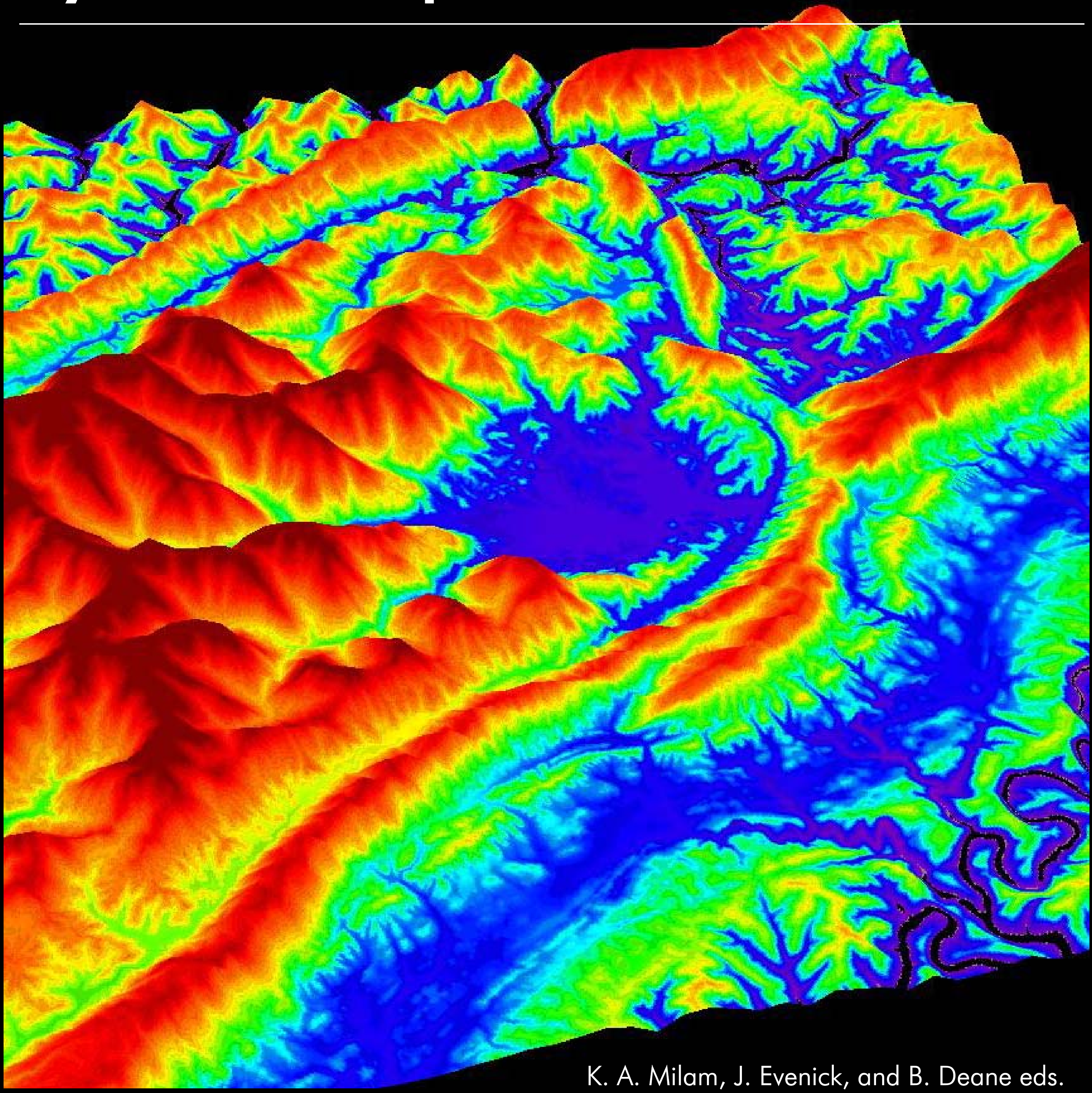
Field Guide to the Middlesboro and Flynn Creek Impact Structures



K. A. Milam, J. Evenick, and B. Deane eds.

A publication of the
Impact Field Studies Group

Field Guide to the Middlesboro and Flynn Creek Impact Structures

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Introduction

Welcome to the 2005 Meteoritical Society / Impact Field Studies Group field trip to the Middlesboro and Flynn Creek impact structures! We're glad you will be joining us for the next few days. After today's departure from Gatlinburg, we'll head to the northeast toward the Middlesboro impact structure. This afternoon, we'll make a couple of stops examining the regional geology of the Southern Appalachians and will be staying the night in the historic town of Cumberland Gap, Tennessee. Tomorrow, we'll examine the Middlesboro impact structure, starting with an overview from the Pinnacle Overlook, followed by a trip to the central uplift and visits to various points around the eastern crater rim. Tomorrow night, we'll travel toward the Flynn Creek impact structure, staying the night in Cookeville, Tennessee. On Sunday morning, we'll visit Flynn Creek and return to Knoxville in the evening. We hope you enjoy the trip and encourage you to participate along the way. If you have any additional questions during the trip please let us know.

Your Field Trip Leaders,

Keith A. Milam
Bill Deane
Jonathan Evenick

Figure 1. View of the Great Smoky Mountains in the winter (photo by A. Kenst).

From Gatlinburg to Middlesboro

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Introduction

The trip from Gatlinburg to Middlesboro provides a unique opportunity to observe Precambrian to Pennsylvanian (Carboniferous)-aged stratigraphy and Alleghenian (Carboniferous) deformation. The Mid-Atlantic Region Geologic Map (Map 1) in the back of this guidebook contains a generalized stratigraphic column for Tennessee that may be used as a reference. The stratigraphic column however, does not cover facies changes across the Sevier basin (Ordovician Foreland basin). A brief overview of southern Appalachian basin geology is needed to fully understand the context and significance of the rocks you will see along this entire trip.

During the Precambrian, the Great Smoky Group strata were being deposited in shallow water environment on the supercontinent called Rodinia. Subsequent rifting of Rodina (~565 Ma) led to the formation and deposition of the Chilhowee Group. This successful rifting event created the Iapetus Ocean and is indicated in the stratigraphic record by the deposition of the Shady Dolomite (massive-bedded, dark gray). Further opening of the Iapetus Ocean led to the deposition of the Rome Formation (thin-bedded, red shales). The formation is dominated by shallow water shales that preserve ripple marks, mudcracks, salt crystals, and raindrop impressions. The Rome Formation served as the basal or master décollement horizon for Alleghenian faulting. Deposited on top of this unit is the Conasauga Group, which is dominated by shales and capped by a limestone unit. From Late Cambrian through Early Ordovician eastern Laurentia was a stable carbonate platform. During this period, the Knox Group (gray dolomite with minor limestones) was deposited. Equivalent dolomitic strata can be found from Newfoundland (Beekmantown Group) to Texas (Arbuckle or Ellenberger Group). During the Middle Ordovician, a volcanic island arc collided and accreted to eastern Laurentia. This orogenic event, called the Taconic Orogeny, created a foreland basin with 2133 m (7000 ft) of siliciclastic sediments (the Sevier Shale). The Sevier Shale changes facies westward into a carbonate bank-edge facies around Knoxville and to a carbonate platform facies near Oak Ridge. Later, during the Devonian, Laurentia collided with at least one microcontient (probably similar to the Avalon terrane in the northern Appalachians). This collision was called the Acadian Orogeny. During this orogeny, a thin unit called the Chattanooga Shale (thin-bedded, black shale) was deposit hundreds of miles to the west. During the Mississippian (Early Carboniferous), a regional carbonate platform existed once again and reef and limestones units were deposited. These sediments were then overlain by Pennsylvanian (Late Carboniferous) siliclastic units. During the Late Pennsylvanian – Early Permian, strata in the region was faulted and folded by numerous décollements mostly soled in the Rome Formation. Alleghenian deformation was then differentially eroded into present-day valleys and ridges.

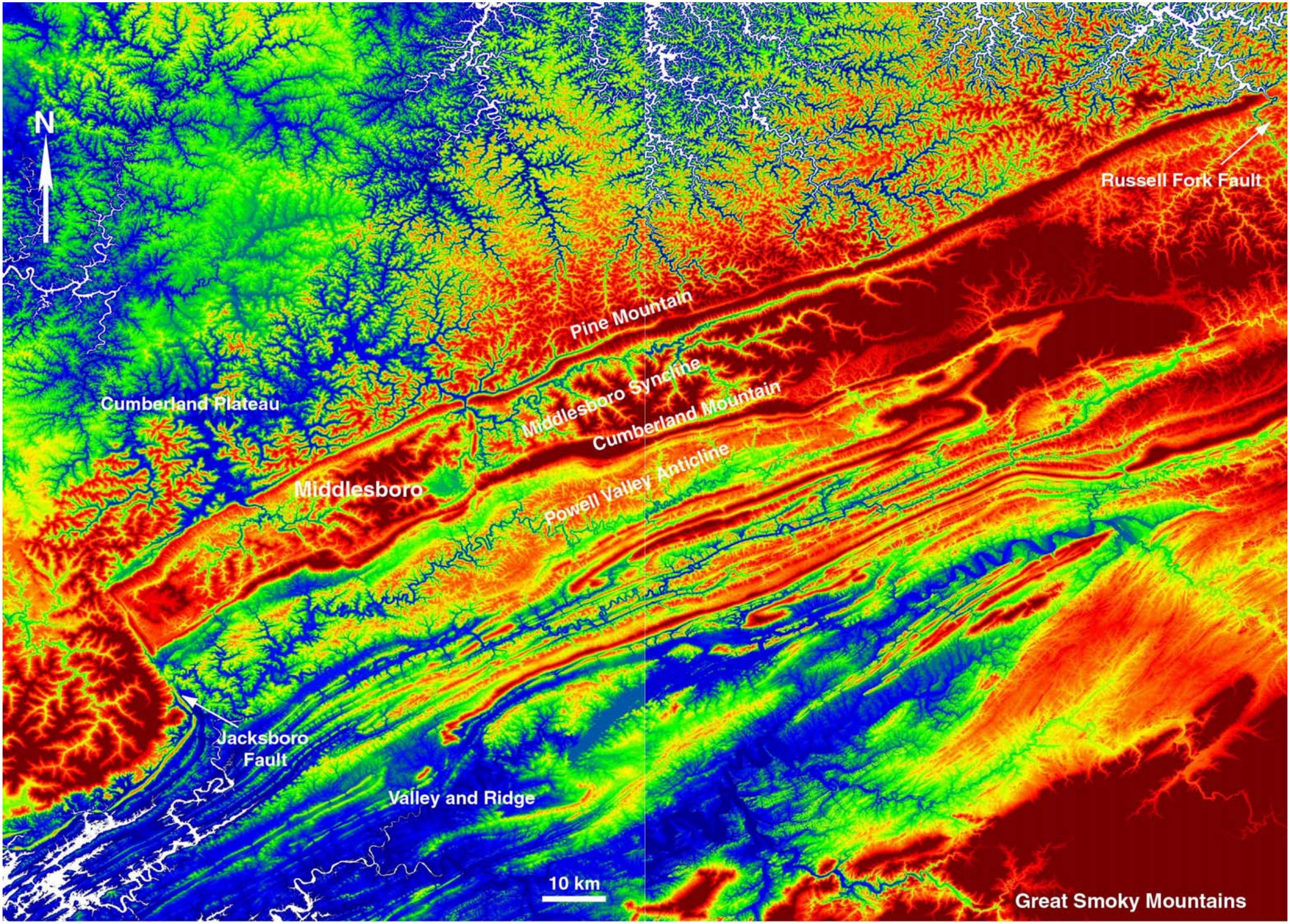
N
Russell Fork Fault
Pine Mountain
Cumberland Plateau
Middlesboro Syncline
Cumberland Mountain
Middlesboro
Powell Valley Anticline
Jacksboro
Fault
Valley and Ridge
10 km
Great Smoky Mountains

Figure 2 (previous page). Digital elevation model (DEM) of the Pine Mountain Overthrust Sheet and surrounding areas, produced from Space Shuttle Radar Topography Mission (SRTM) data. Highest elevations are shown in red, lowest areas are shown in blue/white.

Gatlinburg to Maryville (McGhee-Tyson airport)

As we travel from Gatlinburg to Maryville, we will transition from the Great Smoky Mountains (Figure 1) to the Valley and Ridge province (Figure 2). Along the way we will cross numerous faults, including the Great Smoky fault, and stratigraphic units of various ages. Driving through the Great Smoky National Park we can see Precambrian through Ordovician stratigraphy. The park is composed mostly of Precambrian-aged rocks, but is dotted with coves, that exist where the shallowly dipping Great Smoky fault has been breached. These windows exposed Ordovician carbonates that were more easily eroded and formed flat land that was cultivated by early settlers. Exiting Gatlinburg the rocks on both sides of the road are dominantly chlorite-grade slates and metasiltstones which belong to the Walden Creek Group. Note that while driving towards Pigeon Forge the road and Pigeon River mark the approximate position of a large tear fault. Entering Pigeon Forge, we pass from the Blue Ridge into the Valley and Ridge province. The Valley and Ridge is characterized by brittle thin-skinned faulting (duplexing and imbrication) and folding (buckle and passive). Near the intersection of Hwys 411 and 441 in Sevierville, is an exposure of Ordovician rocks in the hanging wall of the Guess Creek fault. Just north of this intersection the Guess Creek fault outcrops in Guess Creek (not visible from the vehicle). Looking to the southwest, Chilhowee Mountain should be visible. The Great Smoky fault outcrops near the base of the mountain. The Foothills Parkway is built on top of this mountain, though it is frequently closed due to landslides. The road was built on a dip-slope, as is a large stretch of I-40 near the Tennessee-North Carolina border, and therefore they both commonly have massive landslides when there are significant rainstorms. The next few miles will contain few notable faulted and gently folded Cambrian and Ordovician shales, carbonates, and dolomites. Passing through Shooks Gap, small outcrops of the Rome Formation may be seen on the sides of the road. These red shales denote the Dumplin Valley fault. Nearing John Sevier Highway their will be numerous exposures of the Sevier Shale. These calcareous turbidite deposits were deposited in the Taconic foreland basin. They are estimated to be between 2000 – 3000 m (7000 – 10000 ft) thick. Research is ongoing to better constrain the true thickness of the unit and to subdivide it on the basis of lithofacies and biostratigraphy. Turning west onto John Sevier Highway, the road will parallel regional strike and numerous small Sevier Shale outcrops will be present. At the intersection of John Sevier Highway and Alcoa Highway, turn left (south) and head towards Maryville. Near the McGhee-Tyson airport, the Smoky Mountains will be visible again on the left side of the vehicle.

Maryville (McGhee-Tyson airport) to Middlesboro

Continuing north from Maryville, northeastern trending valleys and ridges along with a panoramic view of the Smokies become evident off to the right side of the vehicle. Each ridge has a typical geomorphology that is associated with the stratigraphy being weathered. Approaching Knoxville, the bank-edge, middle Ordovician facies outcrops along the road. Knoxville, not surprisingly, is the type locality for the Knox Group. The airport and the city of Maryville were also built on the Knox Group. While crossing the Tennessee River, large dolomite outcrops can be seen from the vehicle on the right. Just before the road merges with Interstate 40, the Bays Formation outcrops. This lithologic change is due to passing over the Knoxville fault, which places Knox Group (Cambro-Ordovician) strata on the Bay Formation (Ordovician), so the fault has minimal displacement. Upon turning north on Interstate 75 there will be few outcroppings until passing through Sharps Gap. On the left side of the road, the Saltville fault outcrops. The fault has over 100 km of displacement and places the Rome Formation on the Knox Group. Further up the road near the Raccoon Valley exit, an outcrop on the left will expose a klippe of the Copper Creek fault. The stratigraphy on top of the outcrop is again the Rome Formation. Continuing on I-75, the Cumberland Plateau will become evident on the left side of the vehicle (~ mile marker 129). This part of the Cumberland Plateau is called the Wartburg basin and is anomalously higher than other areas of the plateau. Near Caryville the stratigraphy on the right side of the road is gently dipping whereas the stratigraphy on the left side of the vehicle is flat lying. This is because the road was built on the Jacksboro tear fault. The Jacksboro tear fault marks the southern end of the Pine Mountain thrust block. This thrust block is visible from space and is the type locality of a fault bend fold. Getting off I-75, the rest of the trip will be mostly along the flank of the Powell Valley anticline until reaching Cumberland Gap.

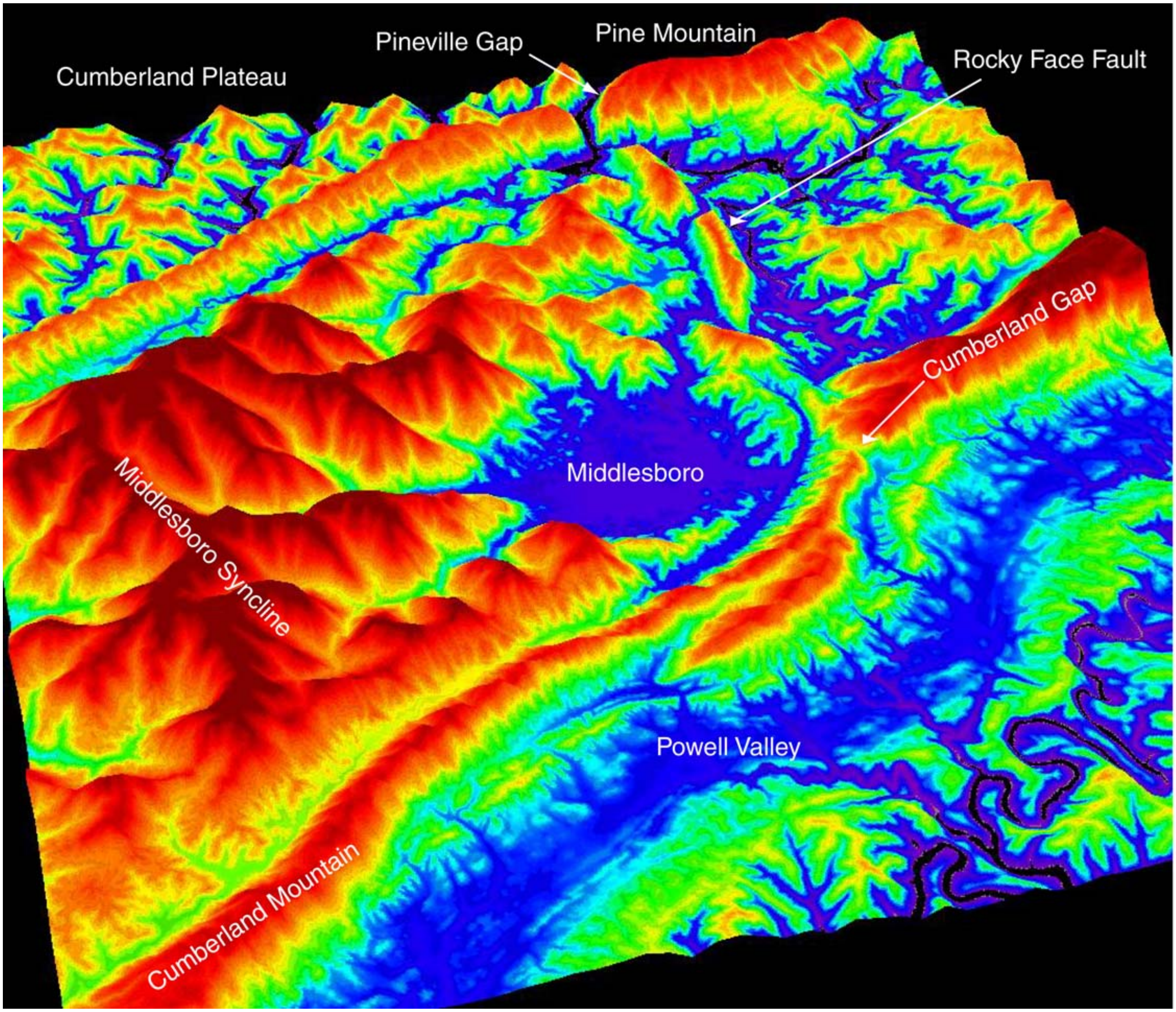

Figure 3. Space Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) including the Middlesboro impact structure (center) and the surrounding terrain (vertical exaggeration 5x). View is to the northeast.

The Middlesboro Impact Structure

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History of Middlesboro

Middlesboro Basin (Figure 3) has long held both historic and scientific significance for this part of the Southern Appalachians. Initially, it served as a stopover for settlers migrating from the east through the Cumberland Gap. Middlesboro's lowland topography provided abundant water for immigrants, but was also notorious for its wetland quagmires that hindered settlers traveling along the Wilderness Road.

Prior to the late nineteenth century, Middlesboro consisted of scattered dwellings and trading posts along the Wilderness Road. The 1890's brought the extraction of iron ore and coal reserves from local Silurian and Pennsylvanian strata (respectively), which, in turn, led to a booming local economy. With the addition of English investment and the influx of new workers, the town of Middlesboro was established in 1889 by local coal baron Alexander Arthur and named after Middlesborough, England. Middlesboro's economic boom continued until the crash of 1893 and a major fire that destroyed part of the town. After a slow rebound, Middlesboro recovered and still maintains its mining-based economy.

Early Scientific Investigations

Before the turn of the 20th century, geologists began to take interest in the southern Appalachians and the conspicuous Middlesboro Basin. N.S. Shaler of Harvard University conducted the first geologic survey of the region and simultaneously ran a geologic field school for students from 1875 to 1880 (Kincaid, 1999), making it one of the first geology field camps in the country. Other early investigations focused on possible origins for Middlesboro Basin itself. Ashley (1904) and Ashley and Glenn (1906) discovered strata within the broad, flat, alluviated basin that were "greatly disturbed by folding and faulting". Both researchers attributed the disturbed strata to "stresses that produced the formation of the Appalachian province" (Glenn, 1904). Modification of the basin by stream erosion occurred as a result of the erosion of weakened strata and subsequent ponding within the basin. In 1934, John L. Rich agreed with Ashley and Glenn's conclusions, adding that Middlesboro resulted from the collapse of a small dome, followed by gravitational settling and ponding of water.

Later United States Geological Survey mapping of the area led to a different interpretation. Englund and Roen (1962) thought Middlesboro Basin to be the site of an ancient bolide impact. They cited the presence of a circular basin, intensely deformed rock, normal faulting with circular trends around the basin, overturned beds, 'shattered' quartz grains, and a central core of uplifted material as evidence of impact. Such observations are consistent with an impact model for Middlesboro, but can also result from endogenic processes.

Confirmation of an impact origin came in 1966, when Robert Dietz discovered shatter cones around the central uplift area and later petrographic analyses of sandstone specimens led to the identification of shocked quartz (Bunch, 1968; Carter, 1968). Additional examination of shocked conglomeratic sandstones from the center of impact found additional shocked quartz and extensive microfaulting that may have resulted from central uplift formation (Milam and Kuehn, 2002). Additional magnetic and gravity surveys (Seeger, 1970, 1974; Steineman, 1980) have further supported an impact origin.

Although these early studies have identified Middlesboro as an impact crater, detailed mapping and petrologic analyses have yet to reveal the true mechanics and morphology of this impact.

Part I: Regional Geology

Pine Mountain Thrust Sheet

The Middlesboro impact structure is situated in the southern Appalachians near the junction of the Kentucky, Tennessee, and Virginia borders. Middlesboro is a circular, approximately 5.5 km (3.4 mile) diameter, alluviated, geomorphic basin drained by Yellow Creek northward into the Cumberland River. The Middlesboro structure is superimposed on the Pine Mountain Thrust Sheet, a large (202 x 41 km, 125 x 25 mile) northeast–southwest-trending overthrust block (Figure 2) that exposes Upper Devonian to Middle Pennsylvanian strata (Figure 4). This overthrust was produced by lateral compressive forces during the late Paleozoic assembly of the North American, European, and African continents to form the supercontinent of Pangaea. This collision, known as the Alleghenian Orogeny, was the final stage in forming the Appalachian Mountains along with a series of northwest-displaced imbricate thrust blocks in the foreland basin. The major detachment faults developed in the sedimentary cover rocks, with the least competent lithologies, including shales of the Rome Formation (Middle Cambrian) and Chattanooga Shale (Upper Devonian). Eventually these faults ramped upward, steeply crosscutting younger strata and creating large folds in some areas. The Pine Mountain Thrust Sheet is bounded by faults on all four sides (Figure 2). The northwest leading edge is the Pine Mountain Thrust; the southeastern trailing edge (Virginia and Tennessee) is the Hunter Valley Fault. The Jacksboro wrench fault in northern Tennessee defines the southwestern end of the block and indicates about 11 mi of movement. The Russell Fork wrench fault (Kentucky and Virginia) on the northeastern end indicates about 4 mi of westward movement. Within the thrust sheet, between the Pine and Cumberland Mountains, is the Middlesboro Syncline, with surface exposures of the Pennsylvanian Breathitt Formation. The Middlesboro impact is situated just southeast of the synclinal axis. Farther southeast, beyond Cumberland Mountain, are exposed lower Paleozoic strata of the Powell Valley Anticline (Rice and Maughan, 1978).

Local Stratigraphy

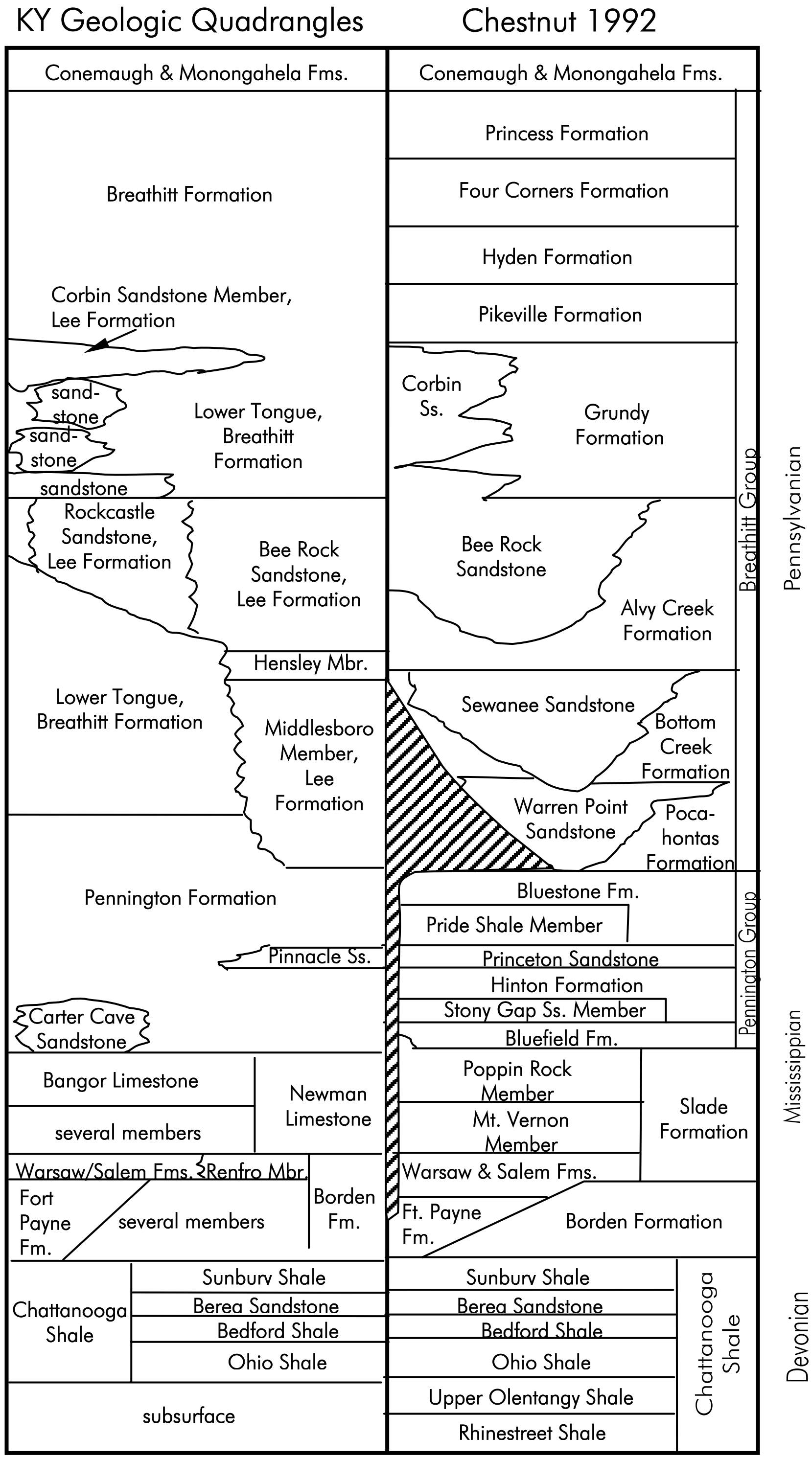

Figure 4. Correlation chart showing the two stratigraphic systems used in eastern Kentucky (after Chestnut, 1992). System on the left is based on the Middlesboro North (Englund et al., 1964), Middlesboro South (Englund, 1964), and Kayjay-Fork Ridge geologic quadrangles (Rice, 1978).

The stratigraphy within the thrust sheet ranges from Upper Devonian Chattanooga Shale to the Mississippian Grainger, Newman, and Pennington formations to the Pennsylvanian Lee and Breathitt formations. The rock units of primary concern for this field trip are the Lower Pennsylvanian Lee Formation and the Lower to Middle Pennsylvanian Breathitt Formation (Figure 4). The Lee Formation, whose type area is nearby Lee County, Va., consists of sandstone, shale, siltstone, mudstone, coal, limestone, and conglomeratic units that were deposited in marginal-marine and fluvial settings during Late Mississippian to Early Pennsylvanian time. In the field area, the Lee Formation is easily identifiable by its conglomeratic units ranging from 287 – 543 m (940-1780 ft) in thickness. Quartz pebbles are present throughout as thin, graded, or cross-bedded

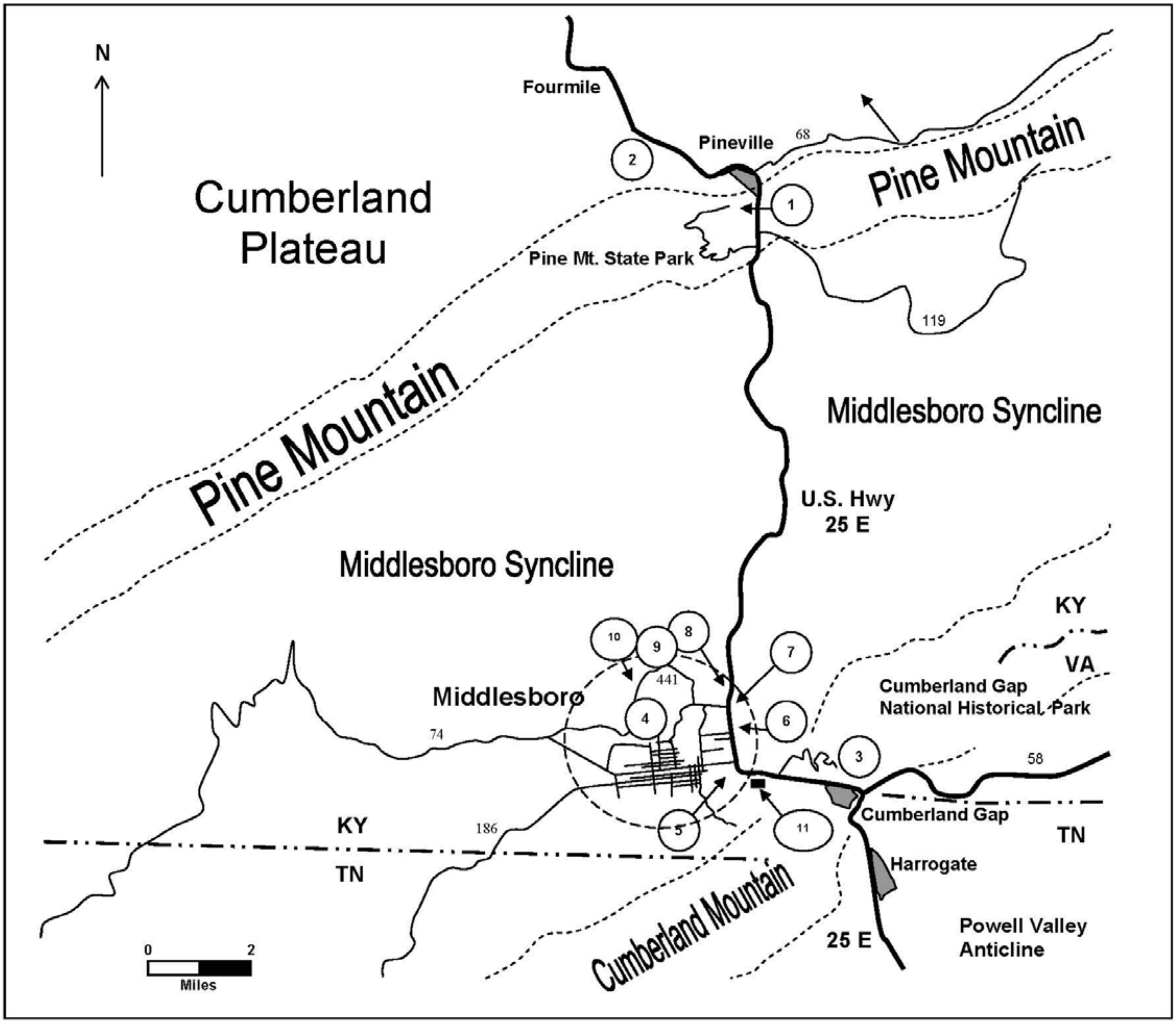

Figure 5. Map showing stop locations for the Middlesboro portion of field trip. Circled numbers correspond to stops mentioned in this field guide.

lenses. These units are well exposed along Cumberland and Pine Mountains. The overlying Breathitt Formation consists of Lower to Middle Pennsylvanian sandstones, shales, siltstones, mudstones, and coal beds that were deposited in marginal marine and/or terrestrial depositional settings. The Breathitt Formation is well known for its abundance of *Stigmaria* and *Calamites*, as well as assorted fern and other carbonized leaf impressions.

Our field trip begins from the Ramada Inn hotel in Cumberland Gap, Tennessee (Intersection of U.S. Hwys. 58 and 25E; Figure 5). From the Ramada, travel south for <0.1 km (<0.1 mile). Make a U-turn (right) and travel north onto U.S. Hwy. 25E. During this trip, you will travel through Cumberland Mountain via the Cumberland Gap Tunnel, Cumberland Gap National Historical Park, and the town of Middlesboro, Kentucky. Upon passing the Cumberland Gap National Park visitor center, travel for 17.1 km (10.6 miles) until reaching a turnoff on the left (west) for Pine Mountain State Resort Park (this is near the Wasioto Golf Course). Turn left. After 5.47 km (3.4 miles) you will enter Pine Mountain State Resort Park. Continue for 7.4 km (4.6 miles), following the signs, to the Chained Rock Overlook parking lot. Hike the (0.8 km) 0.5 mile trail to Chained Rock Overlook. (Caution: this stop has very steep drop-offs and is very dangerous for climbing. No handrails are present).

Figure 6. View of the leading edge of the Pine Mountain Overthrust Sheet along Pine Mountain from Chained Rock Overlook. The Cumberland Plateau is visible along the horizon further to the north.

Stop 1. Pine Mountain / Chained Rock Overlook

High atop Pine Mountain in Kentucky, you are now viewing the leading edge of the Pine Mountain Thrust Sheet (also known as the Cumberland Overthrust Sheet) to the north (Figure 6).

The escarpment along the leading edge of the thrust sheet contains exposures of southwest-dipping Devonian to Pennsylvanian-aged strata. Pine Mountain is capped here by the resistant, conglomeratic sandstones of the Lower Pennsylvanian Lee Formation (using the USGS classification), similar to those on Cumberland Mountain. Additional conglomeratic sandstone exposures just above the overlook provide a vantage point for viewing most of the features associated with regional tectonism (Cumberland Plateau, Pine Mountain Thrust, Middlesboro Syncline, and Cumberland Mountain).

The gap visible just below and to the northeast was produced by the downcutting of the Cumberland River through Pine Mountain as uplift occurred. This is the only point in Kentucky where a modern-day stream breaches Pine Mountain along its entire length (McGrain, 1975).

Chained Rock Overlook (Figure 7) is approximately 671 m (2200 ft) above sea level and 366 m (1200 ft) above the town of Pineville, Kentucky. Chained Rock gets its name from the large, yet-to-be-detached boulder chained to the mountain here. Local tradition has it that, in the early 1900's, residents from Pineville, concerned with the threat the boulder posed to the town, attached a chain to the ominous rock, anchoring it to Pine Mountain. The chain (31 m (101 ft) in length with 3 kg (7 lb) links) was purportedly carried to the mountaintop by four-mule teams in two trips. The chain seen today is a 1933 replacement of the original one. The effectiveness of this preventative measure is left open to debate.

Figure 7. Chained Rock Overlook, Pine Mountain State Park looking northeast toward Pineville Gap. Notice the southeast-dipping strata of the Lee Formation.

Retrace your route, exiting Pine Mountain State Resort Park, and return to the intersection with Highway 25E (Figure 5). Take a left and continue north along 25E for 5-6 km (3-4 miles). Travel beyond Pineville, Kentucky. Pull off the highway at some spectacular exposures of Pennsylvanian-aged Breathitt Group along mile marker 16. (Note: this site receives heavy traffic and extreme caution should be used when viewing this outcrop).

Stop 2. North of Pineville, Kentucky

Horizontal strata of the Lower-Middle Pennsylvanian Breathitt Group are exposed here in the Cumberland Plateau. Note the variety of lithofacies (sandstone, siltstone, shale, and coal) and the extent of their lateral continuity (Figure 8). The Breathitt Formation (USGS nomenclature) lies immediately above the Lee Formation

Figure 8. View of the flat-lying stratigraphy of the Breathitt Formation within the Cumberland Plateau, northwest of Pineville, KY at Stop #4.

in the field area (Figure 4). These strata represent deposition in marginal marine/terrestrial environments. It is important to get a sense of the undeformed strata here prior to entering Middlesboro, where similar units are heavily disturbed.

From the parking lot at Chained Rock, retrace your route to U.S. Hwy 25E. Turn right (heading south) and travel for 17.1 km (10.6 miles) through the town of Middlesboro and to the exit for Cumberland Gap National Park visitor center. Turn right off of the exit, travel for several tens of meters (couple hundred feet), and take a left (heading southeast) onto Pinnacle Road. Travel for 5.8 km (3.6 mi) (Figure 5). This winding road is not suitable for trailers and large vehicles over 6.1 m (20 ft) in length. A parking lot is available at the top. From the parking area, take the short hike to Pinnacle Overlook. During inclement weather, the overlook can be very windy.

Stop 3. Cumberland Mountain/Pinnacle Overlook

This stop in Virginia affords a breathtaking view of Cumberland Mountain, Powell Valley, and at least the southern half of the Middlesboro impact structure, depending upon the time of year and amount of foliage (Figure 9).

Most natural features within view are a part of the Pine Mountain Thrust Sheet (also know as the Cumberland Overthrust Block), a large northeast-southwest oriented thrust sheet extending through Kentucky, Tennessee, and Virginia (Figure 2).

Pinnacle Overlook is situated atop Cumberland Mountain, an exposed section of northwest dipping, Devonian to Pennsylvanian-aged rock. Cumberland Mountain forms the northwestern limb of the Powell Valley Anticline, whose axis of lower Paleozoic strata lies within the valley viewed to the southeast from the overlook.

A brief examination of strata at the overlook reveals graded and cross-bedded conglomeratic sandstones of the Lee Formation (Figure 10). These coarse grained sandstones containing very well-rounded quartzite pebbles (up to 3.8 cm (1.5 in) diameter) were deposited during the Late Mississippian-Early Pennsylvanian Periods (Rice, 1984). Pennsylvanian *Calamites* flora is present within this unit. You have seen this prominent ridge-forming unit exposed on Pine Mountain at Stop 1 and will see it again at Middlesboro.

This anomalous nature of Middlesboro, situated atop the Pine Mountain Thrust Sheet, led early researchers to hypothesize various formation mechanisms (see 'Early Scientific Investigations'). More recent geologic mapping of the Middlesboro North (Englund et al., 1964), Middlesboro South (Englund, 1964), and Kayjay/Forkridge (Rice and Maughan, 1978) quadrangles led Englund and Roen to propose an impact origin for Middlesboro in 1963.

Surrounding Middlesboro and visible to the northwest are the flat-lying strata of the Pennsylvanian-aged Breathitt Formation. These units form a deeply incised plain and in this area you may see the scars of strip mining for coal.

Retrace your route from the Pinnacle Overlook parking lot to the Visitor Center. From there, follow the signs to U.S. Highway 25E North to Middlesboro (Figure 5). Approximately 0.8 km (0.5 mile) after getting on 25E, just inside the city limits of Middlesboro, take a left at the first stop light onto Cumberland Avenue. Continue for 2.1 km (1.3 miles), passing through the downtown area, until reaching 27th Avenue. Take a right (go north). Continue for 7 blocks until reaching Circenster Avenue. Take a left (go west). At the next intersection, take a right (go north) onto Haywood Road. Take the next left (west) into Middlesboro Country Club. Park in the parking lot next to the clubhouse. Hours are 10am-8pm (winter); 9am –10pm (summer); and 8am-10pm

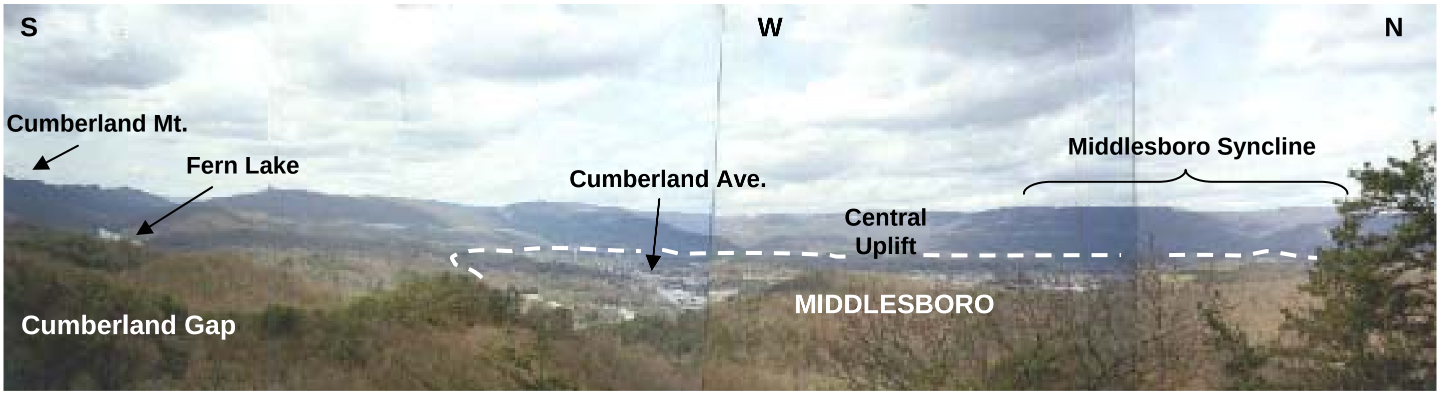

Figure 9. Westward view of the Middlesboro Basin from the Cumberland Mountain showing prominent landmarks. White dashed line demarcates the approximate outer boundaries of the modified Middlesboro impact.

weekends. (Note: permission must be obtained from the manager prior to viewing exposures and collecting is not allowed).

Part II: Middlesboro Impact Crater

Middlesboro is a 5.5 – 6 km diameter complex impact structure of post-Alleghenian age located just northwest of Cumberland Gap (Map 2). Target rock consists of Pennsylvanian-aged shales, siltstones, sandstones, and coal of the Breathitt Group. Evidence confirming an impact origin for this site includes shatter cones and shocked quartz found at the first stop on this field trip. Today, we will spend most of the day examining the crater from the central uplift and moving along the eastern crater rim (both transient and modified).

Stop 4. Central Uplift / Middlesboro Golf Course

You are now standing at "ground zero" of the Middlesboro impact structure. Englund and Roen (1962) first noted the presence of conglomeratic sandstones of the Lee Formation here (now a part of the Breathitt Group) and suggested that this area was an uplifted core of material bounded by "steeply inclined normal faults" common in complex craters. They also noted that "shattered" quartz grains with "parallel arrangement of fractures" were present in the core conglomerates. Bunch (1968), Carter (1969), and Milam and Kuehn (2002) later identified shocked quartz containing PDFs in these rocks, providing confirmation of an impact origin for Middlesboro.

It was at this site that Robert Dietz (1966) noted the presence of "concave striations suggestive of shatter coning" in an outcrop to the northeastern end of the parking lot adjacent to the clubhouse. Uncertainty exists as to whether or not this is actually an outcrop. It is possible that this is only a remnant boulder. A couple of hundred yards to the northwest, Dietz reported finding boulders that were "intensely shatter coned", however. These boulders no longer exist because of extensive landscaping, but additional samples of Lee conglomerate can be viewed in a cobble field approximately 30 m (100 ft) north of the clubhouse. In 1999 the authors located a single sample of coarse-

Figure 10. Cross-bedded conglomeratic sandstone of the Lee Formation along Cumberland Mountain near Pinnacle Overlook, Cumberland Gap National Historical Park

grained siltstone from Middlesboro containing approximately ten shatter cones (Figure 11a) owned by Dr. Nicolas Rast (now deceased) of the University of Kentucky (Milam & Kuehn, 1999). Additional rare shatter cones were found by the lead author (Figure 11b) in 2002.

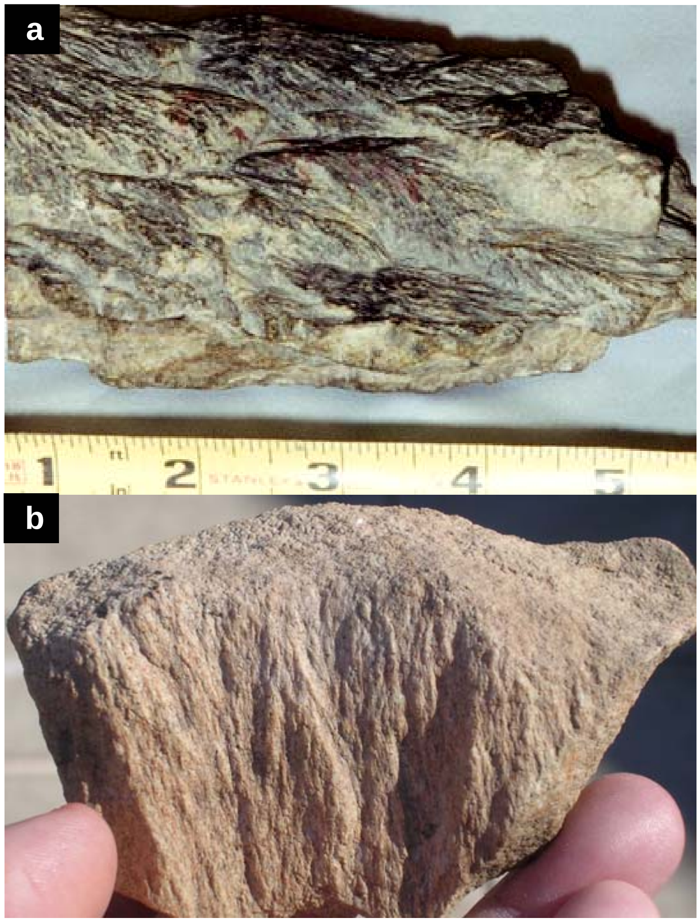

Figure 11. Shatter cones collected from the Middlesboro impact structure in (a) Breathitt siltstone and (b) Lee Formation sandstone.

In 1999, new samples of Lee conglomerate were collected from the central uplift area and have undergone petrographic examination (Milam and Kuehn, 2002). They show intense shattering and fracturing of the fine-grained conglomeratic sandstone, possible melt textures, sheared quartzite pebbles, planar fracturing, and planar deformation features. These textures are providing new insight into the impact cratering process and specifically, central uplift formation (ibid). Additional fieldwork has allowed us to further document and delineate additional surface exposures of the Lee Formation. Structural data from the crater rim, however, suggest that the center of impact may have actually been present further to the northeast. Now that we've examined the center of the impact, let's look at some exposures along the rim areas.

Return to the parking lot and retrace your route back to Cumberland Avenue (Figure 5). Take a left (heading east) and travel for 1.9 km (1.2 miles) and turn right (south) onto the last road on the right before Highway 25E. Continue for 0.2 km (0.1 miles) to the parking lot of the Faith Missionary Baptist Church. Exposures are behind the church. This is a heavily weathered, sloping site that isn't easily visible from the parking lot. A better view can be obtained by cautiously climbing the slope (Note: Permission must be obtained from the proper church officials before viewing this site).

Stop 5. Transient Crater Rim / Faith Missionary Baptist Church

Now you are near the southeastern rim of the transient crater that was initially formed at Middlesboro (Figure 12). This exposure preserves the ejection and modification stages of impact. At the top of the site you'll notice a series of primarily reverse faults (Figure 13) in southwest-dipping sandstones, siltstones, and shales from the Pennsylvanian-aged Breathitt Group with interspersed normal faults. Bedding strikes to the northeast and dips to the southeast, away from the central uplift. Notice the drag folds associated with the reverse faults (Figure 13). Approximately 3 m (10 ft) further down section you'll notice monoclinal folds oriented according to similar stress fields. Fault planes and fold axes have northeast strike and northwest dip orientations. The primary strain that was placed on these strata appears to have come from the northwest of this site, from the direction of the central uplift area.

Figure 12. Exposure of Breathitt Formation near a church in southeast Middlesboro along the transient crater rim.

Figure 13. High-angle reverse faults along the Middlesboro transient crater rim at stop 5. Notice the offset coal beds and drag folds located along fault planes.

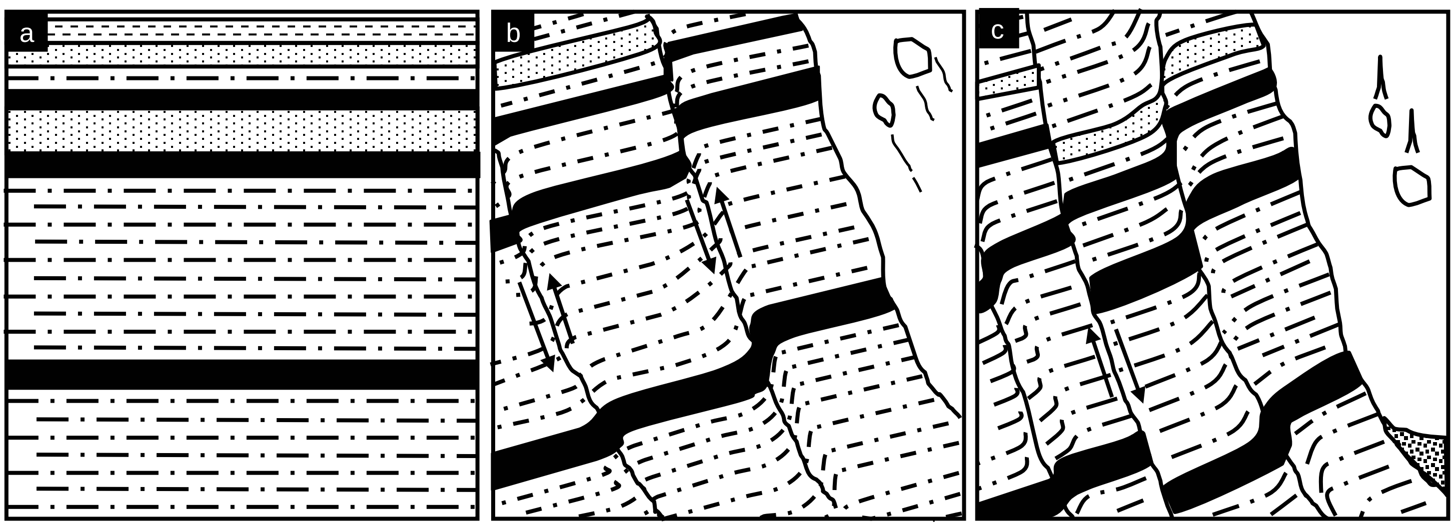

Figure 14. Diagram demonstrating the formation of the transient crater rim and subsequent collapse near stop 5. Figure 14(a) depicts pre-existing (relatively flat-lying) stratigraphy, (b) shows strata being faulted and folded along the transient crater rim during the ejection/excavation stage, and (c) shows collapse of the transient crater rim and fallback of ejecta during the modification stage of impact.

This site thus preserves an instant in time during crater formation when material was being thrown from the transient crater and strata near the rim was being pushed up, out, and away from the center of impact (Figure 14). Some of the material was ejected, while the rest was thrust up along high angle reverse faults (such as at this site). Following the ejection stage, large blocks of material then slumped back into the basin along arcuate normal faults. The hill containing this exposure may be one such block, but only future excavations to the south will determine this.

Retrace your route back to Cumberland Avenue (Figure 5) and take a right (heading east). Turn left at the next stoplight and head north on Highway 25E. Approximately 1.1 km (0.7 miles) down the road on the right is an outcrop behind a restaurant (Lee's Famous Recipe). Park at the rear of the parking lot. Walk around behind the fence to view the outcrop (Note:

permission must be obtained from the restaurant manager before viewing this site).

Figure 15. Exposure of deformed strata along eastern (modified) crater rim at stop 6.

Stop 6. Deformed Strata / Lee's Famous Recipe

At this stop you will view deformed shale, siltstone, sandstone, and coal of the Breathitt Formation (Figure 15) that is relatively undisturbed as the exposure continues to the south. Along the northern end, several faults, small folds, and drag folds are present within this cut. A normal fault has resulted from inward collapse of the crater rim.

It isn't clear exactly how the easternmost block of material relates to the impact model. Were these strata thrust from the east upon nearly horizontal strata (to the west) and you are viewing the leading edge of an arcuate fault along which a terrace block has collapsed during crater modification? Or is this a localized slump feature? Future examination of new exposures to the north and south may reveal the answer in time, but for now, you are the judge.

The westernmost block exposed to the north of the restaurant contains relatively flat-lying strata that contain a small listric normal fault. Along this fault, material has collapsed inward to the excavated crater.

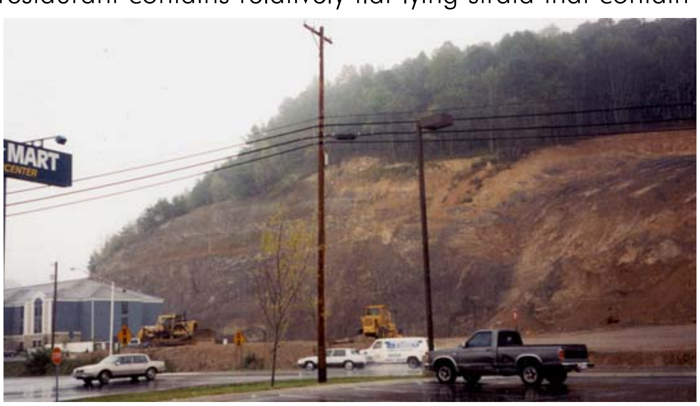

Figure 16. Collapsed terrace block along modified crater rim, Middlesboro, Kentucky at stop 7.

Return to your vehicle and exit the parking lot by taking a right (heading north) onto Highway 25E (Figure 5). Drive for 1.3 km (0.8 miles) and turn right into the parking lot of Holiday Inn Express. (Note: exposures are behind a Hardee's restaurant, Holiday Inn hotel, and Ryan's Steakhouse. Please obtain permission from each facility's manager before viewing the site)

Stop 7. Modification Stage/ Holiday Inn Express

The entire hillside is a footwall of Breathitt Formation that was displaced along a normal fault to the east following excavation of the transient crater (Figure 16). Most of the material that you are viewing consists of siltstones and shales, heavy with carbonaceous plant fossils. These rock layers contain small channels of dark brown fluvial sands (as viewed at the upper southern end of the outcrop). The top of the hill is capped by a thick, coarse-grained, cross-bedded, fluvial sandstone unconformably overlying stringers of coal and their associated underclays. Bedding here dips gently to the north.

One of the most noticeable features of this cut is its heavily fractured nature. Fractured strata here, some of which dip anomalously to the southwest, pose a rock fall/landslide hazard to businesses located at the western base of this hillside. At one time, the hill slope actually extended across present-day Highway 25E. Much of this hill has been cut away to accommodate businesses along the highway.

Due to the densely fractured nature of the strata and the orientation of the bedding, slumping, rock falls, and slides are quite common here. This situation has been alleviated somewhat by "benching" the slope of the outcrop to control minor sliding.

Return to your vehicle and take a right (heading north) out of the parking lot (Figure 5). Continue through the stop light and 0.3 km (0.2 miles) after the last stop take a left at the International Truck Co. Exposures are behind the buildings. (Note: Permission must be obtained form the manager prior to viewing these cuts)

Stop 8. Modified Crater Rim / International Truck Co.

Nearly horizontal strata of the Breathitt Formation are preserved in the southern end of this cut. To the northern end, rocks dip away from the center of Middlesboro Basin (to the northeast). Many normal and reverse faults whose fault planes are parallel to the center of impact are preserved here (Figure 17). Radial faults, localized folding, and cataclasis may also be found. Following impact, material collapsed back into the transient crater along listric normal faults. The identification of key marker beds at the southern end this outcrop shows that the southernmost block has dropped approximately 244 m (800 ft) from its normal stratigraphic position.

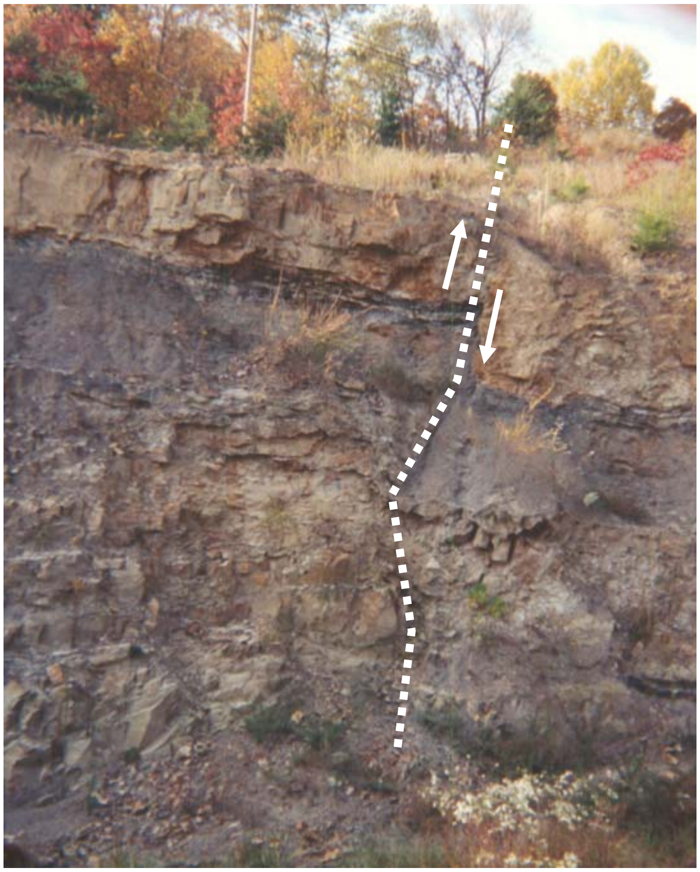

Figure 17. Example of fault along the northeast modified crater rim at stop 8.

Take a right (heading south) form the parking lot onto Highway 25E (Figure 5). Continue for 0.3 km (0.2 miles) to the stoplight. Take a right (heading west) at the stoplight onto Highway 441 (Hollywood Rd.). Continue on Highway 441, go for 0.3 km (0.2 miles) taking a right, continue for 0.6 km (0.4 miles) and take a left on Belt Line Road. Travel for approximately 1.6-2.4 km (1-1.5 miles past Red Oak Baptist Church to a road cut with a small pull-off on the left. Safer parking may be obtained by contacting church officials for permission to use their parking lot.

Stop 9. Deformed Strata / Yellow Creek Bypass Site

This site shows severely deformed Breathitt Group strata that have experienced faulting and folding likely related to crater wall collapse. Some of the shales, with interbedded siderite nodules stand vertically here. A short hike to the Yellow Creek streambed across the road shows additional exposures of sandstone (forming a waterfall) that Englund and Roen (1963) mapped as being completely overturned as a result of the impact event.

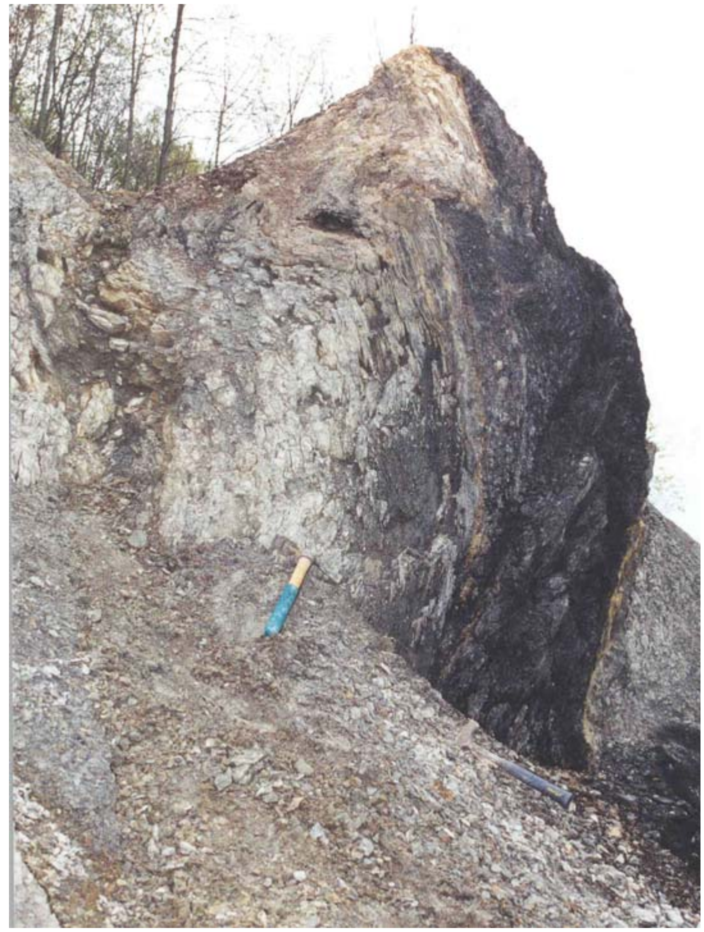

Figure 18. Nearly overturned siltstone, shale, and coal of the Breathitt Formation along the Middlesboro transient crater rim, northern Middlesboro, along Yellow Creek.

Travel approximately 0.8 km (0.5 miles) (you should eventually see Yellow Creek Bypass (a stream) on your left) until you reach a small cut on the right (north) between Lick Fork and Stevenson Roads (Figure 5). Turn in to the right and park. (Note: this is private property, so permission should be obtained from the current landowner).

Stop 10. Transient Crater Rim (optional)

This last stop of the trip also preserves the effects of excavation on the transient crater rim. It displays deformed strata of the Breathitt Formation (Figure 18). Shale, siltstone, sandstone, and coal of the Breathitt Formation all strike 15-35˚ to the northeast and dip 44-68˚ to the northwest (generally away from the center of the impact).

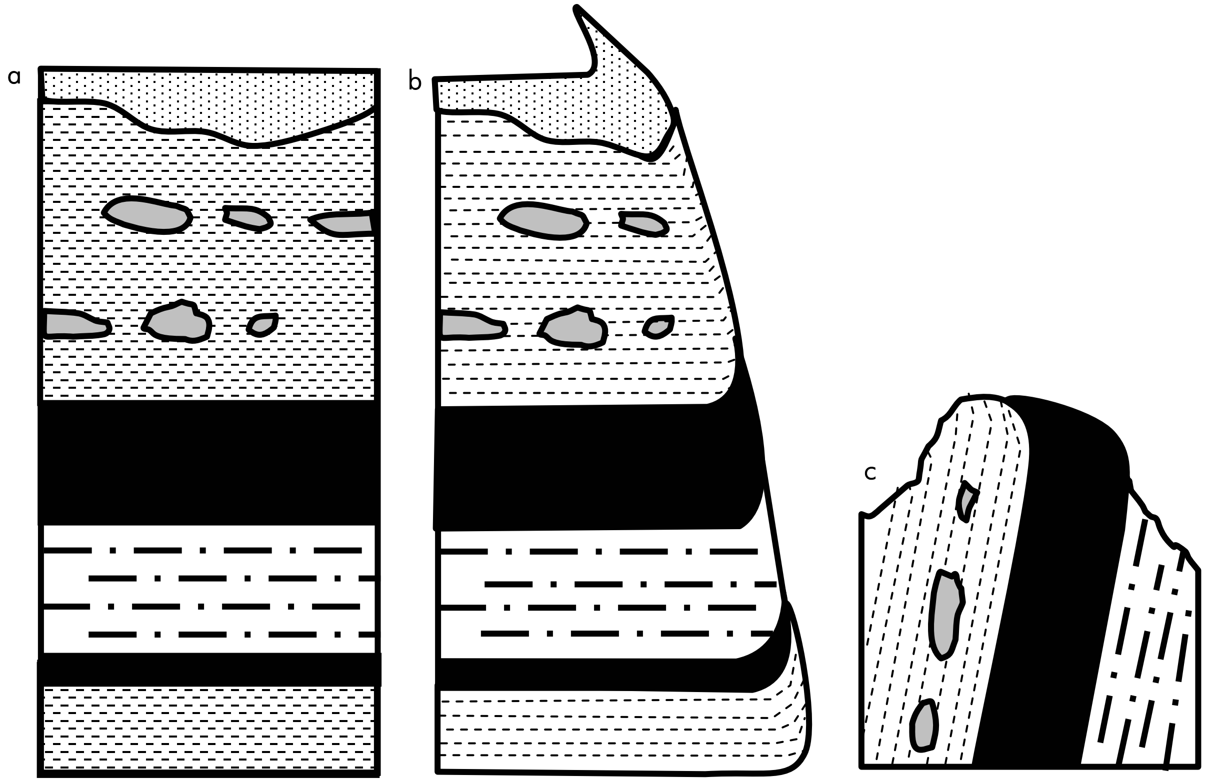

Figure 19. Sequence of impact-related events that led to deformation at stop 10: (a) original pre-impact target rock stratigraphy, (b) strata along the transient crater rim are overturned at the surface and nearly overturned farther down the crater wall, and (c) the unstable crater rim collapses (and rotates) along an arcuate normal fault, resulting in sub-vertical orientations for rock layers.

The most interesting feature of this cut is the nearly overturned flap of shale, coal, and underclay. Similar structures have been noted in other impact structures. Overturned bedding in the form of an "ejecta flap" was first recognized at Barringer Meteor Crater, Arizona (Shoemaker, 1960) and has been shown to be a distinguishing feature of transient crater rims. This site represents nearly overturned strata just below the transient crater rim in the northwest. During the impact ejection stage, this flap of material was nearly overturned and was followed by collapse of the crater rim (Figure 19). During crater wall collapse, the block of material shown moved along a normal listric fault, leading to rotation of bedding and thus the current orientation of strata in this exposure.

Retrace your route toward back to U.S. Highway 25E (Figure 5). Turn right, traveling south through Middlesboro. Just south of town, ~ 1.6 km (1 mile) before entering Cumberland Gap Tunnel, take the exit (on the right) to the Cumberland Gap National Park Visitor Center. Turn right off the exit ramp and drive 0.2 km (0.1 mile) into the visitor center parking lot.

Stop 11. Cumberland Gap National Historical Park Visitor Center

Our trip ends with a visit to the Cumberland Gap National Historical Park Visitor Center. The visitor center houses cultural and natural history exhibits from the Cumberland Gap area. The center provides a historical and cultural context for the remainder of an otherwise scientific trip.

The geology of this region and the human saga has been intertwined for thousands of years. Northeast-southwest trending mountains, such as Cumberland Mountain and Pine Mountain, have influenced human settlement and commerce. Both Native Americans and early European-descent settlers crossed these mountains through natural wind or water "gaps". From 1790-1810, approximately 250,000 settlers from eastern states crossed through Cumberland Gap on their way to Kentucky and Tennessee. Cumberland Gap was also of strategic value for funneling supplies and troops to the north and south during the Civil War. The gap remained a primary transportation route until 1995, when the Cumberland Gap Tunnel, a 1400 m (4600 ft) twin bore tunnel, was opened. The tunnel was designed to better accommodate growing traffic along Highway 25E in the Cumberland Gap area. It enters/exits Cumberland Mountain west of the gap. An important component of the tunnel project has been restoration of the landscape through Cumberland Gap by the National Park Service. Historical documentation was used to provide information about the Gap's appearance circa 1790-1810. After removal of the abandoned U. S. Highway 25E through the Gap, fill material from the tunnel excavation was used to restore original topographic contours. While such impressive engineering feats have improved traffic flow, natural gaps still serve as important transportation corridors through the Southern Appalachians.

From Middlesboro to Flynn Creek

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The route from the Middlesboro impact structure to the Flynn Creek impact crater provides a useful overview of the regional geology of the Southern Appalachians. Along the way, you'll have a chance to view many of the regional geologic structures and provinces (Figure 2). Please augment the following travelogue with Geologic Map #1 (American Association of Petroleum Geologists Geologic Map No. 4 of the Mid-Atlantic region) included at the back of this guidebook.

Travel 4 km (2.5 miles) from the Ramada Inn at Cumberland Gap, Tennessee southward on U.S. Hwy. 25-E to the town of Harrogate, TN. At the intersection of 25E and State Hwy. 63, turn right and travel to the west.

Powell Valley Anticline

For the next 61 km (38 miles), you'll travel along the northwestern limb of the Powell Valley Anticline and parallel to the anticline axis. For this segment of the trip, Cumberland Mountain towers above the northwestern horizon (to the right), exposing Mississippian-aged carbonates and thick sandstones of the Breathitt Group (Pennsylvanian-aged), similar to those seen yesterday and earlier today. As you may recall, Cumberland Mountain lies along the southeastern limb of the Middlesboro Syncline. On this side of the mountain, you're traveling in the valley cut by the Powell River and its tributaries along the axis of the Powell Valley Anticline. For the next few km, note the northwest-dipping Ordovician-aged carbonates. To your left (and out of view) are Middle and Upper Cambrian-aged carbonate units of the core of the Powell Valley Anticline. As you travel through LaFollette and Jacksboro, TN, you'll begin to notice a high, flat plain to the west. This is the Cumberland Plateau.

Continue until Hwy. 63 intersects Interstate-75, just west of Jacksboro. At this interchange, cross the interstate, veering right onto the southbound lanes. Travel for approximately 42 km (26 miles) toward Knoxville, Tennessee. Stay on I-75 (southbound). I-75 will merge with I-640(westbound) and I-40(westbound) through Knoxville. Travel for 161 km (100 miles) to the Baxter, TN exit (Exit 280). Turn right from the exit onto Hwy. 56. Travel northward for 12.6 km (7.8 miles) to the intersection with Flynn Creek Road (just past a gas station on the left). Turn left onto Flynn Creek Road and proceed for 2.3 km (1.4 miles) to stop

Jacksboro Fault and Cumberland Plateau

As you travel along I-75, for the next ~ 8 km (5 miles), you will parallel, and in some places drive over, the Jacksboro Fault. This tear (strike-slip) fault defines the southwestern boundary for the Pine Mountain Thrust Sheet. (If you were to travel 40 km (25 miles) to the north on I-75, you would encounter the leading edge of the Pine Mountain Thrust Block again). To the right (southwest) lies the escarpment that defines the Cumberland Plateau, which rises ~ 610 m (2000 ft) above the interstate. On your left, you will be able to view strata along a traverse of the Powell Valley Anticline. As you continue southbound, on the left (east), you will soon begin to see southeasterly-dipping strata of the Valley and Ridge.

Valley and Ridge

At ~ mile marker 129 along I-75, we leave the Cumberland Plateau escarpment and travel into the Valley and Ridge physiographic province. For the next ~ 104 km (65 miles), you'll observe a series of northeast-southwest trending linear ridges with southeasterly-dipping Cambrian-Silurian-aged strata. Valleys coincide with imbricated and/or duplex thrust faults, where shales that are less resistant to weathering form the valleys themselves. In several places, you will also notice exposures of red ("terra rosa") clays that commonly overly the carbonates in this part of the Valley and Ridge.

Climbing Walden Ridge

Between mile markers 246 and 247, we leave the Valley and Ridge and begin our ascent of Walden Ridge, moving up onto the Cumberland Plateau. Along the way, you'll view northwestwardly-dipping Mississippian aged carbonates overlain by Pennsylvanian siliciclastic rocks (sandstones, siltstones, shales, and coal). Between mile markers 340-341, we have ascended the Cumberland Escarpment and are now making our way onto the Cumberland Plateau.

On the Cumberland Plateau

For the next ~ 69 km (43 miles), we'll travel across the top of the Cumberland Plateau. Along the way, you'll have a chance to view marginal marine deposits, mostly sandstones and shales, of Pennsylvanian age. Watch for extensive cross-bedding and ripple marks in exposed sandstones. Just west of mile marker 299, take special notice of the light orange, cross-bedded sandstone exposed along roadcuts on both sides of the interstate. This is representative of a channel that that cut into lagoonal sediments that later formed the gray shales and siltstones exposed to either side of the paleochannel.

Eastern Highland Rim

At mile marker 297, we are poised at the top of the Cumberland Escarpment and will now be traveling down onto the Eastern Highland Rim. During our descent, we will be leaving the Pennsylvanian-aged sandstones, shale, siltstones, and coal and will be transitioning into Mississippian-aged carbonates. The first to be observed is the Pennington Formation, consisting of red shales and minor siltstone and gray limestone beds exposed to either side of the interstate. At mile marker 292, we've now driven onto the Eastern Highland Rim, which continues for the next 32 km (20 miles). It is in this province where the Flynn Creek impact structure is situated. Along this part of the journey, we'll be traveling over Mississippian-aged carbonates of the Warsaw Limestone and Fort Payne Formation.

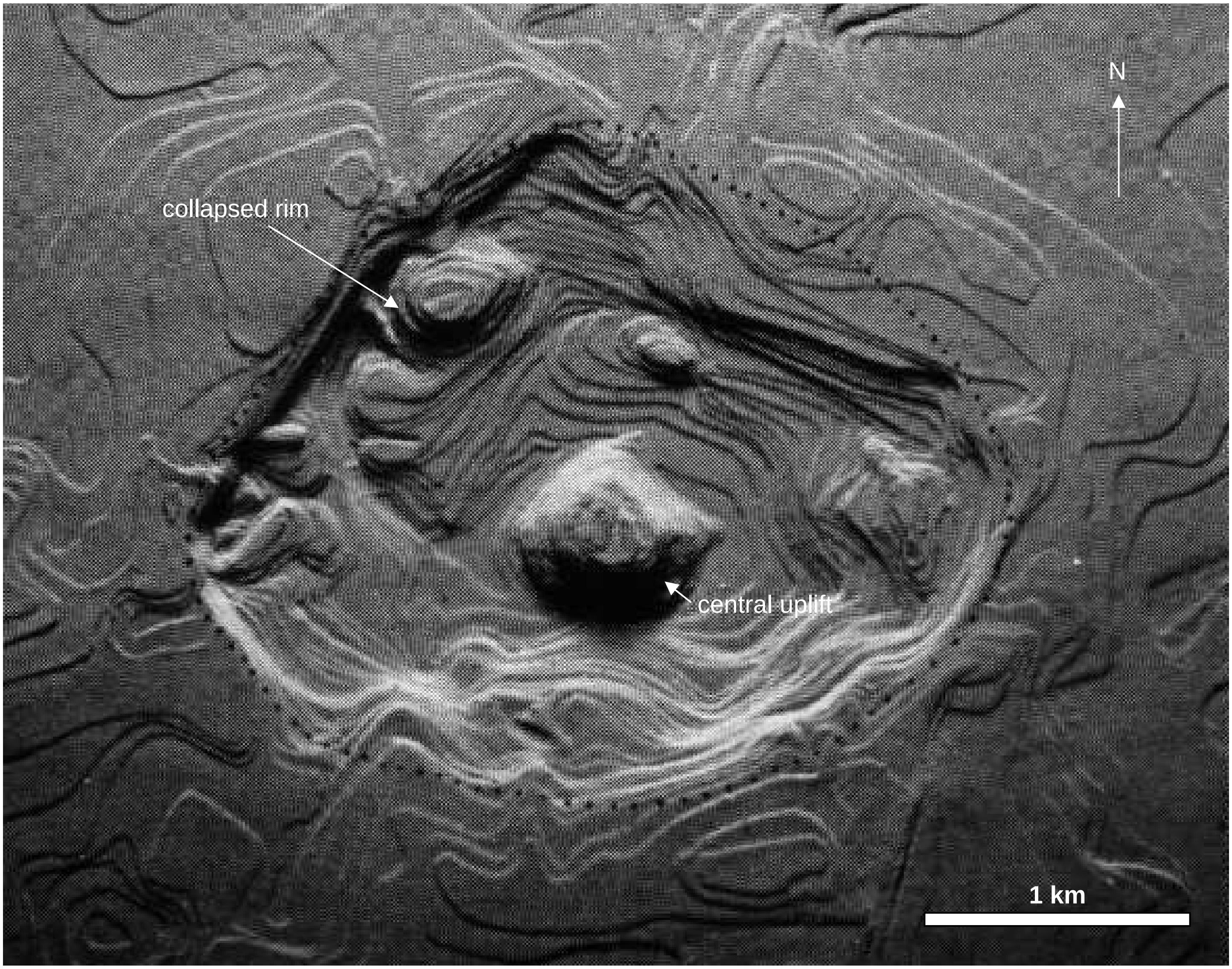

Figure 20. Aerial view of the Flynn Creek impact structure from structure contour map (modified from Roddy, 1966). Contours (10 ft contour interval) are drawn to the base of the Chattanooga Shale, showing a pre-Chattanooga morphology. Dotted line represents the approximate top of the crater wall. Lighting is from the north.

The Flynn Creek Impact Structure

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Introduction

The Flynn Creek impact structure (Figure 20) is located in Jackson County, Tennessee, USA (36°17′ N, 85°40′ W) along the Eastern Highland Rim physiographic province. The structure was first mapped as a crypto-volcanic by Wilson and Born in 1936. Although they did not properly identify the stratigraphy within the crater or the causal mechanism, they did correctly define the horizontal extent of the crater (Roddy, 1979; Wilson and Roddy, 1990). More detailed surface and subsurface research by Roddy (1966, 1968, 1977a, 1977b,1979) and Wilson and Roddy (1990) accurately described the crater as being a 3.8 km diameter complex impact crater, with a central uplift and terraced (collapsed) crater rim. Putting aside morphology as circumstantial evidence, confirmation of an impact origin came in with the discovery of shatter cones in Knox Group exposures of the central uplift (Roddy, 1977). Planar features in quartz and enhanced micro-deformation in calcite have been reported (Roddy, 1977), but no detailed petrographic information has been published (Koeberl and Anderson, 1996).

The Flynn Creek impact occurred around 360 Ma, which corresponds to the interval between the deposition of the Nashville Group and the Chattanooga Shale (Roddy, 1968; 1979. Target rocks are all Ordovician in age (with the possible exception of the Chattanooga Shale, see below) ranging from the Knox Group through Leipers Catheys Formation. Although there is limited rock outcrop in the area, there are exposed surface faults, folds, and large outcrops of impact breccia within the crater. Almost all rim exposures consist of Leipers Catheys Formation, while central uplift exposures are primarily Knox and Stones River Groups.

Following impact, in the Upper Devonian, Flynn Creek crater was filled with dark marine mud that later became the Chattanooga Shale. In this area, the Chattanooga Shale normally is up to ~6 m (20 ft) thick, but in the Flynn Creek structure reaches thicknesses of ~60 m (200 ft). The shale was subsequently overlain by the Lower Mississippian Fort Payne and Upper Mississippian Warsaw Limestone (Wilson and Roddy, 1990), which now cap the ridges in the Flynn Creek area.

Later, this area was uplifted as a result of formation of the Nashville Dome to the west during the late Paleozoic. This led to increased incision of this landscape and exposure of the buried astrobleme.

Driving Directions:

Take I-40 for ~ 142 km (88 miles) from Knoxville, Tennessee to exit 280 (West of Cookeville, TN) and turn right (North) on Route 56. Continue 12.6 km (7.8 miles) and turn left (West) on Flynn Creek Road. Proceed 2.3 km (1.4 miles) to stop 12. Pull off on right side and be cautious of traffic.

Stop 12. Outside the Crater in the Devonian-Mississippian

Here one can view exposures and contact of Upper Devonian Chattanooga Shale and Lower Mississippian Fort Payne Formation in the undisturbed strata outside of the crater (Figure 21). The Fort Payne (Figure 22) consists of interbedded siltstone, shale, limestone, and dolostone, with lenses of chert (the Fort Payne Formation is often locally referred to as the Fort Payne Chert). At the base of the Fort Payne lies a greenish-gray to buff colored shale or claystone known as the Maury Shale. The Chattanooga Shale is a dark gray to black, fissile, pyritic shale that contains a thin bentonite layer in the middle of the unit. Outside the crater, the Chattanooga Shale is ~ 6 m thick; however, the post-impact deposition of Chattanooga mud resulted in thicknesses of up to 60 m inside the Flynn Creek impact structure.

Figure 21. Outcrop of the Fort Payne Chert (top) – Chattanooga Shale (bottom) contact.

Figure 22. Outcrop of the Fort Payne Chert with some weathered geodes.

Proceed 2.1 km (1.3 miles) on Flynn Creek Road to stop 13 (Map 3). Pull off on right side.

Stop 13. Outside the Crater in the Ordovician

Here we view an exposure of Middle-Upper Ordovician Catheys Formation (Upper Nashville/Trenton Group; Figure 23). Note that the Leipers and Catheys Formations were previously mapped in the area as one unit because they are lithologically identical.

Figure 23. Exposure of the Catheys Formation displaying some boudinage probably due to depositional dewatering.

Proceed ~ 0.3 km (0.2 miles) on Flynn Creek Road. Turn right onto Peters Hollow Road and travel for ~0.2 km (0.1 miles) down a gravel road to a gate. Approximately 40-50 m ahead on the left is an old chimney. Park and walk north about 50 m toward the hillside to the entrance of Wave Cave. Note: Wave Cave is on private property and permission must be obtained from the landowner prior to entry.

Figure 24. Entrance to Wave Cave, just outside the crater rim of Flynn Creek crater.

Stop 14. Ramping Up to the Rim / Wave Cave

Wave Cave (Figure 24, Appendix 1) lies in the Catheys Formation and is located approximately 450 m from the crater rim. The cave has formed in a plunging anticline, whose axis trends almost due north-south. Bedding along the western and eastern limbs are oriented N 6 E, 61 NW and N 4 W, 28 NE respectively. Approximately 140 ft. of passageway has formed right along the axis of the anticline, due to preferential weathering of axial extensional fractures. Near the end of the cave, two side crawls lead into a large (~6 x 12 m (20 x 40 ft)) room that has developed parallel to the strike of bedding on the western limb of the anticline. An unusual inverted breakout dome is forming on the western side of this room due to gravitational collapse along bedding planes.

The proximity of this anticline to the Flynn Creek structure and, with the exception of the 0.5° regional dip of the eastern Nashville Dome, the lack of tectonic deformation in the vicinity, argue that this fold was formed as a result of impact. USGS geologist David Roddy (1979) suggested that this anticline was the manifestation of a normal listric fault at depth just beneath the surface, along which the transient crater wall collapsed.

Return to Flynn Creek Road. Take a right, heading north for ~ 0.3 km (0.2 miles) to Stop 15 (Map 3). Pull off on the left side of the road. Carefully cross the road to an ephemeral stream bed. Follow the stream bed for ~ 10 m to the entrance of Birdwell Cave. Note: Birdwell Cave is on private property and permission must be obtained from the landowner prior to entry.

Figure 25. Entrance to Birdwell Cave, along the modified crater rim of the Flynn Creek impact structure.

Stop 15. Eastern Crater Rim / Birdwell Cave

Now we are standing along the eastern (modified) rim of the Flynn Creek Crater (Figure 25). Like many other caves found in the Catheys Formation here, Birdwell Cave (101 m (330 ft.) long) has formed just along the steepest part of the crater rim (where the Chattanooga Shale begins to thicken to the west). Like Wave Cave, Birdwell Cave (Appendix 2) is oriented almost approximately north-south, perpendicular to the center of impact the likely direction of maximum strain that crater rim experienced. As you enter Birdwell, notice that development of the box-shaped cross-section by dissolution subsequent collapse has occurred along strike. A small cobble-filled crawlway leads from the left-hand side of the cave near the rear for several tens of meters to the north.

Proceed 0.8 km (0.5 miles) on Flynn Creek Road to stop 16 (Map 3). Pull off on left side and be cautious of traffic around the curve in the road.

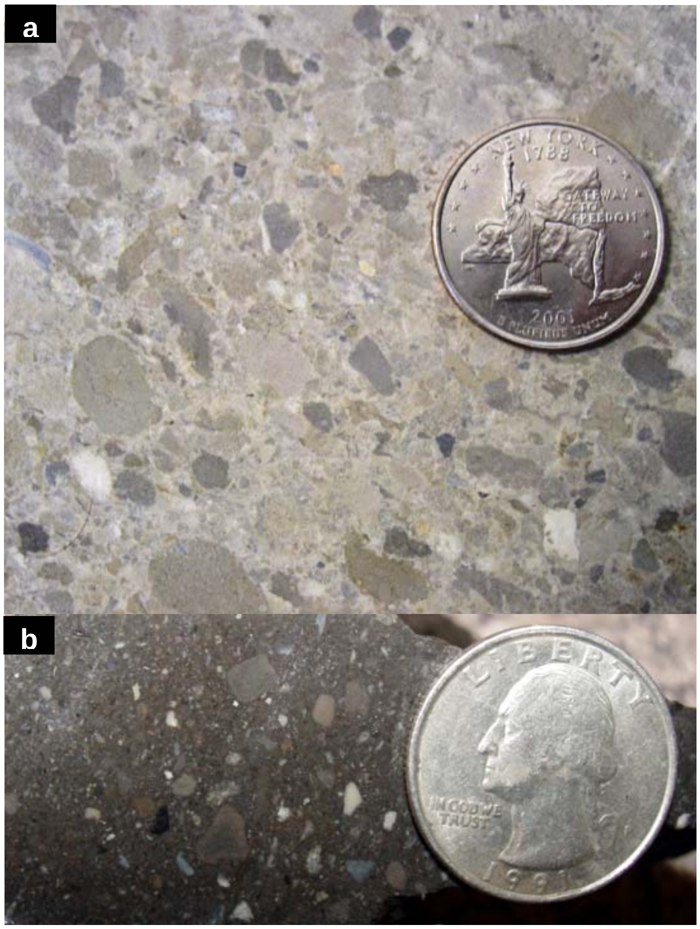

Figure 26. Typical impact breccia (a) with carbonate and shale clasts. Impact breccia with non-calcareous matrix and various types of clasts (b).

Stop 16. Allogenic Impact Breccia

Here we will view allogenic impact-generated breccias as mapped by Wilson and Roddy (1990). The breccia contains mainly carbonate clasts derived from the Stones River Group, but also note the presence of shale and dolomite clasts with minor calcite and bitumen (Figure 26). In some places, calcite veins, slickenslides, and possible bedding are visible.

Wilson and Roddy (1990) recognized three major types of breccia (bedded, non-bedded and mega-) in the crater, with several subtypes. The breccias are typically poorly sorted and contain angular limestone and dolomite clasts derived from the Nashville, Stones River, and Knox Groups, which are Ordovician in age. Some of the breccias, however, are mainly composed of black shale clasts (Figure 27) that are probably of Chattanooga Shale (Upper Devonian) affinity and do not appear to contain any limestone or dolomite clasts. This suggests an early syndepositional impact event rather than Ordovician or pre-Chattanooga Shale impact. A non-calcareous, fine-grained bedded breccia with an occasional overlying tan to medium gray, fine-grained, dolomitic, gradational unit that grades upward occurs at the base of the Chattanooga Shale. This further illustrates that the impact probably occurred during the Devonian and was followed by marine deposition of a fine-grained dolomitic unit within the crater.

Figure 27. Impact breccia showing black shale clasts indicating an early Chattanooga Shale (Upper Devonian) syndepositional impact.

Thin sections from bedded and non-bedded breccia have revealed linear inclusion planes (LIPs) similar to tectonic LIPs, possible minor spot melt at grain boundaries, rare flow textures, pre-impact stylolites, and sub-grain development. The LIPs and subgrain development may be related to post-impact deformation, but the presence of spot melt and flow textures further support the structure's impact origin. Supplemental microprobe work is planned to identify composition of the impact melts.

Proceed ~ 0.5 km (0.3 mile) on Flynn Creek Road to stop 17 (Map 3). Pull off in church parking lot at the junction to Cub Hollow Road. Walk to the east along Cub Hollow Road for approximately 180 m (600 feet) where carbonate exposures in Cub Hollow Creek appear.

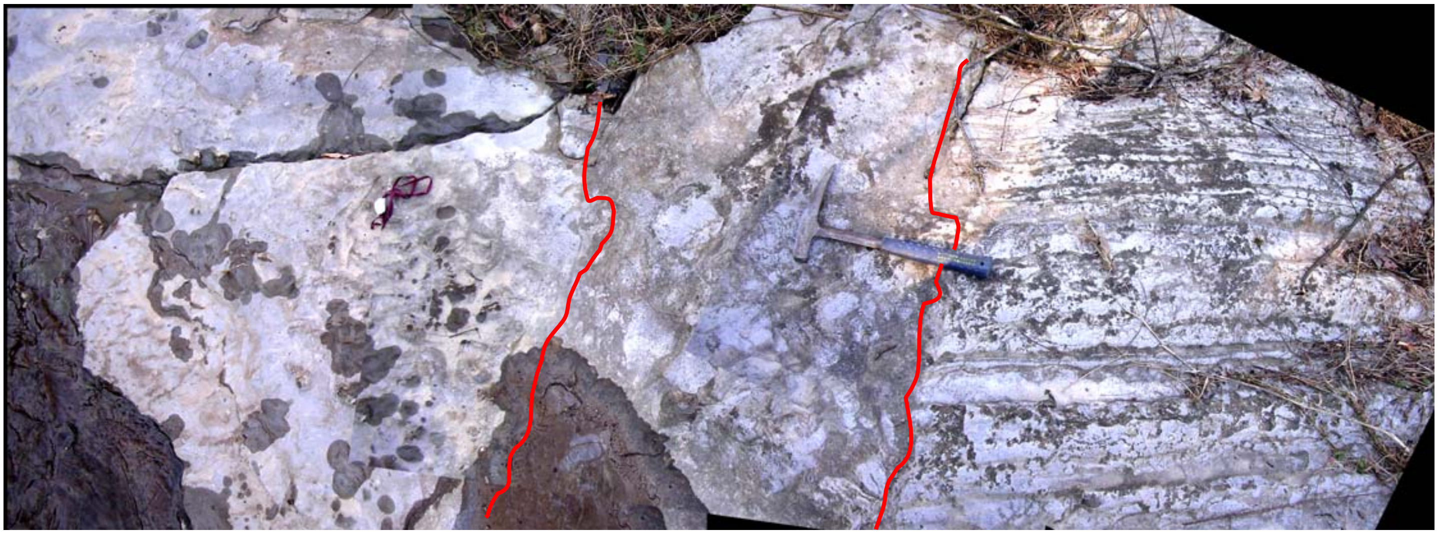

Figure 28. Exposure of the Flynn Creek crater floor along Cub Hollow Road. The breccia dike (whose boundaries are highlighted in red) separates a horizontally-oriented block (left) from vertically-dipping strata (right).

Stop 17. The Crater Floor

As you walk up the creek to stop 17, notice the Chattanooga Shale exposed in the hillside to the right and in the streambed itself. Farther up the stream, we approach the base of the Chattanooga and the underlying carbonates of the crater floor become exposed (Figure 28). Bedding orientations indicate that large blocks along the floor have been rotated by as much as 90° from their normal stratigraphic positions. There are at least 2 polymict breccia dikes separating blocks here. The larger, westernmost dike is fine-grained, while the easternmost dike contains larger angular clasts, many derived from the adjacent wall rock, with remnant bedding still visible.

Proceed ~ 0.5 km (0.3 mile) on Flynn Creek Road to stop 17 (Map 3). Pull off on left side and be cautious of traffic especially near the eastern side of the roadcut.

Stop 18. The Central Uplift

At this stop, we'll examine exposures along the northern flank of the Flynn Creek central uplift (Figure 29). Here, exposures of (primarily) Stones River and (to a lesser extent) Knox Groups that have been structurally uplifted by as much as 450 m above their normal stratigraphic positions. Net movement of the central uplift was inward and upward. Roadcut exposures and stream bank outcrops along the northern flank are dominated by westward-dipping Stones River Group limestones and interbedded shales (Roddy, 1968; 1977). Farther to the east, what has been described as a "chaotic breccia zone" (Roddy, 1968) separates these westward-dipping strata from lesser (by volume) eastward-dipping strata. These exposures, in addition to drilling data (Roddy, 1977) suggest that the domical central uplift is actually asymmetric, with overall movement from west to east along major thrust faults. Exposed megablocks are separated by sharp fault contacts and monomictic authogenic breccias (Figure 30).

Additional work in Hawkins Impact Cave (see Appendix 3 and 'Caves of the Flynn Creek Impact Structure'), the only known cave in a central uplift in the world, suggests that the central uplift is significantly different in character to the south. A larger number of megablocks with more variable displacements occur

Figure 29. Photo mosaic of Stones River Group strata exposed along Flynn Creek Road in the northern half of the central uplift. The center of this view is to the north.

closer to the core of the central uplift. Ongoing research at Hawkins Impact Cave will be discussed and smaller trips to various surface exposures in the central uplift will be available at this stop.

Proceed 1 km (0.6 miles) on Flynn Creek Road to stop 6. Pull off on left side near the intersection.

Figure 30. Monomictic breccia consisting of clasts of the Ordovician-aged Stones River Group exposed high on the northern flank of the Flynn Creek central uplift. Photo represents 0.3 m in width.

Stop 19. Impact Breccia/Chattanooga Shale Contact

On the northern side of the road lies more impact breccia that is similar to that viewed at stop 16; however, this bedded breccia appears to be locally vesicular. Here, breccia overlain unconformably with a dolomitic unit that is in gradation contact with the Chattanooga Shale (Figure 31).

Proceed 1.8 km (1.1 miles) on Flynn Creek Road to stop 19. Pull off on right side.

Stop 20. Northwestern Rim of Flynn Creek Crater

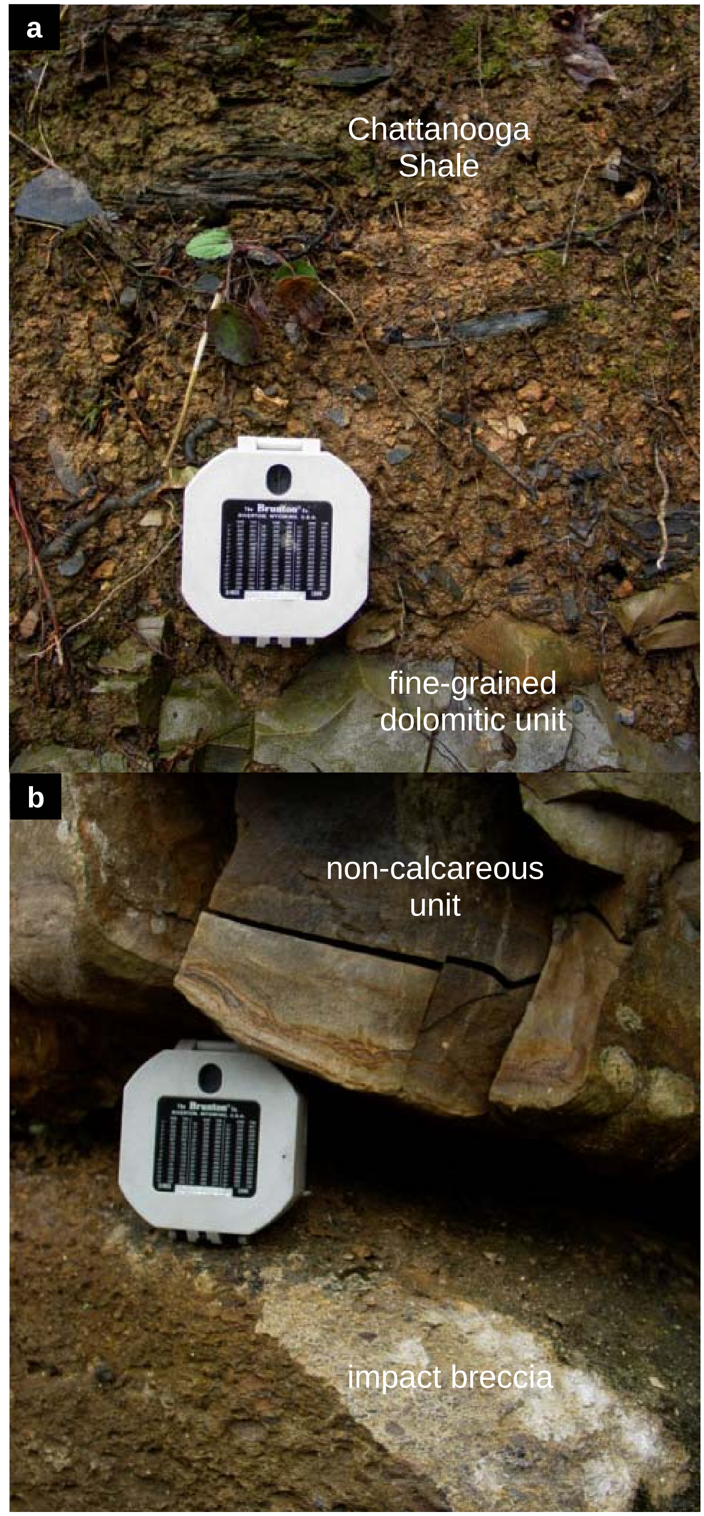

Figure 31. Types of contacts between impact breccia and younger crater fill: (a) gradational and (b) sharp.

This stop lies along the northwestern (modified) crater rim of the Flynn Creek impact structure. As with the crater rim elsewhere, this roadcut is extensively faulted and contains collapsed caves (look for associated speleothems). Following these exposures farther to the northwest, we notice that the westward-dipping strata are again undisturbed.

Karst Modification of the Flynn Creek Impact Structure

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Introduction.

The Flynn Creek impact structure (36°17'N, 85°40'W) in Jackson County, Tennessee was formed in the gently-dipping Lower-Middle Ordovician carbonates commonly found in the Eastern Highland Rim of north-central Tennessee (Figure 32). This partially exhumed astrobleme is a 3.8 km diameter complex crater, with collapsed crater rim and prominent central uplift. The impact event destroyed and ejected a large volume of material (~0.8 km^3, Roddy, 1979), while the remaining target strata were severely deformed. Along the crater perimeter, limestone and shale dip radially away from the center of impact, forming a raised crater rim. Subsequent to the formation of a transient crater rim, large blocks collapsed along listric normal faults, resulting in an enlarged final (modified) crater diameter. Along the crater floor, rocks have been faulted, folded, and brecciated. The central uplift consists of large blocks of limestone and dolostone from the Knox and Stones River Groups with primarily eastward displacements along major thrust faults (Roddy, 1979).

In the Upper Devonian, Flynn Creek crater was filled in with dark marine mud that now forms the Chattanooga Shale. In the region outside the crater, the Chattanooga is normally up to ~6 m thick (20 ft), but in the Flynn Creek structure reaches thicknesses of ~60 m (200 ft). The shale was subsequently overlain by the Lower Mississippian Fort Payne and Upper Mississippian Warsaw Limestone (Wilson and Roddy, 1990), which now cap ridges in the Flynn Creek area.

Uplift (associated with formation of the Nashville Dome) that had began during the Cambrian continued all the way into the Holocene (Wilson, 1935; Stearns and Reesman, 1986). This led to increased incision of this landscape and exposure of the buried astrobleme. Flynn Creek itself continues to cut from east to west through the crater and empties into the Cumberland River to the northwest. Tributary drainage into Flynn Creek itself is dendritic-radial and is controlled by the underlying structure of the crater itself in places. Several springs emerge at the surface from Ordovician carbonates, contributing to surface drainage. However, some flow over land for some distance before sinking again to underground aquifers.

Observations

Karst Development of the Eastern Highland Rim

A result of regional uplift associated with the formation of the Nashville Dome has been continued modification of the landscape by surficial processes, leading to dissection of the Eastern Highland Rim. With continued erosion, detrital sedimentary rocks of the Pennsylvanian were breached and eroded away, exposing underlying Mississippian carbonates (Warsaw Limestone and Fort Payne Formation). It was in these geologic units (and once overlying Upper Mississippian rocks) that a first generation karst landscape developed. Here, cave passage development, was controlled by gentle, eastward-dipping bedding (along strike and/or dip) and/or joint orientations.

Continued dissection of the landscape eventually exposed the underlying Chattanooga Shale, a thin regional aquitard, and underlying Ordovician-aged carbonates (Map 3). As a result, a second generation karst landscape was formed locally in the Leipers-Catheys, Bigby-Cannon, and Hermitage Formations, as well as the underlying Stones River and Knox Groups. Caves here are similar to those formed in the previous generation of karst.

Karst Features of Jackson County, Tennessee

There are 73 known caves in Jackson County, Tennessee or one cave for every 13.14 km^2 (not including caves associated with target rock of the Flynn Creek impact structure). These caves are developed in both generations of karst landscape (generation (1): 14% of caves, generation (2): 86%). Most of the caves (56%) are concentrated in the Leipers-Catheys Formation, which outcrops along the banks and associated tributaries of the Cumberland River and along the rim of the Flynn Creek structure, with the highest amount of exposure at lower elevations in southwestern Jackson County. The remainder occurs in the Bigby-Cannon (30%) and Fort Payne Formations (14%). The Bigby-Cannon is also exposed primarily along the banks of the Cumberland River and its tributaries. Caves in Jackson County range from 1 to 975 m in length (not included target rock caves from the Flynn Creek structure) and also occur with other karst-

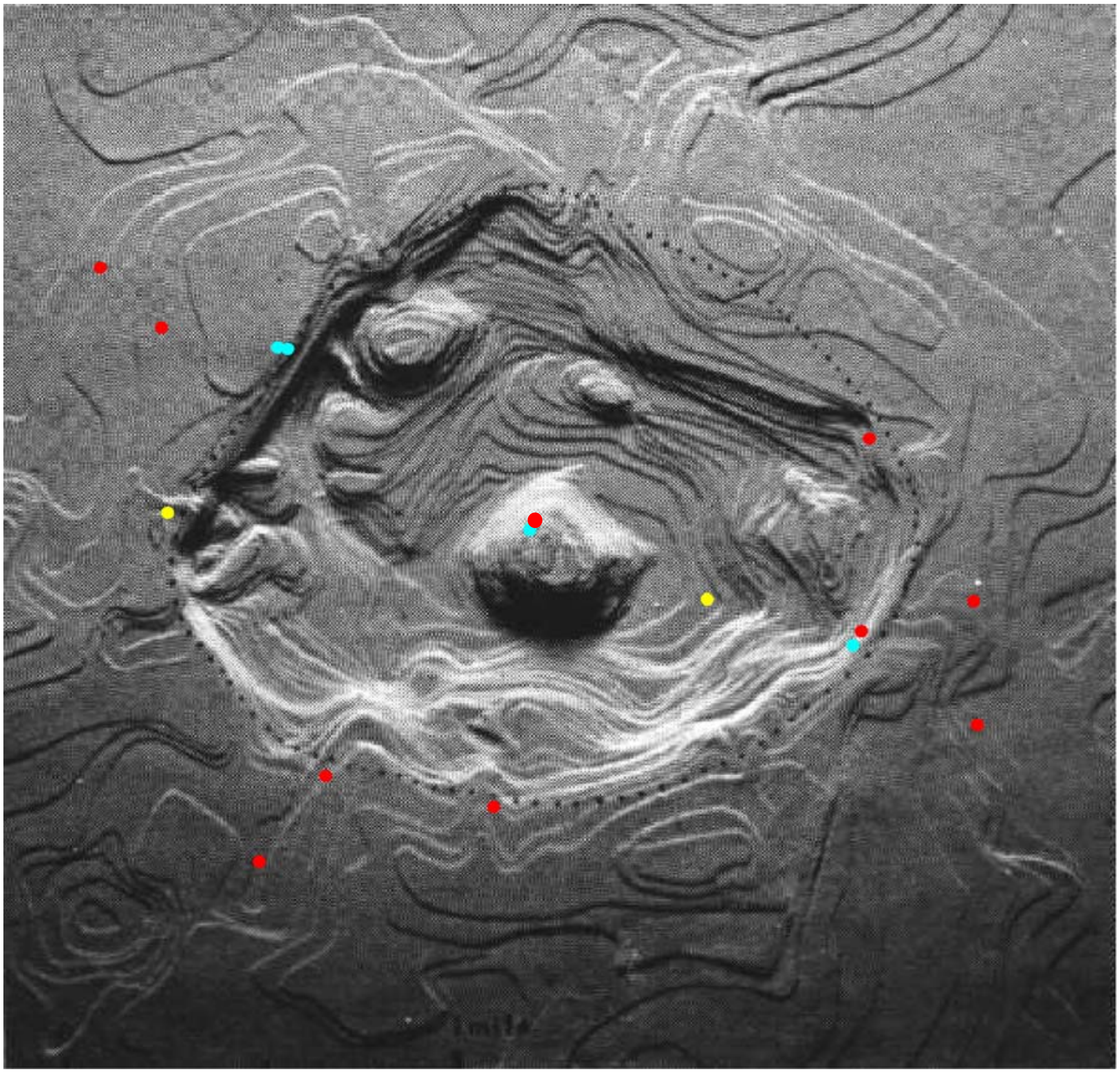

Figure 32. Aerial view of the Flynn Creek impact structure from structural contour map by Roddy (1966), modified. Contours are drawn to the base of the Chattanooga Shale, showing a pre-Chattanooga morphology. Dotted line represents the approximate top of the crater wall. Lighting is from the north, no vertical exaggeration. Red dots represent target rock caves, yellow dots represent crater fill caves, and blue dots represent various other karst-related features (i.e. sinkholes, springs, etc.)

related landforms such as: sinkholes, underground streams, sinking streams, and surface springs.

Flynn Creek Crater: A Unique Karst Terrain?

As with the surrounding terrain, the dual-generation karst landscape also occurs at the Flynn Creek impact structure (Figure 32). Two caves (Antioch School Cave and Mahaney Pit) occur in the crater fill in the Fort Payne Formation (first generation karst). Karst development has been observed in the crater fill of the Chicxulub structure (Figure 33) where cenotes are aligned with buried faults along the crater perimeter. The two known crater fill caves at Flynn Creek, however, do not correlate with structural features of the impact crater itself and so, similar other Jackson County caves are not thought to be directly affected by the Flynn Creek structure.

Caves and karst within the target rocks of the Flynn Creek structure, however, are unique from those exposed outside the crater and may be somewhat rare for impact structures in carbonate rocks on Earth. As of this printing, only a handful of other caves are known to be associated with the target rocks of other impact craters. The larger, 12 km Wells Creek impact crater in northwestern Tennessee, only has one cave, Richardson Cave, associated with impact-deformed target rocks. Ries crater, Germany, is home to a cave near Wallerstein, approximately 6 km away from the crater

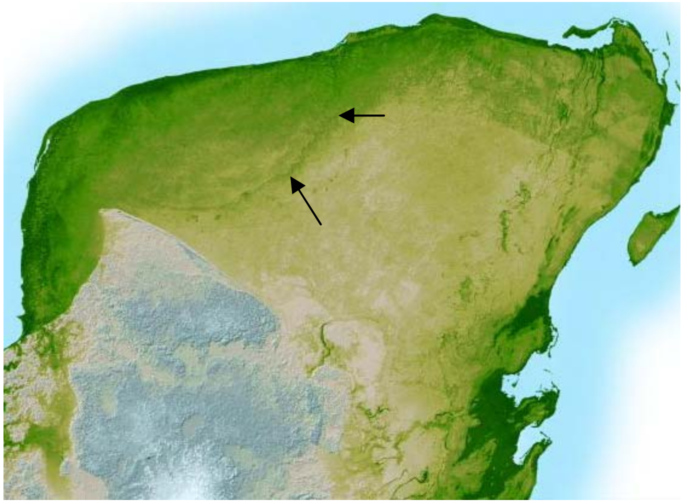

Figure 33. Shaded-relief SRTM-DEM of the Yucatan Peninsula, Mexico, February, 2000. Arrows indicate the circular alignment of cenotes (in crater fill) that coincide with the outer rim area of the Chicxulub crater (buried). Image courtesy of NASA.

center. The search is still underway at other impacts in carbonate target rocks.

At least 10 caves are found in the target rock of the Flynn Creek impact structure (within a ~ 2.4 km radius from the crater center) from the approximate crater ramp, ~ 450 m from the crater rim, to the crater center). These target rock caves are unique in terms of: density per unit area, total length of passages, average passage length, and geographic distribution. Target rocks contain 5.5x the concentration of known caves elsewhere in Jackson County, Tennessee, with 1 cave/2.38 km^2. Outside the impact structure, however, one cave can be found for every 13.14 km^2. Similarly, 7.5x more total cave passage can be found associated with the crater area, compared to surrounding areas. Target rock contains 0.061 km of cave passage/km^2, whereas 0.008 km of cave passage/km^2 can be found outside the crater in Jackson County. Additionally, the average length of target rock caves is also higher (159 m) when compared to the average length of caves elsewhere within the county (108 m).

The location of target rock caves and other karst features are also unique in that they correlate with uplifted strata along the crater rim or the modified rim edge itself and the central uplift of the Flynn Creek structure. Figure 32 shows a map of the Flynn Creek crater (after Roddy, 1966, 1968) with subsurface contours to the base of the Devonian-aged Chattanooga Shale, which, after fallback ejecta, was the first post-impact depositional unit. This is effectively the shape of the crater itself following impact, subsequent collapse of the crater rim, and rise of the central uplift. Nine of the ten known target rock caves (and several springs) have formed along (and just outside of) the modified crater rim in the Leipers Catheys Formation. No caves have been found beneath the crater floor. Hawkins Impact Cave has formed in the central uplift itself in Stones River Group strata.

Potential Contributing Factors

It is initially unclear as to why there are more and (on average) longer caves associated with the target rock of the Flynn Creek impact structure. Here we examine several factors which may have contributed to the enhanced development of caves and karst at Flynn Creek. Specifically we address whether or not the following factors contributed to or limited karst development in the vicinity of the Flynn Creek impact:

1. impact-modified level of carbonate exposure
2. target rock fracturing, faulting, and folding
3. bedding orientations
4. crater fill materials

Carbonate Exposure

Increased subaerial exposure of limestone and dolostone results in a higher number of recharge points for karst aquifers, permitting more surface runoff to penetrate underground. The presence of an overlying, less soluble, cap rock retards solutional collapse and facilitates the development of extensive subterranean drainage systems. High-levels of carbonate exposures result in development of significant sinkhole plains and, in general, less extensive cave systems.

The level of carbonate exposure at present-day erosional levels at Flynn Creek is different from that of comparable surrounding terrain as a direct result of the impact event. Crater excavation, ejection, and wall collapse lessened the amount of carbonates available for subsequent exposure at given erosional levels. Rise of a central uplift, uplift along the crater rim, and deposition of (carbonate) fallback ejecta, however, countered this. The net result was a lower percentage of exposure of karst-forming units in the impact crater vs. outside the structure. The Fort Payne, Leipers-Catheys, and Bigby-Cannon Formations, in addition to the Stones River Group are exposed over 85% of the terrain outside the Flynn Creek impact structure, whereas these karst-forming units comprise 59% of the crater interior. Thus, less carbonates are exposed inside vs. outside the impact structure. This would limit the number of recharge points for karst aquifers, thus restraining the development of caves inside vs. outside the crater.

Most of the caves formed in target rock here are formed in the Leipers-Catheys Formation, the dominant karst-forming unit in Jackson County. Nearly twice as much Leipers-Catheys Formation is exposed outside (34%) vs. inside the crater (18%). This would also serve to reduce surface runoff infiltration of cave-forming units, thereby limiting karst development within the crater. However, for the Leipers-Catheys, the overall density (1 cave/ 2.64 km^2 for this unit alone) and average passage length (142.71 m) is higher when compared to non-impact related caves of the same unit (1 cave/23.66 km^2 and 108.28 m). Thus, the level of exposure of karst-forming units, such as the Leipers-Catheys Formation, is not responsible for the higher cave density/area and longer caves (on average) associated with the Flynn Creek impact structure.

Fracturing, Faulting, and Folding

As noted earlier, target rock cave passages are, on average, longer than those outside the Flynn Creek structure. To some, this may be somewhat counterintuitive. One might suspect that average cave passage lengths would be shorter in the highly fractured and faulted target rock of an impact crater, with passages being truncated by major faults. However, fractures and faults are also zones of weakness where limestone dissolution is enhanced (higher permeability), leading to longer passage lengths. Such is the case at Flynn Creek, where fracturing and faulting have enhanced speleogenesis of target rock caves.

Flatt Cave, in the southern crater rim has developed within at least four major fault blocks of the modified crater rim. Bounding faults do not limit passage development; rather they serve as conduits for groundwater. Many speleothems in this cave have even formed along major fault boundaries.

Dissolution and gravitational collapse have occurred preferential to fault boundaries in Hawkins Impact Cave. Hawkins has formed in the faulted, fractured, and folded rocks of the central uplift of the Flynn Creek structure. Limestone dissolution of the Stones River Group was partially controlled by strike and dip orientations within central uplift megablocks. However, between megablocks, cave passages were developed along major fault boundaries. Passage enlargement has occurred along minor fractures, known as microfractures, due to collapse. Two large rooms (the Mars and Upper rooms) were formed by dissolution and subsequent collapse at the intersection of several major faults.

Wave Cave (Figure 24), located along the eastern crater rim, developed along the axis of an asymmetric plunging anticline. The cave developed in the hinge of the anticline along extensional fractures. Roddy (1979) suggested that this anticline is associated with a listric normal rim fault just beneath the surface that formed from rim collapse.

Bedding Orientations

Cave passages commonly develop in phreatic settings along strike and under vadose conditions parallel to dip, as seen in gently or steeply dipping caves (e. g. Palmer, 1981, 1985; Saunders, 1985). Dipping rock is exposed along the crater rim, crater floor, and central uplift of the Flynn Creek structure and has exerted influence over the development of caves here. Like other impacts, rocks along the crater rim at Flynn Creek (generally) dip radially away from the center of impact, with corresponding strike orientations lying tangential to the crater rim. Both Birdwell and Cub Hollow Cave have developed sub-parallel to strike. The Tilted Room in Wave Cave (Appendix 1) has developed along the strike of steeply-dipping (61°) beds of the western limb of the anticline. Several prominent sections of Hawkins Impact Cave (Appendix 3), which lies in the central uplift, formed as a result of vadose dissolution of limestone along dip.

The Influence of Crater Fill Materials

With the exception of Hawkins Impact Cave, no caves have been found on the crater floor, due to the paucity of exposures at present-day erosional levels. However, the paucity of karst development in the crater interior and the concentration of caves along the crater rim may relate to the nature and presence of fill materials.

Impact-generated allogenic breccias occur along the floor and rim of Flynn Creek crater at contact between underlying Ordovician rocks and the overlying Chattanooga Shale (Roddy, 1968). These breccias have been interpreted as fallback ejecta from the Flynn Creek event (Roddy, 1968). These breccias consist primarily of limestone and dolostone clasts from the Hermitage, Bigby-Cannon, and Leipers-Catheys formations (Wilson and Roddy, 1990).

No caves have been found in association with any of these breccias. Birdwell Cave lies adjacent to impact breccias in the southeastern portion of the crater, but is wholly developed within the Leipers-Catheys Formation. It is unclear as to why caves have not developed in this otherwise porous material. Breccias are dominated by limestone (vs. dolomite) clasts; however, some dolomitic breccias and breccias with a dolomitic matrix have been reported (Roddy, 1968; Wilson and Roddy, 1990). The larger dolomite component in breccias over that of target rocks suggests that these impact breccias may be less soluble than underlying or adjacent target rocks. Thus, rim rocks may be more susceptible to dissolution by acidic groundwater than ejecta material.

While breccias likely have a higher primary porosity than surrounding target rock, in most cases, they lack bedding planes, joint surfaces, and fractures/faults that would serve as pathway for secondary porosity development. In other words, these rocks may have a higher porosity, but lower permeability. This may have been enhanced by thermal welding of breccias following impact. Some breccias just beneath the base of the Chattanooga Shale in the northwestern part of the crater (at stop 19) contain vesicles supporting this hypothesis.

The Chattanooga Shale is a regional aquitard/aquiclude is also an important component of crater fill material that has likely affected the distribution of caves along the crater rim. Thick deposits of Chattanooga Shale would prohibit inward groundwater flow from the crater rim,

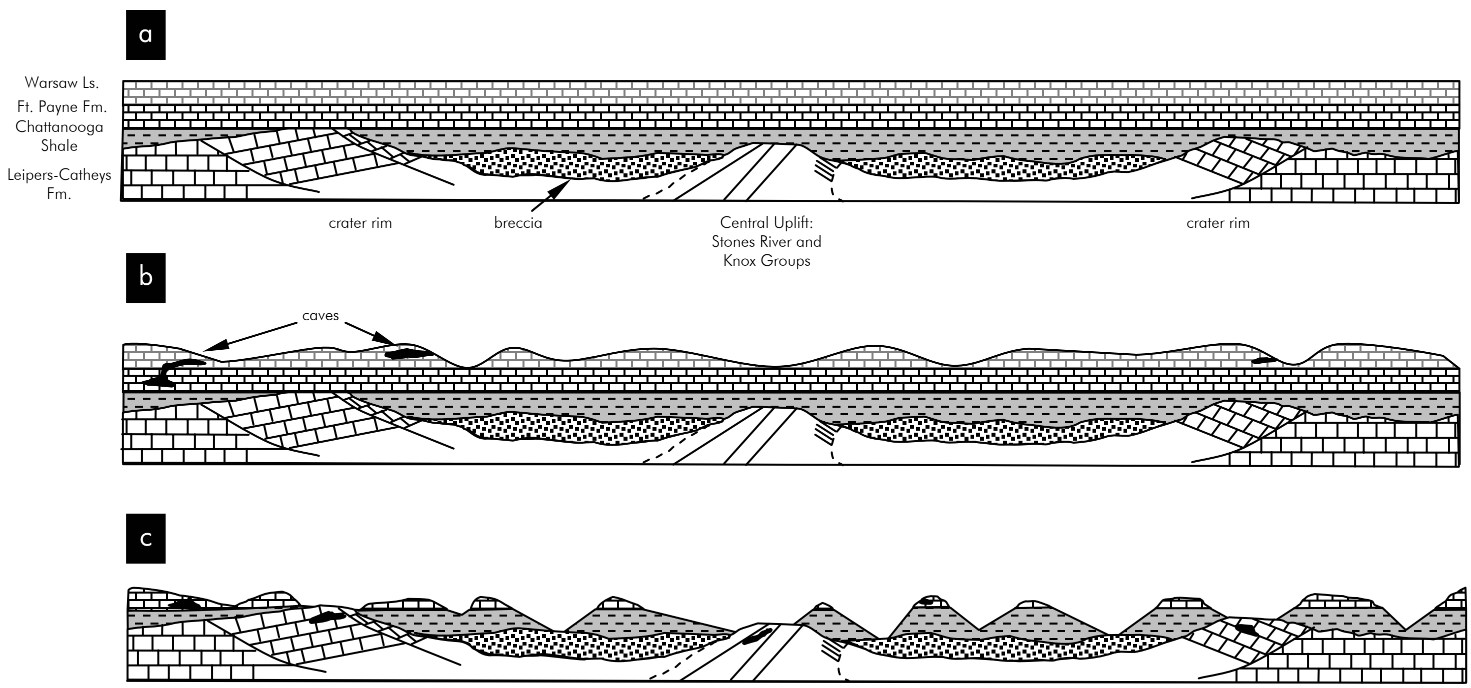

Figure 34. Generalized model for speleogenetic modification of the Flynn Creek impact structure and overlying crater fill materials. Figure 33(a) depicts the buried astrobleme and the Knox Group through Warsaw Limestone stratigraphy following impact. Overlying units are not depicted. In (b), the Warsaw Limestone has been weathered and a first generation of karst begins to develop. After continued erosion and dissolution, the Fort Payne Formation also undergoes karstic development. Eventually (c), the Chattanooga Shale is breached by surface drainage and Ordovician-aged target rocks become the subject of dissolution to develop a second generation karst along the crater rim and central uplift. Most of the caves here appear to be controlled by the structural geology of the crater.

forcing flow along the rim or down the crater wall to springs located within the Flynn Creek structure. This flow retardation would serve to enhance dissolution along the crater rim.

Alternatives

It is possible that the results of this study are biased by more intensive scientific scrutiny of the Flynn Creek impact structure than the surrounding portions of Jackson County, Tennessee. However, this portion of the Eastern Highland Rim has been investigated by numerous researchers (Barr, 1961; Matthews, 1971; and Tennessee Cave Survey listing) for the past 50 years searching for new cave locations, not specifically associated with the crater. With the exception of Wave Cave, much of the early research conducted by U.S.G.S. geologist David Roddy apparently did not even note the presence of target rock caves (Roddy, 1979).

A Model for Post-Impact Speleogenesis at Flynn Creek

In the absence of the Flynn Creek impact structure, a dual-generation karst landscape would have developed in this area similar to that seen outside the crater and elsewhere in Jackson and surrounding counties. However, the higher density of caves in target rocks, longer average cave lengths, their spatial association with Flynn Creek crater, and specific correlation with impact-related structures suggest that the impact crater has exerted some control over subsequent karst development in target rock caves. This occurred despite the fact that the impact event led to less carbonate exposure at present-day erosional levels. Those target rock carbonates that were first to be exposed lied along the crater rim and central uplift. Fractures, faults, folds, and dipping bedding led to enhanced cave and karst development here. Relatively low permeability breccias and the (Chattanooga) shale aquitard within the crater led to constrained development of cave passage along the crater rim. Some flow down the crater wall along the contact with the shale and/or breccia to interior springs located along Flynn Creek and its tributaries may have also occurred.

The overall result is a unique (and still developing) karst landscape (Figure 34) that is home to extensive underground flow, speleothems, and a wide variety of cave fauna. Continued study of Flynn Creek crater may yet reveal that this terrestrial impact structure may be analogous to potential subterranean environments on other planets, such as Mars.

Caves of the Flynn Creek Impact Structure

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The Flynn Creek impact structure (36°17'N, 85°40'W) in Jackson County, Tennessee was formed in the flat-lying Lower-Middle Ordovician carbonates commonly found in the Eastern Highland Rim physiographic province of north-central Tennessee.

The 360 Ma impact event destroyed and ejected a large volume of material while the remaining target strata were severely deformed along the crater rim, floor, and central uplift areas. Breccias superposed on the crater floor have been interpreted as fallback ejecta from the event (Roddy, 1968). Along the crater perimeter, limestones, dolostones, and shale dip radially away from the center of impact, forming a raised crater rim. After formation of the initial (transient) crater, large blocks collapsed along listric normal faults, resulting in an enlarged final (modified) crater diameter. Along the crater floor, rocks have been faulted, folded and brecciated. The central uplift consists of large blocks of limestone and dolostone from the Knox and Stones River Groups with primarily eastward displacements along major thrust faults (Roddy, 1977).

In the Upper Devonian, Flynn Creek crater was filled in with dark marine mud that now forms the Chattanooga Shale. In this area, the Chattanooga Shale normally is up to ~6 m (20 ft) thick, but in the Flynn Creek structure reaches thicknesses of ~60 m (200 ft). The Chattanooga Shale was subsequently overlain by the Lower Mississippian Fort Payne and Upper Mississippian Warsaw Limestone (Wilson and Roddy, 1990), which now cap the ridges in the Flynn Creek area.

Later, this area was uplifted as a result of formation of the Nashville Dome to the west (Wilson, 1935; Stearns and Reesman, 1986). This led to increased incision of this landscape and exposure of the buried astrobleme. Flynn Creek itself continues cutting east-west through the crater, emptying into the Cumberland River to the northwest. Tributary drainage into Flynn Creek is dendritic-radial and is controlled by the underlying structure of the crater itself in places.

The deformed carbonate target rocks and the overlying shale and limestones, make the Flynn Creek impact a unique and complex karst landscape in central Tennessee. The area within and along the boundaries of the Flynn Creek impact structure contains a very high density of known caves (see 'Karst Modification of the Flynn Creek Impact Structure'). Here we highlight the unique caves in both the crater fill and target rocks of the Flynn Creek impact structure. Cave maps (all mapped by survey crews led by Ken Oeser) can be found in the appendix at the end of this field guide.

Crater Fill Caves: The First Generation

As what is now central Tennessee was uplifted to form the Nashville Dome, the landscape of the Eastern Highland Rim was increasingly dissected by surface drainage. As a result, gentle eastward-dipping (0.5° regional dip) Mississippian-aged carbonates (Fort Payne and Warsaw Formations) overlying the Flynn Creek structure were exposed to dissolution by acidic groundwater, forming a first generation karst landscape. There are two known caves in the crater fill (exclusively in the Fort Payne Formation) overlying the Flynn Creek crater: Antioch School Cave and Mahaney Pit.

Antioch School Cave

Antioch School Cave is located in the overlying Fort Payne Formation at ~244 MSL (meters above sea level) in the eastern half of the Flynn Creek impact crater. The cave is situated within the ridge between Flynn Creek Road and Cub Hollow. This 198 m-long cave is developed along joints in the Fort Payne Formation. The cave entrance lies within a steep drain on the southwest side of the ridge.

Mahaney Pit

Mahaney Pit is situated in the Fort Payne Formation along the southwestern rim of the Flynn Creek impact structure. It lies at an elevation of ~ 280 MSL. The cave has not yet been visited by the authors but *Barr* [1972] describes the cave entrance as two 5 m drops, beyond which exploration has not continued.

Target Rock Caves

With additional uplift of the Nashville Dome, erosion of the Eastern Highland Rim continued, with dissection of crater fill. This denudation breached the Chattanooga Shale, a local aquitard, exposing underlying target rocks of the crater rim, floor, and central uplift of the Flynn Creek impact structure. With Ordovician-aged carbonates now exposed to subaerial weathering, a second generation of karst landscape began, and continues, to form. Structures that had

Figure 35. Blue hole opposite Birdwell Cave. The three persons in this view are standing on a rock bridge which cuts through the middle of the hole.

Figure 36. Entrance to Cub Hollow Cave along the eastern rim of the Flynn Creek impact structure. This entrance has been repeatedly flooded.

been formed during the Flynn Creek impact event exerted control over the development and distribution of caves and karst features at this level. The majority of caves in this generation formed along the crater rim in the Leipers and Catheys Formation in anticlines and along bedding planes, while one formed in the central uplift itself. The descriptions that follow are of known caves in this second generation of karst and their relationships to the Flynn Creek impact structure.

Birdwell Cave

Birdwell Cave (116 m surveyed length) is a north-south trending cave formed in the Leipers and Catheys Formation along the eastern rim of the Flynn Creek impact structure (Figure 25; Appendix 2). The entrance to Birdwell (named for the Birdwell family, who live in this part of the crater) is ~ 20 m to the north of Flynn Creek Road. Access to the square-shaped entrance is gained by walking from the road along a boulder-filled ephemeral stream. The 3 meter-high entrance leads into a square cross-section passageway that continues for ~30 m until the passage splits. To the right, a short climb up a mud slope reveals a small northwest-southeast trending passage that lies 2.5 m above the entrance elevation. The left branch is a small, gravel-filled crawlway that, in some places is 30-40 cm high. This phreatic passage developed by limestone dissolution along bedding planes. The crawlway opens up into a passage that has been enlarged by dissolution along an ~east-west trending fissure. In places, this passage is filled with pools of water whose depths fluctuate seasonally. A local resident has reported that this cave has flooded Flynn Creek Road during passage of a hurricane a few years ago.

A blue hole (Figure 35) lies approximately 100-150 m across the road to the south. It is split in half by a north-south trending rock bridge. To the east of the bridge is the deepest part of the blue hole, which is developed along a north-south trending fissure. The other half of the blue hole shallows to the west and eventually empties into a tributary of the Flynn Creek. Based on the proximity of Birdwell Cave to this blue hole and their similar structural patterns, it is possible that these two karst features may be connected hydrologically.

Cub Hollow Cave

Cub Hollow Cave (Figure 36) lies along the eastern rim of the Flynn Creek impact structure along the Cub Hollow tributary at an elevation of ~ 232 MSL. The cave is situated within the Lower-Upper Ordovician Leipers and Catheys Formation. Entrance to the cave is afforded by descent into a narrow gorge that, during wet periods, drains water into the cave. Sediment deposits to either side off the gorge are evidence that this cave entrance has repeatedly flooded. The observation that sediments have been sharply incised suggests that rapid down-cutting has occurred. With the considerable amount of plant debris at various points inside the cave, it is likely that the cave has been choked with brush periodically, causing the entrance to flood. This is corroborated by Harley Allen, former owner of the cave. Mr. Allen states that prior to his ownership, he was told that local women used to wash laundry using water from the cave. At the time that Mr. Allen purchased the cave, the entrance was flooded and on occasion, water flowed over the road into the adjacent valley. After several efforts to excavate and re-expose the entrance, a hard rain unplugged the opening approximately 30-40 years ago (1965-1975).

Inside the cave, a swift flowing stream enters from the east and flows along a rocky stream in a wide crawlway to the northwest. Water flow and passage development is occurring parallel to strike. Cub Hollow Cave has been mapped at 30 m, but during a recent trip during low water, the cave was observed to continue to the northwest for another 12-15 m.

Flatt Cave

Flatt Cave (named for the Flatt family who live in this part of the crater) is situated along the southern crater rim within the Leipers and Catheys Formation just beneath the unconformity with the Chattanooga Shale (Figure 37). After entering a small (1 x 2 m) opening on the west side of the ridge in which the cave is situated, Flatt Cave opens into an ~ 122 m long dry passageway. Similar to Wave Cave (on the eastern rim of the crater), this passage is formed along a northwestern-trending anticline that appears to be locally brecciated. Conspicuous piles of gravel and cave dirt, in addition to dig holes, suggest that this passage may have once been mined to some extent. A helectite-filled crawlway at the end of this passage leads into a large (~15 x 23 m) room that has formed in steeply-dipping carbonates. Several passageways branch off of this room in varying directions and contain smaller side passages and wet drains of their own.

Figure 37. Bill Deane in the entrance to Flatt Cave, located along the southern (modified) rim of Flynn Creek crater.

At least four major (and sharp) changes in bedding orientations occur throughout Flatt Cave. This is likely because of Flatt's location along the crater rim. Crater rims commonly contain large blocks of material (collapsed terrace blocks) that have been displaced along listric normal faults during collapse of the transient crater rim. Flatt Cave is quite probably developed in several of these blocks along the rim of the Flynn Creek impact structure.

Figure 38. The easternmost crawlway entrance to Forks Creek Cave. This entrance is less than 0.5 m high.

Forks Creek Cave

Forks Creek Cave (Figure 38) is exposed in a road-cut along the southern banks of the Flynn Creek. The cave lies in the Leipers and Catheys Formation of the Flynn Creek impact structure itself at an elevation of 172 MSL. There are four entrances developed along the same stratigraphic horizon that lead to tight interconnected crawlways. Although this cave is situated approximately 1220 m from the crater rim, it lies in rock layers that are gently dipping (4-5°) to the west away from the impact, indicating that this cave may be formed in strata that have been slightly uplifted distally from the crater rim.

Figure 39. Inside of Hawkins Impact Cave looking south to the climb towards the Upper Room. This part of the cave passage lies within a single megablock of the central uplift.

Hawkins Impact Cave

Hawkins Impact Cave (HIC) is the only cave in the world known to be developed in the central uplift of a complex crater (Figure 39; Appendix 3). Discovered in 1989 by landowner Michael Hawkins (namesake) and mapped (277 m long) by a Tennessee Cave Survey crew led by Ken Oeser, HIC lies in the core of the central uplift Flynn Creek impact crater. The 360 Ma impact occurred in flat-lying limestones, dolostones, and shale of the Lower Ordovician Knox Dolomite and Middle Ordovician Stones River Group (Roddy, 1968). Following impact, rocks were uplifted ~450 m above normal positions forming a central uplift (Roddy, 1968; 1979). Uplifted exposures consist primarily of westward dipping Stones River strata and lesser eastward-dipping rocks separated by a "chaotic breccia zone" (Roddy, 1968).

Exposures in HIC provide a unique perspective into the processes of central uplift formation and their relative age relationships. Structural fabrics, similar to those observed in surface exposures of other central uplifts (Milam and Deane, 2005), are present in HIC. Bedding is dissected by extensive networks of listric microfractures (mfrs) and microfaults (mfs), indicating brittle failure of target rock during impact. Reverse and normal displacements (typically < 1 cm) along mfs represent localized compression and extension of target rock, likely during the contact/compression and modification stages of impact. Several sets of mfrs are cut by multiple generations of mfs. Monoclinic, antiformal, and much more complex folds also occur with mfrs and mfs in large (up to several hundred m^3) wedge-shaped megablocks of target rock.

Megablocks contain bedded to thinly-bedded carbonates with strike and dip orientations that vary from one block to the next. They are bound by narrow ($<$ 1cm) major faults containing little or no breccia or cataclasis; dissimilar to fault breccias observed along major faults in other central uplifts. Major fault dissection of mfrs and mfs indicate subsequent movement after mfr/mf formation. Relative displacements are difficult to discern due to the paucity of slip indicators; however, drag folds are present along some major faults. Megablock rotation and transport likely occurred during uplift and subsequent collapse.

Impact-related structures served as major controls on limestone dissolution and passage development in HIC. Water penetrated the cave from the southwest, preferentially dissolving limestone along major faults and at angles controlled by strike and dip directions of bedding inside of megablocks. As the water table continued to drop with base level, collapse along bedding planes and mfrs enlarged HIC passages. Passage morphology varies between megablocks and is affected by changes in structural fabric of the central uplift.

Kelson Cave

Kelson Cave (Figure 40) is located along the southwestern crater rim in Steam Mill Hollow, to the southwest of Spalding Cave. The cave entrance is exposed along an old dirt road at the base of a hill on the western side of the hollow. Entrance is gained through a small (0.5 m diameter) hole that leads into a small room approximately 1 m high. A low, wet, sinuous crawl to the southwest and an upward squeeze leads into a muddy room in which three side passage diverge. The cave continues for several tens of meters through an "I" shaped canyon passage. This cave is home to numerous cave crickets and surface crayfish. Kelson Cave was first explored on August 5, 2005 by Bill Deane, Keith Milam, and Zacary Mires. The cave was named using nine-year-old Zacary's middle name in honor of his trip into his first unexplored cave. Kelson Cave is currently the target of mapping efforts.

Figure 40. First explorer of Kelson Cave, Zacary *Kelson* Mires sits outside the cave entrance just outside the southwestern crater rim.

Mahaney Cave

Mahaney Cave is located approximately 610 m from the western crater rim in the subhorizontal beds of Leipers Catheys Formation. The cave entrance is located on the southwest side of Flynn Creek at the base of a hillside along Earnest Mahaney Road.

A low, tight crawlway, artificially opened about 1947, leads into a cave of several irregularly-shaped chambers. The entrance is < 0.3 m high and 0.8 m wide, and leads to a crawlway that slopes down to the left for 9 m to a junction. To the sharp right, back toward the entrance almost, is a crawlway 9 m long to a climb-up blocked by boulders, but a room can be seen above the boulders. This crawlway is jointed by a joint passage up to 5 m and 9 m long. Halfway through this passage, a low crawl under a ledge leads back to the first junction in the cave. At the end of the joint passage another short crawl leads into a larger passage 1 m high and 2 m wide. To the right it goes 15 m to a stream junction. Left goes upstream 12 m and ends in a sump, and right goes downstream 9 m before enlarging to a stoopway for 21 more meters and ending in a sump. Back at the larger junction, straight goes 12 m to another split. Straight ahead goes as a low gravel crawl that hasn't been pushed. Right goes 12 m to a room with flowstone hanging on the walls. This room is 3 m long and 5 m wide, and a 4 m climb-up is on the opposite side. This has not been climbed and may not go any farther than this room. *(The above description of Mahaney Cave was provided by the Tennessee Cave Survey).*

Rash Spring Cave

Rash Spring Cave lies approximately 914 m from the southeastern rim of the Flynn Creek impact structure in the Leipers Catheys Formation. The walking (2 x 3 m) entrance lies along the west banks of the Flynn Creek itself. This 262 m long cave trends to the west for several tens of meters before intersecting a prominent northwestern joint set along which the cave follows to its terminus. An active stream still runs through the cave and exits at the cave entrance. Historically, this spring has served as a water supply for property owners.

Figure 41. The wet crawlway leading into Spalding Cave along the southwestern crater rim at Flynn Creek.

Spalding Cave

Spalding Cave (est. 91 m long) lies along the southeastern rim of the Flynn Creek impact crater in the Leipers and Catheys Formation at an elevation of ~213 m (Figure 41). The cave entrance is situated along the eastern side of Steam Mill Hollow, a tributary of Flynn Creek. Water flows out of the 1 m high, 2 m wide entrance to this cave, making it impassable during wet periods. A wet crawlway heads east from the mouth for 17 m, averaging 0.5 to 0.6 m high with 0.15-0.18 m of airspace. This connects into a small room 4.5 m long, 1.5 m wide and 4.5 m high. A waterfall can be climbed 2.5 m to a passage averaging ~ 1 m high and 1 m wide, heading roughly east for about 70 m to another waterfall dome. This dome is 4.5 m high, 2.5 m wide, and 4.5 m long. A small waterfall pours in through a hole in the middle of the east wall about 3 m off the floor. A small passage at the top is reported to continue to a second entrance, a small hole on a hillside. Spalding Cave has yet to be mapped. *(Description of Spalding Cave provided by the Tennessee Cave Survey)*.

Wave Cave

Wave Cave (Figure 24; Appendix 1) lies in the Catheys Formation and is located approximately 450 m from the crater rim. The cave has formed in a plunging anticline, whose axis trends almost due north-south. Bedding along the western and eastern limbs are oriented N 6 E, 61 NW and N 4 W, 28 NE respectively. Approximately 43 m of passageway has formed right along the axis of the anticline, due to preferential weathering of axial extensional fractures. Near the end of the cave, two side crawls lead into a large (~ 6 x 12 m) room that has developed parallel to the strike of bedding on the western limb of the anticline. An unusual inverted breakout dome is forming on the western side of this room due to gravitational collapse along bedding planes.

The proximity of this anticline to the Flynn Creek structure and, with the exception of the Nashville Dome, the lack of tectonic deformation in the vicinity, argue that this fold was formed as a result of impact. USGS geologist David Roddy (1979) suggested that this anticline was the manifestation of a normal listric fault at depth just beneath the surface, along which the transient crater wall collapsed.

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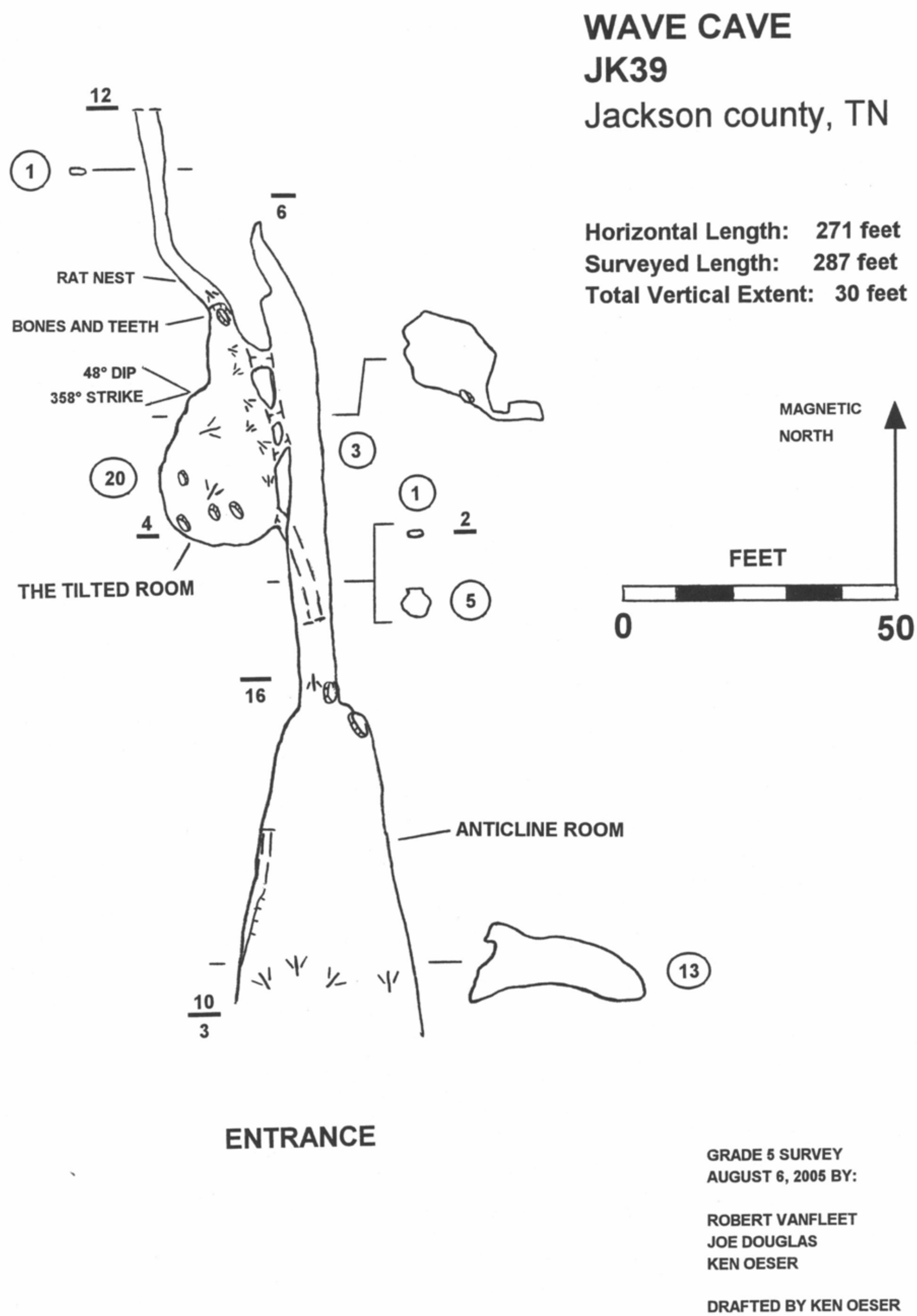
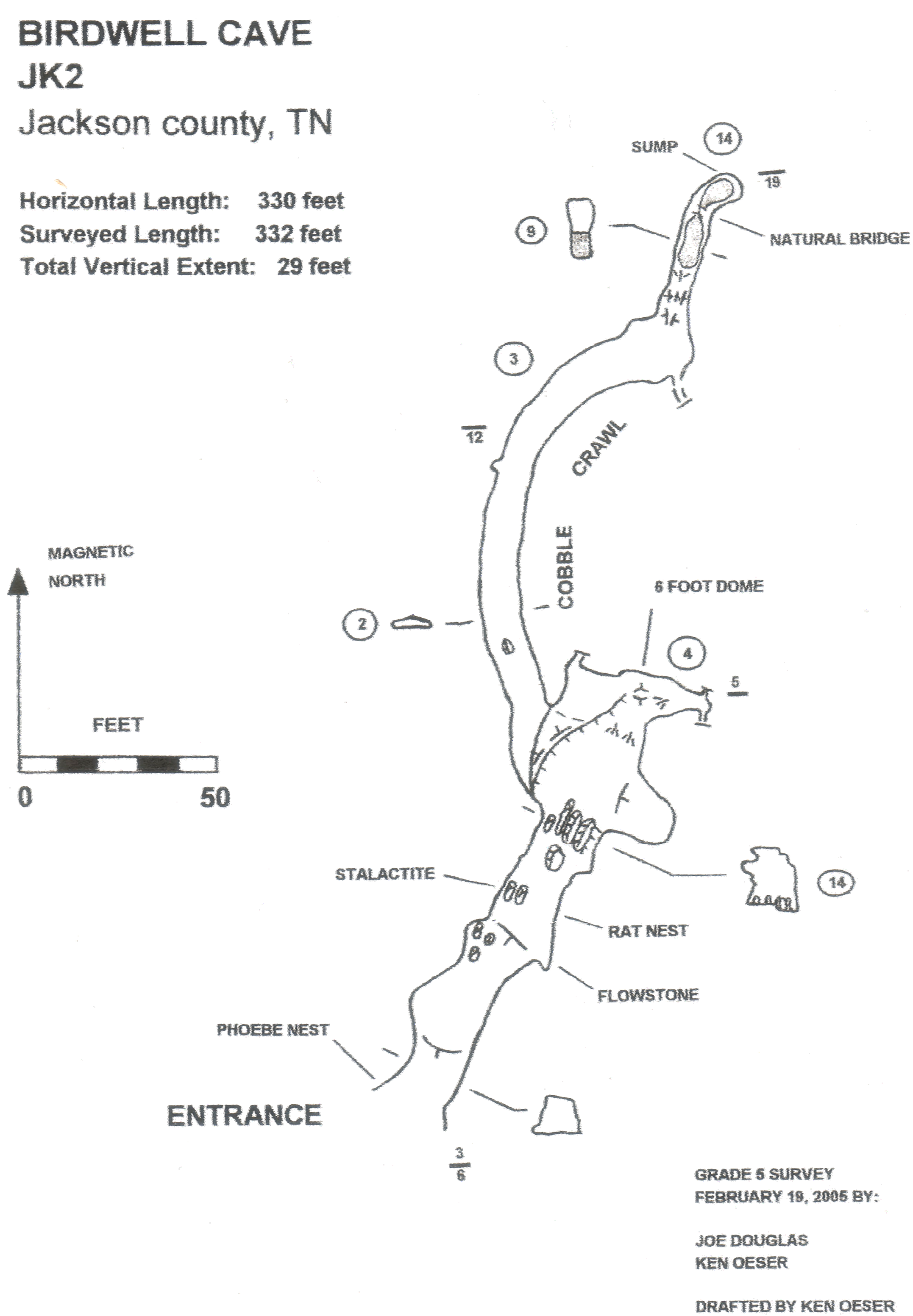
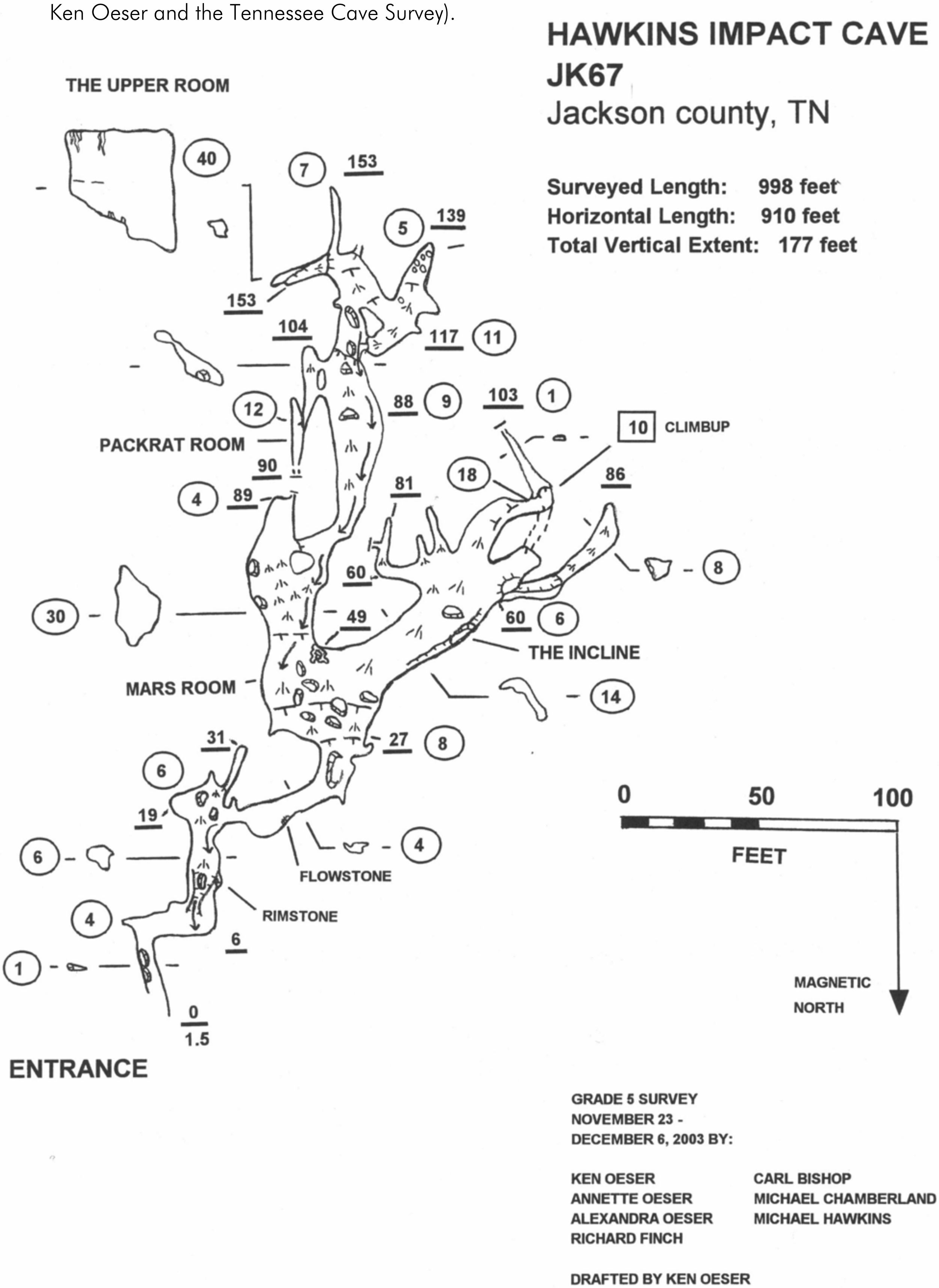
Appendix 1. Map of Wave Cave (provided by Ken Oeser and the Tennessee Cave Survey).



Appendix 2. Map of Birdwell Cave (provided by Ken Oeser and the Tennessee Cave Survey).



Appendix 3. Map of Hawkins Impact Cave (provided by Ken Oeser and the Tennessee Cave Survey).



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