, north edge of the central block, along the bank of the Cumberland River, view westward.

The Cumberland City fault here is offset by the Clements Branch radial fault. Cherty Fort Payne limestone and lower Warsaw limestone dip to the right and away from the viewer (northward) along the far bank of Wells Creek on the left side of the photograph. Farther right, beyond the Cumberland City fault, St. Louis limestone crops out in the foreground along the bank of the Cumberland River. Alluvium covers the Cumberland City fault, but alignments of the contact between Fort Payne and St. Louis along the Cumberland City fault on either side of Wells Creek indicate an offset of about 300 feet.

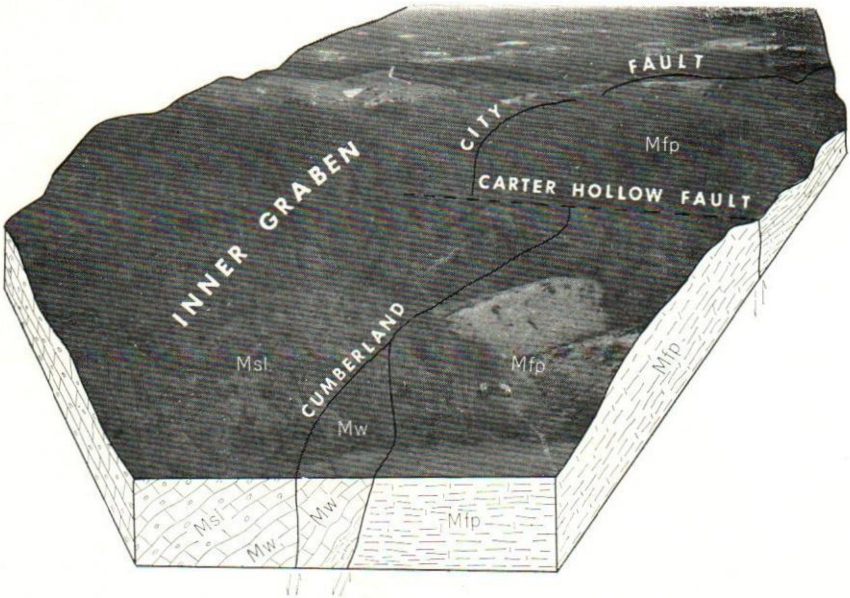

FIGURE 23.—Oblique aerial photograph with surface and subsurface geology, south edge of the central block, west of Wells Creek, view westward from Wells Creek valley over Carter Hollow.

The Cumberland City fault circles around the south basin rim, marked by contrasting St. Louis and Fort Payne chert in juxtaposition. The control is good enough to indicate about 500 feet of offset along the Carter Hollow fault. A small "horse" of Warsaw limestone occurs in the foreground along the Cumberland City fault in the mouth of the hollow that extends westward from the Wells Creek flood plain.

Wells Creek Basin

(Inside the Central Block)

INTRODUCTION

In general the geologic pattern of Wells Creek Basin is simple. The central area of Knox Dolomite, which is about 6,000 to 7,000 feet in diameter, is surrounded by successive belts of Stones River, 1,000 to 2,000 feet in width; of Fernvale-Hermitage, 500 to 1,000 feet in width; and of Silurian and Devonian,[1] about 1,000 feet in

[1] Henceforth, throughout the description of structure the Fernvale Limestone at the top of the Ordovician System will be given with the Silurian and Devonian. Fernvale Limestone is similar to many units in the Silurian and Devonian.

width. The major variations in width of these belts are due to changes in dip. Also, local imbrication of structure, piling up slice upon slice, increases the width of these belts.

Section A-A′ (pl. 2) crosses the basin from South Sheep Ridge on the west to Negro Ridge on the east.

Although the geologic pattern of Wells Creek Basin is simple in general aspects, it is complicated in detail. Changes in strike cause the belts to "swing" in and out, but the major variation in symmetry is produced by the offsets of the belts by the many radial faults.

Physiographically (fig. 2), the belt of Silurian and Devonian rocks coincides with the outer annular valleys, the Hermitage Formation with the inner annular ridges, and the Stones River Group with the inner annular valleys. The central hills are formed by Knox Dolomite.

The geology of each of these belts will be described for each segment between major radial faults. The descriptions begin with the Dolomite-Carter Hollow fault segment on the south and proceed clockwise around the basin.

BELT OF SILURIAN AND DEVONIAN

Dolomite-Carter Hollow fault segment.—Throughout most of this segment the Silurian and Devonian have been beveled by erosion and veneered by alluvium of Wells Creek. Exposures of these beds are restricted to the south side of Dolomite Station Hill. The beds exposed are in a syncline that strikes northeast-southwest. Within the syncline the Laurel Limestone is the youngest formation and the Fernvale Limestone is the oldest. Dip of the limbs of the syncline is 45° to 50°.

Carter Hollow-South Schmid fault segment.—Here the entire Silurian and Devonian sequence is present. The main anomaly in this segment is major deviations in strike of the strata caused by a small unnamed radial fault about midway in the segement. Dips range from 10° to 60° to the south and southwest.

South Schmid-North Schmid fault segment.—The beds in this segment are offset northeastward by the South Schmid fault relative to the beds in the Carter Hollow-South Schmid segment.

This fault wedge, which converges inward toward the center of the structure, is postulated to be bisected by the Middle Schmid fault covered by alluvium along Schmid Branch. This fault is postulated to offset the Decatur Limestone and the Devonian formations. Otherwise, the beds follow the circular swing of the structure. Dips range from 25° to overturned.

North Schmid-Hollister Branch fault segment.—The beds in this segment are offset to the east by the North Schmid fault relative to beds in the South Schmid-North Schmid fault segment to the south.

Within this long segment, which forms the west-central part of the structure, the pattern of beds is offset at three localities. About 1,000 feet north of the North Schmid fault a minor fault cuts obliquely across the strike and offsets beds in the Brownsport Formation, Decatur Limestone, and Devonian formations. Dips in these beds range from 10° to 60°. About midway within the segment are the two parallel Scott faults between which the beds have been dropped down relative to those north and south of these parallel faults. The downdropped beds between the faults are offset eastward accordingly. Just west of the Scott House is an imbrication that contorts the beds.

Most of the strata in this segment dip westward between 10° and 80°.

Hollister Branch-Indian Hill fault segment.—The beds in this segment are offset to the west by the Hollister Branch fault relative to the beds in the North Schmid-Hollister Branch segment. In order to explain this pattern the Hollister Branch fault is postulated to extend beneath the alluvium of Hollister Branch.

The North Sheep Ridge fault north of the Hollister Branch fault causes a northwest offset of beds of the entire exposed sequence. The Clements Branch fault is postulated to extend beneath the alluvium of Wells Creek to explain the offset of beds on either side of this creek. Dips generally range from 25° to 90°, but some beds are slightly overturned.

The major structural feature in this segment is the marked imbrication on the hill north of the site of the Potter House. At this locality beds of the Wayne and Brownsport are piled up in slices. Section B-B′, plate 2, across this structure, shows their relationships. On this section the dip of the faults is shown to be nearly vertical.

Between Wells Creek and the Indian Hill fault the beds are without structural complication and dip to the north in normal sequence. Dips in the Brownsport, Decatur, and Devonian rocks are generally lower than they are in other segments.

Segment between Indian Hill fault and L & N railroad tracks.—The beds in this segment are offset southward by the Indian Hill fault in reference to those in the Hollister Branch-Indian Hill fault segment.

The major structural anomaly in this segment is the Steele Ridge fault, which splits northward into two faults that diverge outward.

Between the Indian Hill fault and the west split of the Steele Ridge fault the sequence of formations on the map looks normal, Devonian on the north and Fernvale Limestone on the south. Most of this block, however, between the Fernvale-Hermitage contact and the point where Section C-C′, plate 2, crosses the west split of Steele Ridge fault, is overturned. The younger beds in the northern part of Indian Hill dip normally to the north.

The beds between the two splits south of Allen Ridge appear to be dipping normally between 30° and 75° to the north. The outcrop belt of the Dixon Formation widens eastward. Allen Ridge is capped by a synclinal preservation of the Camden-Ross Formations. Along the river bluff the underlying Decatur Limestone and Brownsport Formation, in general, dip southward from 25° to 65° beneath Allen Ridge. They come to the surface again south of this ridge. The Allen Ridge syncline is shown on section C-C′, plate 2, north of the west split of the Steele Ridge fault. The Mill Spring Branch fault cuts across the eastern end of Allen Ridge and drops the Fort Payne downward, where it dips 30° to 60° northeastward.

The beds between the east split of Steele Ridge fault and the L & N railroad tracks on the north slope of Steele Ridge dip normally in sequence between the Fernvale Limestone and the Dixon Formation, the youngest formation at the surface. The strike of the beds in this block is slightly north of east, askew to the general pattern.

Segment between L & N tracks and Bishops Branch fault.—East of the tracks and west of the alluvium of Mill Spring Branch the structure of the east end of Allen Ridge and its south slope and the structure of the north slope of Steele Ridge to the south are about the same as described in the preceding segment.

Along the west split of the Mill Spring Branch fault there is a right-angle discrepancy between the strike along the north slope of Steele Ridge in the preceding segment and the belt of north-south-striking beds within the segment being described (and also the offset in the Hermitage-Stones River contact).

This segment is unusual in two respects. First, the strike of this belt is almost north-south and not in harmony with the curvature of the pattern of the structure. Second, the belt of Silurian and Devonian strata is divided into two belts by the Mill Spring Branch fault (east split) and a narrow strip of the Hermitage Formation throughout most of the length of this segment. It is divided by the Mill Spring Branch fault (east split) for the remainder of the distance southward to the Bishops Branch fault. The Mill Spring Branch fault is shown on Sections A-A′ and D-D′, plate 2.

The Mill Spring Branch fault (east split), which forms the eastern part of the structure, has a north-south straight trend instead of curving with the rest of the circular pattern. It will be shown later that this straight fault is parallel to a master joint set in the region. This is the only major tangential fault in the central block.

North of the east-west section A-A′, plate 2, a narrow belt of beds ranging between the Fernvale and Lego Limestones occurs between the east split of the Mill Spring Branch fault on the east and the main belt of the Hermitage Formation on the west. The belt is about 250 feet wide and is characterized by high dips, from 70° to nearly vertical. To the east there is a "splinter-belt" of the Hermitage Formation, also about 250 feet wide, which in part may be anticlinal. However, it includes the beginning of the east dip characteristic of the eastern belt of Silurian and Devonian strata east of the Mill Spring Branch fault. Recorded dips in this eastern belt are between 40° and 70°.

South of the east-west section A-A′, plate 2, the western belt of Silurian and Devonian described above continues southward to the Bishops Branch fault. In the vicinity of section D-D′, plate 2, this belt, west of the Mill Spring Branch fault, passes into a syncline with minor faulting and some overturning of beds. Section D-D′, plate 2, shows this structural feature to good advantage. Lego

Limestone occupies the center of this syncline. Not far to the south of section D-D′ the syncline ends abruptly at the Mill Spring Branch fault. This fault continues southward to the Bishops Branch fault, with Brassfield Limestone on its east side and Lego and Laurel Limestones on its west side.

About 800 feet south of section A-A′ and near section D-D′, the Hermitage "fault-splinter" on the east side of the Mill Spring Branch fault disappears below the surface. South of here the Fernvale Limestone is in contact with the east side of the fault for a short distance and the Brassfield Limestone is in contact with the fault for the rest of the way southward to the Bishops Branch radial fault.

East of the long narrow belt of Hermitage Formation (north of section D-D′) is the eastern belt of Silurian and Devonian, which dips eastward at 40° to 70°. This belt persists more or less unchanged for practically the full length of this segment.

Bishops Branch-Lickskillet fault segment.—The beds in this segment are offset to the northwest by the Bishops Branch fault in reference to the beds in the Mill Spring Branch-Bishops Branch fault segment.

In the northeastern half of this segment the beds are crowded into a complex imbrication, shown in section E-E′, plate 2, consisting of three major fault slices. In this section the dip of the faults is shown to be nearly vertical. Beds known to be involved in this structure range from Brassfield to Decatur. Associated with this structural complication recorded dips range from 65° to overturned.

In the southwestern half of this segment the imbrication ends and the belts of outcrop of Silurian and Devonian formations are parallel to each other, their strike swinging westward around the hill north of Lickskillet Branch. Dips range from 20° to 75°.

Lickskillet-Dolomite fault segment.—The beds in this segment are askew to the general circular pattern. They are offset to the southeast by the Lickskillet fault relative to the beds in the Bishops Branch-Lickskillet fault segment. On the west side of this segment the beds are offset to the north by the Dolomite fault relative to the beds in the Dolomite-Carter Hollow fault segment. The beds generally strike about N.80°W.

Westward, the beds between the Lego Limestone and the Brownsport Formation are duplicated by a minor unnamed tangential fault. South of this fault the beds dip southward from 15° to 45°. North of this fault the outcrop areas of the Lego and Laurel Limestones locally are exaggerated in width in the vicinity of Dolomite. Dips here are very erratic and those recorded are between 10° and 10° overturned. The latter dip is visble in the railroad cut at Dolomite, where the Laurel, Osgood, and Brassfield formations are overturned.

BELT OF HERMITAGE FORMATION

The Hermitage Formation makes an almost complete circular belt around Wells Creek Basin. In the Dolomite-Carter Hollow fault segment on the south and the Hollister Branch-Indian Hill fault segment on the north the formation has been beveled by Wells Creek and almost completely veneered with its alluvium. The major structural anomaly is in the Mill Spring Branch-Bishops Branch fault segment where there are two parallel belts of Hermitage, the eastern one being associated with the north-south tangential Mill Spring Branch fault. Where complete the belt between the underlying Stones River and the overlying Fernvale Limestone ranges from 200 to 1,200 feet in width, averaging 500 to 1,000 feet.

Although exposures of fresh rock are rare, this formation is an excellent structural datum zone. Its outcrop areas are strewn with shaly and sandy flakes and slabs and scattered masses of silicified fragments, all in a sandy, yellowish-brown soil residuum. Furthermore, the formation forms the inner annular ridges that rise above the lower levels of the Stones River and Silurian limestones. This combination of features makes the Hermitage outcrop areas conspicuous and thus relatively simple to map accurately. Also, these features are excellent guides for accurate mapping of the offset in the Hermitage belt caused by the radial faults. Imbrication parallel to the strike, on the other hand, is almost impossible to identify.

Because of the scarcity of exposures of fresh rock, measurable dips are rare. Those taken range from 20° to 80°. The beds are overturned locally, particularly in the vicinity of the radial faults. Cores and excavations of fresh rock commonly show particularly complex small scale structure in Hermitage shaly rock. Folds and faults a fraction of an inch in amplitude and spacing are common.

The Hermitage is present in sections A-A′, B-B′, C-C′, D-D′, and E-E′, plate 2.

BELT OF STONES RIVER GROUP

The outcrop of Stones River limestone is not as continuous as that of the Hermitage Formation, as this group forms the inner annular valleys that include a high proportion of alluviated stream valleys. For example, Wells Creek both in the northern and southern parts of the basin, Schmid Branch, Hollister Branch, Bishops Branch, and Lickskillet Branch divide the Stones River belt into isolated areas of outcrop.

Inasmuch as exposures are discontinuous and the residual soil lacks identifying characteristics, unlike the Hermitage soil, it is difficult to trace the radial faults across the Stones River belt. Within this belt these faults commonly are covered by alluvium, but locally the offset may be mapped in the Stones River-Hermitage contact. The Steele Ridge fault is the only radial fault that was mapped across the entire width of the belt, and therefore this is the only fault on which the offset in the Knox-Stones River contact is shown. This offset is well exposed on Wickham Ridge about 1,000 feet west of the Wickham House.

Exposures of the Stones River generally are small and scattered, with the exception of the fairly continuous section measured and described on the hill north of the Bishops Branch fault (Section 2, Appendix A).

Although dips occur in all compass directions, in general the exposures of limestone dip radially away from the center of the structure. Dips commonly range from 20° to 90°, and some beds are overturned. Locally, the strike swings from its usual circumferential pattern to parallel some of the radial faults, and the associated dip is commonly away from the fault.

On the east and northeast side of the basin near the Bishops Branch and Steele Ridge radial faults, the Stones River becomes involved with the chaotic central core of "megabreccia" that includes most of the Knox Dolomite outcrop area described below.

CENTRAL AREA OF KNOX DOLOMITE

The central area of Knox has a diameter of 6,000 to 7,000 feet. The contact between the Stones River Group and the Knox Dolomite is present at the surface only in two areas. One of these is less than 1,000 feet north of the postulated point of convergence of the three splits of the Schmid fault. Here the contact is present at the surface for a distance of about 1,250 feet. The other area is along Wickham Ridge west of the Wickham House, where the contact is present at the surface for a distance of about 1,500 feet within which the contact is offset by the Steele Ridge fault. Elsewhere in Wells Creek Basin the Stones River-Knox contact is covered by alluvium of Wells Creek and its tributaries within the basin.

The Knox Dolomite crops out on four hills—(1) Central Hill, (2) Fairgrounds Hill, (3) the western part of Wickham Ridge that is surrounded by alluvium, and (4) the eastern, or main, part of Wickham Ridge. The first two of these hills have better exposures.

An area on the western part of Central Hill was stripped for a possible quarry site, but the quarry was not developed and the stripped area was covered. This exposure consisted of fault blocks, or breccia blocks, ranging up to at least 25 feet in dimension, in a matrix of smaller breccia. Within the limits of each large block the nearly vertical beds have approximately the same strike. Blocks abut against each other, and the strike of beds in adjacent blocks commonly is at right angles. The quarry on Fairgrounds Hill also contains breccia blocks but of much greater magnitude, ranging up to at least 600 feet in dimension. These two exposures are considered to be typical megabreccia. In this report similar megabreccia is interpreted as occupying a central core about 5,000 feet in diameter. The only Knox Dolomite that is considered to be outside the central core of megabreccia is an area at the southwest end of Central Hill just north of Schmid Branch. This conclusion is based, in part, upon the consistent strike pattern of the scattered individual outcrops.

Smaller scale brecciated bodies in the Knox have several modes of occurrence. In some places an entire Knox exposure is brecciated; in other places breccia occurs along bedding planes or along fractures between blocks, and locally as dikes that cut across the bedding. As will be explained later in this report, much of the smaller scale breccia may have formed during Ordovician time by a solution-collapse process long before the Wells Creek event.

Much of the smaller scale breccia of the Knox is not of tectonic origin, but the megabreccia most certainly is.

GEOLOGICAL INTERPRETATION OF STRUCTURAL DATA

GENERAL FORM OF THE STRUCTURE

(Fig. 11)

The Wells Creek structure is essentially circular in plan view. Deviations from this circularity are caused by pre-existing joints that altered the pattern. If joints had not been present, the structure probably would be more symmetrically circular.

Superimposed upon the general circularity is a bilateral symmetry, the axis of which trends north-northeast. This north-northeast alignment is manifested by: (1) pinchout of the outer graben just west of the south periphery (fig. 11); (2) inferred deep downthrow of the south part of the inner graben (fig. 25); (3) steep overturning of Silurian and Devonian strata in the north-northeastern part of Wells Creek Basin along the Cumberland River (pl. 2, section C-C′); (4) slight north and northeastward elongation of the outcrop "rings" of Ordovician strata in the basin (pl. 2); and (5) to a lesser extent, development of features symmetrically east and west of the axis of bilateral symmetry such as (a) more thrusts on the east and west sides of the basin (pl. 2), (b) matched pairs of structurally "deep spots" adjacent to faults in the inner graben (fig. 11), and (c) the 1-mile-longer north-northeast and south-southwest diameter than the east-west diameter —45,500 feet in contrast to 40,000 feet. This bilateral symmetry also is evident in gravity data, as will be shown (fig. 64).

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

STRUCTURAL MOVEMENTS

Estimates of the amount of lateral and vertical movement are based on both knowledge and assumptions of the original position of rock masses or structures. Because we know the approximate relative vertical position of rock throughout the area, we know that the rocks have moved upward in the central portion of the central block and in the five local anomalous highs within the otherwise undisturbed horst. The rocks definitely moved downward in the two grabens. These vertical movements have been contoured on figure 11. Lateral movements are not directly known but can be inferred with considerable certainty from the structural relationships.

Total Structural Configuration

The total structure contoured on figure 11 is a composite of (1) all "normal" post-Fort Payne structure, together with any initial dip on top of the Fort Payne; and (2) the vertical structural rearrangement due to the Wells Creek cryptoexplosive event. The structure due to this event can be separated from the sum-total of all structure in the area by assuming that some areas were not disturbed by the Wells Creek event. Areas inferred to be unmoved by the event are the annular horst and the outer edge of the central block; and, as based upon lack of evidence of disturbance, the area outside the structure.

Normal Regional Structure of the Area

Outside the rings, except near the northeast-trending Carlisle fault, the normal regional structure consists of a series of roughly north-trending 100-foot highs and lows superimposed on a gentle north regional dip that totals approximately only a hundred feet across the structure (fig. 24). That is, the lows that are at about 500 feet in elevation near the south edge of the structure are at 400 feet or less at the north edge, about 8 miles to the north.

Contours are arbitrarily projected from the outside region into the annular rings to connect with elevations on the horst and at the perimeter of the central block in accordance with our assumption that these are vertically undisturbed. The map (fig. 24) illustrates the resulting interpretation that the north-trending highs and lows continue across the structure. It is interesting to note that a high crosses the center of the structure from south to north, and that the highest elevation of the Fort Payne in the region occurs at the south-center of the structure.

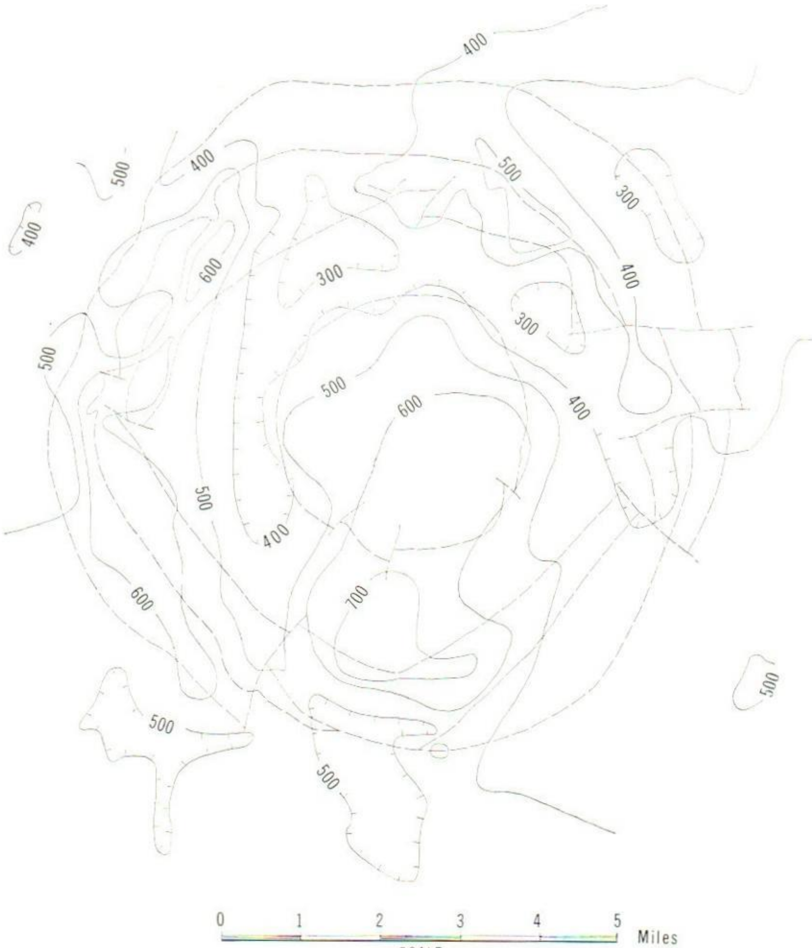

FIGURE 24.—Configuration of the top of the Fort Payne projected across the structure, by using the horst and the periphery of the central block as control areas.

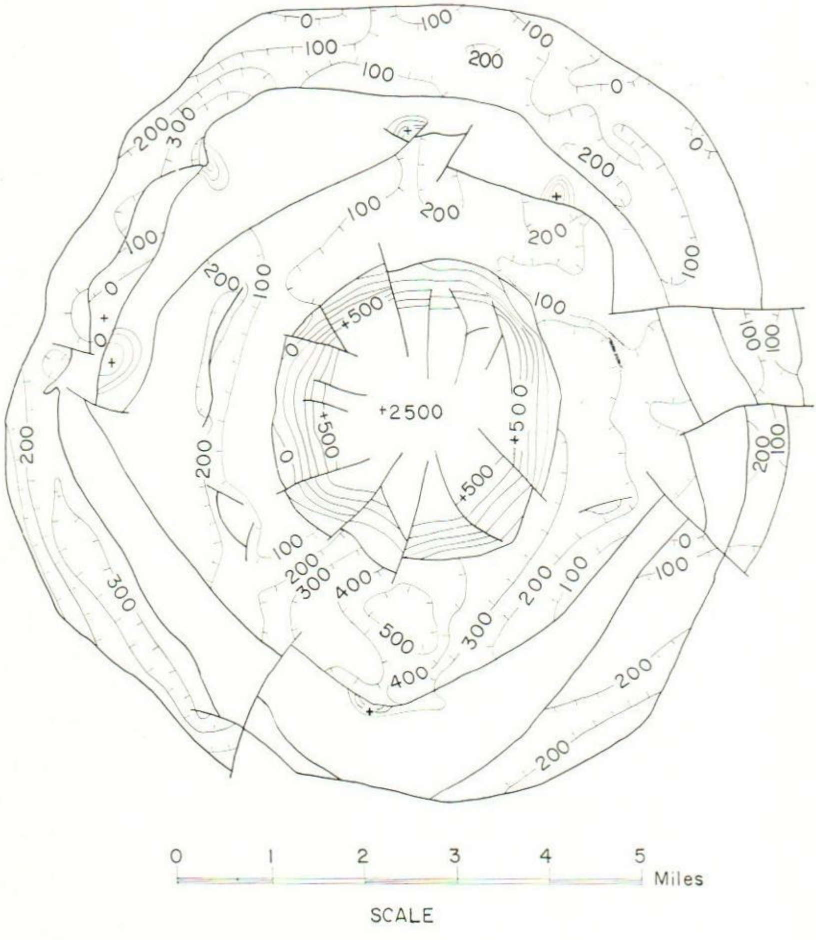

FIGURE 25.—Residual structure contour map showing vertical movement due to the Wells Creek cryptoexplosive event (downward unless marked "+"). This map is constructed by subtracting figure 24 from figure 11.

Vertical Movements Due to the Wells Creek Event

(Fig. 25)

The shift of the top of the Fort Payne due to the event is constructed by subtracting the contours on figure 24 from those on figure 11. Where figures 11 and 24 coincide, in the areas judged to be in their original vertical position, figure 25 shows zero movement. Elsewhere, the movement is down in the grabens, up in the central block, and up in the five anomalous areas in the horst where the Chattanooga Shale is exposed.

The outer graben has been lowered an average of about 200 feet, from 0 to 250 feet around the east half and as much as 350 feet around the west half. Generally the inner graben is lowered from 100 to 250 feet except at the south-center, where it has been dropped about 550 feet; the average amount of lowering is about 200 feet.

About half a mile inward from the edge of the central block (the Cumberland City fault), the Fort Payne has been lifted 500 feet all the way around. Farther toward the center, erosion of the Fort Payne, high dips, complex faulting, and megabreccia make the projection meaningless, but it can be concluded that the Knox breccia blocks at the center have been lifted 2,500 feet or more above their normal level.

John M. Kellberg [1] of the Tennessee Valley Authority suggested that there is a volume-balance between the uplift of the central block and the downsinking of the grabens.

To test Kellberg's idea the top of the Fort Payne Formation was used as a datum, and the following assumptions were made: (1) the volume of graben downsinking is equal to the volume of rock necessary to "fill up" the grabens to the general level of the top of the Fort Payne; and (2) the volume of uplift is equal to the volume of Fort Payne and older rocks raised above the normal level of the top of the Fort Payne. In other words, if it is assumed that all post-Fort Payne rock has been removed and that all Fort Payne and older rock has been preserved from erosion, and that the grabens are topographic depressions and the central uplift is a topographic hill; then the hypothesis is that by beveling the rock

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[1] Personal communication, in connection with a paper presented to the Southeastern Section, Geological Society of America, at Chapel Hill, North Carolina, in 1959.

from the hill and using it to fill the ring depressions the top of the Fort Payne would be leveled off.

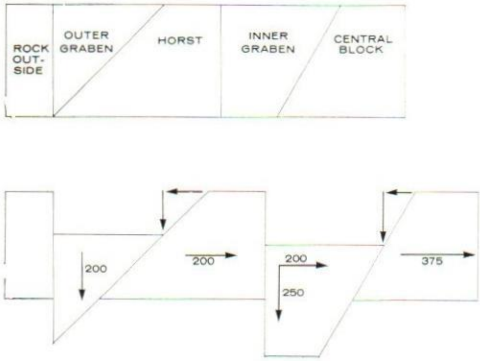
The Fort Payne top is used because a relatively accurate estimate for graben downsinking below this datum can be obtained from figure 25. Because the volume of rock raised and eroded over the crater must be estimated, it is less accurate than the measured volume of downsinking. Because the uplift of the structure is 2,500 feet (minimum estimate), the Fort Payne was projected 2,500 feet above its normal level.

Approximately 1.8×10^{11} cubic feet of post-Fort Payne rock is calculated to have been dropped down in the grabens below the level of the top of the Fort Payne. An estimated 2×10^{11} cubic feet of Fort Payne and older rock has been lifted above the normal level of the top of the Fort Payne. The calculated uplift is 10 percent more than the downsinking, but the technique of projection was an estimate of the maximum uplift drawn with a flat top rather than rounded, so that actual uplift was probably somewhat less, and likely equal to downsinking.

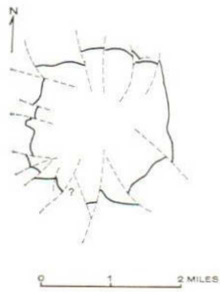
The volumetric balance between uplift and grabens is consistent with the geophysical evidence that suggests no intrusion at depth or uplift of basement rocks. It is also consistent with the theory that near-surface uplift is related to lateral movement of rock, which opened the ring cracks to permit downdropping (as will be described later).

Relative Movements

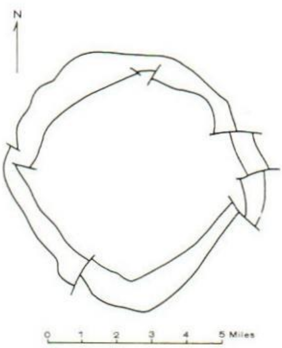
Along the vertical Erin fault (outer limit of the structure) rocks of the outer graben have only slid downward (fig. 26). Adjacent to the horst at the inner edge of the outer graben the rocks of the graben slid outward and down relative to foot-wall rocks of the horst, which underlies the outer graben at depth. The rocks of the inner graben, next inside the horst, have slid vertically downward relative to the horst along the Marable Hollow fault; and along the Cumberland City fault rocks of the inner graben have slid outward and downward relative to foot-wall rocks of the central block. Inside the central block, which includes Wells Creek Basin, outward dipping inbricate thrust faults occur; uppermost Ordovician and Silurian rocks of the hanging wall have moved inward and upward relative to Stones River and Knox at the center of the



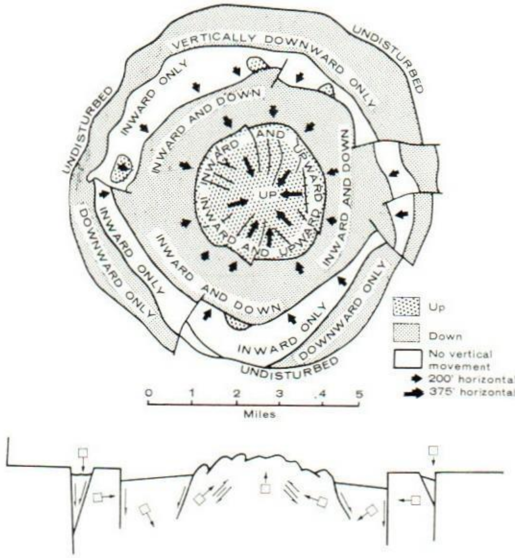
(a) Relative and inferred absolute movement of rocks of the grabens, horst, and central block. Relative movements are shown by arrows above blocks, absolute movements by arrows inside blocks.



(b) Map of outcropping Brassfield Limestone. This appears to be a circle collapsed inward about 240 feet.



(c) Map of horst ring. This appears to have collapsed inward about 250 feet.



(d) Map and cross section showing inferred absolute movements.

FIGURE 26.—Rock movements of the Wells Creek structure; (a), as inferred from cross sections of grabens; (b) and (c), as inferred from plan view of apparent collapsed ring structure; and (d), combined interpretation.

basin. These are all relative movements, and absolute movements cannot be determined directly from these relationships, although they must be taken into account in the following interpretation of absolute movements.

Absolute Movements

Absolute movements are inferred from three types of information: (1) the basic concept is that rocks outside the structure are unmoved, so that movement was confined to the inside of the structure itself; (2) apparent shortening of circular arcs can be used to calculate absolute lateral (radial) movements; and (3) movements relative to (1) or (2) become absolute movement.

These three concepts lead to the following conclusions about the rock near the top of the Fort Payne Formation (fig. 26a):

(1) rock of the outer graben has been dropped about 200 feet,

(2) rock of the horst has moved inward about 200 feet to accommodate the downdipping rock "wedge" of the outer graben with no vertical displacement recognized,

(3) rock of the inner graben has moved both 200 feet inward with the horst and 250 feet downward,

(4) rock at the outer edge of the central block has moved inward about 375 feet and upward, this despite the presence of a plug of Knox which appears to have pushed outward, and

(5) younger rock of the central block moved inward more than the older rock of the same block. This is shown by outward-dipping thrusts, where younger rocks have moved inward. By implication lateral movement of all the elements probably diminishes at depth.

ABSOLUTE LATERAL MOVEMENT BASED ON SHORTENING OF CIRCULAR ARCS

Inward Movement of the Brassfield Limestone Within the Central Block.—Many of the radial faults are not precisely radial to the structure but are oblique instead. In places the movement is such that, when viewed in a true radial direction from the center of the basin, the Brassfield Limestone in front of a fault overlaps, or is duplicated by, the Brassfield beyond the fault, and in a few places there is a gap between a formerly continuous belt of this limestone. The amount of such overlap, or duplication, less the amount of "gapping" around the perimeter is the minimum amount of net collapse of an original circle of rock that moved toward the center and broke along the radial faults. Wrinkling and overlap along small concealed faults would increase this figure somewhat. The net overlap is estimated to be 1,500 feet, and a resulting 240 feet of inward movement is calculated. The decrease in radius so that the circumference of a circle is reduced 1,500 feet is 1,500 divided by 2π, or about 240 feet (fig. 26b).

Thus, we infer that outcropping Brassfield strata around Wells Creek Basin have moved *inward* about 240 feet. It also should be noted that, because of the imbricated thrusts, younger strata have moved inward even more (in a later section of this chapter we conclude that rocks near the top of the Fort Payne Formation have moved inward 325 feet). Also, they have moved upward more than 500 feet as can be measured directly from their uplifted position relative to their normal position near sea level.

Inward Movement of the Horst.—The inward movement of the annular horst can be estimated by using a technique similar to that applied to the Brassfield. This is done by assuming that the Marable Hollow fault, bounding the inside of the horst, was once a continuous, almost circular fracture later offset by radial faults. Because some of these radial faults are oblique, as in the case of the Brassfield, offset has resulted in both overlap and "gapping" when segments of the Marable Hollow fault are viewed simultaneously across the oblique faults from the center of the structure. This technique is less accurate than the measurements of Brassfield overlap, because concealment by alluvium and soil has resulted in less information on the oblique faults of the horst (fig. 26c).

Collapsing ring interpretation for the horst has a more questionable foundation than the Brassfield movement. There is no necessity for the Marable Hollow fault to have ever been a continuous circular fracture; the reasoning applies, however, as long as radial offsets in the original fault neither overlapped nor gapped.

Measurements indicate that the horst has moved inward about 250 feet, the net shortening (overlap) is estimated to be about 1,600 feet (i.e., $250 = \frac{1{,}600)}{2\pi}$. This can be independently checked by remembering that the Erin fault is vertical and the observed outward dips of the Brownsville fault average about 45°. If the rock outside the Erin fault is unmoved (as it is), as the horst moved inward the rock in the outer graben would have dropped down by the amount of the inward movement of the horst. This averages about 200 feet, which is reasonably consistent with the 250-foot estimate based on assumed constriction (collapsing) of the Marable Hollow fault ring.

Inward movement of the horst without general upward movement was accomplished in two ways: (1) by oblique faulting and (2) by buckling in the five anomalous spots, which are marked by inliers of Devonian rock surrounded by Mississippian rocks.

ABSOLUTE LATERAL MOVEMENT BASED ON RELATIVE MOVEMENTS IN RELATION TO KNOWN MOVEMENT

Lateral and Vertical Movement of Rocks of the Outer Graben (Fig. 26d).—If it is a valid conclusion that the horst has moved inward whereas rock outside the structure is unmoved, then the rocks of the outer graben have had no net *horizontal* movement. As the horst moved inward, this graben either slid directly down along the Erin (outermost) fault as the horst moved inward, or it first moved inward as part of the horst and later sheared off and slid outward and downward along the outward-dipping Brownsville fault until it struck against the rocks outside the structure. We prefer this second alternative because of our hypothesis of dynamic events associated with a meteor impact.

Lateral and Vertical Movement of Rocks of the Horst.—Although it has been inferred that rocks of the horst have had no appreciable vertical movement, they must have moved laterally 200 feet or so to accommodate the dropped ring wedge of the outer graben. Also, about 250 feet of movement has been inferred by considering the horst to be a collapsed ring.

Lateral and Vertical Movement of Rocks of the Inner Graben.—Because the Marable Hollow fault inside the horst is nearly vertical, the rocks of the inner graben must have moved inward with the horst. In addition, rocks of the inner graben have moved vertically downward as shown on figure 25. Thus, the rocks of the inner graben moved inward and downward; inward a net of 200 feet or so with the horst and downward an average of 250 feet. Rocks of the inner graben also might have had a more complicated movement, going inward farther with the central block and then shearing off to slide back outward and downward against the horst.

Again we prefer this second alternative in relation to a meteor-impact origin. Additionally, tangential crushing must have occurred, if the inner graben had the calculated 1,500 to 2,000 feet of tangential shortening.

Movements of Rocks of the Central Block.—The inner graben represents rock fallen down into a gap where the central block and the horst have moved *relatively* away from each other; in other words, the horst moved inward toward the central block, but the central block must have moved inward even more. We cannot measure shortening of the assumed original circular perimeter of the central block as we did for the horst because of poor exposures. However, we can estimate it by using fault attitudes to calculate heave adjacent to rocks of the inner graben and by using fault attitudes and known throw adjacent to the outer graben as we did for the horst. The Marable Hollow fault appears to be approximately vertical and the Cumberland City fault dips outward from 45° to 70°; an average of 60° was used for calculations. Therefore, the amount by which the central block moved inward and upward away from the horst to form the space in which to drop rocks of the inner graben (ignoring circularity) is about half the vertical movement of rocks in the graben (average of 250 feet). This is an *extra* movement inward of about 125 feet in addition to the 200 feet it moved inward with the horst.

Thus it can be estimated that the outer perimeter of the central block has moved inward about 325 feet. This also implies a tangential shortening around its edge of about 2,000 feet.

This 325 feet of inward movement at the perimeter of the central block is consistent with the conclusion that movement greater than 250 feet occurred for the Brassfield inside the central block in Wells Creek Basin. Also, there was an upward movement greater than 500 feet, as shown on figure 25.

CONSEQUENCES OF THE INWARD MOVEMENT

The inward- and upward-moving mass of material either moved into a crater already excavated through Mississippian-Silurian and probably upper Ordovician rock, or, alternatively, it formed a sizable mound of jumbled rock (no crater necessary). That there was inward movement is clear from many lines of evidence. That this inward movement was cumulative from the edge inward is also clear. The cause of this unusual structural pattern, however, is not clear.

STRUCTURAL FABRIC

(*with* Sam M. Puryear)

INTRODUCTION

Even though the Wells Creek structure is approximately circular in outline, it has marked deviation from perfect radial and concentric symmetry. Concentric faults, which might be expected to curve everywhere, are straight for considerable parts of their circumferences. Radial faults, which might all be expected to diverge from each other, have many examples of parallelism. For example, on figure 9 (the fault map) the outer circular Erin fault at the north edge of the structure trends straight east-west; nearly parallel to this straight portion of the concentric fault are several radial faults; the north Schmid fault, the two Scott faults, the Hollister Branch fault, and two unnamed faults near the west perimeter. The north-northeast trends of the Spring Branch, Carter Hollow, Dolomite, Steele Ridge, and Willsons Branch radial faults are approximately parallel to nearly straight portions of the Erin, Brownsville, and Marable Hollow faults in the southeastern part of the structure. These are related to dominant joint trends predating the structure. Shoemaker (1959, p. 12) found similar control by joints at Meteor Crater, Arizona.

Stereograms and rose diagrams are used to compare data from many localities. These diagrams have the advantage of permitting direct nongeographic compilation and comparison of data.

In disturbed areas such features as fault trends, bedding orientations, and joint trends are compared. Each of these features demonstrates strongly "preferred" orientations that can be related to pre-existing joints.

For more detailed and statistical information on the fault and joint trends of this area the reader is referred to a Master's Thesis by Sam M. Puryear (Vanderbilt University, 1968).

FAULT TRENDS

(Fig. 27)

Strike measurements of the radial faults were taken to coincide with, or be tangent to, faults at 2-inch intervals from a structure map having a scale of 1:24,000. As corroboration of results obtained by this measurement technique, measurements also were taken without regard to length of the faults, and two strike measurements were taken on faults that curve appreciably. Both give similar patterns, so that only the results of the first technique are illustrated (fig. 27). Similar techniques were used to measure the strikes of the concentric faults. The results indicate a relationship between the regional joint system and the strike of faults. The faults, both radial and concentric, were preferentially formed parallel to the existing joint sets in the area.

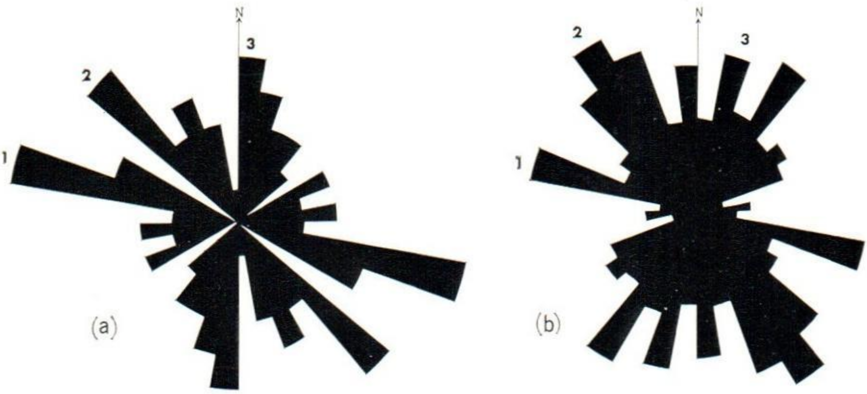


FIGURE 27.—Rose diagrams showing strikes of (a) radial faults and (b) concentric faults.

The rose diagram of the strikes of radial faults (fig. 27a) shows three maxima: (1) slightly north of west, (2) N.30°W.-N.50°W., and (3) slightly east of north. For concentric faults, the rose diagram (fig. 27b) also shows (1) and (2), but (3) is not clearly defined. Because all strikes must be represented in any system of circular faults, the conspicuous minimum of N.70°E.-N.110°E. is anomalous.

The structure demonstrates a pattern, especially the Marable

Hollow fault, which is "squarish" in shape (fig. 9). The two major joint sets in the area parallel the diagonals of this square. Shoemaker (1959, p. 12) found similar joint control of shape of the crater rim at Meteor Crater.

BEDDING ORIENTATION

(Figs. 28, 29, 30, and 31)

Figure 28 is a preferred orientation diagram prepared from dip and strike measurements of bedding planes taken from the entire structure. These were converted to poles where Φ is the dip direction measured around the net outer circle and ρ is the dip measured from the center of the circle.

FIGURE 28.—Preferred orientation diagram showing the fabric of 1027 poles to bedding in all parts of the Wells Creek structure. Contours on this figure and figures 29, 30, and 31 are percent of poles that fall within 1 percent of the area of the net, as is standard for contouring such plots.

A surprisingly strong threefold fabric of poles is concentrated (a) slightly east of north and west of south (equivalent to a strike approximately east-west); (b) slightly north of west and south of east (equivalent to a north-northeast strike); and (c) at N.40°E. and S.40°W. (equivalent to a northwest strike). These bedding trends correspond to fault trends (1), (2), and (3), respectively, as described above; the strike is 90° away from the pole map direction Φ. The maximum near the center shows nearly flat beds scattered throughout the structure.

Figure 29 is based on data from the central core area of megabreccia. The fabric of figure 28 is also evident here. Comparison shows that the megabreccia blocks are not as randomly oriented as they appear to be. Rather, even the bedding within the blocks strikes preferentially parallel to exterior fault trends. Dip is steep.

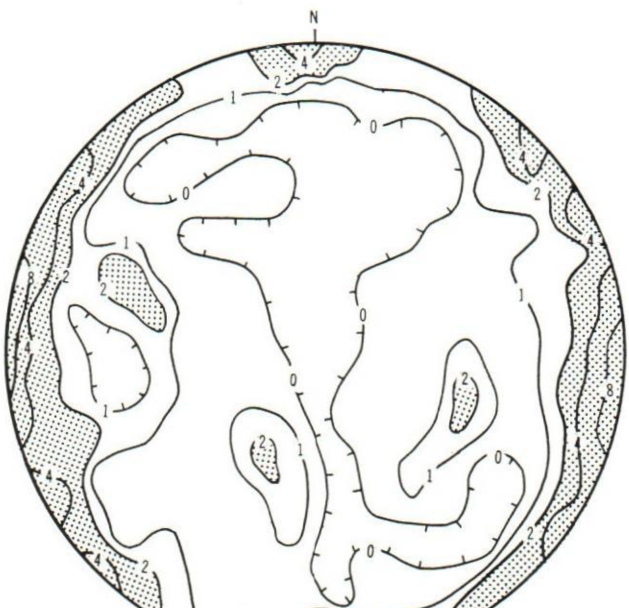


FIGURE 29.—Preferred orientation diagram showing the fabric of 309 poles to bedding in the outcrop area of Knox and Stones River Groups, mainly in the central megabreccia zone in Wells Creek Basin.

Figure 30 shows the fabric of bedding of Ordovician, Silurian, and Devonian strata inside the central block but outside the megabreccia area, where the rocks are broken into discrete fault blocks. Here, also, strike is parallel to the exterior fault trends.

FIGURE 30.—Preferred orientation diagram showing the fabric of 328 poles to bedding in the Ordovician, Silurian, and Devonian rocks outside the megabreccia zone in Wells Creek Basin.

Figure 31 shows the fabric of bedding in the grabens and horst. Strike is less generally parallel to faults.

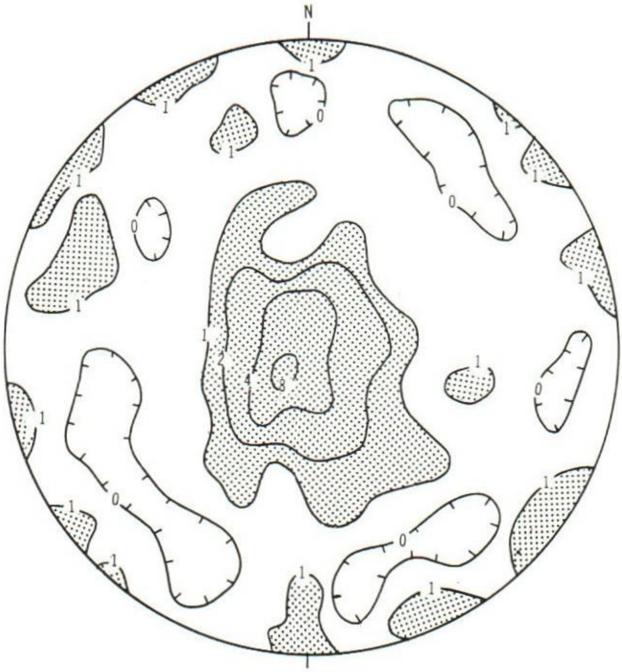


FIGURE 31.—Preferred orientation diagram showing the fabric of 387 poles to bedding in the grabens and horst outside the central block of the Wells Creek structure.

JOINTING

Joint measurements were taken as exposures permitted inside a circular area 20 miles in diameter, centered over the Wells Creek structure. Approximately 2,360 joints were measured at 114 localities. Formations in which joints were measured include the St. Louis, Warsaw, and Ft. Payne of Mississippian age and the Lego and Decatur Limestones of Silurian age.

Outside the structure 1,862 joints were measured at 97 exposures (fig. 32). On the rose diagram (fig. 33a) two directions dominate—a maximum slightly north of west, which corresponds to trend (1) for faults (fig. 27) and (a) for bedding (fig. 29); a maximum slightly east of north, which corresponds to trend (3) for faults (fig. 27) and (c) for bedding (fig. 29).

The 498 dip-restored joints measured inside the structure were

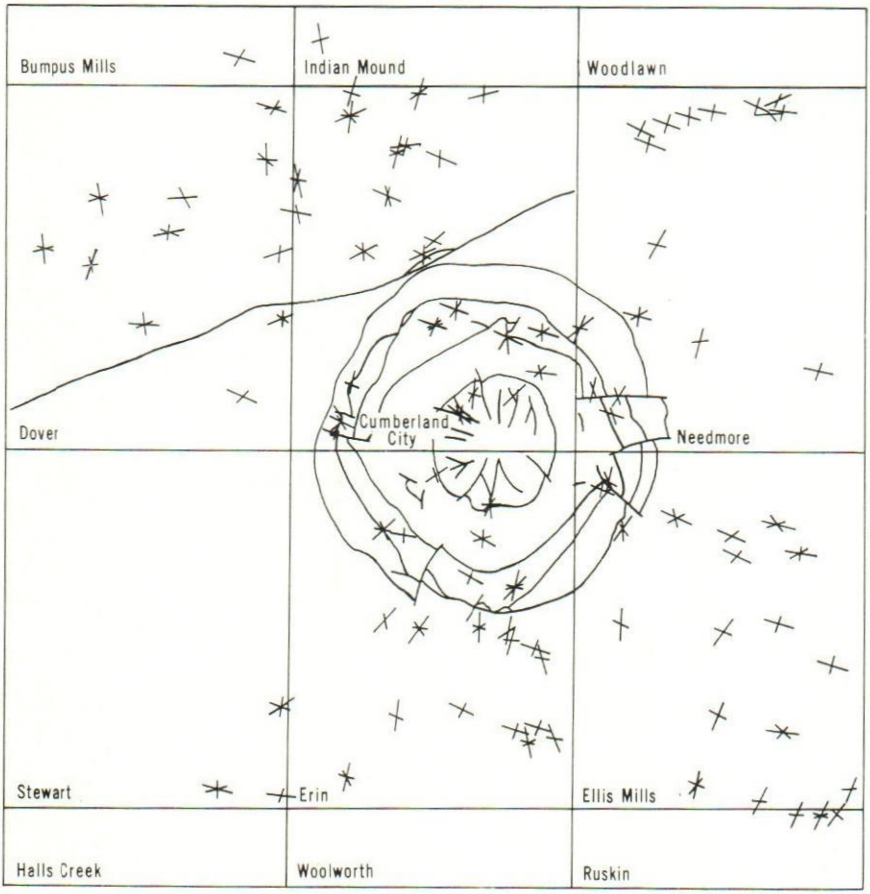


FIGURE 32.—Map showing joint trends in and near the Wells Creek structure.

taken at 17 exposures of tilted Mississippian and Silurian strata. This was done to compare the joint sets in dipping rocks inside the structure with "undisturbed" joint sets outside the structure.

Joint strike measurements taken inside the structure were corrected for dip by rotating associated bedding through the smallest angle to make bedding horizontal (as also was done to restore shatter cones to their inferred original orientation). The resultant joint strikes are shown plotted on figure 33b. The dominant joint trends inside the structure are parallel to those outside

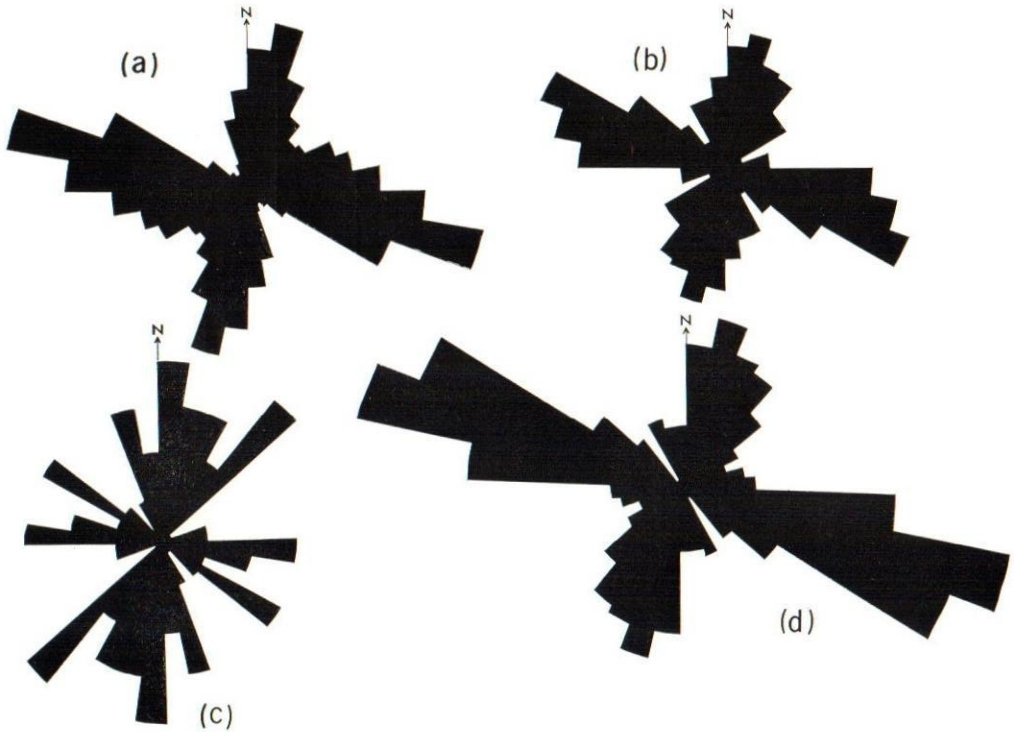


FIGURE 33.—Rose diagrams showing strikes of joints—(a) 1642 joints measured outside Wells Creek structure; (b) 496 restored joints measured in dipping Mississippian rocks inside Wells Creek structure; (c) 34 restored joints measured in dipping Ordovician and Silurian rocks inside the basin; and (d) 239 joints measured inside the horst.

the structure and to those in the horst. Because dip-corrected strikes of these tilted joints are parallel to the vertical joints outside the structure, we infer that the tilted joints existed before deformation and were tilted by the Wells Creek event. Because the joint system predated the structure and because many faults and bedding strikes are parallel to them, the joints clearly influenced fault trends and strike directions of appreciably tilted beds.

Joints in Mississippian rocks explain two-thirds of the fabric. The N.30°-50°W. trends, (2) of faults and (b) of bedding, are not parallel to preferential joint trends in Mississippian rocks. Probably these northwest trends are related to some "grain" in pre-Mississippian rocks, perhaps buried joints, as suggested by the limited data on such joints (fig. 33c).

CONCLUSIONS

(1) There are two main joint sets in the Wells Creek area (approximately N.10°E. and N.85°W.) that predominate outside of and throughout the structure.

(2) This joint system existed prior to the Wells Creek event and was not influenced by this structural event. Joints, whether measured in horizontal or tilted strata, are essentially perpendicular to bedding. Tilted joints were tilted with the beds.

(3) The dip-corrected strike trends of joints measured in tilted strata inside the structure are identical to the dominant joint strike trends measured in flat-lying beds inside the structure. They are also the same as the joint strike trends measured outside the structure.

(4) The pre-existing joint system relates closely to and probably controlled the deformation at Wells Creek on both large and small scales. The radial faults preferentially strike parallel to the two dominant joint sets in the area. The main concentric faults also show a relationship, though not quite as strong, to the regional joint system. The shape of the Marable Hollow concentric fault is "squarish". The joint sets parallel the diagonals of this square. At smaller scales, the strike of bedding in strongly disturbed portions of the structure is preferentially parallel to joint strikes, even in the central megabreccia zone.

(5) The N.30°-50°W. trend of faults and strike of jumbled bedding, which does not coincide with a joint trend in Mississippian rocks, perhaps is controlled by buried early Paleozoic joints.

SHATTER CONES

(*with* Phyllis S. Marsh)

INTRODUCTION

Shatter cones are curious striated complex cones that were first described from the Steinheim Basin of Germany (Branca and Fraas, 1905, p. 36-38) as pressure phenomena. Dietz (1960, 1963) concludes that they have been observed only in hard rock at crypto-explosive structures and have only been reproduced experimentally by hypervelocity impact or high explosive shock. This conclusion was questioned by Bucher (1963, p. 631-640), who asserted that shatter cones are not unique. Certainly, his photographs of cone structures in coal from West Virginia (Bucher, 1963, fig. 13a and b, p. 634) do resemble shatter cones.

Shatter cones were first reported in the United States from the Wells Creek structure by Bucher (1936, p. 1070). In this structure all known shatter cones are in the Knox Dolomite (fig. 34). A thorough study of shatter-cone features was undertaken because it was believed that the Wells Creek structure and the cones had a common origin.

All in-situ shatter cones accessible in 1964-65 in Wells Creek Basin were measured. Because shatter cones are so abundantly and favorably exposed here, the shape, size, and relationship to the bedding of the rock in which they occur and to brecciation can be most favorably observed.

The two generally accepted theories for the origin of the Wells Creek structure are that the shock came either from above (by meteor impact) or from below (by subterranean explosion). Because shatter cones are believed to point toward the direction from which shock waves came, it is important that their in-place orientation be observed in the field. Dachille and Ulmer (1964) showed that it is unlikely that a supercritical steam chamber of a reasonable size at moderate depth can generate the energy necessary to form cryptoexplosive structures, particularly without leaving considerable evidence of hydrothermal activity. Therefore, if a subterranean explosion is inferred it must have originated from considerable depth.

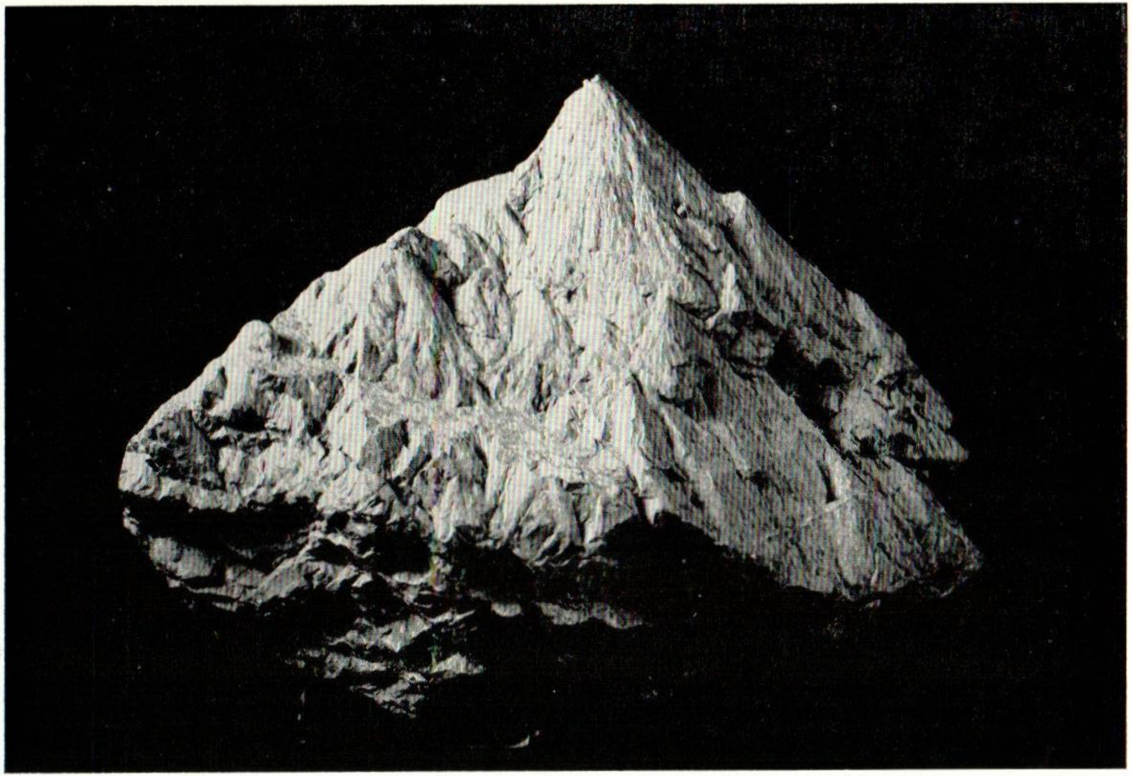


FIGURE 34.—A shatter-cone group collected by the writers and Robert S. Dietz from the Old Quarry on Central Hill. The specimen is about 1 foot high.

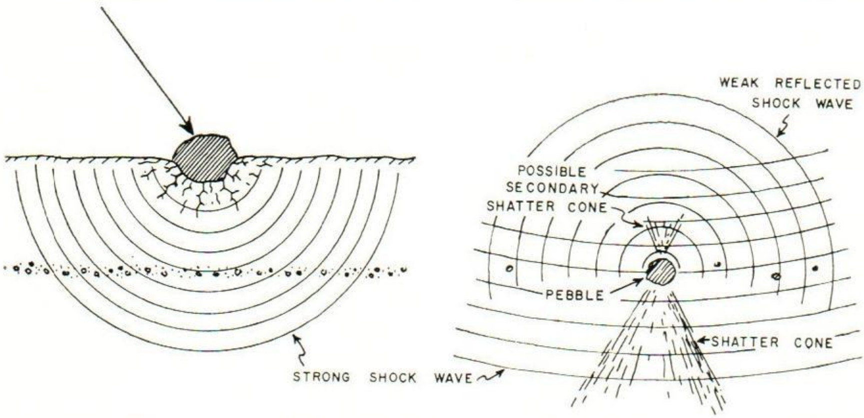
As suggested by Dietz (1959, p. 503) choosing between force from above and force from below would be important in choosing between a meteor or deep-seated single explosion origin for the Wells Creek structure and (by implication) other cryptoexplosive structures. That shatter cones in particular exposures point stratigraphically upward already was shown for the Kentland, Indiana, structure by Dietz (1959, p. 503) and for Crooked Creek, Missouri, by Hendricks (1954, p. 60). Moreover, Manton (1965, p. 1038) has shown that shatter cones in the Vredefort Ring, South Africa, point nearly parallel to bedding and (upon restoration of bedding) point up and toward the center of the structure. At the Wells Creek structure cones point obliquely to bedding at several separated localities, so there is an opportunity here to see whether the cones point in some pattern; and if so, upward or downward, inward or outward?

Results of this study show that if bedding was horizontal when the cones formed, they formed pointing inward and upward. This is consistent with the view that a shock wave radiated in a downward direction from a source above the level of the shatter-cones and the rocks were rotated subsequent to shattering.

A consistent shatter-cone orientation pattern was discovered. It is interesting that this pattern exists despite the facts that (1) the original horizontal position of shattered Knox Dolomite has been shifted by the Wells Creek event; (2) the original stratigraphic positions of these rock masses probably range as much as several hundred feet; and (3) the original source was certainly not a point.

SHATTER CONES AS SHOCK STRUCTURES

Dietz (1963, p. 658) interpreted shatter cones to have formed by high-velocity shock waves coming in contact with some inhomogeneity in the rock to form a cone with the apex (fig. 35) at that point of inhomogeneity (Dietz, 1963; Johnson and Talbot, 1964, p. 21). Dietz further pointed out that such shattering in this manner would have taken place immediately after impact. Our working hypothesis is that cones did form in this way, and that their apices point in the direction from which the first and most intense shock waves came. Secondary cones may point away from "ground zero" but have their apices at the same inhomogeneities, because the shock waves are reflected and move once again back from the inhomogeneities (fig. 35). Such secondary cones are present though uncommon at Wells Creek.



To show the probable effect of a localized discontinuity, such as a pebble, on the development of a shatter cone. The shock wave from a meteorite passes through homogeneous bedrock; a pebble acts as a secondary source at which another shock wave is generated. Interaction causes rarifaction (and hence tension) along a conical surface, producing a shatter cone. Cone axis points toward the on-coming shock wave; reflection can occasionally produce an inverted cone.

FIGURE 35.—Sketch showing the formation of shatter cones (after Dietz, 1963).

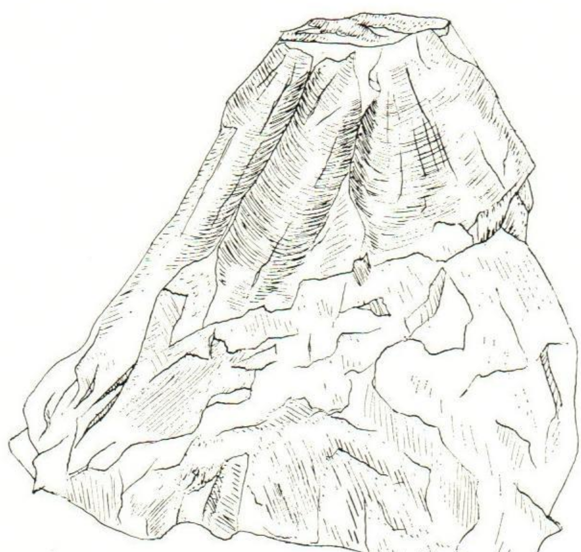


FIGURE 36.—Blast cone showing sharp ridges and rounded concave valleys (drawing by R. A. Miller). Specimen is about 4 inches wide at the base.

Shatter cones superficially resemble blast cones commonly observed at the bottoms of holes drilled for explosives in quarrying and excavation. Two main differences are evident (fig. 36): (1) shatter cones have flutes with convex rounded ridges and sharp "valleys," whereas blast cones are fluted with concave "valleys" and sharp ridges; and (2) shatter cones have an intricate pattern of tributary cones and flutes with striations that branch in horsetail fashion away from the cone apex, whereas blast cones are single with rough surfaces (Dietz, 1959, p. 501 and pl. 1) or plumose markings. Differentiation of these is important because two of the Wells Creek shatter-cone localities are in quarries where blasting has been common.

LOCALITIES IN WELLS CREEK BASIN

(Fig. 37)

Curiously, all known shatter-cone localities are in the southern part of the Knox outcrop area. In 1936 Bucher reported shatter cones in a rock pavement of Knox Dolomite just south of the "Old Quarry" on Central Hill. Many fine shatter cones were collected in this quarry, locality 1 (fig. 37). This quarry was opened in about 1950 and soon was abandoned.

In 1959 Robert Dietz and the writers visited the area and discovered cones where the quarry of Road Materials, Inc., is now located (locality 2). At that time the quarry was only a small excavation, but it is now much larger.

Locality 3 is in a dry stream bed on Central Hill about 500 feet west-northwest of the old quarry.

Two more shatter-cone areas were found when all areas of Knox outcrop in the center of the structure were visited by Phyllis S. Marsh and student assistants. Locality 4 is on the flank of Central Hill about 1,000 feet northwest of the old quarry and about 500 feet north of locality 3. Locality 5 is about 1,500 feet east-southeast of the old quarry, on the east end of Central Hill and southwest of an abandoned house. All other exposures of the Knox at Wells Creek were searched and some even broken with a sledge hammer, but no more shatter cones were found.

Apical angles and orientations of 886 in-situ cones were measured. These were distributed as follows:

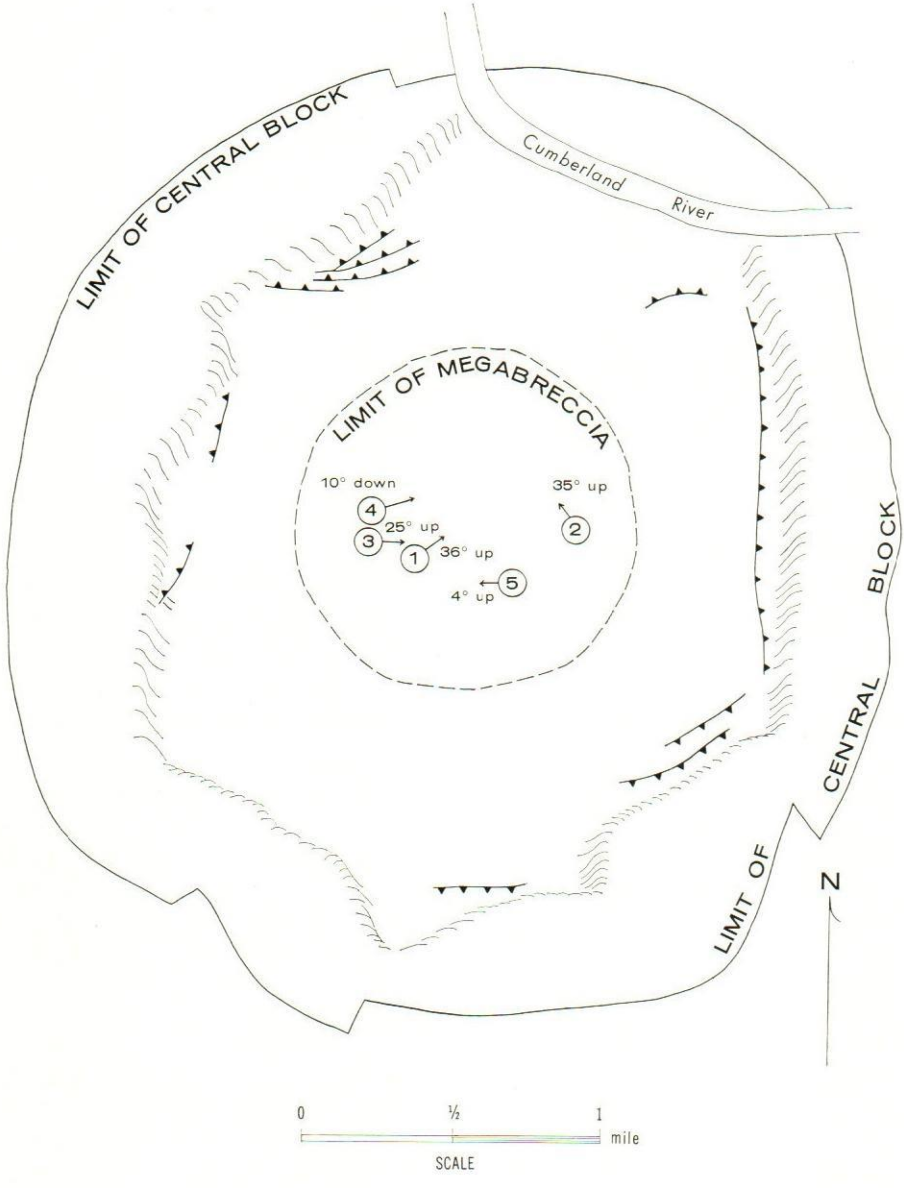


FIGURE 37.—Shatter-cone localities in the central block portion of the Wells Creek structure, showing average azimuth and inclination of restored shatter-cone axes. Note outward-dipping thrust faults.

TABLE 3.—*Number of cones measured at each shatter-cone locality.*

	Number of Cones Measured:	
Locality	Apical angle	Orientation relative to bedding
1—Old Quarry on Central Hill	289	245
2—Road Materials, Inc. Quarry	...	[1] 86
3—Stream on Central Hill	460	331
4—Flank of Central Hill	137	[1] 166
5—Southwest of abandoned house east of Old Quarry	...	[1] 25
Total cones measured	886	853

[1] At locality 2, 86 orientations were estimated visually, but apical angles were not measured. At locality 4, 29 cones were estimated visually, and the rest were measured. At locality 5, 25 orientations were estimated visually, but apical angles were not measured.

DESCRIPTION OF CONE OCCURRENCES

Cones are generally found in dense, fine-grained, unbrecciated or slightly crackle-brecciated dolomite zones or layers between rubble-breccia zones or layers. When hit with a hammer or sledge, the shattered dolomite splits readily along surfaces parallel to obvious cone sides. In the field almost all the cones within a given zone point in the same general direction; also, where cones have curved axes the curvature is always in the same direction.

Where well exposed, cones were seen to occur in layers ranging in thickness from 1 to 5 feet alternating with layers of breccia of about the same thickness. Layers that contain the cones may be filled completely with small cones or may have only a few cones scattered throughout. Cones occurring in a single bed of dolomite have approximately parallel axes. In layers filled with cones, the cones are mostly 1 to 2 inches long. Where cones are scattered, they tend to be larger and incomplete, with nearly flat surfaces, 4 to 5 inches long, curved or twisted, and with only a narrow portion showing. Some bedded clusters of cones at locality 3 curve in unison 10° or more, so that the sharp apex is noticeably bent.

Shatter-cone formation preceded at least some brecciation, because three pieces of cones were found as fragments in rubble breccia at locality 2. That some brecciation preceded shattering can also be demonstrated; one cone in breccia cuts across the breccia-clast fragments and the fine-grained matrix.

The working hypothesis, that shatter-cones were formed by a single shock event, is consistent with the notion that there are at least two ages of brecciation. An early breccia is interpreted to be from solution collapse related to Ordovician post-Knox erosion, as is widely distributed in East Tennessee. Later breccia originated with the Wells Creek event.

TYPES OF CONES

Cones occur alone either straight or with curved portions (fig. 38); in groups with coalescing bases (fig. 34); in series with com-

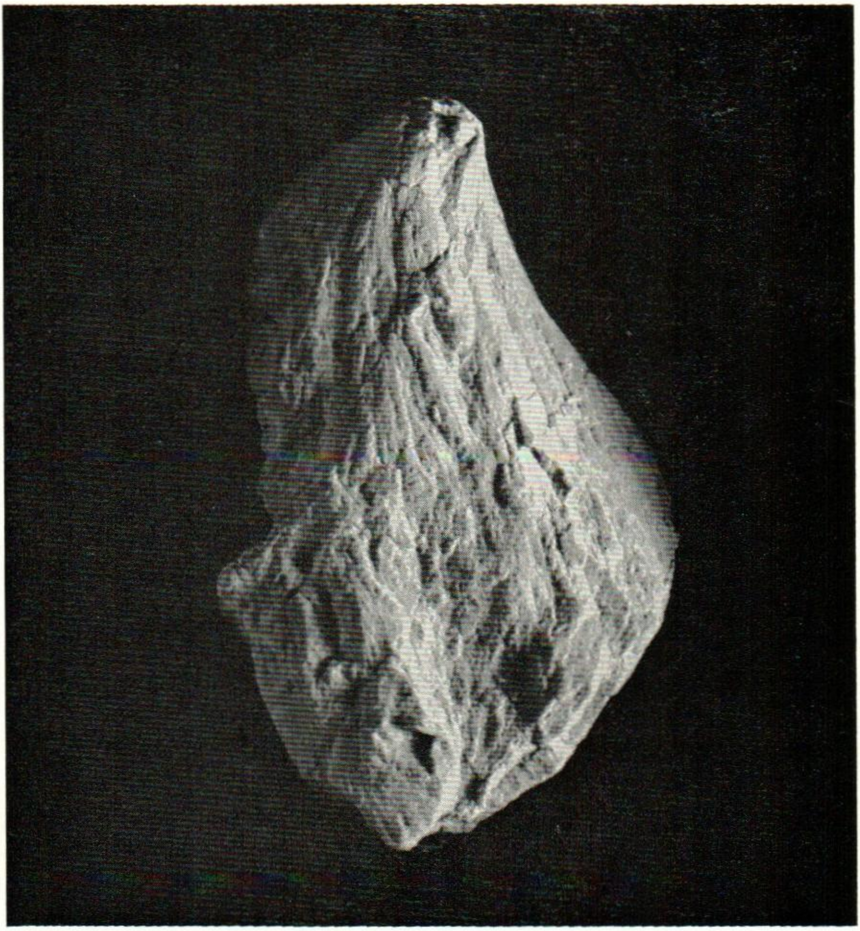


FIGURE 38.—A curved shatter cone from locality 3. Specimen is approximately 2 inches long.

mon axes (fig. 39); as parasitic cone segments (or tributary cones) on larger cones (fig. 40); as incomplete cones; as individual or cone groups with an angle change, sharpest at the apex and increasing away from the apex; and as a "curtain" of cone striations somewhat similar in appearance to stylolites. In a wall of the quarry of Road Materials, Inc. (locality 2) two cones point-to-point with a common axis were observed. These two cones probably are

FIGURE 39.—Two shatter cones with a common axis from locality 1. Specimen is approximately 3 inches long.

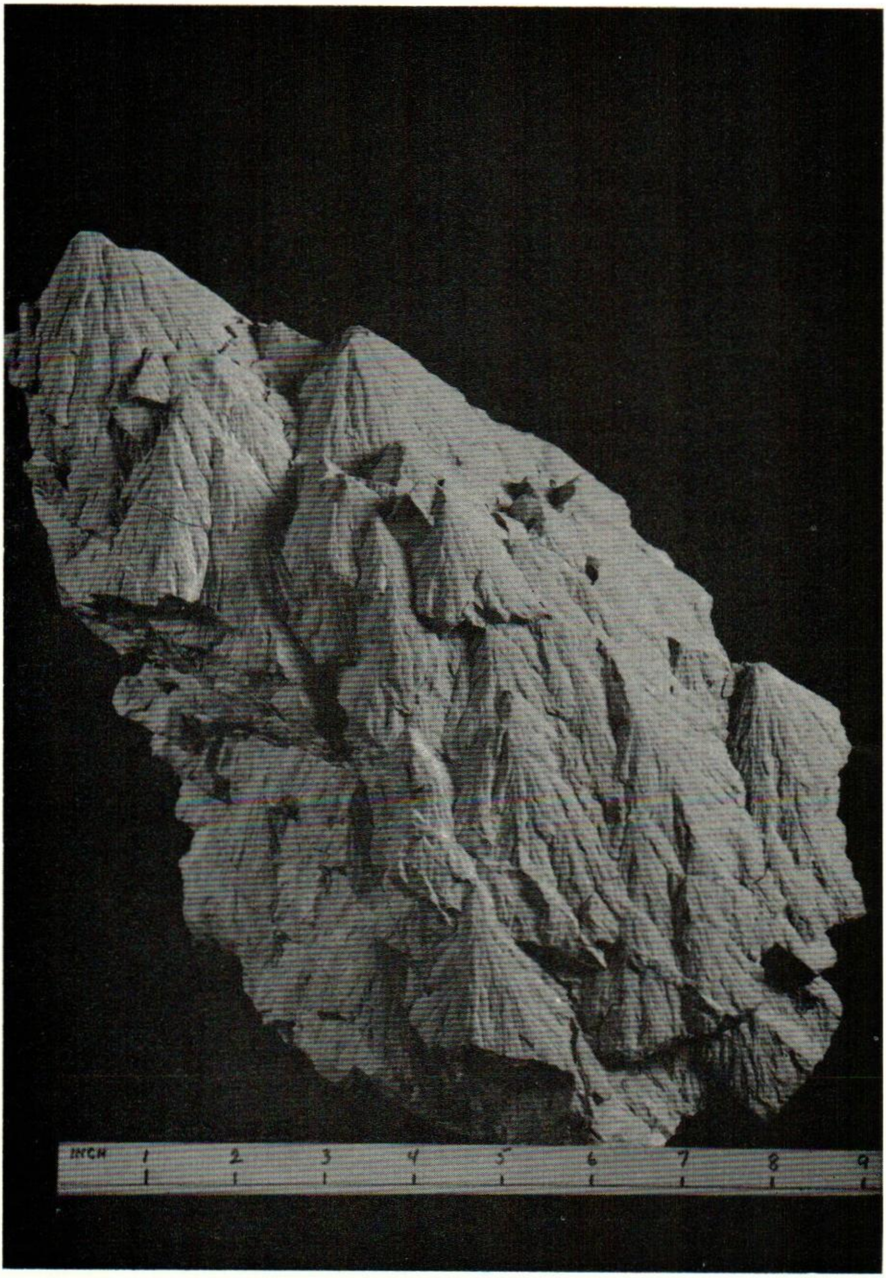


FIGURE 40.—Two main shatter cones with tributary cones.

a primary and a secondary cone (fig. 35). Double cones such as this were predicted by Johnson and Talbot (1964). A double-pointed cone (base-to base) was collected at the old quarry (locality 1).

A single cone actually may be unattached to other cones, or it may be just the common apex of several larger coalescing cones, or an apex of a parasitic cone on a larger one. Single cones were observed to range in length from about ½ inch to about 7 inches and in basal diameter from about ½ inch to 10 inches. Most cones are less than 4 inches long.

The bases of most cones, which are at an axial distance of 2 or more inches from the apex, coalesce with those of one or more other cones (fig. 41). Where cones are thoroughly developed the dolomite has conical cleavage, so that some sections of rock can be broken repeatedly to form different cones parallel to and/or cutting through previously exposed cones.

Cones, particularly those 1 to 2 inches long, may occur in a series 12 inches or so in length, having a common axis.

Parasitic cones show up as individual points or as conic sections on the sides of larger cones (figs. 34 and 40).

The term, cone segment, is used for surfaces that appear to have cone striations, that is, surfaces with radiating striations. Such surfaces tend to be long and narrow and have curved striations.

Several different continuous curved striated surfaces cut across 4 to 5 feet of the floor of the quarry of Road Materials, Inc. There appears to be no measurable change in the orientation of striations. These surfaces may well be small segments of much larger cones that have axial lengths of many feet. Such large cones were observed by Dietz (1959, p. 503 and pl. 5B) in the Kentland, Indiana, structure.

Many single cones have an apical filling of calcite. Theoretically, this was the position of some original inhomogeneity which scattered the shock waves to form a cone. Perhaps calcite-filled vugs were the inhomogeneities in these instances, but it is believed more likely that the crushed material has been replaced or recrystallized there into vugs.

FIGURE 41.—A group of shatter cones partly broken to show conical cleavage and coalescing bases. Specimen collected by R. S. Dietz in 1959.

APICAL ANGLES[1] OF CONES

(Tables 4 and 5, and Fig. 42)

Based on measurement of 886 cones, the following data on apical angles were obtained (fig. 42). Apical angles of cones range from 35° to 85°. The median angle is 56°; 95 percent of the cones have apical angles of 40° to 75°, and about half the angles are 50° to 65°. A few cones were observed at the extreme angle of about 140°. Probably these consist of coalescing cones that individually have much smaller apical angles.

Accurate measurement is difficult where cone angles do not remain the same along the length of the cone. The "apical" angles of many cones increase away from the apex. For example, a cone might be 60° at the apex and 80° 2 inches from the apex. A change of as much as 5° is common. Furthermore, the cones are not always symmetrical. A cone viewed from a "side" might appear to be 60° and from an "end" might appear to be 70°. In other words the cone is actually elliptical in basal section.

The relatively small apical angles are not in accord with the theoretical predictions of 90° for apical angles (Johnson and Talbot, 1964, p. 45), nor do they agree with the 90° to 120° observed by Manton (1965, p. 1021) at the Vredefort Ring. Because observed apical angles range from 34° to 120° with smaller angles observed at Wells Creek and larger angles at Vredefort, it may be possible that the angle is controlled by differences either in material shattered or difference in pressures or speed of shattering.

FIELD MEASUREMENTS OF SHATTER-CONE ORIENTATION

All shatter cones that could be seen readily in the field were studied. The main part of the field study involved measuring four parameters—(1) the azimuth of each shatter-cone axis, actually measured with a compass by "eyeballing" the direction of the crest line of the cone (the crest line is the line that bisects the cone sides when viewed from above, and which is easily followed along striations); (2) the angle of pitch or rise toward the apex of the crest line of each cone as exposed; (3) the apical angle of each cone; and (4) dip and strike of the enclosing bed. Operations 1, 2, and 4 were done with a brunton compass.

[1] The apical angle is the angle (less than 180°) between cone sides that is bisected by the cone axis of symmetry.

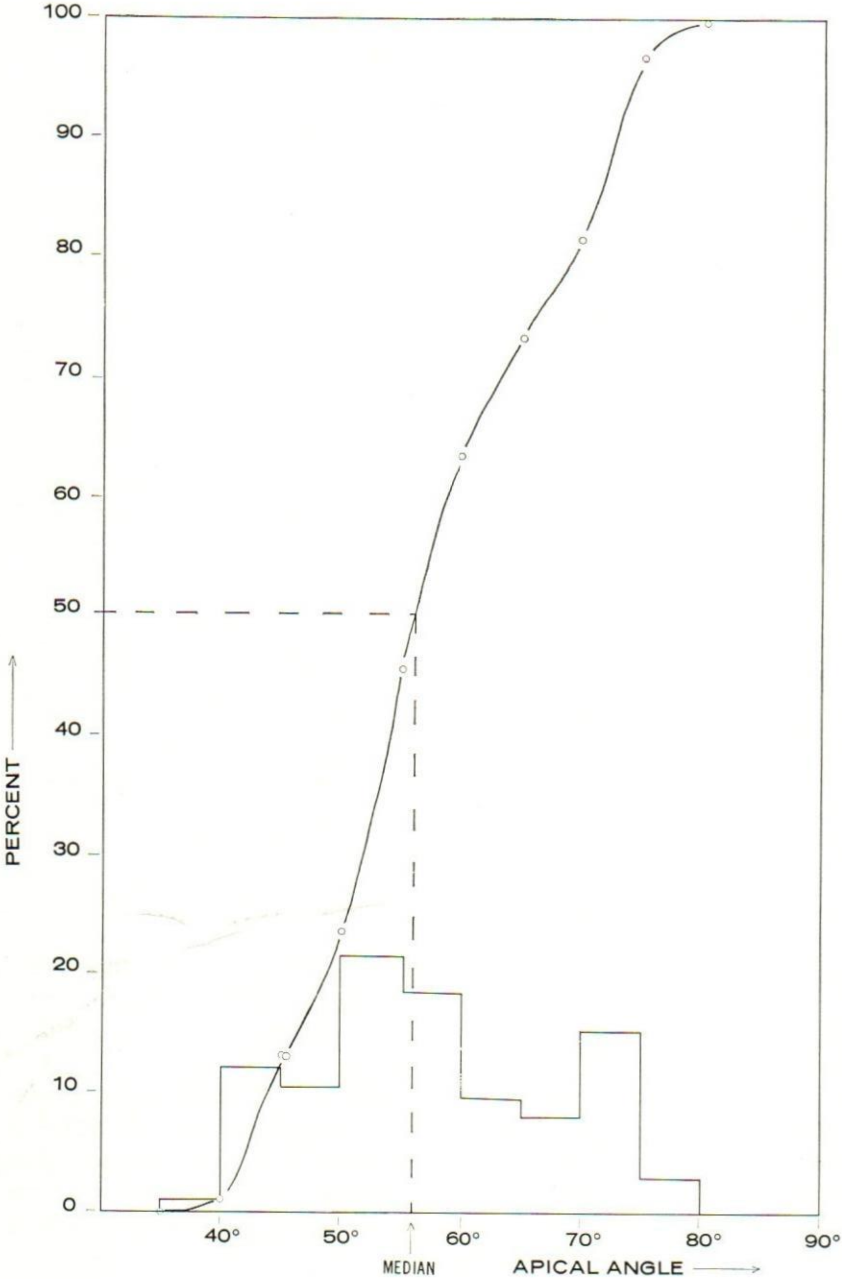


FIGURE 42—Histogram and cumulative curve showing distribution of apical angles of 886 cones.

TABLE 4.—*Apical angles and their percentage distribution in all cones measured (fig. 42).*

Apical Angle[1]	Number of Cones Measured	Percentage of Total Cones Measured	Cumulative Percentage[2]
30°-34°	1	0.1	
35°-39°	9	1.0	1.1
40°-44°	107	12.1	13.2
45°-49°	92	10.4	23.6
50°-54°	193	21.7	45.3
55°-59°	164	18.4	63.7
60°-64°	86	9.7	73.4
65°-69°	71	8.0	81.7
70°-74°	135	15.4	97.8
75°-79°	26	3.0	99.8
80°-84°	2	0.2	100.0
	Total—886		

[1] Larger values are abcissas of points on fig. 42.
[2] Values are ordinates of points on fig. 42.

TABLE 5.—*Shatter-cone apical angles tabulated by locality and apical angle.*

Apical	Locality 1		Locality 3		Locality 4	
Angles	Number	Percentage	Number	Percentage	Number	Percentage
30°-34°	0	0	1	0.2	0	0
35°-39°	3	1	6	1	0	0
40°-44°	64	22	38	8	5	4
45°-49°	25	9	59	13	8	6
50°-54°	87	30	83	18	23	16
55°-59°	62	22	90	19	12	9
60°-64°	32	11	47	10	7	5
65°-69°	11	4	16	3	44	32
70°-74°	2	0.7	108	23	25	18
75°-79°	3	1	12	2	11	8
80°-84°	0	0	0	0	2	1
Total	289	100.7	460	97.2	137	99

Total cones, all localities—886

The apical angle was determined (operation 3) by use of a simple goniometer, made of two straight pieces of cardboard or stiffly folded paper. After the cone angle was measured with the goniometer, the angle was read on a protractor to obtain the cone angle. Particular care was exercised to insure that the full angle was measured. In some locations it was necessary to chip away rock from the apex of a cone to expose at least half of its apex.

Direct clinometer measurement of the inclination of cone axis was impossible for most cones. With measurements of both inclination of the cone crest and apical angle, the inclination of the cone axis was calculated. Calculation involved adding half the apical angle to the angle of rise (taken as a positive angle) or pitch (taken as a negative angle) of a cone crest.

STEREOGRAMS OF SHATTER CONES AND BEDDING

(Figs. 43-48)

If shatter cones were formed by the first shock wave to affect the rock, then the wave probably encountered horizontal beds. This bedding orientation is assumed to have been the case; and it is further assumed that subsequent breaking and tilting of the beds was accomplished without appreciable twisting. By employing these assumptions, we can restore graphically the original orientation of the cones by manipulation of stereonet plots (e.g., Manton, 1965, fig. 15, p. 1033).

The attitudes of shatter-cone axes were plotted as points on stereonets using the directly observed axis azimuths as Φ and calculated axis inclinations as ρ. The attitude of encasing or adjacent bedding was plotted as a great circle on the same net with the encased or adjacent cones. A separate stereo plot was made for each outcrop where shatter cones can be related to recognizable bedding. A total of 26 plots for the 5 localities were made, but only 4 selected nets are shown on figure 43.

At locality 1 (fig. 43), the bedding strikes northeastward and dips steeply northwestward; the shatter cones point upward toward the northwest (shown as circles drawn on the upper hemisphere). One cone in this outcrop points steeply downward toward the southeast (shown as an "x" projected from the lower hemisphere). When the bedding is rotated to horizontal, the plot rolls so that the upper hemisphere rotates toward the east-southeast. This moves the shatter cones so that their restored direction is upward toward the northeast (18 of the cones plotted on fig. 44). The single cone that pointed downward will, upon rotation, have the restored direction downward toward the southwest (also one of the points on fig. 44).

At locality 2 (figs. 43 and 45) the bedding strikes northeastward and dips southeastward. Shatter cones are nearly vertical. Upon

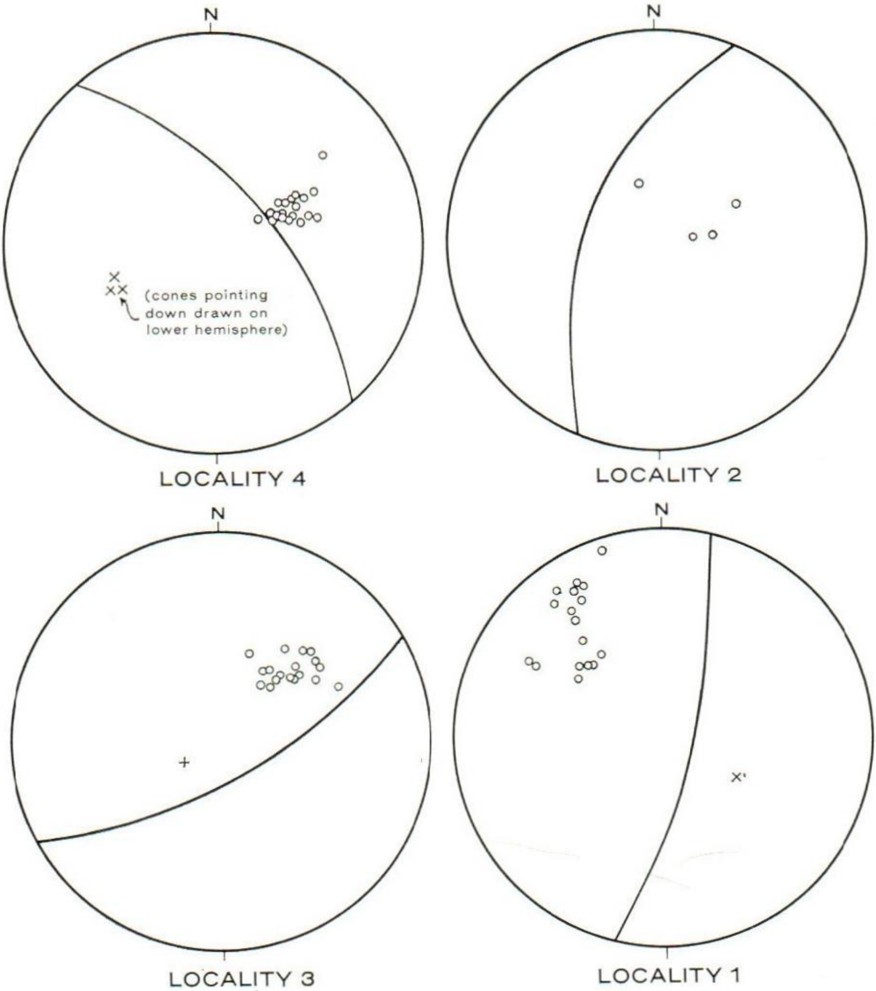


FIGURE 43.—Stereograms of typical individual outcrops showing bedding plotted as great circles on upper hemisphere, cone axis direction toward apices drawn on upper hemisphere.

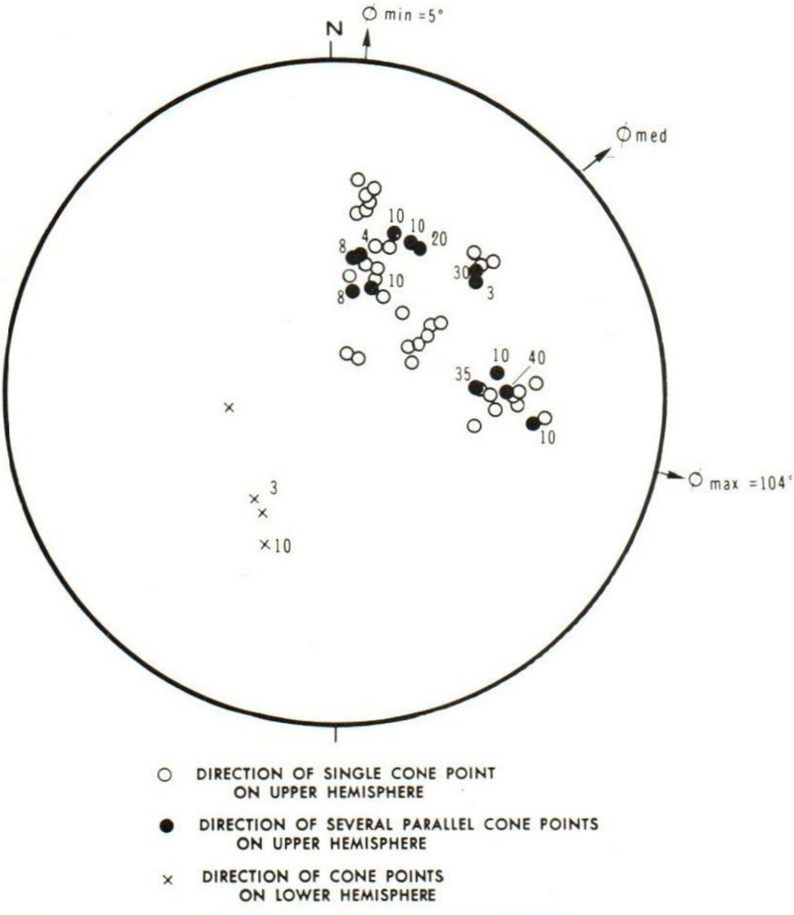


FIGURE 44.—Stereograms showing orientation of 245 shatter cones relative to bedding at 7 outcrops in the Old Quarry (locality 1). Azimuth ranges from 5° to 104°, median 50°; inclination ranges from 76° up to 25° up, median 36° up.

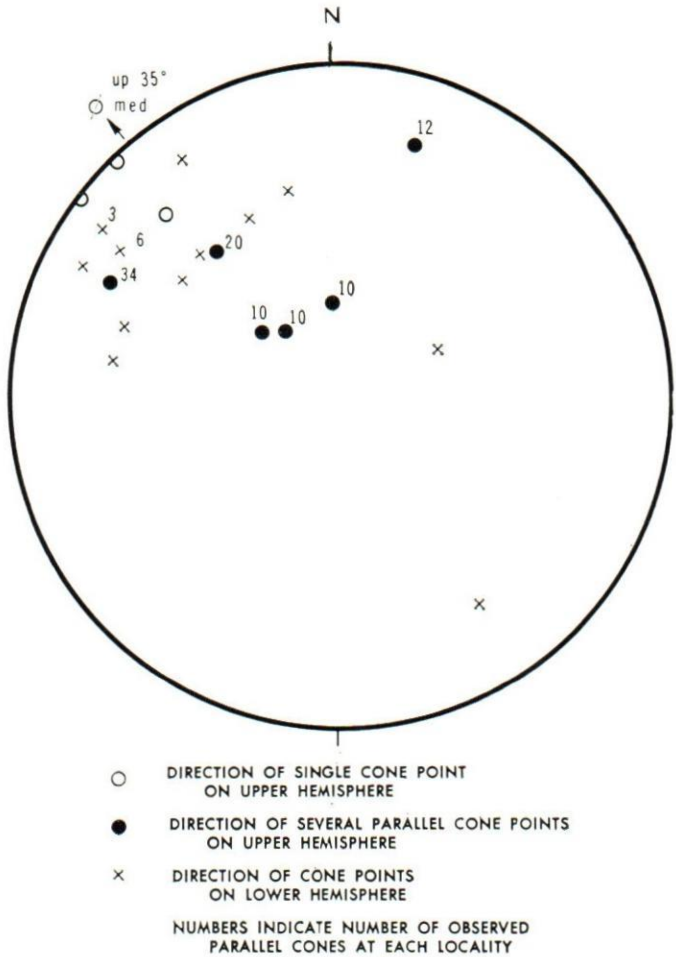
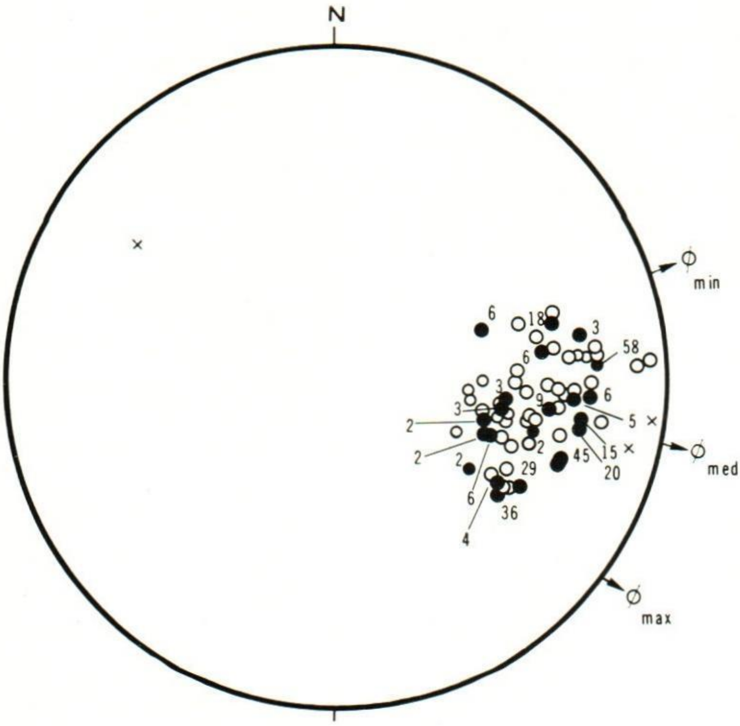


FIGURE 45.—Stereograms showing orientation of 87 shatter cones relative to bedding at 8 outcrops in the Road Materials, Inc. Quarry on Fairgrounds Hill (locality 2). Azimuth ranges from 278° to 17°, median 320°; inclination ranges from 60° up to 30° down, median 35° up.



○ DIRECTION OF SINGLE CONE POINT ON UPPER HEMISPHERE

● DIRECTION OF SEVERAL PARALLEL CONE POINTS ON UPPER HEMISPHERE

× DIRECTION OF CONE POINTS ON LOWER HEMISPHERE

NUMBERS INDICATE NUMBER OF OBSERVED PARALLEL CONES AT EACH LOCALITY

FIGURE 46.—Stereograms showing orientation of 331 shatter cones relative to bedding at 11 outcrops on the west side of Central Hill (locality 3). Azimuth ranges from 72° to 127°, median 103°; inclination ranges from 44° up to 5° down, median 25° up.

rotation the upper hemisphere is rotated toward the northwest. The restored position of the shatter cones is pointing upward at a moderate angle toward the northwest.

At locality 3 (figs. 43 and 46) the bedding strikes northeastward and dips steeply to the northwest. Shatter cones rise steeply to the northeast. Upon rotation of the net the upper hemisphere rotates toward the southeast, and the restored position of the cones rises gently toward the southeast. At locality 3, as at locality 1, one opposite-pointing cone was seen. Its restored direction points downward at a slight angle toward the northwest.

At locality 4 (figs. 43 and 47), the bedding strikes northwestward and dips steeply to the southwest. Shatter cones rise steeply to the northeast. To restore this outcrop the upper hemisphere must be rotated toward the northeast. All but one of the shatter cones, in a restored position, point slightly downward to the northeast. The opposite-pointing cones are plotted with a small "x" to show the position on the lower hemisphere, and upon rotation of the net, rise slightly to the southwest.

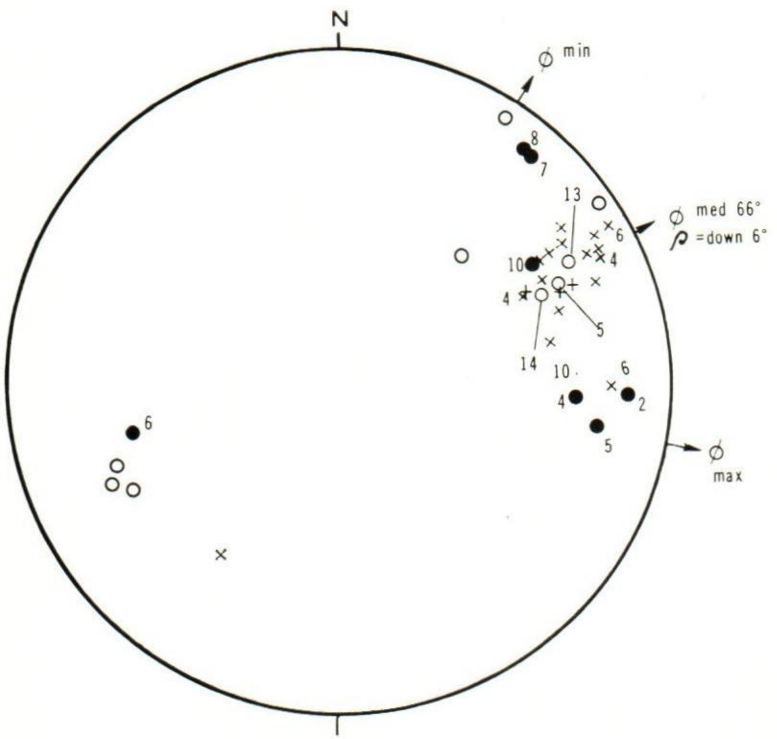
Locality 5 (fig. 48) has few cones and the bedding is vertical. Upon rotation, these point slightly upward and toward the west-northwest.

When the nets are rotated through the minimum angle to make beds horizontal (that is, keeping strike constant), the results are as plotted on figures 44-48. At 4 of the 5 localities, cones point upward, and generally inward. This indicates (assuming shock origin) that the initial shock waves radiated downward and outward from a central source.

In the 2,000 feet of Knox Dolomite core taken from Central Hill in 1947 by the Ordman Company, shatter cones are less abundant, less complete, and more poorly defined with depth. This is also consistent with the interpretation that the shock source was from above and that the intensity of shattering diminishes downward.

INTERPRETATION

The meteor-impact hypothesis is favored by the very presence of shatter cones, as they have been experimentally produced in dolomite only under conditions believed to be highly unlikely in shallow volcanic explosions (Dietz, 1960, p. 1782, for cones de-



○ DIRECTION OF SINGLE CONE POINT ON UPPER HEMISPHERE

● DIRECTION OF SEVERAL PARALLEL CONE POINTS ON UPPER HEMISPHERE

× DIRECTION OF CONE POINT ON LOWER HEMISPHERE

NUMBERS INDICATE NUMBER OF OBSERVED PARALLEL CONES AT EACH LOCALITY

FIGURE 47.—Stereogram showing orientation of 166 shatter cones relative to bedding at 5 outcrops on an excavated rock pavement on the northwest side of Central Hill just south of the Scott House-Central Hill Road (locality 4). Azimuth ranges from 32° to 100°, median 66°; inclination ranges from 33° up to 25° down, median 10° down.

veloped from shock phenomena related to chemical and atomic explosions; and personal communication for cones produced by hypervelocity impact).

Shatter-cone orientation data support the interpretation of a meteorite penetrating from an ancient surface to such a depth that shock waves emanated mainly from near the top of the Knox Dolomite (a position at least 2,000 feet underground at the time). This shatter-cone pattern also may result from an explosion sufficiently violent to create shatter cones at a depth of perhaps as little as 2,000 feet.

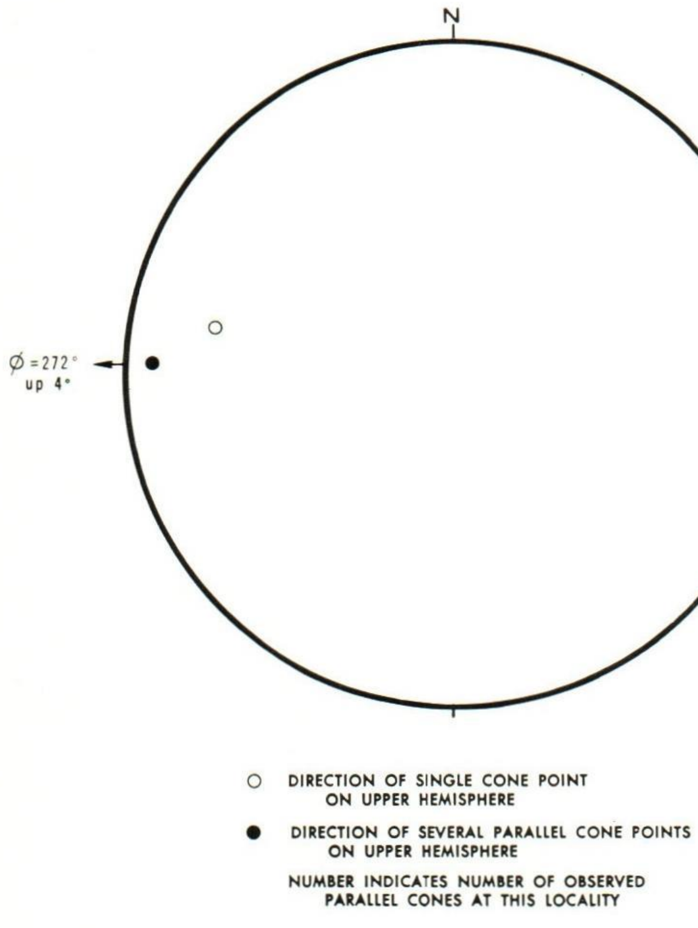


FIGURE 48.—Stereogram showing orientation of 16 shatter cones relative to bedding at 2 outcrops at the abandoned house on the southeast edge of Central Hill (locality 5). Fifteen of the cones are parallel, pointing toward 272°, up 4°.

BRECCIATION

(*with* J. T. Wilcox)

INTRODUCTION

General Statement

The Wells Creek structure has remarkable displays of breccia at its center and adjacent to outer ring faults. Association of this breccia with the structure suggests a common origin. A genetic relationship to the Wells Creek structure is more likely, however, for the breccia in Mississippian rocks (mainly St. Louis Limestone) adjacent to the exterior faults, and in post-Knox Ordovician, Silurian, and Devonian rocks of the basin. Such breccias have not been observed in these rocks where they are exposed elsewhere in Central Tennessee. The Knox, however, is brecciated extensively in East Tennessee and also in the subsurface of Central Tennessee (e.g., in the du Pont Co. disposal well at New Johnsonville, Humphreys County).

Most of the smaller scale breccia in the Knox of Wells Creek Basin is similar in appearance (and much is probably of similar origin) to the breccia in the upper part of the Knox in East Tennessee. The problem at Wells Creek is how much of the breccia is of "sedimentary" (nontectonic) pre-Stones River origin and how much resulted from the Late Mississippian or younger deformative stress that formed the Wells Creek structure. The same problem apparently exists in East Tennessee, except there the later stress was associated with the Appalachian orogeny.

The Knox and locally the Stones River are broken into jumbled "megabreccia" blocks, some as large as hundreds of feet across. This jumbled mass of material (1) is nearly circular in outline, (2) is concentric with the geometric center of the structure, and (3) does not coincide with stratigraphic contacts. For these reasons it is interpreted to have originated with the Wells Creek structure (fig. 49). The association of megabreccia with smaller scale breccia suggests that some of the smaller scale breccia also originated with the structure. However, most of the smaller scale Knox breccia is believed to have developed in the Ordovician when the Knox

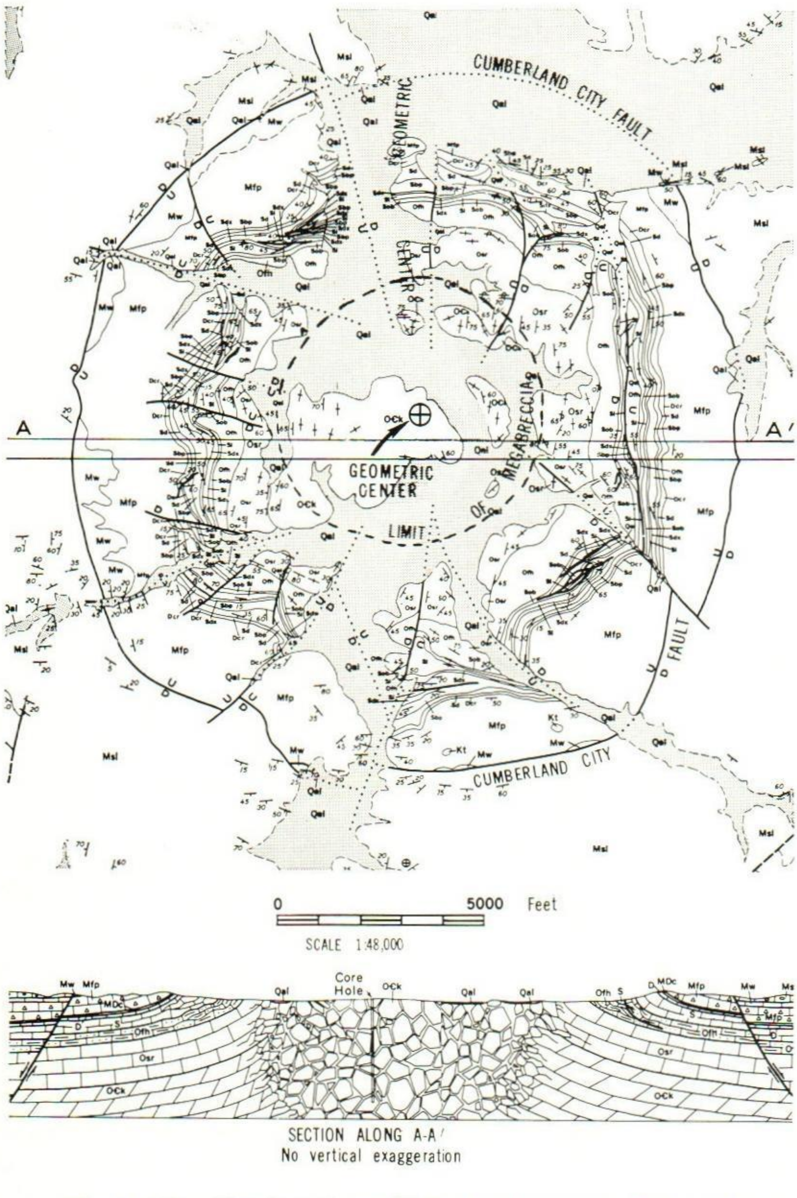


FIGURE 49.—Megabreccia at Wells Creek Basin. Note that Stones River limestone is megabreccia on the east and northeast and that Knox is not megabreccia to the southwest.

paleokarst topography was formed, to be later buried beneath Middle Ordovician strata.

Undoubted breccia occurs in Knox Dolomite and Silurian limestone. The following "breccias" might be called something other than breccia: (1) crackle breccia, which is part of a continuum with true breccia, might be called "fractured dolomite;" (2) fractured chert breccia in St. Louis Limestone is broken chert in an apparently unbroken matrix, and might be referred to merely as "fractured chert;" (3) megabreccia made of large jumbled blocks of Knox and Stones River might be referred to as a mass of helter-skelter fault blocks; and (4) material that clearly originated by slumping during diagenesis might be referred to as "intraformational conglomerate."

BRECCIAS IN THE KNOX DOLOMITE

Introduction

The similarity of much of the Knox breccia in Wells Creek Basin to breccias in the zinc district of East Tennessee, coupled with the evidence that the latter breccias were formed mainly in pre-Middle Ordovician time, means that, for all we know, most of the smaller scale breccia in Wells Creek Basin predates the Wells Creek event and therefore has no bearing on its origin. No megabreccia is known to be associated with Knox in East Tennessee. Although some of the fractures observed in Wells Creek breccias appear likely to be genetically related to the structure, we cannot clearly distinguish Ordovician breccia from Wells Creek event breccia.

The most extensive exposure of breccias is in the quarry of Road Materials, Inc., on Fairgrounds Hill in the central block. Additional exposures of small scale breccia and megabreccia formerly were visible in a field on the west side of Central Hill, but these are now covered. Core samples from the single deep hole drilled on Central Hill near the center of the central block contain much breccia. This hole initially was drilled to a depth of 2,000 feet by the Ordman Company in 1947, and a generalized description of the core was published by Wilson (1953, p. 765-768). The hole was extended to a depth of 2,500 feet as part of the present investigation. For a partial description of this core see Appendix B.

Although the hole was not surveyed, it is assumed that it is approximately vertical throughout its depth. Throughout much of the core, bedding attitudes cannot be determined, so the amount of Knox section penetrated is not known. Where bedding is observed it is usually steep or vertical, perhaps averaging 65° to 70°. Thus, the hole may cut less than 1,000 feet of Knox section. The significance of this is that all of the rock observed may be stratigraphically near the top of the Knox where karst breccia is common in East Tennessee. However, it is not necessary for the breccia to occur near the top of the Knox to be "common Knox breccia" merely associated with Knox, not with the structure. For example, cores from the du Pont disposal well at New Johnsonville in Humphreys County, only 25 miles to the southwest, contain breccia 2,300 feet below the top of the Knox.

The smaller scale breccias are of such fragment size that they can be observed in both outcrops and core samples of the Knox Dolomite. In this respect they are different from megabreccia, composed of blocks so large as to be recognized only on the basis of zigzag outcrop pattern. It is not known whether there is a continuum of breccia-clast size from the smaller scale to megabreccia. However, there appears to be a gap in size from about 3 feet, the apparent upper size limit of smaller scale breccia, to 20 feet or so, the apparent lower size limit for megabreccia blocks.

The problem of distinguishing brecciated from nonbrecciated rock exists on a smaller scale in core samples. Because some breccias contain fragments as much as several feet across it is not possible to distinguish with certainty brecciated from nonbrecciated rock in the core. Some rock in the core must be megabreccia, because dips are nearly all steep, as was observed for dips of bedding within blocks at the surface throughout the megabreccia (fig. 49).

Breccia Types

Knox breccias from the Wells Creek structure are extremely varied in appearance; however, most Knox breccias at Wells Creek may be placed in one of three groups: (1) crackle breccia, (2) homogeneous rubble (monomict) breccia, and (3) heterogeneous rubble (polymict) breccia. The three ideal types may represent points on a continuum from no displacement or rotation of fragments (crackle type) to relatively long distance movement of fragments in the heterogeneous rubble type.

CRACKLE BRECCIA

The term crackle breccia is adopted from parlance of the East Tennessee zinc district. This breccia is characterized by angular fragments separated by a complex system of fractures and fracture zones. Fragments generally consist of fine-grained, massive, light-gray to tan dolomite. The matrix constitutes a relatively small part of the rock and is typically lighter in color—commonly almost white (fig. 50). Examination of thin sections indicates that the matrix generally consists of comminuted material of the same composition as the fragments. Where the matrix is white, it is

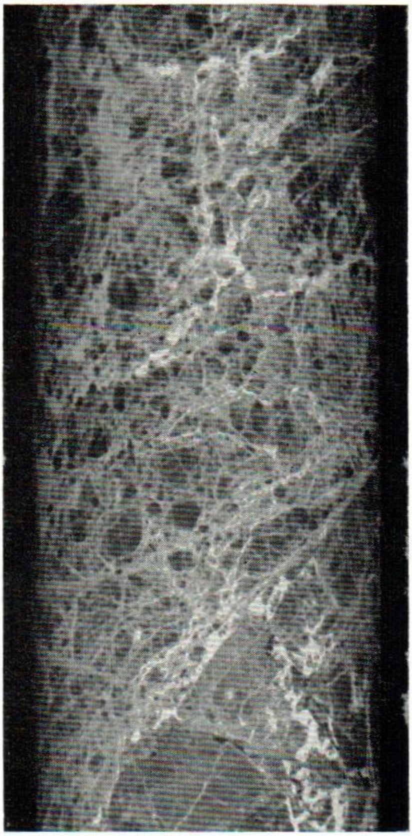


FIGURE 50.—Knox core sample from drill hole on Central Hill, showing typical crackle type brecciation. Both fragments (dark) and matrix (light) are dolomite. Core diameter is about 2 inches.

caused by recrystallization of dolomite (fig. 51) and consequent removal of dark material adjacent to fracture zones.

Estimates of the fragment-matrix ratio were made by counting points on a square grid superimposed on polished breccia surfaces. Points falling on particles larger than about 0.5 mm were counted as fragments, and those falling on smaller material were counted as matrix. The 0.5 mm size limit is arbitrary, and much of the material called matrix consists of smaller fragments. This definition was adopted because particles larger than 0.5 mm could be recognized readily in hand specimens as being compositionally identical with larger fragments. On this basis a typical crackle breccia consists of about 70 percent fragments and 30 percent matrix. The relatively minor offset of dark bands that cross several fragments indicates that displacement of fragments is minor.

Because crackle breccia is gradational into fractured dolomite

FIGURE 51.—Thin section (plane polarized light) of crackle breccia in Knox Dolomite. Sample is from deep drill hole on Central Hill. Recrystallization of dolomite along fracture margins is indicated by large grains. These have been fractured by a later stage of deformation.

on the one hand and homogenous rubble breccia on the other hand, no attempt was made to determine the amount of this breccia present either in outcrops or in cores. However, a very rough estimate of the abundance of this breccia in the deep core drill samples is 10 to 20 percent.

HOMOGENEOUS RUBBLE BRECCIA

Homogeneous rubble breccia is characterized by fragments of almost uniform composition, generally dolomite, less commonly limestone, in a carbonate matrix. Both dolomite fragments in calcite matrix and limestone fragments in dolomite matrix were observed; in some places one type is in contact with the other. In general, the fragments are more rounded than those of the crackle breccia and the proportion of matrix is higher, commonly more than 50 percent.

Figure 52 shows a typical variety of this breccia. The fragments consist of fine-grained, massive, brown dolomite. Thin sections show

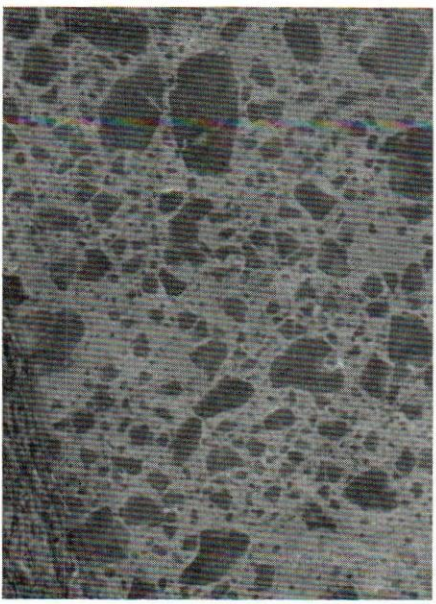


FIGURE 52.—Hand specimen of homogeneous rubble breccia from operating quarry of Road Materials, Inc. Both fragments and matrix are dolomite. Matrix constitutes more than 50 percent of sample. Photograph represents approximately actual size.

that the dolomite fragments consist of a dense intergrowth of rhombohedral grains, mostly between 25 and 150 microns across. The matrix also consists of dolomite grains that range from about 10 to 500 microns across; most grains are less than 25 microns.

HETEROGENEOUS RUBBLE BRECCIA

Heterogeneous rubble breccia is the most distinctive of the three types recognized (fig. 53). In hand specimens the rock appears to consist of fragments that may include virtually any lithic type seen in the Knox of Wells Creek Basin. Chert fragments of various colors are especially common. The matrix is commonly dark gray. The only sphalerite observed in the entire 2,500 feet of core consisted of several grains, each about 1 mm across, in the gray matrix of this breccia. In some places the breccia displays a distinct lineation that involves both alignment of fragments and color banding in the matrix.

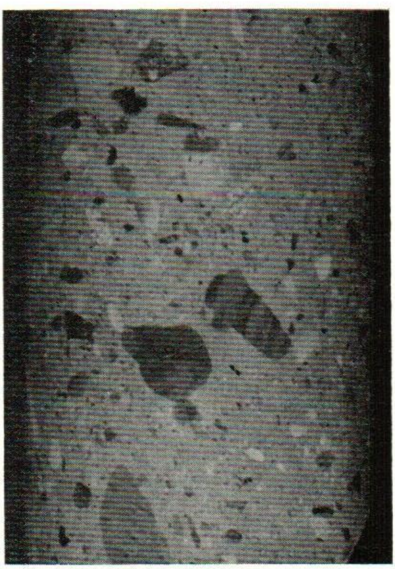


FIGURE 53.—Knox core sample from Central Hill showing heterogeneous rubble breccia. Although fragments of considerable variety are present, virtually all are dolomite or chert fragments or quartz sand grains. The matrix is fine-grained dolomite. Core is from depth of 514 feet and is about 2 inches across.

Thin sections of the breccia confirm the presence of a variety of lithologies in the fragments. Mineralogically, however, the breccia is rather simple. It consists almost entirely of dolomite, chert, and quartz. An x-ray powder diffraction photograph of breccia shows only lines for dolomite and quartz.

The matrix of the heterogeneous rubble brecica is composed of interlocking dolomite grains, many approximately 10 to 20 microns across. Fragments consist of (1) chert of the microcrystalline quartz variety, in which additional crystallites are approximately 5 to 10 microns across; (2) somewhat coarser and less even-grained chert, partly microcrystalline quartz and partly chalcedony; (3) rounded to subrounded quartz grains, commonly 0.2 to 0.6 mm across; and (4) dolomite rock fragments.

Authigenic chert, which is abundant throughout much of the Knox core, is common in heterogeneous rubble breccia in addition to fragmental chert. Authigenic chert may be of either the microcrystalline-quartz or chalcedonic varieties. It replaces both fragments and matrix of the breccia. In at least one instance this authigenic chert is cut by fractures that subsequently were filled with carbonate, probably dolomite (fig. 54). Changes in thickness and in trend of the carbonate veinlets are observed at the chert-breccia boundary. These features show that the chert predates the fractures. Scattered veinlets and disseminations of pyrite also are present in some specimens of breccia.

The coarse and irregularly grained, partly chalcedonic chert is especially distinctive. It commonly forms as a replacement of dolomite. Some of this chalcedonic chert exists as siliceous (perhaps silicified) oolites. The term "siliceous" oolite is preferred to "silicified" oolite because it is not premised on any interpretation as to when the oolites became siliceous. Fragments of this siliceous oolite are present in the heterogeneous rubble breccia, establishing that the silicification preceded brecciation.

The rounded quartz grains are comparable in size and roundness with those in sandstone beds observed both in core samples and in Knox outcrops. The several varieties of dolomite fragments all have counterparts in unbrecciated Knox.

Fragments within heterogeneous rubble breccia commonly display evidence that the source rock itself had undergone deformation. For example, fragments themselves may be brecciated,

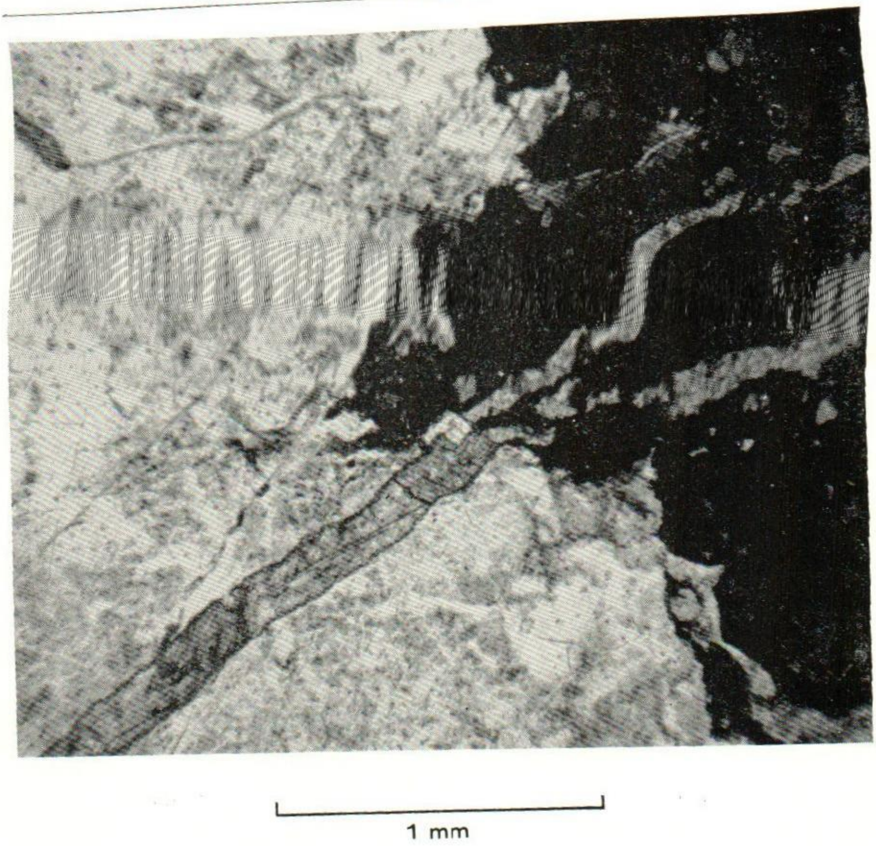


FIGURE 54.—Photomicrograph of heterogeneous rubble breccia with authigenic chert (light). The chert and matrix (dark) are cut by fractures which have been filled with carbonate, probably dolomite.

implying different episodes of brecciation. Chert fragments commonly are fractured, and the fractures in some cases are filled with dolomite.

Because the heterogeneous breccia is distinctive in appearance, an estimate of its abundance and distribution in the deep core-drill hole was made. The estimate was prepared by totaling the lineal inches of heterogeneous breccia in each 100-foot interval of core. The entire cross section of core commonly consists of heterogeneous breccia, in some zones for a length of several feet. Commonly, however, the breccia is present in thin stringers (fig. 55), which generally have a low angle of intersection with the core axis. As a result long intervals of core consist of a cylinder of solid rock containing a thin seam of heterogeneous breccia. In order for the

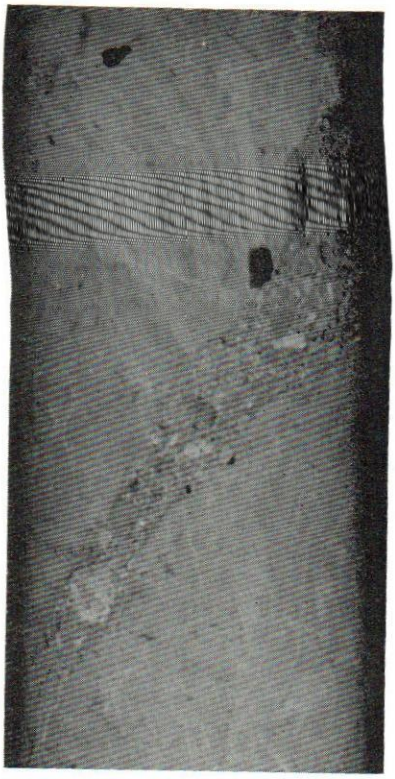


FIGURE 55.—Drill core sample showing stringer of heterogeneous rubble breccia in Knox Dolomite. Such stringers are abundant in the core and are commonly about ½ inch wide. Core diameter is about 2 inches.

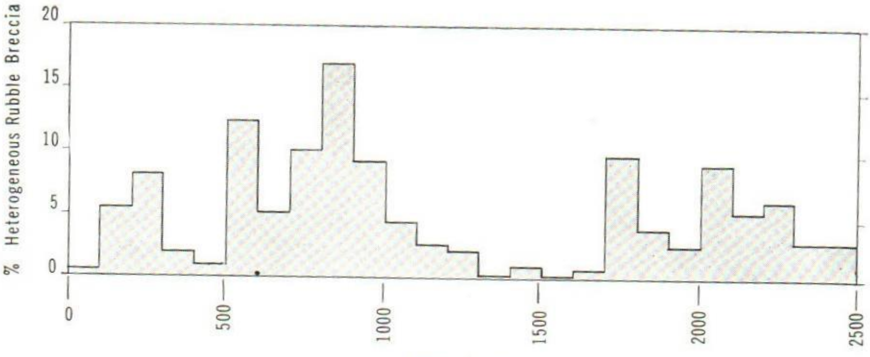


FIGURE 56.—Histogram showing percent of heterogeneous rubble breccia in each hundred-foot interval of core from deep drill hole in central uplift area. Average for entire 2,500 feet is 5 percent.

estimate to reflect the volumetric abundance of the breccia, the tabulation was based on a line along the core length—specifically, the line along the uppermost portion of the core as it lay in the box. Where thin stringers of breccia happened to fall along the line they were counted; otherwise, they were not.

The results of this "line count" of heterogeneous rubble breccia are presented in figure 56. Several facts are apparent. First, no 100-foot interval in the nearly half a mile of core is free of the material. The amount ranges from 1/4 percent (3 inches per 100 feet) to nearly 17 percent. The average abundance for the entire 2,500 feet is 5 percent, and this is also the average for the lower 500 feet of the core. Though the distribution is erratic, four zones show well-defined concentrations. These are the intervals at 100-300 feet, 500-1,000 feet, 1,700-1,800 feet, and 2,000-2,300 feet.

Age Relations

INTRODUCTION

Because the breccias are significant to the origin of the Wells Creek structure, time relations of breccias to each other, to shatter cones, and to mineralized fractures are considered.

RELATION OF BRECCIAS TO EACH OTHER

The crackle-type breccia is suggestive of brittle behavior and probably would occur only after lithification. From this one might conclude that the crackle breccia is a type likely to be associated with the formation of the structure. However, crackle breccia occurs adjacent to rubble breccia in East Tennessee. Also, where the crackle and heterogeneous rubble breccias are in contact the fractures of the crackle breccia nearly everywhere terminate abruptly against heterogeneous rubble breccia (fig. 57). If the failure of heterogeneous rubble breccia to later form crackle breccia were caused by its unconsolidated condition at the time of crackle brecciation, the fractures would be expected to cross the contact and end in the heterogeneous rubble. The very sharp termination of fractures is considered to indicate that, in most cases at least, the crackle breccia formed before the heterogeneous rubble breccia. Dolomite fragments in the heterogeneous rubble are commonly fractured and in some places brecciated, but in such cases deforma-

FIGURE 57.—Core sample from deep drill hole showing relationship of crackle and heterogeneous rubble breccias. Note that fractures of crackle breccia terminate abruptly at contact with rubble breccia, which suggests that crackle breccia is earlier. Also note bedding lineation (or flow banding). Core diameter is about 2 inches.

tion appears to postdate formation of enclosing heterogeneous rubble breccia.

Fragments observed in the smaller scale breccias range in size up to about 3 feet in diameter. Breccias of this scale are abundant in the Road Materials, Inc. quarry, which apparently is developed mainly in a single block of megabreccia at least 500 feet long. Most of the Knox Dolomite in this block shows distinct bedding with a rather uniform vertical attitude. The presence of much smaller scale breccia within a single block of megabreccia is evidence that the two breccias are not cogenetic. This reinforces the hypothesis, originally based on an apparent lack of continuity of breccia clast size, that the smaller scale breccia and the megabreccia have unrelated origins. Most of the smaller scale breccia probably originated in Ordovician time, whereas the megabreccia is related to the structure.

RELATION OF BRECCIAS TO SHATTER CONES

In Wells Creek Basin shatter cones most commonly are found in massive dolomite. However, they also occur in breccia, particularly in the crackle or homogeneous rubble types. It appears that most of the shatter cones were formed after the crackle and homogeneous rubble breccias, and possibly after the heterogeneous rubble breccia as well. However, some breccia is known to have formed later than shatter cones, because Phyllis S. Marsh observed two shatter cone points as clasts in breccia. The writers observed one shatter cone cut and offset by a breccia veinlet about ¼ inch wide.

SEQUENCE OF EVENTS

The presence of authigenic chert in heterogeneous rubble breccia, and the fact that this chert subsequently was fractured and the fractures mineralized, already have been mentioned. In another instance heterogeneous rubble breccia is cut by carbonate veins that in turn are offset by a complex fracture system (fig. 58).

The time relations noted above suggest the following sequence of events in the origin and subsequent deformation of heterogeneous rubble breccia: (1) silicification of original dolomite or dolomitized limestone rock, (2) formation of crackle and homogeneous rubble breccias, and formation of carbonate veins in chert of stage 1, (3) formation of heterogeneous rubble breccia, probably by filling solution cavities with available debris, (4) development of authigenic chert in heterogeneous rubble breccia (this step probably was followed by a great hiatus from Ordovician to late Paleozoic time), (5) fracturing of the authigenic chert (accompanied by shatter coning and jumbling of megabreccia blocks), (6) formation of carbonate veins in fractures of stage 5, and (7) probably another generation of fractures filled with carbonate.

The above relationships signify that several episodes of disturbance (fracturing and brecciation) were separated by sufficient

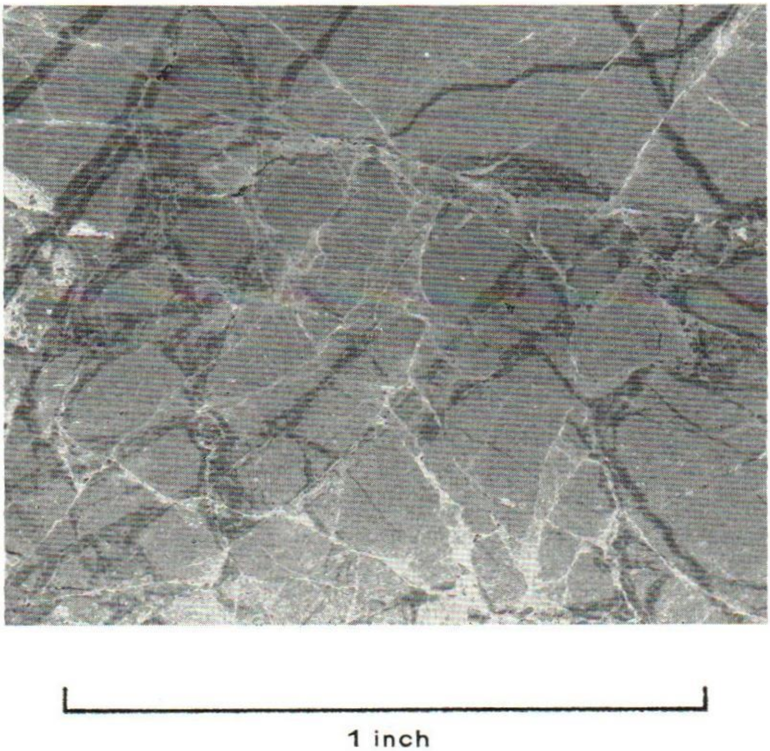


FIGURE 58.—Photograph of thin section from Knox Dolomite in deep drill hole. Heterogeneous rubble breccia at left margin is cut by carbonate veins (black). The carbonate veins in turn are offset by an intricate fracture system (white).

time for carbonate veins and chert to form. Therefore, all the breccias certainly could not have been formed by a single violent event. Some smaller scale breccia would have formed with the Wells Creek event subsequent to shatter coning, perhaps as part of the jumbling process that formed the megabreccia.

The youngest fractures observed, i.e., those that offset carbonate veins and authigenic chert in heterogeneous rubble breccia, very likely are related to the major structural event. The shearing of quartz grains (fig. 59) and severe fracturing of carbonate rhombs (fig. 60) both are related to these post-breccia fractures.

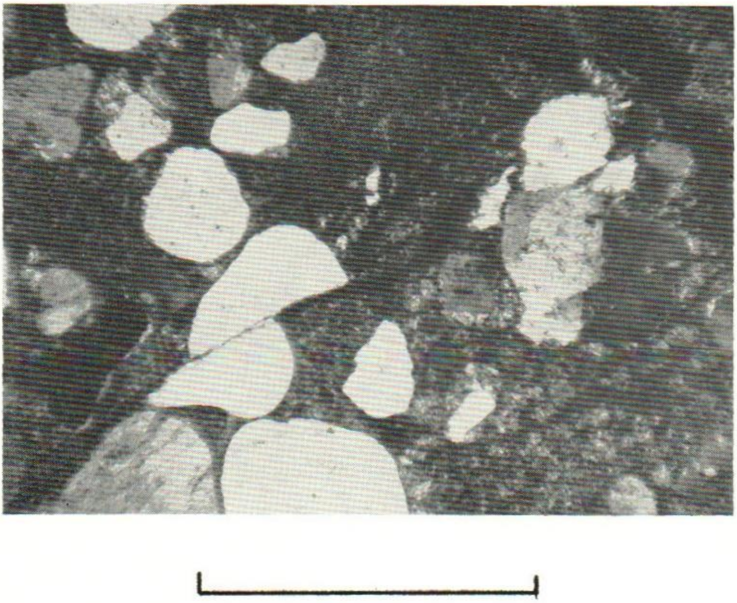


FIGURE 59.—Sheared quartz grains in silicified sandy Knox Dolomite. Elsewhere in same thin section fractures involved in quartz-grain shearing offset carbonate veins.

History of Concepts of Origin of Knox Breccia in Wells Creek Basin

Bucher (1932) considered the brecciated character of the Knox Dolomite to have resulted from the force that formed the Wells Creek structure. One of his three observations that this structure arose from an explosive shock is "The extreme fragmentation and confusion of the central area" i.e., the Knox Dolomite.

In 1936 (p. 1067, 1068) Bucher described Wells Creek Basin briefly and referred to the "intensely disturbed" Knox Dolomite, which is

* * * broken up into blocks, large and small, which are tilted and twisted into all sorts of positions.

One prophetic statement of Bucher (p. 1067) is of interest:
The extraordinary disordering of the Wells Creek limestone in the center * * * stands in curious contrast to the rather regular domed structure of the Silurian and later beds.

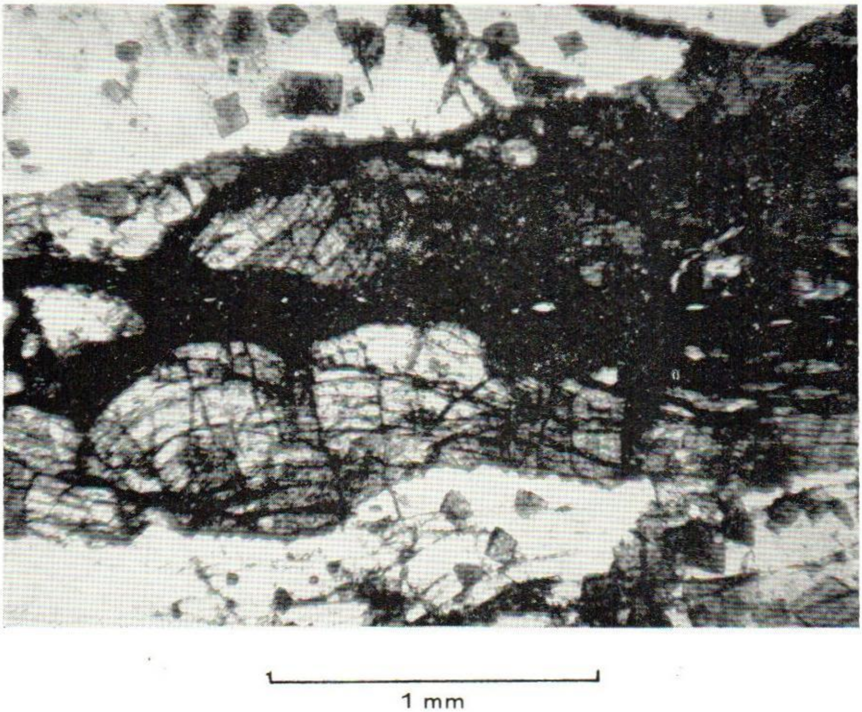


FIGURE 60.—Severely fractured and distorted dolomite rhombohedron in vein cutting fractured chert (light). Such intense deformation commonly is the latest episode when more than one stage of deformation is indicated. (Plane polarized light)

Wilson (1953, p. 765-768) was convinced that the brecciation of the Knox Dolomite occurred at the time of application of the deformative force that produced the Wells Creek structure. During the 1930's and 1940's, however, when Wilson led several field trips through Wells Creek Basin, he heard that some geologists working in East Tennessee thought that the Knox breccias at Wells Creek Basin were similar in appearance, and therefore probably similar in origin, to breccia in the upper part of the Knox in East Tennessee. Among these visiting geologists the earliest expressions of this possibility were made by C. R. L. Oder, who suggested further that the breccias are nontectonic.

Professor George D. Swingle of the University of Tennessee, who is well acquainted with the Knox breccias in East Tennessee, examined the Knox breccias of Wells Creek Basin at our request and compared them with those in East Tennessee. He concludes that probably 90 percent of the breccia in the Knox of Wells Creek Basin is "sedimentary" (nontectonic) and that some of the remainder may have resulted from the later deformative stresses that formed the Wells Creek structure.

BRECCIATION IN POST-KNOX ORDOVICIAN, SILURIAN, AND DEVONIAN ROCKS

Introduction

Breccia in post-Knox Ordovician, Silurian, and Devonian rocks is rare in surface exposures; in fact, the only good example found is on the hill south of the intersection of Scott and Schmid Branch Roads. A tabular body of granular breccia is exposed here involving Decatur Limestone and containing small angular fragments of Chattanooga Shale and oolitic chert. In the cores taken by the TVA in the north-central part of the basin, however, zones of brecciation were found in Stones River, Hermitage, Silurian, and Devonian strata. These relatively thin zones are separated by intervals of steeply dipping fractured limestone. The dip, fracturing, and brecciation in these beds are thought to be the results of the deformative stresses that formed the Wells Creek structure, mainly because the formations involved are unbrecciated outside the Wells Creek structure.

Brecciation at Top of Decatur Limestone

DESCRIPTION

A small tabular body of granular breccia is exposed on the crest of the spur about 600 feet south of the intersection of Schmid Branch and Scott Roads. The breccia consists essentially of chert and calcite fragments in a dolomitic matrix. Some small angular fragments of black Chattanooga Shale, rounded quartz grains, and a few phosphate pellets are present. The chert is of the microcrystalline quartz variety, although chalcedony is present as a constituent of some chert fragments. Thin sections of chert fragments that contain siliceous oolites are similar in appearance to oolitic chert in the Knox Dolomite, but possibly they came from the oolitic and cherty upper part of the St. Louis or younger limestones. These are the only obviously "exotic" fragments, others having counterparts in nearby Silurian limestone and black Chattanooga Shale.

The breccia matrix consists almost entirely of fine-grained dolomite that has partly replaced earlier calcite. Some authigenic chert and minor pyrite and glauconite are present.

DEFORMATION OF THE BRECCIA

The breccia was deformed after its formation. Some broken chert has been rebroken and the fragments have been slightly displaced. Also, subparallel fractures in calcite have been filled with dolomite. Although these fractures commonly are short, some cross fragment boundaries of the earlier calcite, and in at least one case a chert fragment is offset by a fracture that also cuts calcite. Where the fracture passes through calcite it is filled with dolomite. This fracturing is clearly later than the formation of the breccia.

Much of the calcite shows undulating extinction, and the deformation that caused this evidence of strain presumably was the Wells Creek event. Intense twinning of some grains attests to deformation of fragments possibly related to the Wells Creek event, though it also could have occurred before the breccias formed.

ORIGIN

The breccia probably accumulated by washing of deformed fragments into a crevice in the Decatur Limestone. It is not definitely known whether such a crevice was (1) a solution pocket in the limestone that could have formed at any time after the Wells Creek event, or (2) an open fracture formed during the event (possibly even a solution pocket formed shortly after the event). If the oolitic chert is St. Louis or younger, the former is possible; but if the oolitic chert is Knox, it could have been washed into an open fracture or solution pocket only from the hill of Knox debris that is postulated to have occupied the central part of the structure for a relatively short time. This small occurrence of breccia, therefore, could be the only exposure of original debris preserved from erosion.

BRECCIATION IN THE ST. LOUIS LIMESTONE

General Statement

Breccias occur in St. Louis Limestone near the Erin, Brownsville, and Marable Hollow annular faults. Fractured chert breccia is particularly well exposed in the St. Louis Limestone of the outer graben in the quarry on the north side of State Highway 149 about a mile east of Erin. An unusual feature here is that brecciation and shearing are more noticeable in the chert concretions than in the enclosing limestone.

The breccias are of two types: (1) chert-fragment breccia composed of angular unfractured fragments of chert in gray limestone matrix and (2) fractured chert breccia, which consists of fractured chert fragments. The first type may be a pseudobreccia.

Chert-Fragment Breccia

Exposures of St. Louis Limestone in the outer graben commonly display a distinctly brecciated appearance because of chert fragments, typically light colored, in a dark-gray calcarenite matrix. The breccia is especially prominent where chert fragments stand out in relief as the result of differential weathering. The brecciated rock commonly shows bedding in which very fine and coarser grained layers alternate. Chert fragments are common in both fine and coarse layers and may cross the contact between two layers. The chert may have either a sharp or gradational contact with the adjacent calcarenite matrix.

Thin sections of the breccia reveal that the matrix is a hash of microfossil fragments and that the chert constitutes zones in which calcarenite has been partially replaced by silica. In some places the replacement process is nearly complete, but in other cases there is a skeletal network in which more than half of the rock consists of carbonate. The fossil hash between chert fragment also is evident within the chert, and some individual fossil fragments cross the boundary between chert fragments and matrix. This indicates that this material is a pseudobreccia with angular chert replacements in limestone. This material may represent chert replacement of a diagenetically disrupted calcareous sediment. Therefore, much of the St. Louis chert-fragment type of breccia may be more apparent than real.

Fractured Chert-Breccia

In much of the chert breccia, chert nodules and lenses are offset by fractures. In places these fractures can be traced into adjacent limestone, but generally they cannot. It seems likely that in the latter cases at least fracturing occurred while the St. Louis limestone was only partially consolidated but contained consolidated or semiconsolidated chert concretions and chert lenses. If this interpretation is correct, it could date the major deformation as late Mississippian.

PETROGRAPHIC EVIDENCE FOR SHOCK DEFORMATION

During the petrographic study of breccias, consideration was given to the presence or absence of several features that are widely believed to be indicative of shock deformation. One such feature is the occurrence of the dense silica materials, coesite and stishovite. Although these dense minerals were not found, their absence is not considered to preclude an impact origin of the structure. Some evidence of crystal damage that may have resulted from unusually intense shock deformation was seen.

Coesite and stishovite with densities of about 2.9 and 4.3, respectively, have been synthesized only under very high pressures and have been found at several cryptoexplosive craters (Chao, Shoemaker, and Madsen, 1960; Chao, Fahey, Littler, and Milton, 1962). They have not been found in any natural environment that is clearly *not* related to a meteor impact.

In order to determine whether either of these materials is present in the disturbed Knox Dolomite of the central block, samples of quartz sandstone and fractured chert were treated in a dilute solution of nitric and hydrofluoric acids, following the procedure of Chao, Fahey, and Littler (1961). Because coesite and stishovite are less soluble than quartz in dilute hydrofluoric acid, the treatment effects a concentration of the dense minerals. X-ray powder diffraction photographs of the residues from the above treatment showed none of the lines for coesite or stishovite, though a sample of shocked Coconino Sandstone from Meteor Crater, Arizona, subjected to the same treatment, did show lines for the two minerals.

In nuclear blast tests of Project Plowshare, coesite was found only within a limited distance of the explosion center (N. M. Short, personal communication). Lack of coesite and stishovite from siliceous Knox Dolomite, therefore, probably establishes only that if a meteor impact did occur, the zone in which shock pressures were sufficient to develop these minerals has been removed by erosion.

The most severe deformation noted in quartz is somewhat widely spaced fracturing (fig. 59).

The most pronounced evidence for severe deformation is distortion and fracturing (fig. 60) and undulatory extinction in carbonate crystals, which was observed both in the Knox Dolomite and in calcite in the breccia at the top of the Decatur Limestone. This may be a result of shock deformation. Perhaps undulatory extinction is a manifestation of the same crystal disordering that was noted by Simons and Dachille (1965) on the basis of asterism in single crystal X-ray diffraction photographs. One other sign of deformation is seen in the breccia at the top of the Decatur Limestone, where calcite crystals have been broken into platy fragments. Twinning is prominent in the calcite of this breccia but not in the dolomite of the central block.

GEOPHYSICS

(*with* Phyllis S. Marsh)

INTRODUCTION

Anomalies in the gravity field and possibly the magnetic field might be expected to reflect the Wells Creek structure if: (1) it is related to an event involving magnetic or unusually dense or light igneous rock, (2) brecciation to a considerable depth results in density deficiencies, or (3) material from an impacting meteor is buried in the structure. The latter case is considered unlikely on theoretical grounds, because an explosive impact should have caused most of the meteorite to be destroyed or ejected from the crater.

Geophysical data have been used to investigate actual craters and other cryptoexplosive structures. Several Canadian craters were observed to have substantial negative gravity anomalies (Beals, Innes, and Rottenberg, 1960; Innes, 1961), and the Des Plaines structure in Illinois also has a negative anomaly (Emrich and Bergstrom, 1962).

A substantial negative gravity anomaly would favor the meteor-impact theory (assuming that the Canadian craters having negative gravity anomalies are of meteoritic origin). A substantial positive gravity anomaly coinciding with either a positive or negative magnetic anomaly would, on the other hand, favor the volcanic-intrusion origin.

Rocks in the Paleozoic sedimentary sequence are not magnetic, so disarrangement of the rocks will not result in a magnetic anomaly. Deeper strata are sufficiently dense (e.g., Knox Dolomite), however, to result in gravity anomalies if uplifted. Gravity results, therefore, do not necessarily indicate the depth of the source of any anomalies.

Most of the limestone strata underlying the region have specific gravities of about 2.67 gm/cc. Variation from this is known for 3 rock formations. The most dense is Knox Dolomite, which has an excess mass (more than 2.67 gm/cc) of about 0.1 gm/cc. St. Louis and younger limestones commonly have an excess mass of about 0.05 gm/cc. The Fort Payne Formation (400 feet thick) has a deficiency of about 0.1 gm/cc and the next youngest formation, the Warsaw Limestone, has a deficiency of about 0.04 gm/cc. Breccia at the surface is not porous and not significantly different in density from the adjacent unbrecciated rock. Deep breccia may be more porous and hence less dense. The only sample of this (a ½″ diameter core sample from a depth of about 2,500 feet) has sizable holes or vugs. Therefore, sizable mass deficiencies from breccia at depth may be suspected but are not established.

Regional gravity patterns may be seen on the gravity map of Tennessee (Johnson and Stearns, 1967). A gravity map[1] of the Wells Creek area (fig. 61 and pl. 4), gravity profiles (E-W, fig. 62; N-S, fig. 63), and a north-south magnetic profile (fig. 63) were prepared. The north-south magnetic and gravity profiles were selected so that the magnetic profile would coincide with a gravity profile showing the greatest definition of density contrast.

AREA OF GRAVITY SURVEY

The gravity map of the 20- by 25-mile larger area is based upon 740 stations shown in plate 4. Station spacing is no more than 2 miles in the area outside the Wells Creek structure; but within the exposure area of the disturbed zone, spacing is much closer. In data reduction the gravity values are referred to the base station at the Nashville Airport, and the datum for this detailed survey is adjusted to that for the gravity map of Tennessee.

ACCURACY OF GRAVITY DATA

The gravity survey was made with a Worden Gravity Meter #443, loaned by the U. S. Bureau of Mines. The slight drift and excellent accuracy of this instrument provided closures for tie and drift corrections of the order of 0.4 milligal for the average reading at a given station.

GRAVITY MAP

(Fig. 61)

The major pattern of gravity in the region of the Wells Creek structure consists of (1) an east-west ridge of high anomaly that

[1] Plate 4 (in pocket) shows gravity contours and station locations on a planimetric base at a scale of 1/48,000. Figure 61 shows generalized gravity contours of the area together with the outer limits of the Wells Creek structure.

FIGURE 61.—Bouguer gravity anomaly map of the region and the Wells Creek structure. Note that all values are negative. Contours in milligals.

crosses the southern part of the map, from which a promontory of relatively high anomaly extends northward, and (2) low anomalies in the northwest and northeast corners. The east-west ridge in the south has relief of about 7 milligals (—18 to —25 milligals), the highest point being in the southeast corner of the Erin quadrangle. The positive gravity promontory, which extends northward through the eastern parts of the Erin and Cumberland City quadrangles, includes two areas of —25 milligals or higher. One of these is centered over the Wells Creek structure in the southeast corner of the Cumberland City quadrangle; the other is in the northeast quadrant of this quadrangle. The low in the northwest corner of the map is about 12 milligals lower than the positive closure in the north end of the promontory, whereas the low in the northeast corner is about 17 milligals lower than this high.

The gravity pattern of the Wells Creek structure requires more detailed examination. There, the contours show greater details of configuration because of closer spacing of gravity stations. The centrally located high of —25 milligals coincides with the inner core of the central block. Surrounding this high is a circular belt of "depression contours" of lower gravity connected by "saddles." The circular belt of relatively low gravity, 2 to 4 milligals lower than the gravity high in the center, coincides with the Cumberland City fault. A concentric belt, 1 to 2 milligals higher than in the circular low, can be identified to the east, west, and north of the circular low. This horseshoe-shaped belt, which occurs within the inner graben, however, cannot be traced around the south side of the structure. It is believed to be related to the structure because of its symmetry relative to the center, not because it relates in detail to an individual structural feature. Other less discrete concentric patterns may be identified outside the high belt but not with sufficient certainty to define. This pattern, shown on figure 64, indicates the same bilateral symmetry as the structural features.

The gravity map (fig. 61) shows control by features readily visible on the geologic map, namely uplift of relatively dense dolomite (excess mass of about 0.1 gm/cc) of the Knox at the center of the central block. The diameter of the central anomaly indicates that the uplifted Knox is not rootless but spreads out at depth in conformity with dips in overlying beds seen at the surface, because the anomaly is more than twice the size of the area of exposed Knox. Less dense rock, perhaps breccia, may lie buried along the

Cumberland City fault at the edge of the central block. Also, relatively light Fort Payne is the bedrock here, and, because it is nearest the instrument, will have greater effect on recorded gravity values. This is the concentric belt of low gravity. The next outward belt of high gravity apparently reflects relatively heavy bedded rock of younger St. Louis and Ste. Genevieve limestones at the surface within the inner graben. There are no recognizable symmetrical pairs of anomalies clearly associated with the horst or the outer graben.

GRAVITY, MAGNETIC, AND STRUCTURAL PROFILES

(Figs. 62 and 63)

Because of the complexity of the regional gravity field and the approximate north-south trend of its symmetry, it is convenient to compare the relationships of the Wells Creek structure and gravity and magnetic anomalies by east-west and north-south profiles (figs. 62 and 63).

The main features directly related to the Wells Creek structure on the east-west gravity profile (fig. 62) and the north-south gravity profile (fig. 63) are: (1) the central high, (2) the encircling belt of low gravity, and (3) the horseshoe-shaped encircling belt of higher gravity. These already have been described from the gravity map (fig. 61). Gravity features shown on these profiles and on the gravity map outside of this encircling belt of high gravity cannot be definitely related to the Wells Creek structure.

A north-south magnetic profile (fig. 63) was measured through the regional gravity highs north and south of the Wells Creek structure, in addition to crossing this structure between them. Readings for this profile were taken from 19 stations with an Askania balance-type magnetometer borrowed from the Tennessee Division of Geology. The north-south gravity and magnetic profiles (fig. 63) are in close agreement except that the magnetic profile shows no close coordination with elements of the Wells Creek structure; whereas, the gravity profile does, as described earlier.

The lack of a magnetic anomaly coincident with the central uplift is consistent with a view that there is no intrusion beneath the Wells Creek structure; rather, the positive gravity anomaly is associated with uplift of the nonmagnetic denser dolomite of the

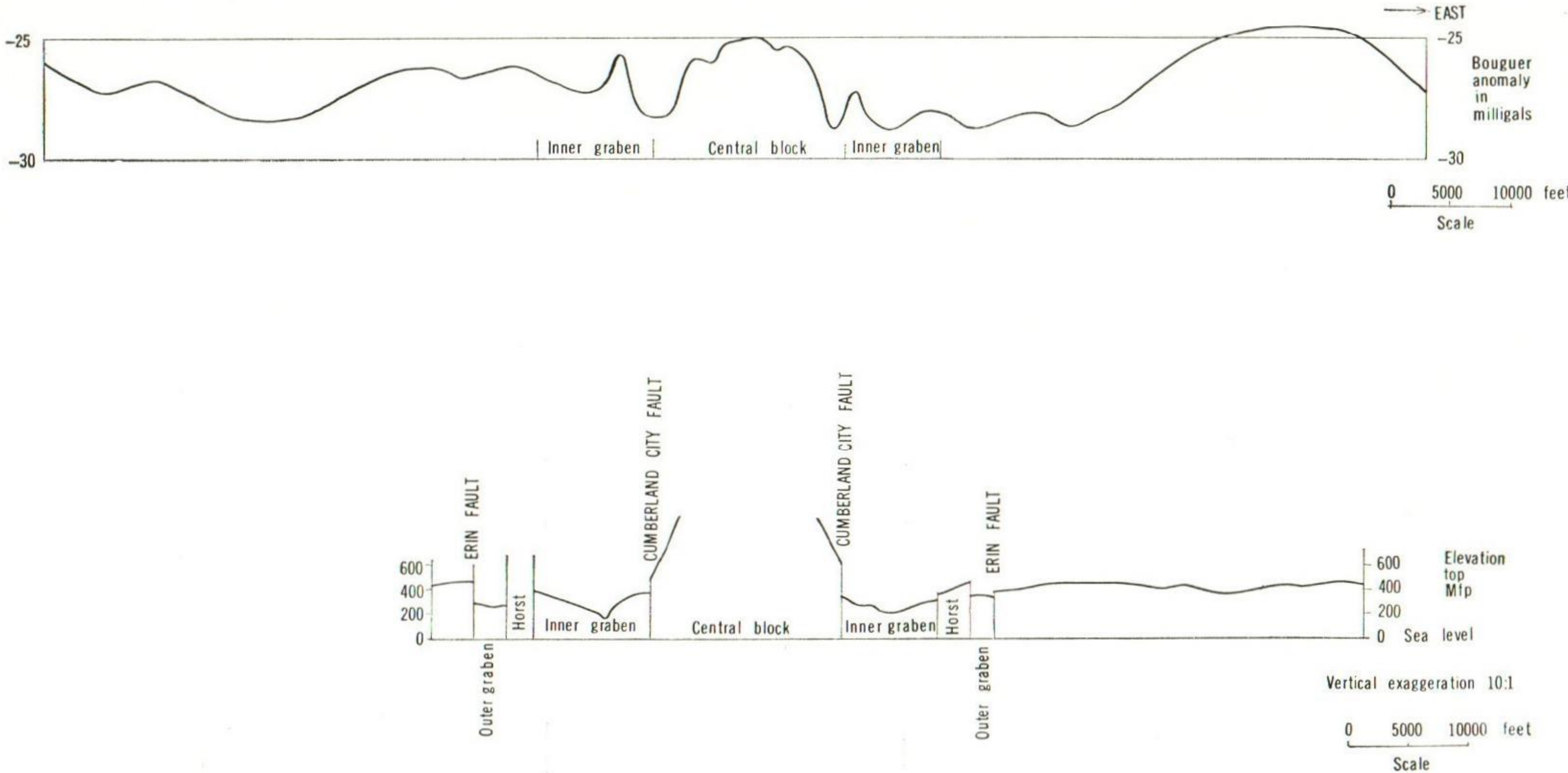


FIGURE 62.—Gravity and structural profiles extending east-west across the Wells Creek structure.

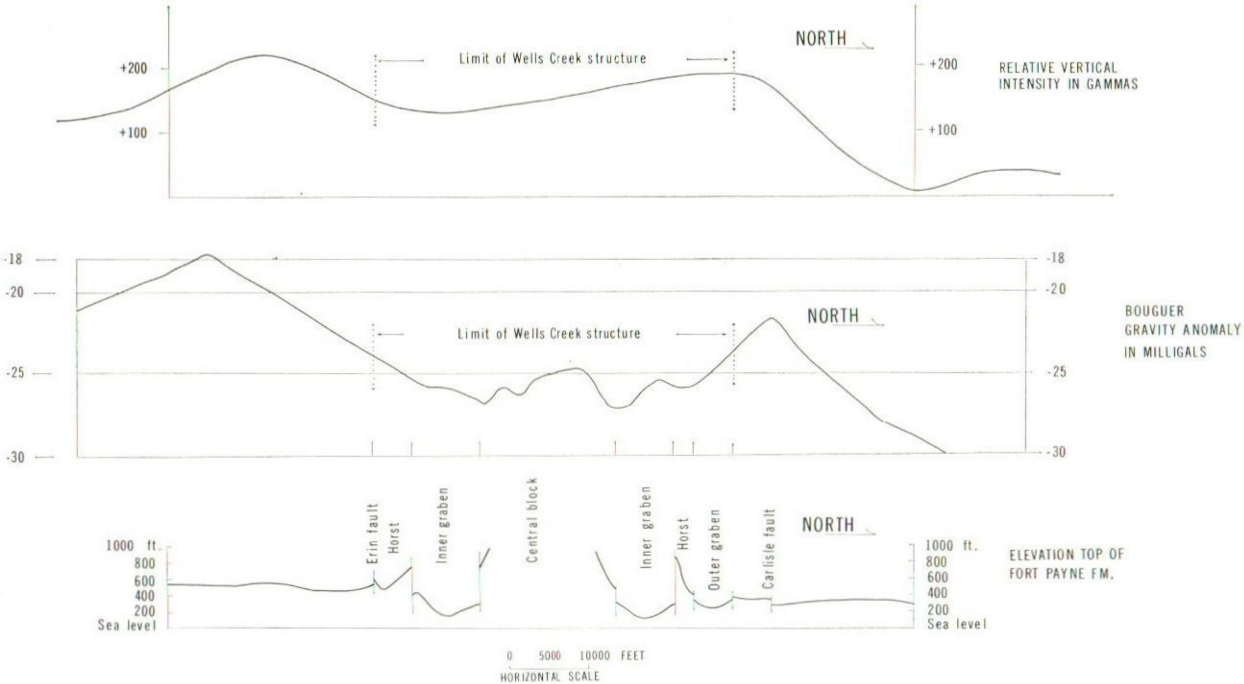


FIGURE 63.—Magnetic, gravity, and structural cross sections extending north-south across the Wells Creek structure. The magnetic profile is not corrected for the regional gradient, which is positive northward about 6-10 gamma per mile. This correction would make the magnetic profile slope to the right more nearly parallel to the corrected Bouguer gravity profile.

Knox. This is also consistent with the meteor-impact theory, which requires that surface contortions diminish with depth. Geophysical data does not, however, preclude the possibility of a nonmagnetic relatively low-density intrusion beneath the structure.

BILATERAL PATTERN OF WELLS CREEK GRAVITY ANOMALIES

(Fig. 64)

The trends of anomalies in the vicinity of the Wells Creek structure are shown on figure 64. The central high coincides ex-

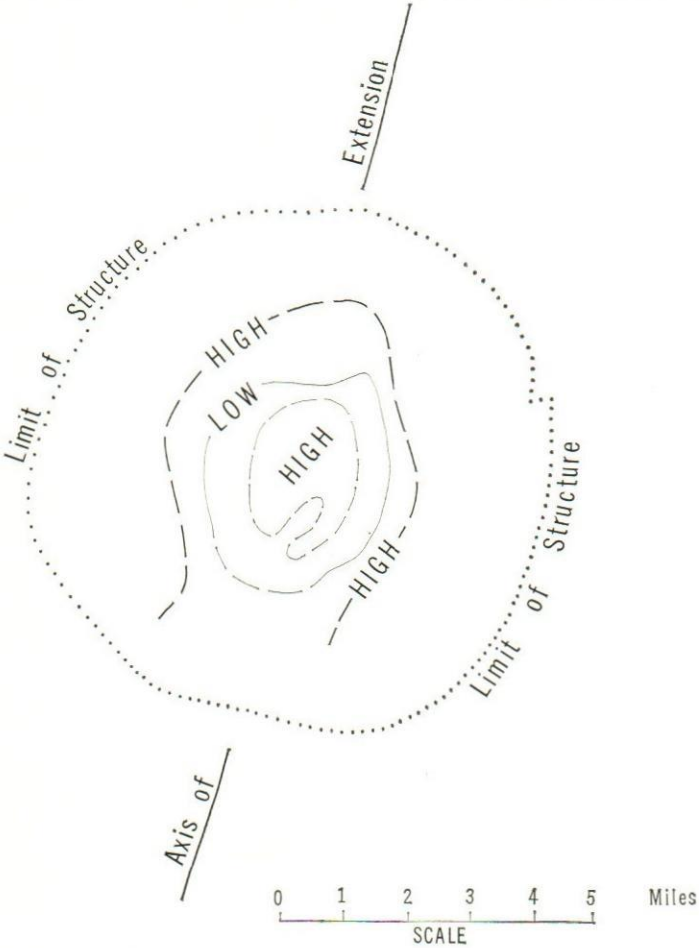


FIGURE 64.—The apparent pattern of anomalies related to the Wells Creek structure. Note the apparent north-northeast extension.

actly with the structural center, and the interior low is readily traced nearly around the structure, although it is slightly elongated in a north-northeast and south-southwest direction. The exterior high is not circular but horseshoe-shaped, being open to the south-southwest and perhaps also north-northeast.

The pattern of anomalies drawn on figure 64 shows an extension slightly east of north. This apparent trend does not parallel the main gravity promontory, nor does it cross the crest of the nose. The structure is not located symmetrically with respect to any of the regional features, nor does its symmetry parallel regional trends. It is approximately parallel to a main regional joint set trending N. 10° E. Because the joint set predates the structure and appears to control the structural shape at the surface, it may have controlled the shape of buried breccia masses or Knox dolomite and so influenced the gravity field.

INTERPRETATION OF ORIGIN OF THE WELLS CREEK STRUCTURE

HISTORY OF CONCEPTS OF ORIGIN

In Safford's earliest known description of Wells Creek Basin (1869, p. 147), no reference is made to the possible origin of the structure other than, "The strata were lifted in a high dome, the top of which has been worn and washed away." Safford (Killebrew and Safford, 1874, p. 761-762) describes "signs of great disturbance" and states that, "There are evidences of a terrible subterranean convulsion at one time" and, "The center of the basin has been elevated by subterranean forces."

In Goodspeed's History of Tennessee, 1887 (volume including Montgomery, Houston, and Stewart Counties, p. 974) the following quote is the earliest known specific (but unique) reference to origin:

> The views of the State Geologist [Safford] and of eminent scientists who have visited this locality, disapprove the usual theory of novices that this basin was formed by volcanic action.

Safford and Lander (Wilson and Stearns, 1966) were more concerned with the description of the annular faults than with an interpretation of origin of the structure.

Bucher (1936) described six structures in the United States, including Wells Creek Basin, which he called "cryptovolcanic," the name originally used by Branca and Fraas (1905) for the Steinheim Basin in Germany. His generalizations on Wells Creek and other cryptovolcanic structures are as follows (p. 1074-1076):

> 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 permit 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 * * *. The structures here described must be considered unsuccessful attempts of volcanic materials to break through to the surface.

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 uplifting 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 French Auvergne. In fact, the largest known explosion crater, the Ries Basin of Germany, was formed in precisely this way.

* * *

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'):

(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.

In 1936 and 1938 Boon and Albritton published papers on meteoritic craters, suggesting that Wells Creek Basin is an example of an ancient meteoritic scar on the earth's surface.

Thus there were established the two major theories of the origin of Wells Creek Basin: (1) cryptovolcanic, as proposed by

Bucher, and (2) meteor impact, originated by Boon and Albritton. For a period of years the conflict between the two schools of thought was relatively dormant. During this period Wilson (1953) accepted the meteor impact origin of the Wells Creek structure with it subsidiary Indian Mound craters and a similar origin for the Flynn Creek structure. Dietz entered the discussion as early as 1946, strongly advocating origin by meteor impact and stressing the genetic significance of shatter cones. He first suggested use of the noncommital name "cryptoexplosive" to replace "cryptovolcanic" of Bucher and later proposed the name "astrobleme" (starwound) for the structures (Dietz, 1959, 1960, and 1963).

In 1963 the two protagonists, Bucher and Dietz, marshalled their arguments in the American Journal of Science.

With the advent of the Space Age and the study of the moon much work has been done and many papers published on the nature of these structural features, in large part concerning their possible genetic relationships to the craters of the moon. Interest in crater origin is indicated by the 782 publications on this subject listed in Bulletin 1220 of the U. S. Geological Survey (Freeburg, 1966).

ALTERNATIVE INTERPRETATIONS

We shall endeavor to set forth the possible conclusions that may be drawn both from results of this project and from results and interpretations of other investigations. Finally, we shall present the meteor impact hypothesis which we prefer.

At this time the two hypotheses that appear to the writers to be capable of explaining the Wells Creek structure are (1) the meteor impact hypothesis, or (2) the cryptovolcanic (volcanic steam explosion) hypothesis. The writers find it easier to rationalize all the data known about the structure by using the meteor impact theory rather than the volcanic blowout theory, and so we will discuss the meteor impact theory at greater length.

Observations that can be rationalized readily by the meteor impact theory but not by the volcanic theory are: (1) the inward movement of the ring horst without any recognizable net vertical movement, and the inward movement of the rocks of the central block; and (2) the pattern of shatter cones pointing inward and upward relative to bedding.

The presence of the "subsidiary" Indian Mound craters [1] aligned with the structural axis of symmetry, joint direction, and gravity extension might be as readily explained as subsidiary blowout craters than fragments from or satellites of a main meteor.

Unfortunately, the data and logical conclusions from this study, as in the case of the other studies of cryptoexplosive features, are equivocal, so that more than one interpretation is possible—in this case meteor impact or volcanic explosion. Unfortunately, also, debates as to the origin of such equivocal structures usually center on which side should bear the burden of proof. Any theory of origin must rationalize all the data and account for all the relationships. The words of Beals (1965, p. 913) seem particularly appropriate here:

> In conclusion I should like to suggest that in addition to more thorough observation of ancient craters it is important to examine critically the fundamental physical criteria of identification, wherever possible, in quantitative terms. It would appear that volcanologists and meteoriticists could well collaborate in such an effort, especially if each would be prepared to do a little leaning over backward to understand the point of view of the other. Even when satisfactory theoretical criteria of identification and interpretation are worked out, it frequently happens, especially in scientific fields such as geophysics, geology, and astronomy, that there are serious difficulties in the way of obtaining sufficiently complete data for final proof. Under such circumstances it is necessary to rely on the gradual accumulation of relevant material, the development of hypotheses and their alteration or rejection as investigations proceed. It looks as though this will be the prospect for the identification of lunar and terrestrial craters, at least for the immediate future.

WELLS CREEK STRUCTURE AS A VOLCANIC BLOWOUT FEATURE

Figure 65 shows a hypothetical cross section of the Wells Creek structure as a volcanic explosion feature. The inner ring graben is interpreted as a collapse cone that converges downward into a zone under the center of the structure, where from time to time there were steam pockets. The steam drove a plug of rock within the central block upward. This upward moving rock plug dragged up adjacent beds.

It is visualized that when a gas blowout occurred it created a void at depth by lifting the plug of rock in the center toward the

[1] The Indian Mound craters, unfortunately now largely concealed, were used by Wilson (1953, p. 765) as evidence for meteor impact but by Bucher (1963, p. 624-625) as evidence for volcanism.

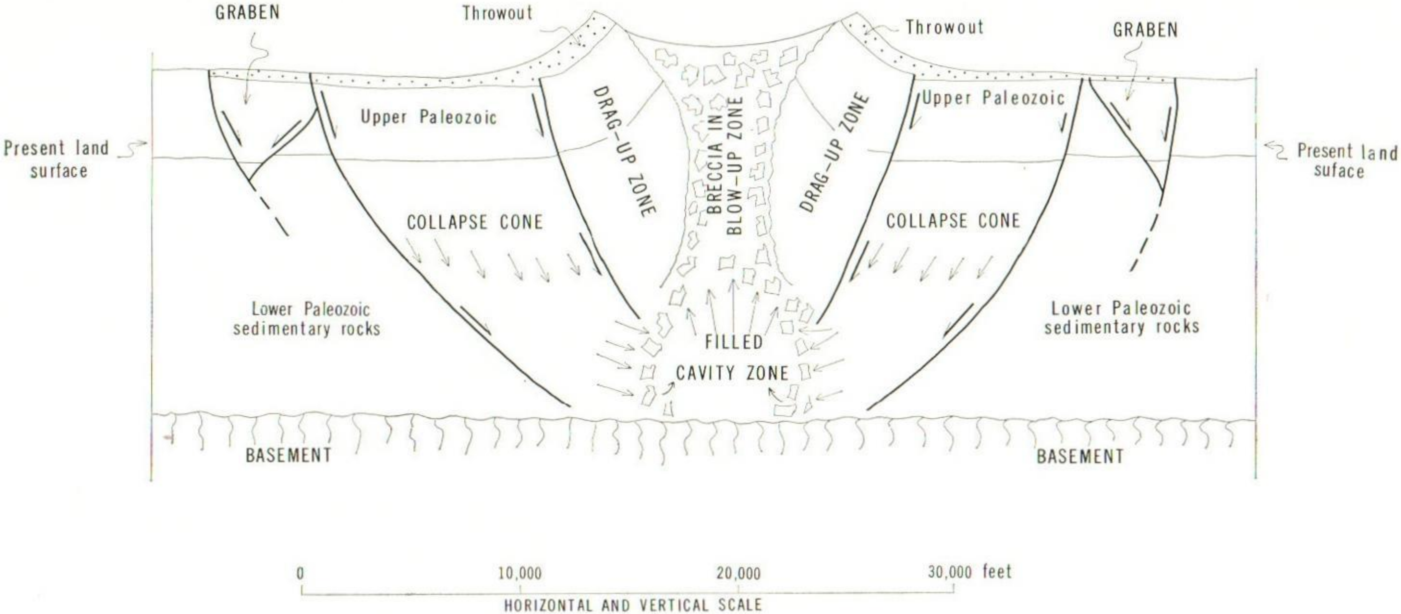


Figure 65.—The Wells Creek structure interpreted as a volcanic blowout surrounded by collapse cones and a graben. Note that an ancient land surface nearly a mile above the present surface can be assumed.

surface. After this, the void was filled rapidly by rocks collapsing inward from the collapse cone, i.e. the inner graben. The inward movement of the horst perhaps can be explained as lateral slippage toward the inner graben collapse cone. If the outer graben is interpreted as a collapse cone extending beneath the horst, it is very difficult mechanically for the horst to have maintained its normal position. The writers cannot understand how forces in a volcanic eruption could move the horst inward. We have interpreted the outer graben as terminating at depth, where inward movement of the horst ceases.

This theory permits repeated gas-jet events rather than one horrendous violent volcanic explosion. However, such a single explosion, in structural principle, could have occurred; the central Knox might have been blown out as a gigantic plug in one upheaval, and the rock of the ring structures crushed inward and downward in one rapid event. Dachille and Ulmer (1964) argue against the volcanic explosion theory, suggesting that it is highly improbable that enough supercritical steam could be gathered in one place at one time to form such a structure without leaving clearly recognizable field evidence of thermal activity. This argument is most effective against the single explosion model but cannot be used as readily against a multiple event model.

The balance between uplift of the central part of the structure and downsinking of the grabens strongly suggests that there was no intrusion of an igneous mass at depth (unless stoping balanced intrusion). Therefore, this hypothetical event, if it occurred, involved eruption of steam without magma emplacement.

Lack of mineralization (other than large amounts of silicification, and negligible amounts of sphalerite and fluorite) or volcanic material weakens the cryptovolcanic theory (just as lack of remains of a meteorite weakens the meteor impact theory). An additional problem for cryptovolcanic origin is to explain how the horst and perimeter of the central block would have "ended up" at approximately their original horizontal position during such an occurrence, although the explanation for this is difficult with any theory. The explanation of shatter cones by the contrary hypothesis of meteor impact weakens the volcanic theory; that is, the volcanic hypothesis fails to rationalize shatter cones.

THE STRUCTURE AS A METEOR IMPACT CRATER

Theory of Explosive Meteor Impact

The following is an outline of the events that would have accompanied the impact of a sizable meteor traveling at the several-miles-per-second velocity necessary to form the Wells Creek structure. It is based mainly on Baldwin (1963, especially p. 69-71), Shoemaker (1959), and Gault, Quaide, and Overbeck (1966).

A sizable object strikes the earth at a velocity that far exceeds the speed of sound in rock (for example 10 to 50 miles per second). At such velocity events occur that are beyond ordinary earthly experience. In both the meteorite and the rock that it compresses, pressures may rise to millions of atmospheres, and temperatures to hundreds of thousands of degrees centigrade. The rocks are deformed in unprecedented, "unearthly" manner. As a further result, a crater is "blasted out" as with the energy of an atomic explosion.

When the meteor strikes it may penetrate about twice its diameter into the earth. As it hurtles into the earth some rock, in addition to part of the meteorite, is "jetted" out to make the preliminary crater, but all the rock beneath the meteorite is "not able to get out of the way" and is violently compressed. Thus the meteorite drives before it a compressed buffer wad of rock. When the meteorite comes to rest (in the case of Wells Creek, perhaps after a tenth of a second), the highly compressed meteorite and wad of rock explode. The result is both a crater and a mushroom cloud similar to an atomic explosion.

During the explosive stage there probably is a fiery gas ball at the center of the exploding mass. Next to the gas ball would be a spherical shell of molten rock surrounded by solid rock. The explosion of the whole mass excavates a vast crater by ejection and compression with much destruction, crushing, pulverization, bending and fracturing of rocks beneath and beyond the limits of the actual crater, to make the circular deformation patterns of Wells Creek and other cryptoexplosive structures.

Much compressed material is blown out of the crater, including the squashed and shattered meteorite which for an instant occupied the top of the wad of highly compressed rock before complete fragmentation and destruction. From the center of the explosion zone enormous pressures produce shock waves that travel outward in all directions. These shock waves travel faster than the speed of sound in the rock, and their effect is to create breccia and shatter cones. Eventually, the shock waves attentuate and become elastic seismic waves.

The Wells Creek Structure

PENETRATION OF THE METEORITE

Orientation of shatter cones, which supposedly point toward the direction from which hypervelocity shock waves came, shows that shock waves originated within the top of the Knox Dolomite. If we assume that this is a meteor impact structure, the meteorite penetrated beneath the earth's surface to a depth sufficient to result in shock waves emanating from near the top of the Knox Dolomite; that is, the meteorite (and the compressed wad of rock beneath it) penetrated as deep as the lower Stones River limestone and upper Knox Dolomite. It is estimated that the meteorite itself must have penetrated at least 1,500 feet and perhaps 2,000 feet into the ground.

Strata preserved in the grabens show that a minimum of about 2,500 feet of rock covered the Knox Dolomite before the Wells Creek event. How much additional rock covered this area and subsequently was removed is not known. A reasonable estimate would be that the meteorite itself penetrated at least 1,500 feet of rock and that the highly compressed rock wad extended at least another 500 feet, so that when it exploded shock waves originated from at least 2,000 feet underground (above the Knox). If any additional rock is presumed to have covered the region, the meteorite and leading rock wad must have penetrated correspondingly deeper than 2,000 feet.

Baldwin (1963) has shown that depth of penetration and size of the meteor are related. Diameter of the meteor is about half the penetration depth. Therefore, if our judgment of penetration is correct, the meteor probably was from 750 to 1,000 feet in diameter.

POSITION OF PRESERVED ROCK RELATIVE TO THE ORIGINAL CRATER

We believe that the topographic Wells Creek basin exists today only because the uplifted limestone rocks were carved out by differential erosion. Rock now exposed at the surface, though it was jumbled into megabreccia, probably was never actually lifted into the air. No loose crater breccia has been preserved from erosion. There is some possibility, however, that breccia in Decatur Limestone (600 feet south of the intersection of Scott and Schmid Branch Roads) may contain some redeposited crater debris.

RELATIONSHIP OF GRABENS AND HORST TO ORIGINAL CRATER[1]

Three examples of craters surrounded by exterior structures are described in published reports. One is the Deep Bay crater in Canada (Innes, Pearson, and Geuer, 1964). A second is an analysis of the remaining original rims at the Ries Kessel (Johnson and Vand, 1967). The third is the Orientale Basin at the visible edge of the moon.

At Deep Bay an exterior ring depression makes the total structure about twice the diameter of the actual crater. At Ries Kessel there are at least two "subsidiary rims," which perhaps reflect ring structure. The Deep Bay crater's exterior depression makes that entire structure about 12 miles in diameter (the exterior depression perhaps is the analog of the Wells Creek outer graben; the analog of the Wells Creek interior graben perhaps is underneath the edge of the Deep Bay crater itself).

The larger the structure, the more exterior rings relative to the central crater might be expected. The Ries Kessel is larger than the Wells Creek structure, so that of its two exterior rings the interior one by analogy might correspond to the outer graben of the Wells Creek structure; the equivalent of the inner graben of Wells Creek might be beneath the main inner rim at the Ries Kessel; and the outer structure at the Ries Kessel would have no analog at the Wells Creek structure.

John McCauley of the U. S. Geological Survey is quoted by *Time* Magazine to the effect that the vast ring depression structure on the moon's surface, the Orientale Basin, is a large impact crater with exterior rings (*Time* Magazine, June 16, 1967, p. 54).

These relationships suggest that the original crater diameter at Wells Creek probably was considerably less than the 8-mile diameter of the ring deformation zone.

[1] The reader is referred to a discussion of exterior structures on the experimental 500-ton-TNT (Snowball) crater made by the Defense Research Establishment, Suffield, Canada (Roddy, 1968, p. 314-317).

RECONSTRUCTION OF THE ORIGINAL CRATER BASED ON RELATIONSHIPS BETWEEN CRATER PARAMETERS

The Wells Creek structure has been eroded to an unknown extent (more than 500 feet, and we will arbitrarily use 1,000 feet as a basis for later reconstruction), and therefore any estimate of the original crater is automatically an exercise in hypothetical reconstruction requiring many assumptions. First, it is assumed that the relationships between crater parameters as set forth by Baldwin in 1963 (chapters 7 and 8) are correct, and that they are applicable to this structure. Because the original crater has been destroyed, it is necessary to assume several crater sizes as a basis for comparison and restoration. For this purpose we will use the following three crater sizes:

(1) The distance from the middle of the outer graben to the corresponding point across the structure is about 40,000 feet. This diameter, measureable at the surface today, will be used as the maximum possible size of the crater.

(2) Baldwin (1963, p. 150, fig. 25), placing the crater rim over the horst zone, interpreted the Wells Creek structure as having a diameter of 6½ miles or 34,500 feet. This will be used as the intermediate possible size of the crater. This is only slightly larger than the 6-mile diameter postulated by Wilson in 1953 (p. 765).

(3) A minimum diameter of 21,500 feet (approximately half the average diameter of the Wells Creek structure) is derived by the relationship between the pattern at Wells Creek and the Deep Bay crater (Innes, Pearson, and Geuer, 1964). The Deep Bay crater is approximately half the diameter of the deformed zone. The deformed zone at Deep Bay, like Wells Creek, includes a depression or grabenlike structure that surrounds the actual crater. This is the preferred interpretation, as will be shown.

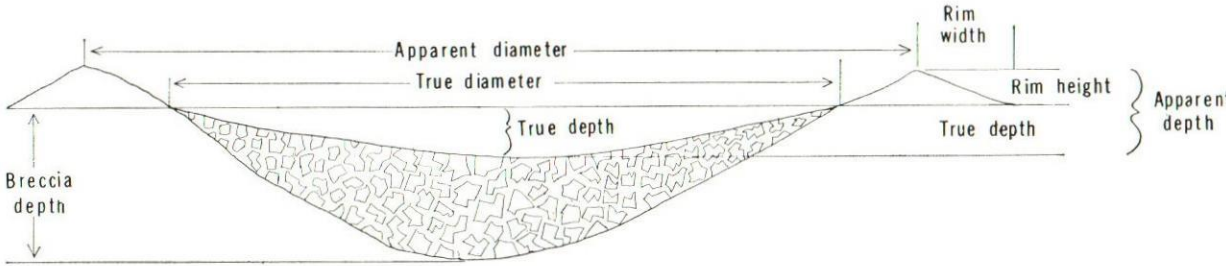
The following estimates are used in this interpretation (based upon our evidence for Late Mississippian age of the structure and our postulation of 1,000 feet of erosion below the original land surface): (1) the breccia depth below the original land surface was at least 4,500 feet, but we estimate it to have been no more than 7,000 feet; (2) the true crater depth would have been less than 3,000 feet (true crater depth is the depth of the crater floor beneath the level of the surrounding region); and (3) the breccia depth below the true crater was at least 2,000 feet, and we estimate it to have been closer to 4,000 feet.

The three proposed diameters help us to calculate the other components of the structure and to determine whether they are consistent with our estimates. This comparison led us to prefer a crater diameter of 21,500 feet. The various measured components of craters and the equations relating them are shown in a reconstruction of an idealized crater without a central uplift (fig. 66). Table 6 gives the parameters calculated from the three proposed diameters.

TABLE 6.—*Parameters (in feet) of three alternative craters for Wells Creek structure.*

	Maximum	Baldwin's est.	Preferred minimum
Apparent diameter	40,000	34,500	21,500
Apparent depth	4,100	3,800	2,500
True diameter	33,200	28,600	17,800
True depth	2,800	2,700	1,800
Rim height	1,250	1,100	700
Rim width	8,000	6,900	4,300
Breccia depth (depth below original ground surface to base of breccia)	10,800	10,000	6,000

The true crater depths calculated from the three diameters are all consistent with our estimate. Close to our 3,000-foot maximum estimate are the depths calculated for diameters of 40,000 and 34,500 feet, where the true depths are calculated to be 2,800 and 2,700 feet, respectively. By using the breccia-depth estimate, we find that both the 40,000-foot and 34,500-foot diameter craters require breccia to extend nearly 11,000 or 10,000 feet below the original surface. This exceeds our maximum estimate of 7,000 feet by 4,000 feet and 3,000 feet, respectively. From these calculations we conclude that if our maximum estimate of breccia depth is correct (and this estimate is not based on facts), the diameter of the crater more likely would be nearer the minimum estimate of 21,500 feet derived by analogy between Wells Creek and the Deep Bay crater in Canada.



$$D = 0.0256d^2 + d + 0.6300$$

$$R_H = 0.004366D^3 - 0.054571D^2 + 1.1316D - 1.3800$$

$$R_W = D - 0.70$$

$$B = 1.2658d_1 - 0.3417$$

where D = Log of apparent diameter in feet

d = Log of apparent depth in feet

R_H = Log of rim height in feet

R_W = Log of rim width in feet

B = Log of depth to base of breccia lens below the original ground level

d_1 = true crater depth below original ground level

True diameter = 0.830 apparent diameter

FIGURE 66.—Scale drawing of an idealized impact crater showing parameters (from Baldwin, 1963). Equations are after Baldwin, p. 137, 143, 145, 147, and 148.

ESTIMATION OF VELOCITY, MASS, AND SIZE OF METEOR

We find from calculation that an impacting Ni-Fe meteor, 1,000 feet in diameter, traveling 10 miles per second, would penetrate an appropriate distance, and would yield enough energy to make a crater 21,500 feet in diameter; or a stony meteor only slightly smaller (900 feet in diameter) traveling at 25 miles per second would form a crater of similar size. A meteor traveling slower than 10 miles per second would be too large, and a meteor traveling much faster than 25 miles per second would be too small. Ten miles per second, therefore, seems a reasonable minimum speed estimate (for a Ni-Fe meteor; this would be too slow for a stony meteor 1,000 feet or less in diameter), and 25 miles per second seems a reasonable maximum (for a stony meteor; this would be too fast for the minimum Ni-Fe meteor).

By using Baldwin's equations, graphs, and tables (1963, table 16, p. 170) relating the energy of impact to crater size, and relating meteor size and velocity to energy, we can estimate the possible meteor velocities necessary to form craters of various sizes. From Baldwin's tables we can derive a specific energy necessary to form a specific size crater, but having done this a velocity must be assumed to calculate a mass, or vice versa.

We can calculate the mass and then the diameter of a meteor that would yield the necessary energy for any given crater size only if we assume a velocity (and vice versa). For convenience, we will use velocities of 10, 25, and 50 miles per second for which related masses and energies have been calculated by Baldwin (1963, table 16, p. 170). A velocity of 10 miles per second is the approximate minimum necessary to create shock phenomena, such as shatter cones, and 50 miles per second is the approximate maximum observed velocity of meteors. Table 7 shows the results of these calculations.

The preferred interpretation is that a meteor nearly 1,000 feet in diameter and weighing from 20,000,000 to 100,000,000 tons struck the earth while traveling between 10 and 25 miles per second (36,000 to 90,000 miles per hour).

MINIMUM ENERGY EXPENDED TO FORM THE STRUCTURE

By mass uplift inferred from geologic sections, about 1.6×10^{17} foot pounds of net work must have been done in lifting the rock

TABLE 7.—*Energies and corresponding meteor characteristics necessary to form the original Wells Creek crater.*[1]

	Diameter of 40,000 feet		Diameter of 34,500 feet		Diameter of 21,500 feet*	
Estimated total energy (calories)	4 x 10^{19}		2 x 10^{19}		3.8 x 10^{18} *	
Estimated minimum energy to form crater and rim (calories)	8 x 10^{17}		4 x 10^{17}		6.6 x 10^{16} *	
Estimated minimum energy to form central uplift (calories)	5 x 10^{16}		5 x 10^{16}		5 x 10^{16} *	
Mass of meteors (pounds) that would yield estimated total energy for three selected velocities:						
10 miles per second	3.6 x 10^{12}		1.7 x 10^{12}		3.0 x 10^{11} *	
25 miles per second	5.6 x 10^{11}		2.6 x 10^{11}		4.3 x 10^{10} *	
50 miles per second	1.3 x 10^{11}		6.4 x 10^{10}		1.1 x 10^{10}	
Diameter of meteors (feet) corresponding to the above mass figures for Ni-Fe meteors and stony meteors:						
	Ni-Fe	Stony	Ni-Fe	Stony	Ni-Fe	Stony
10 miles per second	2,100	2,900	1,800	2,500	1,000*	1,400
25 miles per second	1,200	1,700	1,000	1,400	600	900*
50 miles per second	800	1,700	700	900	400	500

[1] Calculations mainly based on Baldwin, 1963, p. 157 and 170. Numbers are approximate. Preferred interpretations indicated by asterisks.

near the center of the Wells Creek structure. This is calculated only on the basis of vertical uplift and neglects lateral shifting and rock breakage. This expenditure of energy (equal to about 5 x 10^{16} calories), though large, is only equal to about 1 percent of the total estimated impact energy (Baldwin, 1963, table 16, p. 170). Indeed, the minimum energy used in excavating the crater and forming the rim (table 7) was only about the same modest fraction of the total estimated energy. Much more energy was dissipated by rock breakage, lateral movements, and unrecorded greater vertical movements as upthrown rock fell back. Still more energy was dissipated as heat.

DIRECTION OF APPROACH OF METEOR AS RELATED TO SHATTER CONES AND THE INDIAN MOUND CRATERS

A guess concerning the direction from which the meteor came can be developed by considering that shatter cones are markedly more abundant in the southern part of the Knox outcrop area, a zone that could have been ahead of a penetrating meteorite coming in from the north-northeast. Perhaps lesser accompanying meteors were slowed sufficiently by the atmosphere that they fell more vertically and behind the main meteor to form the Indian Mound craters.

FORMATION OF THE WELLS CREEK STRUCTURE (FIGURE 67)

General Interpretation.—The preferred interpretation is that a meteor nearly 1,000 feet in diameter and weighing from 20,000,000 to 100,000,000 tons traveling between 10 and 25 miles per second (36,000 to 90,000 miles per hour) struck the earth possibly from a north-northeast direction and penetrated about 2,000 feet before exploding. The explosive impact is interpreted to have resulted in a crater about 4 miles in diameter with a large central mound and exterior ring depressions (fig. 67).

Formation of Rock Structures by Rebound and Subsequent Collapse.—In the Wells Creek structure, we can infer from geological data the elastic rebound phenomena that followed impact. We advance no dynamic mechanism to explain why rebound effects were concentrated at the ring faults rather than being distributed as a myriad of small fractures. The indefinite "rebound" process is based on the structure as it is, rather than on fundamental mechanical principles.

We might suppose that the limit of the structure was controlled by the distance from the center that rebound exceeded the short-time tensile strength of rock. There may be a relatively sharp downward limit to the Wells Creek structure, i.e. the depth at which the tensile strength of rock exceeded the tension during rebound. This limit could be as sharp as the lateral limit at the surface.

Energy created when the meteorite was halted was consumed in part by hypervelocity shock waves, which compressed rock downward and outward as they advanced. The outward passage of these shock waves produced the Wells Creek structure as exposed today. As the wave approached a given imaginary point, the rock there was subjected to intense compressional stress (and was actually compacted for a short time); at the instant the wave front passed through this point, the rock was no longer being compressed and

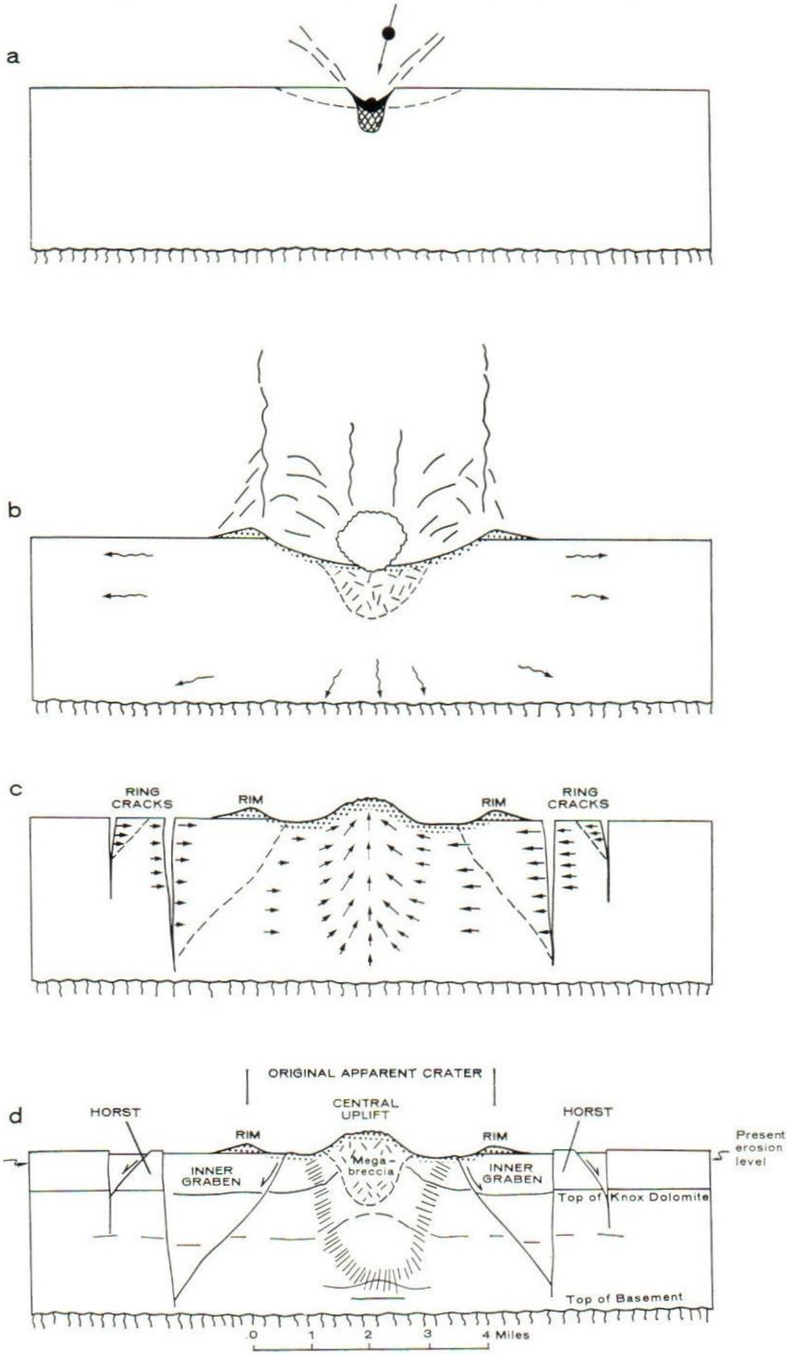


FIGURE 67.—Reconstruction of stages of formation of the Wells Creek structure as a meteor scar.

was free to expand; then after the wave front passed beyond the rock at this point, the rock was subjected to very rapid elastic volume expansion and tension.

Under the influence of this abrupt volume increase the rock first rebounded upward to form the central uplift, then inward to form the grabens and horst.

After the shock wave passed, intensely compressed rock "elastically" expanded. This threw rock near the initial crater inward and upward. However, while inward movement was occurring near the center, rock farther out was still being compressed by the advancing shock wave. Rock moved upward into the original crater first to form the central uplift because increasingly stronger rock at depth made vertical elastic rebound faster. Inward rebound continued and thrusts developed, slice-on-slice, as upper rock (Silurian) moved farther inward than lower rock (Ordovician). Inward movement near the surface, while outward compression continued, resulted in opening of a ring crack that was to be the Marable Hollow fault (fig. 67c). The shock wave front continued outward. Continued rebound still farther out resulted in opening another ring crack at the present outer limit of the structure (Erin fault). Finally, rocks of the grabens sheared off and slid downward and outward to close the Marable Hollow and Erin ring cracks (fig. 67d). The structure of today had been formed.

APPENDIX A

Descriptions of Surface Sections

This appendix includes descriptions of 15 surface sections in the vicinity of the Wells Creek structure, which are presented here to supplement the descriptions in the chapter on *Stratigraphy*. The appendix includes the entire stratigraphic interval between the youngest beds involved in the structure, the post-Ste. Genevieve (Paint Creek Limestone), and the oldest exposed beds in the Knox.

The sections were measured and described by James A. Hulme, assisted by R. C. Lagemann and M. F. Geiger, under the supervision of Richard G. Stearns and Herbert A. Tiedemann.

All surface sections are described in units from oldest to youngest, except Section 1, which is described from youngest to oldest.

SURFACE SECTION 1

Knox Dolomite

Quadrangle: Cumberland City
Location: Road Materials, Inc., quarry on Fairgrounds Hill
Tennessee Coordinates: [1] 727,000N., 1,513,400E.

This is the only good section of Knox Dolomite in the basin. It was easy to measure because the beds stand vertical, or nearly vertical. There are no covered intervals. The strike averages N.30°E. All measurements were made with tape.

At the time this section was measured the quarry consisted of the main excavation, oriented north-south, and an extension to the northwest. Measurement of the section was begun in the southeast corner of the main excavation, with the unit believed to be the youngest present. This orientation of the section is based only on minor cut and fill structures; it is therefore possible that those beds presently believed to be oldest are actually youngest. The section was continued westward along the road down the ramp along the south wall of the quarry to the southwest corner of the

[1] The Tennessee Coordinate System is a 10,000-foot rectangular grid established from a base point at the intersection of 86°00′ W. Longitude and 34°40′ N. Latitude, near Scottsboro, Alabama. This base point is assigned the values 2,000,000 feet east and 100,000 feet north.

main excavation. From here a bed was traced northward to the north wall of the main excavation, where the section was continued westward along this wall to the northwest corner of the main excavation. From here a bed was traced northward to the north wall of the extension. The section was continued westward along this wall to a point near the northwest corner of the extension, beyond which the section was inaccessible. At least 200 feet of beds were visible but not accessible. At that time 380 feet of Knox was measured and described, and an additional 200 feet or so was visible, making a total of about 600 feet exposed in the quarry.

A year later the quarry consisted of only one excavation, including both the main excavation and the northwest extension of 1965, the wall between the two having been removed. The procedure used to measure the beds in the quarry during July and August of 1965 is presented above although, because of changes in the quarry, this course cannot be traced now. Approximately 600 feet of Knox was still exposed in the quarry in 1966.

Thickness	
2′4″	Limestone, very pale-orange to yellowish-gray, fine-grained, in part coarse-crystalline. This is believed to be the youngest bed exposed in the quarry.
1′2″	Limestone, very pale-orange to yellowish-gray, fine-grained, in part coarse-crystalline; grayish-green streaks; dense, medium-gray chert inclusions more than 3 mm across; strike of bedding plane N.16°E., dip is 80°NW.
2′8″	Dolomite, light to medium greenish-gray, fine-grained, dense; some crystalline calcite; fractures filled with fine-grained calcite; some fractures show slickensides; greenish material on bedding plane
1′5″	Limestone, very pale-orange to yellowish-gray, fine-grained, in part coarse-crystalline
4′1″	Dolomite, yellowish-gray, fine-grained, in part medium-crystalline; calcite fills many fractures
1′	Limestone, very pale-orange to yellowish-gray, fine-grained, in part coarse-crystalline, dense appearance; some oolites; ¼″ of green shale
10″	Limestone, very dense, fine-grained, with scattered calcite crystals as much as 1″ across; 5″ on either side of bedding plane of preceding unit are chert inclusions;

Thickness	
	on the west side the inclusions are stopped by two or three vertical bedding planes filled with greenish material; pyrite crystals present
11′6″	Limestone, very pale-orange to medium-gray, fine-grained; some crystalline calcite along fracture surfaces; specks and stringers of greenish material; highly fractured; slickensides; bedding planes uneven; average thickness of beds 10″
8″	Dolomite, light olive-gray, fine-grained, in part cryptocrystalline; crystalline calcite along fractures; medium- to dark-green crusts also on fractures and bedding surfaces; some sphalerite present
11′6″	Limestone, very pale-orange to yellowish-gray, fine-grained, in part coarse-crystalline, dense appearance; greenish stringers concentrated in middle foot of the lithology; highly fractured; bedding planes uneven, look like stylolites; the bedding plane separating this lithology from the next has a light-green crust
3′2″	Dolomite, light olive-gray, fine-grained, in part cryptocrystalline, sugary texture, massive; streaks of medium- to dark-gray dolomite, average ¼″; many calcite-filled fractures
3′6″	Limestone, pale yellowish-brown, fine-grained, in part medium-crystalline, highly fractured; grades vertically into dolomite; slickensides
10′6″	Dolomite, medium-light gray to medium-gray, fine-grained, in part cryptocrystalline, some medium-crystalline calcite along fractures; grades vertically into dolomite, yellowish-gray to very light-gray, very fine-grained, dense, sugary texture
3″ to 12″	Limestone, pale yellowish-brown, fine-grained, in part medium-crystalline, highly fractured
1′	Dolomite, medium-light gray to medium-gray, fine-grained, in part cryptocrystalline, some medium-crystalline calcite along fractures
18′	Limestone, pale yellowish-brown, fine-grained, in part medium-crystalline, highly fractured; stylolites; some mottled, breccialike limestone
15′10″	Dolomite, dark yellowish-brown to brownish-gray, fine-grained, some fine-crystalline calcite along fractures; sugary texture; some white calcite veins; brecciated dolomite occurs with calcite; grades vertically into dolomite, pale yellowish-brown, fine-grained, in part medium-crystalline, fractured; apparent dip 50°

Thickness	
2′4″	Dolomite, light brownish-gray to dark yellowish-brown with inclusions of light olive-green; white calcite veinlets; calcite-filled fractures; slickensides on bedding planes; apparent dip 47°
45′	Dolomite, light brownish-gray to dark yellowish-brown, fine- to medium-grained, with dolomite, dark yellowish-brown to brownish-gray, fine-grained; dusky yellowish-green specks; much more breccia, probably due to intense folding; calcite veins cutting across and parallel to bedding; calcite along fractures; dark-green material along fractures and bedding; slickensides; example of calcite and dolomite breccia; areas of heterogeneous rubble breccia; dolomite in places is very limy and possibly contains a few lenses of limestone; within 3′ of contact of this lithology and the next bed of limestone are vertical color bands of dolomite cut through by heterogeneous rubble breccia; stylolites
2′3″	Limestone, very pale-orange, fine- to medium-grained
12′8″	Dolomite, very pale-orange to pale yellowish-brown, medium-grained, in part coarse-crystalline; grades into lithology of the preceding unit of dolomite; much heterogeneous rubble breccia, calcite rhombs in cavities
2′8″	Limestone, pale yellowish-brown, fine-grained, with medium-crystalline calcite; fractures; the first 4″ to 5″ of this lithology is transitional with preceding unit; slight brecciation
24′	Dolomite, light brownish-gray to dark yellowish-brown, fine-grained, mixed with dolomite, dark yellowish-brown to brownish-gray, fine-grained; good heterogeneous rubble breccia and chert breccia
3″ to 7″	Dolomite, dusky yellow-green, fine-grained, sugary texture; darker specks of dolomite
20′5″	Dolomite, light brownish-gray to dark yellowish-brown, fine-grained, mixed with dolomite, dark yellowish-brown to brownish-gray, fine-grained, highly fractured; bedding planes unrecognizable; tiny calcite veinlets
4′3″	Limestone, very pale-orange to yellowish-gray, very fine-grained, dense, brecciated, highly fractured; where breccia is not present the beds are fine-grained; some oolites; most breccia seems parallel to bedding; 2′ is limestone breccia; 7″ very pale-orange, very fine-grained limestone; 1′2″ of limestone; 6″ light breccia
1′8″	Limestone, very pale-orange to yellowish-gray, fine-grained, in part microcrystalline; color bands or lamina-

Thickness	
	tions; brecciated zones parallel to bedding; apparent dip 80° SE.
7″	Limestone, yellowish-gray, fine-grained, some oolites, argillaceous, very thin-bedded; shalelike appearance due to weathering; light greenish-gray to greenish-gray partings, may be weathered products; calcite veinlets along fractures
1′10″	Limestone, very pale-orange to yellowish-gray, very fine-grained; brecciated and fractured
6″	Limestone, very light-gray to greenish-gray, filled with light olive-gray sand grains; apparent dip 79° SE.
4′	Dolomite, light olive-gray with dark-gray specks throughout, light and dark color bands alternate; fine-grained; breccia throughout; calcite veinlets
8′5″	Limestone, yellowish-gray to light olive-gray with medium-gray specks and streaks, fine-grained, fractures and stylolites filled with crystalline calcite; bedding plane curves, and parts of the preceding lithology seem to be either faulted into the limestone or are lenses within the limestone; the thickest bed is 4′2″; stylolites commonly filled with dark-gray limy substance; breccia common; conchoidal fracture; bedding planes uneven and filled with dark greenish shaly, limy material
8″-9″	Limestone and shaly limestone, light olive-gray, fine-grained; some fine breccia; laminations in the lower 2″; some of the shaly material is greenish-gray
2′	Limestone, yellowish-gray to light olive-gray, fine-grained; no brecciation; conchoidal fracture; bounded on the east by a fairly sharp contact, on the west by uneven stylolitic contact
5′6″	Limestone, yellowish-gray to light olive-gray, fine-grained; brecciated, with breccia fragments less than ½″ across; breccia grades into light olive-gray, fine-grained limestone, with much crystalline calcite; many stylolites that include grayish blue-green partings in the bottom 2″; pyrite and limonite crystals; base of the bed dips 78° SE.
1′-1′3″	Shale, grayish blue-green, mixed with limestone, light olive-gray, fine-grained; shale is very undulating, compacted by overlying rocks; flowage appearance in places; pinches in and out; fractures in limestone filled with white crystalline calcite; shale is brittle because of thinness

Thickness	
	At about 12′ from measured line this lithology is faulted and many microstructures are visible; there are folds, tiny faults, compression of beds; the bed seems to be displaced approximately 1′; near the top of the quarry the shale bed is thinned to 3″-4″
7′3″	Limestone, yellowish-gray with some light olive-gray, fine-grained; some brecciation; veinlets of white crystalline calcite; fractured
3″	Shale, grayish blue-green, and limestone, yellowish-gray with some light olive-gray, fine-grained; some brecciation; veinlets of white crystalline calcite; fractures
20′	Limestone, yellowish-gray with some light olive-gray, fine-grained; some brecciation; veinlet of white crystalline calcite; fractures; lenses of greenish shale; one lens of the greenish shale is cut off from the parent mass; shale seems to be thin at the top—approximately 3″; it is about 1′ thick where it is separated into two parts; stylolites; fractures; joints
3′	Limestone, yellowish-gray to light olive-gray, fine-grained; some brecciation along the bedding; apparent dip of bedding plane 70° SE
7″-9″	Limestone, dark-gray to olive-gray with light-gray calcite crystals in the matrix, medium-grained with some coarse-grained areas, dolomitic; at the bottom are lenses of dolomite, dusky yellow-brown, fine-grained, highly fractured; brecciated where dolomite is mixed with limestone
4′3″	Dolomite, light olive-gray, fine-grained, with scattered specks of grayish-black dolomite that is covered with pyrite; banding occurs because of the lineation of these dark specks; calcite veinlets; beds (less than ½″) of light olive-gray, very fine-grained dolomite; darker dolomitic material seems to fill fractures and bedding planes
2′8″	Dolomite, transitional zone in alternations with the preceding unit of limestone
4′4″	Dolomite, dusky yellowish-brown, fine-grained; very highly fractured, fractures filled with fine-grained calcite, some patches of fine-grained sand
1′3″	Dolomite, transitional zone in alternations with preceding two units
2′10″	Dolomite, light olive-gray, fine-grained, sugary texture; bandings of olive-gray dolomite and greenish-gray,

Thickness	
	very fine-grained dolomite; commonly very crenulated; fractures filled with dolomitic material; one major joint filled with 3 mm of pure white calcite
3′2″	Dolomite, brownish-gray, fine-grained; fractures filled with calcite; upper 5″ faintly banded by olive-gray dolomite
6′	Dolomite, light olive-gray, fine-grained, sugary appearance; fractured, some calcite veinlets; color banding; grades vertically into dark yellowish-brown dolomite, highly fractured, fine-grained; apparent dip 68° SE; pyrite crystals
7′	Dolomite, pale yellowish-brown, fine-grained; highly fractured; possibly along a zone of movement; grades vertically into brownish-gray dolomite, fine-grained, sugary texture, with partings of brownish-gray dolomitic shale
10′	Dolomite breccia, brownish-gray, fine-grained, sugary texture; angular fragments as much as 1″ across; zones of unbrecciated, pale yellowish-brown dolomite; some patches of fine-grained sand
1′	Dolomite, pale yellowish-brown, fine-grained, sugary texture; specks of dark greenish-gray dolomite, dense
2′	Dolomite breccia, brownish-gray, fine-grained, sugary texture; angular fragments as much as 1″ across; zones of unbrecciated pale yellowish-brown dolomite; weathers to soft friable mass; large calcite-filled geodes
2′	Limestone, light olive-gray, very fine-grained, highly fractured; splotchy appearance due to darker dolomitic inclusions
2′6″	Dolomite, greenish-gray, fine-grained; specks and splotches of greenish-gray dolomite parallel to bedding; at top of this bed is a 1″ zone of very sandy, granular dolomite; apparent dip 75° SE
1′	Limestone, light olive-gray, fine-grained, dense; medium-crystalline calcite scattered throughout; some darker brown calcite crystals
6″	Dolomite, yellowish- to greenish-gray, fine- to medium-grained; some grains appear well-rounded, medium sand size; joints; color banding parallel to bedding; lower bedding plane is gradational with the next lithology
7′6″	Limestone, very light-gray to light olive-gray, fine-grained, dense, conchoidal fracture; calcite veinlets and calcite

Thickness	
	filling many fractures; medium bluish-gray argillaceous fillings in many fractures and along bedding planes; brecciated areas are composed of limestone, brownish-gray dolomite, and bluish-gray argillaceous material; also some blebs of dolomite outside the brecciated areas; beds average 2′ thick
7′4″	Dolomite, light olive-gray, micrograined to fine-grained, sugary texture; bluish-gray argillaceous material scattered throughout as irregular masses parallel to bedding; weathers medium-gray; fine-grained calcite also fills joints and fractures; beds of fine- to medium-grained limestone; seems to thicken slightly near ground level
1′	Dolomite and limestone; an interbedding of the preceding and following units
2′6″	Limestone, very light-gray to very pale-orange, fine-grained, dense, fractured; fractures filled with fine- to medium-grained white calcite
7′5″	Dolomite, white to light olive-gray, medium- to coarse-grained; calcite-filled fractures; nodular calcite, moderate yellowish-green
2′10″	Limestone, very light-gray to pale yellowish-gray, fine-grained with some medium- to coarse-grained calcite; dense; highly fractured
11″	Limestone, light olive-gray, fine- to coarse-grained, fragmental, crystals as large as 3 mm; appears to be a lens, with breccia on the bottom
1′	Dolomite, very pale-orange, very fine-grained, very argillaceous, highly weathered; shear fractures
4′3″	Dolomite, white to medium-gray, fine-grained, fractures filled with fine-grained white calcite; the lower foot is brecciated to a large extent and there is mixing of preceding and following two units
5′	Dolomite, light bluish-gray to medium-dark gray (color bands with wavy bands ½″ apart), fine-grained to microcrystalline, dense; many microstructures visible in the bands; bottom 6″ of this dolomite is mixed with the following bed, and there is some breccia; apparent dip 69°
1′6″	Dolomite, very light-gray to light olive-gray, fine-grained, dense; elongated dark-gray specks of dolomite
2′3″	Dolomite, dark yellowish-brown to dusky yellowish-brown, fine-grained; tiny calcite-filled fractures

Thickness	
3′10″	Dolomite, very light-gray to light olive-gray, fine-grained, dense; elongated dark-gray specks of dolomite; calcite-filled fractures, some pyrite crystals
4′	Dolomite, dark yellowish-brown to dusky yellowish-brown, fine-grained; tiny calcite-filled fractures
5′	Dolomite, yellowish-gray to light olive-gray, fine-grained, dense; tiny calcite-filled veinlets; stylolites and breccia occur together
12′+	Dolomite, dark yellowish-brown to dusky yellowish-brown, fine-grained; tiny calcite-filled fractures; interbedded with dolomite, yellowish-gray to light olive-gray, fine-grained; calcite veinlets; dense; brecciation and thrusting of beds common. This is believed to be stratigraphically the oldest bed measured in the quarry.
380′	Total

SURFACE SECTION 2

Stones River Group

Quadrangle: Cumberland City

Location: Section begins on east side of railroad tracks opposite south end of spur of Road Materials, Inc., and continues eastward from the tracks, north of, and parallel to, Bishops Branch

Tennessee Coordinates: 726,100N., 1,514,300E.

This is the only good section of the Stones River Group in the basin. The oldest Stones River in this section is believed to be 200 to 400 feet stratigraphically above the Knox measured at Section 1 in the quarry, which is a distance of about 1,200 feet northwest of the base of Section 2. This section is believed to include practically the entire sequence of the Stones River, as it begins near exposures of Knox and ends about 100 feet west of a field in which slabs and chert of the Hermitage Formation are exposed.

Because of the length of this section, plane table and alidade were used. Angle shots were kept at a minimum, and most of the shots were less than 200 feet. Thicknesses of beds were calculated from dips and strikes recorded on the plane table sheet.

Thickness	
2′	Limestone, light olive-gray (weathers to medium-gray), very fine grained to cryptocrystalline; conchoidal fracture; fractured
135′	Covered by railroad tracks; the true horizontal distance was 140′ but a dip of 79° was used and the thickness obtained was 135′
7′6″	Limestone, pale yellowish-brown to dark yellowish-brown (weathers to medium-gray), very fine-grained; fractured; taken east of the railroad tracks; strike north-south, dip 90°; beds are 1′ to 2′ thick; some shaly limestone in upper 3′ to 4′
6′	Covered
5′10″	Limestone, pale to dark yellowish-brown (weathers light- to medium-gray), very fine-grained to cryptocrystalline; slight conchoidal fracture; beds average 8″ thick
16′	Limestone, pale to dark yellowish-brown (weathers light- to medium-gray), very fine-grained; knobby or cobbly; calcite-filled fractures; strike N. 8° W., dip 75° SW.
3′10″	Limestone, pale yellowish-brown to yellowish-gray (weathers light-gray), very fine-grained; calcite-filled fractures; beds are thin—3″ to 4″ thick; upper 2′ platy, with some beds 1″ to 2″ thick; outcrop extends approximately 5′ to the north; strike N. 5° W., dip approximately 72° SW.
11′10″	Limestone, pale to dark yellowish-brown (weathers light- to medium-gray), very fine-grained; knobby; calcite-filled fractures; massive-bedded—as much as 3′ thick; strike north-south, dip 76° W.; one large block is 4′x8′
7′10″	Limestone, pale yellowish-brown to medium-gray, very fine- to medium-grained; crystals as large as 2 mm; surface weathers light- to medium-gray; some calcite partings; conchoidal fracture; cobbly; beds 1½′ to 2′ thick; strike north-south, dip 80° W.
5′10″	Limestone, pale to dark yellowish-brown, very fine-grained to cryptocrystalline; calcite-filled fractures; a few small calcite crystals; knobby, cobbly; massive-bedded; strike N. 7° W., dip 80° SW.
10′10″	Limestone, pale to dark yellowish-brown, very fine-grained to cryptocrystalline; calcite-filled fractures; knobby, cobbly; some very small calcite crystals; massive-bedded; strike N. 5° W., dip variable
15′8″	Limestone, pale to dark yellowish-brown, very fine-grained

Thickness	
	to cryptocrystalline; calcite-filled fractures; knobby, cobbly; some very small calcite crystals; beds range from 6″ to 1′ thick; strike N. 8° W., dip 85° SW.
20′	Limestone, pale to dark yellowish-brown (weathers light-gray), very fine-grained; knobby; cobbly; one calcite crystal about ¼″; strike N. 13° W., dip 86° SW.
12′8″	Limestone, pale yellowish-brown (weathers light-gray), very fine-grained; calcite geode ¼″ across; a few small calcite crystals and partings; massive; cobbly; strike N. 4° W., dip 81° SW.
12′8″	Limestone, pale yellowish-brown (weathers light- to medium-gray), very fine-grained; knobby, cobbly; massive; a few small calcite crystals and partings; strike N. 11° W., dip 73° SW.
3′10″	Limestone, pale to dark yellowish-brown (weathers to dark-gray), medium crystals in a fine-grained matrix; most calcite crystals less than 1 mm; beds range from 6″ to 1′ thick; cobbly
1′10″	Limestone, pale yellowish-brown (weathers light-gray), fine-grained to cryptocrystalline; knobby, cobbly; beds range from 6″ to 1′ thick; strike N. 5° W., dip 87° SW.
6′	Limestone, pale to dark yellowish-brown (weathers light-gray), fine-grained; knobby; a few calcite partings; beds average 12″ thick; strike N. 21° E., average dip 69° SE. From here to the end of the section the strike and dip change.
15′	Covered; some limestone blocks with same lithology as preceding unit
15′	Limestone, pale yellowish-brown (weathers light-gray), fine-grained; small calcite crystals; knobby; beds average 12″ thick; strike N. 21° E., dip 65° SE.
46′	Covered; some limestone blocks with same lithology as preceding unit and many chert blocks that probably weathered from the limestone; chert is dense, grayish-orange where fresh, highly fractured
7′	Limestone, pale yellowish-brown (weathers light- to medium-gray), fine-grained to cryptocrystalline; a few small calcite crystals; rough surface; beds average 12″ thick; strike N. 20° E., dip 63° SE. Chert nodules and lenses weather out in relief in the basal bed; chert is grayish-orange and intermixed in the limestone when viewed on a fresh surface

Thickness	
2′	Covered; much brecciated chert in soil
7′7″	Limestone, pale yellowish-brown (weathers light- to medium-gray), fine-grained, cryptocrystalline; a few small calcite crystals; rough surface; beds average 12″ thick; strike N. 20° E., dip 63° SE.
2′	Limestone, pale yellowish-brown (weathers very light-gray), very fine-grained to cryptocrystalline; some calcite crystals as large as 2 mm; calcite partings; knobby; beds average 4″ to 6″ thick; this is on the downslope (eastern) of the first small hill; strike N. 22° E., dip 82° SE.
6′4″	Covered; some loose limestone blocks similar in lithology to preceding unit
7′1″	Limestone, pale to dark yellowish-brown (weathers light-gray); calcite crystals as large as 2 mm; also calcite cyrstals in partings and small geodes; partly fine-crystalline; beds range from 6″ to 1′ thick; strike N. 14° E., dip 37° SE. to 42° SE.; this is near the bottom of a small valley
8′1″	Limestone, pale to dark yellowish-brown (weathers light-gray), very fine-grained; calcite-filled fractures; some chert nodules; beds range from 6″ to 1′ thick; strike N. 20° E., dip 55° SE.
3′10″	Limestone, pale to dark yellowish-brown (weathers light-gray), fine-grained; some calcite crystals as large as 2 mm; knobby; beds range from 1′ to 1½′ thick; strike N. 30° E., dip 56° to 58° SE.
7′7″	Limestone, pale yellowish-brown (weathers light-gray), fine-grained matrix, some medium-crystalline; some calcite crystals as large as 1 cm; beds range from 6″ to 1′ thick; strike N. 30° E., dip 50° SE.
9′1″	Limestone, pale yellowish-brown (weathers light-gray), very fine-grained to cryptocrystalline; small calcite veinlets; cobbly; beds average 1′ thick; strike N. 25° E., dip 52° SE.
4′7″	Limestone, pale yellowish-brown (weathers light-gray), very fine-grained to cryptocrystalline; small calcite veins; cobbly; beds average 4″ to 8″ thick; strike N. 25° E., dip 50° SE.
7′7″	Limestone, pale to dark yellowish-brown (weathers light-gray with almost chalky appearance), fine-grained in part, medium-crystalline; calcite crystals larger than 1

Thickness	
	mm; cobbly; beds range from 4″ to 8″ thick; strike N. 21° E., dip 42° SE.
15′6″	Limestone, pale to dark yellowish-brown (weathers light-gray), fine-grained to cryptocrystalline; a few small crystals; cobbly appearance in part; beds range from 6″ to 1′; strike N. 32° E., dip 42° SE.
10′7″	Limestone, pale to dark yellowish-brown (weathers light-gray), fine-grained; calcite partings; fractures; some small calcite crystals; knobby; strike N. 30° E., dip approximately 48° SE.
7′1″	Limestone, pale to dark yellowish-brown, fine-grained to cryptocrystalline; some calcite partings with crystals as large as 2 mm; beds range from 2″ to 4″ thick; strike N. 29° E., dip approximately 51° SE.
13′7″	Limestone, pale yellowish-brown (weathers same to light-gray), fine- to medium-grained; some calcite partings; beds range from 2″ to 4″; strike N. 23° E., dip 50° SE.
25′	Limestone, dark yellowish-brown (weathers same to light-gray), fine-grained matrix with crystals, medium up to 1 cm; knobby; beds range from 2″ to 4″ thick; strike N. 23° E., dip 50° SE.
35′	Covered
6′	Limestone, pale to dark yellowish-brown (weathers light-gray), fine-grained, some medium-crystalline; some fairly large calcite crystals; very rough weathered surface; beds range from 3″ to 6″ thick; strike N. 25° E., dip 46° SE.
5′	Covered
5′	Limestone, pale to dark yellowish-brown (weathers light-gray), fine-grained, some medium-crystalline; very rough weathered surface; chert, grayish-orange, dense, fractured and brecciated, weathers to porous, soft mass; beds range from 6″ to 1′ thick
15′	Covered
6′	Limestone, pale to dark yellowish-brown (weathers light-gray), fine-grained, some medium-crystalline; very rough weathered surface; cobbly beds range from 6″ to 1′ thick
25′	Covered
6′	Limestone, pale to dark yellowish-brown with specks of

Thickness	
	medium-gray; fine-grained; fossils; surface is pitted; massive; dense; strike N. 20° E., dip 44° SE.
5′	Covered
5′	Limestone, pale to dark yellowish-brown with specks of medium-gray; fine-grained; massive, dense; beds range from 5″ to 8″ thick; cobbly in places
10′8″	Limestone, pale to dark yellowish-brown (weathers light-gray), fine-grained; knobby; calcite veinlets; some small calcite crystals; beds average 1′ thick; strike N. 21° E., dip 53° SE.
13′10″	Limestone, very pale-orange to pale yellowish-brown (weathers light-gray), fine-grained; knobby; some small calcite crystals; beds range from 1½′ to 2½′ thick; strike N. 35° E., dip 54° SE.
20′	Limestone, pale yellowish-brown with grayish-orange argillaceous partings (weathers same), fine-grained to cryptocrystalline; some calcite crystals as large as ¼″; beds range from 6″ to 10″ thick; strike N. 35° E., dip 45° to 50° SE.
	Here, the bed changes its strike. There are many covered areas and much slumping. A fairly massive bed near the top of the last unit was traced to the north into a field containing several exposures of limestone that are not far below the base of the Hermitage Formation. The beds are all massive.
8′	Limestone, strike N. 5° W., dip 80°
12′	Covered
40′	Limestone; strike N. 7° E. at lower part and N. 5° W. at upper part; dip fairly consistent at 72° SE.
43′	Limestone; strike due north, dip approximately 85°
100′	Covered
3′	Limestone; a few small outcrops are approximately 150′ south of the line of measurement; strike due north, dip 85°
32′	Covered
3′	Limestone, fairly massive; strike north, dip 70° W.
33′	Mostly covered; a few small outcrops along strike, but none has definite strike or dip
5′	Limestone; a series of massive beds that average 1′ in thickness; strike north, dip 86° E.

Thickness	
49′	Covered
13′	Limestone, massive, with average thickness of beds 1′; strike N. 17° W., dip 84° SW.
1004′2″	Total

Hermitage chert and slabs in the soil about 100 feet to the east of this outcrop.

SURFACE SECTION 3

Fernvale Limestone

Quadrangle: Erin

Location: South side of Dolomite Station Hill, about 500 feet west of State Highway 149

Tennessee Coordinates: 720,100N., 1,510,500E.

Section begins about 8 feet west of the first exposure of Fernvale in the edge of a field and continues across the beds and covered intervals to the first exposure of Brassfield Limestone. About 26 feet of Fernvale was recorded. An interval of 17 feet is approximately the thickness of the Brassfield Limestone here.

On Dolomite Station Hill the beds strike N. 30° E. and commonly dip 30° SE. The section on a limb of a faulted syncline is broken by minor faults. The section was measured by tape.

Thickness	
1′6″	Limestone, yellowish-gray with dark yellowish-orange dolomite staining (weathers dark-gray), fine- to coarse-grained; fragmental texture; slightly argillaceous, with shaly partings
4′6″	Limestone, pale yellowish-brown with dark yellowish-orange staining (weathers dark-gray); in part fine-grained, in part coarse-grained and fragmental; argillaceous partings; most calcite crystals average 1 to 2 mm; fossil brachiopod and possibly bryozoa; thin-bedded with average 2″ to 4″; 2′ covered in this interval
2′	Limestone, pale yellowish-brown with dark yellowish-orange staining (weathers dark-gray); in part fine-grained; in part coarse-grained and fragmental; argillaceous partings, moderate dusky-red and greenish-

Thickness	
	black; areas of white calcite; beds range from 2″ to 3″; weathers to a soft sandy mass
16′	Covered
2′	Limestone, grayish-yellow to very pale-orange (weathers light- to medium-gray), fine- to medium-grained; massive; strike N. 35° E., dip 31° SE.
18′	Covered; probably Fernvale concealed here Note: Fernvale seems to be faulted over Brassfield in a small syncline, the section being measured on the west limb of the syncline. Strikes and dips are disturbed by folding and faulting. Beyond this covered interval are the basal beds of the Brassfield, which are light olive-gray, fine-grained, glauconitic limestone.

SURFACE SECTION 4

Brassfield, Osgood, Laurel (interval only), and Lego Formations

Quadrangle: Erin

Location: In Bishops Branch just east of State Highway 149 between Erin and Cumberland City

Tennessee Coordinates: 723,700N., 1,516,800E.

The Brassfield, Osgood, and Lego are fairly well exposed along Bishops Branch, but the Laurel Limestone is covered except for about 1 foot. The thicknesses are:

	Feet	*Inches*
Brassfield Limestone	18	11
Osgood Formation	42	10
Laurel Limestone (interval)	27	6
Lego Limestone	16	6
Dixon Formation (base only)	2-3	

The thicknesses were calculated from recorded strike and dip and from horizontal measurements with a tape. The dip, which is steep, is toward the center of the basin.

Thickness

Brassfield Limestone

1′	Limestone, light olive-gray, fine-grained, slightly crystalline, dense; many dusky bluish-green glauconite specks

Thickness	
2′7″	Limestone, light olive-gray to dusky-yellow (weathers to dusky-yellow), fine-grained; yellowish-gray rind is product of weathering; strike N. 56° E., dip 62° SE.
5′4″	Limestone, pale olive with greenish-gray argillaceous partings (weathers light greenish-gray), fine- to medium-grained; dense, subconchoidal fracture where not weathered; few specks of glauconite; beds 4″ to 10″; strike N. 53° E., dip 64° SE.
2′6″	Limestone, pale olive to light greenish-gray (weathers grayish-brown), fine-grained, some medium- to coarse-crystalline; few specks of glauconite; weathers to deep-red clayey soil
7′6″	Covered
Osgood Formation	
3′	Limestone, medium to dark reddish-brown with blebs or splotches of grayish-orange, argillaceous, very fine-grained; argillaceous partings give cobbly effect; some crinoid stems weather out; soil is reddish-brown
28′5″	Covered, with reddish-brown soil
11′5″	Limestone, medium to dark reddish-brown with blebs or splotches of grayish-orange, argillaceous, very fine-grained
Laurel Limestone	
27′6″	Covered
Lego Limestone	
16′6″	Limestone, medium- to coarse-grained, fragmental; concentrations of hematite specks; greenish-gray argillaceous partings; strike N. 79° E., dip 52° SE.
Dixon Formation	
2′-3′	Shale, greenish-gray, with fossiliferous clay shale

SURFACE SECTION 5

Laurel and Lego Limestones

Quadrangle: Erin

Location: On hillside east of State Highway 149, about 0.25 mile northeast of the point where the highway crosses Bishops Branch

Tennessee Coordinates: 724,700N., 1,516,800E.

This is a good section of Laurel and Lego, extending from the top of the Osgood to the base of the Dixon. The exposures are in a gully, and the strike is at right angles to its banks. Dip is fairly steep. Most of the section is continuous, but there are covered intervals in both Laurel and Lego. The thicknesses are:

	Feet	*Inches*
Osgood Formation (top only)		
Laurel Limestone	21	7
Lego Limestone	30	5
Dixon Formation (base only)		

Measurements were made with a tape, which was held across the strike. The average strike and dip of the entire section are N. 10° W. and 60° NE.

Thickness	
Laurel Limestone	
10″	Limestone, light-brown to moderate reddish-brown, fine-grained matrix with medium-grained white to light-brown calcite crystals throughout; crystals and fossil fragments weather in relief on surface; possibly a transition zone between Osgood and Laurel, having the lithology of both
2′11″	Limestone, dusky-yellow to grayish-orange (weathers dusky-yellow), fine-grained; argillaceous partings; rough weathered surface
5′10″	Covered
12′	Limestone, dusky-yellow to grayish-orange (weathers dusky-yellow), fine-grained; argillaceous partings; crenulated surface; isolated areas of moderate reddish-brown hematite specks; medium-bedded; rounded weathered surface; highly weathered beds are more pitted and rough
Lego Limestone	
7′7″	Limestone, moderate red to dusky-red (weathers moderate brown), medium- to coarse-grained, crystalline in areas; argillaceous partings are moderate yellowish-brown; fossil and calcite fragments weather in relief
2′11″	Covered

Thickness	
19'11"	Limestone, moderate red to dusky-red (weathers moderate brown), medium- to coarse-grained; argillaceous partings are dusky-yellow; fragmental; fossil and calcite fragments weather in relief; beds average 1½'; upper 4' to 5' has many more white calcite crystals on weathered surface; crinoid stems; fewer argillaceous partings

Dixon Formation

Limestone, dark reddish-brown (weathers moderate to dark reddish-brown), very fine-grained, argillaceous; few white to light-gray calcite crystals weather in relief on surface; argillaceous partings are dark yellowish-orange

SURFACE SECTION 6

Dixon, Brownsport, Decatur, and Fort Payne Formations

Quadrangle: Erin

Location: Along road up Lickskillet Branch, beginning a short distance east of State Highway 149 and continuing in the Fort Payne up the hill north of the road

Tennessee Coordinates: 720,600N., 1,514,200E.

This is the classic section of beds of the Silurian System in the basin. The formations, Dixon through Decatur, are all well exposed along the road. The Ross Formation, formerly exposed along the road, is no longer recognizable. The Chattanooga Shale is exposed in a small ravine north of the road. The section of the Fort Payne Formation begins with the top of the Chattanooga Shale and extends eastward along the road for a distance before turning northward up the hill to the north. Measurement of the Fort Payne was continued as far up the hill as bedrock could be found, and beyond as far as Fort Payne residuum could be recognized. The thicknesses are:

	Feet
Dixon Formation	38 plus
Brownsport Formation	
Beech River Member	21
Bob Limestone Member	17
Lobelville Member	37

Decatur Limestone	72
Ross Formation (not exposed)	
Chattanooga Shale (present but not measured)	
Fort Payne Formation	
Bedrock	235
Residuum	126

The strike crosses the road at a fairly low angle, and the dip of the beds is less than 45°. The beds of the Silurian and lower part of the Fort Payne along the road were measured by tape, but that part of the Fort Payne on the hill to the north was measured by hand level.

Thickness

Dixon Formation (an additional 10 feet of Dixon may be concealed below this section)

38′ Limestone, dark reddish-brown to light olive-green (weathers medium-gray), fine-grained; with argillaceous beds that weather light-yellow to olive-green; calcite crystals as large as 1 mm; layers of red and green splotchy beds; fossils, mostly crinoid stems, weather in relief, causing rough surface; some brachiopods and horn corals; the rock weathers to shaly material the same color as the rock; beds range from 6″ to 10″ in thickness

Brownsport Formation:

Beech River Member

14′ Limestone, light olive-gray (weathers medium-gray to light-brown), fine- to medium-grained; white to light-gray calcite replaces fossil fragments; in the lower 2′ glauconite grains compose 2 to 3 percent of the rock and commonly are less than 1 mm; fossil fragments weather in relief on surface; thickness of beds ranges from 7″ to 10″; thin, irregular clay partings coincide with undulated bedding planes

1′ Covered

3′ Limestone and shaly limestone, light olive-gray, fine- to medium-grained; many fossil fragments—mostly crinoid stems; average thickness of limestone beds 4″

3′ Shale and limy shale, light olive-gray, some fossils; average thickness of plates ½″

Bob Limestone Member

2′ Limestone, light olive-gray, fine-grained, argillaceous; a

Thickness

	few areas of medium-sized calcite crystals, light yellowish-gray; average thickness of beds 6″
2′	Covered
4′	Limestone, light olive-gray, fine-grained, argillaceous; a few areas of medium-sized calcite crystals, light yellowish-gray; average thickness of beds 2′
3′	Limestone, yellowish-gray to light olive-brown, shaly, fine- to medium-grained, crystalline; a few specks of glauconite; fossils weather in relief on surface; beds range from 1′ to 1½′ in thickness
6′	Limestone, light-gray (weathers light-green to grayish-black), coarse-grained; cobbly; beds average 4″ thick

Lobelville Member

37′	Limestone, light olive-gray (weathers light-green), fine-grained to coarse-crystalline; thickness of beds averages 4″; alternating with limy shale, with shale plates about 1″ thick; thin, uneven clay partings; cobbly; upper part transitional with lower Decatur; abundant crinoid fragments throughout

Decatur Limestone

72′	Limestone, light brownish-gray (weathers dark-gray), medium- to coarse-crystalline; calcite crystals; medium-bedded, average thickness of beds 2′; some beds have crenulated surfaces due to argillaceous partings; geodes; specks of hematite in several beds In the top 20′ of the exposed Decatur the beds are very fossiliferous, and some of the limestone is reddish-brown.

Top of Decatur Limestone

Break in section, including Ross Formation and Chattanooga Shale, within a horizontal distance of about 100 feet

Fort Payne Formation (beginning with top of Chattanooga Shale)

34′	Covered interval, has a few loose chert blocks
8′	Limestone, dark yellowish-brown (weathers grayish-orange), fine-grained, argillaceous, thin-bedded, platy; some small fragments of chert; strike N. 33° E., dip 35° SE.
3′5″	Covered
8′2″	Limestone, dark yellowish-brown (weathers grayish-orange), fine-grained, argillaceous, thin-bedded, platy.

Thickness	
	Chert, dusky yellow-brown (dark bluish-gray when dry), dense, very slightly crystalline; conchoidal fracture; bedded as lenses and nodules; some is streaked
38′6″	Covered, with scattered limestone and chert as in first unit
30′6″	Limestone, same as first unit, fine-grained, massive; beds appear about 3′ thick when weathered. Chert is medium-gray to olive-gray; chert and limestone are well-mixed; chert is in beds 3″ to 4″ thick and also as nodules and blebs that weather out on surface. N. 15° E., 15° SE. and N. 30° E., 25° SE. are the strike and dip of the last 10′ measured vertically
5′	Limestone with chert, same as preceding; chert occurs as nodules and lenses in relief on surface and parallel to bedding; beds average 12″ thick
13′3″	Limestone with chert, same as preceding two units; beds generally massive, 1′ to 2′ thick
6′3″	Chert, grayish-brown to dark yellowish-brown (weathers dark yellowish-orange), dense, conchoidal fracture; beds range from 4″-6″
15′3″	Limestone, light olive-gray to olive-gray, fine-grained, argillaceous; chert, grayish-brown to dark yellowish-brown, some beds dusky yellowish-brown; beds average 1″ thick; a few geodes
2′9″	Limestone, dark yellowish-brown (weathers light olive-gray), thin, platy, fine-grained. Most of unit is chert, dark yellowish-brown, fractured and jointed, very rough, streaked; other chert is dusky yellowish-brown; beds are no more than 2″ thick
2′7″	Covered
1′2″	Limestone, light olive-gray to olive-gray, fine-grained, argillaceous. Chert, grayish-brown to dark yellowish-brown, some beds dusky yellowish-brown; beds are 4″ thick; a few geodes
2′2″	Covered
25′	Limestone, dark yellowish-brown (weathers grayish-orange), fine-grained, argillaceous, thin-bedded, platy, slightly streaked appearance; chert, dusky yellowish-brown and dark bluish-gray; dip 23° SE
26′	Limestone, light-gray to dark yellowish-brown (weathers pale yellowish-brown), fine-grained, argillaceous. This marks the beginning of the typical upper Fort Payne; no bedded chert; chert weathers to a scraggy surface.

Thickness	
12′	Covered
1′	Limestone, light-gray to dark yellowish-brown (weathers pale yellowish-brown), fine-grained, argillaceous; "scraggy" chert weathers from limestone
126′	Covered, with scraggy chert and large chert blocks up to top of hill

SURFACE SECTION 7

Decatur Limestone and Ross Formation

Quadrangle: Cumberland City

Location: On south bank of Cumberland River about 1.1 miles west of Cumberland City

Tennessee Coordinates: 733,100N., 1,513,700E.

This is the best section of the Decatur and Ross formations in the basin. The section starts with the topmost beds of the Brownsport Formation at the edge of the river (now flooded by the lake) and continues southward up the bank to the old Dover-Cumberland City Road. The top of the Ross Formation could not be identified. The thicknesses are:

	Feet	*Inches*
Brownsport Formation (top only)		
Decatur Limestone	68	4
Ross Formation	39	10
Loose blocks of Camden-Harriman chert south of road		

The dip in this section is fairly low, southward into the river bank. The strike intersects the bank at an oblique angle. The section was measured by tape, directly across the strike.

Thickness	
Brownsport Formation (upper part)	
	Limestone, dusky-yellow, some light olive-gray, fine-grained, some coarse-crystalline
Decatur Limestone	
5′	Limestone, grayish red-purple to dusky red-purple, fine-

Thickness	
	grained matrix with coarse-grained calcite crystals, argillaceous; crinoid stems with recrystallized calcite; argillaceous partings; strike N. 28° W., dip 46° SW.
4′10″	Limestone, moderate-red to pale-olive; beds show differential weathering where the argillaceous partings weather more readily; coarse-grained; beds 8″ to 10″ thick; upper part has large calcite crystals and crinoid stems; strike N. 17° W., dip 46° SW.
3′10″	Limestone, light olive-gray to light olive-brown, medium- to coarse-grained, slightly argillaceous
1′8″	Limestone, moderate-red to pale-olive, coarse-grained; beds show differential weathering where argillaceous partings weather more readily
9′	Limestone, grayish-orange, medium- to coarse-grained; chert, light brownish-gray nodules, slightly porous, with argillaceous material, grayish-orange to dark yellowish-orange; fossils weather into relief on surface; dip 48° SW.
1′	Limestone, grayish yellow-green, fine-grained; crinoid stems; argillaceous or shaly partings; strike N. 35° W., dip 25° SW.
20′	Limestone, yellowish-gray, fine- to medium-grained
15′	Limestone, dark yellowish-orange, medium- to coarse-grained; argillaceous partings; calcite crystals as large as 2 mm, appear to be fossil fragments; approximately 3′ from the base are many crinoid stems
8′	Limestone, moderate yellowish-brown, medium-grained; crinoid stems; strike N. 20° W., dip 41° SW.
Ross Formation	
39′10″	Limestone, pale olive

SURFACE SECTION 8

Chattanooga Shale

Quadrangle: Cumberland City

Location: In roadcut on State Highway 149 about 0.5 mile west of Cumberland City, just south of intersection of this highway and the new Dover-Cumberland City Road

Tennessee Coordinates: 731,800N., 1,516,500E.

This section begins with clay and chert residuum of the Camden Formation and continues to the overlying Maury Shale. The thickness of the Chattanooga is 51 feet 1 inch.

Thickness	
Camden Formation	
	Clay, pale yellowish-brown; chert in the clay is light-brown to yellowish-gray, dense, slightly chalcedonic
Chattanooga Shale	
17′4″	Shale, pale yellowish-brown; some siltstone; strike N. 11° E., dip 46° NW. Above the 17′4″ unit the strike and dip change at a minor fault.
35′1″	Same as preceding unit; dip of beds lower at fault; strike N. 57° W., dip 10° NE.
5′8″	Same as preceding unit, except medium dark-gray where fresh; strike N. 70° W., dip 30° NE.
Maury Shale	
	Shale, weathered; identified by phosphate nodules

SURFACE SECTION 9

Fort Payne Formation

Quadrangle: Erin

Location: Along both sides of State Highway 149, beginning about 1,000 feet south of where the road down Spring Branch joins the highway, and continuing southward; about 1½ miles northeast of Erin

Tennessee Coordinates: 709,400N., 1,507,200E. to 710,300N., 1,508,300E. (west side of highway)

This section of Fort Payne, beginning at its contact with the Maury and Chattanooga Shales, extends southward along the bluff on the west side of the highway for about 1,750 feet. About 245 feet of Fort Payne was measured, along with about 30 feet of scraggy residuum above, making the total thickness 275 feet.

Dips are as low as 10° to 12°, and measurements were made with tape.

Thickness	
Chattanooga Shale	
	Soft weathered shale, pale yellowish-brown; about 1 foot of Maury Shale
Fort Payne Formation	
9′5″	Siltstone, dark yellowish-orange to dark yellowish-brown, thin-bedded (beds about 1″ or less), a product of weathering of "nonscraggy" limestone; interbedded with chert, grayish-brown, dense, in layers 4″ to 6″ thick at intervals of about 5′
12′7″	Siltstone, light-buff to light yellowish-brown; with a foot of limestone, olive-gray (weathers medium-dark gray), fine-grained, argillaceous. (This and the preceding unit probably correspond to the "basal shaly unit")
23′10″	Limestone, reddish-brown and olive-gray to brownish-black, fine-grained; beds 3″ to 7″ thick, the majority being 3″; with chert beds that average 1′ apart; geodes as much as 2″ in diameter; most of the limestone has been weathered to pale yellowish-brown silty clay
24′4″	Siltstone and limestone; with chert, as lenses and thin beds within the limestone, dove-gray, flintlike; limestone is generally olive-gray, shalelike in appearance, and fine-grained; the chert and limestone beds average about 1′ in thickness. There is a transitional zone between limestone bedrock and the silty interbedded mass that consists of beds of chert weathering directly out of the limestone.
2′5″	Limestone, dark yellowish-brown (weathers pale yellowish-brown), fine-grained, argillaceous, weathers shaly; calcite geodes; chert, olive-gray, dense, as large nodules and lenslike masses
26′4″	Limestone, dark yellowish-brown (weathers dark bluish-gray), fine-grained; chert (within limestone), pale yellowish-brown, lenses about 4″ thick; lighter colored chert seems to be a more highly weathered form of the darker chert; cherty limestone beds range from 6″ to 10″ in thickness
	Begin measurement again 200 feet south on the same side of the road; it is believed that there is no stratigraphic gap or overlap here.
3′11″	Limestone, yellowish-gray to light olive-gray (weathers light brownish-gray), fine-grained, porous; chert, bluish-gray, streaked and porous

Thickness	
2′11″	Covered
9′8″	Limestone, dark yellowish-brown (weathers pale yellowish-brown), fine-grained; platy weathering; beds to 2″; interbedded with chert (weathers to pale yellowish-brown), dense, beds 2″-3″; nodules of chert throughout the limestone; three beds of shaly limestone, each 2″ thick, 2½′ apart, with apparent dip of 6°
21′	Limestone, pale to dark yellowish-brown; and chert, dark yellowish-brown, streaked
	The next unit was described approximately 200′ south along the same bluff.
22′6″	Limestone, pale yellowish-brown, fine-grained; beds appear to be about 3″ thick; calcite geodes; and chert, dense, dark yellowish-brown (weathers pale yellowish-brown), as nodules, lenses (average 4″ thick), and inclusions; chert and limestone are streaked, mottled; apparent dip of 7°
12′6″	Limestone, light olive-gray (weathers light-gray), fine-grained; chert nodules; rough surface; platy weathered surface; calcite geodes; beds range from 3″ to 6″; beds are generally cherty and irregularly bedded, but are less cherty and more platelike in upper 3′ to 4′
	Again there is a 200-foot gap. Measurement is resumed about 200 feet south. Here, the variable, partly weathered beds were correlated by using the average dip.
74′6″	Limestone, very pale-orange to dark yellowish-brown (streaked), fine-grained, argillaceous; on weathered surface chert appears interbedded with the limestone; platelike beds ½″ to 1″ thick; rough surface; scraggy chert in soil; limestone and chert when dry are buff to light-tan. This ends that part of the section on the west side of State Highway 149.
30′	Covered; from the top of the exposed rock to the top of the hill is approximately 30′ of soil containing typical scraggy chert of the Fort Payne
275′11″	Total
	Just southeast of this section across Wells Creek additional exposures of fresh rock (similar to the 74′6″ above) plus 70 feet of residuum makes a total section of approximately 350 feet.

SURFACE SECTION 10

Fort Payne Formation and Warsaw Limestone

Quadrangle: Erin

Location: On north side of State Highway 49, about 800 feet northwest of Cedar Valley Methodist Church Cemetery

Tennessee Coordinates: 700,100N., 1,517,000E.

The contact between the Fort Payne and the Warsaw is well exposed, along with the upper part of the Fort Payne and the basal part of the Warsaw. Here, the contact is a distinct break in contrast with the usual gradational relationship. The thicknesses described are:

	Feet	*Inches*
Warsaw Limestone (partial......	11	6
Fort Payne Formation (partial)..	22	4

The beds in this section are so flat that a direct measurement by tape was used.

Thickness	
Fort Payne Formation	
20′	Limestone, yellowish-gray to light olive-gray (weathers medium-gray), fine-grained, streaked; geodes as large as 2″ in diameter; weathers to scraggy mass; beds approximately 6′
1″	Limestone, light olive-gray, fine-grained; chert, same as in following unit
2′3″	Limestone, yellowish-gray to light olive-gray, fine-grained, slightly argillaceous, streaked, cobbly, platy; chert, in very small amounts, nodular and lenticular, similar to chert in Warsaw but possibly darker
Warsaw Limestone	
2′	Limestone, light olive-gray, fine-grained; some stringers of light-gray material; lenses of medium-gray chert 1″ to 2″ thick and as much as 1′ long
1′6″	Limestone, yellowish-gray matrix with light olive-gray cal-

Thickness	
	cite crystals (weathers pale to dark yellowish-brown), medium-grained crystals in subchalky[1] matrix
3′10″	Limestone, yellowish-gray matrix with light olive-gray calcite crystals (weathers dark yellowish-brown), medium-grained crystals in subchalky matrix
2′6″	Limestone, light olive-gray, fine-grained, with a few calcite crystals less than ½ mm, slightly argillaceous; near the bottom of the unit the rock is more crystalline
1′8″	Limestone, dark yellowish-brown to olive-gray (weathers light olive-gray), fine-grained; interbedded with layers of olive-gray speckled to medium-gray chert; scattered calcite geodes

SURFACE SECTION 11

Warsaw Limestone

Quadrangle: Erin

Location: On north side of road up Bateman Branch near gas-line crossing about 0.5 mile northwest of Rye Loop Road (Sage Hollow)

Tennessee Coordinates: 690,000N., 1,519,200E.

This section is believed to begin near the base of the Warsaw Limestone. The thickness of Warsaw Limestone described is 64 feet 7 inches. Warsaw chert to the top of the hill extends up an additional 93 feet, indicating at least 157 feet of Warsaw.

In these essentially flat-lying beds measurement was made with tape.

Thickness	
Warsaw Limestone	
8′6″	Limestone, pale yellowish-brown to light olive-gray (weathers light-gray), medium- to coarse-grained; fossiliferous at base but less so ascending; beds 3″ to 6″ thick; lenses and blebs of chert and cherty limestone,

[1] The terms "chalky" and "subchalky" are used for distinctive limestone types that occur mainly in the Warsaw. These are the beds that weather to porous "cinder block" chert. "Chalky" limestone is composed of fine, silt-sized calcite that may consist mostly of finely broken fenestellid bryozoan fronds or other delicate fossil material. "Subchalky" limestone is more like ordinary granular limestone, as the fine fragments are mixed with larger fragments.

Thickness	
	reddish-brown; crinoid stems abundant; a few beds of fine- to medium-grained rock of the same lithology; small nodules of porous medium-gray chert
6′	Limestone, yellowish-gray to light olive-gray (weathers medium-gray), coarse-grained crystals in subchalky matrix; numerous small vugs; fossil bryozoa and small crinoids; beds more than 6″ thick; no chert nodules
3′6″	Limestone, light olive-gray to olive-gray (weathers medium-gray), very fine-grained; chert nodules, dark yellowish-brown, scattered in layers throughout but more concentrated near top of unit
2′3″	Limestone, yellowish-gray to light olive-gray (weathers light-gray), medium-grained with many calcite crystals averaging 1 mm; entire bed very fossiliferous (fragments of crinoid stems)
13′6″	Limestone, pale to dark yellowish-brown (weathers to pale yellowish-brown), fine-grained, somewhat argillaceous; some thin layers of dark yellowish-brown, very coarsely crystalline limestone, fragmental appearance, with fossil fragments and chert weathering out on surface, calcite crystals as large as 3 mm; thin-bedded cobbly-appearing limestone interbedded with lenses and nodules of dense, olive-gray chert
7′6″	Limestone, yellowish-gray, coarse-grained, calcite crystals averaging 1 to 2 mm; bryozoa; beds 3″ to 6″
6′8″	Limestone, light olive-gray (weathers light-gray), fine- to medium-grained crystals in subchalky matrix; abundant bryozoa and brachiopods; beds ½″ to 2½″; weathers to platelike masses; bedding surface undulated; thin beds probably represent argillaceous material remaining after calcite was dissolved
5′6″	Limestone, yellowish-gray (weathers light-gray); fine-grained matrix with coarse-grained crystals "floating" in the matrix—chalky; many calcite crystals averaging 1 mm; abundant fossil bryozoa; medium-bedded, beds range from 8″ to 12″
10′6″	Limestone, yellowish-gray (weathers light-gray), medium- to coarse-grained, calcite crystals as large as 1 mm; many fossils; beds average 6″ thick; near the top the beds become more coarsely crystalline, and a number of small geodes occur
8″	Limestone, yellowish-gray to light olive-gray (weathers light-gray), fine-grained with calcite crystals through-

Thickness	
	out as large as ½ mm; argillaceous; very fossiliferous, with bryozoa *(Fenestella)* and brachiopods
93′	Covered to the top of the hill; scattered blocks of Warsaw chert
157′7″	Total

SURFACE SECTION 12

Warsaw and St. Louis Limestones

Quadrangle: Cumberland City

Location: Bluff on north bank of Cumberland River, about 0.5 mile northwest of mouth of Bullpasture Creek

Tennessee Coordinates: 751,300N., 1,501,000E.

This good section includes the Warsaw-St. Louis contact. Typical Warsaw limestone with a chalky-white matrix, exposed near the level of the river, grades vertically into typical fine-grained, dark St. Louis limestone. Thicknesses measured are:

	Feet	*Inches*
Warsaw Limestone (partial)	18	1
St. Louis Limestone (partial)	58	2

Thickness	
Warsaw Limestone	
5′+	Limestone, chalky, exposed on the bluff approximately 150′ north of the following series of beds
1′7″	Limestone, yellowish-gray to light olive-gray (weathers medium-gray), fine-grained, some medium-crystalline; highly fossiliferous, especially *Fenestella;* rough weathered surface; lithology measured from ground level upward
6″-8″	Chert, very pale-orange to grayish-orange, speckled; very fossiliferous, especially *Fenestella;* slightly porous; blocky weathering
3′7″	Limestone, yellowish-gray to light olive-gray (weathers light olive-gray), coarse-grained; calcite fragments and crystals as large as 3 mm; some medium-gray calcite crystals; a few calcite geodes; crinoid stems; surface appears banded because of solution weathering

Thickness	
2′10″	Limestone, pale yellowish-brown, fine-grained with some medium-grained crystals less than 1 mm; a few brachiopods and *Fenestella;* weathers to platelike masses; grades into medium-grained limestone as in preceding unit; beds thin and thicken horizontally
10″	Limestone, yellowish-gray, medium-grained; some calcite crystals as large as 2 mm; bryozoa
4″-6″	Limestone, light olive-gray (weathers medium-gray), fine-grained; argillaceous partings, light olive-gray throughout

Transition zone between Warsaw Limestone and St. Louis Limestone (mapped with Warsaw)

3″	Limestone, yellowish-gray (weathers pale yellowish-brown), fine-grained; scattered calcite crystals and fossil fragments; slightly argillaceous; cobbly and platelike weathering
3′	Limestone, yellowish-gray (weathers light olive-gray), medium- to coarse-grained; some calcite crystals as large as ½ cm; fragmental; friable; some fossils; grades laterally into limestone, yellowish-gray, fine-grained subchalky matrix with medium to coarse grains, fossil fragments, crystals and fragments parallel to bedding
18′1″	Total

St. Louis Limestone (lower unit)

1′	Limestone, moderate yellowish-brown, fine-grained, some coarse-grained
2′4″	Limestone, pale-brown (weathers pale yellowish-brown), fine-grained, very argillaceous; calcite geodes
2′6″	Limestone, yellowish-gray to light olive-gray (weathers pale yellowish-brown), fine-grained matrix with medium to coarse crystals and fragments of calcite, pale yellowish-brown; slightly argillaceous; calcite geodes; friable on weathered surface; fossil fragments in relief on weathered surface
1′4″	Limestone, moderate to dark yellowish-brown (weathers light-brown), fine-grained; argillaceous; some bryozoa. Grades vertically into limestone, light brownish-gray (weathers medium-gray), fine-grained, with some medium-grained fossil fragments and calcite crystals parallel to bedding, slightly argillaceous

Thickness	
2′10″	Limestone, yellowish-gray to light olive-gray, fine- to medium-grained, slightly argillaceous; calcite crystals, medium-gray; fossil fragments
15′4″	Limestone, pale to dark yellowish-brown (weathers pale yellowish-brown), fine-grained; bryozoa; fragments parallel to bedding; argillaceous; platelike weathering, plates less than 1″ thick; some nodules or lenses of chert, dark yellowish-brown
16′8″	Limestone, dark to dusky yellowish-brown (weathers pale yellowish-brown), fine-grained, dense; no argillaceous partings as in beds below; thin beds of previous lithology alternate with this limestone; near top some dark to dusky yellowish-brown chert (weathers medium-gray)
2′8″	Limestone, dark yellowish-brown, fine-grained, some coarse-grains
2′10″	Limestone, grayish orange-pink to pale-brown (weathers light olive-gray), fine-grained, some medium sized crystals in matrix; fragmental; fossiliferous; grades laterally into limestone, fine-grained, some medium-grained; calcite and fossil fragments weather in relief on surface
3′10″	Limestone, pale-brown (weathers light-gray), fine-grained, some coarse-grained; grades into areas of fine-grained, some medium-grained; calcite and fossil fragments weather in relief; some interbedded chert (weathers medium-gray)
St. Louis Limestone (upper unit)	
6′10″	Limestone, dark yellowish-brown (weathers pale yellowish-brown), fine-grained; bryozoa, fragments parallel to bedding; argillaceous; platelike weathering, plates less than 1″ thick; nodules of chert, light olive-gray (weathers medium-gray)
58′2″	Total
90′-100′	Covered interval to top of hill, scattered St. Louis chert

SURFACE SECTION 13

St. Louis Limestone

Quadrangle: Erin

Location: On west side of Denmark Road between Brigham Branch and Wallace Hollow

Tennessee Coordinates: 715,000N., 1,496,600E. and 714,500N., 1,497,400E.

This section is on a bluff along Brigham Branch. The rocks in this bluff are only slightly disturbed, although a fault that dropped Fort Payne down in contact with St. Louis is only a few hundred feet east along the road. This section was measured in two parts. Total section measured is 112′7″. Although the position of this section within the St. Louis is not known precisely, it is presented because it is the longest known undisturbed section of St. Louis in the area.

The beds occur in an essentially vertical bluff and dip into the bluff at low angles.

Thickness	
Base of section in St. Louis Limestone	
7′	Covered interval from level of paved road to the beginning of the first bed of rock in place
1′4″	Limestone, dark yellowish-brown (weathers pale yellowish-brown), sublithographic to fine-grained; small calcite-filled vugs; very small calcite crystals; brachiopods
3′2″	Limestone, pale yellowish-brown (weathers light olive-gray), fine-grained, slightly argillaceous; a few calcite crystals less than 1 mm
11″	Covered
11″	Limestone, pale yellowish-brown (weathers light olive-gray), fine-grained, slightly argillaceous; few calcite crystals, average 1 mm
1′9″	Covered
11″	Limestone, pale yellowish-brown, fine-grained; extremely fossiliferous (brachiopods, bryozoa, crinoids); fragments weather out on surface; large platy calcite crystals ¼″ to 1 mm; gypsum geodes; glauconite grains
11″	Covered
11″	Limestone, pale yellowish-brown (weathers moderate yellowish-brown), fine- to medium-grained; calcite

Thickness	
	crystals less than 1 mm, few larger than 1 mm; fossils (brachiopods) weather in relief on surface
1'9"	Limestone, pale yellowish-brown (weathers light olive-gray), coarse-grained; brachiopods, crinoid stems in relief on surface; medium-gray calcite crystals
11"	Limestone, pale yellowish-brown (weathers dark-gray), medium-grained; calcite crystals as large as 1 mm; a few fossil bryozoa and brachiopods; inclusions of very fine-grained material
2'7"	Limestone, light-gray (weathers light-gray with some white spots), fine-grained, some very fine-grained; subchalky; calcite crystals as large as 1 mm; brachiopods
2'7"	Limestone, pale yellowish-brown (weathers olive-gray, splotchy), fine-grained, partly sublithographic; grades into coarse-grained near top; cobbly; a few fossil brachiopods and bryozoa
1'4"	Limestone, pale yellowish-brown (weathers medium-gray), coarse-grained crystals (some very large) in subchalky (?) matrix; brachiopods and bryozoa
1'9"	Limestone, pale yellowish-brown (weathers light-gray), fine- to medium-grained; fossils in relief on surface; near the base becomes fine-grained, with no fossils
1'9"	Covered
11"	Limestone, pale yellowish-brown (weathers medium-gray), fine- to medium- grained; calcite crystals as large as 1 mm; fossil fragments in relief on surface
1'4"	Limestone, pale yellowish-brown (weathers light-gray), fine-grained, some medium-grained; calcite crystals less than 1 mm
1'9"	Limestone, light olive-gray (weathers medium-gray), fine-grained
2'7"	Covered
1'9"	Limestone, dark yellowish-brown, fine-grained, some medium- to coarse-grained; calcite crystals as large as 2 mm; chert inclusions, moderate yellowish-brown; some recrystallized fossils; crinoid stems and brachiopods in relief on surface
13'	Limestone, dark yellowish-brown (weathers light-gray), fine-grained; calcite crystals less than 1 mm; darker yellowish-brown chert nodules, also in inclusions with

Thickness	
	brecciated appearance; crinoid stems; conchoidal fracture; alternate layers are moderate yellowish-brown, fine-grained, argillaceous; crinoid stems and bryozoa; beds average 3′ thick but weather to platelike appearance because of clay and silt particles
2′2″	Limestone, dark yellowish-brown (weathers medium-gray), fine-grained, argillaceous; crystallized brachiopods. This unit was walked northward approximately 500 feet.
	Above this 2′2″ unit a covered zone of 40 feet consists of 35 feet of soil and 5 feet with angular chert blocks.
	The following part of the section begins about 300 feet west of the point where Denmark Road crosses Brigham Branch. The upper part of the preceding portion was walked approximately into the next unit.
1′	Limestone, dark yellowish-brown (weathers pale yellowish-brown), fine-grained; fossils (bryozoa) replaced by calcite crystals; some argillaceous partings
2′6″	Limestone, dark yellowish-brown, medium-grained, isolated light olive-gray calcite crystals as large as 4 mm; few fossils on weathered surface
6″	Limestone, dark yellowish-brown; transitional bed, being partly medium- to coarse-grained similar to the preceding unit and partly fine-grained similar to the next unit; many calcite crystals as large as 1 cm; fossil fragments (crinoids) in relief on weathered surface; strike N. 34° W., dip 17° SW.
10′6″	Limestone, dark yellowish-brown (weathers pale yellowish-brown), fine-grained; smooth weathered surface; fragmental appearance; lenses of cherty limestone
4′6″	Limestone, dark yellowish-brown to dusky yellowish-brown (weathers pale yellowish-brown), fine-grained, slightly argillaceous; platy where exposed to weathering; beds from 1½′ to 2′; strike N. 46° W., dip 29° SW.
1′3″	Limestone, dark yellowish-brown (weathers pale yellowish-brown), fine-grained; smooth weathered surface; fragmental appearance
4″-5″	Covered
13′2″	Limestone, dusky yellowish-brown and light olive, medium-grained, with isolated calcite crystals as large as 4 mm; few fossils on weathered surface; platelike weathering near surface; nodules of chert weathered out on surface, medium-dark gray with specks of medium bluish-gray; strike N. 50° W., dip 17° SW.

Thickness	
5″	Limestone, pale yellowish-brown (weathers moderate yellowish-brown), medium-grained, with scattered calcite crystals as large as 2 mm; few bryozoa
6′	Covered
4′2″	Limestone, dark yellowish-brown with streaks of pale yellowish-brown (weathers pale yellowish-brown), fine-grained; a few very thin argillaceous partings; some areas are medium-grained; calcite geodes; "*Lithostrotion*" in bedrock
4″	Limestone, dark yellowish-brown (weathers to pale yellowish-brown), fine-grained matrix with coarse-grained calcite crystals; fragmental; calcite geodes; similar lithology to preceding unit except for slightly darker color; chert nodules weathered in relief on surface
6′	Covered
7′10″	Limestone, dark yellowish-brown (weathers light olive-gray), fine-grained matrix with calcite crystals as large as 3 mm; strike N. 40° W., dip 26° SW.
112′7″	Total

SURFACE SECTION 14

St. Louis and Ste. Genevieve Limestones

Quadrangle: Erin

Location: On the Schmid Branch-Erin Road 0.75 mile west of intersection of Scott Road and Schmid Branch Road

Tennessee Coordinates: Section begins at 721,600N., 1,502,300E., and continues southward for a distance of about 1,700 feet, where it turns westward on a side road for about 500 feet

This section is parallel to a fault. Because of its proximity to this fault and because of the many covered intervals, the calculated thicknesses are not accurate. This section is important because it includes uppermost St. Louis and lower Ste. Genevieve beds that occur only in strongly deformed areas. The rocks are exposed in the bed of the creek, in exposures along the road, and within 200 feet on both sides of the road.

"Lithostrotion," the colonial coral characteristic of the St. Louis, was found near the middle of the section. The beds beneath this occurrence are considered to be St. Louis. Loose blocks of "Lost River" chert were found just above the middle of this section at the lower limit of the light olive-gray limestone identified as Ste. Genevieve. The red limestone in the upper unit of this section is important, because it serves as a tie between the upper part of Section 14 and the lower part of Section 15, which includes the youngest Mississippian strata in the region.

Thickness	
St. Louis Limestone	
1′	Limestone, olive-gray (weathers light-gray), medium- to coarse-grained; some calcite crystals as large as 1 mm; fossil fragments
17′5″	Covered
4′	Limestone, light olive-gray (weathers medium-gray), medium-grained; some calcite crystals; fossil fragments give a rough weathered surface; oolitic; on fresh surface some oolites are darker than matrix; beds approximately 2½′ thick; strike N. 50° W., dip 25° SW.
10′7″	Covered
7″	Limestone, olive-gray (weathers medium-gray), fine-grained; more dense than previous bed but not oolitic; lenses of medium-gray dense chert
10′2″	Covered
20′4″	Limestone, medium-light gray to dark-gray (weathers medium-gray), fine-grained; some calcite crystals; medium-gray chert nodules scattered throughout; chert appears brecciated; crinoids; strike N-S, dip 25° W.
24′6″	Limestone, olive-gray (weathers pale yellowish-brown, with speckled appearance due to light olive-gray calcite crystals); crystals ½ to 3 mm, average 1 mm
2″	Limestone, dark yellowish-brown (weathers medium-gray), fine-grained, dense. There is an abrupt change between this and the preceding unit.
1′	Limestone, olive-gray to olive-black (weathers light- to medium-gray), very fine-grained, sublithographic, conchoidal fracture
34′4″	Covered

Thickness	
Possibly Ste. Genevieve but more likely uppermost St. Louis	
18′2″	Limestone, dark yellowish-brown (weathers to moderate yellowish-brown), fine-grained; calcite crystals; crinoid stems; medium-bedded (1′ to 2′); interbedded with limestone that is more crystalline; cannonballs of dense, medium- to dark-gray chert 5″ to 8″ in diameter
8′	Limestone, dark yellowish-brown (weathers light- to medium-gray), very fine-grained, sublithographic; conchoidal fracture; cannonballs in bedrock
10′7″	Limestone, yellowish-gray to light olive-gray (weathers pale yellowish-brown), very fine-grained; most crystals less than 1 mm but some as large as 3 mm; chert is scattered in small nodules
9′1″	Limestone, pale yellowish-brown (weathers light-gray); crystals scattered in matrix; pink inclusions (possibly chert) as large as 5 mm
8″	Limestone, light olive-gray, some light-brown (weathers dark-gray), fine-grained; calcite crystals; fossil fragments in cross section; rough surface. This unit appears to be a lenslike body. Small cannonballs and chert nodules in nearby soil are weathering from this limestone.
7′	Limestone, yellowish-gray (weathers white to light-gray), coarse-grained; coarse crystals throughout matrix; some crystals as large as 1 mm
3′2″	Limestone, light olive-gray to olive-gray (weathers light- to medium-gray), medium- to coarse-grained
1′	Limestone, light olive-gray (weathers pale yellowish-brown), fine-grained; sparsely scattered calcite crystals as large as 3 mm; some argillaceous partings stained reddish-brown generally parallel to bedding; fossil fragments most conspicuous on weathered surface; cobbly appearance due to argillaceous material
9′4″	Covered
10′5″	Limestone, light olive-gray, medium- to coarse-grained with calcite crystals as large as 2 mm; crinoid stems in relief on weathered surface; scattered throughout are thin beds of slightly coarser crystalline and darker limestone; lenses of dense, light-brown to light-gray chert near top of unit
4′	Limestone, light olive-gray (weathers light- to medium-

Thickness	
	gray), fine-grained; calcite crystals as large as 1 mm; massive appearance; slightly argillaceous
21′5″	Covered
6′1″	Limestone, pale yellowish-brown, medium-grained; crystals average 1 mm
8′2″	Covered
241′2″	Total St. Louis and "likely St. Louis." This section has been thickened by duplication and contortion of beds.

Ste. Genevieve probably begins here, as loose "Lost River" chert was found here.

26′7″	Limestone, light olive-gray (weathers light-gray), fine-grained; calcite crystals as large as 1 mm; some argillaceous material; massive; zones of fine-grained material and medium-grained material; fine-grained variety of limestone is commonly argillaceous or clayey and dark in color; fossil fragments replaced by very light-brown calcite; chert, dark-gray (weathers white and reddish-brown); strike N. 20° W., dip 50° SW.
1′6″	Limestone, pale yellowish-brown (weathers light- to medium-brown), dolomitic, clayey
110′	Covered
7′	Limestone, light olive-gray (weathers light- to medium-gray), medium-grained; oolites less than ½ mm; fossil fragments
11′	Limestone, light olive-gray (weathers light- to medium-gray), fine-grained with a few medium-grained crystals scattered throughout; laminated argillaceous limestone; fossil fragments; several lenses of dark bluish-gray chert; somewhat porous
10′	Limestone, light olive-gray (weathers brownish-gray), fine-grained; calcite crystals as large as 1 mm; chert as in preceding unit
9′	Limestone, light olive-gray, medium-grained; calcite crystals abundant; fossil fragments on weathered surface
95′	Covered
1′	Limestone, light grayish-brown (weathers medium-gray), medium-grained, chalky; scattered calcite crystals; fossil fragments; small calcite geodes
3′6″	Covered

Thickness	
2′6″	Limestone, yellowish-gray (weathers light- to medium-gray), coarse-grained, calcite crystals as large as 1 mm; very fossiliferous, fossils weather into relief on surface, mostly crinoid stems. This is the last bed measured in the creek. The next five units were taken on the hillside about 200 feet west of the main road.
9′	Limestone, yellowish-gray, medium-grained, slightly argillaceous; many fossil fragments—crinoid stems, brachiopods, horn corals, *Fenestella;* massive beds; fossils weathered on surface seem to align with the bedding; oolitic; rough surface; calcite crystals as large as ½ mm
1′6″	Limestone, yellowish-gray (weathers medium-gray), coarse-grained; fossil fragments less numerous than in preceding unit and also lighter in color; calcite crystals larger than in preceding unit
1′	Limestone, light olive-gray (weathers medium- to dark-gray), fine-grained; some calcite crystals; massive; weathered surface same as in preceding two units; nodules of dark-gray chert
6′6″	Covered
1′6″	Limestone, light olive-gray (weathers light- to medium-gray), fine-grained, slightly argillaceous; dark crystals scattered throughout; fragmental and oolitic on weathered surface; ovoid "cogwheel" crinoid stem fragments may be *Platycrinus*
2′	Limestone, yellowish-gray to light olive-gray (weathers medium- to dark-gray), fine-grained matrix, medium-grained calcite crystals; fairly massive
10′	Limestone, moderate yellowish-brown (weathers dark yellowish-gray), medium-grained; calcite crystals are white to light-gray; crinoid stems weather into relief on surface; scattered small splotches of medium- to dark-gray limestone, fine-grained; few fossils and calcite crystals. This is the first of a series measured in the ditch, and up the hill from the ditch, along a side road that turns northeastward from the main road.
25′	Covered
1′	Limestone, yellowish-gray to light olive-gray (weathers light- to medium-gray), fine-grained, argillaceous; argillaceous partings are slightly greenish-brown; few fossils or calcite crystals

Thickness	
30′	Covered; probably mostly weathered green shale. About 27′ of laminated grayish-green shale is exposed along an unmapped side road that extends N. 80° W.
75′+	Few scattered outcrops; limestone, light olive-gray (weathers light-gray), fine-grained; massive. Red limestone and clay in the upper part of this unit are believed to correlate with the red beds at the base of Section 15.
439′7″	Total of "probable Ste. Genevieve." This section has been thickened by duplication and contortion of beds.

SURFACE SECTION 15

Ste. Genevieve and Younger Beds

Quadrangle: Ellis Mills

Location: Section along a gully south of the Lickskillet Branch-Cumberland City Road 4,500 feet south of the northeast corner of this quadrangle. Section runs about S. 20° E., beds dipping about 45°, N. 20° W.

Tennessee Coordinates: 721,300N., 1,521,400E.

The 207 feet of strata in this section is the youngest Mississippian preserved in the region. The beds dip down the gully steeper than its gradient, and therefore younger beds occur down the gully. Older beds are encountered up the gully toward the top of this section to weathered residuum of upper St. Louis Limestone on the top of the hill.

The second unit, which consists of 12 feet of red shale and red limestone, is strikingly similar to the upper unit in Section 14, and it is believed that in these two sections (though contorted and duplicated in part) we have the most complete section of these youngest beds in the region. Elsewhere, only scattered exposures and residual cherty soils mark the presence of these rocks that are so rarely preserved.

Thickness

Upper part of Ste. Genevieve-Renault (*Msg* on the maps)

1′	Coarsely fossiliferous limestone

Thickness	
12′	Red shale and red fine- to medium-grained limestone near top. This unit is correlated with the topmost unit in Section 14.
10′	Limestone, light-gray to light brownish-gray, fine- to medium-grained; basal part white, chalky, and oolitic; interval about two-thirds exposed and about one-third covered
2′	Covered

Possible Bethel Sandstone equivalent:

2′	Sandstone, fine-grained, brown
6′	Covered

Possible Paint Creek Limestone equivalent:

1′6″	Limestone, light to medium brownish-gray, fine- to medium-grained; coarse crystals of calcite
10′	Covered
2′	Limestone, light-orange to light-brown, medium- to coarse-grained, many calcite crystals; looks like the Decatur Limestone
7′	Covered
1′	Limestone, light-gray to light-brown, fine-grained; few oolites and fossils
5′	Covered
1′6″	Limestone, light-gray, fine- to medium-grained, oolitic and calcarenitic
7′	Covered
3′6″	Limestone, very light-gray, very fine- to medium-grained, oolitic and fragmental
1′	Covered
2′	Sandstone, light reddish-brown, fine-grained, massive
1′6″	Covered
1′6″	Limestone, oolitic, medium brownish-gray, massive
40′	Covered. Loose 6″ sandstone block near top
1′	Limestone, dolomitic, tan to light brownish-gray, fine-grained
24′	Covered

Thickness	
2′	Sandstone, fine-grained; numerous holes where shale or limestone pebbles have weathered out; loose pods of sandstone with flute marks and load cast marks nearby
2′	Covered
6′	Limestone, medium-dark gray, fine-grained, "snarly" surface, flaky and "worm-eaten"
2′6″	Covered
10″	Sandstone, fine-grained, massive
9′	Covered
1′	Limestone, light brownish-gray, coarse-grained; some fossil fragments
4′	Covered
6′	Shale, dark brownish-gray and greenish-gray; some limy nodules and layers
1′	Covered
4′	Limestone, medium grayish-brown, coarse-grained; numerous fossils (includes fossils of the Paint Creek Limestone of Kentucky)
1′	Limestone, dolomitic, silty, tan, olive and brownish-gray, fine-grained
2′6″	Shale, dark brownish-gray, no nodules
1′	Covered
4′6″	Limestone, light brownish-gray, fine-grained, very fossiliferous (crinoids and bryozoa)
4′	Shale, brownish-gray, with limy nodules
1′	Covered
3′	Limestone, silty, medium brownish-gray, fine- to coarse-grained
2′	Limestone, silty, gray, fine-grained, cobbly
3′	Covered
1′	Limestone, medium-brown, fine-grained
2′6″	Covered
1′	Limestone, medium grayish-brown, fine-grained

The section terminates near a fault manifested by St. Louis residuum to the north.

207′4″	Total

APPENDIX B

Core of Knox Dolomite and Breccia

The following is a series of descriptions of typical sections of the Knox in the 2,500-foot core. Because the full description is lengthy and consists largely of repetition of similar lithologies and conditions, the full log is not published. It is available for inspection in the files of the Tennessee Division of Geology.

The top 106 feet and bottom 55 feet are presented in their entirety. Additionally, descriptions of the core at hundred-foot intervals are given. These are believed to be typical of the entire 2,500-foot sequence.

If we assume that this hole cuts across bedding stratigraphically downward throughout, it cuts nearly 1,000 feet of Knox.

The core was logged by John M. Colvin, Jr., assisted by Robert Lagemann. Brecciated zones were examined by J. T. Wilcox.

Depth	*To*	*Interval*	*Description*
0	23′7″	23′7″	No core
23′7″	33′6″	9′11″	Dolomite, fine-grained, light olive-gray; intricate fracture and shear pattern; shatter cones at 26′
33′6″	35′5″	1′11″	Dolomite, with some very coarse-grained fragments of homogeneous breccia in matrix of fine-grained dolomite, all light olive-gray
35′5″	40′	4′7″	Dolomite, fine-grained, light olive-gray; numerous fractures produce intricate fracture pattern; shatter cones abundant at 36′, stylolites at 37′; no suggestion of bedding
40′	41′6″	1′6″	Dolomite breccia, homogeneous, in fine-grained dolomitic matrix, highly fragmented and broken, all light olive-gray
41′6″	46′	4′6″	Dolomite, fine-grained, light olive-gray; intricate fracture pattern; 6″ of heterogeneous breccia consists of fine- to medium-grained sandy dolo-

Depth	*To*	*Interval*	*Description*
			mitic matrix with coarse-grained fragments of homogeneous dolomite and dense, waxy, light-gray chert
46′	47′6″	1′6″	Breccia, dolomitic, homogeneous, light olive-gray; shatter cones in unbrecciated zones
47′6″	50′	2′6″	Dolomite, light olive-gray, fine-grained; intricate fracture pattern; manganese stains; shatter cones
50′	52′	2′	Breccia, dolomitic, homogeneous, fragmental, light olive-gray
52′	54′	2′	Dolomite, fine-grained, light olive-gray; manganese stains along stylolites; thin heterogeneous breccia at 54′
54′	57′6″	3′6″	Breccia, dolomitic, homogeneous, light olive-gray
57′6″	62′	4′6″	Breccia, dolomitic, sandy; matrix contains well-rounded quartz sand grains, medium-grained; a few chert fragments in the breccia, light olive-gray
62′	74′6″	12′6″	Breccia, dolomitic, light olive-gray; shatter cones abundant in upper and lower part
74′6″	79′	4′6″	Dolomite, fine-grained, light olive-gray; intricate fracture pattern; slickensides at 76′
79′	80′	1′	Heterogeneous breccia dike, dolomitic, sandy, medium-gray, medium- to coarse-grained
80′	83′	3′	Dolomite, fine-grained, light olive-gray; suggestion of vertical bedding; shatter cones
83′	84′	1′	Heterogeneous breccia dikes, medium-gray, dolomitic, sandy; contains angular fragments of Knox dolomite and chert
84′	106′	22′	Dolomite, fine-grained, light olive-gray; shatter cones in bedded material abundant throughout this in-

Depth	*To*	*Interval*	*Description*
			terval; vuggy along fractures near the top; intricate fracture pattern throughout interval; some light homogeneous brecciation near base of interval
106′	200′	94′	Not described
200′	204′	4′	Dolomite, fine-grained, light olive-gray; fractured; shatter cones
204′	215′	11′	Dolomite, fine-grained, light olive-gray, with alternating bands of dolomitic breccia; shatter cones in lower half; thin zones of medium-gray heterogeneous breccia near base of interval; dolomite beds dip vertically; numerous fractures, intricate fracture pattern
215′	296′	81′	Not described
296′	299′	3′	Dolomite, fine-grained, light-gray; fractures; some local brecciation
299′	320′	21′	Breccia, dolomitic, light-gray to mottled gray and brownish-gray; highly fractured; locally contains irregular dikes of heterogeneous breccia; a few shatter cones present
320′	345′	25′	Breccia, dolomitic, light-gray; brecciated zones are discontinuous; scattered shatter cones
345′	400′	55′	Not described
400′	403′	3′	Dolomite, fine-grained, light olive-gray to light-gray; a few fractures
403′	407′	4′	Breccia, dolomitic, light-gray, homogeneous
407′	499′	92′	Not described
499′	500′	1′	Dolomite, fine-grained, light olive-gray; shatter cones; fractures
500′	514′	14′	Breccia, dolomitic, homogeneous; a few unbrecciated zones; shatter cones at 506′
514′	583′	69′	Not described

Depth	*To*	*Interval*	*Description*
583′	627′	44′	Breccia, dolomitic, homogeneous, olive-gray to light olive-gray; medium-gray heterogeneous breccia dikes common; shatter cones at scattered intervals; intricate fracture pattern; unbrecciated beds dip 70°
627′	700′	73′	Not described
700′	704′6″	4′6″	Dolomitic limestone, fine-grained, light olive-gray; some local homogeneous brecciation; fractured
704′6″	791′6″	87′	Not described
791′6″	798′6″	7′	Dolomitic limestone, fine-grained, light olive-gray; shatter cones abundant; beds dip about 70°
798′6″	810′9″	12′3″	Breccia, dolomitic, homogeneous and heterogeneous, light olive-gray to olive-gray to medium-gray; intricate fracture pattern; a few unbrecciated zones of fine-grained dolomite and dolomitic limestone
810′9″	888′6″	77′9″	Not described
888′6″	901′	12′6″	Breccia, dolomitic, homogeneous; sandy zones near top; intricate fracture pattern
901′	904′	3′	Dolomite, fine- to medium-grained, light olive-gray; shatter cones; highly fractured, intricate fracture pattern
904′	958′	54′	Not described
958′	1013′6″	55′6″	Breccia, dolomitic, homogeneous, light olive-gray, matrix light-gray; brecciated dolomite broken at intervals by chert nodules and fine-grained dolomitic and heterogeneous breccia dikes; shatter cones in both brecciated and unbrecciated intervals; manganese stains along bedding and fracture planes
1013′6″	1086′6″	73′	Not described
1086′6″	1108′6″	22′	Dolomite, fine-grained, light-gray; local homogeneous breccia, sandy heterogeneous breccia; fractures

Depth	*To*	*Interval*	*Description*
			common; beds dip 45°-70°; shatter cones common
1108′6″	1194′6″	86′	Not described
1194′6″	1199′	4′6″	Dolomite, fine- to medium-grained, mottled gray color
1199′	1202′	3′	Breccia, dolomitic, homogeneous, light olive-gray to light-gray
1202′	1284′6″	82′6″	Not described
1284′6″	1307′	22′6″	Breccia, dolomitic, homogeneous, some heterogeneous, light olive-gray to medium-light gray; very cherty near top; intricate fracture pattern
1307′	1324′	17′	Sandstone, quartzitic, medium-grained, very light-gray, cemented with dolomite or calcite; a few oolites; some local homogeneous breccia
1324′	1400′	76′	Not described
1400′	1417′	17′	Dolomite, fine-grained, light olive-gray; faulted, intricate fracture pattern; shatter cones; some local homogeneous breccia
1417′	1500′	83′	Not described
1500′	1502′	2′	Dolomitic limestone, fine- to medium-grained, light olive-gray to light-gray
1502′	1595′	93′	Not described
1595′	1613′6″	18′6″	Dolomite, fine-grained, dense, lithographic, light-gray to very light-gray; faulting and fracturing common; shatter cones; manganese stains and dendrites along fractures and bedding planes; beds dip 70°-75°
1613′6″	1695′	81′6″	Not described
1695′	1703′	8′	Dolomite, sandy, medium- to coarse-grained, olive-gray
1703′	1800′	97′	Not described
1800′	1801′	1′	Dolomite, sandy, fine-grained, dark-gray

Depth	*To*	*Interval*	*Description*
1801′	1889′	88′	Not described
1889′	1905′	16′	Dolomite, fine-grained, light olive-gray; few narrow dikes of heterogeneous breccia
1905′	1999′6″	94′6″	Not described
1999′6″	2000′	0′6″	Breccia, dolomitic, homogeneous, pale yellowish-brown, olive-gray, cherty; badly fractured. This is the deepest core in the hole drilled in 1947 by the Ordman Company.
2000′	2100′	100′	Not described
2100′	2103′	3′	Dolomite, mottled, light-gray to dark-gray to olive-gray, fine- to medium-grained; light crackle breccia; intricate fracture pattern
2103′	2197′5″	94′5″	Not described
2197′5″	2200′1″	2′8″	Siliceous oolitic or sandy dolomite, medium- to coarse-grained, dark yellowish-brown to olive-gray; intricate fracture pattern
2200′1″	2296′11″	96′10″	Not described
2296′11″	2300′11″	4′	Dolomite, light olive-gray to olive-gray, very fine- to fine-grained; intricate fracture pattern
2300′11″	2304′8″	3′9″	Crackle breccia, dolomitic and cherty, light-gray to light olive-gray, very fine- to fine-grained; intricate fracture pattern; badly broken and shattered
2304′8″	2397′10″	93′2″	Not described
2397′10″	2401′10″	4′	Dolomite, olive-gray to light olive-gray, slightly sandy, very fine- to medium-grained; intricate fracture pattern
2401′10″	2460′	58′2″	Not described
2460′	2469′5″	9′5″	Dolomite with crackle breccia, fine-grained, mottled light olive-gray to light- to medium-gray; vugular porosity; some heterogeneous breccia; intricate fracture pattern; last few feet are cherty

Depth	*To*	*Interval*	*Description*
2469′5″	2470′6″	1′1″	Dolomite and crackle breccia, medium- to coarse-grained, light olive-gray, mottled; vugular porosity; intricate fracture pattern
2470′6″	2472′1″	1′7″	Dolomite, light olive-gray, very fine-grained; manganese stains; fractured
2472′1″	2479′3″	7′2″	Dolomite, with some chert, light olive-gray, mottled, medium- to coarse-grained; some crackle breccia; some vugular porosity; intricate fracture pattern
2479′3″	2480′9″	1′6″	Dolomite, light olive-gray, coarse-grained, crystalline, some chert; intricate fracture pattern
2480′9″	2482′3″	1′6″	Dolomite, cherty, light olive-gray, medium- to coarse-grained, vugular porosity; intricate fracture pattern
2482′3″	2488′10″	6′7″	Dolomite, light olive-gray to light-gray, mottled, medium- to coarse grained; few shatter cones; intricate fracture pattern
2488′10″	2490′	1′2″	Dolomite, light olive-gray, fine- to coarse-grained; intricate fracture pattern
2490′	2494′10″	4′10″	Crackle breccia, dolomitic, light olive-gray; intricate fracture pattern
2494′10″	2498′2″	3′4″	Dolomite and crackle breccia, mottled light olive-gray to light- to medium-gray; flow structures common; intricate fracture pattern
2498′2″	2502′10″	4′8″	Dolomite, light olive-gray to mottled, fine- to medium-grained; beds dip 70°; some scattered crackle breccia; a few large uncemented fractures reveal fracture porosity; intricate fracture pattern
2502′10″	2503′4″	0′6″	Heterogeneous breccia, light-gray
2503′4″	2505′10″	2′6″	Crackle breccia, dolomitic, light olive-gray, fine-grained matrix; intricate fracture pattern; few poorly developed shatter cones

Depth	*To*	*Interval*	*Description*
2505′10″	2506′3″	0′5″	Heterogeneous breccia, light-gray
2506′3″	2507′9″	1′6″	Crackle breccia, dolomitic, light olive-gray, fine-grained matrix; intricate fracture pattern
2507′9″	2514′9″	7′0″	Crackle breccia, dolomitic, light olive-gray, fine-grained matrix; intricate fracture pattern; well-developed shatter cones throughout this interval
2514′9″			Total depth

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