Geology of the Carter Caves Area

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Carter Caves State Resort Park

Introduction

Carter Caves State Resort Park is located in north-central Carter County, Kentucky, at the corner of the Wesleyville, Olive Hill, Tygarts Valley, and Grahn 7.5-minute quadrangles. It is 30 mi west of Ashland and some 90 mi east of Lexington, Kentucky.

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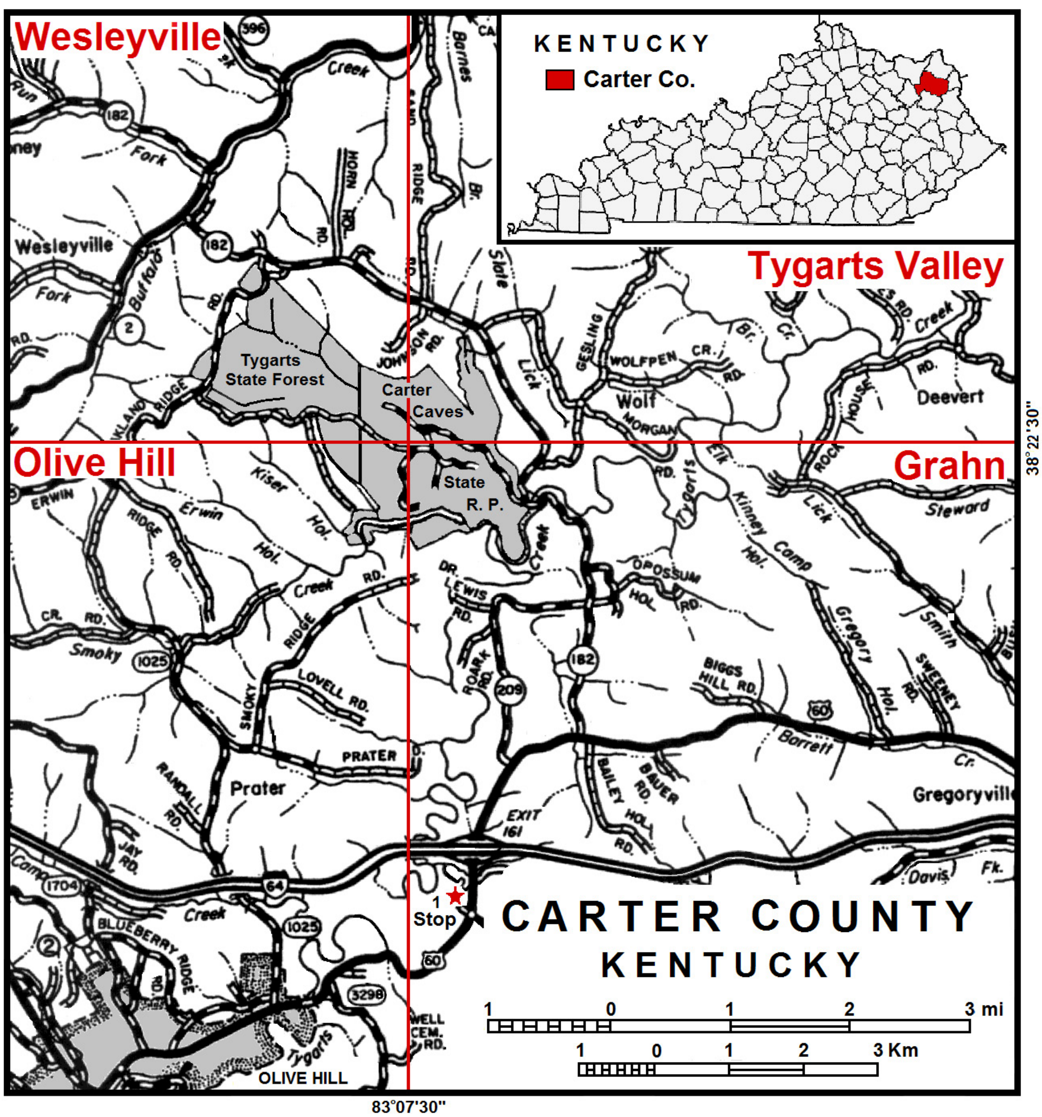

Figure 1. Map of Carter Caves State Resort Park and surrounding area showing roads, cities, principal streams, and quadrangle boundaries for 7.5-minute topographic maps.

History

The Carter Caves State Park was established on July 31, 1946. The area making up the park had been in private hands since the region was first settled in the late 1700's. In 1946, landowners from Carter County and several adjacent counties donated 945 acres (≈ 1.475 square mi) to the Commonwealth of Kentucky for the establishment of a state park. One of the principal landowners responsible for donating the caves and surrounding land was the J.F. Lewis family. Other investors, including several local Rotary Clubs, also contributed to this effort. Kentucky Gov. William Jason Fields (1923–1927), a native of Carter County, was the primary force in purchasing the land and establishing the park.

In 1959, a nearby cave system known as Cascade Caves also became a part of the Carter Caves State Park System. Up to this point, Cascade Caves had been a privately owned commercial enterprise that had been in operation since 1925. This, along with additional land obtained by the park, eventually increased the total area to nearly 2,000 acres (≈ 3 square mi). On December 16, 1981, the Kentucky Nature Preserves Commission set aside 146 acres (0.228 square mi) within the park as nature preserves. Called Bat Cave and Cascade Caverns State Nature Preserves, this area was designed to protect several rare and endangered species, including the Indiana bat *(Myotis sodalis),* mountain maple *(Acer spicatum),* and Canadian yew *(Taxus canadensis).*

Just to the northwest and adjoining the park are 874 acres (≈ 1.4 square mi) belonging to the Tygarts State Forest. This is one of seven forests managed by the State of Kentucky. It was established in 1957 and is currently governed by the Department of Natural Resources, Kentucky Division of Forestry.

As previously stated, Carter Caves State Resort Park covers an area of nearly 2,000 acres and boasts over 26 mi of hiking trails. Popular activities within the park include guided cave tours, spelunking, hiking, camping, horseback riding, bicycling, rock climbing, rappelling, fishing, kayaking and canoeing, bird watching, photography, nature studies, in addition to a nine-hole regulation golf course and a miniature golf course.

Physiography

Physiographically, the Carter Caves State Resort Park lies along the western edge of the Allegheny or Cumberland Plateau (a physiographic province that extends from New York to Alabama). It consists of stream-eroded hills and ridges with narrow valleys. The principal geologic features within the park include caves, sinkholes, natural bridges, waterfalls, box canyons, deep gorges, steep-sided cliffs, and rock houses. Elevations in the area typically range from 700 to 1,100 ft above sea level. Karst topographies tend to occur in many of the valleys that are underlain by carbonate rocks. Streams in the area generally have upland characteristics, with moderate to high gradients, low-lying waterfalls, and a riffle and pool structure. Riffles are short, relatively shallow sections along a stream that flow at higher velocities. These are formed on coarser sediments (i.e., cobbles, pebbles, and gravel) over which the stream flows. Pools are deeper, calmer areas along the stream that alternate between riffles.

Most of the higher hills and ridges in the area are capped by Pennsylvanian sandstones and conglomerates. Mississippian carbonates, equivalent to the limestones found in the Mammoth Cave region, are commonly exposed in many of the valleys.

Climate and ecology

According to Köppen–Geiger's climatic classification, the area around Carter Caves is a humid mesothermal (C) type climate. This climate occurs in low, middle-latitude (between 25 and 35° latitude) in which the average temperature for the coolest month is below 18° C (64.4° F). The climate graph below presents data on the monthly temperatures and rate of precipitation as an average for the past 20 years. Winters in the area are usually quite cold (ranging from a minimum of 21° to a maximum temperature of 46° F). Summers are generally warm (minimum of 65° to a maximum temperature of 91° F). Rainfall tends to be evenly distributed throughout the year and is fairly abundant, with a mean annual precipitation rate of 40 and 46 in. (Woods and others, 2002).

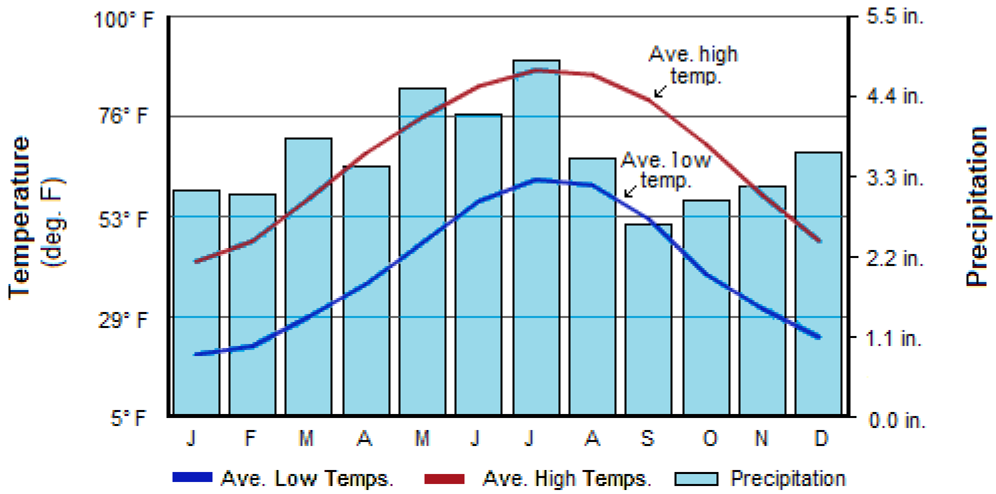

Figure 2. Climate graph for the area of Grayson, Kentucky, about 12 mi east of the Carter Caves area. Graph includes both plots of temperature and precipitation. Web site: www.usclimatedata.com/climate.php?location=USKY0955.

The park itself lies within an ecological region called the Carter Hills. Vegetation within the Carter Hills is characteristic of a mixed mesophytic forest. Mixed mesophytic forests are located in temperate regions on the earth's surface and have some of the highest biological diversity of any ecologic region in the world. In these areas, forest communities often support more than 30 canopy tree species in a single region. Mesophytic forests have rich understories of ferns, mosses, perennial and annual herbaceous plants, shrubs, small trees, along with diverse animal communities. In the upland areas of the region, the most common tree species include beech, sugar maple, yellow poplar, and northern red oak. Some of the dryer upland areas tend to be dominated by mixed oak and hickory forests. In the more poorly drained bottom lands, forests are predominantly sycamore, pin oaks, northern red oak, red maple, sweet gum, river birch, hackberry and slippery elm. In some of the well-drained valleys, yellow poplar, black walnut, white oak, white pine, northern red oak, hickory, and sugar maple are found. In many of the deep ravines, hemlock and magnolia dominate the environment with an understory of mainly rhododendron (Woods and others, 2002).

Field Trip Guide

Leave Caveland Lodge parking lot

- Anticipated time of departure: 8:00 a.m.

Stop 1

Valley Stone Quarry, Pleasant Valley, Kentucky

- 0.3 mi south of the junction of U.S. 60 and Interstate 64 on U.S. 60; turn right into hidden quarry entrance.
- West-central rectangle of the Grahn 7.5-minute quadrangle
- (Latitude: 38°19′20″N; Longitude: 83°07′16.9″W)
- Anticipated time: 8:30–9:30 a.m.

We are stopping first at this quarry in order to observe the limestones of the Slade Formation in a relatively fresh, uncovered exposure. These are the limestones in which the caves at Carter Caves State Park form, although it is difficult to see the entire limestone unit at the park because it is largely covered, weathered, and eroded or present in the subsurface. This quarry exhibits about 155 ft (47 m) of the Slade Formation, which is composed largely of limestones, except for some thin red and green shales that compose the Cave Branch and Maddox Branch Members. The Slade Formation largely represents deposition in relatively shallow (< 100 ft or 30.5 m), well-lit, subtropical seas, in which bottom life was abundant.

Before 1984, the Slade Formation was known as the Newman Limestone, but because the lithologies and units present in the Slade Formation are not the same as those present in the Newman Limestone in its type section in eastern Tennessee, the name was changed by Ettensohn and others (1984) to the Slade Formation, named after its type section in Slade, Kentucky. The Slade Formation would normally contain 11 subdivisions (Fig. 4), or members; however, at this site at least the lower three members (Ste. Genevieve, St. Louis, and Renfro) are missing at the bottom because of erosion during the high-energy deposition of the Warix Run Member (Fig. 5). The erosion of units like this actually means that there is a gap in time and in the rock record at the base of the Warix Run Member; the surface that represents this gap in time and rock is called an unconformity. The unconformity at the base of the Slade Formation (Warix Run Member) is not exposed in this quarry, but we will see it at Stop 2. Another unconformity is present at the top of the Mill Knob Member, just below the thin, lower shales of the Cave Branch Member. Normally, the Slade Formation conformably overlies the Borden Formation (Fig. 4), but in this quarry the contact is not visible and is probably unconformable.

The Slade Formation in this quarry is conformably overlain by the Paragon Formation, which is largely composed of dark shales and sandstones (Figs. 5–6). The Paragon Formation was formerly known as the Pennington Formation, but this name was also changed for similar reasons by Ettensohn and others in 1984. About 25 ft (7.6 m) of the Paragon Formation is present at the top of the quarry. Just above the upper part of the Slade Formation (Poppin Rock Member), the Paragon Formation includes the lower dark shale member, containing fossiliferous shales with limestone lenses, and the overlying clastic member, which is composed of a basal sandstone and red and green shales. The lower dark shale member has been interpreted to represent a platform lagoon, whereas the overlying clastic member is interpreted to represent an adjacent tidal-flat sequence. High in the quarry wall that we are observing, the basal sandstone thickens abruptly from thin lens-shaped bodies at the top of the lower dark shale member to a channel-fill sandstone more than 25 ft (7.6 m) thick (Figs. 5–6). As the sandstone thickens to the north toward Carter Caves, in the quarry, it erodes away the underlying units (lower dark shale, Poppin Rock, and Maddox Branch Members), forming another unconformity below the sandstone (Figs. 6–7). So, interestingly, high in the quarry wall, we can observe the change from a conformable Slade-Paragon transition to an unconformable relationship between the two formations. This sandstone thickens to more than 90 ft (27.4 m) to the north in Carter Caves State Park, where it is called the Carter Caves Sandstone. This sandstone and the underlying Slade limestones will be critical in understanding the origins of the Carter Caves at Stops 3–7.

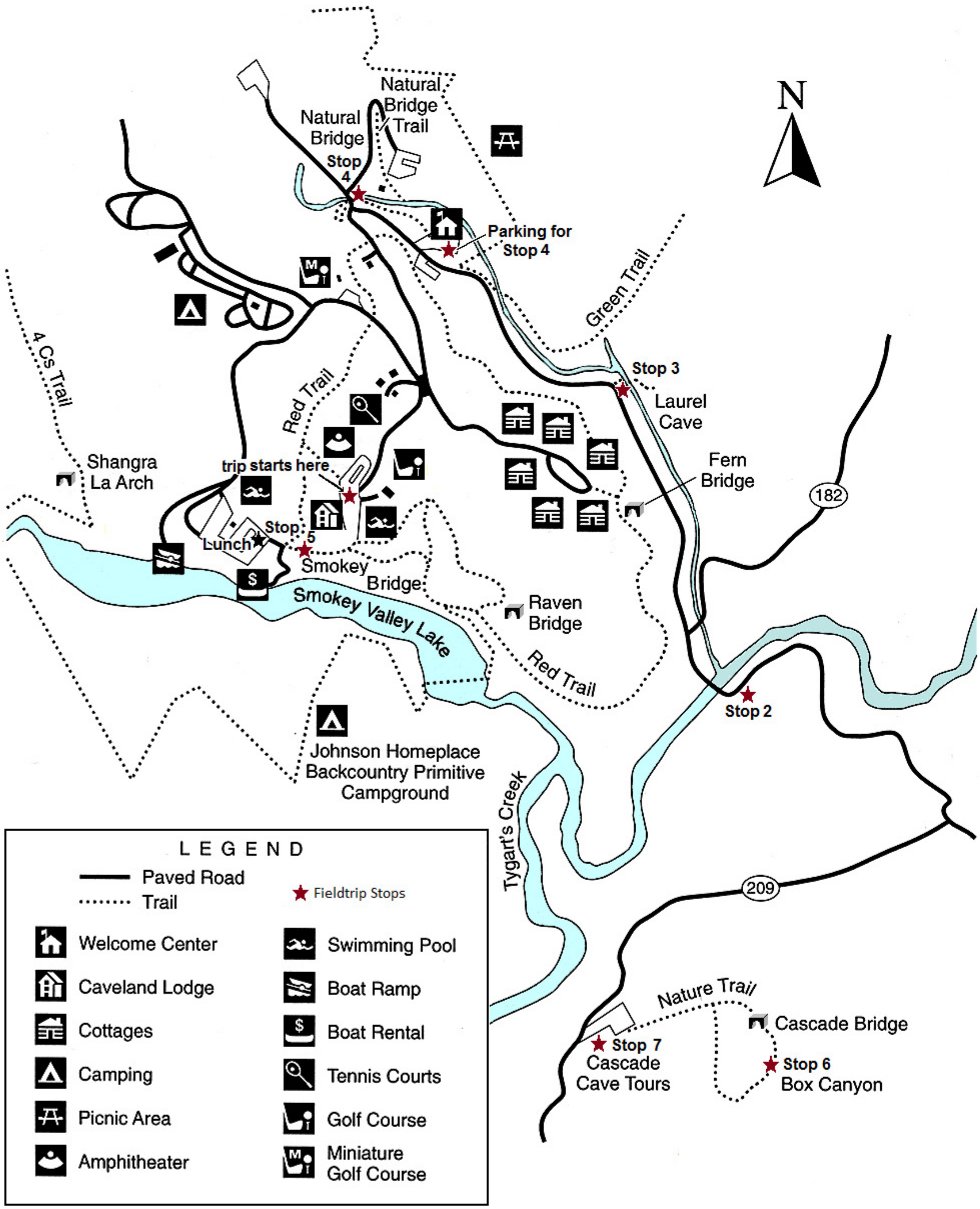

Figure 3. Map of Carter Caves State Park (adapted from Elliott and Elliott, 1998) and field-trip area.

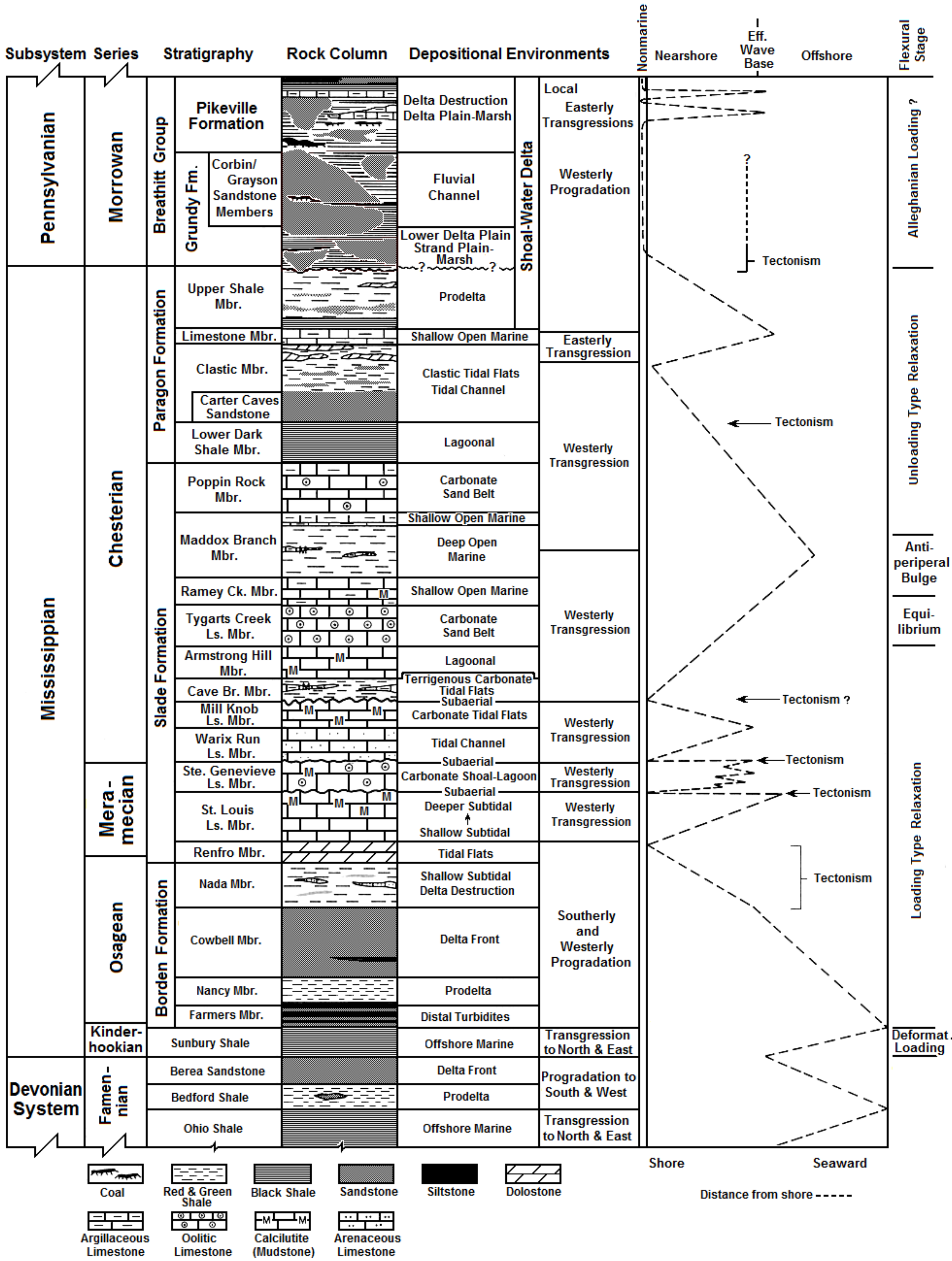

Figure 4. Generalized stratigraphic section for Upper Devonian through Middle Pennsylvanian rocks in northeastern Kentucky.

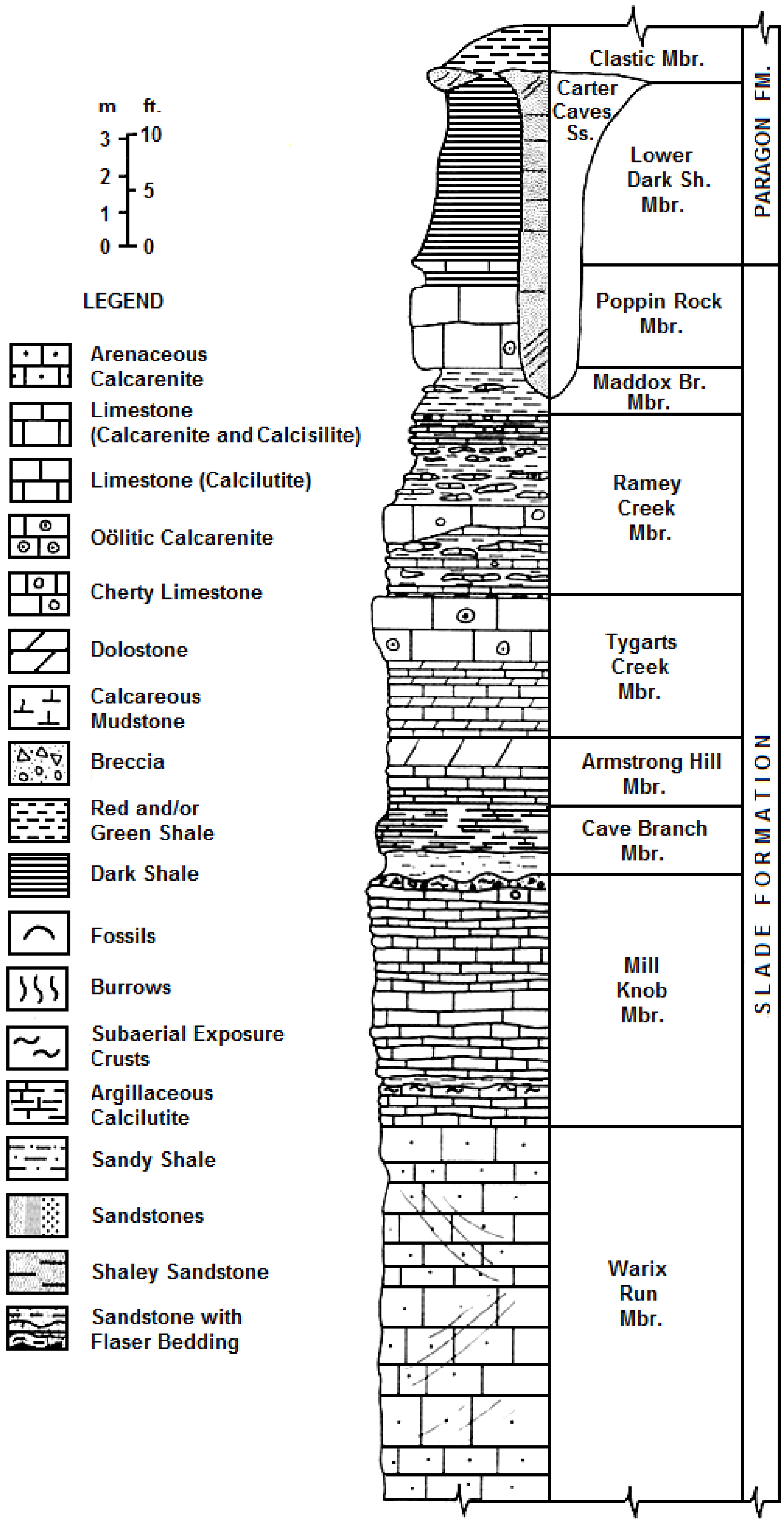

Figure 5. The stratigraphic section exposed at Stop 1 (see Figure 4).

Stop 2

Unconformity at the Base of the Slade Formation (see Fig. 3)

- About 0.2 mi southeast of the entrance to Carter Caves State Park on Ky. 182.
- Northwest corner of the Grahn 7.5-minute quadrangle
- (Latitude: 38°22′3.8″N; Longitude: 83°6′30.3″W)
- Anticipated time: 9:45–10:15 a.m.

We will pull off on the north side of the road adjacent to Tygarts Creek. Once you leave the vans and cars, take a moment to look at the outcrop on the south side of the road. The basal 15–20 ft (4.6–6.1 m) of blue-green siltstones and interbedded shales is the Cowbell Member of the Borden Formation (Figs. 4 and 8). The same Borden member was probably below the Slade Formation at Stop 1, but the quarry bottom did not penetrate the contact. The Cowbell Member here contains some small-scale crossbedding, as well as several different types of trace fossils. The Cowbell Member has been interpreted to represent the gently sloping front (delta front) of a vast subaqueous delta that emanated from the Acadian/Neoacadian Mountains along the eastern margin of the continent at this time. This delta largely developed below water (subaqueous) and extended across parts of Kentucky, Tennessee, Ohio, Indiana, and Illinois.

Above the Cowbell Member you will see an irregular layer of dark yellowish-orange dolostone (Figs. 8–9) that ranges in thickness from 2 to 8 ft (0.6 to 2.4 m). This dolostone layer represents a zone of intense intrastratal weathering that includes part of the Cowbell Member as well as part of the overlying Warix Run Member of the Slade Formation. Because parts of the Cowbell Member, as well as the entirety of the Nada, Renfro, St. Louis, and Ste. Genevieve members, are missing due to erosion during the high-energy deposition of the Warix Run Mem-

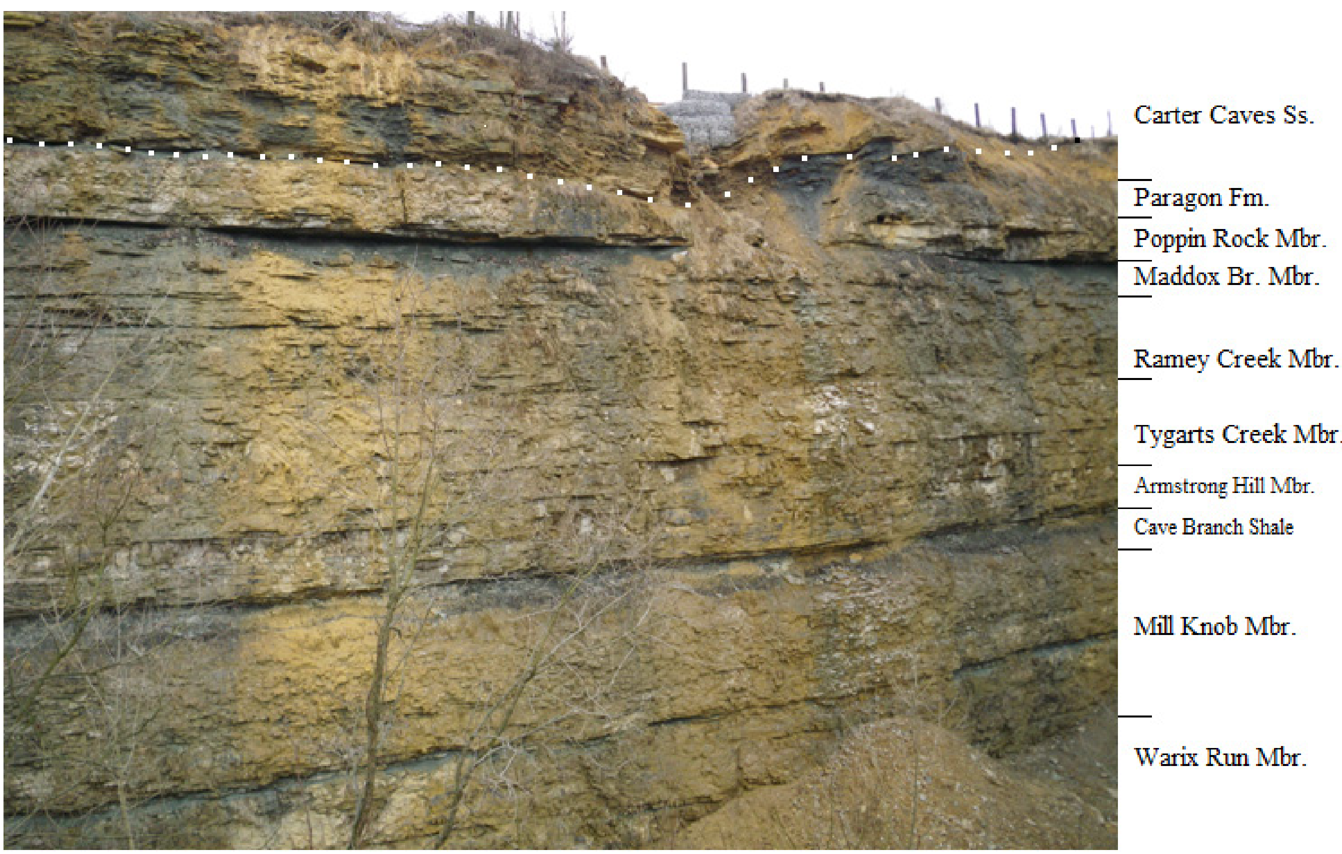

Figure 6. Photo showing units exposed on the southern highwall at Stop 1. Note the that the Carter Caves Sandstone has channeled through the lower dark shale member of the Paragon Formation and sits on top of the Poppin Rock Member of the Slade. The surface between the Carter Caves and Poppin Rock is an unconformity.

Figure 7. Photo showing units exposed on the southern highwall at Stop 1. In this view, the Carter Caves has channeled farther downsection and sits unconformably on the Maddox Branch Member of the Slade.

ber of the Slade Formation, the contact between the Warix Run and Cowbell members is an unconformity. The actual contact itself is within or near to the dark yellowish-orange dolostone layer. The irregularity of the dolomitic zone in part reflects the irregularity of the erosional contact between the two members. The dolomitic zone itself is a product of weathering within the subsurface between the two members (intrastratal) and would be expected even if the rocks were not exposed. The Warix Run Member is locally porous and permeable, and joints running through the unit make it even more porous. Hence, water will slowly percolate downward through the Warix Run Member, dissolving out various mineral constituents, but especially iron. Where the waters percolate through the unit and reach the clayey Cowbell Member below, they are prevented from moving farther downward by the clayey, impermeable nature of the Cowbell shales. The water may effectively "pile up" on top of this contact or move laterally along the contact until it finds a place to exit at a spring. The entire zone is very moist as the water "piles up," and in one place where a joint penetrates the Warix Run Member, a spring has developed (Fig. 9). Where the water piles up and sits for periods of time, the precipitation of various iron, manganese, and magnesium ions and compounds will form deposits and alter the Warix Run limestones and the Cowbell siltstones. Some iron oxides are especially insoluble and will precipitate thin layers or lamina after lamina of iron oxides. The yellow-brown color of the zone is a result of replacement of the calcium ions in the limestone by magnesium and iron ions to form ferroan dolostones at the water "piles up" at the impermeable boundary. Hence, a close look at this yellow-brown zone not only shows ferroan dolostones, but also accumulations of various iron oxides (hematite, limonite) in the form of laminae (Fig. 8). Because some of these dolomitized limestones are fairly massive, spheroidal

Figure 8. Photo showing the contact (arrow) between Warix Run Member of the Slade Formation and the Cowbell Member of the Borden Formation. The brown coloration represents dolomitization and accumulation of iron oxides at the contact.

weathering has developed locally in this zone (Fig. 8).

In most parts of this exposure, basal parts of the Warix Run Member are included in the yellow-brown dolomitic zone. The upper part of the exposure shows about 40 ft (12.5 m) of the Warix Run Member of the Slade Formation, and this member is very important because this member hosts most of the caves in the park. The Warix Run Member is a sandy (arenaceous) limestone that contains sand-size grains of quartz or chert (Fig. 10), and it is the only member of the Slade Formation to contain so much quartz or chert sand (10–20 percent). The Warix Run Member at this exposure shows a 5-ft- (1.5-m-) thick ledge of massive limestone with laminae and low-angle crossbeds. The overlying 35 ft (10.7 m) of the unit shows large high-angle crossbeds that represent the migration of large sand dunes in an energetic, shallow sea. Overall, the Warix Run Member is interpreted to represent deposition in a high-energy, tidal-sand-bar belt. The high-energy nature of the depositional environment is no doubt responsible for the erosion of the underlying members. Up to 90 ft (27.4 m) of erosion has occurred below the Warix Run Member in this area. As we stated above, upper parts of the Cowbell Member, as well as the entirety of the Nada, Renfro, St. Louis, and Ste. Genevieve members, are missing due to erosion during deposition of the Warix Run Member.

Figure 9. Photo showing the contact of the Warix Run and Cowbell Members, as well as the location of a spring at the point where a joint intersects the contact.

Figure 10. Close-up of the Warix Run Member of the Slade Formation showing laminae with concentrations of sand. The presence of quartz and chert sand is a diagnostic characteristic of the Warix Run Member.

Stop 3
Karst Solution Valley, Laurel and H_2O Caves (see Figure 3)

- Located about 0.6 mi northwest of the entrance to Carter Caves State Park from Ky. 182
- Southwest corner of the Tygarts Valley 7.5-minute quadrangle
- (Latitude: 38°22′29.2″N; Longitude: 83°6′56.4″W)
- Anticipated time: 10:30–10:45 a.m.

For the last 0.6 mi, we have been driving northwestwardly along the valley of Cave Branch Creek, a valley that has walls more than 100 ft (30.5 m) above the base of the creek (Fig. 11). The valley actually seems a little large for the size of the stream within it, and off to the side of the valley at several levels are various caves. Just to the north of us at this stop is the entrance to Laurel Cave. Just a little farther upstream at the bend in Cave Branch is H_2O Cave with a stream emanating from it that drains Horn Hollow, another northwesterly-oriented karst valley. Both caves are largely developed in the Warix Run Member of the Slade Formation, and the unconformable contact between the Cowbell Member of the Borden Formation and the Warix Run Member is visible in front of Laurel Cave (Fig. 12). The roof of Laurel Cave shows a diagonal bent or slant that parallels the large crossbeds in the Warix Run Member. This suggests that dissolution of the cave was controlled by the dipping crossbeds in the member.

However, we have stopped here not only to discuss the origin of the caves, but also the origin of the long valley through which we have just driven. The valley seems too large to have been formed wholly by Cave Branch. More than likely, the valley along Cave Branch creek represents part of a collapsed cave system; caves like Laurel and H_2O were formerly parts of the cave system that entered this large trunk cave. Apparently, the entire length of Cave Branch was completely underground and confined to a subterranean existence many thousands of years ago. At some point the roof sections overly-

Figure 11. View looking to the southeast along Cave Branch Creek to the left. The valley probably represents a large collapsed cave. Note the presence of large collapse blocks of limestone on either side of the road.

Figure 12. View looking across Cave Branch Creek to Laurel Cave. Note the contact between the Warix Run and Cowbell Members.

ing this underground stream began to collapse, creating the surface stream we see today. Valleys that form in this fashion are called karst solution valleys, or uvalas. Some large collapse blocks of limestone can still be seen along the margins of this valley.

The valley of Cave Branch has a total of four caves and one natural bridge that occurs along its length. This includes Bat Cave, Saltpeter Cave, X-Cave, Laurel Cave, and Carter Caves Bridge. In the 3¼ mi covered by this creek, it disappears underground and reappears three times before eventually connecting with Tygarts Creek at the end of its run. It first sinks into the ground near the head of Bat Cave and flows through the cave before coming to the surface near the entrance of Bat Cave. It then flows a few hundred yards and passes beneath Carter Caves Bridge. Once leaving the southeastern entrance to Carter Caves Bridge, it winds past the picnic area and enters Cave Branch Cave, below X-Cave tourist entrances, and resurges into Cave Branch Cave below the Lover's Leap area at the opposite end of X-Cave. From this point on, the stream is underlain by the Cowbell Member of the Borden Formation (a noncarbonate) and continues along the surface until it finally flows into Tygarts Creek.

The Carter Caves area is a small example of areas that are called karst regions. The word *karst* comes from the Yugoslav word *kras,* meaning "stone," which is the root of the Italian place name Carso for a part of the former Yugoslavia and eastern Italy along the Adriatic Sea, dominated by topography caused by the solution of limestones. Such regions are characterized by sinkholes, caves, and underground drainage, all of which we will see on this field trip. The northwestward orientation of the valley and many of the caves in this area is probably related to the northwest-southeast orientation of regional jointing in the area. Because these joints are places of easy access and weakness, subsurface waters will naturally try to flow along them, and in the process, solutional features like caves will preferentially develop along such joint systems.

Laurel Cave, like Bat Cave, Horn Hollow Cave, and Saltpeter Cave, are home to many endangered Indiana bats *(Myotis sodalis)* that hibernate in these caves during the winter months. All but two of the caves in the park have been closed until further notice because of the occurrence of a disease called "White Nose Syndrome" that has been devastating bat populations in the eastern United States. This deadly disease has been documented in states all around Kentucky (including West Virginia, Ohio, Indiana, and Tennessee). So far, Kentucky has been spared its ravages. It is thought that the disease may be transported on the boots and clothing of humans entering the caves. For this reason, access to these caves has been severely restricted. Even with this threat to the park's native species, two of the park's caves still offer guided tours year-round, Cascade Cave and X-Cave. We will be visiting Cascade Cave later today.

Stop 4
Welcome Center and Natural Bridge Trail

- About 0.6 mi farther northwest along the park road in Cave Branch valley; turn north (right) into the parking lot behind the Welcome Center
- Southeast corner of the Wesleyville 7.5-minute quadrangle
- (Latitude: 38°22′39.0″N; Longitude: 83°07′22.9″W)
- Anticipated time: 11:00 a.m.–12:30 p.m.

At this stop we can use the restrooms as well as grab a snack or a drink. The Welcome Center sits at a higher point in the valley of Cave Branch, where cave collapse was apparently not so severe. Several caves occur at various levels around the Welcome Center. We will take a 15-minute break here and then proceed on an approximately half-mile-long hike up and back along the valley of Cave Branch. The hike is an easy hike, mostly on level terrain and crossing the creek a couple of times; it should take us no longer than 45 minutes. The hike will be entirely within the Warix Run Member of the Slade Formation and shows a more upstream and up-dip portion of the collapsed cave system. Our hike will be along Natural Bridge Trail, which begins just behind the Welcome Center and proceeds up-valley past the picnic area and on to Carter Caves Natural Bridge. The trail is easy to follow and is marked with white blazes. The area in front of the bridge is a small karst window, or an area of collapse in which a stream flows out of a cave on one side across an open area and back into a cave on the other side.

Of particular interest along the hike, we will see herringbone crossbedding in the Warix Run Member. This type of crossbedding, which shows dips in two directions at an angle to each other (Fig. 13), illustrates the two common directions of tidal currents (ebb and flood) and is thought to be a good indicator of former tidal activity. We will also cross under and over a natural bridge or karst bridge; in the park, this karst bridge is known as Natural Bridge (Fig. 14) and a park road crosses the top of it (lat. 38°22′36.5″N, long. 83°07′33.9′W). This impressive natural bridge is one of the landmarks of the area. The opening is 180 ft long, 60 ft wide, and nearly 40 ft high. The thickness of the overhead span averages 15 ft and is thick enough to support the road running over it. Since the arch crosses a stream valley (Cave Branch creek), we can correctly refer to this as a natural bridge. This bridge is actually a remnant of the roof of the former underground cave that largely followed the present-day course of Cave Branch. A vertical shaft or dome pit in the roof of Natural Bridge represents the place where a vertical fall of water flowed from one level of the cave to another or where a small surface sinkhole emptied into the cave. The hike will end at Bat Cave, which represents a part of this large cave system that has not collapsed.

Carter Caves Natural Bridge holds the distinction of being the only natural arch in Kentucky that carries a paved highway across the top, reinforcing the fact that it should be called a natural bridge. The only other arch in the state with a road is a weather-eroded sandstone arch with a dirt road on top located on the edge of Natural Bridge State Resort Park. It is called White's Branch Arch (also known as the Narrows) and the road going over it is referred to as the Narrows Road.

Figure 13. Photo showing bidirectional (herringbone) crossbedding in Warix Run Limestone Member of the Slade Formation. This kind of crossbedding is an indicator of tidal action.

Figure 14. Photo showing Carter Caves Natural Bridge. This is a natural limestone arch or bridge that spans Cave Branch.

Stop 5

Lunch Stop and Smokey Bridge (see Figure 3)

- Drive about 1 mi to the southeast along park roads to the swimming pool and basketball courts; we will park in the lot, have lunch on nearby picnic tables, and visit Smokey Bridge, which sits just below Caveland Lodge.
- Northeast corner of the Olive Hill 7.5-minute quadrangle
- (Latitude: 38°22′6.8″N; Longitude: 83°7′30.5″W)
- Lunch: Anticipated time: 12:30–1:30 p.m.
- Smokey Bridge: Anticipated time: 1:30–2:00 p.m.

From the parking lot, we will walk a short distance to Smokey Bridge, another natural or karst bridge (Fig. 15). Smoky Bridge is a limestone arch that spans Smoky Creek. It is longer than Carter Caves Bridge, with an opening 220 ft long, 45 ft wide, and 35 ft high. The lintel or the overhead span averages about 40 ft thick. Smoky Bridge is regarded as the largest natural arch in the state of Kentucky. The bridge is formed wholly within the Warix Run Member of the Slade Formation, with the overlying Mill Knob Member forming the limestone ledge that caps the bridge. Again, note the large-scale crossbeds that characterize the Warix Run Member.

The best way to see the bridge is first to walk across the top of the bridge, and then turn left onto a trail that parallels the stream, which runs under the bridge. A branch of this trail then will turn left into the small creek valley that runs under the bridge. Because a stream like this is largely dry except during periods of heavy rainfall, it's called a dry bed. From this vantage point you can easily see the bridge and the dry bed (Fig. 15). However, as you move a little farther down the dry bed toward the bridge, you will see small springs on both the right and left. The springs represent rises or resurgences, or places where waters that have been diverted to underground routes reappear as surface-water springs.

Figure 15. Photo of Smokey Bridge. This arch is larger than Carter Caves Bridge with an opening 220 ft long, 45 ft wide, and 35 ft high. The lintel or crest of the arch is some 40 ft thick, making this the largest natural bridge in the state of Kentucky.

In the rising spring on the right, the water exits a solution tube or anastomosis tube developed between two Warix Run crossbeds and has eroded a channel into the solid limestone (Fig. 16). Except during heavy storms, these two rising springs appear to supply all the water that flows under Smokey Bridge.

Smoky Bridge is generally interpreted to be a waterfall arch (McGrain, 1966). This type of arch forms when the stream above a waterfall has been redirected through a series of enlarged joints and/or bedding planes and eventually emerges below the face of the original fall. Over time this undercuts and isolates a portion of its streambed, leaving behind a lintel that is supported by the two banks of the stream (see McGrain, 1966, Fig. 33).

Figure 16. One of two springs along the dry creek bed of Smokey Creek. These are called *rises* or *resurgences*, or places where water that has been diverted to underground routes reappears as surface-water springs.

Stop 6

Box Canyon (see Figures 3 and 17)

- From the last stop (Stop 5), return to the park entrance and turn right (southeast) onto Ky. 182 and drive 0.9 mi to the junction with Ky. 209; turn right (west) onto Ky. 209 and drive nearly a mile to Cascade Caves parking lot. Turn right into the lot and park.
- Northwest corner of the Grahn 7.5-minute quadrangle
- (Latitude: 38°21′19.8″N; Longitude: 83°06′42.8″W)
- Anticipated time: 2:30–3:30 p.m.

On this stop we will be hiking about 0.75 mi into a small side canyon that is part of a larger valley called Box Canyon. The entire hike should take us 45 minutes to an hour and involves some moderate climbing up and down collapse boulders. Box Canyon Trail is one of the most scenic trails in the park and passes an assortment of geologic features. It is a trail that begins at the Cascade Caves parking lot, proceeds to the head of Box Canyon, and loops back to the parking area. The trail can be quite steep and may be a bit difficult to climb. It is marked with orange blazes on many of the trees along the trial.

The canyon has an inauspicious beginning as a surface stream called James Branch. James Branch is a rather small, *insignificant* creek that begins just north of I-64. It flows northward for about 2 mi before plunging over the falls you see at the head of Box Canyon. Most of the valley floor in this canyon is underlain by the Slade Formation. Once the stream enters the canyon, it flows a short distance along the valley floor (≈ 1,800 ft) and sinks into cracks and fractures in the limestone. Throughout the remainder of its journey the stream remains below ground, flowing in a north/northwest direction through the Cascade Cave system and eventually toward Tygarts Creek.

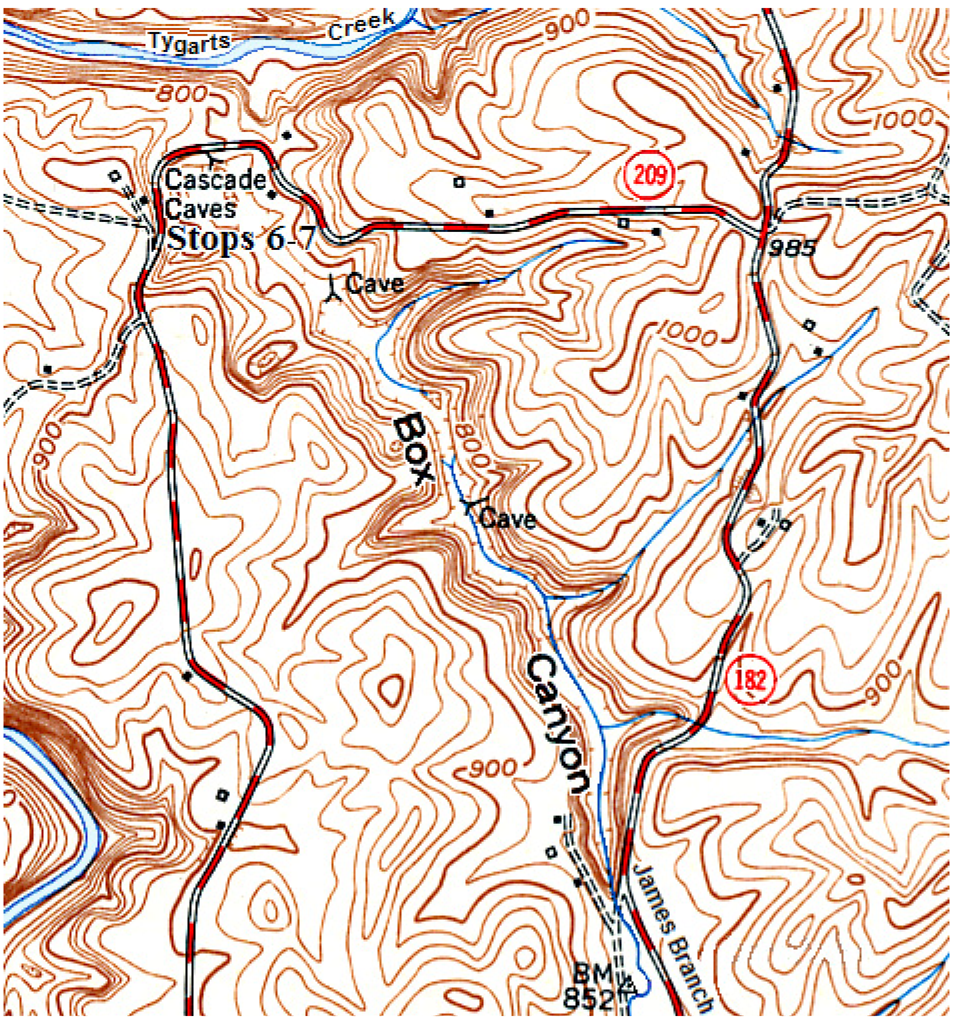

Figure 17. Topographic map of the northwest corner of the Grahn 7.5-minute quadrangle, showing the location of Box Canyon and Cascade Caves.

Box Canyon, like the entrance-drive valley into the park (Stop 3, Fig. 11), is a northwest–southeast-oriented karst solution valley or uvala. Like the entrance-drive valley, Box Canyon valley probably represents a large, collapsed trunk cave, and many of the caves that occur in the walls of this valley probably represent uncollapsed parts of the system that originally entered the main trunk cave. Although the large joint that is responsible for this valley is not the same as that responsible for the entrance-drive valley, they are part of the same northwest–southeast-oriented system of joints. The entrance-drive valley is also different than this valley, because it is floored with the relatively impervious Cowbell Member of the Borden Formation, giving it a rather uniform elevation throughout, with no solution features. The Box Canyon valley, however, is floored with Slade Formation limestones and is pockmarked with sink holes due to solution of the limestones, giving the valley bottom a hummocky appearance. As we begin hiking on the trail, note the sinkholes to your right.

Like the small valley we saw at Stop 5 near Smokey Bridge, Box Canyon valley is largely a dry bed, because most of the drainage enters the subsurface through the many sinks in the valley. Only during major storms would we see any streamflow in this valley, and only then until the underground stream courses, which we will see in Cascade Cave, can accommodate the flow.

As we walk farther up toward the head of this small tributary valley, we see a wall of sandstone looming above us. This is the Carter Caves Sandstone, a Mississippian sandstone that is more than 100 ft (30.5 m) thick. We saw the Carter Caves Sandstone earlier at Stop 1, but we were on the thinning southwestern margin of the sandstone body there, where it was intertonguing with the clastic member of the Paragon Formation (Figs. 4–5). The Carter Caves Sandstone is a linear body of sandstone that extends nearly north-south for 14 mi (Fig. 18). It is at its thickest in the Carter Caves Park area. This sandstone has been interpreted to represent a tidal-channel deposit that formed to the east of the Waverly Arch, a structure that was apparently elevated at the time. In Late Mississippian time when this channel formed, the area was dominated by extensive tidal currents. The Waverly Arch was apparently high enough at the time to block major tidal currents and force them to move only on its eastern flank. Hence, these currents were forced to move south parallel to the arch, and in so doing eroded a deep, nearly north-south channel and filled it with sand deposited by migrating sand bars. The evidence for these migrating sand bars is present in the prominent high-angle trough crossbeds that are present throughout the body. These crossbeds are clearly visible where we first encounter the sandstone (Fig. 19). These crossbeds are oriented in one direction (unimodal), suggesting that they were made by the dominant tidal flow direction. In places, smaller ripple marks were superimposed on these dune (crossbeds) surfaces by the opposite, less dominant, tidal-flow direction (Fig. 20). At the head of the valley, the Carter Caves Sandstone unconformably sits on the Tygarts Creek Member of the Slade Formation (Figs. 4–5), indicating that the sandstone channel resulted from more than 90 ft (27.4 m) of channel erosion through Paragon sandstones and shales as well as Slade limestones and shales.

Although now eroded or collapsed in many of the large solution valleys throughout the park, at one time the Carter Caves Sandstone was present across the entire park area, and probably played an important role in cave formation.

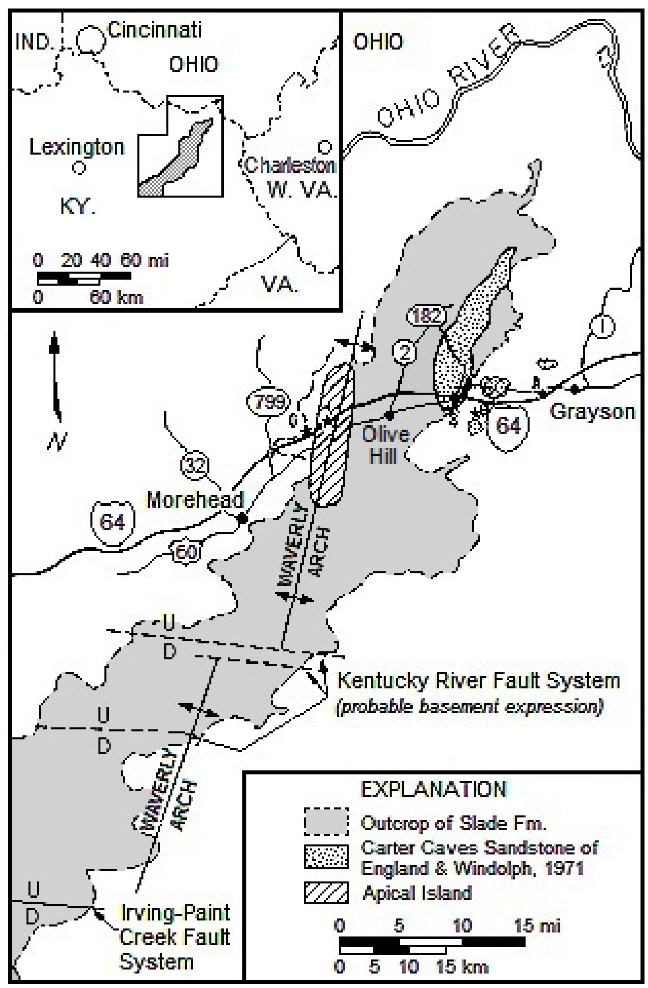

Figure 18. Map showing the location of the Carter Caves Sandstone (stipple) relative to structural features in the area. Note that the Carter Caves Sandstone occupies a valley that parallels the Waverly Arch to its west.

Figure 19. Outcrop in the Carter Caves Sandstone showing well-developed unimodal, trough *crossbedding* in Box Canyon.

Erosion of overlying sands, shales, and limestones below the limestone meant that dissolving waters had shorter distances to travel to get to the thickest limestone units, and no doubt, the porous, permeable nature of the overlying sandstone acted as a large conduit that funneled water downward toward the limestones. The presence of the Carter Caves Sandstone was probably necessary for the development of the underlying caves. Much of that sandstone roof has now been destroyed by erosion and collapse in the karst solution valleys or uvalas.

As we first encounter the sandstone on the trail, we not only see the crossbeds (Fig. 19), but also an arch-like structure that has been called Cascade Bridge (Fig. 21). This structure is not really a bridge or an arch, as it is closed off on one side. This is a collapse alcove that formed by collapse of the sandstone as supporting limestones were dissolved from under the sandstone. This "bridge" or alcove in part reflects the influence of joints in the area. The vertical surface behind the alcove, as well as the flat surface of the sandstone wall defining the head of this valley, are large vertical joints, along which weathering has proceeded. Inasmuch as joints are stress-related breaks in the rocks, they allow access to weathering agents like air, water, and various natural acids, as well as freeze and thaw, which facilitate breakdown of the rock along them. As you walk a little farther along the trail, note the steep vertical wall in the Carter Caves Sandstone (Fig. 22). This is a joint surface along which the head of the valley wall developed. If you look just below the sandstone cliff, you will also see that a series of sliver-like joints have developed in the underlying Tygarts Creek Limestone (Fig. 23).

The limestones in the area are largely subject to weathering and erosion via solution. Except for the area just under the sandstone and in the caves, the rapid destruction of limestones by solution makes them difficult to observe. The sandstone, however, although subject to weathering and erosion, is more resistant to these processes, and hence forms large, bold, steep exposures like those seen at the head of the valley. The steep walls of the canyon are over 60 ft high and in places meet at a nearly perfect 90° angle.

Figure 20. Photo showing *ripple marks* superimposed on a crossbed surface in the Carter Caves Sandstone. This is typical of tidal regimes.

The square corners and high vertical cliffs result from collapse of the sandstone along two sets of intersecting joints. The floor of the canyon is covered by large blocks of fallen sandstone from this unit.

The Carter Caves is a white to very light gray sandstone that is typically a fine- to medium-grained, well-sorted quartzarenite that is crossbedded (tabular crossbeds) and sparsely conglomeratic. Pebbles can range up to ½ inch in diameter and usually consist of milky quartz. Moreover, because the sandstone is more resistant, weathering phenomena are more prominent and longer-lasting than those expected in the limestones, and several of these phenomena are visible in the Carter Caves Sandstone. These include liesegang bands (Fig. 24), related to the dissolution of iron compounds and their rhythmic precipitation as bands in the sandstone, and boxwork weathering (Fig. 25), related to the selective weathering of poorly cemented sandstones. Boxwork weathering structures have

Figure 21. Photo showing “Cascade Bridge,” a structure best described as a *collapsed cave*.

Figure 22. Steep vertical wall in Box Canyon formed in the Carter Caves Sandstone.

Figure 23. Thin, closely spaced joints in the Tygarts Creek Member of the Slade Formation. At this locality the Tygarts Creek is unconformably overlain by the Carter Caves Sandstone.

many other names, including cavernous weathering, alveolar weathering, stone lattice, beerock, honeycomb weathering, and talfoni. Plants may also exert a powerful force in weathering through root wedging and solution by organic acids. A prominent example of this is present in the sandstones as we climb out of the valley (Fig. 26).

Figure 24. Photo showing example of *liesegang* banding in the Carter Caves Sandstone.

Figure 25. Photo showing an example of *boxwork* weathering in the Carter Caves Sandstone.

Figure 26. Photo showing example of *root wedging* in the Carter Caves Sandstone.

Stop 7

Cascade Caves (hike in cave; see Figs. 3, 17, 27)

- Northwest corner of the Grahn 7.5-minute quadrangle
- (Latitude: 38°21′23″N; Longitude: 83°06′46″W)
- Anticipated time: 3:30–5:00 p.m.

Cascade Cave is the name for three different caves in the same area (Fig. 27) and is together the largest cave in the park. From its beginning to its end, James Branch, the stream in the cave, rises or reappears seven different times. Cascade Cave is noted for its large chambers and numerous cave formations and has been open to visitors since 1925. It is cut from the Warix Run Member of the Slade Formation. The cavern itself is made up of a series of parallel passages that are filled with dripstone formations of different types. The large size of the passages suggests that they formed along a series of bedding planes and vertical joints. The entrance to Cascade Cave is located along one of the many sinkholes in the area, just north and west of Box Canyon. It is an exceptionally beautiful cave with a wide range of features. Some of the highlights of the Cascade Cave include:

- **Counterfeiters Room**: The "Counterfeiters Room" is the name given to the initial passage that leads into the Cascade Cave system. Here, legend has it that a group of counterfeiters carried out their operations along this passageway over a century ago.
- **Lake Room**: The "Lake Room" is named for a large reflecting pool of water that is located in the cave. It is situated at the intersection of two sets of joints. As active groundwater ran down these joints, they were enlarged. A beautiful array of stalactites called the "Hanging Gardens of King Solomon" are attached to the ceiling and hang directly over the lake. Water from James Branch enters the lake along a lower-level passage and exits the cave system through a small opening along the base of the northeast wall. It then makes its way to Tygarts Creek.
- **Cathedral Room** (Fig. 28): In a separate part of the cave the "Cathedral Room" forms beneath several sinkholes. It is reached by taking a short path outside the "Lake Room" to the base of a large limestone cliff. The room contains a variety of speleothems that have rather colorful names: the "Cardross Castle," the "Ice-capped Mountains," and the "Temple Bells." Sinkholes above the "Cathedral Room" conduct surface water into cracks and crevices leading down into the "Cathedral Room." These sinkholes have diverted a large amount of surface water into the cave, which has allowed a number of dripstone formations to form over the years.
- **Frozen Cascades**: The "Frozen Cascades" are a series of small travertine "waterfalls" (principally flowstone) from which the "Cascade Caves" takes its name. It occurs along a narrow passage that is aligned along a joint fracture. This part of the cave is mostly dry and active growth of these speleothems no longer takes place.
- **Underground Waterfalls**: The "Underground Waterfalls" are located some 300 ft west of Cascade Cave exit. It is reached through a man-made entrance. Water, flowing along a bedding plane, has been diverted downward through a vertical joint and cascades nearly 35 ft into a plunge basin below. The water eventually flows into James Branch, which is now an underground stream within the Cascade Cave system. Over the years this joint plane has been gradually enlarged and sculpted by the flow/solution of water over its surface. Visitors can view the underground waterfall from a platform constructed at the midpoint of the falls.
- Other interesting points in and around Cascade Cave include: "Dance Hall," where a previous owner held weekly dances. There are other passageways that are not shown on the guided tours. They are either undeveloped passages or have never been mapped.

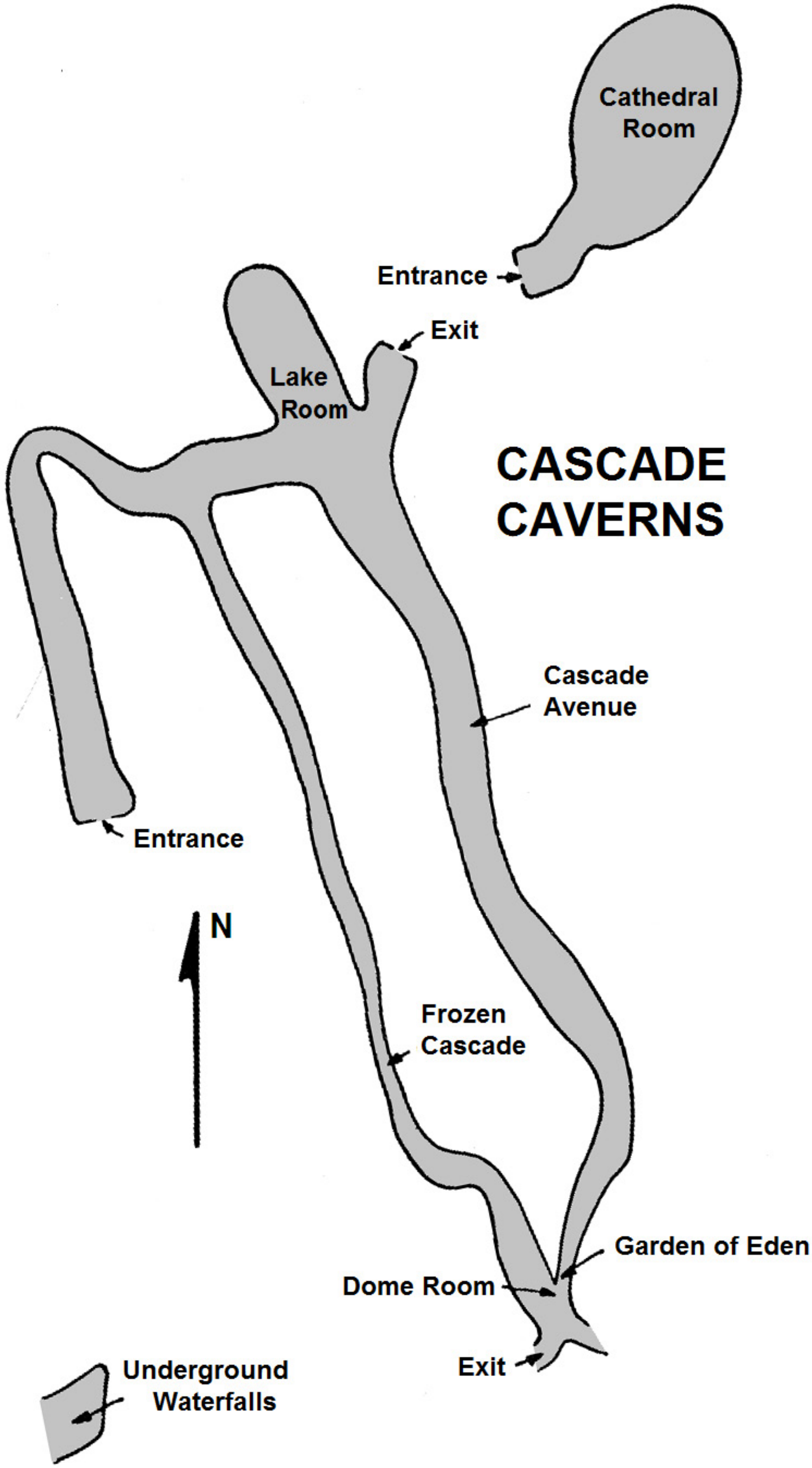

Figure 27. Sketch map showing passage plan of Cascade Caverns (adapted from McGrain, 1966).

Figure 28. View in the Cathedral Room showing a variety of speleothems, including stalactites, stalagmites, columns, soda straws, and draperies.

Glossary of Field Trip Features and Terms

Caves (how do they form?)

A cave or cavern is a natural opening or passage under the ground, especially one with an opening that leads to the surface. Other definitions state that a cave is a natural underground space large enough for a human to enter. Caves form when rainwater trickles down along cracks, joints, or bedding planes in a rock (usually limestones or dolostones) and slowly dissolves the rock. As rainwater passes through the atmosphere, it combines with carbon dioxide (CO_2) and forms a weak acid called carbonic acid (H_2CO_3). This reaction, called *carbonation*, is shown in Formula 1 below. This results in lowering the pH of rainwater to between 5.5 and 6.0. When rainwater reaches the surface of the ground it filters into the soil below. The air found within soil is greatly enriched in CO_2; in fact up to 25 percent of the air in a soil is CO_2; compare this to 0.03 percent in the atmosphere. The source of all this CO_2 in a soil comes from the decomposition of organic matter, the activity of bacteria in the soil, and the release by CO_2 by the respiration of plant roots. Ultimately this lowers the pH of the groundwater, making it even more acidic.

$$\underbrace{CO_2}_{\text{carbon dioxide}} + \underbrace{H_2O}_{\text{water}} \Rightarrow \underbrace{H_2CO_3}_{\text{carbonic acid}}$$

Formula 1 Carbonation

Once this acid comes in contact with the bedrock, it begins to dissolve the rock. This is especially true of limestone, which consists primarily of the mineral calcite ($CaCO_3$) and is extremely vulnerable to chemical attack by groundwater. The acidic groundwater trickles through fractures, crevices, and cavities in the rock and slowly dissolves the limestone, gradually enlarging the network of passageways. The chemical reaction that is taking place is illustrated in Formula 2 below:

$$\underbrace{H_2CO_3}_{\text{carbonic acid}} + \underbrace{CaCO_3}_{\text{calcite}} \Rightarrow + Ca^{+2} + \underbrace{2(HCO_3)^-}_{\text{bicarbonate}}$$

Formula 2 Solution

As more and more limestone dissolves, joints, tunnels, networks of passageways begin to form. Limestone caves that develop by this process require hundreds of thousands if not millions of years to grow large enough for a human to be able to pass through. Several conditions need to be present for cave systems to form in this way.

1. The rock in which a cave system forms needs to have a calcium carbonate ($CaCO_3$) content of at least 80 percent. Generally, the purer the limestone with respect to $CaCO_3$ the greater the tendency for caves to form. Not only should the bedrock be a relatively pure limestone, it should also be massive, hard, and crystalline.
2. The bedrock also needs to be fractured or jointed so the water can flow through or follow these joints or fractures.
3. Bedrock also needs to be relatively close or at the surface and the total thickness of the carbonate should ideally exceed 100 m in thickness.
4. A fourth requirement for cave formation is a relatively moderate annual rainfall (> 20 in., > 500 mm). Caves are best formed in humid temperate or tropical climatic conditions. They can be particularly well developed in tropical regions due to accelerated chemical weathering (i.e., higher temperatures, high rates of precipitation, and lush vegetative cover).
5. The fifth requirement is a thick vegetative cover. Vegetation enhances the process of cave formation by producing more available acids (i.e., carbonic acid, as well as various organic acids such as humic acid and fulvic acid).
6. A final requirement is adequate amount of time for caves to form or develop, and by adequate time we mean tens of thousands to hundreds of thousands and even millions of years. (www.uwec.edu/jolhm/cave/caveform2.htm)

Most caves are created at or just below the water table in a groundwater zone called the Zone of Saturation (a groundwater region in which the pore spaces of the rock are completely filled with water). If the water table is stable for long periods of time, large openings can be created when the slightly acidic groundwater comes in contact with all surfaces of the cave, gradually dissolving away the limestone. Should the water table drop, the area of active cave formation moves to a lower region in the bedrock and the upper openings are left in the Zone of Aeration (a groundwater region in which pore spaces in the rock are filled with both air and water) (Fig. 29).

Once a cave and its network of tunnels have formed, different types of cave formations or speleothems can begin to develop in the zone of aeration. Water seeping through cracks in a cave's surrounding bedrock dissolves certain components, usually calcium carbonate. The rate depends on the amount of carbon dioxide (CO_2) held in solution, the temperature of the groundwater, and on other factors. When the solution drips into an air-filled cavity, carbon dioxide (CO_2) may be released from the solution (a process called *degassing).* The release of carbon dioxide (CO_2) alters the water's ability to keep these minerals in solution, causing calcium carbonate ($CaCO_3$) to precipitate (Formula 3). Over time, which may span tens of thousands of years, secondary accumulations of these precipitates gradually form. These are collectively known as cave formations or *speleothems*.

$$\underbrace{Ca^{+2} + 2(HCO_3)^-}_{\text{(composition of groundwater)}} \Rightarrow \overset{\text{degassing (removal of } CO_2\text{)}}{\underset{\text{carbon dioxide}}{CO_2}} + H_2O + \underset{\text{calcite precipitates}}{CaCO_3}$$

(composition of groundwater) — $2(HCO_3)^-$: *bicarbonate* — *Formula 3*

Speleothems can take on a variety of forms or shapes depending on whether the water drips into the cave, flows, or ponds in the cave (Fig. 30).

- **Stalactites** are pointed pendants of calcium carbonate that hang from the ceiling of a cave. The average growth rates for dripstones (stalactites) are about ½ in. per 100 years.
- **Stalagmites** are the "ground-up" counterparts of stalactites, often with blunt ends.

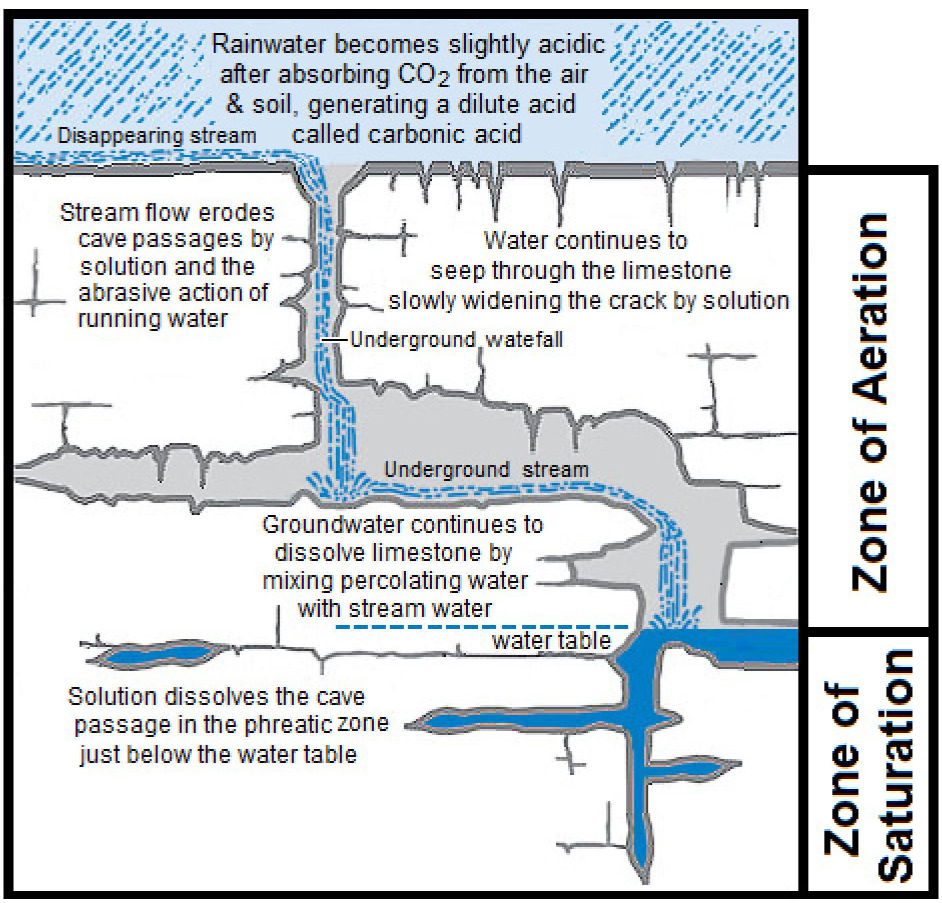

Figure 29. Limestone cave formation: Illustration showing steps in the formation of an open cave, including dissolution by acidic groundwater and streamflow through the cave passages.

- **Columns:** Stalactites and stalagmites often grow in pairs. These sometimes grow together, forming a long continuous column or pillar.
- **Draperies** or **curtains** are thin, wavy sheets of calcite that hang downward from the ceiling.
- **Flowstone** is a sheet-like deposit of calcium carbonate that coats the wall or floor of a cave; this forms when water flows down the walls or along the floor of a cave.
- **Soda straws:** Soda straw stalactites form along a drop of water and continue growing down from the cave ceiling, forming a tubular stalactite, which resembles a drinking straw in appearance.

Stream erosion

Although dissolution is the dominant process operating in many cave systems, other processes can contribute to a cave's evolution and development. These other processes that operate within a cave include stream erosion and roof collapse or "sapping." As underground cavities become larger, greater and greater amounts of water flow through the ever-expanding passageways. As water flows through these openings, it abrades and erodes the rock around it. This physical erosion chews away at the sides of the cave and washes away fine rock debris and sand. Gradually the cave passages grow larger and larger and the flow of water eventually forms an underground stream.

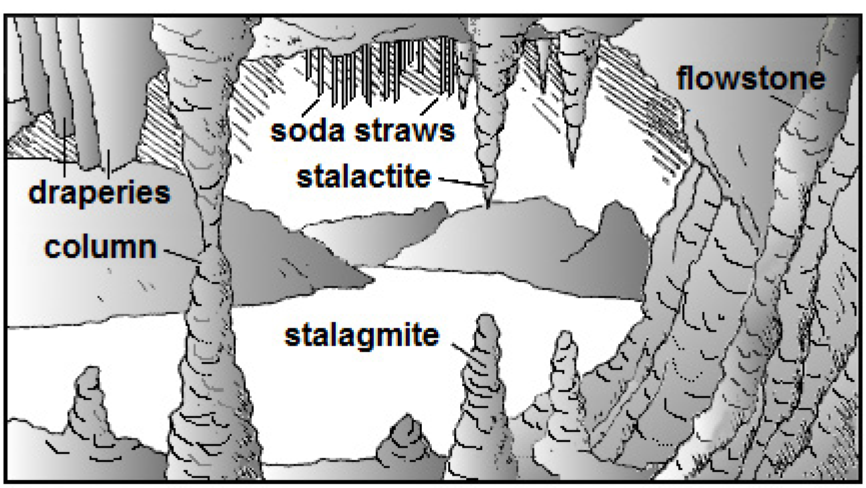

Figure 30. Illustration showing several secondary deposits of calcium carbonate known as cave formations or speleothems.

Roof collapse and *sinkhole development*

As caves grow larger, the open space within the cavern can become so large that the rock making up the cave's roof collapses and forms a sinkhole. Sinkholes are bowl-shaped or funnel-shaped depressions in the land surface that form over underground caverns. These depressions can range from a few feet to several hundred feet in diameter and result from the natural collapse of the roofs of caves eroded in soluble bedrock. Immediately beneath these sinkholes one can find a pile of cave breccia or solution-collapse breccia. These are composed of angular blocks of rock formed by collapse of the cavern roof due to dissolution of the surrounding bedrock. The weight of the overlying bedrock is simply greater than the cavern's ceiling can support, and the roof collapses (Fig. 31). Commonly, what is needed for this to occur is a triggering mechanism to cause this collapse. These triggers can include heavy rains or floods; even drought can lead to a roof collapse. In this instance, a collapse occurs as the level of the groundwater slowly lowers during a drought. This is because in a carbonate aquifer the roof of a cave can be partially supported by the water filling the opening. When this additional support is removed, the roof may collapse under its own weight.

Disappearing streams

In karst regions, a surface river or stream can sometimes flow into a sinkhole or crack in the earth and into an underground or cave river system, literally disappearing from sight (Fig. 29).

Underground or subterranean streams

An underground river is a river that runs beneath the ground surface, flowing through cave systems. In karsted areas, rivers may disappear through sinkholes or swallets and continue underground. When a surface stream flows into a sinkhole or a deep crack in the bedrock, it may reappear underground as a subterranean stream (Fig. 29).

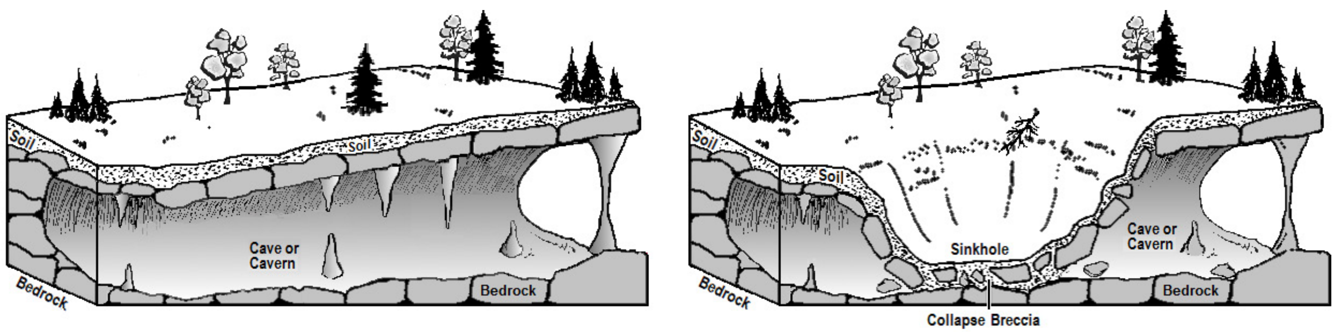

Figure 31. Illustration showing development of a sinkhole and associated collapse breccia.

Karst terrain

In areas where extensive limestone formations occur, a distinctive landform known as karst can form. Karst is a type of landform characterized by sinkholes, solution valleys, underground drainage, caverns, disappearing streams, etc. It is formed by the dissolution of soluble bedrock, usually limestone or dolostone, by natural waters. Although karst topography is characteristic of humid areas, few surface streams are present because of the underground drainage channels (Fig. 32).

Karst solution valley

A karst solution valley is a closed depression formed by the coalescence of several sinkholes; its drainage is generally in the subsurface, and its size is measured in hundreds of meters to a few kilometers. It usually has an irregular floor and a scalloped margin inherited from the sinkholes (Fig. 32).

Arches and *natural bridges*

Both natural arches and bridges are rock exposures that have a passageway or opening passing completely through the arch and are formed by selective removal of rock in such a way that it leaves behind a relatively intact frame or arch. A natural bridge is an arch that spans a valley. By this definition, all natural bridges are arches, but not all arches are natural bridges. Carter Caves State Resort Park has at least seven arches, which include: Fern Bridge, Raven Bridge, Shangri La Arch, Cascade Bridge, Smokey Bridge, and Carter Cave Bridge. The largest of these natural arches is Smokey Bridge, which stands an impressive 90 ft (27 m) high and 120 ft (37 m) long, and is considered the largest natural arch in the state. Carter Cave Bridge is the only natural bridge in Kentucky with a paved road on top. Within the Carter Caves area, arches and natural bridges can be formed by several different processes.

A. **Ridgetop arches**: Most natural arches form along narrow ridges that are walled to either side by steep cliffs. This is the case for Cascade Bridge.
    1. The formation of a ridgetop arch is in part related to the presence of deep fractures or joints that penetrate the rock making up the arch.
    2. Erosion slowly wears away exposed rock layers and enlarges these surface cracks, eventually isolating and narrowing the rock walls or fins.

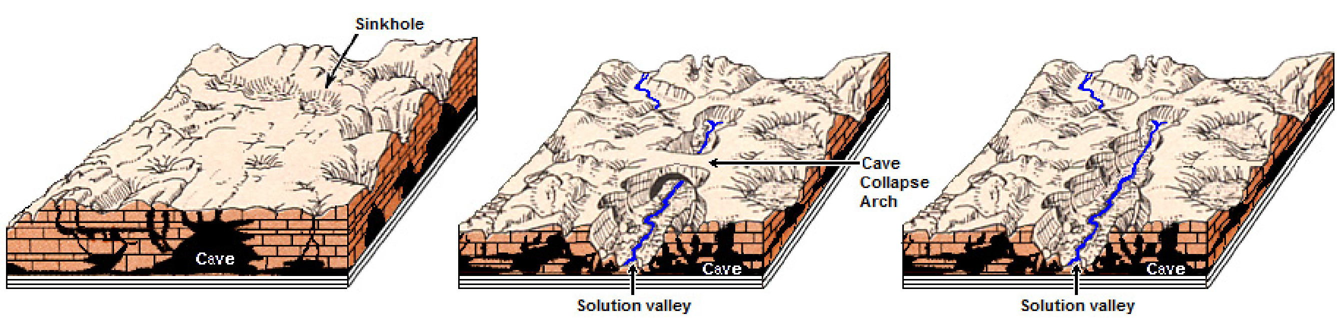

Figure 32. Illustration showing evolution or development of a karst solution valley (adapted from Raisz ,1960).

3. Alternating freezing and thawing and root-wedging causes crumbling and flaking of the rock, and it eventually cuts through some of the fins. Gradually, large sandstone blocks detach from the sides of the ridge or cliff and slip downslope to either side of the ridge. As the ridge steadily becomes narrower, the softer rock that lies beneath the arch is gradually undercut by erosion until an overhang or "natural rock shelter" forms on either side of the ridgetop. Continued erosion deepens the overhang and undermines the rock shelter. Eventually, these shelters break through from either side of the ridge and a natural arch is formed.

B. **Waterfall Arch:** This type of natural arch occurs when water percolates downward along a joint plane or bedding plane just upstream of a falls, flows laterally, and emerges from the lower face of the falls. The movement of water within rock loosens and removes rock material to the point that the entire stream passes underneath the former waterfall, forming a rock arch (in this case a natural bridge). The presence of a waterfall either at the arch or upstream from the natural arch is a good indicator of a waterfall natural bridge. The waterfall gradually retreats upstream from the natural arch as time passes (Fig. 34).

C. **Cave Collapse Arch:** A cave collapse arch forms when the roof of rock that was overlying a subterranean passage or cave becomes so thin that it can no longer support its own weight. This results in the structural failure and collapse of the roof. A natural arch can form when a pair of sinkholes collapse and the cave roof is left standing in between the two sinkholes. Naturally, the passageway connecting one sinkhole to the other also remains. This is an important type of arch in regions with well-developed cave systems. This appears to be the case for a number of the arches in the park, including: Smoky Arch and Carter Cave Bridge. Like all rock formations, natural bridges are subject to continued erosion, and will themselves eventually collapse and disappear (Fig. 35).

Liesegang banding

Liesegang banding (Fig. 36) is a secondary or diagenetic sedimentary structure that consisting of swirling colored bands of cement that precipitate in the pore spaces of a rock. These are most often observed in sedimentary rocks and typically cut across bedding or other primary sedimentary structures. These brightly colored bands are caused by the precipitation of minerals, mainly oxides and hydroxides of iron (Fe) and manganese (Mn), within the rock. Under the right set of conditions these precipitate out

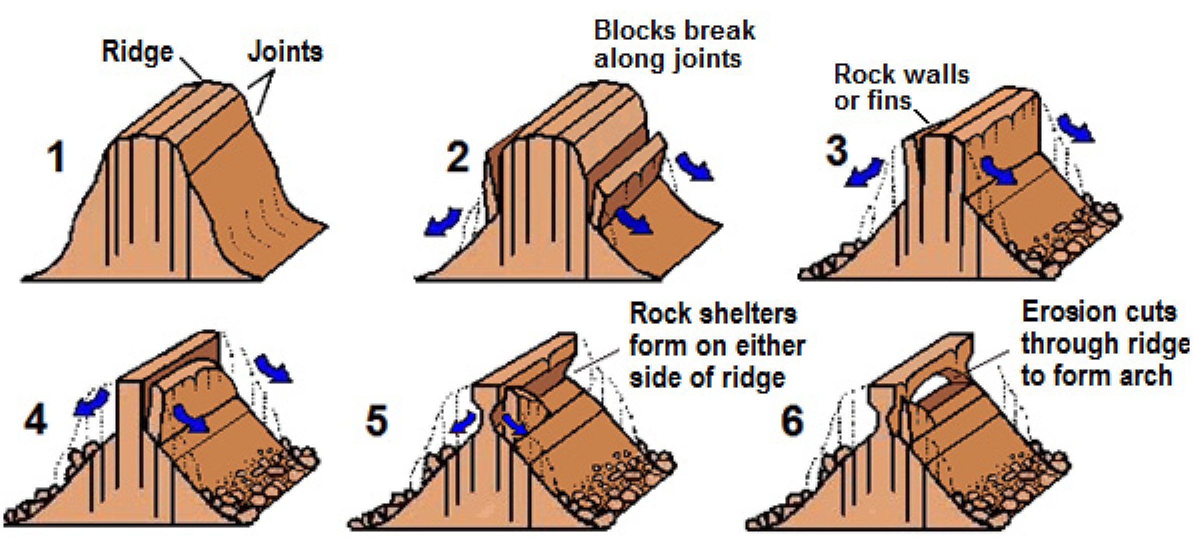

Figure 33. Illustration showing steps involved in the formation of a ridge-top arch.

of solution from mineral-rich groundwater that slowly percolates through the rock. The elements making up these minerals, in particular iron (Fe) and manganese (Mn), are sensitive to subtle changes in the amount of dissolved oxygen in the water. Interestingly enough, both of these elements have more than one oxidation state: for example, iron has an Fe^{2+} and Fe^{+3} state, and manganese an Mn^{+2} and Mn^{+4} state. Both elements behave very differently when their oxidation state changes. Both iron and manganese are soluble in water when they are in reduced state (Fe^{2+} and Mn^{+2}); for this to occur, there must be a lack of oxygen in the water. However, when oxygen-rich water is introduced, the oxidation states of these elements change to an Fe^{+3} for iron and Mn^{+4} for manganese. At this point they are no longer soluble in water, and they precipitate out of solution. This typically occurs along a contact front between these two different bodies of water. If groundwater that is lacking oxygen encounters water with an excess of oxygen, both Fe^{3+} and Mn^{4+} precipitate out of these solutions as distinct bands, typically as hematite ($Fe^{+3}_2O_3$) or pyrolusite ($Mn^{+4}O_2$).

Honeycomb weathering

A pitted or honeycomb pattern (Fig. 37) can sometimes develop on the weathered surfaces of many rocks. This happens as groundwater percolates through the rock and deposits minerals along an

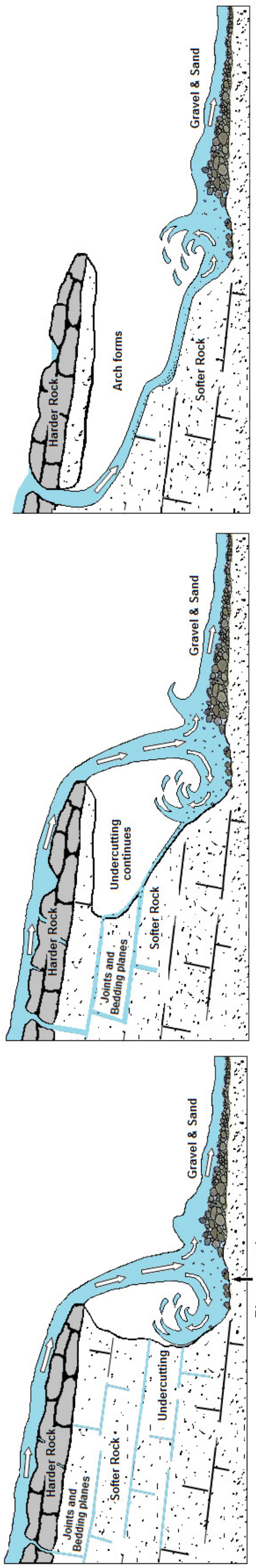

Figure 34. Illustration showing steps in the formation of a waterfall arch.

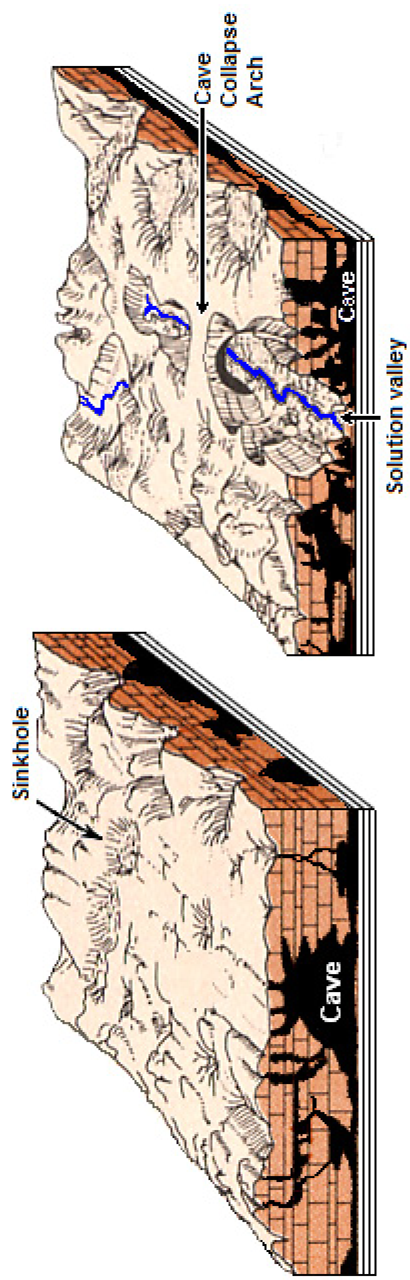

Figure 35. Illustration showing steps in the formation of a cave-collapse arch.

Figure 36. Photo showing an example of liesegang banding.

Figure 37. Photo showing an example of honeycomb weathering.

exposed surface. This may include silica (SiO_2), calcium carbonate ($CaCO_3$), or various Fe-oxides (Fe_2O_3) and hydroxides (FeOOH), and carbonates ($FeCO_3$). This forms a crust on the surface of the rock as water evaporates and leaves behind its load of dissolved minerals along the exposed rock surface. This crust or case-hardened surface is resistant to weathering. However, once this outer surface is eventually breached by weathering, the soft interior is easily loosened and carried away by wind and water. This leaves behind a series pits or depressions on the surface of the rock. This feature is also called cavernous weathering, talfoni, or alveolar weathering.

Boxwork structures

Boxwork (Fig. 38) is box-shaped or triangular patterns of iron oxide or siderite in many rocks. These structures form in much the same way that honeycomb weathering develops. As groundwater slowly trickles through the pore spaces of a rock, it can dissolve a variety of minerals. Under the right set of chemical conditions these minerals will precipitate out along cracks, crevices, joints, or bedding planes in the rock. This is a common occurrence with various iron-rich minerals such as hematite (Fe_2O_3), limonite (FeOOH), or siderite ($FeCO_3$). As the rock is exposed to the elements and slowly weathers, these more chemically resistant areas stand out from the surface of the rock. With time it develops a surface that resembles a set of intersecting lines or planes.

Crossbedding

Crossbedding (Fig. 39) is an arrangement of layers of sediment that are deposited at an angle to the main stratification. The most common type of cross-stratification is produced by the migration of sand dunes or ripples. Crossbedding can form in any environment in which water or wind flows over a bed of sand. It is most common in stream deposits, in tidal areas, or as wind blow dunes. The direction of inclination of the crossbeds reflects the direction of the current responsible for depositing these inclined layers; this can show us the direction that ancient streams flowed or the direction that winds once blew (these are called paleocurrents). Geologists believe the paleocurrents responsible for the deposition of the crossbedding seen in the sandstone of the Carter Caves occurred along an ancient beach (Fig. 39).

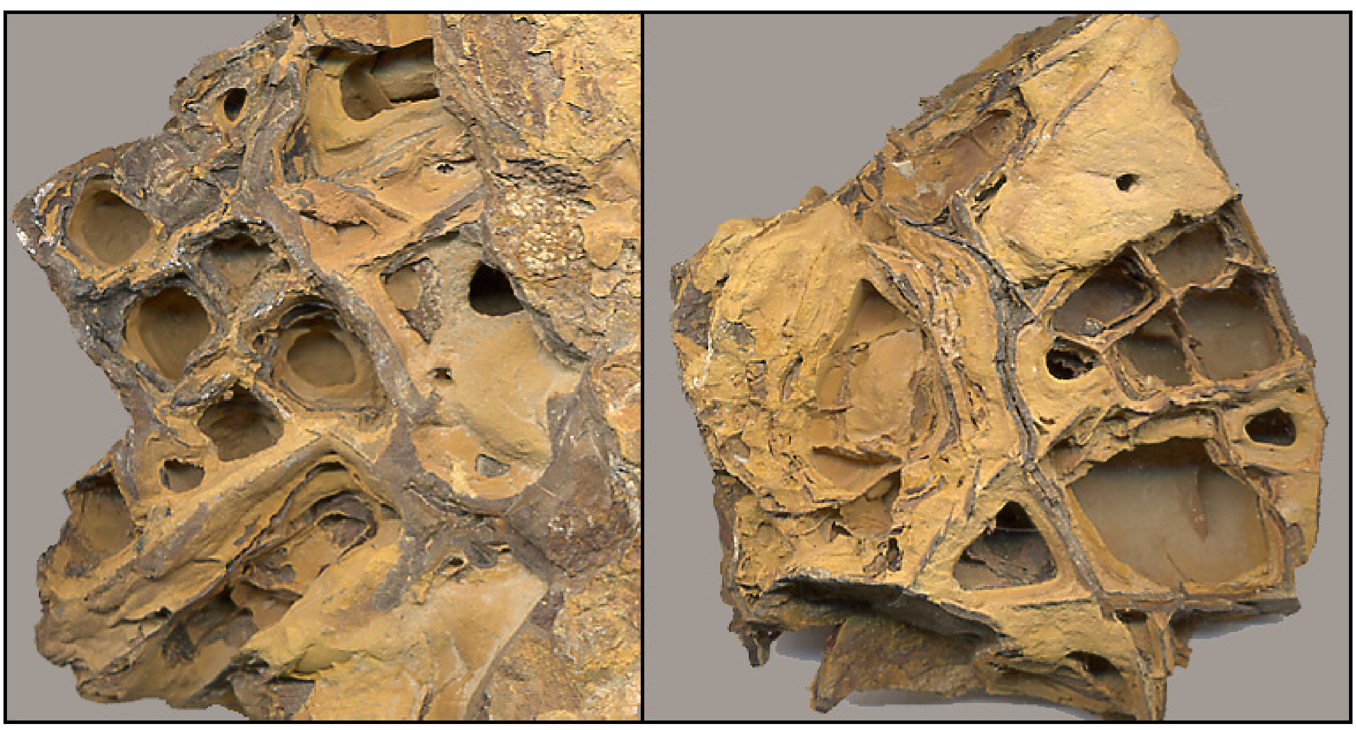

Figure 38. Photo showing an example of boxwork structures.

Cave scallops

These are the small scoop-like depressions found on the walls of caverns. They vary in size from a few centimeters to more than 1 m. They are slightly asymmetrical in cross section, having a steeper wall on the upcurrent side and a gentler slope on the downcurrent side (Fig. 40). Scallops provide us with information as to the direction of water flow in passages. Local eddies in the water flow produce turbulent swirls in the water, which dissolve away the bedrock. The length of a scallop (l) is inversely proportional to the velocity of the water that formed them; that is, the faster the water flows, the smaller the resulting scallop. They are quite useful to geologists because they can be used to tell the direction that water flowed in the cave. Keep a sharp eye out for these structures as we explore Cascade Caves.

White Nose Syndrome

White Nose Syndrome is an illness of unknown origin that has killed hundreds of thousands of bats across the northeastern United States over the past 3 years and continues unchecked. It was first discovered in 2006 in an area just west of Albany, New York. It has been spreading steadily to the south and west, and confirmed cases have been discovered as far south as Tennessee and North Carolina and as far west as Indiana. Caves in which White Nose Syndrome has been confirmed commonly see mortality rates on the order of 90 to 100 percent. While hibernating, affected bats develop a white fungus that grows around the animals' noses, faces, and body parts. A newly discovered cold-loving fungus, called *Geomyces destructans,* seems to be responsible. The disease is believed to be spread between bats and between bats and the caves in which they live. There is also strong evidence that human activity might also be a cause for the spread of the disease.

The disease threatens to spread to the Midwest and the Southeast, home to many federally endangered bat species as well as some of the

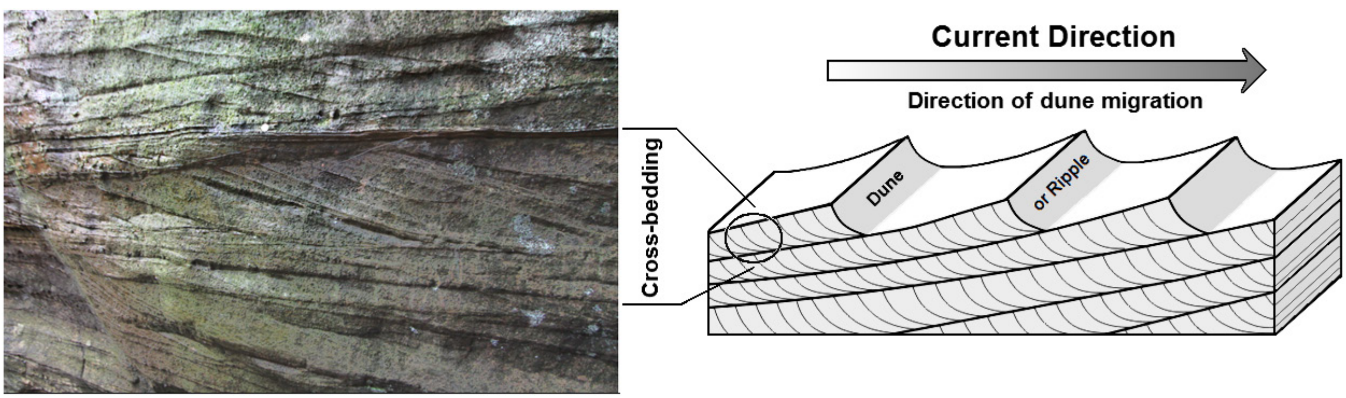

Figure 39. Crossbedding from the Carter Caves Sandstone relative to current direction.

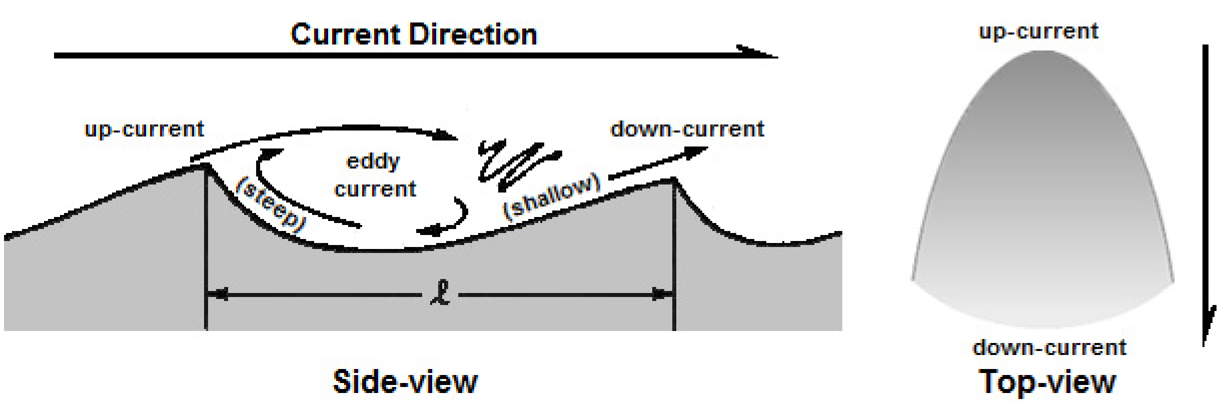

Figure 40. Illustration showing general shape, configuration, and formation of cave scallops.

largest bat populations in the country. White Nose Syndrome has spread as close to Carter Caves as south-central Ohio. At this time it has not been found in Kentucky. Bat Cave, Saltpeter Cave, and Laurel Cave are all important bat hibernation sites for the federally endangered Indiana bat *(Myotis sodalist).* In fact, the number of Indiana bats hibernating within these three caves during the winter makes up over 60 percent of the total population in the state of Kentucky, some 40,000 bats. In 2009, the Department of Parks closed all caves in the park system except park-led tours of X-Cave and Cascade Cave in order to help prevent the introduction of White Nose Syndrome into eastern Kentucky bat populations. (www.fws.gov/northeast/white_nose.html)

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