42nd Annual Meeting of the American Institute of Professional Geologists

"Geologic Information: Racing into the Digital Age"

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Introduction

The Red River Gorge contains the largest concentration of natural arches east of the Mississippi River. More than 150 arches have been identified by the U.S. Forest Service (Dever and Baron, 1986). Part of the gorge (29,000 acres) was designated as a "Geological Area" by the U.S. Park Service in 1974 and a National Natural Landmark in 1976. The U.S. Congress designated 19 miles of the Red River, which runs through the gorge, as a National Scenic River in 1993. The Federal Highway Administration designated 46 miles of roads around the gorge as National Scenic Byways (shown in Fig. 1). In 2003, some 30,000 acres in the gorge area were designated as a National Archeological District and the gorge was added to the National Register of Historic Places.

The Red River Gorge area is located in the Daniel Boone National Forest, on the Slade (Weir, 1974a) and Pomeroyton (Weir and Richards, 1974) 7.5-minute quadrangles in Powell, Menifee, and Wolfe Counties. The steep cliffs and famous arches are formed along the dissected margin of the Cumberland (Pottsville) Escarpment, on the western edge of the Eastern Kentucky Coal Field. The geology of the area has been described by McFarlan (1954) and in a trail guide by Ruchhoft (1976). Because the gorge is a popular area for hikers and rock climbing, there are also numerous Web sites dedicated to the scenery and arches. A virtual field trip can be seen at the Kentucky Geological Survey Web site (www.uky.edu/KGS/). Today's field trip will examine the geology of the escarpment in the gorge and adjacent Natural Bridge State Resort Park along the National Scenic Byway.

Geology and Structure

The field trip area is on the eastern flank of the Cincinnati Arch, a broad regional anticline. Along the crest of the arch, Ordovician through Mississippian strata are exposed. On the eastern flank of

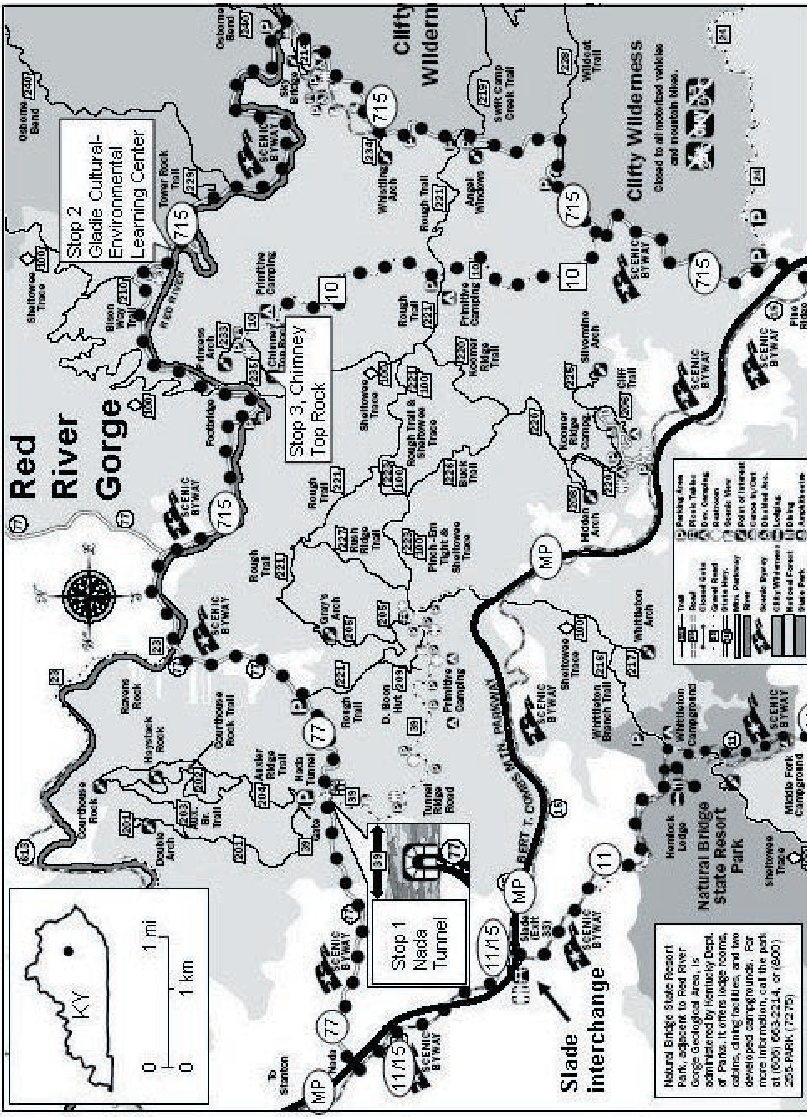

Figure 1. Location of the Red River Gorge area in eastern Kentucky. Bold dotted line is field trip route. MP=Mountain Parkway. Stops 1 through 3 shown. Stops 4 through 7 are in the Natural Bridge State Resort Park area and are shown in more detail in Figure 8. Modified from Forest Service map at www.fs.fed.us/r8/boone/documents/maps/rrg.pdf.

the arch, Mississippian carbonates dip toward the southeast into the central Appalachian Basin. Eastward, progressively younger Mississippian strata and then Pennsylvanian strata are exposed. The outcrop limit of Pennsylvanian strata are generally used to define the western limit of the Eastern Kentucky Coal Field, which is part of the larger central Appalachian Basin. Because Lower Pennsylvanian strata contain thick conglomeratic sandstones that are resistant to erosion, the outcrop limit of Pennsylvanian strata is characterized by the rugged Cumberland Escarpment.

Stratigraphy

Figure 2 shows the stratigraphy of Mississippian and Pennsylvanian strata in the Red River Gorge and adjacent Natural Bridge Resort State Park. Figure 3 is a generalized cross section through the ridge topped by Natural Bridge, showing the distribution of strata and the relative slopes formed by the strata in the gorge area.

Lower Pennsylvanian

Corbin Sandstone, Grundy Formation, Breathitt Group. The cliff-forming strata on the tops of the ridges in the Red River Gorge and at Natural Bridge State Resort Park is the Corbin Sandstone (Fig. 3). This sandstone was previously considered a member of the Lee Formation, but is now considered a member of the Grundy Formation (Chesnut, 1992). In the gorge, the Corbin is 100 to 280 feet thick (Weir, 1974a, b; Weir and Richards, 1974). Thickness variation is a function of incision in underlying parts of the Grundy Formation, and locally, into underlying Mississippian strata. The Corbin consists of very fine- to coarse-grained, crossbedded, conglomeratic quartzarenites (more than 90 percent quartz). Conglomerates are composed of quartz pebbles. Iron staining is common in cliff exposures. This unit will be seen at stops 1, 3, 4, and 4c.

Grundy Formation, Breathitt Group. The Corbin is underlain by 30 to 220 feet of shale, siltstone, and thin coal (Weir, 1974a, b; Weir and Richards, 1974). This unit was previously considered the lower tongue of the Breathitt Formation, but Chesnut (1992) elevated the Breathitt to group status and named this part of the Breathitt the Grundy Formation (Fig. 2). This part of the Grundy is not well exposed in the park, generally forming vegetated slopes beneath the Corbin cliffs. Thickness variability is interpreted as a function of incision by the overlying Corbin, and incision in underlying Missis-

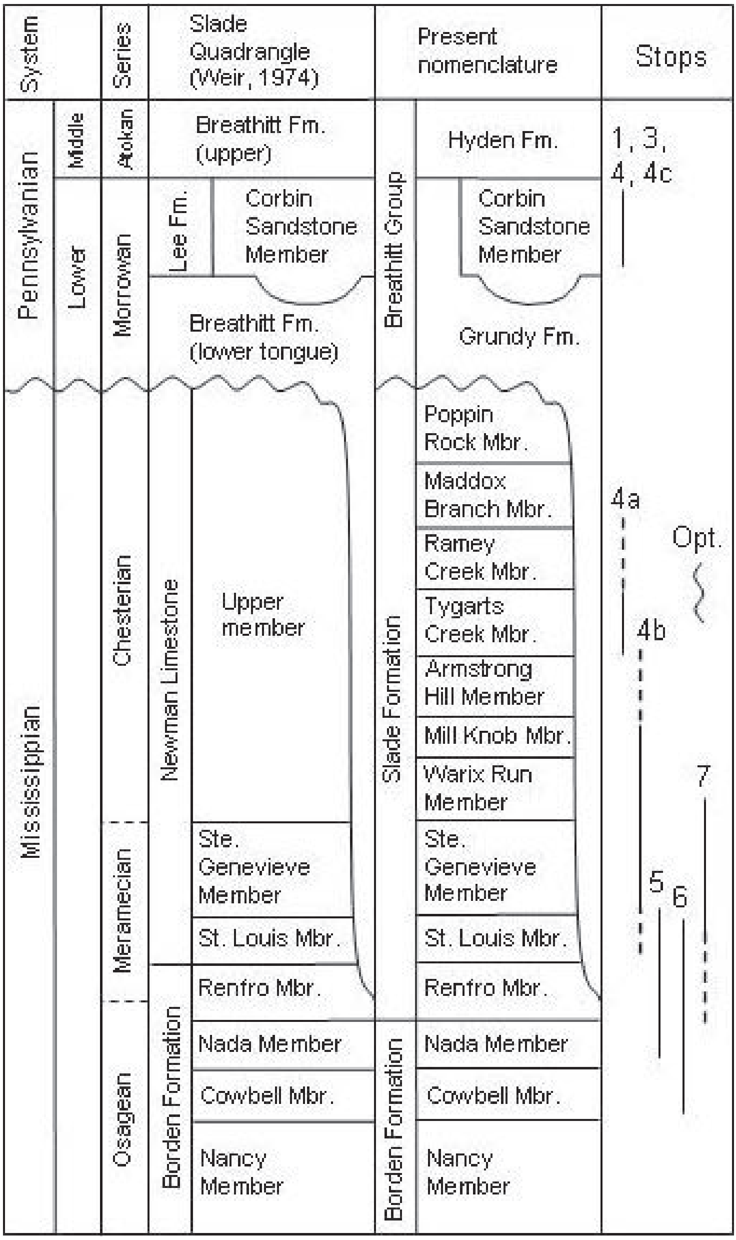

Figure 2. Stratigraphy of the Red River Gorge and Natural Bridge State Resort Park. Present nomenclature is based on revision of (1) Pennsylvanian stratigraphy by Chesnut (1992) and (2) Mississippian stratigraphy by Ettensohn and others (1984). Lines beneath stop numbers correspond to stratigraphic interval at that stop. Curved line indicates unconformity visible at the optional stop.

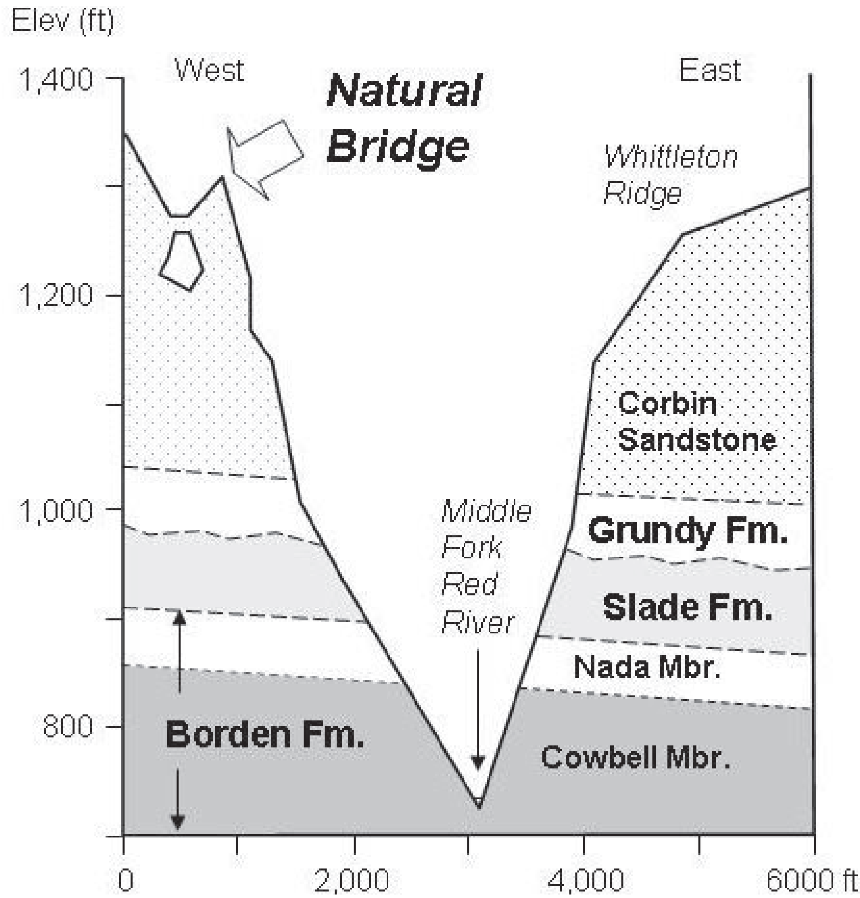

Figure 3. Cross section through the ridge that contains Natural Bridge (from Chesnut, 2002).

sippian strata. The base of the Grundy in this area is an unconformity on top of the Mississippian, which is not well exposed in the area, although it can be seen on the Mountain Parkway, which is described as an optional stop 2 miles east of the Slade interchange.

Paragon Formation. The Paragon is the uppermost Mississippian (upper Chesterian, Elviran) strata preserved in the field trip area. The Paragon was previously termed the Pennington Formation, but was renamed by Ettensohn and others (1984). The Paragon consists of variegated red, green, and gray shales, sandstones, siltstones, and thin limestones. West of the gorge, the Paragon is as much as

35 feet thick (Weir, 1974a, b), but in the gorge the unit is truncated by overlying Pennsylvanian strata (which is why it is not shown in Figure 2). We won't see the Paragon today.

Slade Formation. The Slade Formation was named by Ettensohn and others (1984) for units previously called the Newman Limestone and the Renfro Member of the Borden Formation. The type section was defined in the Natural Bridge Stone Quarry near Bowen, Ky., not far from Natural Bridge. Several of the members of the Slade Formation are exposed in the gorge area as carbonate cliffs or ledges. Some of the units that will be seen on this field trip (Fig. 2) include the Tygarts Creek, Warix Run, Ste. Genevieve, St. Louis, and Renfro Members. The Tygarts Creek Member is a white, medium- to thick-bedded, crystalline calcarenite. The basal parts of the Tygarts Creek tend to be oolitic. The Warix Run Member is a crossbedded, quartzose calcarenite (Ettensohn and others, 1984). Thick crossbeds characterize the Warix Run. The underlying Ste. Genevieve Member is a light gray, fine- to coarse-grained, bioclastic to oolitic calcarenite. The base of the Ste. Genevieve is sharp and irregular and is considered a regional unconformity (Weir, 1974a, b). The St. Louis Member is a light-colored, micritic, calcirudite to calcarenite with common to abundant chert and silicified corals. The Renfro Member is an orange-weathering, silty dolostone, limestone, and shale. The basal contact is sharp with underlying shales of the Nada Member of the Borden Formation. The Renfro was originally assigned to the Borden Formation (see, for example, Weir, 1974 a, b) but was reassigned to the Slade so that the Upper Mississippian carbonates would be in a separate unit from the underlying Mississippian clastics (Ettensohn and others, 1984). The Renfro is 10 to 50 feet thick (Weir, 1974a, b; Weir and Richards, 1974). The Slade (excluding the Renfro) is 15 to 100 feet thick (Weir, 1974a, b; Weir and Richards, 1974). Where thin, the unit is truncated by overlying Pennsylvanian strata. The Slade is dominated by carbonates, which form minor cliffs and slope breaks in the gorge region. Various members of the Slade Formation will be seen at stops 5, 6, and 7 and the optional stop at Hensons Arch and the Mississippian-Pennsylvanian unconformity (Fig. 2).

Nada Member, Borden Formation. The Renfro is underlain by the Nada Member. The Nada consists of 30 to 55 feet of shale (80 percent) and siltstone (20 percent). Shales are greenish-gray and are sometimes variegated red and green. Siltstones are calcitic and dolomitic. Bioturbation is common (Weir, 1974a, b; Weir and Richards, 1974). The type section is along the Mountain Parkway near Nada, just west of the Slade exit. This unit is poorly exposed in the gorge and tends to form vegetated slopes. The unit is exposed in outcrops along Mill Creek Lake, at stops 5 and 6 (Fig. 2).

Cowbell Member, Borden Formation. The Nada is underlain by the Cowbell Member. The Cowbell is 70 to 180 feet thick and consists of siltstone (70 percent) and shale (30 percent). The unit is generally differentiated from the overlying Nada by a transition to bedded siltstones (Weir, 1974a, b; Weir and Richards, 1974). Siltstones are green to brown-gray to purple-gray. This unit is poorly exposed in the gorge and tends to form vegetated slopes. In general, where this unit forms valley bottoms, the valleys are steeper than in units floored by the underlying Nancy Member. The unit is exposed in outcrops along Mill Creek Lake, at stops 5 and 6 (Fig. 2).

Nancy Member, Borden Formation. The Nancy is the lowermost unit exposed in the gorge. It consists of greenish-gray shales and minor siltstone. Siderite nodules are common, as is bioturbation, especially *Zoophycos*. Only the upper part of the unit is exposed in the gorge area, generally forming the lowest slope above road level (0 to 100 feet). The total thickness of the unit is more than 360 feet thick (Weir, 1974a, b). Where the Nancy forms the valley bottoms, valleys are generally wide.

Geology along the Mountain Parkway

The following summary of the roadside geology on the way to the Red River Gorge area is summarized from Dever (1971). At the entrance to the Mountain Parkway from Interstate 64, Ordovician strata of the Lexington Limestone and Clays Ferry Formation are exposed. Nine miles east, the Silurian Brassfield Formation is exposed. Just past the bridge over Upper Howard Creek (9.7 miles), the Duffin Member of the Ohio Shale (Devonian) is exposed. Near the Powell County line, the Devonian Ohio Shale (black to yellow-weathering, fissile shale) is well exposed in several outcrops. Eighteen miles from the entrance to the parkway, the Lower Mississippian Borden Formation is exposed. The Borden forms the base of the hillsides throughout the Red River Gorge area. The greenish-gray shale and shaly siltstone along the Mountain Parkway from

18.8 miles to the bridge across the Red River (24.7 miles) is the Nancy Shale Member of the Borden Formation. At mile 31.1, the road crosses Ky. 77. This is the road that goes through the Nada tunnel (Fig. 1), although the road must be accessed at the Slade interchange. Several roadcuts between the Red River and Slade interchange (Ky. 11) expose members of the Borden Formation and the lower part of the Slade Formation (previously Newman Limestone).

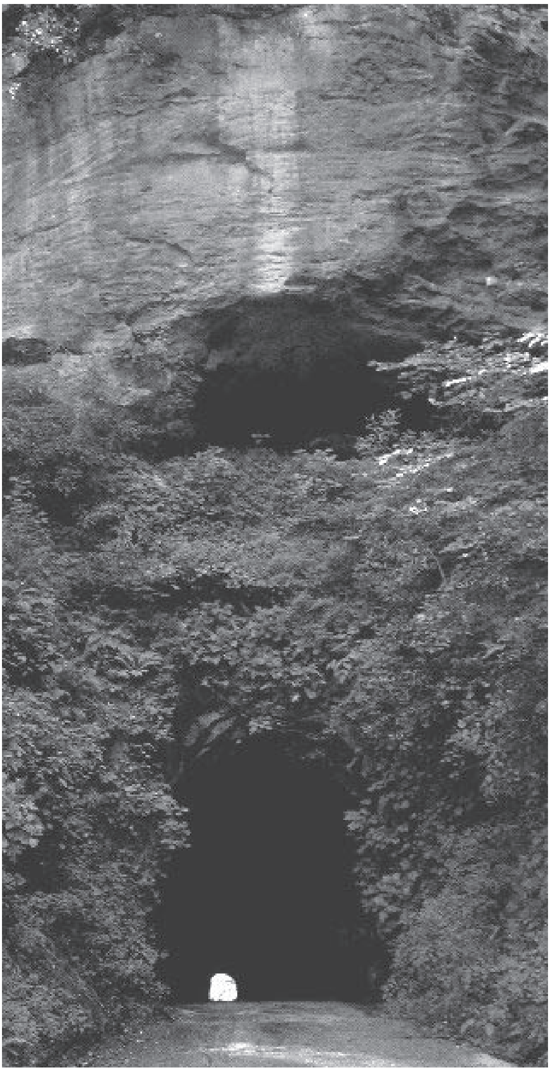

Figure 4. The Nada Tunnel and Corbin Sandstone as viewed from the north side entrance. Tunnel is 12 feet high.

Stop 1: Nada Tunnel

The Nada tunnel is a commonly used entrance to the Red River Gorge (Fig. 4). From the south, the tunnel is accessed by getting off the Mountain Parkway at the Slade (Natural Bridge) exit and then turning left (north) onto Ky. 11. Cross under the parkway and make another left (west) onto Ky. 11/15 toward Nada. Approximately 1.5 miles west of the interchange, take Ky. 77 north, back under the Mountain Parkway. The tunnel is located 2 miles north of the parkway, on Ky. 71.

The Nada tunnel was originally built as a railroad tunnel in 1911. The tunnel was cut through the ridge by the Dana Lumber Company in order to more quickly haul lumber from timber operations in the gorge to a mill 15 miles away at Clay City. More information about the tunnel is available at the Gladie Cultural and Environmental Learning Center, down the road from the tunnel (stop 2). The Forest Service indicates that the tunnel is 900 feet long, 12 feet high, and 12 feet wide. That means one-way travel (cars take turns on either side).

Sandstone cliffs (60 to 80 feet high) in the Corbin Sandstone Member are exposed on both sides of the tunnel (Fig. 4). This unit forms the ridgeline throughout the gorge. Several scales of cross-bedding are visible in the cliff faces. Paleocurrent measurements indicate unimodal orientations to the west and northwest. Liesegang banding (iron swirls and patterns in the rock) is also common. Bedding and banding within the sandstone will be discussed in more detail at stop 4.

On the north side of the tunnel, a rock shelter (overhang) is exposed along the road (Fig. 5). Shelters like this are common in the gorge and serve as an example of the type of feature that precedes the formation of a natural arch (discussed at stop 4). The shelters were also resting and camping sites for early Americans who passed through the gorge. According to the Park Service, archeological excavations of rock shelters in the gorge have uncovered

Figure 5. Crossbeds and liesegang banding in Corbin Sandstone exposed in rock overhang/shelter just north of the Nada Tunnel.

numerous artifacts, including seeds, which indicate that humans were cultivating wild plants in the gorge 3,000 years ago. The geology of the shelters played an important role in preservation of the artifacts. Nitrates are common in the soils beneath and within the cliff-forming sandstones. Many of the shelters also keep rainwater off of the soils, providing relatively dry conditions, which aid in the preservation of artifacts. Unfortunately, the rich archeological heritage is one of the reasons that many of the shelters have been vandalized and pillaged. To help protect the shelters, the Park Service designated the gorge as a National Archeological District.

Stop 2: Gladie Cultural-Environmental Learning Center

The U.S. Forest Service maintains a visitors' center to the gorge at Gladie on Ky. 715, 10 minutes from the Nada Tunnel. Take Ky. 77 north from the tunnel and just after the road crosses the Red River turn right onto Ky. 715 (Fig. 1). The center has some wonderful exhibits on the geology, geography, archeology, and social history of the gorge.

Stop 3: Chimney Top Rock

This stop is located on the back side of the ridge just south of the Gladie Cultural Center. To get to the ridge, however, you have to drive around the ridge on one of the gorge's scenic byways. From the Gladie Cultural Center travel east on Ky. 715 approximately 6.6 miles, past Sky Bridge and Whistling Arch (two of the gorge's popular arches). Turn right (west) onto Chimney Top Road (road 10). This is a gravel road, but is well maintained by the park service. The parking lot and trailhead to Chimney Top Rock is located 3.2 miles north and west of Ky. 715 (Fig. 1). It is a short walk from the parking lot onto Chimney Top Rock.

Chimney Top Rock is a sandstone cliff that rises 150 to 200 feet from the underlying slope, 500 feet above the Red River (and Gladie Center at stop 2). The rock was named because of its chimney shape when viewed from the next ridge. A fracture slightly separates the edge of the cliff (where the viewing platform is located) from the rest of the ridgeline (Fig. 6), forming a chimney-like feature. You can see the fracture as you walk over the small connecting bridge from the ridgeline to the viewing platform. Be careful; there are no guardrails.

The vista from Chimney Top Rock provides a good view of the topography of the gorge area. Numerous cliffs in the Corbin Sand-

Figure 6. A fracture separates Chimney Top Rock from the rest of the ridgeline.

stone Member of the Grundy Formation are visible at the tops of the ridges on either side of the Red River. These ridges are narrow and highly dissected. Narrow, resistant conglomerates capping the ridges are one of the reasons the gorge has so many natural arches. The rock formation in that part of the ridgeline south of the viewing platform is called Half Moon Rock. Half Moon Arch is located in the same ridge. Just north of the overlook, Princess Arch is formed in the same ridge.

Optional Stop: Mississippian-Pennsylvanian Unconformity

The Mississippian-Pennsylvanian unconformity is exposed on the Mountain Parkway 1.9 miles east of the Slade interchange, on the south side of the road (approximately 4 miles west of the Pine Ridge interchange). Figure 7 is a line drawing from a photograph

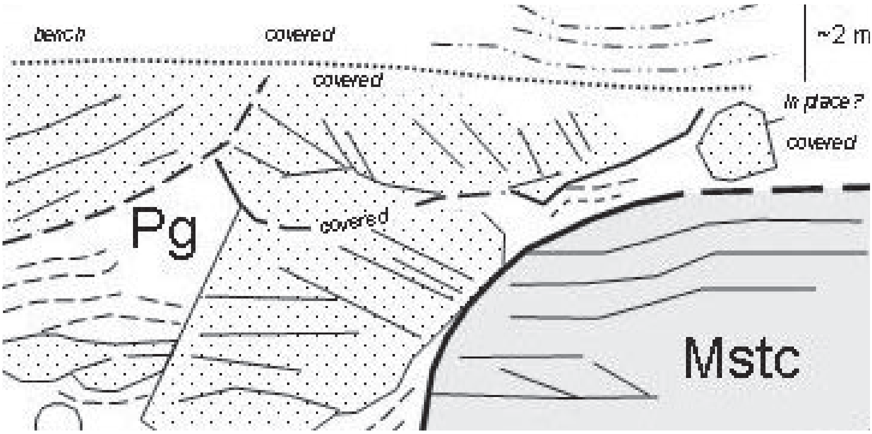

Figure 7. Line-drawing tracing of paleokarst and overlying paleoslumps along the Early Pennsylvanian (Mississippian-Pennsylvanian) unconformity from a photograph from Dever (1971, Fig. 14). Pg=Pennsylvanian Grundy Formation. Mstc=Mississippian Tygarts Creek Member, Slade Formation.

published by Dever (1971). The outcrop is more overgrown now than it was at the time of the photograph. At this location, Pennsylvanian sandstones of the Grundy Formation (previously Lee Formation) are juxtaposed against the Mississippian Tygarts Creek Member of the Slade Formation (previously Newman Limestone). Laterally, the Pennsylvanian strata rise in elevation above the Ramey Creek Member of the Slade Formation. Shales are squeezed between sandstone blocks in the Pennsylvanian strata. Several sandstone blocks appear rotated along curved contacts.

The abrupt contact between the Pennsylvanian and Mississippian strata at this location has been interpreted as localized fill and paleoslumps above paleosolution, possibly a paleosinkhole, in the underlying Slade carbonates (Dever, 1971; Dever and Baron, 1986). Solution features in the Slade Formation were presumably formed during the Early Pennsylvanian (Mississippian-Pennsylvanian) unconformity, similarly to the formation of karstic solution features in the Slade Formation that have formed in more recent times. Solution features were infilled by Early Pennsylvanian sedimentation. Subsidence above the uneven unconformity surface led to slumping in overlying strata. Paleoslumps are very common along the unconformity surface in eastern Kentucky (Greb and Weisenfluh, 1996).

Stop 4: Natural Bridge

Natural Bridge State Resort Park is not actually in the Red River Gorge proper, although it contains the same geology and scenic features, several of which will be visited on this trip (Fig. 8). To get to the park from stop 3, return on Chimney Top Road to Ky. 715. Take Ky. 715 south past the Mountain Parkway (1.9 miles) and turn left on Ky. 715/15. In less than a mile continue south on Ky. 715 for approximately 5 miles to Ky. 11. Turn right on Ky. 11 and travel north approximately 5 miles to the state park entrance.

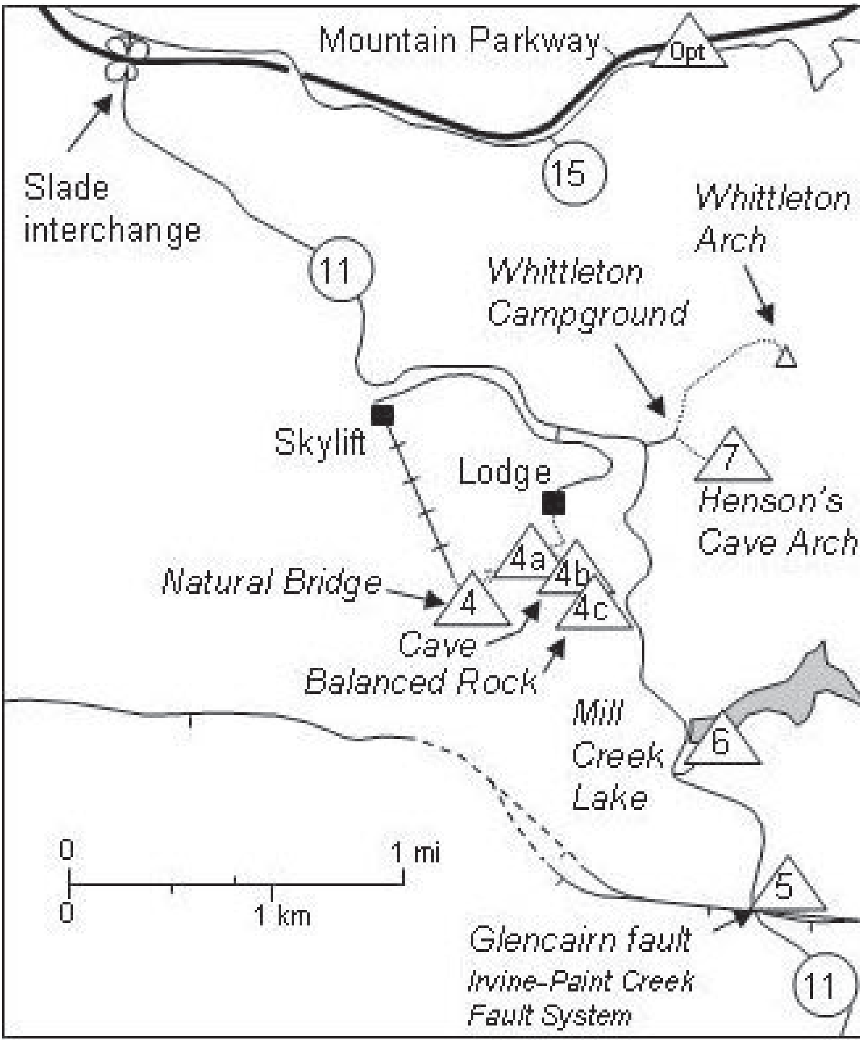

Figure 8. Map of field stops 4 through 7 in the vicinity of Natural Bridge State Resort Park.

Once within the park, there are several ways to get to Natural Bridge, the most visited natural arch in the area. A skylift offers the easiest route (for a small fee). The lift affords scenic views of the cliffs and easy access to the ridgeline and Natural Bridge. For those who want to hike, drive to the lodge and park. From the lodge take the Original Trail 0.75 mile up the ridge to Natural Bridge. The trail is well maintained and is the most-traveled route to the bridge. The Original Trail starts out with a steep set of stairs where the trail rises through the Slade Formation, becomes less steep in the top of the Slade and Lower Breathitt (all covered along the trail), and then steepens again in the Corbin Sandstone cliffs beneath Natural Bridge. The Balanced Rock Trail also leads to Natural Bridge, but along a much steeper route. A set of steep stairs along the cliff line was built for this trail. From the lodge, it is easier to climb up to Natural Bridge on the Original Trail and climb down on the Balanced Rock Trail.

Arch Formation. Natural Bridge is a natural arch (Fig. 9). There are some natural arch specialists who would only call this type of feature a “bridge” if it crossed water. By that definition, Natural Bridge would not be a natural bridge. You could also argue that thousands of people walk across this arch every year, which seems reason enough to call it a bridge! There are no guard rails along the arch, so *be careful* along the edge: it’s 50 to 65 feet to the base of the arch.

Figure 9. Natural Bridge from the southwest side of the arch.

There are several types of arches in the Red River Gorge area. Natural Bridge is a type of arch called a “lighthouse” arch. Lighthouse arches form by the convergence of two valleys on opposite sides of a narrow ridge. If you look down the valley on either side of the bridge, you can see that small streams cut valleys on either side of Natural Bridge. Figure 10 is a diagram showing the sequential development of a lighthouse arch. The ridge in which this type of arch occurs is fractured (Fig. 10-1). Fractures are oriented parallel to the length of the ridge where the arch occurs. Through time, water in the valleys on either side of the ridge erodes deeper into the ridge, but also upward into the ridge (Fig. 10-2). Most of the time, creeks on either side of a ridge do not meet at the same place at the top of the ridge. In those cases, arches don't form, although overhangs or rock shelters might. When the ridge is eroded in approximately the same spot on either side of the ridge, an arch can form.

Fractures and Arch Formation. Formation of the arch is also related to fractures in the ridge. The length of the arch parallels a fracture set with an average strike of 303° (Dever and Baron, 1986). If you look at both sides of Natural Bridge, you can see that the cliff line on the sides of the bridge is very straight. That's because the bridge occurs between parallel fractures at the top of the ridge. As water on either side of the ridge eroded the slopes away, slabs of rock broke

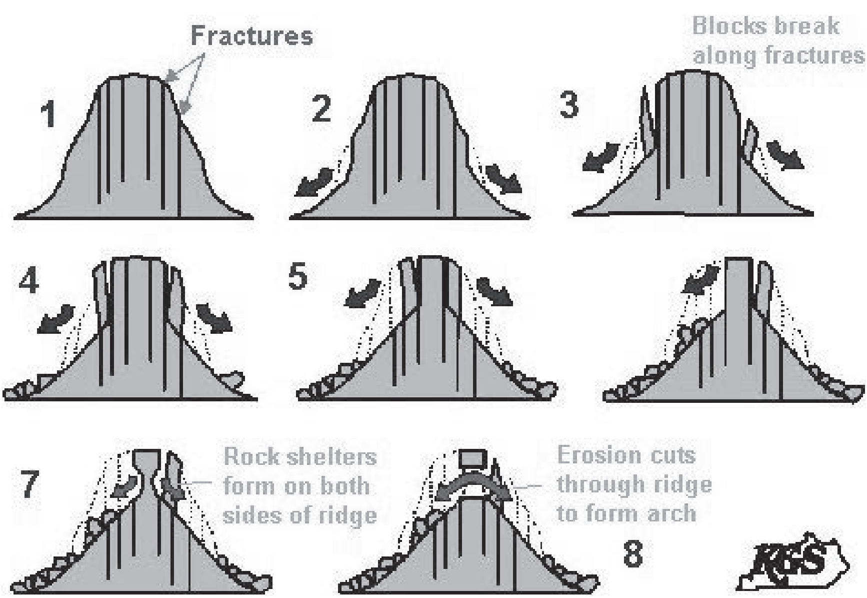

Figure 10. Diagram showing the development of a ridgetop, lighthouse-type arch.

away along parallel fractures (Fig. 10-3). Freeze-thaw weathering and root-wedging on the forested slopes helped to widen fractures and detach blocks of rock from the cliffside. It may help to imagine opening a book, binder side down, and letting the pages fall away from the middle of the book. Slabs of rock fell downslope, until only the center of the ridge was left (Figs. 10-4 – 10-6).

Ultimately, the streams on either side of the present arch eroded back to the level of the narrow ridgeline (Fig. 10-6). In some cases, lighthouse arches form rock shelters on either side of the ridge (Fig. 10-7). Subsequently, erosion (headward from the streams and vertical rockfalls and undermining in the rock shelter) connects the back of the shelters through the ridge to form an arch. In the case of Natural Bridge, it appears as if a large rock shelter formed on the northeast side (Original Trail side, lodge side) of the ridge, which broke through the ridge in an area where the back side of the ridge had broken along a fracture. If you stand beneath Natural Bridge, you can see that the underside of the bridge is more rounded to the northeast (toward the lodge).

The narrow trail and stairs in the rock up the back side of the arch is a natural fracture in which steps have been carved to get to the top of Natural Bridge (Fig. 11). The flat, back side of the arch is separated from the part of the cliff that has moved outward, away from the ridge. Through time, fractures like these widen, through freeze-thaw mechanisms and plant rooting, until large blocks of the sandstone fall away from the ridge.

Bedding and Arch Formation. Vertical erosion to the present shape of the arch closely follows bedding. The bridge span is composed of several thick, tabular crossbeds (Figs. 9, 12). When walking up the stairs on the back side of the arch, trace the bedding from the bottom of Natural Bridge sideways along the cliff face. There is a gap in the bedding plane adjacent to the bridge, and several erosional pockets along bedding. This bedding plane separates underlying beds from a thick crossbed above. It seems as if during rock-shelter formation, beds broke upward along bedding planes to the level of this bedding plane. The present bridge owes its shape to the overlying, thick tabular crossbeds. These crossbeds are oriented subparallel to the orientation of the bridge (Fig. 12), ultimately helping to maintain the span.

Figure 11. Staircase along the fracture-bound side of Natural Bridge.

Corbin Sandstone Deposition. The Corbin is the youngest and westernmost of a series of Lower Pennsylvanian quartzarenite belts (Fig. 13). At least four of these belts onlap the basin margin, each shifting progressively westward (Chesnut, 1992; Greb and Chesnut, 1996; Greb and others, 2004). Paleocurrent measurements in these belts are generally to the southwest, and the source of the quartz pebbles is attributed to extra-basinal sources northeast of the basin (Siever and Potter, 1956; Bement, 1976; Greb and Chesnut, 1996).

The Lower Pennsylvanian quartzarenites of the basin have been interpreted in many ways. Lower Pennsylvanian quartzaren-

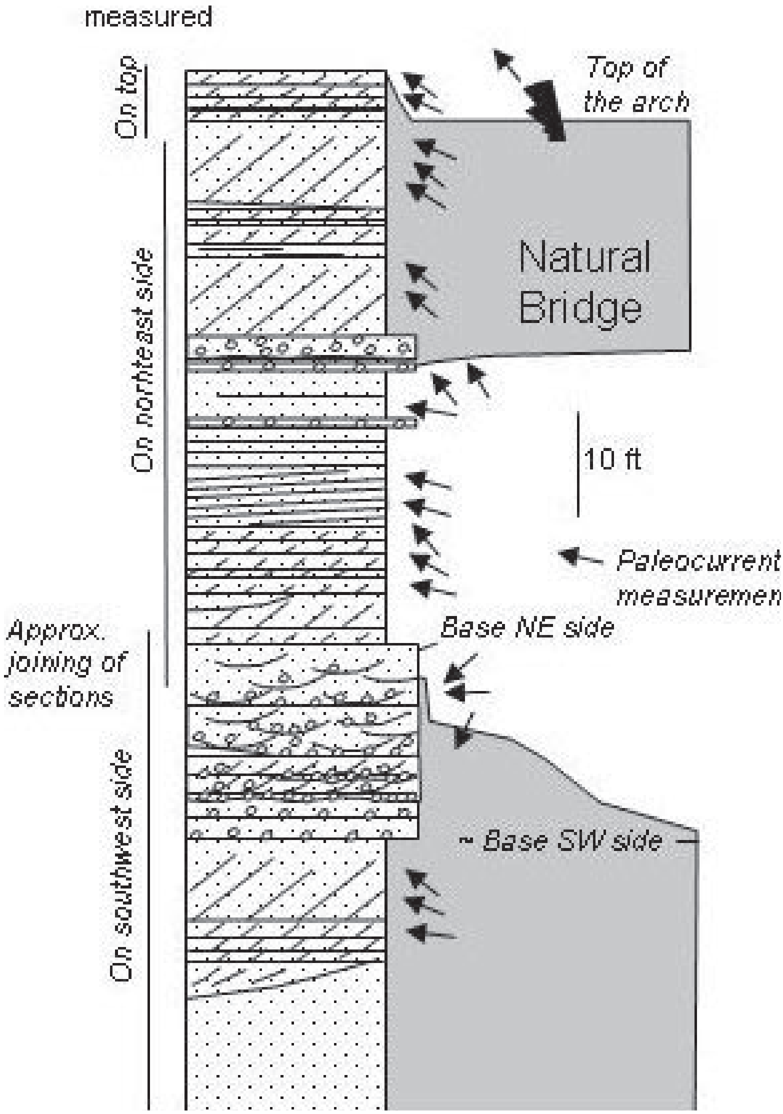

Figure 12. Measured section of the Corbin Sandstone Member of the Grundy Formation at Natural Bridge. The gray silhouette shows the shape of the arch relative to the bedding in the sandstone.

ites were previously interpreted as beach barriers (see, for example, Ferm and others, 1971), tidal strait deposits (see, for example, Cecil and Englund, 1989), and fluvial facies (see, for example, Potter and Siever, 1956). Recent investigations have favored fluvial deposition, with most investigators interpreting the thick quartzarenites

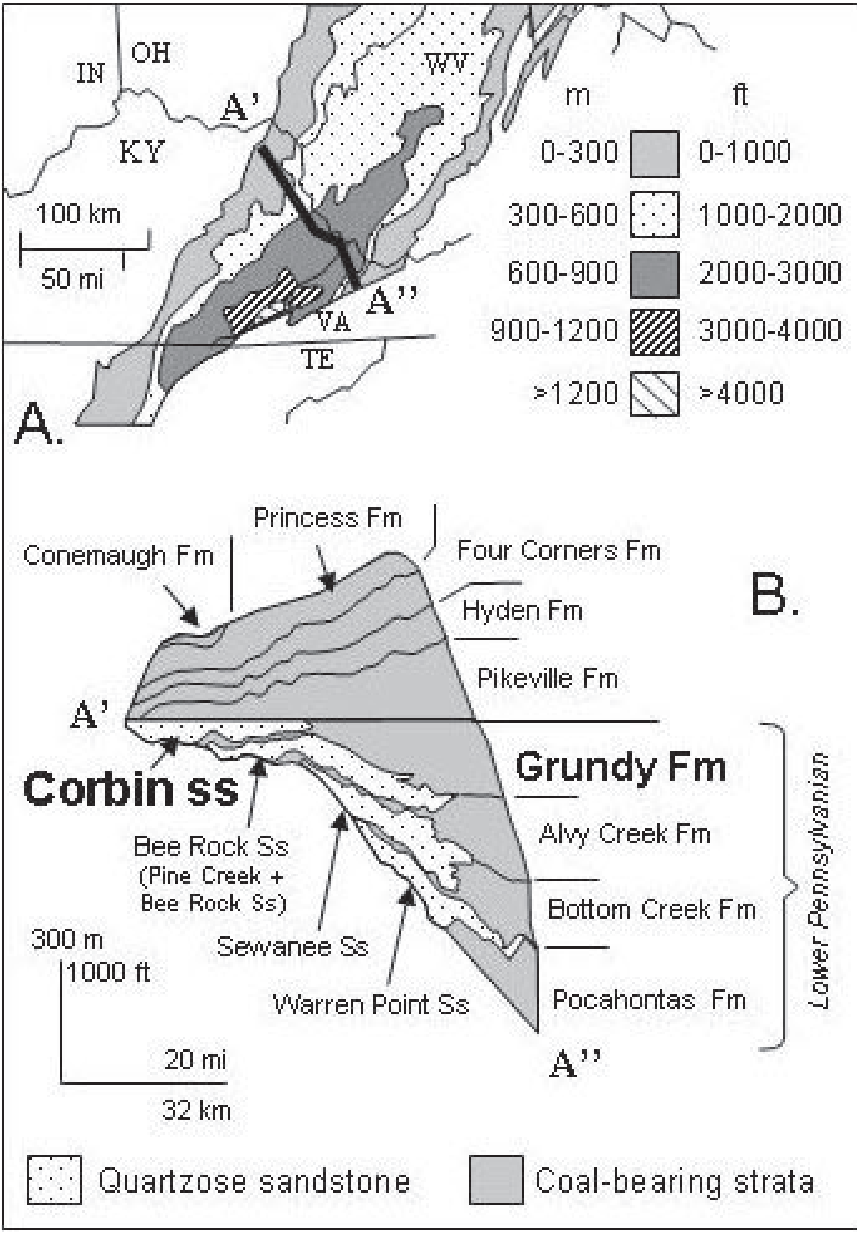

Figure 13. (A) Cross section of Pennsylvanian strata in eastern Kentucky showing (B) the position of thick quartzarenites and thinning of Lower Pennsylvanian strata eastward out of the basin. Natural Bridge is formed in the Corbin Sandstone (after Chesnut, 1992; Greb and others, 2004).

as braidplain deposits (Bement, 1976; Rice, 1984, 1985; Chesnut, 1992; Rice and Schwietering, 1988; Wizevich, 1992; Barnhill, 1994). Regional mapping of these quartzarenites indicates that they may have been part of giant paleodrainage systems cut during successive sea-level lowstands (Archer and Greb, 1995). Greb and Chesnut (1996) showed that although many of the quartzarenite belts are dominated by fluvial facies, tidal facies occur locally toward the top of each unit, which suggests that during transgressions, some of the braidplain channels were converted to estuaries. A wide variety of estuarine facies have been documented at the tops of the quartzarenites (Greb and Martino, 2005), but these have not been observed at Natural Bridge.

The Corbin tends to exhibit south to southwest paleocurrents in southeastern Kentucky, but west to northwest paleocurrents in northern Kentucky, as at Natural Bridge (Fig. 12). Figure 14 is an isopach map of the Corbin Sandstone. West and northwest paleocurrents in the Red River Gorge area can be seen to parallel a westward orientation of the Corbin Sandstone belt north of the Irvine–Paint Creek Fault System. Along the western outcrop margin, the Corbin shifts to a southward orientation south of the fault system (Fig. 14). The Corbin is thickest north of the fault system and is thinner south of the fault system (Fig. 14). Likewise, the Corbin truncates progressively younger strata to the north and west, incising down to the Borden Formation in parts of northeastern Kentucky (Chesnut, 1992; Greb and others, 2004). These attributes have been used to indicate fault control of the Corbin paleovalleys (Barnhill, 1994; Greb and Chesnut, 1996). The thickness of the Corbin north of the faults is one of the reasons it is a prominent ridge-former in the gorge region.

The exposures at Natural Bridge provide a look at a typical section of the Corbin in this area. Wizevich (1992, 1993) examined bedding within the Lower Pennsylvanian quartzarenites of eastern Kentucky and concluded that each consisted of a hierarchy of nested bedding elements. These increased in scale from small dunes and scours to larger bars (macroforms), which in turn were part of broader channels (generally fining upward), which were nested into larger braidplains (paleovalleys). At Natural Bridge, you can trace individual beds around both sides of the ridge to get a better perspective of the changes in bedding in three dimensions and the hierarchy of bedforms that make up the Corbin at this location (Figs. 9, 12). From the top of Natural Bridge, if you look across to

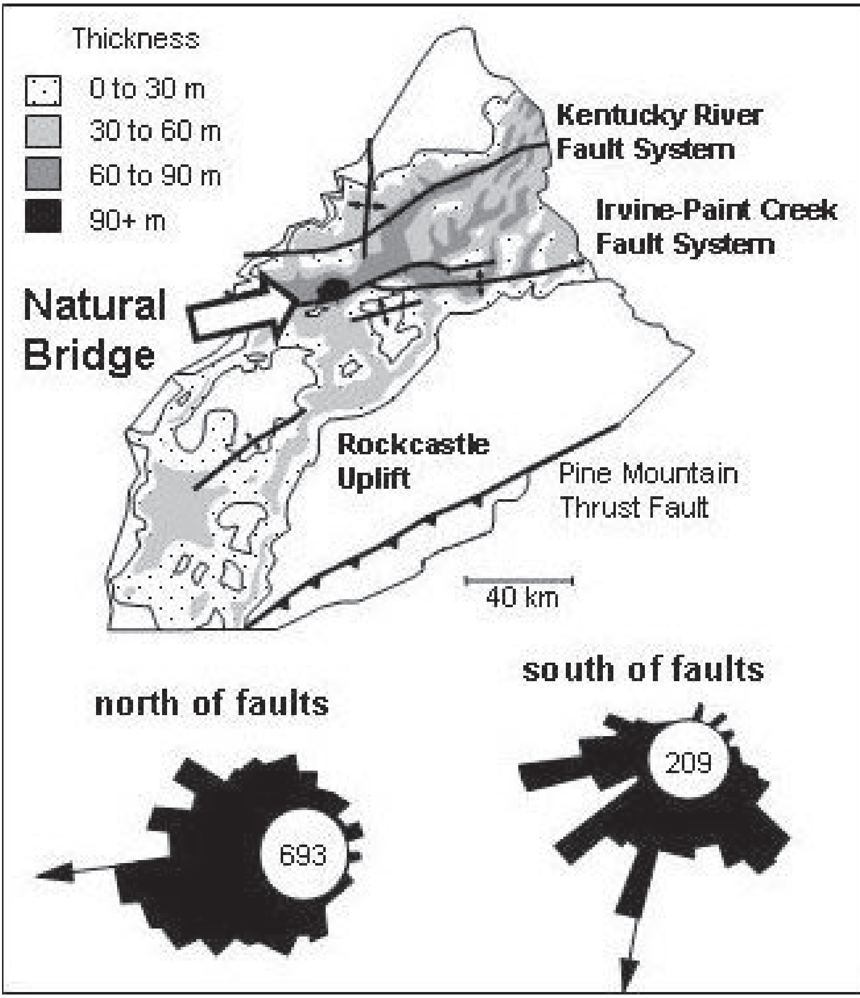

Figure 14. Regional isopach map of the Corbin Sandstone (after Chesnut, 1992; Barnhill, 1994) showing location of Natural Bridge. Rose diagrams from Rice (1984).

Lookout Point you can see some of the broad channel forms that comprise the sandstone (Fig. 15). The bases of the channel forms tend to be sharp, but broadly concave. They tend to be conglomeratic and may be associated with fossil wood debris (Fig. 16).

Some crossbeds (like those that comprise the span of the arch) are mostly tabular, and represent relatively two-dimensional, straight-crested bedforms. Some of the thinner crossbeds on the sides of the arch (midway up the stairs) have a low angle of dip and represent

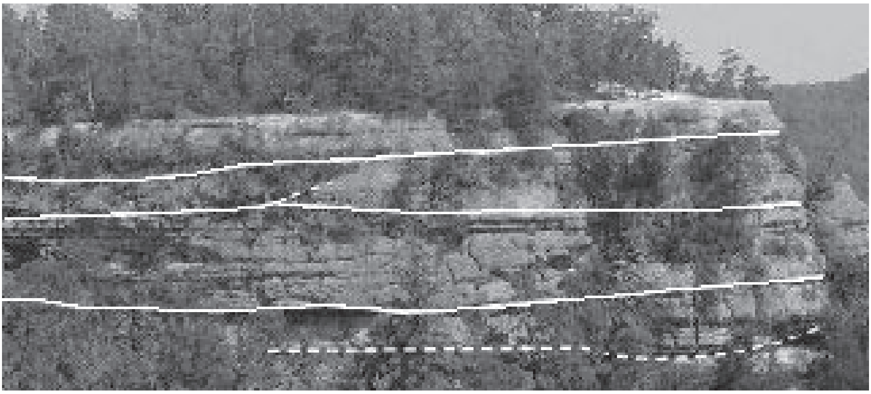

Figure 15. View of Lookout Point from Natural Bridge showing possible channel scours in the cliff-forming sandstones (white lines).

compound crossbeds. Compound crossbeds are formed from the migration of small bedforms down the lee side of larger bedforms at different flow levels within the paleochannel. Those with asymptotic foresets or tangential to trough crossbeds represent sinuous, three-dimensional bedforms. In general, trough crossbedding is more common when looking down the axis of primary current direction, which is under the arch at Natural Bridge.

Liesegang Banding and Iron-Staining. On the north side of Natural Bridge, just past the arch opening, along the ridge toward Battleship Rock, there is a beautiful exposure of iron-staining in the cliff wall. These types of curving, ornate, deposits of iron are called liesegang bands (Fig. 17). Liesegang bands are formed when iron and manganese in groundwater precipitate on a cliff surface. At first glance the patterns may appear random, but if you look closely there are many circular to oval shapes. In fact, if you observe at an angle, you can see that several

Figure 16. Fossil wood debris and quartz pebbles in fall block below Natural Bridge.

Figure 17. Liesegang banding along fracture at Natural Bridge.

of the bands have three-dimensional pipe shapes, which stick out slightly from the cliff face because the precipitated iron cements the cliff face and makes it more resistant to erosion. These pipe-like weathering features show how the groundwater was moving in the ridge. At this location, a fracture runs through the liesegang bands and may have aided water movement. Another example of liesegang banding along fractures can be seen near Balanced Rock (and many other places in the Red River Gorge area).

Stop 4a: Cave and Solution Features on Original Trail

Just past the point in the trail where Balanced Rock Trail connects to the Original Trail (Fig. 8), or just up from the stairs on the trail from Hemlock Lodge to the Original Trail, there is natural cave opening (to the left of the Original Trail). The opening is a short shaft, which descends into a cave (Fig. 18). It is very steep and slippery, and easy to fall into: *use caution when approaching*. The shaft occurs in the Tygarts Creek Member of the Slade Formation, just beneath sandstone cliffs of the Corbin Sandstone Formation. After a rain, water that hits the top and slopes of the ridge enters the thin soil that covers the ridge. When the water passes through the soil on the ridge slopes it becomes slightly acidic. The water travels within the sandstone and soil until it reaches the less-permeable limestones and shales of the Slade Formation. The water starts to build up along the contact until it finds a fracture or weakness in the limestone. Be-

Figure 18. Vertical solution features in the Tygarts Creek on the Original Trail.

cause the groundwater is slightly acidic, it can dissolve the limestone, forming shafts and caves. This particular shaft may have been part of a pit and dome. Pits and domes are common cave features in Kentucky. In this case, the dome has been eroded, leaving only the pit, which descends into the cave below.

Stop 4b: Rock Shelter and Cave Entrance, Balanced Rock Trail

Along the trail to Balanced Rock, just south of where the Balanced Rock Trail and Original Trail meet, there is a rock shelter, and at the back of the shelter is a cave opening (Fig. 8). This is one of the few limestone rock shelters in the area, most in sandstone (Fig. 19). The crossbedded limestone in the roof of the rock shelter is the Warix Run Member of the Slade Formation (Fig. 2). The cave occurs beneath the Warix Run, in the Ste. Genevieve Member (thin here) near the contact of the Ste. Genevieve Limestone and the underlying, finer-grained, cherty limestones of the St. Louis Member.

The rock shelter is formed in a 6- to 8-foot-thick crossbed in the Warix Run Member (Fig. 19). As with Natural Bridge, a thick, crossbedded unit may have aided in the formation of an overhang at this location. The crossbed is oriented to the northeast (26 to 43^{o}). The crossbeds in these limestones are slightly different than the crossbeds in the sandstones at the top of the ridge. Whereas the crossbeds in the sandstones were deposited as bars in large rivers,

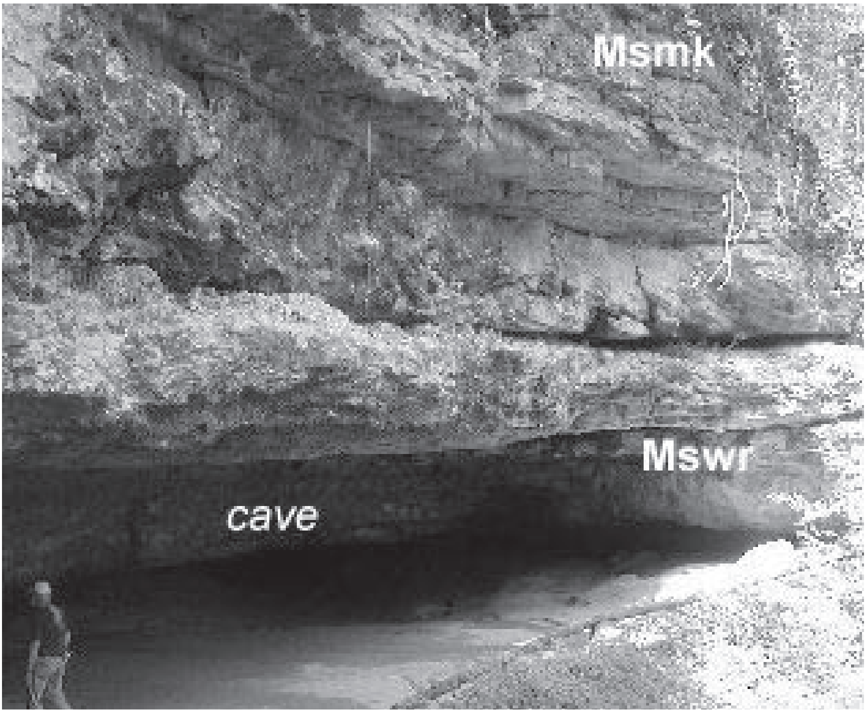

Figure 19. Rock shelter and cave opening in the Warix Run Member (Mswr). Mill Knob Member=Msmk.

these limestone crossbeds were deposited as bars or sand waves in tidal channels (oriented to the northeast) within the ancient Mississippian seas (Klekamp, 1971) or possibly tidal-bar-belt deposits (Horne and others, 1974).

Just above the lip of the rock shelter, there is a gap between two limestone beds. The underlying bed is pock-marked or mottled, and may be a caliche. If a caliche, it represents a paleosol. Several chert layers occur in this layer that may be related to paleosol development. The Warix Run commonly has a paleosol near the top of the unit, which may be the weathered claystone and caliche above the overhang. Paleosols in the Warix Run suggest at least short-term exposure of the Warix Run carbonate tidal channels and bars (Ettensohn and others, 1984).

Overlying thin- to medium-bedded, laminated to crossbedded limestones are part of the Mill Knob Member of the Slade Formation (Fig. 19). The Mill Knob may contain sparse to abundant fossils, including pelmatozoan plates, brachiopods, blastoids, crinoids, and gastropods (Ettensohn and others, 1984). This part of the Slade Formation was deposited in subtidal to supratidal environments (Dever, 1980; Ettensohn and others, 1984).

Cave Entrance. The cave can be entered from the back of the rock shelter; however, there are no lights in the cave, and sunlight only travels a short distance into the cave from the mouth. Beyond that point it is completely dark. *Do not travel into the cave alone or without a flashlight. Caves can be dangerous.* The floor of the cave is wet, slippery, and uneven. There are a few small holes in the cave floor. Also, the ceiling is low in several parts of the cave so that it is easy to hit your head. Be careful if you choose to walk through the cave. The cave passage connects to the shaft entrance (stop 4a) along the Original Trail to Natural Bridge, and many people enjoy climbing through the cave to the other trail. The passage can be clogged with silt and mud, however. You should check with the park naturalist before your hike if you have any questions or want to be instructed on cave safety. This is not a formation cave. There are no stalactites or stalagmites, and little to see except dark limestone walls.

Stop 4c: Balanced Rock

Balanced Rock is located just a short distance up the trail from the cave on the Balanced Rock Trail (Fig. 8). The feature called Balanced Rock (Fig. 20) occurs in a block of the cliff that separated from the saw-toothed cliff wall in the ridge, up slope. The block is formed in crossbedded, conglomeratic sandstone. One of the layers in the upper third of the block is more easily weathered than the rest of the layers. The layer has crumbled away faster than the surrounding rock, so that it looks like the upper rock is balancing on the lower rock (Fig. 21).

Fractures. If you look at the cliffs at the base of the trail, just prior to Balanced Rock, you can see that the cliffs are steep, flat surfaces that are oriented in a sawtooth or zig-zag pattern (Fig. 22). One set of fractures strikes at 164 to 170°, the other at 97 to 105.°

If you look at the large fall blocks of rock between the trail and the cliff, you can see that many have very straight sides and some corners are at near-right angles. The influence of fractures on the scenery of the park can also be seen in the excellent examples of liesegang banding near the stairs up the side of the cliff (Fig. 23). As

Figure 20. Balanced Rock, Natural Bridge State Resort Park.

at Natural Bridge up the slope, these liesegang bands are formed near fractures, which shows the influence of fractures on groundwater flow within the ridge.

Figure 21. Diagram showing the possible formation of Balanced Rock.

Stop 5—Glen Cairn Fault (Irvine–Paint Creek Fault System)

Natural Bridge is located just north of the Glencairn Fault of the Irvine–Paint Creek Fault System (Fig. 8). The Irvine–Paint Creek Fault System is an east–west-oriented, down-to-the-south series of normal faults. The fault system is believed to be related to the basement Rome Trough, and has been shown to have influenced Carboniferous sedimentation (Dever, 1977, 1980, 1986, 1999), including the position of the Corbin paleovalleys (Fig. 14) (Barnhill, 1994; Greb and Chesnut, 1996; Greb and others, 2004).

Figure 22. Saw-toothed cliff faces near Balanced Rock.

At stop 5, the lower part of the Slade Formation and upper part of the Borden Formation are offset along a normal fault (Fig. 24).

Figure 23 Liesegang banding in cliff face near Balanced Rock. Note fore-set bedding in the sandstone.

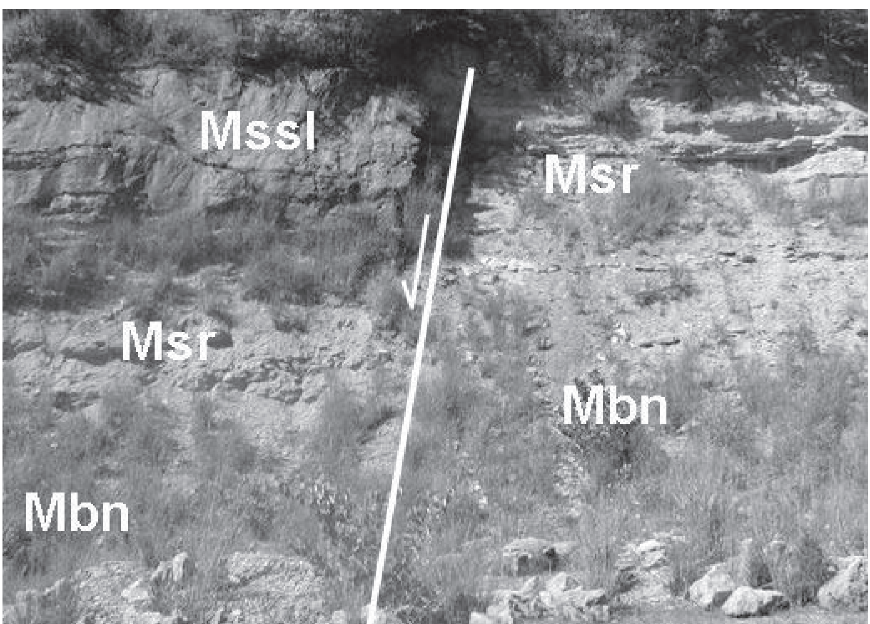

Figure24. Glencairn Fault exposed in old quarry on Ky. 11. Mssl=Mississippian St. Louis Member, Slade Formation; Msr=Mississippian Renfro Member, Slade Formation; Mbn=Mississippian Nada Member, Borden Formation.

Offsets of as much as 100 feet are recorded in the Slade quadrangle (Weir, 1974a), although the offset here is probably less than 20 feet. The youngest strata preserved on the south side of the fault is the St. Louis Member of the Slade Formation. Float from this gray, fine-grained cherty limestone is common on the quarry floor, and St. Louis float blocks contain silicified corals (Fig. 25) and brachiopods (Fig. 26). The St. Louis is generally interpreted as a subtidal marine deposit (Rice and others, 1979; Ettensohn and others, 1984).

The St. Louis sharply overlies the Renfro Member (Figs. 2, 24). The Renfro consists of buff to orange-weathering limestone, dolostone, and green-gray shale. Several dolostone beds on the upper side of the fault appear to be in the same juxtaposition as beds in the Renfro on the south side of the fault, suggesting a 15- to 20-foot offset at this location. The Renfro has been interpreted as shallow-marine to supratidal (high intertidal) deposits deposited on a carbonate platform above the reworked Borden delta (Rice and others, 1979; Chaplin, 1980; Ettensohn and others, 1984).

Figure 25. Silicified corals from the St. Louis Member.

Figure 26. Silicified brachiopods from the St. Louis Member.

Renfro float on the quarry floor contains mudcracks (Fig. 27) and bioturbation, including paired holes of *Arenicolites* (Fig. 28). *Arenicolites* (and the similar-appearing *Diplocraterion)* are U-shaped invertebrate dwelling traces. The top of the U shape forms the paired holes seen on bedding surfaces. *Arenicolites* is a common member of the *Skolithos* ichnofacies, a shallow marine- to brackish-water trace-fossil assemblage (Frey and Seilacher, 1980; Frey and Pemberton, 1984). Mudcracks indicate

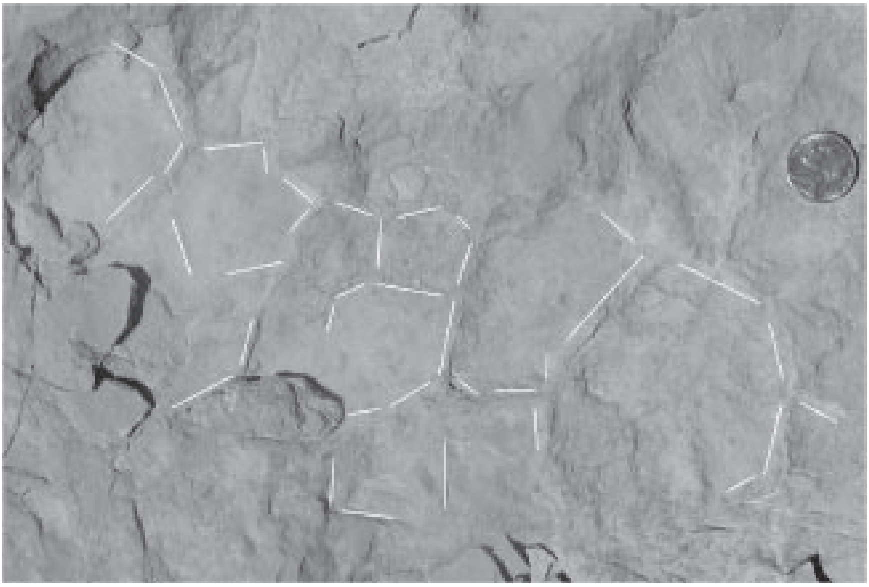

Figure 27. Mudcracks (white lines shown to highlight) from the Renfro Member.

Figure 28. Paired holes (end of white lines) of *Arenicolites* from the Renfro Member.

occasional subaerial exposure of the shallow-water carbonates, and some part of the dolomitization in the Renfro may be pedogenic (Lierman, 1996).

The Renfro is underlain by the Nada Member of the Borden Formation (Figs. 2, 24). The Nada is dominated by greenish-gray shales. Glauconite is common in the shales (Chaplin, 1980). Float consists of fossiliferous and bioturbated shales and siltstones. Fossil hash of crinoidal and fenestrate bryozoans are common (Fig. 29). Chaplin (1980) noted brachiopods, bryozoans, pelamatozoans (especially crinoids), rugose corals, gastropods, pelecypods, and goniatites. A wide range of trace fossils are also known from the Nada (Chaplin, 1980), including *Chondrites* (Fig. 30). *Chondrites* are invertebrate feeding structures, which form downward-branching, conical networks that look like featherdusters oriented handle-side up (Frey and Pemberton, 1984). The Nada is interpreted as a delta-platform deposit that represents the destructive phase of the Borden delta, prior to shallowing and carbonate deposition (Chaplin, 1980).

Figure 29. Fossil hash of crinoidal and bryozoan debris from float in the Nada Member.

Stop 6: Mill Creek Spillway

Mill Creek Lake is a small impounded lake south of the park entrance road on Ky. 11 (Fig. 8). Two large outcrops on either side of the parking lot provide excellent exposures of the lower Slade Formation and upper Borden Formation (Fig. 31). The units seen at stop 5 are visible at the top of exposures (third benches). The St.

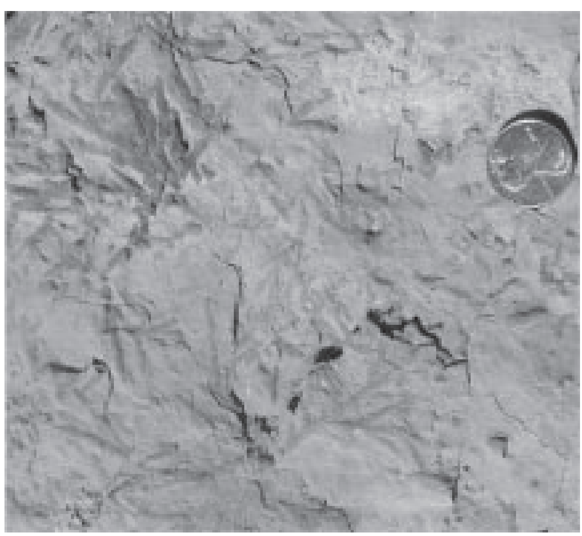

Figure 30. *Chondrites* trace fossils from float in the Nada Member.

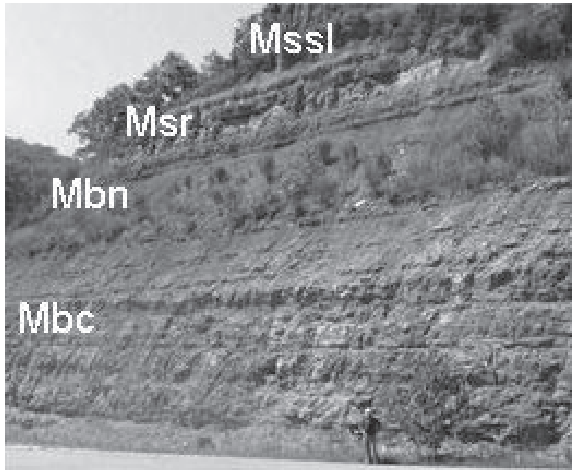

Figure 31. Exposures of the Borden and Slade Formations at Mill Creek Lake, stop 6. Mssl=Mississippian St. Louis Member, Slade Formation, Msr=Mississippian Renfro Member, Slade Formation, Mbn=Mississippian Nada Member, Borden Formation, Mbc=Mississippian Cowbell Member, Borden Formation.

Louis Member of the Slade Formation caps the exposures on both sides of the parking lot. As at stop 5, the St. Louis sharply overlies the orange-weathering dolostones, limestones, and shales of the Renfro Member. The Renfro overlies the dark gray to greenish-gray shales of the Nada Member of the Borden Formation in the second bench of both exposures (Fig. 31) and is exposed midway in the second bench of both exposures. Most of the lower bench and bedding plane exposures in the drainage from the lake are in the Cowbell Member of the Borden Formation.

Cowbell Member. The Cowbell Member is the purple-gray, bedded siltstone exposed at road level on either side of the parking lot (Fig. 31). The upper contact would be drawn at the uppermost persistent siltstone bed, but the intervening shales between siltstone beds show that the contact is relatively gradational. Individual siltstone beds are generally less than 3 feet thick. Most weather massively, although parallel lamination, wavy lamination, and climbing ripples can be seen. In some beds, small scour and fill features are noted, especially toward the base of beds (Fig. 32). Basal contacts of individual beds are sharp. In bedding planes in the spillway, the bases of some siltstone beds can be seen to contain iron-stained or sideritized clasts (either primary siderite or shale), as well as crinoidal fossil debris (Fig. 33). Body fossils of brachiopods, fenestrate bryozoans, rugose corals, pelmatozoans, goniatites, nautiloids, gastropods, and trilobites, have been found in this member at other locations (Chaplin, 1980; Lierman and Mason, 1992). The upper surfaces of

Figure 32. Siltstones of the Cowbell Member at Mill Creek Lake.

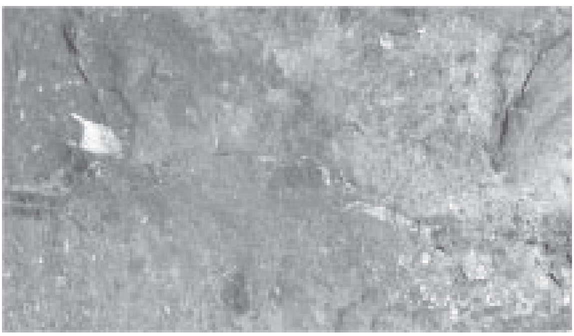

Figure 33. Fossil crinoidal debris and sideritic clasts in the Cowbell Member at the spillway. The crinoid stem in the bottom right is approximately 1.5 cm in length.

some of the siltstone beds exposed in the drainage exhibit ripples. All ripples are low amplitude, with symmetrical to near-symmetrical crests (Fig. 34), indicating wave origins.

Siltstones and interbedded shales in the Cowbell are pervasively bioturbated. Chaplin (1980) noted that vertical burrows tended to be common in coarser-grained facies, whereas horizontal burrows were common in finer-grained facies of the Cowbell. The dominant trace fossil at stop 6 is *Zoophycos* (Fig. 35). In the bedding plane exposures you can see that the *Zoophycos* galleries spiral through several silt layers around a central, curved chamber. *Lophoctenium* (Fig. 36) is similar to *Zoophycos* in appearance, but the internal curved ridges of the grazing traces exhibit oblique, chevron, or complex patterns. *Zoophycos* can occur in many different marine environments and at many different depths, although the *Zoophycos* ichnofacies (assemblage) is characteristic of delta slope environments (Frey and Seilacher, 1980; Frey and Pemberton, 1984). The position of the Cowbell between deeper-water deposits of the underlying Nancy Member and the overlying shallowing-upward succession (Nada and Renfro Members), physical sedimentology, and *Zoophycos* ichnofacies have been used to interpret the Cowbell as a delta-front deposit (Kearby, 1971; Chaplin, 1980; Lierman and Mason, 1992). Although stratigraphically older siltstone beds lower in the Borden (e.g., Farmwood and Kenwood

Figure 34. Low-relief, symmetrical ripples and large, horizontal trace fossil in the Cowbell Member exposed at the spillway.

Members) are interpreted as turbidites (Kepferle, 1977; Rice and others, 1979; Chaplin, 1980), the siltstone beds at stop 6 are interpreted as representing storm beds on the delta front.

Optional Stop: Whittleton Campground

Hensons Arch and Sinking Stream. The trails to Hensons Arch and Whittleton Arch begin at the Whittleton Campground, which is the first left south of the park entrance road on Ky. 11 (Fig. 8). From the campground there is a short (0.3 mile) trail, which rises approximately 100 feet to Hensons Arch (10- to 15-minute walk). This trail is not maintained as the main trails at Natural Bridge are, so watch your step.

Hensons Arch is not a typical arch, and the term "arch" may be a misnomer. Unlike the famous sandstone arches that garner much of the attention in the Red River Gorge area, this small arch is formed in limestone and is a karst feature. The arch is actually a short span above a cave, between two vertical shafts (Fig. 37). At least one of these solution features could be considered a swallow hole, because it captures water from the upstream drainage. The cave is very small, but the park service has provided a ladder so that hikers can climb down

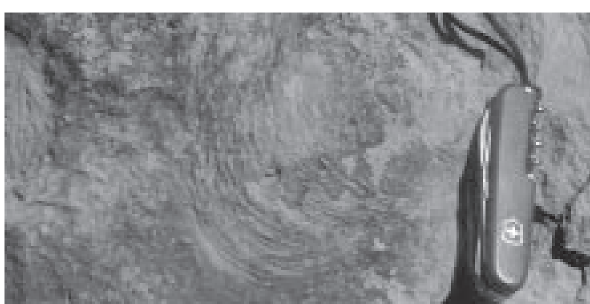

Figure 35. *Zoophycos* trace fossils are common in the Cowbell Member at the spillway.

Figure 36. *Lophoctenium* trace fossils in the Cowbell Member at the spillway. Similar to *Zoophycos* (Fig. 35).

into one of the shafts, pass beneath the arch and look up into the other swallow hole (Fig. 38). The climb down the ladder provides a cool place to rest if you make this hike on a warm day.

The small creek above the arch drains into the swallow hole and then passes through small bedding-plane conduits and fractures beneath the surface, forming a sinking stream. You can see part of the connection to the underground karst network as a hole on the south side of the trail near the top of the ladder. If you look back down the trail, you can see that there is no surface water for several hundred feet downstream. The stream reappears in the valley beneath the exposure of limestone you passed on the way to the arch. The valley walls are steep and vegetated, so it is difficult to see where the stream exactly reappears from the trail (please stay on the trail and do not try to walk down to where the stream reappears), but you can hear the water from the trail and see the stream at several points along the trail. The exposure of the Slade Formation forms a small cliff at the head of the valley where the stream reappears. Large fractures and solution features (both vertical and horizontal bedding-plane conduits) are visible in the limestone, above where the stream comes back to the surface (Fig. 39). Water from Hensons

Figure 37. Vertical solution shaft at Hensons Arch is a swallow hole for the upstream drainage.

Arch likely passes through conduits like these until they reach shales in the underlying Borden Formation. The Borden likely forms an aquitard, which limits continued downward migration of the water, until the water exits the hillside as a spring.

Whittleton Arch. Whittleton Arch is a 40-minute walk from the back of the parking lot at the Whittleton Campground. Like the origin of Natural Bridge, the origin of this arch is related to fractures in the ridge-forming Corbin Sandstone. This arch, however, does not occur at the top of the ridge, as Natural Bridge does, but near the base of the sandstone cliffs on the side of the ridge. Dever and Baron (1986) inferred that water from the valley stream crossed a sandstone ledge and penetrated joints in the stream bed on the backside of what is now the present-day arch. Downward-moving water encountered shales in the Grundy (previously lower Breathitt) beneath the Corbin Sandstone and was forced sideways, emerging as springs in the hillside at the base of the Corbin. Through time, erosion and weathering enlarged the joints (and likely bedding-plane weaknesses) to form a rock shelter on the front side of the cliff. As the rock shelter enlarged, it ultimately grew back into the hillside until it intersected another joint or fracture to form the arch. Vertical rock falls and erosion enlarged the arch to its present shape.

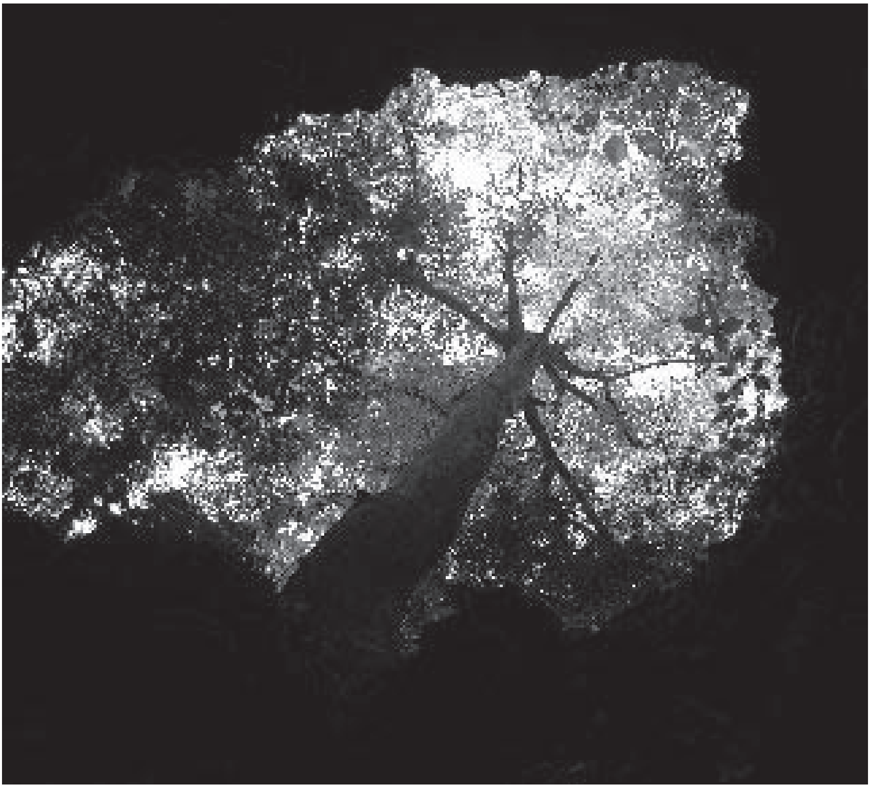

Figure 38. View upward through the adjacent shaft below Hensons "Arch." Photograph by Bethany Overfield.

The processes that formed this arch are ongoing today. When water is flowing in the present stream it flows across the sandstone ledge (small waterfall) just southwest of the arch, and part of its flow enters another fracture in the bedrock and issues downstream from the sandstone face (Dever and Baron, 1986).

Figure 39. The sinking stream flows beneath this outcrop of the Slade Formation, which exhibits vertical fractures and solution features as well as horizontal conduits.

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