# Mud Mounds, Paleoslumps, Crinoids, and More; the Geology of the Fort Payne Formation at Lake Cumberland, south-central Kentucky

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## Field Trip for the Kentucky Chapter of the American Institute of Professional Geologists, May 17-18, 2008

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**Key idea:** *Extensive mixed clastic and carbonate exposures provide an outstanding field classroom for investigating a broad spectrum of Mississippian slope/ramp deposits*

## INTRODUCTION

This field trip is a float trip to view the geology of the Fort Payne Formation along the shores of Lake Cumberland in the vicinity of Jamestown, Kentucky. In 2007, lake levels were dropped to 680 ft (above mean sea level), to allow repairs to be made to Wolf Creek dam. This is the lowest sustained lake level since the original impoundment of the lake and provides exceptional exposure of the famous mud mounds and carbonate buildups of the lower Fort Payne Formation. This field guide is a supplement to Lewis and Potter's (1978) field trip guide book "Surface rocks in the western Lake Cumberland area…" and includes descriptions of numerous outcrops not discussed in the previous field guide, as well as updated information concerning the geology of the Fort Payne Formation. The float trip will stop at outcrops along Greasy Creek (immediately west of the state dock) to see the most spectacular carbonate buildup over a green shale core on the lake, plus typical off-bank sequences; and will stop at outcrops along Lake Cumberland, Caney Creek, and Wolf Creek in the afternoon to view a submarine debris flow, paleoslumps, deformation features, and more buildups. Most of the trip will be on the Jamestown (Thaden and Lewis, 1962) and a small part of it on the Jabez (Thaden and Lewis, 1966) 7.5-minute (1:24,000) geologic quadrangles. Aside from the stop descriptions, appendices on the area's fossils, geodes, and an annotated bibliography of significant previous published studies of the Fort Payne in south-central Kentucky and adjacent Tennessee are provided for more insight into this fascinating formation.

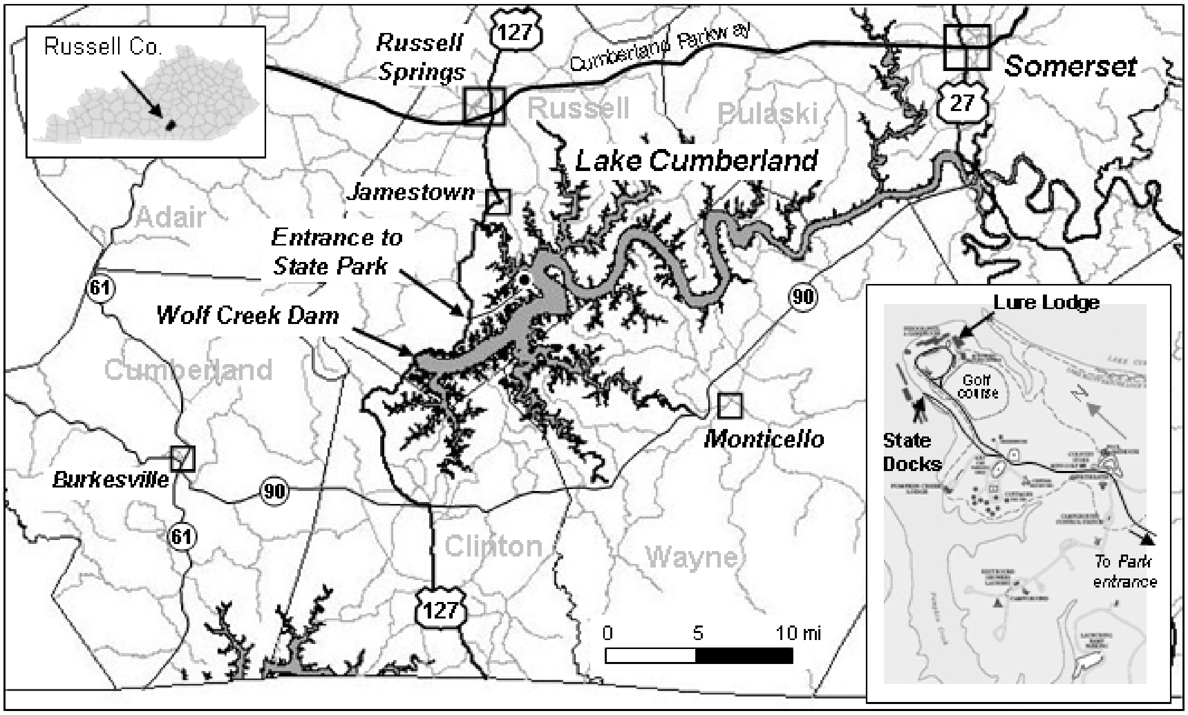


Figure 1. Location of Lake Cumberland Resort Park. Inset shows the road to the Lure Lodge and State Docks.

**About the Lake**

Lake Cumberland is located in south-central Kentucky, near Jamestown, Russell County (Fig. 1). The lake covers more than 50,000 acres and has more than 1,200 miles of shoreline. The lake was formed when the U.S. Army Corps of Engineers constructed Wolf Creek dam on the Cumberland River in 1952. The lake was impounded for flood control and hydroelectric power, and has become a major boating and fishing destination.

**Water Levels**

The principal reason for taking this field trip, at this time, is the exceptionally low water levels in the lake. According to the U.S. Army Corps of Engineers (2008), normal pool elevation in the summer is 723 feet (above mean sea level), which is near the tree line around the lake (~725 ft). Many of the geologic features around the lake, including the mounds, are only partially visible at normal summer pool level. However, in the spring of 2006, repairs began on Wolf Creek dam, and water levels were gradually lowered. For most of 2007, water levels were held near 680 ft, which was the lowest sustained level in decades (Fig. 2). During some winters the lake level drops to near 690 ft when boats are not rented. The 680 foot level was 43 ft below normal summer pool and exposed the lower parts of known mounds and numerous unknown features that had previously been covered by water.

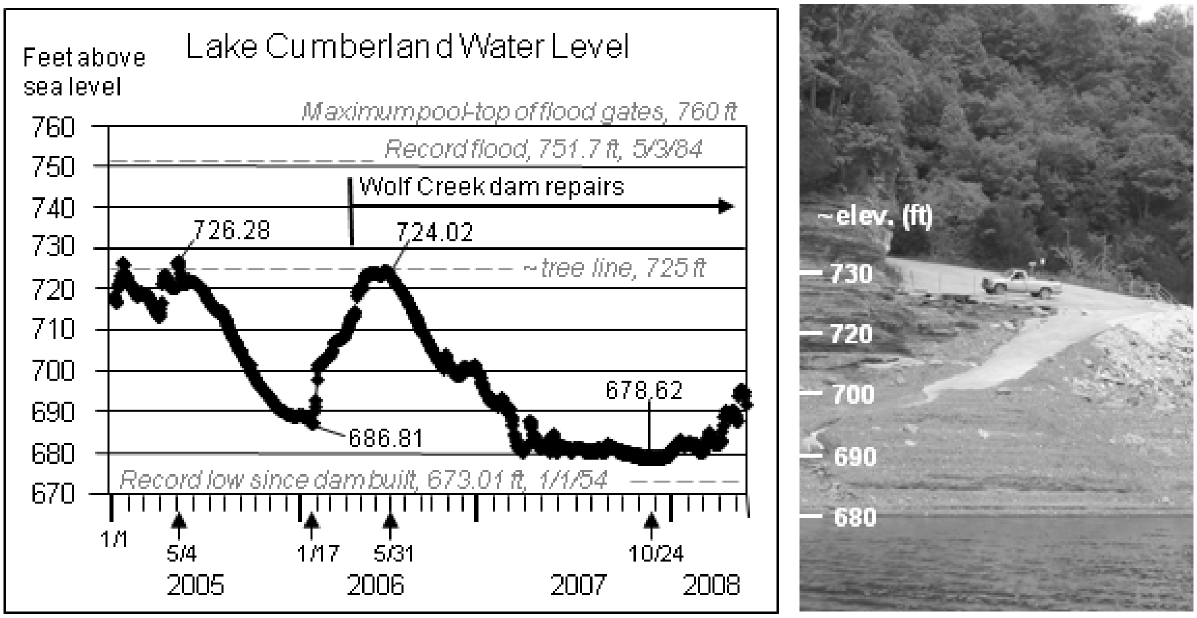


Figure 2**.** Graph of lake level showing ranges of water level in the last several years (data provided from U.S. Army Corps of Engineers (2008) and picture of the Cave Springs Ridge boat ramp, which was left hanging when water level was dropped to 680 ft during repairs to Wolf Creek Dam in 2007 (lake level for photo is 680.9 ft).

**Safety Considerations on the Lake**

Because many of the geologic features around the lake are only accessible by boat, be sure to use **basic water and boating safety procedures** while on the lake. Life jackets are provided in rental water craft, and regulations are posted at the marinas and are available at the U.S. Army Corps of Engineers-Lake Cumberland website. Because lake level changes, the shoreline is ever changing. When stopping along the shore to examine a geologic feature, be very careful getting in and out of a boat. In some places, the shoreline is a gradually rising surface; in others, it may be a steep ledge, which drops off into deep water. Rock ledges can be slippery. Also, be sure to tie your watercraft to the shore (heavy rock or log) so that it doesn’t drift away. A hat and sunscreen are suggested on sunny days. Additionally, be aware that cell phone reception on the lake is variable, and because the lake is served by cell towers that straddle time zones, your cell phone clock may switch back- and-forth between central and eastern times. Restrooms are available *only* at the marinas.

**Background to the Fort Payne Formation**

The Fort Payne Formation is a Middle Mississippian (Late Osagean) mixed siliclastic and carbonate unit. The Fort Payne lies stratigraphically in front of the Borden Formation (Early Osagean and Kinderhookian age) and rests on the underlying Chattanooga (New Albany) Shale of Devonian-Mississippian age (Fig. 3). The Fort Payne extends from south-central Kentucky westward to the Tennessee River and southward across Tennessee into Alabama. In the western Lake Cumberland area, the Fort Payne Formation varies between 210 to 310 feet in thickness (Thaden and Lewis, 1962; 1966).

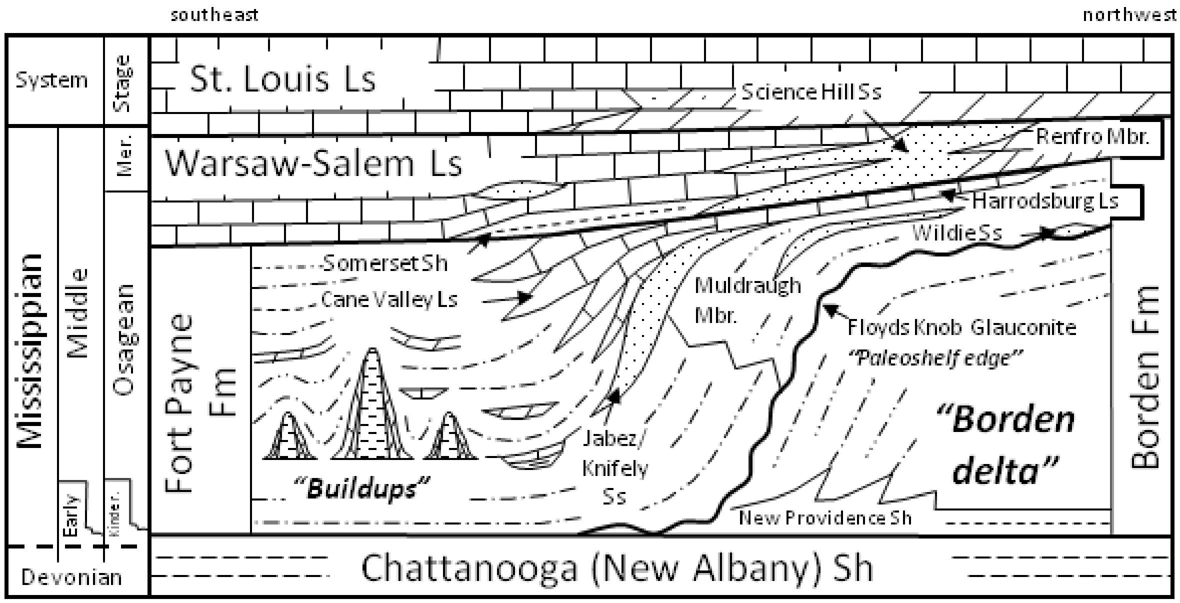


Figure 3. Stratigraphy of the Fort Payne Formation and surrounding units (after Sedimentation Seminar, 1972; Khetani and Read, 2002; Krause and Meyer, 2002; 2004).

The upper contact of the formation with the Middle Mississippian (Late Osagean to Early Meramecian) Warsaw Limestone is near the top of the ridges along the lake (Thaden and Lewis, 1962; 1966). Near the state docks, the base of the Fort Payne (the Chattanooga Shale) is not exposed but occurs beneath the level of the lake. This contact is visible below Wolf Creek dam (Lewis and Potter, 1978, Stop 4) and along Kentucky Highway 61 (Meyer and others, 1997; Krause and Meyer, 2004). The Warsaw is exposed outside of the state park on U.S. Highway 27 toward Wolf Creek dam (Lewis and Potter, 1978, Stop 3), and on Kentucky Highway 61 south of Burkesville (Meyer and others, 1997).

The famous exposures of mud mounds and carbonate buildups around the lake have been described and reported by many authors (see annotated bibliography-Appendix A). They were mapped on the Jabez and Jamestown 7.5-minute quadrangles as “reef limestones” (Thaden and Lewis, 1962; 1966), but are actually deeper water biohermal buildups analogous to European Waulsortian mounds. Waulsortian mounds are carbonate mud-rich buildups that lack obvious framework builders, such as corals in reefs (e.g., Lees, 1964). Similarities and differences between the Fort Payne buildups and Waulsortian mounds are summarized in Lewis and Potter (1978), MacQuown and Perkins (1982), Ausich and Meyer (1990), Knox and Stapor (2003), among others (see Appendix A). Similar biohermal structures are common in several parts of North America and Europe during the Lower and Middle Mississippian (Lees, 1964; Lees and Miller, 1985; King, 1986; Davies and others, 1988; Brown and Dodd, 1990; Lees and Miller, 1995).

A good argument can be made that the Fort Payne Formation is the most diverse unit in Kentucky. The unit exhibits:

(1) Great lithologic diversity

A) Siltstones predominate and are commonly dolomitic and argillaceous

B) Shales range from light to dark gray to green to almost black in color

C) Three broad kinds of limestones: dense massive, fine-grained cores of build ups; well washed, bedded, coarse crinoid-bryozoan limestones and thin dolostones

(2) Rapid and interesting lithologic changes locally and regionally, including the famous buildups

(3) Pronounced regional clinoforms formed by southwesterly dip in front of the abandoned Borden delta

(4) A variety of stratal surfaces, some of which may represent flooding surfaces and parasequence boundaries

(5) A broad suite of soft-sediment deformation and mass flows related to movement on the paleoslope

(6) Dolomitization, with at least two kinds of dolomites present including some thin beds

(7) A variety of porosity types, including shelter and stromatactus cavities in the carbonate buildups

(8) Abundant fossils, especially crinoids, but also bryozoans, brachiopods, sponge spicules, and others

(9) Abundant bioturbation with a wide range of bioturbation densities and types of trace fossils

(10) Abundant geodes, which are popular for collecting, but also provide clues to the diagenetic history of the Fort Payne

(11) Economic importance; including shallow oil production from the Beaver Creek "sand" of the mud mound facies and higher, well-washed limestones, as well as crushed stone and aggregate from quarries in its Cane Valley Member

These characteristics make the Fort Payne a first class laboratory for field trips—so much to see and discuss—with so many puzzles left to resolve! Foremost among these are questions concerning the origins of the green shale mounds and their associated carbonate buildups, as well as the sequence relationships of this diverse unit.

**Depositional Setting**

To understand the lithologic and thickness variability of the Fort Payne Formation, it helps to understand its relationship to the Borden Formation. Although the Borden and Fort Payne Formations both overly the Chattanooga Shale, the Borden was deposited as westerly prograding prodelta silts, prior to deposition of the Fort Payne. The Floyds Knob glauconite bed marks the contact between the Fort Payne and Borden Formations and the limit of an abandoned delta lobe of the Borden delta. As such, it delineates a shelf edge for Fort Payne and Muldraugh Formation deposition that has been estimated to have had more than 150 ft (50 m) of relief (Fig. 3, Sable and Dever, 1990; Khetani and Reed, 2002; Krause and others, 2002). The broad environmental setting that best fits the lateral variability, thickness changes, lithologies, and other features listed above for the Fort Payne, is a marine, oxic to dysoxic southwestward-dipping ramp in front of the abandoned Borden delta lobe (so-called Borden "front" or "paleoshelf edge" in Fig. 3). This ramp or slope was bounded on the west by a

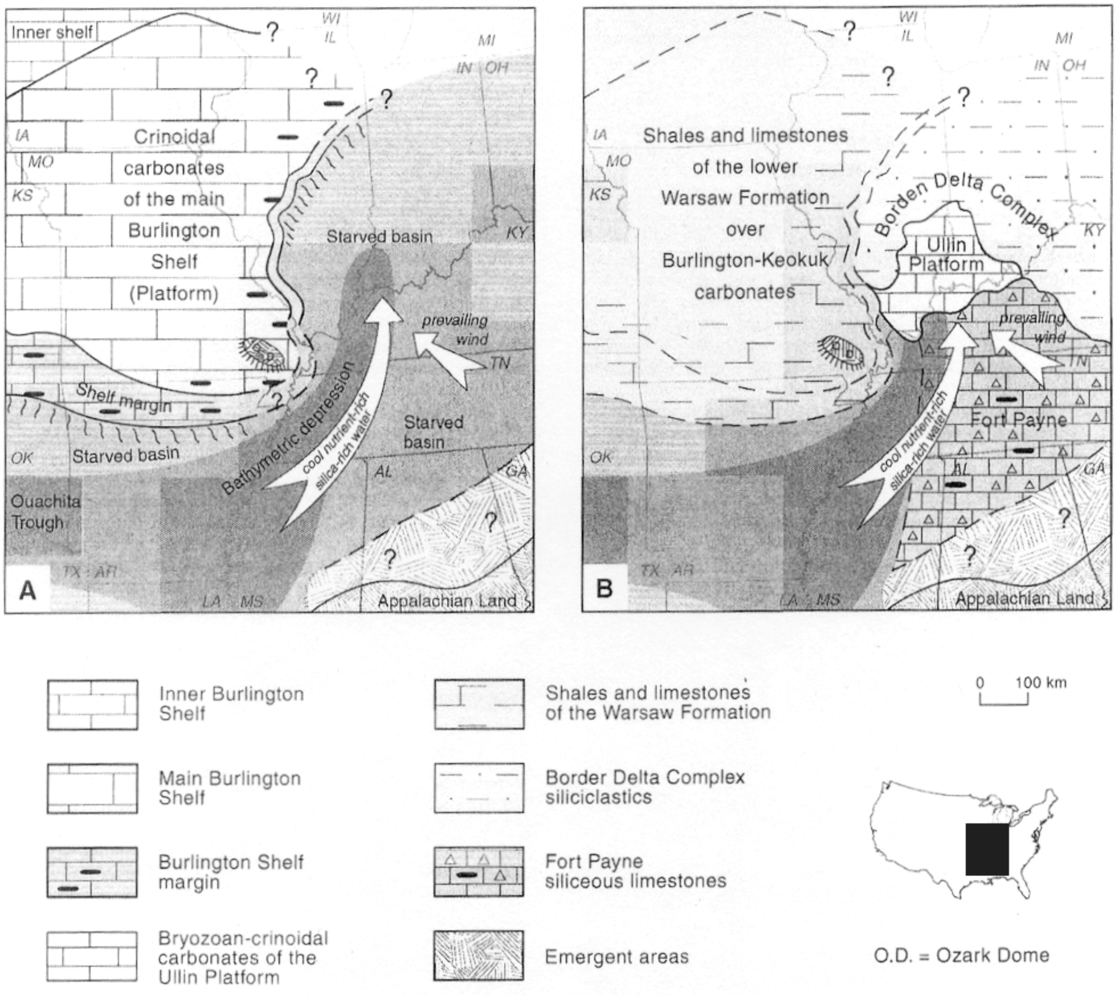


Figure 4. Paleogeographic setting of the Fort Payne and equivalent strata, which began in a starved basin (A) that was subsequently filled (B) in front of the Borden delta complex (from Lasemi and others, 2003, Fig. 11, included here with permission of authors and SEPM (Society for Sedimentary Geology).

deeper, cool water basin (Fig. 4), which was approximately located over the present Mississippi Embayment (Lasemi and others, 1998; 2003). In this moderately deep marine basin, nutrient-rich, cool ocean water mixed with silts and muds carried seaward in warmer water from the Borden delta. Relatively deep-water facies in the lower and middle Fort Payne are confirmed by the lack of typical, shallow water sedimentary structures (MacQuown and Perkins, 1982; Lineback and Cluff, 1985; Lumsden, 1988; Ausich and Meyer, 1990; Lasemi and others, 1994; Khetani and Read, 2002). This is the interval in which the famous buildups are preserved, and the depositional framework that should be considered when viewing the exposures on the trip.

**Oil Production from the Fort Payne**

The carbonates buildups exposed on Lake Cumberland are similar to those that produced oil from limestones 5 to 40 ft. above the Chattanooga Shale in south-central Kentucky (Munn, 1914, p.26 – 29; Wilson, 1971). Munn has pictures of the massive mudstone core (Pls. 1 and 2), but recognized that other associated limestones (the well-washed adjacent and capping limestones with inclined bedding) could also be reservoirs. Whatever its origin, the green shale core facilitated limestone buildups and the traps around and above it. This production was called the Beaver Creek "sand". Eastward in Wayne County, oil is produced from the Beaver Creek, which is stratigraphically low in the Fort Payne, and from the Corder Stray, which are limestones higher and near the top of the Fort Payne. Production in Kentucky was initially from very shallow wells; only 500 to 700 feet deep. Many wells were drilled early in the twentieth century (about the same time as the discovery of the East Texas fields), and production was subsequently found to the west in Metcalfe County in 1959, and to the southeast in the Oneida Field of Scott County, Tennessee in 1982 (Wilson, 1971; MacQuown and Perkins, 1982; Millici, 1996). Differences between the Tennessee and Kentucky buildups are discussed in Marcher (1962), Statler (1971), and Kuslansky and Friedman (1984).

More than 7 million bbl of oil have been produced from the Fort Payne in Kentucky and Tennessee (Millici, 1996) Many of the Fort Payne mound facies in producing fields are elliptical in plan view, and generally 30-75 ft in thickness (Wilson, 1971; Lewis and Potter, 1978; Millici, 1996). This thickness is comparable to the thickness of the buildups exposed along Lake Cumberland. Producing oil fields range in diameter from mounds defined by single wells, to mounds (or perhaps mound complexes) defined by 25 or more wells and having diameters of tens of thousands of feet. Most fields are less than 3 km in diameter (Statler, 1971; Wilson, 1971; MacQuown and Perkins, 1982; Kuslansky and Friedman, 1984). The exposures at Lake Cumberland provide an opportunity to examine facies variability and details within the mound structures that could be related to reservoir properties in the subsurface.

## FLOAT TRIP

The float trip will leave from the state docks marina. The morning trip will examine outcrops on Greasy Creek (Fig. 5). Along this part of the lake outcrops will be examined that illustrate normal or common geology of the Fort Payne Formation, and then the best-exposed mud mound and carbonate buildup on Lake Cumberland. Boats will return to the docks around lunch to use the facilities (no bathrooms on the lake). In the afternoon, outcrops will be examined on the main lake, as well as Caney and Wolf Creeks. Some of these are described in Lewis and Potter's (1978) field guide, including some spectacular paleoslumps and more buildups (Fig. 5). This field guide follows the format of Lewis and others (1978) by presenting descriptions of <u>outcrops</u> to be viewed from the boats, and <u>stops</u> at which field trip participants will leave the boats and explore the shoreline.

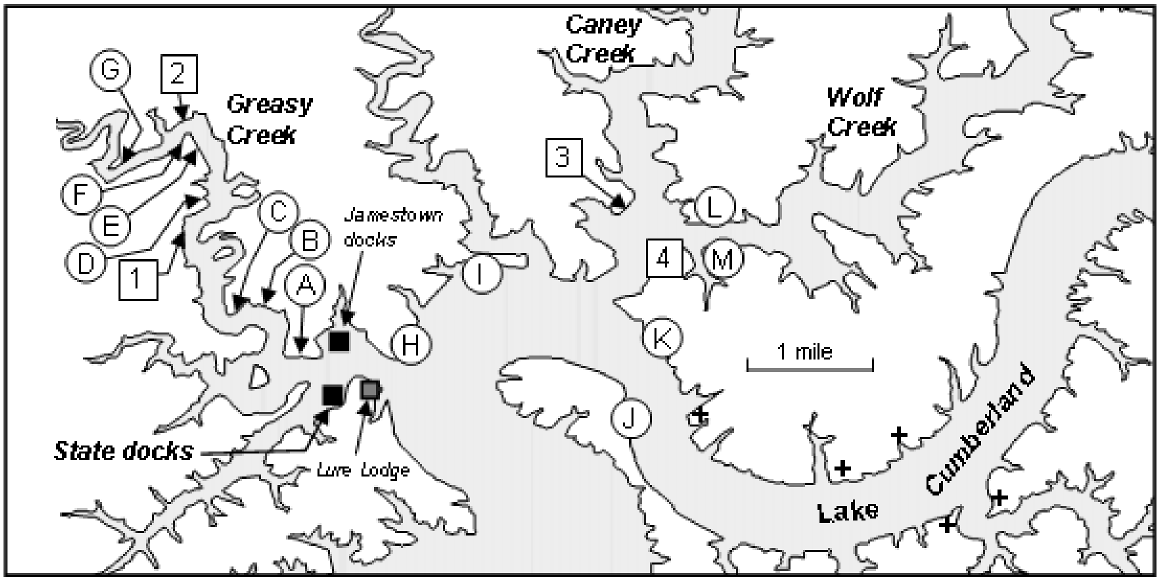


Figure 5. Location map of the float trip showing stops (numbered) and outcrops (lettered) discussed in the text. Outcrops and stops shown in the Lewis and Potter (1978) field guide that are not included in this field guide, are shown with a "+" symbol. Several other mounds are visible along the lake that are not shown on this map.

## Greasy Creek

**Outcrop A (and both shorelines):** From the state boat dock, head west toward Greasy Creek (Fig. 5). Along the way, note the normal rock layering of the Fort Payne Formation (Fig. 6). Ausich and Meyer (1990) reported that most of the flat-lying beds along the shoreline consist of graded beds. Some are coarse-grained, while others are finer grained. The base of coarse-grained graded carbonates are sharp, scour-based and may contain siltstone rip-up clasts. Vertically, these grade into well-sorted, coarse sand- to silt-sized packstone to grainstone (see Appendix B for definitions). Where silt-sized packstones are the basal beds, the basal boundary of the sheet is sharp, but may not appear erosional. Graded carbonates are separated by siliclastic siltstone and mudstone. Bedding is generally absent, although the lower coarse-grained beds may be crossbedded. Upper beds may exhibit horizontal lamination and burrowing (Ausich and Meyer, 1990; Krause and Meyer, 2004).

**Outcrops B and C:** From Stop A, proceed north along the western side of Greasy Creek. Look back toward the eastern shore of lower Greasy Creek (Fig. 5) to see the lateral continuity of the lower Fort Payne sheet-form bedding. From the west side of the creek looking toward the eastern shoreline you can see that the bedding exhibits low-angle, westerly dipping master bedding surfaces, which onlap underlying bedding sets (Fig. 7). Try to envision the potential three-dimensional geometry of these broad onlapping bedding cosets. Note also the dark gray siltstone (looks like shale) that caps many of the carbonate beds as at the outcrops near the docks. These siltstones are commonly densely bioturbated, generally with *Zoophycos* and *Helminthoida* (Ausich and Meyer, 1990).

Figure 6. Typical Fort Payne bedding east of the state docks, showing interbedded, relatively flat-lying siltstone and carbonates. Note the capping, dark gray, shaly siltstone (lake level for photo is 678.96 ft, tree line is ~725 ft).

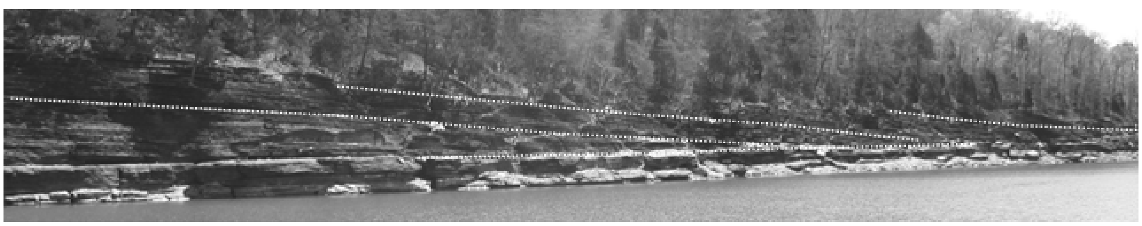

Figure 7. Low-angle dipping beds on the eastern shore of Greasy Creek at outcrop C (lake level for photo is 695.3 ft).

The base of the dark gray siltstone may be a flooding surface, which is a useful surface in sequence stratigraphy (see Appendix B–Glossary). Sequence stratigraphy is a tool well suited for inferring lateral relationships between rock units and facies where there are known large-scale clinoform associations as between the Fort Payne and Borden Formations. However, in distal ramp/slope settings (Figs. 3, 4), care is needed in correlating surfaces because reorganization of the slope/ramp by gravity processes can lead to widespread changes in facies that appear to mark significant shifts in deposition, but which may not be related to more regionally developed depositional sequences.

**Stop 1-Paleochannel:** Most of the shoreline to this point has consisted of well-laminated carbonates and siltstones that are flat-lying or arranged in low-angle onlapping packages capped by dark, gray bioturbated siltstone. At this stop, normal lower Fort Payne bedding is interrupted by a series of small scours, slumps, and a larger scour-form feature filled with dark siltstone (Fig. 8A-C). The outcrops here are steep and may be inaccessible depending on lake level, but are worth examining from the boats. The larger scour is filled with at least 12 ft of dark gray, bioturbated siltstone, which is partially slumped along the channel margin. Above the slump, on the south side channel margin, there is also soft-sediment deformation in the thin carbonates that cap the scour.

**Outcrop D**: North of stop 1, a small lens-form carbonate is exposed in two adjacent outcrops at low water levels (Fig. 9). The carbonate has a sharp base and can be correlated through two adjacent exposures. The dark gray siltstone seen in the first several outcrops, caps the carbonate lens.

**Outcrop E**: Just south of the westward turn in Greasy Creek, bedding along the western shore of Greasy Creek is interrupted by several small scours and slumps. A green shale facies is also well developed. Green shale (g) occurs on both shores. The shale contains abundant crinoidal debris and will be investigated at Stop 2. Along this exposure (Fig. 10), note the association of thick limestone with the green shale. The limestone is a

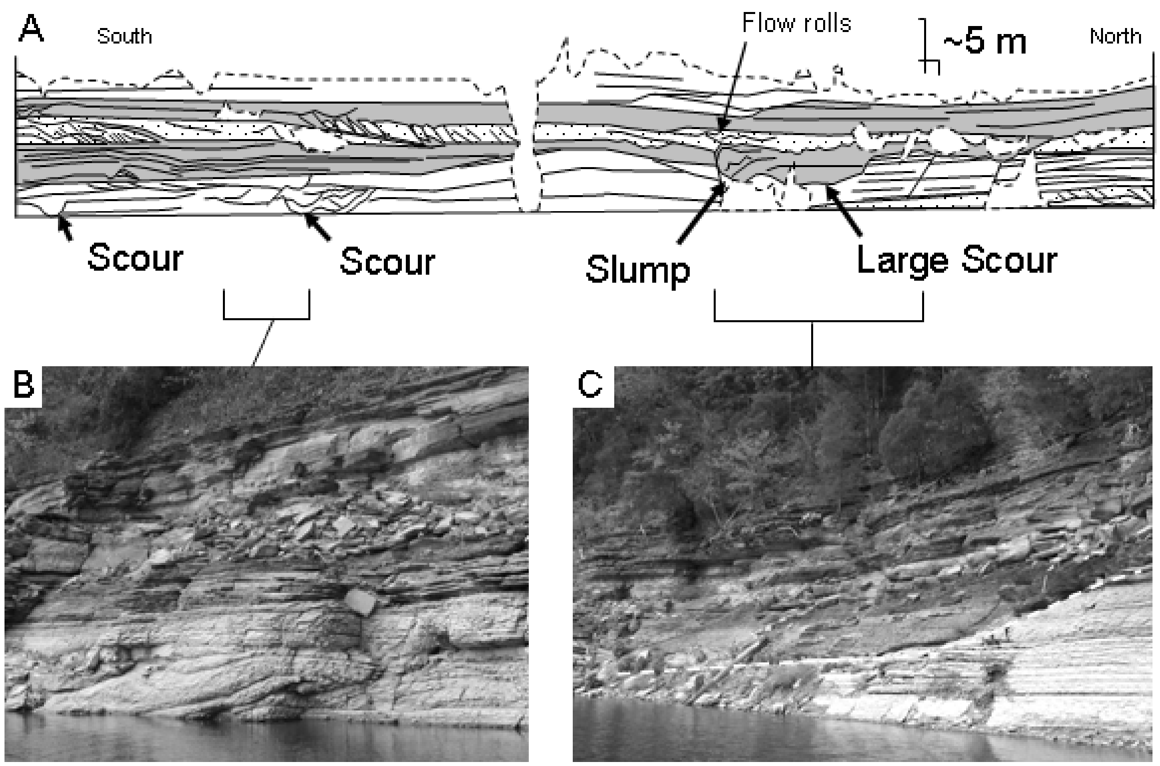


Figure 8. Diagram of the eastern shore of Greasy Creek at Stop 1 (A) based on a photo-mosaic. Horizontal to vertical scale is approximately 2.5:1. There are several small scours with soft-sediment deformation structures (B) and flow rolls, as well as a (C) deep scour, which is filled with dark gray, shaly siltstone (shaded) (lake level for photos is 678.96 ft).


Figure 9. A thin lens-form carbonate cuts obliquely through the eastern shore of Greasy Creek at Outcrop D (dashes and arrows). Lake level for photo is 695.3 ft).

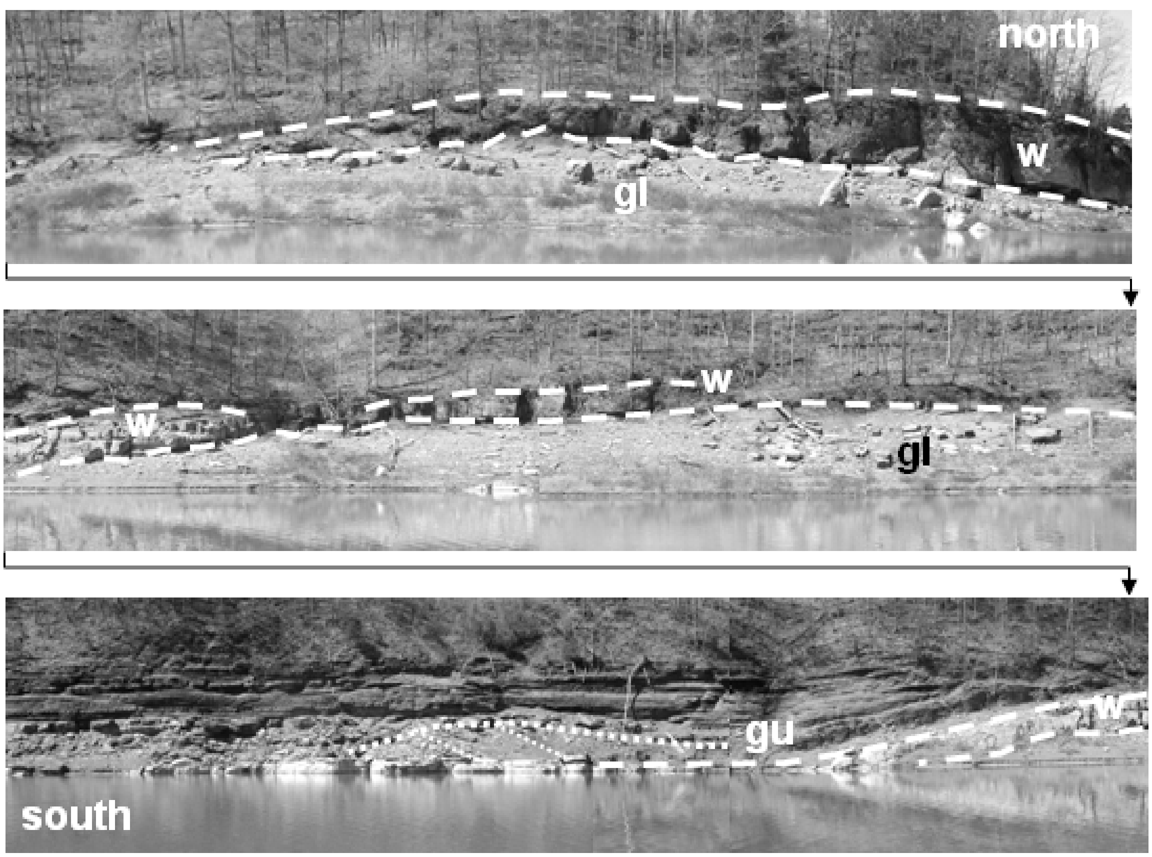


Figure 10. Still northward along Greasy Creek a green shale facies is developed. A somewhat darker blue-gray upper shale (gl) overlies a thick limestone-wackestone (w), and a lower, lighter green shale (gl) underlies the wackestone. The limestone rises above the lower green shale, dips, and then thickens dramatically northward (lake level for photo is 695.3 ft). The upper green shale is slumped on the margin of the carbonate buildup (dotted lines in third panel).

wackestone (see Glossary–Appendix B), and is more than 35 ft thick (Fig. 10). Keep this lithofacies and thickness association in mind at Stop 2, just across the creek.

**Stop 2-Greasy Creek Mound:** A large buildup is exposed in outcrops at Stop 2 (Fig. 5). Before landing, look at the outcrops to the east, and those at Outcrop E to the south. These outcrops are all part of a large mud mound (or composite mound) which extends for more than 1000 ft along this part of the lake. Here we will spend much of the morning to become familiar with the buildup facies. Be sure to tie off the boats securely to the shore, and be careful getting on and off the boats.

On KY Highway 61 north of Burkesville in adjacent Cumberland County, Krause and Meyer (2004) described four outcrops of comparable buildups and recognized five buildup facies (Table 1): Green Fossiliferous Shale (GFS), Tabular Crinoidal Packstones and Grainstones (CPG), Shaly Packstone (SP), Massive Fenstrate Bryozoan-Coral-Crinoidal Wackestone (MW), and Coarse Crinoidal Grainstone (CG). The lateral relationships of those facies on Highway 61 are shown in Figure 11. In these outcrops, two parasequences (see Appendix B–Glossary) were interpreted by Krause and Meyer (2004) based on the presence of erosion surfaces and slumping overlain by coarser-grained carbonates (Fig. 11A). Sequence stratigraphic interpretations are also discussed in Khetani and Read (2002). Look for the five facies at Greasy Creek to see if the geometry of the facies and possible sequences are similar to the exposures on KY Highway 61.

***Green Fossiliferous Shale***
**Description**—Gray to green fossiliferous shale (GFS) occurs throughout the lower Fort Payne Formation and encloses all of the carbonate buildups contained therein. It therefore represents the background sediment preceding and post dating the buildup interval. This facies has a diverse macrofauna that is common to very abundant but has a patchy distribution. Disarticulated echinoderm plates are the dominant faunal element but brachiopods (31 genera) and bryozoans (4 morphotypes) are also common.

***Tabular Crinoidal Packstones and Grainstones***
**Description**—Interbedded with the GFS in most locations are tabular, crinoidal packstone–grainstone (CPG) beds that range in thickness from 2 to 13 cm. These beds are laterally continuous at outcrop scale, ranging in length from 0.5 to 10 m, and are sparsely distributed vertically through each section studied (0.5–3 m spacing). Often, the CPG beds are closely associated with fossiliferous stringers of the GFS facies, and it is not uncommon for them to grade into each other.

***Shaly Packstone***
**Description**—A coarse crinoidal shaly packstone (SP) is present, with a variable thickness (0–0.5 m), at the base of the buildups in the study area. The geometry of these deposits is such that they attain their greatest thickness near the sides of, and pinch out onto, the apices of topographic highs in the underlying fossiliferous green shale. Echinoderms are the dominant faunal components of this facies. Intact calyces and partially articulated arms and stalks are often encountered, but complete disarticulation is common as well.

***Massive Fenestrate Bryozoan–Coral–Crinoidal Wackestone***
**Description**—The lithology overlying the shaly packstone is a massive fenestrate bryozoan–coral–crinoidal wackestone (MW). In the study area, accumulations of this facies have a convex upper surface and an undulose base that conforms to the topography of the underlying deposits (SP and FGS). MW deposits are roughly circular in plan view with dimensions of 15 to 20 m in height and 150 to 200 m in width. This facies is poorly bedded throughout, and no bioturbation was noted. The fauna of the MW is dominated by fenestrate bryozoans, auloporid corals, and several genera of pelmatozoan echinoderms.

***Coarse Crinoidal Grainstones***
**Description**—The fifth distinctive lithology associated with the buildup interval consists of coarse skeletal grainstones and packstones (CG) with a patchy stratigraphic distribution. Deposits of this facies are usually found adjacent to buildups in the study area in what may be a flanking position, and they are not known to occur in areas devoid of buildups. Where exposed, these deposits have a rather sharp basal contact with the underlying buildup (MW facies).

Table 1. Typical facies of the Fort Payne buildup interval (from Krause and Meyer, 2004).

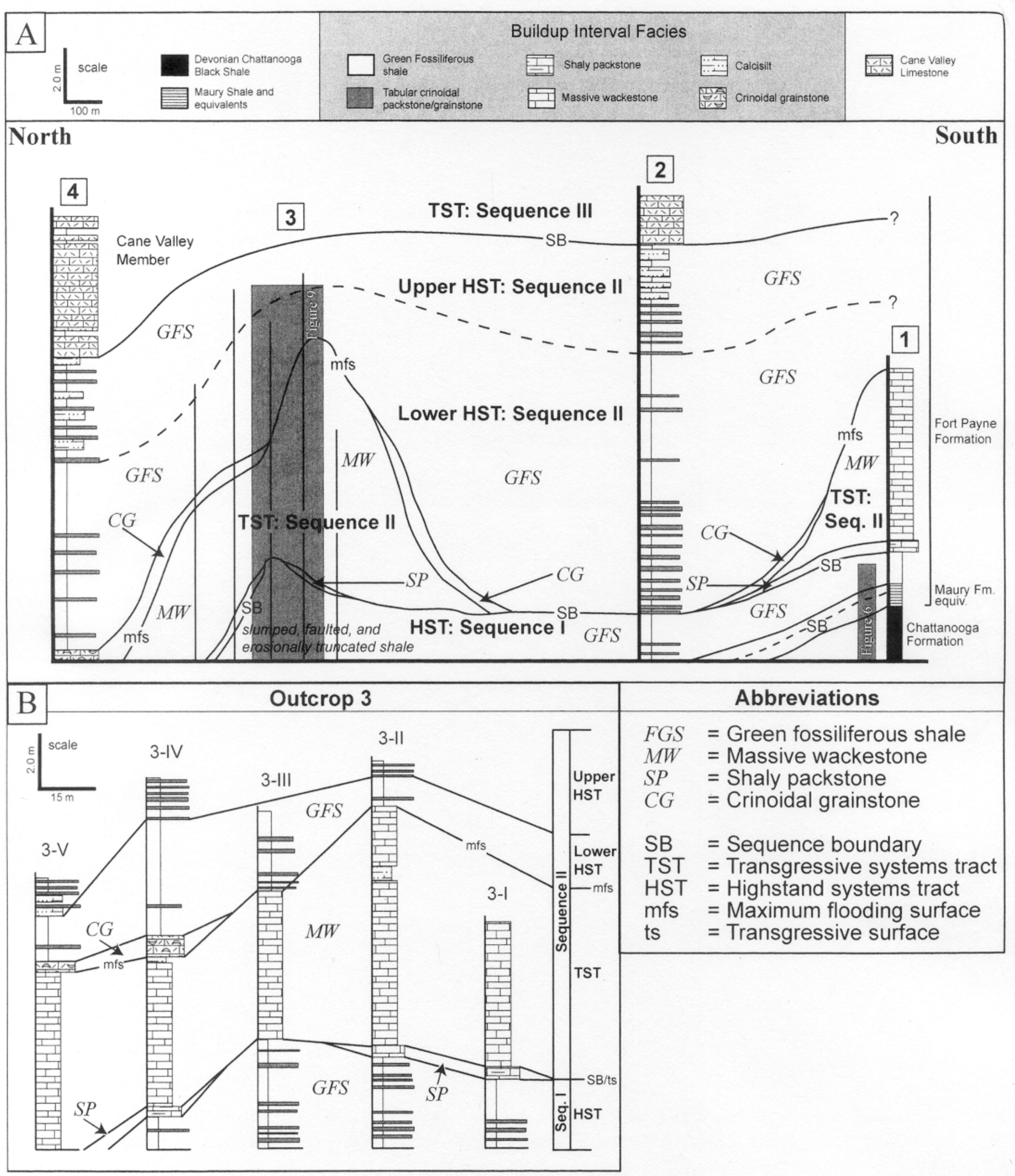


Figure 11. Correlated stratigraphic sections along Kentucky State Highway 61 south and west of lake Cumberland State Park, showing typical facies and inferred sequences for the mound-building interval of he Fort Payne Formation. Basal datum is road level (from Krause and Meyer, 2004, Fig. 4). See Table 1 for facies descriptions. Reproduced with permission from SEPM (Society for Sedimentary Geology).

Characteristic bedding and fossils in the Greasy Creek (north) mound at Stop 2 are shown in Figure 12. Can you place them in the facies described for Kentucky Highway 61? If you are a petroleum geologist, examine the buildup as a petroleum trap. Where might porosity be developed? What types of porosity are evident?

→*In doing any of this, everyone should pay attention to the geometry of the buildup.*

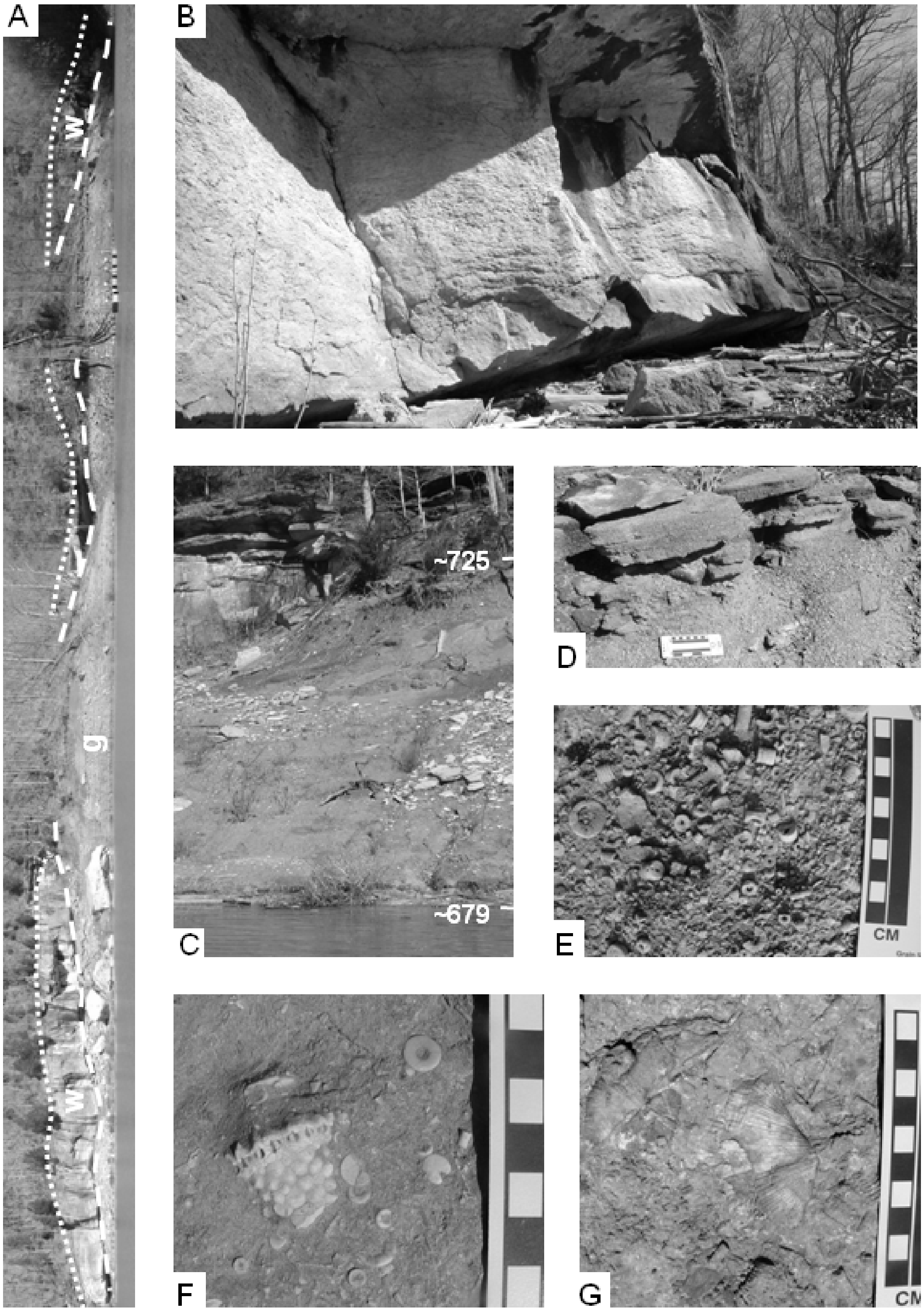


Figure 12**.** Greasy Creek (north) mound. (A) Photomosaic of the north exposures showing green shale (g) core and capping and flanking wackestone-dominated (w) limestone (dashed lines). (B) Forty ft-thick Massive Wackestone Facies with sharp base. (C) Thick, Green Shale Facies in the core of the mound with approximate elevations above sea level. (D) Crinoidal siltstones in the green shale. (E) Crinoidal debris is abundant, although holdfasts are also found. (F) *Eretmocrinus* calyx and (G) Brachiopods from the limestone Scale is in centimeters (lake level for photomosaic is 695.3 ft).

*Fossils in the buildup and their significance:* Fossils are common in the mud mounds and carbonate buildups of the Fort Payne. At this stop, you might like to begin by comparing the fossil content of the massive carbonate buildup to that of the underlying green shale; what are the similarities and differences? Of particular interest is the base of the buildup and transition from the green shale. Typically there is a coarse crinoidal grainstone, as much as 50 cm thick, at the base of the buildup. This is overlain by crinoidal wackestone that makes up the bulk of the carbonate mound. In the mounds, crinoids are often found as complete calyces, but without attached arms and column. Figures 13 and 14 illustrate the most common crinoids found in the mounds. Inadunate, flexible, and camerate are all subclasses of crinoids found in the Fort Payne. Camerate crinoids with well-plated calyces are predominant in the mounds. Columns can only be identified for a few crinoids. Root-like holdfasts can also be found. If holdfasts are found in growth position (i.e., look like a tree trunk), then the crinoids were growing where we find them; if they appear tumbled and broken, then they were likely transported. Observe how the crinoids, both columns and holdfasts, are preserved and think about the depositional processes involved. For more information about crinoids and other fossils from the Fort Payne, we recommend two excellent paleontology texts: Boardman et al. (1987) and Clarkson (1998).

*When finished at Stop 2, continue west a short distance to Outcrop F in order to get a better view of the Greasy Creek mound(s).*

**Outcrop F:** On the south side of the lake at Greasy Creek, the wackestone buildup thins westward along the shore (Fig. 15A-C). The most interesting feature of this flank of the Greasy Creek (south) mound is a large-amplitude “wave-form” or “wrinkles” in the downslope section of the wackestone buildup (Fig. 15C). This deformation appears to involve the entire limestone (3 to 4 m). Underlying strata are covered so it is uncertain if the underlying unit was also deformed. Soft-sediment deformation and slumping are common on the downslope sides of the mounds, and in overlying shales and siltstones that cap the mounds. Look at bedding above the mound flanks on both the north and south shore of Greasy Creek and examine the dip of beds off of the flanks of the carbonate buildup.

An exceptional opportunity to view the three-dimensional distribution of the mound facies is possible from the middle of Greasy Creek west of Stop 2 (Fig. 16). Outcrop F is on the back side (west) of Outcrop E. The actual apex of the green shale core beneath the carbonate buildup in Outcrop F is in Outcrop E. If this apex connects to the core (thickest part of the green shale) at Stop 2, it defines a somewhat elongate core at least 2,000 ft long (0.6 km). It is also possible that the thick green shale “core” in the Greasy Creek (north) and Greasy Creek (south) exposures actually represent a composite or compound mound. It is important to note that this is different than the “area of “reef” limestones mapped on the geological quadrangle (Thaden and Lewis, 1962); some of which combine multiple mounds or parts of mounds into one geologic unit.

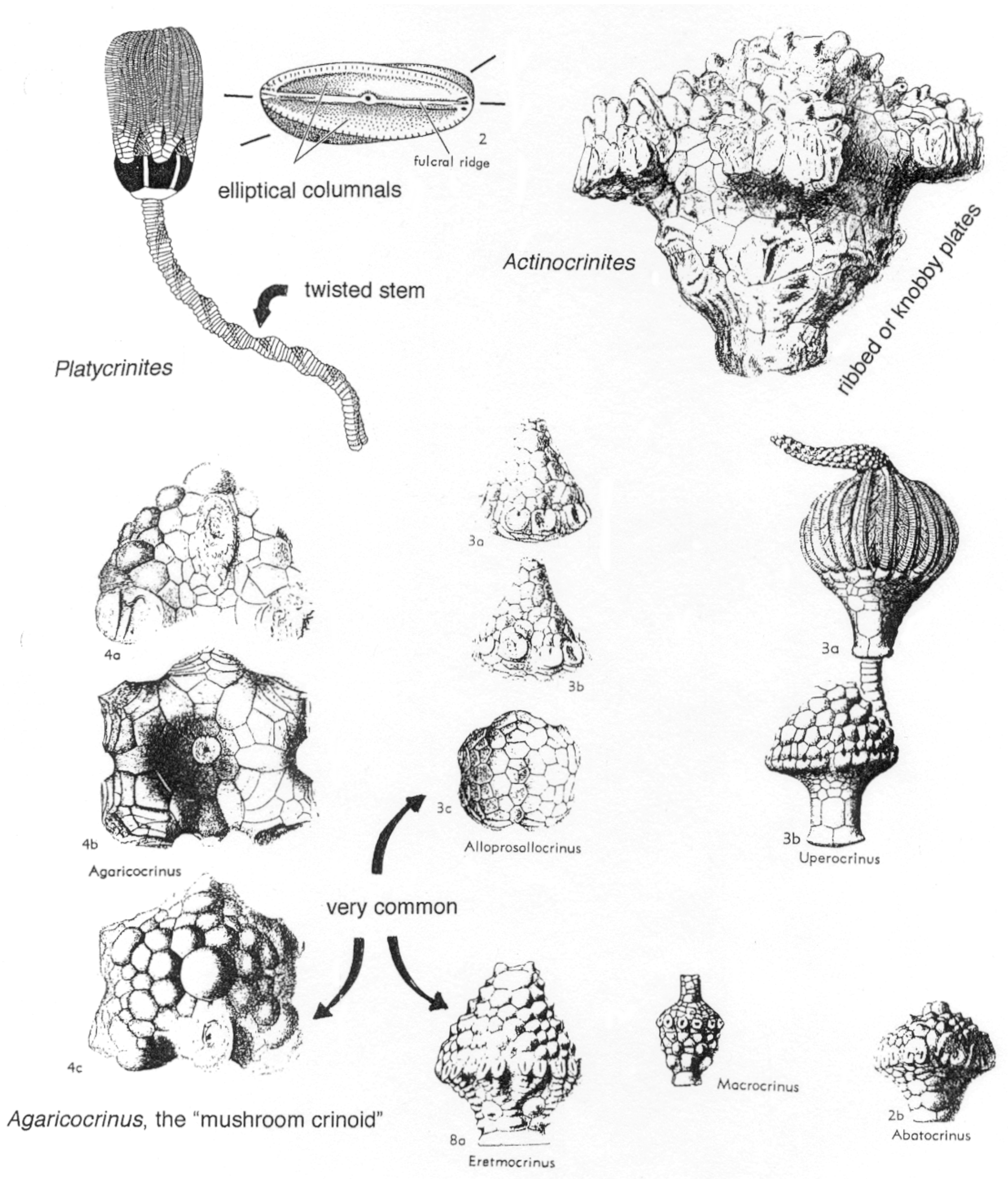


Figure 13. Common camerate crinoids of the Fort Payne Formation.

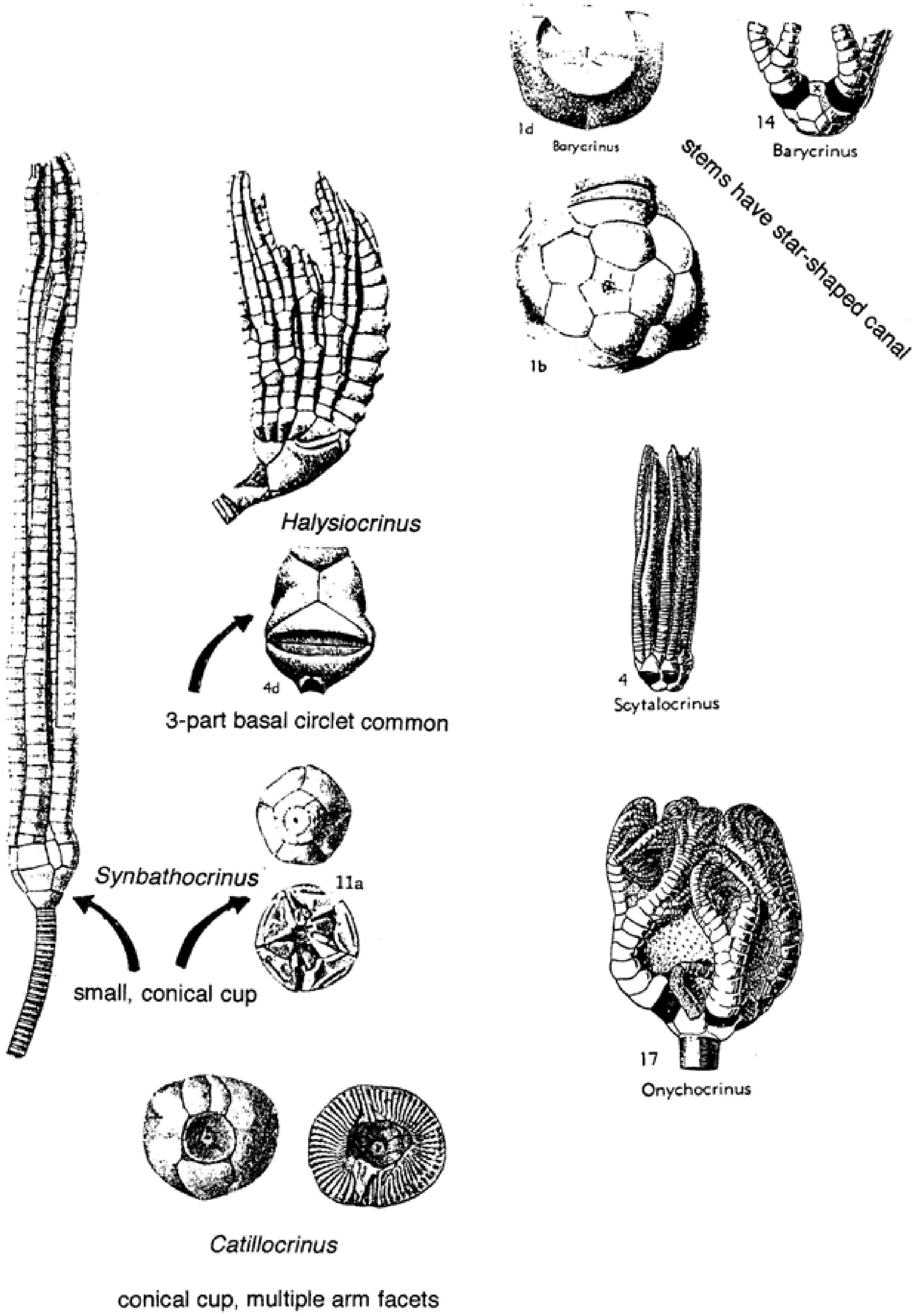


Figure 14. Common inadunate and flexible crinoids of the Fort Payne Formation.


Figure 15. Greasy Creek mound (southwest side) as viewed (A) from the north side of Greasy Creek. The flanking wackestone (B-C) thins westward and becomes “wrinkled” downslope (lake level for photo A is 695.3 ft, B-C is 678.96 ft).

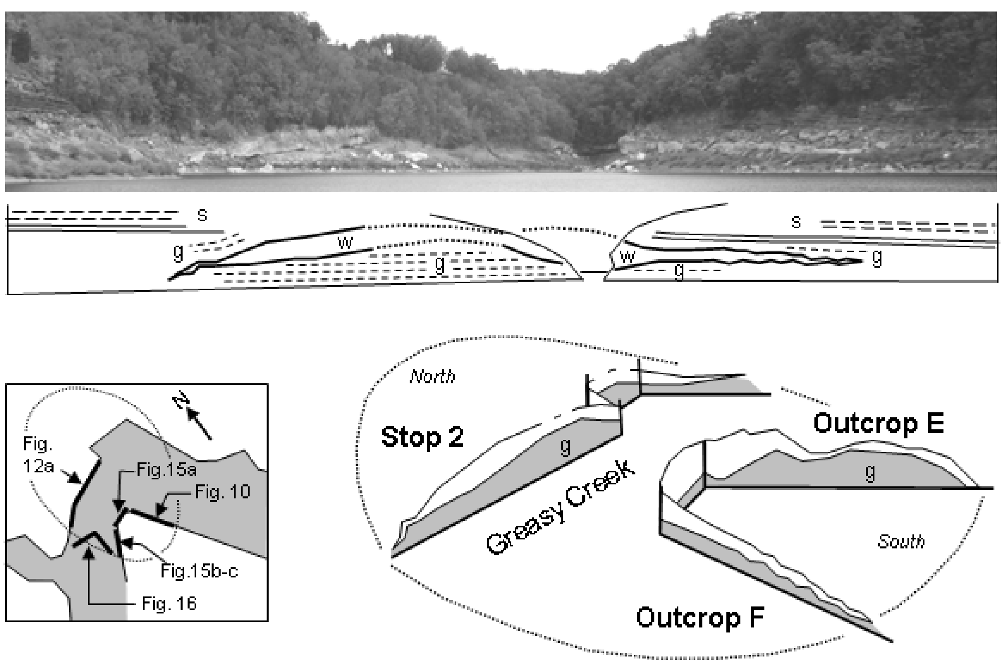


Figure 16. Exceptional three-dimensional view of the Greasy Creek mound(s). View is looking east toward Stop 2 and Outcrop F, which is the back-side of Outcrop E. Green shale is indicated by “g” in the schematic diagram. This diagram is an illustration based on the photomosaics, with no scale inferred (lake level for photo is 678.96 ft).

**Outcrop G:** Further upstream on Greasy Creek (Fig. 5), off of the buildup slope, Fort Payne bedding returns to the "normal" or "background" deposits seen at the first stops; interbedded siltstone and carbonate overlain by a dark gray, shaly siltstone. At several points along this shoreline, fractures are well developed. Siltstones lower in the section have broadly spaced fractures, while a thin, orange dolostone (?) has closely-spaced fractures which creates the effect of protruding blocks in the ledge, somewhat like wooden planks or giant piano keys sticking out of the valley wall (Fig. 17). Look at the persistent orientation of the fracture sets. Look for the oblique sets parallel to this stretch of the creek. Compare the orientations to the right-angle turn the creek makes at this location (see map Fig. 5) to see the influence bedrock fracturing has on stream-reach orientations in this area. On the return trip to the dock, you can see numerous fractures.

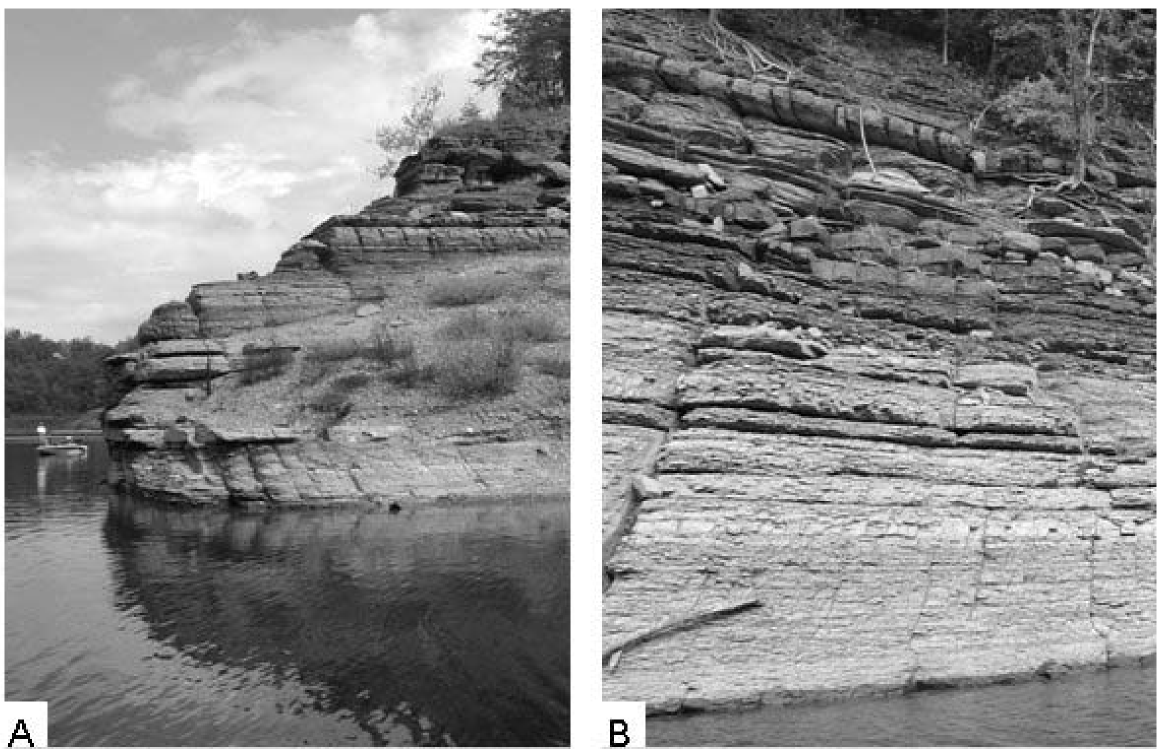


Figure 17**.** Fractures in thin siltstones and carbonates on the north shore of Greasy Creek at Outcrop G.

*This is the end of the morning stops. From Greasy Creek return to the state docks for lunch and a bathroom break.*

## Main Lake Stops

From the State dock head east onto the main body of the lake (Fig. 5). A series of outcrops will be examined on the main part of the Lake, Caney Creek, and Wolf Creek. Several of the outcrops and stops are also described in Lewis and Potter's (1978) field guide; but updated herein with additional information and research that has been published since that guide book was published

**Outcrop H:** Once again, look at the normal style of sedimentation in the Fort Payne Formation. Along much of the shoreline there are relatively flat-lying carbonates and siltstones, capped by dark gray, bioturbated siltstones as seen on Greasy Creek. Likewise, some of the bedding packages have gently dipping master bedding surfaces (Fig. 18), and contain thin, lenticular sheets of siltstone and dolostone.

**Outcrop I**: Farther along the shore, the gently-dipping to flat-lying bedding is interrupted by broad, lenticular scours, slumping, and soft-sediment deformation (Fig. 19A-B). Some of the paleoslumps exposed at low water are quite large (Fig. 19B). Note also the large, folded cherts in the dark, gray silty shales. More slumping and deformation will be seen at the next stop.

From the north side of the lake, cross the lake to the south side to Outcrop J (Fig. 5). This long stretch of exposure was labeled Outcrop E in Lewis and Potter (1978). That field trip included several stops to the east along the lake that are not included in this field guide, because of time limitations. The reader is referred to the earlier guidebook for descriptions and locations of those outcrops.

**Outcrop J:** On the south side of the lake an extensive exposure of deformed bedding is exposed most of the year. As at Stop 1, the slope here is too steep to actually get out of the boats, but this long exposure is worth a close look. Figure 20A is a mosaic of part of the exposure. A relatively flat-lying, sharp-based, dark siltstone to silty shale caps the exposure along its length. This unit is underlain by a series of westward-accreting packages of deformed bedding. Of particular interested is a matrix-supported conglomerate (mc), which looks somewhat like a diamictite. The unit is brown-gray, has a scour base, and contains abundant light-colored, angular clasts of varying sizes (Figs. 20B-C). There are also several large clasts of gray siltstone or silty shale, similar to the host rock (Figs. 20B-C). Along part of the exposure, large clasts appear concentrated along the upper surface of the unit (Fig. 120C). At lower water, the base of the conglomerate is exposed, and can be seen to overlie a gray silty shale to siltstone, or a second interval of deformation, which includes rotated beds of the siltstone, as well as deformed carbonates (Figs. 20D, 21A-C). The most spectacular of these occurs just beneath and east of the thickest part of the conglomerate. At this location a westward-dipping glide plane in the underlying siltstone or silty shale is filled with large, white carbonate blocks and gray, contorted siltstones. Silty shales beneath and to the front (west) of the carbonates are also deformed.

Figure 18**.** Low-angle dipping siltstones, overlain by interbedded, thin- to thick-bedded carbonates and siltstones along the northern shore of Lake Cumberland at Outcrop H.

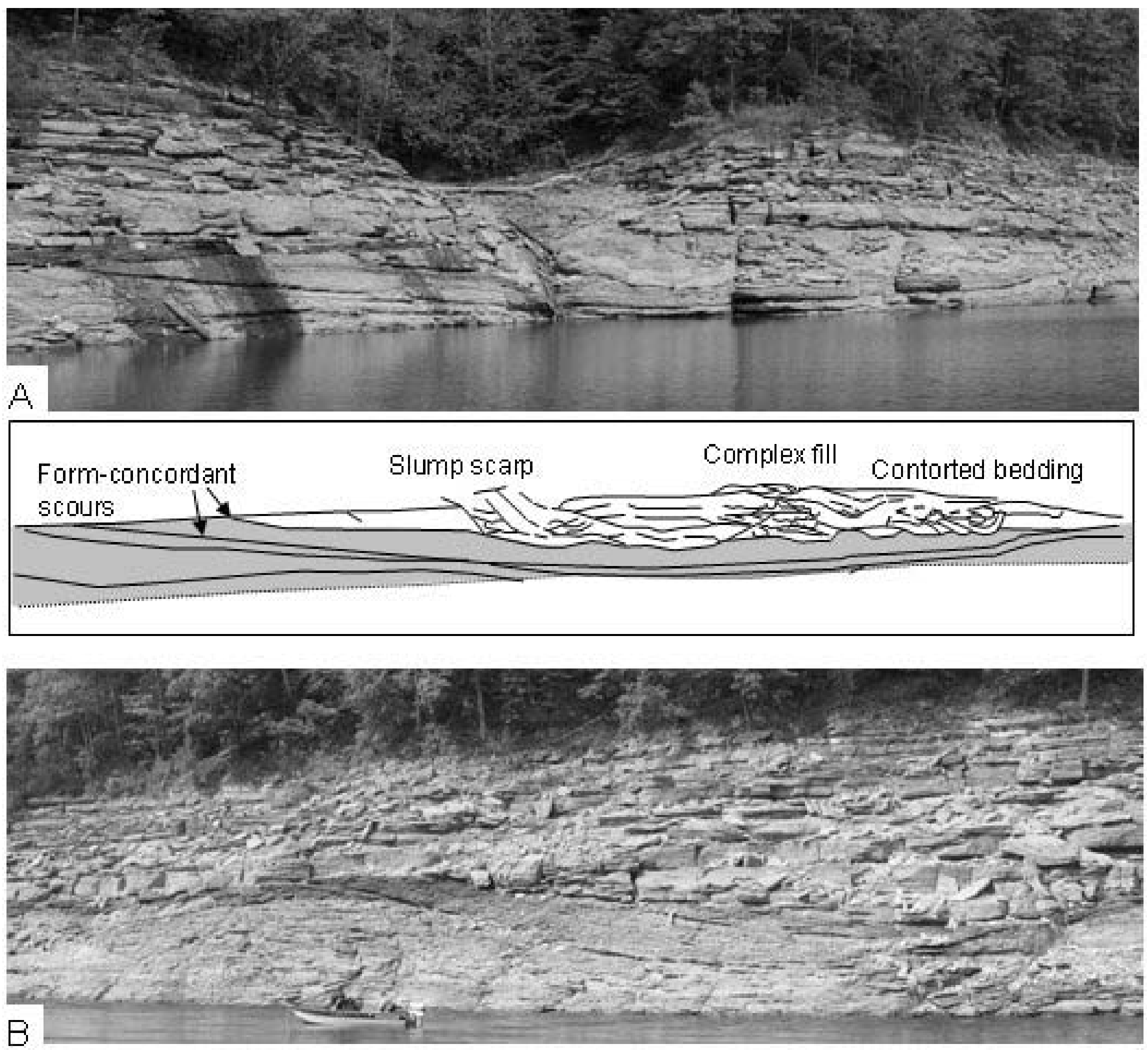


Figure 19. The northern shore of Lake Cumberland northwest of the State marina at Outcrop I exhibits (A) a small scour filled with soft-sediment deformation, and (B) Rotated bedding in lower siltstone (lake level for photos is 680.9 ft). Boat for scale.

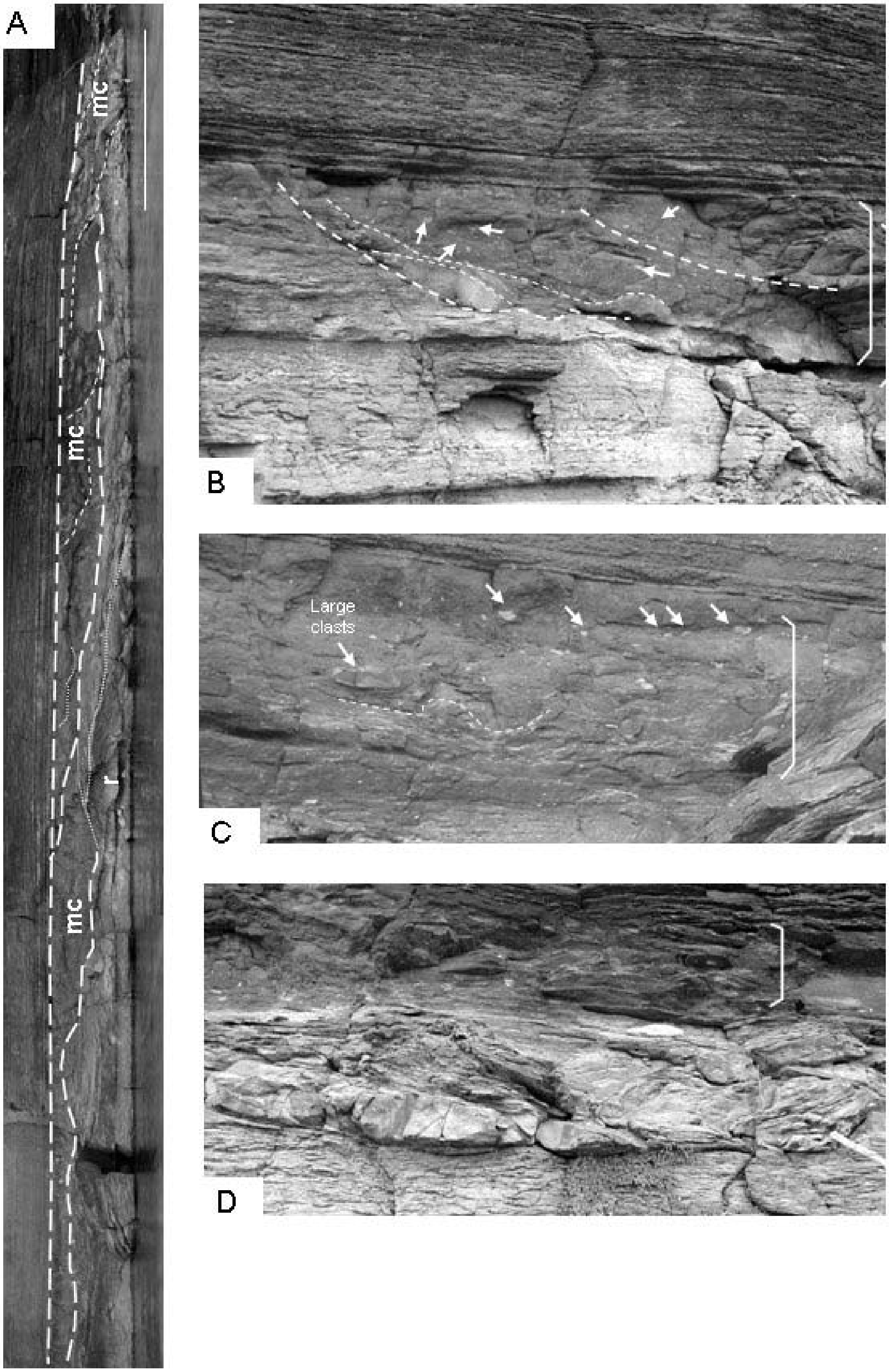


Figure 20. Matrix-supported conglomerates (mc) exposed on the south shore of Lake Cumberland at Outcrop J. (A) Photomosaic of the outcrop showing the succession of westward-accreting lenses that contain the conglomerate. Photomosaic is at relatively high water. (B) The conglomerate (bracketed) is a mass flow deposit that contains internal slumps or scours (dashed lines) and large clasts (arrows). (C) In some areas it appears that large clasts are concentrated

along the top of the flow. (D) Toward its terminus, the mass flow (arrows point to light-colored clasts) is underlain by a scour with soft-sediment deformation (lake level for 19C is at lower water, 680.9 ft).

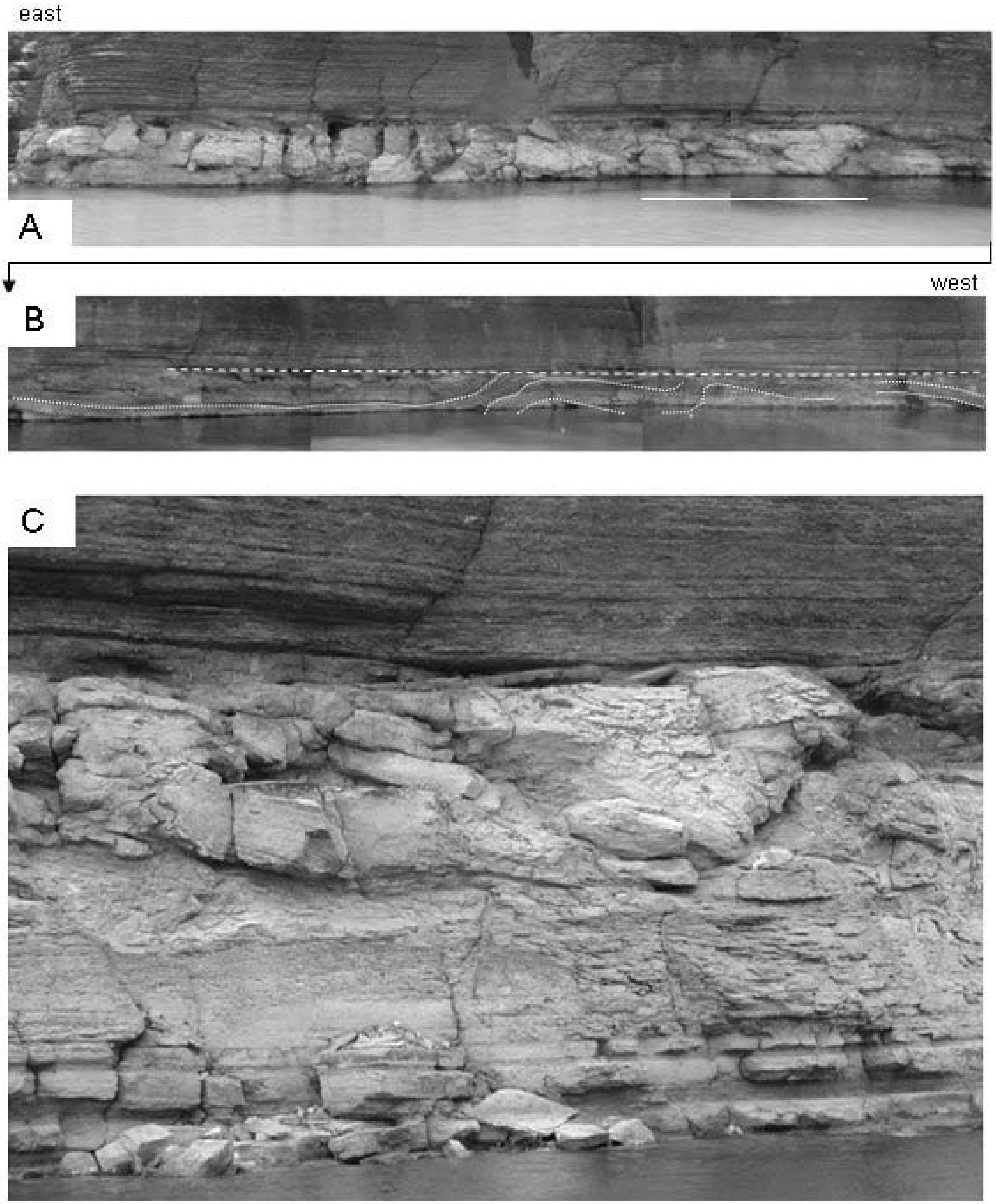


Figure 21. Lower interval of deformed beds at Outcrop J. (A) Mosaic showing the deformed zone with large, white blocks of carbonate and siltstone and deformed siltstones and broader, rolls in underlying-downdip siltstones. (B) At lower water the base of the slump-slide is exposed (location is white line in mosaic A, but only top of the feature is exposed at higher water).

Lewis and Potter (1978) noted the sharp truncation surface above a folded, and slumped zone at this exposure and interpreted the 20 ft (6 m) thick, interval as a submarine slide. Pebbly mudstones or fine-grained matrix-supported conglomerates can be formed in a variety of mass flows, but are commonly formed in debris flows and mud flows (Lowe, 1979; Mulder and Alexander, 2001). The deposits of debris flows are sometimes called "debrites." Debris and mud flows are common in many distal ramp/slope environments and can travel downslope great distances from their source. They can also change character from debris flows to turbidity and other types of currents as they move downslope (e.g., Mulder and Alexander, 2001). More work is needed on this interesting deposit.

The debrites overly another deformed zone, which is exposed at low water. The deformed carbonates appear to be part of a large slump, or slump above a scour. These may represent updip units transported by turbidity currents or mass flows down dip to this location. The relationship between this unit and the overlying debrite requires more work. It would be interesting to see if any of the clasts could be matched to updip strata.

**Outcrop K:** Another green shale mound and carbonate buildup is exposed on the north shore of the Lake at the mouth to Caney and Wolf Creeks (Fig. 5). This mound has been named the Cave Springs Mound (Ausich and Meyer, 1990; Meyer and others, 1995). It has a fossiliferous, green shale core (g in Fig. 22), like the mound(s) at Greasy Creek (north, south), but here the carbonate buildup is dominated by packstone, rather than wackestone (Ausich and Meyer, 1990). Packstone buildups in the area may have slightly different geometries than wackestone buildups, with the apex consisting of interbedded green shale and carbonates. For example, the apex of the green shale in the Cave Springs mound appears to dip slightly and is capped by interbedded shales and carbonates. The carbonate (c  in Fig. 22) buildup grades laterally into unfossiliferous siltstone and vertically into crinoidal grainstone (Ausich and Meyer, 1990).

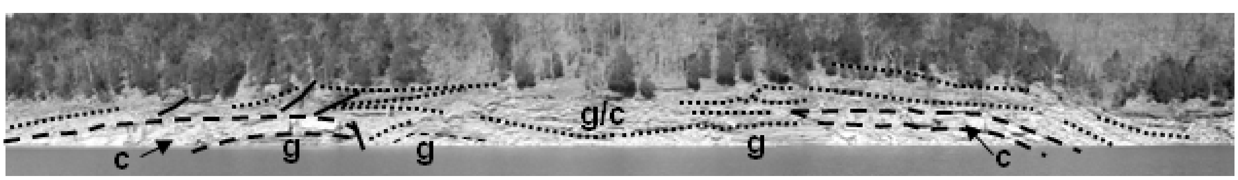


Figure 22. Photomosaic of the Cave Springs Mound on the north shore of Lake Cumberland east of the mouth of Caney Creek. The carbonate buildups (c) on the flanks of the green shale mound (g) are dominated by packstone, rather than wackestone. The carbonates buildups pinch out above the green shale core.

## Caney and Wolf Creeks

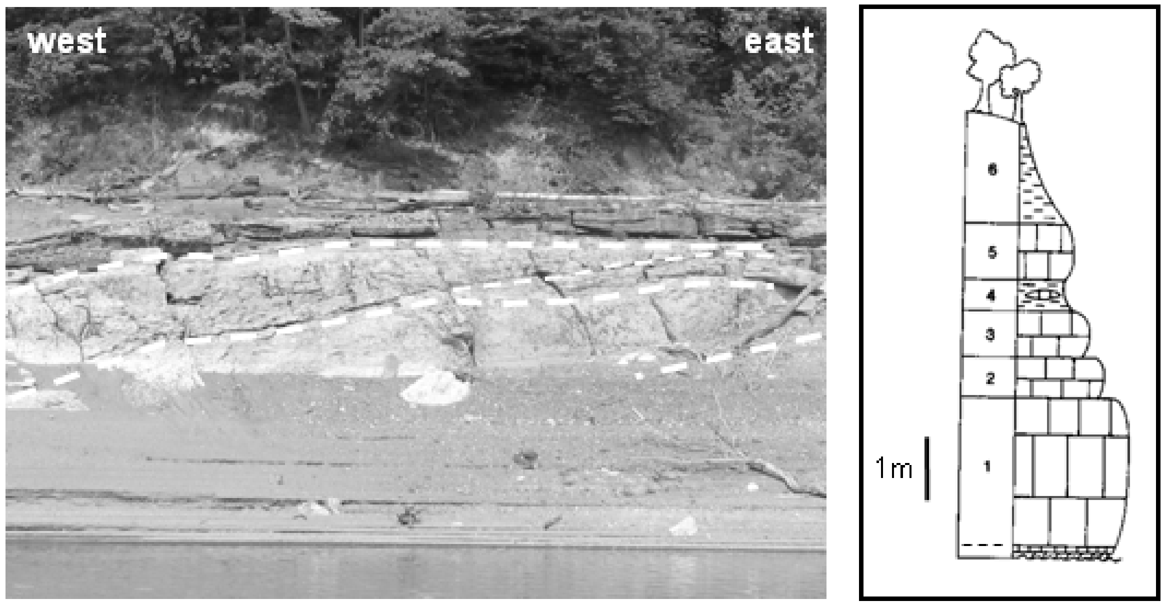


Figure 23. West flank carbonate buildup of the Pleasant Hill mound (A) and measured section of the carbonate mound after Meyer and others (1995, Fig. 6).

**Stop 3: Pleasant Hill mound**

This is Stop 1 in the 1978 field guide (Lewis and others, 1978), and this mound has been discussed in Ausich and Meyer (1990), and Meyer and others (1995). This is one of the few mounds on the lake that is accessible by car, as it is adjacent to the Pleasant Hill boat ramp. Pleasant Hill is a wackestone build up on the flanks of a green shale mound (Figs. 23-24). Compare this mound to the Greasy Creek (north) and (south) mound (s). Certainly, this mound is thinner, but the geometry of the carbonate buildup on the flank of the green shale mound is similar. Ausich and Meyer (1978) reported that the wackestone on the western flank was 15 ft thick (Fig. 23B) and at least 430 ft wide (at lake level of 700.7 ft). At lower lake levels, the lower margin of the west flank can be seen to extend farther to the west (Fig. 24A) Where thick, the carbonate buildup consists (Figs. 24A-B) of a basal, 0.3 ft (0.1 m), coarse, crinoidal grainstone/packstone, 8.2 ft (2.5 m) of massive wackestone containing irregular chert nodules (Figs. 24B-D), 2.1 ft (0.65) m massive crinoidal grainstone/packstone, 2.5 ft (0.75 m), massive crinoidal grainstone with less siliceous material than underlying units, 1.6 ft (0.5 m), fossiliferous green shale, 3 ft (0.9 m), massive crinoidal grainstone/packstone with chert masses and geodes (Fig. 24E), and capped by fossiliferous green shale which covers both flanks of the carbonate buildups (Meyer and others, 1995). The upper and flanking beds contain abundant chert- and quartz-filled vugs and fractures, and many geodes. Geodes are common in many of the buildups, as well as the thin-bedded dolostones and rarer limestones between the buildups in the Fort Payne (see Appendix C). Crinoids are also abundant, as in the other mounds (Fig. 24F). Look at some of the vugs and voids on the flanks of the mound (Figs. 24B-C). Some of these may be a type of stromatactus cavities (*see* Glossary–Appendix B), which are common in Waulsortian-type

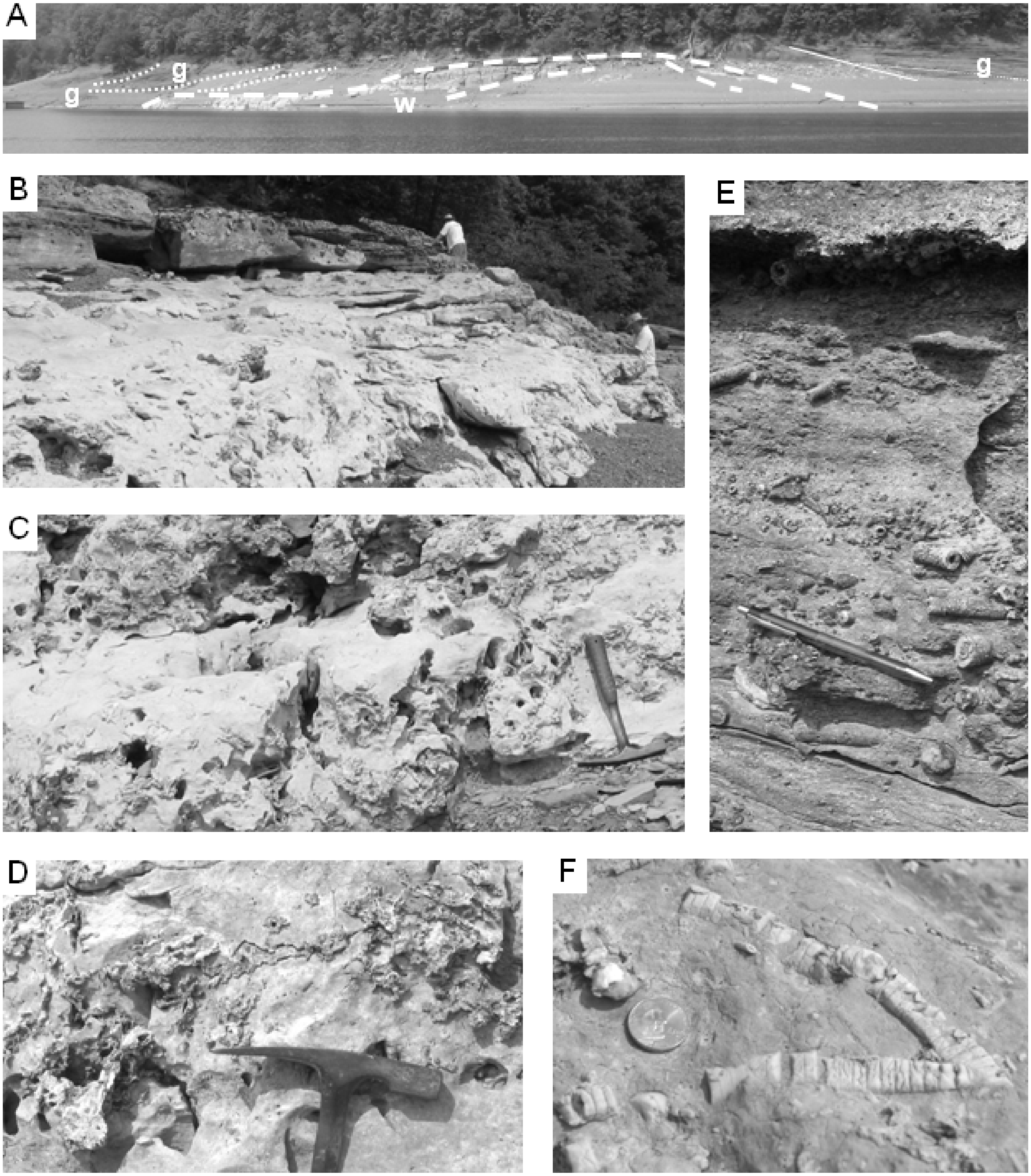


Figure 24. The Pleasant Hill mound is exposed on Caney Creek at Stop 3. (A) Wackestone mound (w) is covered by green shale (g), which dips off each flank, and underlain by green core shale (g). (B) The wackestone is best exposed on the west flank. (C) The wackestone contains large vugs, some of which may be burrows. (D) Possible stromotactis(?) vugs and geodes are common. (E) Packstones cap the thick wackestone mound; both contain abundant crinoidal debris (lake level for photos is 680.9 ft).

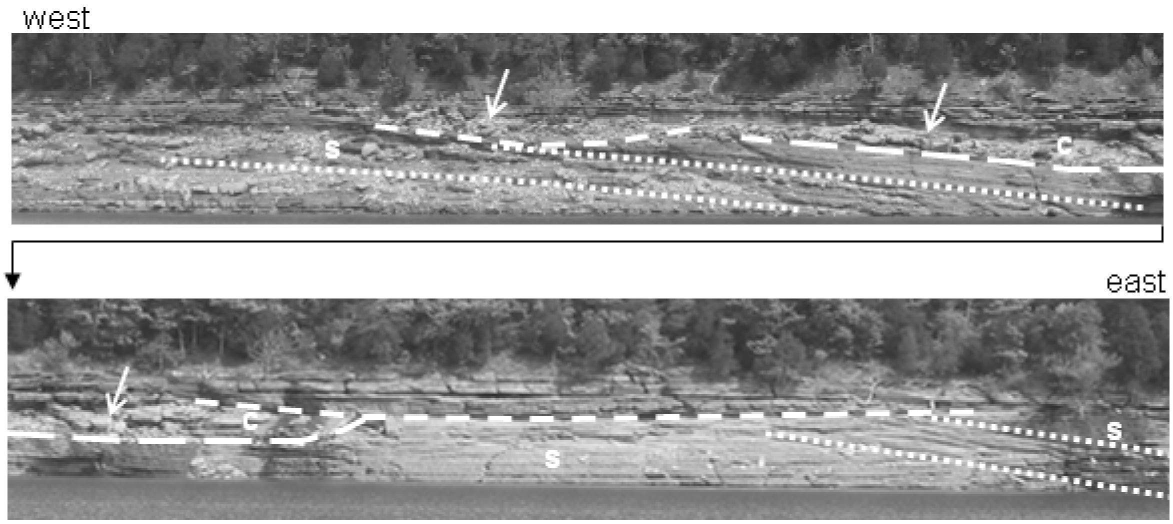

Figure 25. Dipping beds along north shore of Wolf Creek at Outcrop L. A carbonate lens (c, long dashes) with soft-sediment deformation (arrows) is preserved between dipping siltstone (s) beds and cut by scours filled with siltstone (short dashes). Lake level for photomosaic is 680.9 ft.

facies and think about this unit as an analogue to subsurface oil reservoirs. Note also the draping dip of bedding in the capping green shales, as well as evidence of down-slope movement.

**Outcrop L**: Across the creek from Stop 3 note the westward rising bedding along the north shore of Wolf Creek (Fig. 25). Whether this represents the eastern flank of the Pleasant Hill mound, or another mound that has since been eroded from the lake is uncertain, but the influence of paleotopography can be seen by the down-slope rotation direction of slump and deformation features along the shoreline. Compare this to Outcrop E and its relationship to the Greasy Creek (south) mound.

**Outcrop M**: Further upstream on Greasy Creek is an exceptional outcrop of slumping and soft-sediment deformation. The small tributary creek where this feature is exposed provides an exceptional 3-dimensional view of the deformation. Photographs of both sides of the creek were shown in the Lewis and Potter (1978, Figs. 20, 21) field guide. On the Wolf Creek (north-facing) side of the outcrop the deformed interval overlies a sharp, listric contact with several meters of relief, which is truncated by the flat-lying interbedded siltstones and dolostones that cap the deformed interval across the rest of the exposure (Figs. 26A-B). Bedding within the deformed interval consists of a series of elongate folds, which are well-defined by a series of resistant, iron-stained dolostones (Fig. 26B). The view is along the long axis of the folds, with bedding dipping toward Wolf Creek (and out of the photograph) at the base and top of the deformed interval. Several glide planes offset bedding. From the creek side, the bedding is crosscut by multiple glide planes (Figs. 26A, C), and there are complex folds and deformation. This orientation is looking across, or through the recumbent folds. This outcrop is a good illustration of the complexity of deformation in this interval, as well as the significance of the orientation of the exposure to the appearance of deformation.

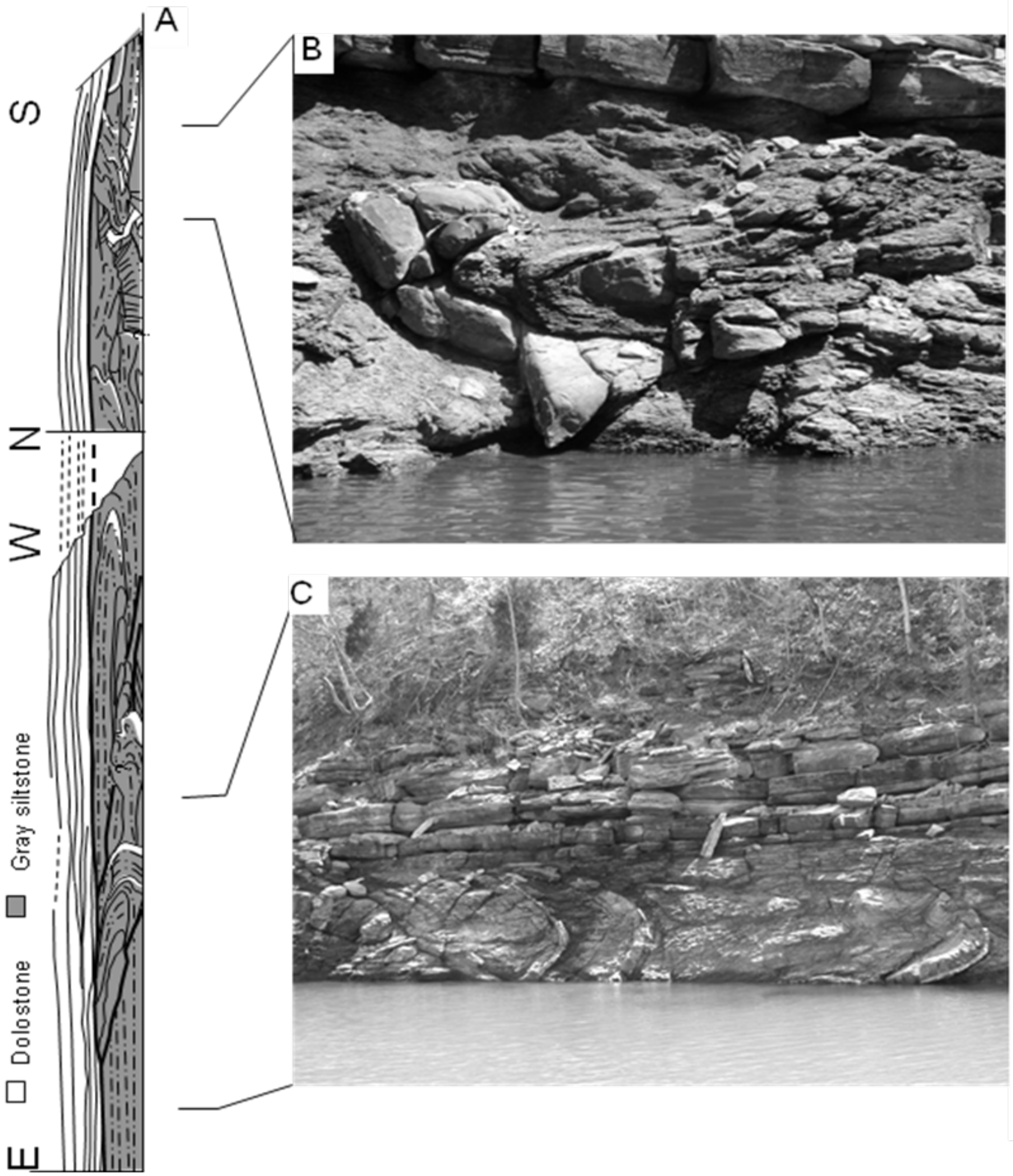


Figure 26. Intense deformation and recumbent folding exposed at Outcrop M. (A) Diagram of the deformation interval based on a photomosaic. Note the change in direction from the Wolf Creek (E-W) to tributary side (N-S) of the exposure. (B) Photo of recumbent folds on the Wolf Creek side, and (C) tributary side of the exposure.

**Stop 4**

This stop was previously described as Stop 2 in Lewis and Potter (1978, Fig. 21) and was also discussed in Ausich and Meyer (1990). It is a great example of a paleochannel and is the largest scour or channel on the lake. It truncates more than 50 ft (15 m) of lateral siltstone and is at least 850 ft (260 m) wide (Figs. 27A-B). Ausich and Meyer (1990) described the fill as beds of crinoidal packstone and wackestone. Coarser litholgies are poorly sorted and may contain siltstone clasts as much as 2 inches (3 cm) in diameter. Bedding is thick to very thick (Fig. 27C). Graded beds are common. Some beds are crossbedded, with crossbeds oriented N64E and 10N, similar to master bedding dip. As at the other stops, crinoids and geodes are abundant.

Several smaller scours have been described along the lake. How does this compare with those? Where is the incision cutting down from? How does this relate to the level of the Pleasant Hill mound, visible across the lake? How would a large, deep, channel like this form in a relatively deep-water environment? Understanding this relationship is important to understanding the depositional sequences in this interval.


Figure 27. Large channel-form carbonates at Stop 4. (A-B) Scour is cut into siltstone (dashed line). Person for scale (white arrow in B. (C ) Channel is filled with dipping wackestones and packstones (yard stick scale).

From Stop 4 head back to the state docks. Along the way think about how the various facies might fit into an overall depositional model.

**Depositional Model**

In the introduction the regional stratigraphic relationships between the Borden and Fort Payne were introduced (Fig. 2). Most modern researchers agree that the lower and middle part of the Fort Payne Formation were deposited in deeper water in front of the Borden front/paleoslope. A lack of shallow-water bedding features (tidal lamination, ripples, etc.), and diagnostic shallow-water bioturbation, confirms the likelihood that the mound interval was deposited in relatively deep water although still within the photic zone because of the occurrence of benthic dasycladacean green algae in the wackestones and packstones (Ausich and Meyer, 1990; Meyer and others, 1995; Ketani and Reed, 2002).

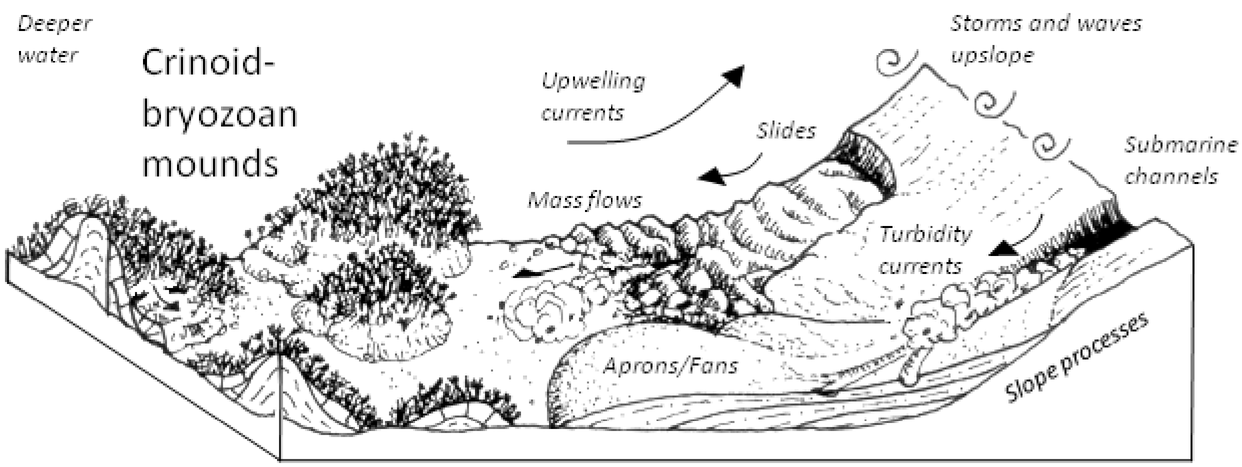


Figure 28. Model of lower Fort Payne paleoenvironment and depositional facies in the Lake Cumberland area (after Ketani and Reed, 2002). No scale inferred.

Figure 28 is a schematic diagram which illustrates a slope and basin environment as inferred for this interval by many studies (MacQouwn and Perkins, 1982; Ausich and Meyer, 1990; Sable and Dever, 1990; Meyer and others, 1995; Lasemi and others, 1998, 2003; Khetani and Read, 2002; Lumsden, 2003; Krause and others, 2002; 2004). Think about the various outcrops seen on this trip and try to place them in their relative position in this diagram. The thin-bedded, flat-lying to slightly dipping, “normal” or “background” sediment in the Fort Payne was deposited as ramp-slope deposits (e.g., Ausich and Meyer, 1990; Sable and Dever, 1990). Such environments would be expected to produce turbidity currents, slumps, slides, and other mass flows. Ausich and Meyer (1990) inferred that some of the sheet deposits might represent carbonate aprons (*see* Mullins and Cook, 1986), which are somewhat analogous to submarine fans, but formed from carbonate muds off of carbonate banks. Submarine fans would be sourced by submarine channels, and might contain numerous smaller “distributary” channels.

The origin of the mounds themselves is still somewhat of a mystery despite research by many authors. Where the base of the green shale mounds are exposed, they appear to have developed above local paleotopographic highs (Lumsden, 1982; Ausich and Meyer, 1990; Stapor and Knox, 1995). MacQuown and Perkins (1982) noted similar relationships with producing Fort Payne carbonate mounds in Tennessee which were developed over structural highs in the underlying Chattanooga Shale. Baffling of sediment by crinoids and fenestrate bryozoans on these highs may trapped sediment creating a kind of self-perpetuating mounding (MacQouwn and Perkins, 1982; Ausich and Meyer, 1990; Stapor and Knox, 1995). Carbonate wackestone and packestone buildups formed along the flanks of the mud mounds by *in situ* accumulations of crinoids and bryozoans. Flanking packestones and grainstones may have been formed by winnowing of the carbonate mounds by storm waves and also by slope processes on the flanks of the mounds (Ausich and Meyer, 1990; Meyer and others, 1995). Subsequent burial of the mounds by shales, siltstones, and other carbonates was influenced by the paleotopography of the mounds themselves.

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Lowe, D.R., 1975, Regional controls on silica sedimentation in the Ouachita System: Geological Society of America Bulletin, v. 86, no. 8, p. 1123-1127.

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Lumsden, D.N., 1988, Origin of the Fort Payne Formation (Lower Mississippian), Tennessee: Southeastern Geology, v. 28, no. 3, p. 167-180.

Lumsden, D.N., 2003, Organodiagenetic dolomite on a deep subtidal shelf, Fort Payne Formation (Mississippian), Tennessee, U.S.A., *in* Ahr, W.M., Harris, P.M., Morgan, W.A., and Somerville, I.D., eds., Permo-Carboniferous Carbonate Platforms and Reefs: Tulsa, Society for Sedimentray Geology, Special Publication, v. 78, p. 323-332.

MacQuown W, C., and Perkins, J. H., 1982, Stratigraphy and petrology of petroleum-producing Waulsortian-type mounds in Fort Payne Formation (Lower Mississippian) of North–Central Tennessee: American Association of Petroleum Geologists, v. 66, p.1055-1075.

Maliva, R.G., 1987, Quartz geodes: Early diagenetic silicified anhydrite nodules related to dolomitization: Journal of Sedimentary Petrology, v. 57, p. 1054-1059.

Marcher, M.V., 1962, Crinoidal bioherms in the Fort Payne Chert (Mississippian) along the Caney Fork River, Tennessee: U.S. Geological Survey Professional Paper 450-E, p. E-43-45.

Meyer, D.I., Ausich, W.I., Bohl, D.T., Norris, W.A., and Potter, P.E., 1995, Carbonate mud-mounds in the Fort Payne Formation (lower Carboniferous), Cumberland Saddle Region, Kentucky and Tennessee, U.S.A.: Special Publications International Association of Sedimentologists, v. 23, p. 273-287.

Meyer, D.I., Potter, P.E., Thies, J.L., Ausich, W.I., and Leslie, S.A., 1997, A deep-to-shallow transition in the Fort Payne Formation (Lower Mississippian), Kentucky Highway 61, Cumberland County, Kentucky: Kentucky Geological Survey, Series XI, Map and Chart Series, no. 12, 1 sheet.

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Munn, M.G., 1914, Oil and gas fields of Wayne County, Ky.: U.S. Geological Survey Bulletin 579, 105 p.

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Sable, E.G., and Dever, G. R., Jr., 1990, Mississippian rocks in Kentucky: U.S. Geological Survey Professional Paper 1503, 125 p.

Stapor, F., and Knox, L. W., 1995, Waulsortian-like bioherms of the Maury and Fort Payne Formations, Tennessee, *in* Driese, S.G., Complier, Guidebook for field trip excursions, southeastern section, GSA (Trips prepared for the 44th Annual Meeting of the Southeastern Section of the Geological Society of America, Knoxville, TN., April 1995), Geological Sciences, University of Tennessee, Knoxville, 90 p.

Statler, A.T., 1971, Fort Payne Production in the Oneida West area, Scott County, Tennessee, *in* Proceedings of the Symposium of Future Petroleum Potential of NPC Region 9 (Illinois Basin, Cincinnati Arch, and northern part of the Mississippian Embayment): Illinois Geological Survey, Illinois Petroleum 95, p. 94-110.

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Thaden, R.E., and Lewis, R.Q., Sr., 1962, Geology of the Jamestown Quadrangle, Kentucky: U.S. Geological Survey, 7.5-minute quadrangle map, GQ-182.

Wilson, E.M., 1971, Fort Payne production in two Cumberland Saddle areas of Kentucky and Tennessee, *in* Proceedings of the Symposium of Future Petroleum Potential of NPC Region 9 (Illinois Basin, Cincinnati Arch, and northern part of the Mississippian Embayment): Illinois Geological Survey, Illinois Petroleum, v. 95, p. 75-93.

## Appendix A—Annotated References to the Fort Payne Formation in South-Central Kentucky and Adjacent Tennessee

Annotated references for Waulsortian mounds and comparisons of the Fort Payne buildups to Waulsortian facies were described in the Lewis and Potter (1978) field guide. Herein, additional references concerning the geology of the Fort Payne buildups in south-central Kentucky and neighboring Tennessee are summarized. Reading these annotations provides a good start to learning about the sedimentation, paleontology, stratigraphy, regional setting, and past oil production of the Fort Payne Formation.

Ausich, W.I., and Meyer, D.L., 1990, Origin and composition of carbonate buildups and associated facies in the Fort Payne formation (Lower Mississippian, south-central Kentucky): an integrated sedimentologic and paleoecologic analysis: Geological Society of America Bulletin, v. 102, p. 129-146.

Five facies of carbonate buildups are recognized in a background of argillaceous silt deposition in the lower photic zone of clinoforms. Paper contains many informative photographs and much tabled data.

Ausich, W.I., Kammer, T.W., and Meyer, D.L., 1997, Middle Mississippian disparid crinoids from the east-central United States: Journal of Paleontology, v. 7, p. 131-148.

Description and definition of the disparid crinoids from the Fort Payne Formation and coeval late Osagean faunas from the midcontinent.

Ausich, W.I. and Meyer, D.L., 1988, Blastoids from the late Osagean Fort Payne Formation (Kentucky and Tennessee): Journal of Paleontology, v. 62, p. 269-283.

Description of the blastoid echinoderms from the Fort Payne Formation of south-central Kentucky. A total of nine blastoids are described, including four new genera and six new species.

Ausich, W.I. and Meyer, D.L., 1992, Crinoidea Flexibilia (Echinodermata) from the Fort Payne Formation (Lower Mississippian; Kentucky and Tennessee): Journal of Paleontology, v. 66, p. 825-838.

Description of 17 flexible crinoids from the Fort Payne Formation of south-central Kentucky. Numerous flexible crinoids are described, including three new species.

Ausich, W.I., and Meyer, D.L., 1994, Hybrid crinoids in the fossil record (Early Mississippian, Phylum Echinodermata): Paleobiology, v.20, p. 362-367.

*Eretmocrinus* is one of the common crinoids on Fort Payne carbonate buildups. *Eretmocrinus magnificus* is very common, and *Eretmocrinus praegravis* are common. In this paper, hybrid specimens that are a cross between these two species are recognized.

Ausich, W.I., Meyer, D.L., and Waters, J.A., 1988, Middle Mississippian blastoid extinction event: Science, v. 240, p. 796-798.

Evolutionary paleoecological patterns of blastoid extinction are described. The Fort Payne Formation blastoids are in a relatively deep-water refuge following the extinction of shallow-water Burlington Limestone blastoids.

Butts, Charles, 1922, The Mississippian Series of eastern Kentucky: Kentucky Geological Survey Series VII, v. 7, 188 p.

In this classic report, Butts recognizes (p. 44-46 and 76-88) the two principal types of limestone in the Fort Payne—the massive mud mounds of the oil-bearing Beaver Creek "sand" and also well-washed limestones — and additionally comments on the abrupt transitions from shale to limestone found in the formation. Butts provides long lists of fossils and relied on them for correlation.

Chowns, T.M., and Elkins, T.M., 1974, The origin of quartz geodes and cauliflower chert through silicification of anhydrite nodules: Journal of Sedimentology Petrology, v. 44, p.885-903.

This paper recognized quartz geodes in the dolostones (and dolomitic siltstones) of the Fort Payne and Warsaw Formations as pseudomorphs after anhydrite nodules (new road cuts show this). The authors proposed a shallow, dry (sabkha) environment for precipitation of the anhydrite. [However,

such geodes also occur in the mudstone mounds, which hardly fit such an environment; nor does this origin fit the regional setting of the Fort Payne — think of “deep water evaporates”.

Kepferle, R.C., and Lewis, R.Q., Sr., 1975, Knifley Sandstone and Cane Valley Limestone: two new members of the Fort Payne Formation (Lower Mississippian), *in* Cohee, G.V., and Wright, W.B., eds., Changes in stratigraphic nomenclature by the U.S. Geological Survey 1974: U.S. Geology Survey Bulletin 1394A, p. A63-A70.

This paper describes several of the facies related to the broad clinoforms of the Fort Payne Formation. The limestones of the Cane Valley Member are essentially similar to those of the flanking, inclined crinoidal-bryozoan beds bordering the wackestone mud mounds, but are present well above the black shale. Well-developed clinoforms are typical.

Khetani, A.B., and Read, J.F., 2002, Sequence development of a mixed Carbonate-siliciclastic, high relief ramp, Mississippian, Kentucky, USA: Journal of Sedimentary Research, v. 72, p. 657-672.

Modern regional analysis of the Fort Payne across Kentucky. Combines thickness map and two cross sections, plus outcrop study to identify four sequences of which two are exposed along the shores of Lake Cumberland. Insightful terminology and concepts including Borden paleoshelf, basin floor deposits, and ramp (describes westward thickening of the Fort Payne into the Reelfoot Trough). Recognizes the “green shale and mound facies”, “siliceous dolosiltite slope and basin fill”, etc.

Knox, L.W., and Stapor, Frank, 2003, Clay-rich, Waulsortian-like mounds in the Mississippian (Osagean) Fort Payne Formation of central Tennessee, *in* Cox, R.T., Complier, Field Trip Guidebook 37th Annual Meeting South Central Section and 32nd Annual Meeting of the Southeastern Section of the Geological Society of America, University of Memphis March 9 -16 2003: Tennessee Division of Geology Report of Investigations 51, p.83-104.

Important regional contribution, which indicates many broad similarities between Waulsortian mounds and the buildups on Lake Cumberland, but also some differences. Well illustrated.

Krause, R.A., Meyer, D.L., and Ausich, A.I., 2002, Carbonate buildups in the Fort Payne Formation (Lower Mississippian), Cumberland County, Kentucky, in Ettensohn, F.L., and Smath, M.L., eds., Guidebook for geology field trips in Kentucky and adjacent areas: Lexington, Kentucky, 2002 Joint Meeting of the North-Central and Southeastern Section of the Geological Society of America, Kentucky Geological Survey, p. 1-13.

Identified five facies in the mounds (see next reference). First application of sequence stratigraphy to the mud mounds.

Krause, R.A., and Meyer D.L., 2004, Sequence stratigraphy and depositional dynamics of carbonate buildups and associated facies from the lower Mississippian Fort Payne Formation of southern Kentucky: Journal of Geology, v. 74, p. 87-100.

This paper recognized five facies — green shale cores with minor tabular crinoidal-bryozoan beds (background sedimentation) and three carbonate mud mound facies — shaley packstone, the massive wackestone of the core, and flanking crinoidal grainstones, with descriptions of excellent outcrops in nearby Cumberland County on KY 61 north of Burkesville. These outcrops are well-documented and very much worth a visit, especially to see the application of sequence stratigraphy. Compare with regional studies by Khetani and Read (2002).

Kuslansky , G.H., and Friedman, G.M., 1984, Hydrocarbon reservoirs in Waulsortian facies: an example from the Fort Payne Formation (Mississippian), Scott County, Tennessee: Compass of Sigma Gamma Epsilon, v. 62, p. 31-44.

Well-argued paper indicates that porosity in the Fort Payne fields of Tennessee is secondary and due to solution–collapse brecciation of evaporates by fresh-water leaching after deposition of the mud mounds (breccia, fractures, and vuggy porosity) and that important production comes from the flanking and overlying limestones. Hypothesizes that algal filaments built the carbonate mud mounds and were the source of oil in the well-washed limestones. Important paper pointing to differences between the buildups from the Lake Cumberland region and the producing mounds of Tennessee.

Lasemi, Z., Norby, E.D., Utguard, J.E., Ferry, W.R., Cuffey, R.J., and Dever, G.R., Jr., 2003, Mississippian carbonate buildups and development of cool-water-like carbonate platforms in the Illinois Basin, Midcontinent, USA, *in* Ahr, W.M., Harris, D.M., Morgan, W.A., and Sommerville, J.D., eds., Permo-Carboniferous carbonate platforms and reefs: Society of Economic Paleontologists and Mineralogists Special Publication 78 and American Association of Petroleum Geologists Memoir 83, p. 69-95.

This study, although much to the west of Lake Cumberland, is of interest because its Figure 16 shows well the paleo-oceanography of the Fort Payne's semi-starved basin and explains why the unit is rich in siliceous sponges.

Leslie, S.A., Ausich, W.I., and Meyer, D.L., 1996, Lower Mississippian sedimentation dynamics and conodont biostratigraphy (lowermost Fort Payne Formation) along the southeastern margin of the Eastern Interior Seaway: Southeastern Geology, v. 36, p. 27-35.

Study of conodonts in the Floyds Knob Glauconite at the base of the Fort Payne Formation, and shows it to be a time-rich bed of 17.5 Ma duration, whereas the Fort Payne itself was deposited in about 2 Ma. In Tennessee the Floyds Knob Glauconite is equivalent to the top of the Maury Formation.

Lewis, R.Q., Sr., and Potter, P.E., 1978, Surface rocks in the western Lake Cumberland area, Clinton, Russell and Wayne Counties, Kentucky: Annual Field Conference of the Geological Society of Kentucky (Published by the Kentucky Geological Survey Lexington, Ky.), 41 p.

Field guide that shows the study area in relation to the Borden Front and recognizes the mud mounds and their well-washed, associated crinoidal-bryozoan limestones as Waulsortian equivalents to those in Belgium. Notable are its photographs of slumps (Figs. 19, 20 and 22).

Lewis, R. Q., Sr., and Taylor, A. R., 1979, The Science Hill Member of the Warsaw Formation and its relation to other clastic units in south-central Kentucky: U.S. Geological Survey Bulletin 1435-D, 15 p.

Paper describes a unit northwest of Somerset and well beyond the Lake Cumberland area, but still relevant to an understanding of the Fort Payne. See Figure 2 for an example of a small delta (up to 12 ft. thick) that supplied mud and silt to the Fort Payne beyond the edge of the Borden paleoshelf.

Lumsden, D.M., 1998, Origin of the Fort Payne Formation (Lower Mississippian); Tennessee: Southeastern Geology, v. 28, p. 167-180.

Petrologic study of four outcrops integrated with regional stratigraphy shows that the Fort Payne of central and northeastern Tennessee was deposited on an isolated high mostly in the dysaerobic zone with some anoxia at its base. Deposition considered to have occurred over 2 Ma. Infers cool-water upwelling from the west as the source of the silica for the many sponge spicules, its most dominant fossil. Overall, the Fort Payne averages about 42% dolomitic impure chert (porcelainite), 21% cherty fossiliferous carbonate and the remainder 37% clay. Compares the Fort Payne to the Monterey Formation of California.

Lumsden, D. M., 2003, Organo-diagenetic dolomite on a deep subtidal-shelf, Fort Payne Formation (Mississippian), Tennessee, USA, *in* Ahr, W. M., Harris, D. M., Morgan, W. A., and Sommerville, J. D., eds., Permo-Carboniferous carbonate platforms and reefs: Society of Economic Paleontologists and Mineralogists Special Publication 78 and American Association of Petroleum Geologists Memoir 83, p. 69-95.

Euhedral 10-50 mm dolomite occurs as zoned rhombs enclosed in a very fine spiculiferous chert. Three types recognized: a primary precipitate, as overgrowths on the 10-50 mm dolomite and after lithification. Argues for a deep shelf setting and makes comparisons with other formations.

MacQuown, W. C., 1984, The Lower Mississippian Waulsortian facies of Tennessee and Kentucky, *in* Bolton, K., Lane H.R., and LeMone, *eds.*, Symposium on the paleoenvironmental setting and distribution of Waulsortian facies: El Paso Geological Society and University of Texas, El Paso, p.34- 42.

Insightful paper that provides structure maps on the underlying Chattanooga Shale, the submound unit, and the mound unit (Fig. 4); schematic cross sections (Fig. 5), and a suggested evolution of the mounds (Fig. 6). Table 1 compares European mounds with the mounds of northeastern Tennessee. Notes interbedded evaporites and secondary porosity due to freshwater leaching.

MacQuown W, C., and Perkins, J. H., 1982, Stratigraphy and petrology of petroleum-producing Waulsortian-type mounds in Fort Payne Formation (Lower Mississippian) of North–Central Tennessee: American Association of Petroleum Geologists, v 66, p.1055-1075.

This paper summarizes the geology of petroleum producing mounds in the Fort Payne and reports that the best reservoirs in the Fort Payne occur in the grainstones above the massive mud mounds. The fields, however, have northeast-southwest trends instead of northwest-southeast trends. Some anhydrite and gypsum noted near base of the Fort Payne. Much petrography. Comparisons made with Waulsortian of Belgium.

Marcher, M. V., 1962, Crinoidal bioherms in the Fort Payne Chert (Mississippian) along the Caney Fork River, Tennessee: U.S. Geological Survey Professional Paper 450E, p. E43-E45.

Pioneering paper reports that bioherms are located at or near the contact of the Fort Payne Formation with the Chattanooga Shale, that they are oval to elongated with direction of elongation of N 30°W, and from 20 to 100 ft. in thickness. Three facies recognized — a core plus inner and outer flanking beds. Descriptions indicate some differences with Lake Cumberland mounds.

Meyer, D.L., and Ausich, W.I., 1992, Fort Payne carbonates facies (Mississippian) of south-central Kentucky: Geological Survey Miscellaneous Report 4, Field Trip 14, Annual Meeting of the Geological Society of America, Cincinnati, Ohio, October 26-29, 20 p.

Little-known guidebook with information concerning the paleontology and facies of the buildups. See Figure 23 for a rare isopach of two buildups, and Figures 12 and 22 for important cross sections.

Meyer, D. L., Potter, P. E., Thies, J. L., Ausich, W. I., and Leslie, S. A., 1997, A deep-to shallow transition in the Fort Payne Formation (Lower Mississippian) Kentucky Highway 61, Cumberland County, Kentucky: Kentucky Geological Survey, Map and Chart Series 12, Series XI.

Map and chart shows that driving south some four miles from Burkesville on KY 61 brings you to some spectacular road cuts in flanking crinoiidal-bryozoan beds and a few wackestone mud mounds just above the 28 ft. thick Chattanooga Shale. These facies are identified on a nearby gamma ray-neutron log (Fig. 6). At the south end of the cuts see a cross section of the inclined (dune?) bedding in the overlying Warsaw Formation.

Meyer, D. L., Ausich, W. I., and Terry, R. E., 1989, Comparative taphonomy of echinoderms in carbonate facies: Fort Payne Formation (Lower Mississippian) of Kentucky and Tennessee: Palaios, v. 4, p. 533-552.

Disarticulation of more than 3,000 specimens of crinoids and blastoids studied at 14 localities in south-central Kentucky and nearby Tennessee to determine relative rates of burial (slow sedimentation produces complete disarticulation whereas rapid burial favors much better articulation). Study added new insights to the relative rates of sedimentation of the five well-recognized buildup facies (Fig. 12).

Meyer, D. L., Ausich, W. I., Bohl, D. T., Norris, W. A., and Potter, P. E., 1995, Carbonate mud mounds in the Fort Payne Formation (Lower Carboniferous), Cumberland saddle region, Kentucky and Tennessee, USA, *in* Monty, C.L.V., Boscence, D.W.J., Bridges, P.H., and Pratt, B.R., eds., Carbonate mud mounds, their origin and evolution: International Association of Sedimentologists, Special Publication 23, p. 273-287.

Review paper summarizing earlier studies is a good starting point for researching the Fort Payne buildups.

Meyer, D. L., Ausich, W. I., and Potter, P. E., 1992, Mississippian clinoform: lithologic and paleoecologic diversity amid slopes, slides and mounds: Palaios, v. 7, p. 335-336.

Short note reports on successful late winter field trip to the Cumberland Saddle showing the value of the region for instruction in paleoecology, taphonomy, and sedimentology.

Munn, M. G., 1914, Oil and gas fields of Wayne County, Ky.: U.S. Geological Survey Bulletin 579, 105 p.

Identifies (Pls. I and II and p. 28-29) the oil-producing Beaver Creek "sand" as being from massive mud mound carbonate core, but also recognizes that some oil production comes from the overlying well-washed carbonates.

Pryor, W. A., and Sable, E. G., 1974, Carboniferous of the Eastern Interior Basin, *in* Briggs, Barrett, ed., Carboniferous of the southeastern United States: Geological Society of America Special Paper 148, p. 281-314.

A classic paper still worth reading today. Its regional maps are especially valuable. Compare with Khetani and Read (2002).

Sable, E. G., and Dever, G. R., Jr., 1990, Mississippian rocks in Kentucky: U.S. Geological Survey Professional Paper 1503, 125 p.

Essential overview for understanding the broad sweep of the Mississippi System across Kentucky.

Sedimentation Seminar, 1972, Sedimentology of the Mississippian Knifley Sandstone and Cane Valley Limestone in south-central Kentucky: Kentucky Geological Survey Series X, Report of Investigation 13, 30 p.

The Knifley Sandstone is a shoaling marine bar located on the crest of the Cincinnati Arch and in front of the Arch. The manuscript also describes well-washed clinoform, crinoidal-bryozoan carbonates (the Cane Valley Limestone Member) identical to those that flank the mudstone cores seen along Lake Cumberland. See Figure 17 for clinoform structure.

Stapor, F., and Knox, L. W., 1995, Waulsortian-like bioherms of the Maury and Fort Payne Formations, Tennessee, *in* Driese, S.G., Complier, Guidebook for field trip excursions, southeastern section, GSA (Trips prepared for the 44th Annual Meeting of the Southeastern Section of the Geological Society of America, Knoxville, TN., April 1995), Geological Sciences, University of Tennessee, Knoxville, 90 p.

Authors emphasize that these Waulsortian mounds are unusual in that they are encased in clay and shale, and additionally, are built over a green shale core. Careful paleontology (Table 1 lists taxa in green shale cores) and petrography. Field trip has five stops in Tennessee, which are not too far south of Lake Cumberland.

Statler, A. T., 1971, Fort Payne Production in the Oneida West area, Scott County, Tennessee, *in* Proceedings of the symposium of future petroleum potential of NPC Region 9 (Illinois Basin, Cincinnati Arch, and northern part of the Mississippian Embayment): Illinois Geological Survey, Illinois Petroleum 95, p.94-110.

This, the first of several reports on petroleum in the Fort Payne of northeastern Tennessee by Statler, points to differences from its occurrence in the Fort Payne of Kentucky — petroleum occurs in the middle of the Fort Payne and the reservoir is different. See also MacQuown and Perkins above who, however, used the term Waulsortian for the host rock.

Stockdale, P. B., 1939, Lower Mississippian rocks of the East-Central Interior: Geological Society of America Special Paper 22, 248 p.

An amazing study with recognition of the massive mudstone core facies and much more. Also fascinating to see what Kentucky looked like 70 plus years ago.
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Thaden, R.E., Lewis, R. Q., Jr., Cattermole, J. M., and Taylor, A. R., 1961, Reefs in the Fort Payne Formation of Mississippian age in south-central Kentucky: U.S. Geological Survey Professional Paper 424 B., p. B88-B90.

This USGS group of mappers, based in nearby Somerset in Pulaski County, confirmed the occurrence of “reefs” in the Fort Payne earlier recognized by Butts (1922) and Stockdale (1939) and mapped all of these thicker than 20 ft, *thus greatly facilitating all the following studies by academics.* These carbonate buildups produced small amounts of oil and called by drillers the “Beaver Creek “sand” and the Corder Stray.

Webb. E.J., 1970, Stratigraphic relations of certain Mississippian-age pools in southeastern Kentucky and northeastern Tennessee, *in* Hutchison, D.W., ed., Proceedings of the 34th and 35th Technical Sessions, Kentucky Oil and Gas Association, 1970 and 1971: Lexington, Kentucky Geological Society, p. 50-58.

Summary of the Oneida West Field at Scott County, Tennessee, which occurs in the Fort Payne Formation, and was first discovered in 1969 followed by many additional wells in 1970. Production was from near the black shale at a depth of 1,500 feet.

Wilson, E. M., 1971, Fort Payne production in two Cumberland Saddle areas of Kentucky and Tennessee, *in* Proceedings of the symposium of future petroleum potential of NPC Region 9 (Illinois Basin, Cincinnati Arch, and northern part of the Mississippi Embayment): Illinois Geological Survey, Illinois Petroleum 95, p. 75-93.

Wilson notes that old Fort Payne fields tend to be oval in shape, and associated with the green shale like that seen at Greasy Creek; typically, these are 35 to 50 feet above the Chattanooga Shale. Paper contains cross sections and shows old Fort Payne fields, most of which are along the Cincinnati Arch and shallow. This appears to be one of the last papers on oil production from the Fort Payne Formation in Kentucky.

## Appendix B—Glossary

**Accommodation –** Space available for deposition; a principal control on the environment of deposition and ability of that environment to have net sedimention.

**Anoxic –** Conditions in which there is little oxygen, and where this occurs on the seafloor, generally some but minimal bottom life.

**Calyx** – The cup-like crown or body of crinoids. Plural is "calyces."

**Camerate crinoids** – A large group of crinoids (a class of stalked echinoderm) in the subclass Camerata, which have a raised or domed tegmen (covering on the top of the crinoid's calyx or crown), generally thick plates, and rigid dorsal cups.

**Clinoform** – Geometric description of large-scale sediment packages that form where sedimentation mantles an inclined surface on which beds thin and pinch-out (downlap) onto the basin floor. Clinoforms are typical of the Borden and Fort Payne Formations.

**Downlap** – The pinch-out of an inclined bed on the basin floor; beds pinch down dip.

**Dysoxic** – Conditions in which there is some oxygen restriction.

**Euxinic** – Conditions in which there is no oxygen and where this occurs on the seafloor, no bottom life.

**Fenestrate bryozoans** – Bryozoans in the order Fenestrata, which have mesh- or lace-like structures.

**Flexible crinoids** – Crinoids (a class of stalked echinoderm) in the subclass Flexibilia, which have flexible cups and tegmens (covering on the top of the crinoid's calyx or crown), with arms usually distinctly differentiated from the cup.

**Glauconite** – A green to blue-green mineral of the micaceous group commonly associated with deep-water marine deposition under very slow sedimentation rates.

**Grainstone –** All carbonate framework grains with virtually no mud; well washed and this grain supported (see classification diagram next page).

**Highstand Systems Tract (HST)** – That part of a depositional sequence in sequence stratigraphy between the maximum flooding surface and the next lowstand surface or sequence boundary. Records deposition at relatively high sea level.

**Holdfast** – The attachment structure for a crinoid; often appears root-like.

**Inadunate crinoids** – Refers to crinoids (a class of stalked echinoderm) in the subclass Inadunata that have a different arrangement of plates than camerates, This subclass has been eliminated in some classification schemes.

**Maximum (marine) flooding surface** – Surface that marks the deepest water facies in a sequence of rock. It is the boundary between the underlying transgressive systems tract and overlying highstand systems tract.

**Mudstone** – Carbonates formed from all carbonate mud. To avoid confusion for the usage of this term in argillaceous rocks, the term *micstone* (after *micrite*) can be used (see classification diagram next page).

**Onlap** – A geometric configuration of strata in which younger beds pinch-out up-dip onto older beds.

**Packstone –** Grain supported, but has some mud (see classification diagram next page).

**Parasequence** – Relatively conformable succession of genetically related beds bounded by marine flooding surfaces and their correlative surfaces.

**Pelmatazoan** – A subdivision of Echinoderms consisting of sessile forms such as crinoids and paracrinoids.

**Ramp (carbonate ramp)** – Carbonate platforms with a low-gradient depositional slope.

**Recumbent fold)** – A structurally overturned fold in which the axial plane of the fold is nearly horizontal.

**Sequence (*in* sequence stratigraphy) –** Genetically related succession of strata bounded by unconformities or their correlative surfaces.

**Sequence stratigraphy** – Organization of strata into natural, hierarchial, genetic packages linked to changes in relative water depth. There are different types or methods of sequence stratigraphy, mostly differing in which types of correlative or bounding surfaces are used to define the sequences. Greatly facilitates understanding and prediction of depositional facies and lithologies.

**Siliclastic** – Non-carbonate rocks, which tend to be dominated by quartz (silica) grains.

**Skeletal shelter cavities**– Irregular, primary cavities formed in limestone by draping of planar skeletal debris such as fenestrate bryozoan fronds over other skeletal debris. Commonly filled with yellowish-colored carbonates, silt or cement in the Fort Payne mounds.

**Stromatactus cavities**– Irregular networks, generally less than 4 inches (10 cm) in length, that may or may not be cement filled, tend to have flat bottoms and irregular tops, and are characteristic of Waulsortian-type mounds. Their origin has never been fully explained.

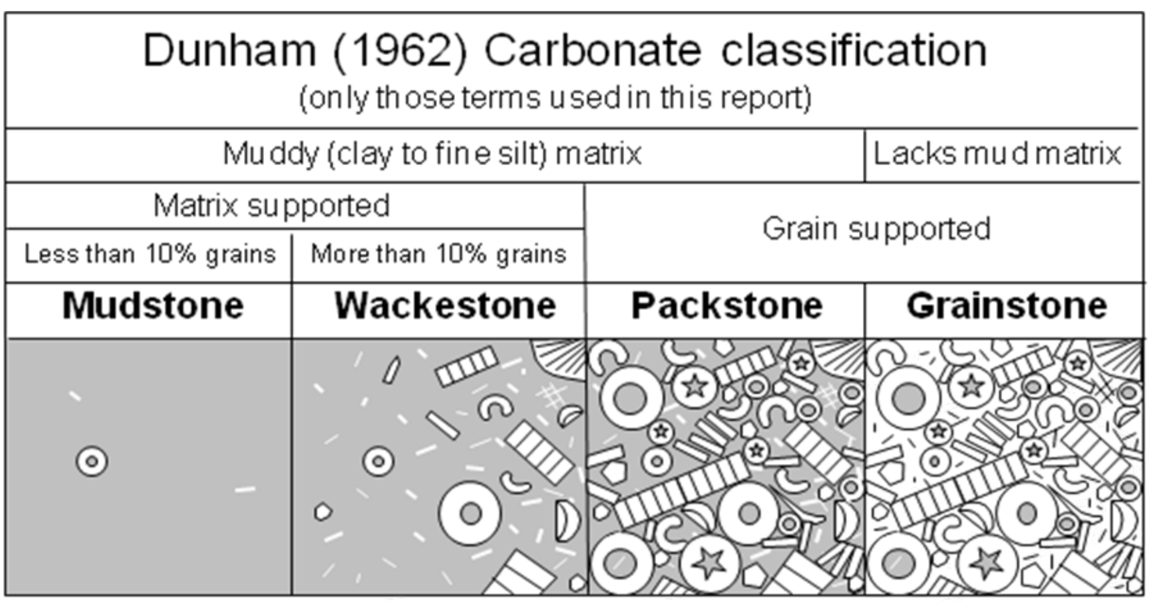
**Taphonomy** – Study of the processes that operate after the death of an organism. When identified, these provide insights to the environment of deposition, rates of sedimentation, and more. A subdivision of paleoecology.

**Time-rich bed** – A thin unit deposited through a long time interval such as the New Providence Member of the Fort Payne Formation (17.5 Ma, Leslie et al., 1996). Likely to have bioturbation, bottom oxygen permitting. Also a *condensed section* or *condensed bed,* in that a significant amount of time is represented by the bed.

**Transgressive Systems Tract (TST)** – That part of a depositional sequence in sequence stratigraphy between the lowest marine flooding surface and the maximum marine flooding surface. Records deposition during relatively rising sea level.

**Wackstone** – Mud-supported carbonate with 10 percent grains (see classification diagram below).

**Waulsortian mound** – Name given to fine-grained (micritic) carbonate mud mounds first recognized near Waulsort, Belgium. Typical of the Lower Carboniferous worldwide, commonly associated with crinoidal debris and contain voids often filled with sparry calcite (stromatactis structures).



## Appendix C—Geodes

Geodes are rock nodules that are hollow on the inside, although the term geode is often used for any quartzose nodule, whether or not they are hollow. On Lake Cumberland, geodes are common in the bedrock, and as free stones weathered from the bedrock. Geodes vary in size from less than an inch to as much as 2 ft in diameter (Thaden and Lewis, 1962). Most of the geodes around the lake have an exterior surface that is bumpy or bubbly, sometimes described as cauliflower-like in appearance. The bumpy outer surface of the geodes in the Fort Payne and updip Borden Formations consist of a quartz (chalcedony) rind. Inside the rind, the quartz nodules (potential geodes) around are mostly filled with solid, large- or coarsely crystalline quartz. True geodes that are hollow on the inside, are less common than solid quartz nodules, but are still very common. Many can be found broken on the shores of the lake. There is no secret appearance for determining which quartz nodules (potential geodes) are going to be solid or hollow from the outside. However, the relative weight of the nodule can be a good hint. If the nodule is lighter than it seems it should be, it may be a hollow geode. Care should be taken when splitting geodes to make sure that those with thin skins (which tend to have well-developed crystals) don't shatter. Basic eye safety precautions should also be observed, since rock chips can fly in any direction when using a hammer to break open geodes.

**How geodes form**

The concentration of geodes in the Lower to Middle Pennsylvanian rocks of Kentucky, Indiana, Illinois, and Tennessee is a result of both large-scale depositional processes and dolomitization. Explanations of the process by Chowns and Elkins (1974) Miliken (1979), Maliva (1987), and Barwood and Shaffer (accessed 2008) are in general agreement that the geodes began as anhydrite ($CaSO_4$), although there are different opinions as to when the anhydrite formed, and the water depths in which the fluids that led to mineral precipitation formed. Small pseudo-nodules (incipient geodes) on bedding surfaces can still be found that retain the general appearance of small anhydrite nodules (Fig. AC:1A). Other geodes appear to fill vertical cracks in the bedrock (Fig. AC:1B), some of which follow linear trends on bedding surfaces (Fig. AC:1C). There are likely a wide variety of void spaces including burrows and fossil skeletal material that we recrystallized.

The importance of initial anhydrite becomes clear when new, deep road cuts in the Fort Payne, Warsaw, or Borden Formations are excavated. Small masses of anhydrite have been reported, which dissolve, and leave rims of silica. Down-hole borehole cameras of wells into the Fort Payne and Warsaw around Bowling Green have also encountered possible thin beds and nodules of anhydrite (personal communication, Randy Shields).

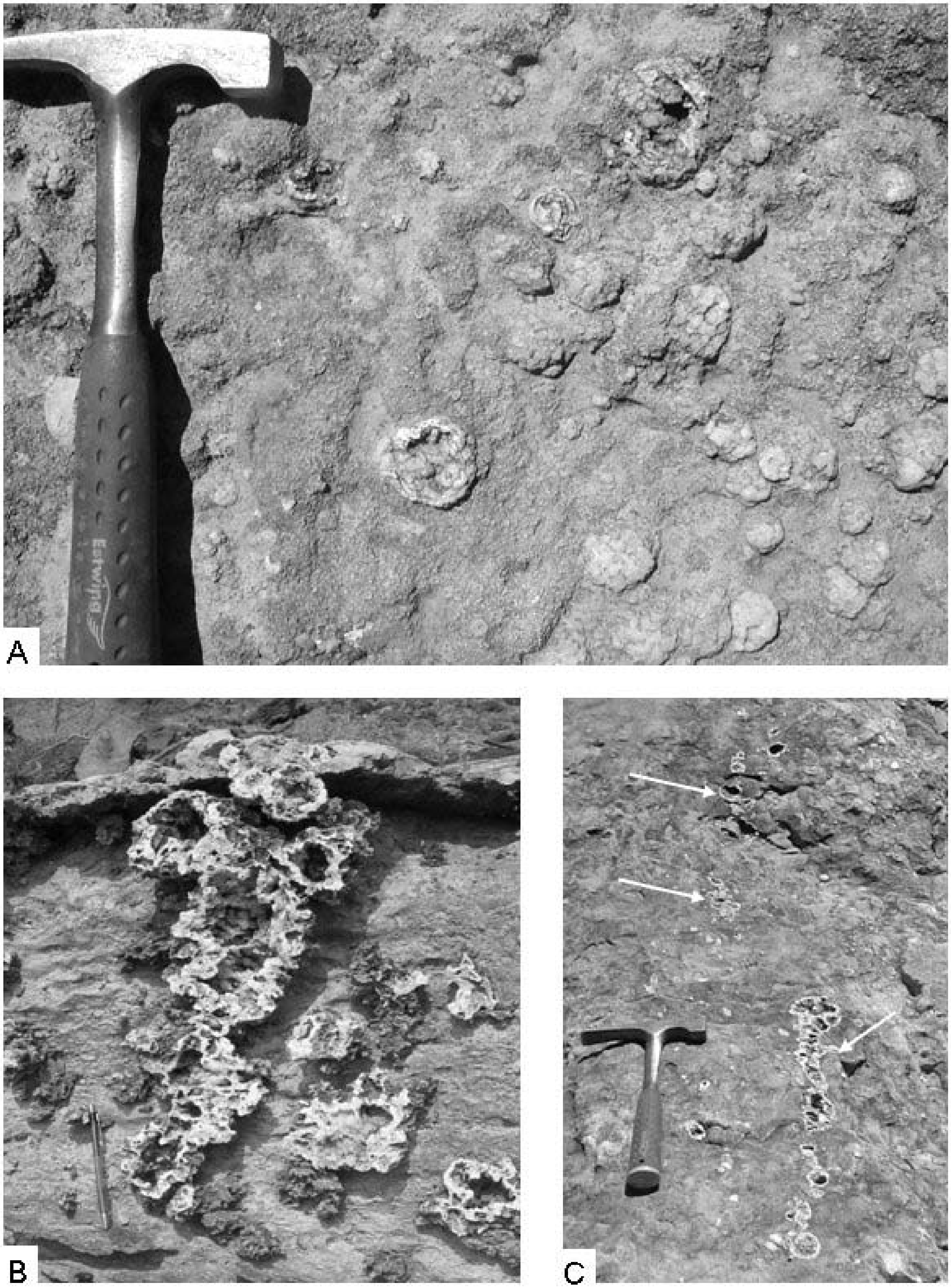



Figure AC:1. Geode crystallization in bedrock along Lake Cumberland. (A) Small incipient “cauliflower” quartz nodules on a bedding surface. (B) Geodes filling a vertical, wedge-form void in a bed, similar to a fracture fill. Pen is approximately 5 inches long. (C) Bedding plane surface with geodes arrange in linear orientations parallel to the long axis of the hammer (white arrows).

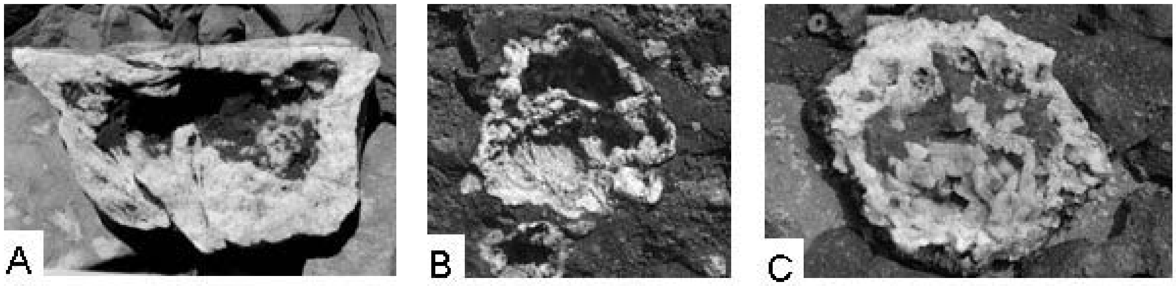



Figure AC:2. Larger geodes in bedrock at Lake Cumberland with (A) narrow, elongate quartz crystal rims, possibly after anhydrite , (B) multi-chamber cavities with remnant needle-shape structures in lower cavity, and (C) sphalerite and iron minerals filling cavities.

An essential requirement for geodes and chert is a source of easily dissolved silica. For the Fort Payne and Warsaw Formations, sponge spicules were the likely source. Spicules are tiny (fine silt size and smaller), needle-like support structures of sponges. They form much of the muddy matrix of the Fort Payne Formation. The upwelling of cold, nutrient-rich water against the ramp/slope (Fig. 4) provided ideal conditions for siliceous sponges to flourish (e.g., Lowe, 1975). The cold water was coming from the west, likely from the Ouachita Trough, in which the Arkansas novaculite (a highly siliceous sediment) was deposited.

Anhydrite crystal growth resulted in expanding nodules while the sediment was still pliable. The previously mentioned studies are in general agreement that the migration of dolomitizing fluids through the Fort Payne and Borden sediments likely produced acidic pore fluids that mobilized silica from the abundant sponge spicules in the organic debris in the Fort Payne. Silica gels then replaced anhydrite, sometimes trapping original anhydrite or preserving the shape of the original anhydrite crystals (Fig. AC:2A-B). Secondary porosity within the nodules was either filled by crystalline quartz (solid nodule) or lined with quartz crystals. In other areas, continued precipitation of gels resulted in banded, agate-filled nodules. Although euhedral quartz crystals are the most common fills in the Lake Cumberland geodes, a suite of accessory minerals including pyrite, barite, fluorite, calcite, sphalerite, and a variety of iron minerals were also available for filling the nodules (Fig. AC:2C). Many of these were likely precipitated as a result of sulfide reduction in the dolomitizing fluids (Chowns and Elkins, 1974; Barwood and Shaffer, accessed 2008). Lumsden (1988; 2003) proposed the possibility of deep water microbial sulfate reduction as a source of dolomitizing fluids, which would be in agreement with the deeper water environments proposed for Fort Payne deposition. In some cases, gastropods and crinoidal skeletal material were also replaced (pseudomorphs) resulting in “exploded” calyxes many times their original size. These can be differentiated from void or anhydrite nodule-replaced geodes by the preservation of the pentagonal plates and in some cases, plate arrangement of the original crinoid material.

**Notes**

**Lake level _________________**