STATE OF ARKANSAS

ARKANSAS GEOLOGICAL SURVEY
BEKKI WHITE, DIRECTOR AND STATE GEOLOGIST

ROADSIDE GEOLOGY SERIES 02

Geologic Road Guide to Arkansas State Highway 10

A Geotour of the Southern Arkoma Basin Fold Belt And Related Ouachita Mountain Tectonic Zones

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Little Rock, Arkansas
2017

STATE OF ARKANSAS
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ARKANSAS GEOLOGICAL SURVEY
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Little Rock, Arkansas 72204-6369
2017

Preface and Acknowledgments

The geology along Arkansas State Highway 10 (AR-10) was selected as the subject for the second Geologic Road Guide for Arkansas because of the western portion of the road being designated an Arkansas Scenic Byway and the region's importance in fossil fuel production. An understanding of the stratigraphic and structural geology of the area has been paramount to exploration for and production of coal and natural gas in Arkansas for over 160 years. More efficient and successful exploration for geologically complex natural gas reservoirs and development of deeper coal deposits requiring technically advanced mining and drilling methods, depends on a thorough understanding of the geology of the region.

The concept and design of the project was developed and planned by me. My wife, Mary, and I drove over the entire route many times visiting and photographing the sites described in the Guide. I researched the references and drafted the narrative. Dr. Jason Patton developed the maps and read the text offering many useful comments. Dr. Victor Vere critically read the text, commented on the maps, and prepared four "Side Trip" discussions (Perryville, Rose Creek Syncline, Mount Magazine, and Blue Mountain Lake) which are included in the Appendix.

Ms. Bekki White, Arkansas' State Geologist, provided encouragement and the support of the staff and facilities of the Arkansas Geological Survey. Geological staff members read the text, offered helpful suggestions, and solved the information technology management issues. Mr. Richard Hutto, Senior Geologist, was especially helpful with his editorial comments and suggestions.

A special word of thanks goes to Ms. Angela Chandler, Geologist Supervisor, Arkansas Geological Survey, who prepared the following illustrations: Physiographic Provinces Map, Glossary Cross-sections, Stratigraphic Column of Coal-bearing Strata, and Coal Beds in the Arkansas Valley Map. She also worked with the final draft of the text, shepherding all components into a publishable format. Without her assistance and expertise, the publication could not have been completed.

Mr. Bill Cains, Independent Exploration Geologist and a Commissioner, Arkansas Geological Commission, also read the text and suggested corrections and additions that improved the clarity and completeness of the Guide.

On behalf of Dr. Patton, Dr. Vere, and myself, I wish to thank all of the persons mentioned above for their assistance. For me this has been a labor of love; love of the science of geology and of the scenic beauty and geologic diversity of Arkansas.

Richard R. Cohoon

July 26, 2017

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Introduction

This road guide was developed for use by the public, geologists not familiar with the region, and students of geology. ***Note: numerous geologic terms are explained in the Glossary located on pages 40-51. These terms are italicized the first time they appear in the text.***

State Highway 10 (AR-10) begins in Little Rock and extends west 139 miles (224 kilometers) to the Oklahoma State Line, 1.2 miles (1.9 kilometers) west of Hackett. From Ola to Hackett it is designated an Arkansas Scenic Byway. The route crosses portions of two of Arkansas' five physiographic provinces exposing a landscape that is both beautiful and geologically complex. Also, you will be introduced to one of Arkansas' major natural gas and *coal*-producing regions.

Physiographic Provinces

(Refer to Map 1)

Arkansas can be divided into five major physiographic regions, namely the following: Ozark Plateaus, Arkansas River Valley, Ouachita Mountains, West Gulf Coastal Plain, and the Mississippi River Alluvial Plain. Each region offers unique landscapes, varied rock types, and a wide range of geological features.

Ozark Plateaus - The Ozark Plateaus are composed mostly of flat-lying *sedimentary* rocks (*limestone, dolostone, sandstone, shale, and chert*) forming mesa-like high areas separated by deeply eroded stream and river valleys. Spectacular vistas abound in the region. The rocks exposed at the surface range in age from Ordovician, approximately 470 million years ago (mya), to Pennsylvanian, approximately 315 mya. ***See page 3 for the Geologic Time Scale.***

Arkansas River Valley - The Valley, located south of the Ozarks, is the northern-most extension of the Ouachita Mountains. The rocks are sandstone and shale of Pennsylvanian age (299 to 323 mya). The once horizontally-bedded rocks were subjected to compressive mountain-building (*orogenic*) forces from the south during the formation of the Ouachita Mountains in Late Pennsylvanian time. These stresses caused the bedded rocks to fold into broad up-folds (*anticlines)* and down-folds (*synclines*). Tensional forces during the latter-stages of the *orogeny* caused fractures (*faults* and *joints*) to develop which led to blocks of the crust being displaced downward toward the south. The landscape offers views of broad river valleys and large, flat-topped mountains, including the highest elevation in Arkansas at Mount Magazine.

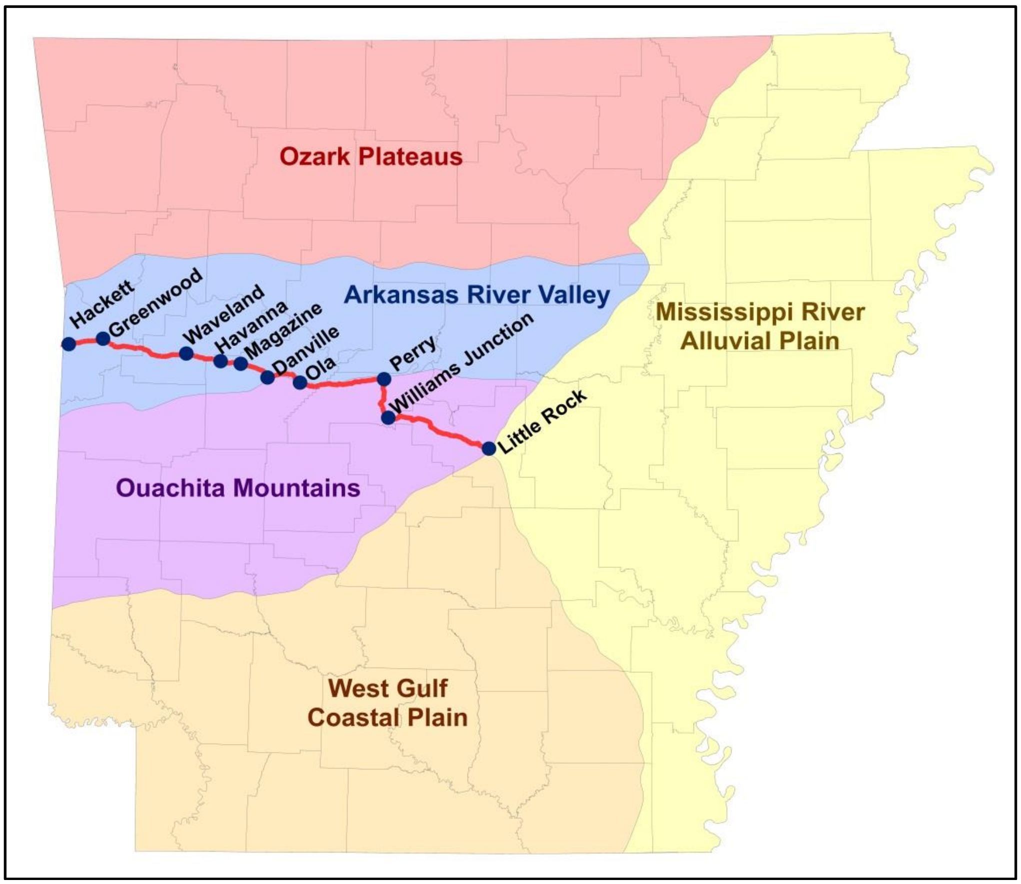
The complex depositional history of the sandstone and shale, in addition to the structural changes caused by the development of the Ouachitas, resulted in a region suited to the formation of natural gas reservoirs and coal deposits. Hydrocarbon exploration geologists know the area as the Arkoma Basin, a detailed description of which will be discussed later in this guide (see Appendix, p. 6A).

Ouachita Mountains - The Ouachitas are south of the Arkansas River Valley. These sedimentary rocks were deposited in an actively-deepening marine trough adjacent to the ancestral North American continent. Some of the rocks had a shallow marine environment, while others were deposited in a deep-ocean basin setting. The sandstone, shale, *novaculite*, chert, and minor amounts of limestone of this province, range in age from Ordovician (485 mya) to Pennsylvanian (299 mya). Mountain-building forces, applied over several million years near the close of the Pennsylvanian period, resulted in extreme amounts of folding and faulting. We see the results today as spectacular vistas of ridges and valleys.

West Gulf Coastal Plain - The Coastal Plain is south and southeast of the Ouachitas. The northwestern portion is Cretaceous-aged (66 to 145 mya) sedimentary rocks composed of gravel, sand, *clay*, clay-rich limestone (*marl*), limestone, and chalk. The southeastern part of the region is composed of Tertiary-aged (66 to 2.6 mya) sediments. These deposits include the following: sand, *silt*, and clay with scattered soft coal (lignite) deposits, some of which are of commercial quality and scale. The region offers broad vistas of forested and agricultural lands.

Mississippi River Alluvial Plain - The eastern-most physiographic region of the state is the Mississippi River Alluvial Plain which contains mostly Quaternary-aged (2.6 mya to present) gravel, sand, silt, clay, and loess (a wind-deposited silt). The topography (landscape) is generally flat-lying and offers unrestricted views of agricultural and forested land.

For more information about Arkansas' physiographic provinces go to: www.geology.ar.gov/education/physio_regions.htm



Map 1. Physiographic Provinces of Arkansas. AR-10 is dark pink, blue dots mark principal towns along route. (Source: Arkansas Geological Survey)

Geologic Time

A geologic road trip requires travel in four dimensions. Four, you say? Yes, three in space and in one more dimension: time. Geologic studies require speculating about time and measuring it in a vastly expanded manner than one does every day. Geologic time spans hundreds of millions of years. The "geologic time concept" has developed for more than 230 years since James Hutton, a Scottish physician, gentleman farmer, and amateur geologist, stated that "we find no vestige of a beginning, no prospect of an end."

The relative time scale was developed by field study methods, including geological mapping and the collection and analysis of fossils found in sedimentary rocks. Such studies formed a basis for placing sedimentary rocks in a relative time position. For example, a sedimentary rock layer at the bottom of a sequence of layers was deposited before the layers above it. A great advance took place after 1900 when it was discovered that some rocks contain radioactive minerals. The radioactive elements in the minerals spontaneously decay at a constant rate into more stable elements. Therefore, through appropriate field collection methods and laboratory analysis, an age since the mineral crystallized can be calculated. These "dates" are applied to the relative time scale (see below) to refine its precision and usefulness.

Geologic Time Scale

(United States Geological Survey, 2012)

ERA	PERIOD	AGE (Est. million years before present)
CENOZOIC	**Quaternary**	**Present – 2.58**
	Tertiary	**2.58 – 66.0**
MESOZOIC	**Cretaceous**	**66.0 – 145.0**
	Jurassic	**145.0 – 201.3**
	Triassic	**201.3 – 251.9**
PALEOZOIC	**Permian**	**251.9 – 298.9**
	Pennsylvanian	**298.9 – 323.2**
	Mississippian	**323.2 – 358.9**
	Devonian	**358.9 – 419.2**
	Silurian	**419.2 – 443.8**
	Ordovician	**443.8 – 485.4**
	Cambrian	**485.4 – 541.0**
PROTEROZOIC		**541.0 – 2500**
ARCHEAN-HADEAN		**2500 – 4600**

Rocks (*Formations*) Encountered along AR-10

(Listed in order from youngest to oldest.) (McFarland, revised 2004, and other sources.)

Savanna Formation (IPsv) (Pennsylvanian Period, Desmoinesian Series)

The Formation is predominantly dark-gray shale, silty shale, light-gray *siltstone,* and fine-grained sandstone. Also, the Savanna may contain several beds of coal. A few plant and invertebrate fossils indicate a shallow marine and coastal swamp environment of deposition. The Savanna is up to 1600 feet (480 meters) thick in Oklahoma but the upper few hundred feet are not present in Arkansas. The Formation caps several synclinal mountains in western Arkansas including Mount Magazine.

McAlester Formation (IPma) (Pennsylvanian Period, Desmoinesian Series)

From its base upward the Formation consists of several hundred feet of shale, thin-bedded sandstone, and coal. The mineable Lower Hartshorne Coal is near the Formation base. It is the first coal seam stratigraphically above the Hartshorne Sandstone which caused the somewhat confusing nomenclature. The Upper Hartshorne Coal is vertically separated from the Lower Hartshorne Coal by several hundred feet of shale and thin-bedded sandstone. The total thickness of the Formation ranges from approximately 500 feet (150 meters) to 2300 feet (700 meters). The depositional environment of the McAlester is considered to have been a *delta*-plain of a large river system (Suneson, 2005, p. 22).

Hartshorne Sandstone / Formation (IPhs) (Pennsylvanian Period, Desmoinesian Series)

The Hartshorne is typically a brown to light-gray, ripple-marked, cross-bedded to massive-bedded, medium-grained, and somewhat loose-grained (friable) sandstone. It is commonly a ridge-former or caprock of flat-topped mountains (Mt. Nebo, Petit Jean Mountain, etc.) in the Southern Arkoma Fold Belt (southern portion of the Arkansas River Valley, refer to Map 2, p. 7). Paleo-stream channels and deposits are present in numerous locations. Thickness ranges from 10 feet (3 meters) to 300 feet (90 meters).

According to one interpretation, the Hartshorne's depositional environment was fluvial-deltaic. This model proposes that the sands were deposited as *point bars* of a large westward-flowing meandering river in a belt about 20 miles (32 kilometers) wide across Central Arkansas during Middle Pennsylvanian time. An alternate interpretation is that the sands were deposited in a delta front with numerous distributary channels (Suneson, 2005, p. 22). A modern analog could be the Mississippi River Delta.

Atoka Formation (IPa) (Pennsylvanian Period, Atokan Series)

The Atoka consists of tan to gray, silt-rich sandstone and gray to black shale. In the AR-10 area the Atoka has been subdivided into lower, middle, and upper units that can be mapped across the region. The lower and upper units tend to be sandstone rich and structurally strong. The middle unit is dominantly sandy shale *turbidite* (*flysch*) which is structurally ductile and more easily deformed. The estimated total thickness of the Formation is 25,000 feet (7620 meters) in the Ouachitas; however, complete horizontal and unfaulted stratigraphic sections are not available for measurement.

Thickness and *facies* changes indicate a shift from a *neritic* continental (*foreland*) depositional environment in the southern part of the Ozark Plateaus (Boston Mountains) to a *bathyal* marine (*orogenic foredeep*) setting in the south (refer to Map 2). The Atoka also contains thin discontinuous coal seams deposited in shallow water (swampy) environments of the Continental Foreland and Southern Arkoma Fold Belt. The change from shallow-water to deep-water sedimentation occurs near the location of the Ross Creek *Thrust Fault* (Arbenz, 2008, p. 10).

Johns Valley Shale / Formation (IPjv) (Pennsylvanian Period, Morrowan Series)

The Formation consists of gray to black, clay-rich shale interbedded with several intervals of gray-black to gray-brown silty turbidite sandstone. The Johns Valley is considered to have been structurally ductile. In the Pennsylvanian-Mississippian Turbidite Sandstone Belt (refer to Map 2) there are zones of abundant erratic rocks and boulders (limestone, dolostone, and chert) emplaced by submarine slumping of older rocks from the Pennsylvanian-aged *continental shelf* positioned to the north of the Ouachita Trough (Arbenz, 2008, Figure 4, p. 14). These erratic (exotic) rock masses are known as olistoliths (see Figs. 4A and 4B). Mappable accumulations (olistostromes) of these chaotic masses mixed with mudstone occur in the Johns Valley. Accurate thickness measurements cannot be made due to structural complexity. An estimated thickness is 1,500 feet (460 m).

Jackfork Sandstone / Formation (IPj) (Pennsylvanian Period, Morrowan Series)

The Jackfork is thin- to thick-bedded, fine- to coarse-grained, brown, tan, or blue-gray *siliceous* sandstone containing minor zones of brown silty sandstone and gray to black shale. These sediments were deposited in a deep-water marine setting. Turbidite sedimentary sequences, submarine landslide sedimentary structures, and exotic rock masses are present in some locations. In northern exposures (Maumelle Chaotic Zone, also known as the Pennsylvanian-Mississippian Turbidite Sandstone Belt) the Jackfork is more shale rich and the sandstone tends to be *lenticular* and occur as distorted masses (olistostromes) enclosed by shale. The Formation is between 3500 feet (1070 meters) and 6500 feet (1980 meters) thick and is considered to have been structurally competent.

Stanley Shale / Formation (Ms) (Mississippian Period)

The Formation consists of dark gray shale with interbeds of fine-grained sandstone. The Hot Springs Sandstone Member, which may be as much as 450 feet (137 meters) thick in the Hot Springs area, is at the base of the Formation where present. Both the Stanley and Jackfork Formations include deep-water turbidite sediments (now rocks) deposited in *submarine fan* systems typical of orogenic foredeeps (Hatcher, 1988, plate 11). The Hatton *Tuff* Lentil is present in the lower portion of the Stanley, while chert may be found in the middle and upper parts of the Formation. The thickness of the Stanley ranges from 3500 to 10,000 feet (1070 to 3048 meters).

To learn more about Arkansas' geology and stratigraphic formations found elsewhere in the state, you can download the <u>Geologic Map of Arkansas</u> at: http://www.geology.ar.gov/ark_state_maps/geologic.htm and its companion document the <u>Stratigraphic Summary of Arkansas</u> at: http://www.geology.ar.gov/info_circulars/ic36.htm.

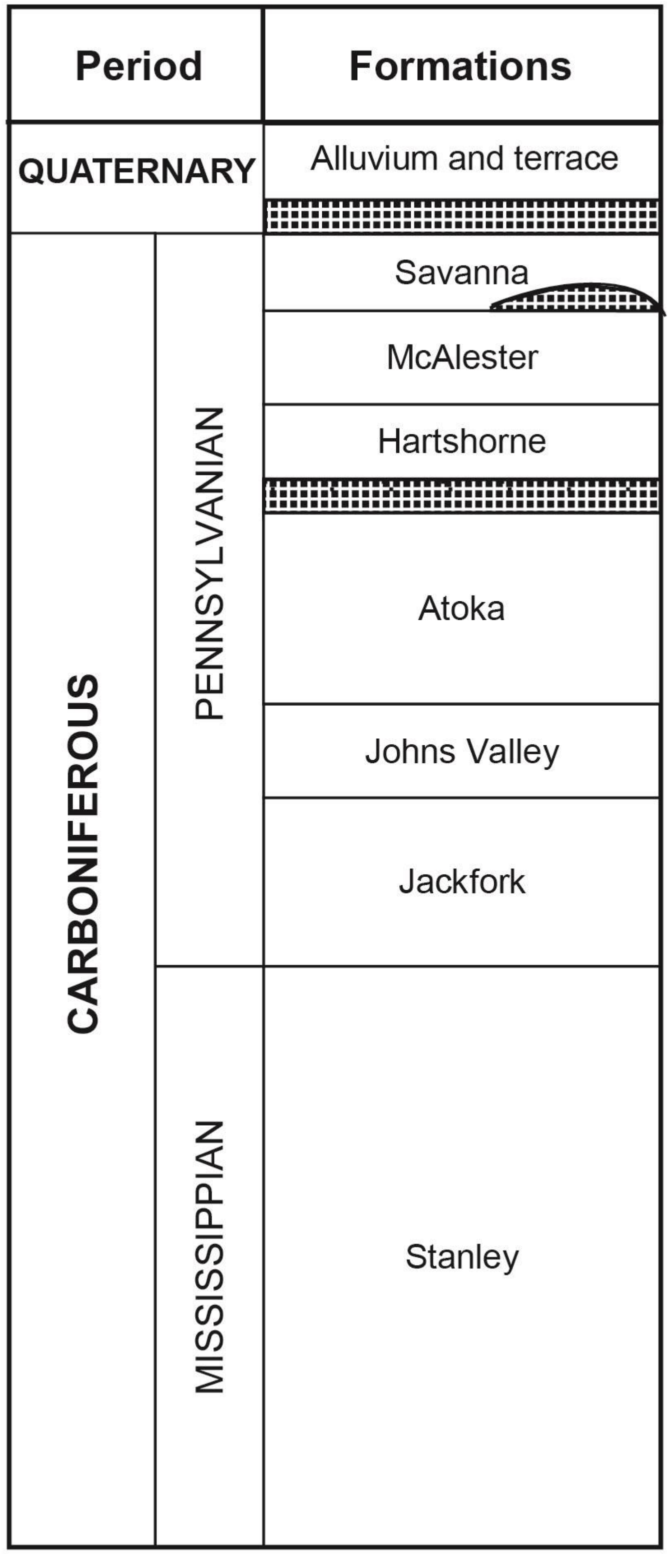
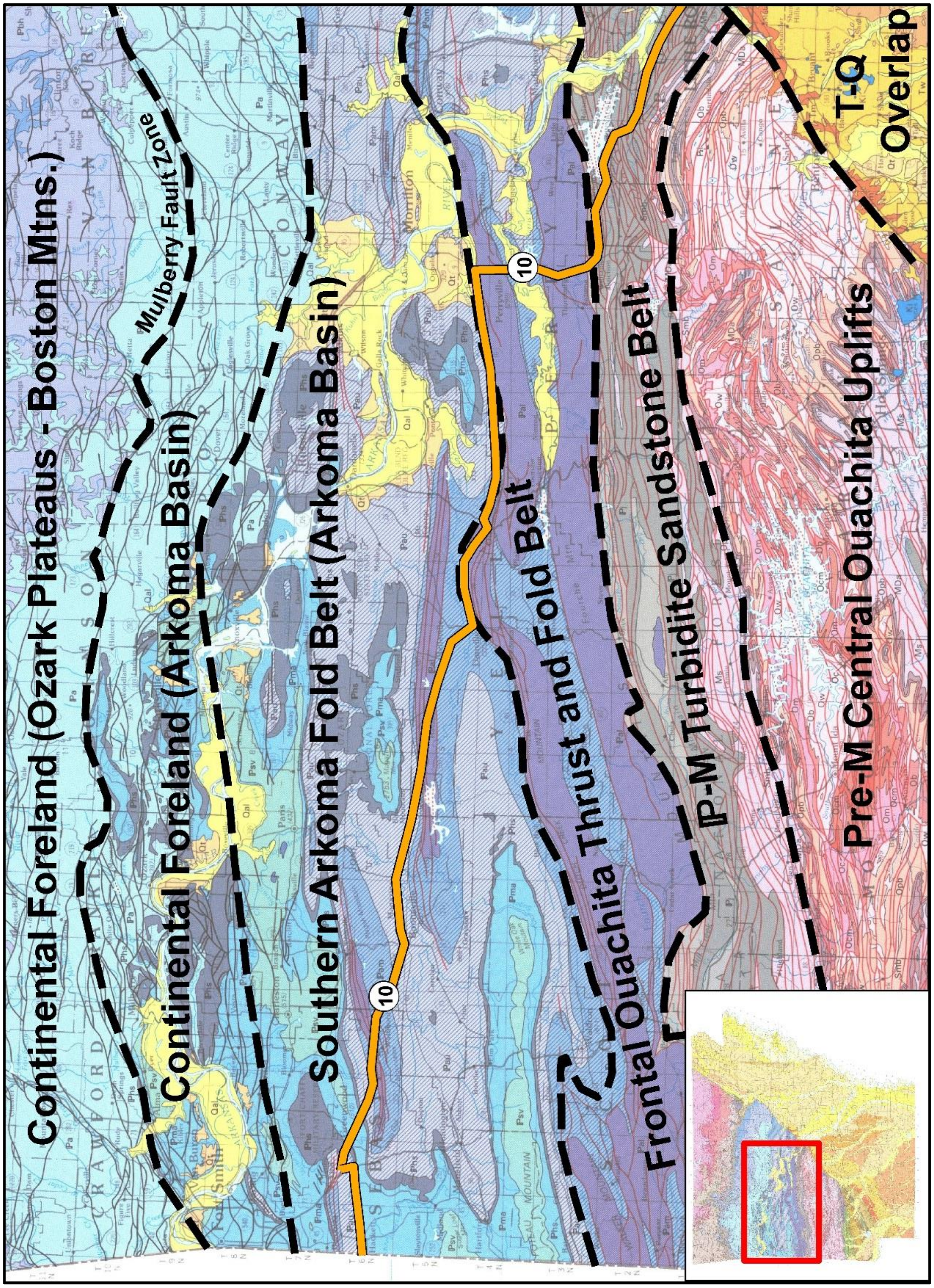


Figure 1. Generalized Stratigraphic Column of Formations Encountered along AR-10. Stipple pattern represents known unconformities. No relative thickness is implied. (Source: Arkansas Geological Survey)



Map 2. Major Structural Regions of Study Area. Inset shows location of study area in Arkansas. Terminology from Arbenz (2008). M = Mississippian, IP = Pennsylvanian, T = Tertiary, Q = Quaternary. Data for map and insert from reference map 2 (see p. 39)

Overview of Major Structural Regions between the Ozark Plateaus and the Pre-Mississippian Core of the Ouachita Mountains

Arbenz, 2008, Plate 1, "Major Structural Provinces"; refer to Map 2, p. 7

Note: Listed in order from north to south. The names of Belts in parentheses are used in earlier reports and maps authored by Haley, Stone, and others.

Continental Foreland (Arkoma Basin): This approximately 30-mile (48-kilometer)-wide, east-west-striking Region of gently-*dipping*, Pennsylvanian-aged sandstone and shale is broken by numerous *normal faults.* The downthrown fault blocks (*foot walls*) are generally on the south side of these faults. Because faulting was active during sedimentation, thicker deposits accumulated there. These faults, in combination with variations in depositional environment (stream channels, swamps, deltas, submarine fans), have produced numerous traps for natural gas in the region. Seismic prospecting and gas-well-drilling data indicate that many of these faults are related to deeper faults in Pre-Cambrian (Proterozoic) *igneous basement rocks*. The Region is bounded on the north by the Mulberry Fault System and on the south by the Southern Arkoma Fold Belt. The Basin in Arkansas and Oklahoma is one of the most productive gas and oil regions in North America.

Southern Arkoma Fold Belt (Arkoma Basin): This Belt lies between the Continental Foreland and the Ross Creek Thrust Fault System. The Belt, which varies in width from 10 miles (16 kilometers) in the east to 30 miles (48 kilometers) in the west, consists of east-west-striking anticlines, synclines, and thrust faults. The hydrocarbon traps in several large gas production fields are formed by combinations of structural deformation (folding, faulting), sedimentary rock type (sandstone, siltstone, shale), and sedimentary body shape (bed, lens, sand bar, etc.). The rock type and body shape are features determined by the original depositional environment, such as a stream channel, swamp, delta, tidal zone, continental shelf, or deep-water submarine fan.

Frontal Ouachita Thrust and Fold Belt (Rover Belt): This approximately 15-mile (24-kilometer)-wide Belt also *strikes* east-west. Rocks in this Region are Pennsylvanian aged (lower Atoka), deep-water turbidite sandstone and shale typical of orogenic foredeeps. The Belt lies between the Ross Creek Thrust Fault System on the north and the Y City Thrust Fault System on the south. The Region contains two large synclinal complexes, the Fourche La Fave in the eastern and central part, and the Black Fork in the western area, approximately 12 miles (19.3 kilometers) north of Mena.

Pennsylvanian-Mississippian Turbidite Sandstone Belt (Aly Belt): This east-west-striking Belt of turbidite sandstone and shale is approximately 5 to 10 miles (8 to 16 kilometers) wide. The Belt is composed of the following Formations: Stanley, Jackfork Group, Johns Valley, and Atoka. The rocks of this tectonic *melange* zone display numerous features of soft-sediment submarine slumping and sliding which resulted in the development of *chaotic sedimentary structures*. The Belt also contains hundreds of smaller-scale thrust faults, broad synclines or *half-grabens*, and tepee-like faulted anticlines.

Structural and Stratigraphic Geology of the Arkoma Basin

The Arkoma is one of several peripheral foreland basins (PFBs) related to the Ouachita Fold Belt. These basins are excellent examples of orogenic foreland basins. An orogenic foreland basin is defined as "an elongate region of potential sediment accumulation that forms on a continental crust between a contractual orogenic belt and the adjacent craton …" (DeCelles and Giles, 1966, p. 105). Other related basins include the following: Marfa, Val Verde, Kerr, and Fort Worth in Texas, and Black Warrior in Mississippi and Alabama. These PFBs were formed due to the collision of the North American ancestral continent with ancestral South America (one of the Gondwanian *tectonic* plates). The Arkoma and related basins began developing in the Early Mississippian Period (359-347 mya) and ended their development in the Middle Pennsylvanian Period (315-307 mya) (Suneson, 2012, p. 39).

The Arkoma Basin extends from the Mississippi River Alluvial Plain on the east into Southeastern Oklahoma where it is overlapped by Cretaceous-aged rocks near Atoka, Oklahoma. The surface area of exposure is approximately 33,800 square miles (54,398 square kilometers). The maximum dimensions of the basin are 315 miles (507 kilometers) east-west and 175 miles (202 kilometers) north-south. The northern boundary of the Arkoma Basin in Arkansas is the Mulberry Fault Zone which separates the Basin from the Boston Mountains (southern portion of the Ozark Plateaus). The Mulberry Fault Zone consists of numerous east-west-striking, overlapping, *down-to-the-south normal faults* which are present in Pennsylvanian, Mississippian, and older strata. Many of the faults display growth-fault characteristics. The southern boundary of the Arkoma is the Ross Creek Thrust Fault in Arkansas. The surface expression of the Arkoma is lost on its eastern end because of coverage by overlapping Tertiary- and Quaternary-aged (66 mya to present) sediments of the Mississippi River Alluvial Plain. At depth, it is bounded by the Reelfoot Rift, the western edge of the Mississippi Valley Graben.

For additional geological characteristics and tectonic development history of the Arkoma Basin, see Appendix.

Road Guides

Road Guide – Little Rock to Lake Maumelle

(Refer to Map 3)

Although AR-10 officially starts at Interstate 30 (I-30) a few blocks east, we will begin our journey at Ottenheimer Plaza in Julius Breckling Riverfront Park in the River Market area of downtown Little Rock.

Benard de la Harpe, a French explorer, discovered an important landmark as he traveled upstream on the Arkansas River in 1722. It is the high bluff on the north bank of the river which he named “Le Rocher Francais” (The French Rock). We now know the bluff, composed of Jackfork Sandstone, as an edge of “Big Rock Mountain” in North Little Rock. Approximately 2.5 miles (4 kilometers) downriver from the bluff, the Quapaw Indians had established a settlement near a smaller outcrop of Jackfork Sandstone on the south bank of the river. The river could be forded at this location in those days. French traders who followed La Harpe found this to be a good landing place and it became known as “La Petit Rocher” (The Little Rock) hence the settlement and later the town became known by this name.

A portion of “The Little Rock” may still be seen below the concrete foundation of the Junction Bridge. The Bridge was built between 1872 and 1884 to connect North Little Rock and Little Rock with a railroad. The construction work involved removing a sizeable portion of the outcrop, and the remainder has been incorporated into Riverfront Park. The history regarding the Bridge and the Rock is well explained and illustrated here in La Petit Roche and Sturgis Plazas.

After viewing "The Little Rock", turn right (west) from the River Market parking lot onto President Clinton Avenue. At Cumberland Street, 500 feet (150 meters) from the River Market, turn right onto La Harpe Boulevard (there is a street name change here; also the AR-10 designation has been added).

La Harpe Boulevard continues west crossing Quaternary *alluvium* and *terraces* of the Arkansas River. Farther west, the road crosses a bridge over the railroad tracks leading to Little Rock's Union Station. After crossing the bridge, La Harpe, now named Cantrell Road, continues west-northwest along the contact between Quaternary alluvium and terrace deposits. As you progress farther west, note that the landscape to the left (south) of Cantrell becomes hilly. These hills are composed of rocks of the Jackfork Formation. After passing Allsopp Park Road on the left (west), Cantrell makes a turn to the north for approximately 1000 feet (300 meters), then swings west going uphill. You will be passing a roadcut in the Jackfork Sandstone until reaching the top of the hill. Cantrell Road continues westward 4.4 miles (7 kilometers) to the Interstate 430 (I-430) Interchange. AR-10's route lies on the Jackfork in this area and runs parallel to northwest-trending thrust faults.

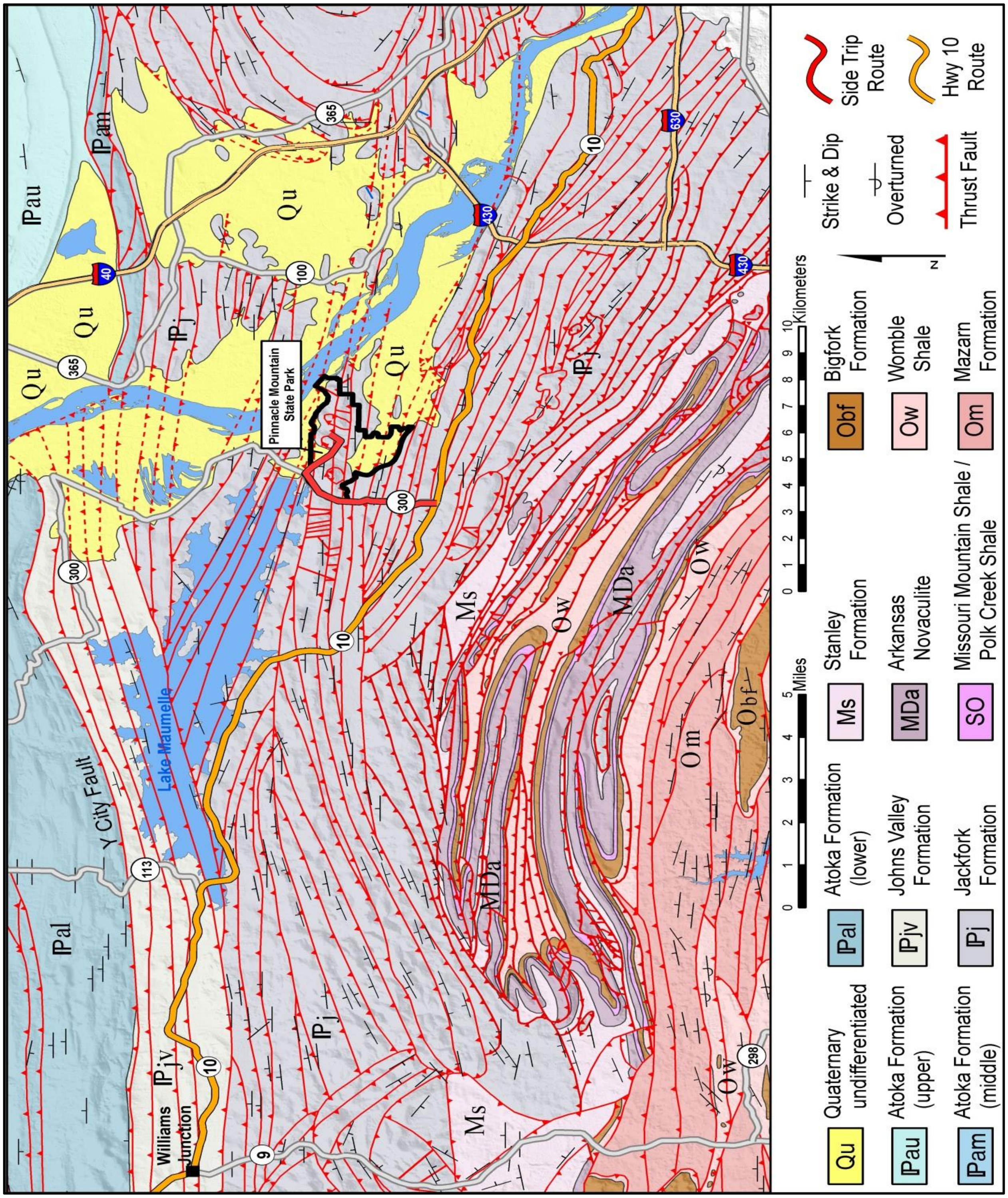
After passing the I-430 Interchange, turn right onto River Mountain Road at the first stoplight.

The Road leads downhill to the Two Rivers Park Bridge. On the downhill trip take note of the excellent exposure of the Jackfork Formation. A short walk from the parking lot will bring you to the pedestrian bridge. About halfway across the bridge you will see the Maumelle Pinnacles to the west. This vantage point will give you an excellent photo opportunity and a preview of what is coming as you travel west.

Return to Cantrell Road and turn right (west) to continue your trip.

Stone and McFarland interpreted the depositional environment of the Jackfork Formation, exposed for approximately 17 miles (28 kilometers) along AR-10's route, as being the outer slope of a submarine fan in which soft-sediment deformation features developed (Stone, 1981, p. 13). According to these authors, the deformation is the result of the following geologic processes: (1) slumping of sediments down a continental slope, (2) northward *overthrusting* of several fault-bounded masses, (3) multiple periods of folding, and (4) later *backfolding* and additional faulting (Stone, 1981, p. 15). Numerous hydrothermal milky *quartz* veins are present along fault planes and fractures.

On its westward route, AR-10 parallels numerous east-southeast-trending thrust faults in the upper Jackfork Sandstone. These low-angle, nearly horizontal, bedding-plane faults cause repetition of the stratigraphic sequence. These structures and rock types are typical of the Pennsylvanian-Mississippian Turbidite Sandstone Belt as described by Arbenz (2008, Plate 1). The complex structures present in this area are considered to also be the result of a sequence of processes as listed above. The east-southeast structural trend (thrust faults in the Jackfork) extends approximately 18 miles (29 kilometers) from the Quaternary and Tertiary overlap in southeast Little Rock to a set of east-west trending thrust faults south of Lake Maumelle.



Map 3. Little Rock to Williams Junction. Stratigraphic order: younger on the left
Data from reference map 4 (see p. 39)

Road Guide - Side Trip to Pinnacle Mountain State Park
(Refer to Map 3)

Turn right onto State Highway 300 and travel 2.9 miles (4.7 kilometers). Turn right onto Pinnacle Valley Road and go another 1.7 miles (2.7 kilometers). On your left is the turn off for the Pinnacle Mountain Visitor Center which is another 0.9 miles (1.4 kilometers).

The Maumelle Pinnacles (cone-shaped hills) extend to the west approximately 4 miles (6 kilometers) along the south bank of the Maumelle River (Fig. 2). Pinnacle Mountain, 1011 feet (308 meters) above sea level, and the Maumelle Pinnacles are composed of nearly vertical north-dipping, repeated units of the Jackfork Sandstone. The repetition is the result of thrust faulting.

Figure 2. Maumelle Pinnacles

Pinnacle Mountain is a unique structural geologic feature known as a *klippe* (Fig. 3). A klippe is defined as an erosional remnant of an overthrust sheet of rock that is isolated from underlying rock by a thrust fault. The base of the mountain is underlain by a mostly horizontal thrust fault in the Jackfork Formation. The mountain may be the surface exposure of a thrust fault *triangle zone* brought to the surface by deep erosion. Where fault zones are exposed, the *slickensides* (scratched and grooved surfaces) are coated with the white clay mineral *dickite.* Also, quartz veins containing the hydrothermal minerals *cookeite* and *rectorite* are numerous (Stone, 1981, p. 29). These features are typical of fault zones in the Ouachitas. Pinnacle Mountain is surrounded on the south and northeast by Quaternary-aged (2.6 mya to present) terrace and alluvial sediments deposited by the Arkansas River.

The mountains to the east of Pinnacle Mountain are named the Fulk Mountains. These "pinnacle-like" hills are also *klippen.* The highest of these peaks is 720 feet (219 meters) above sea level.

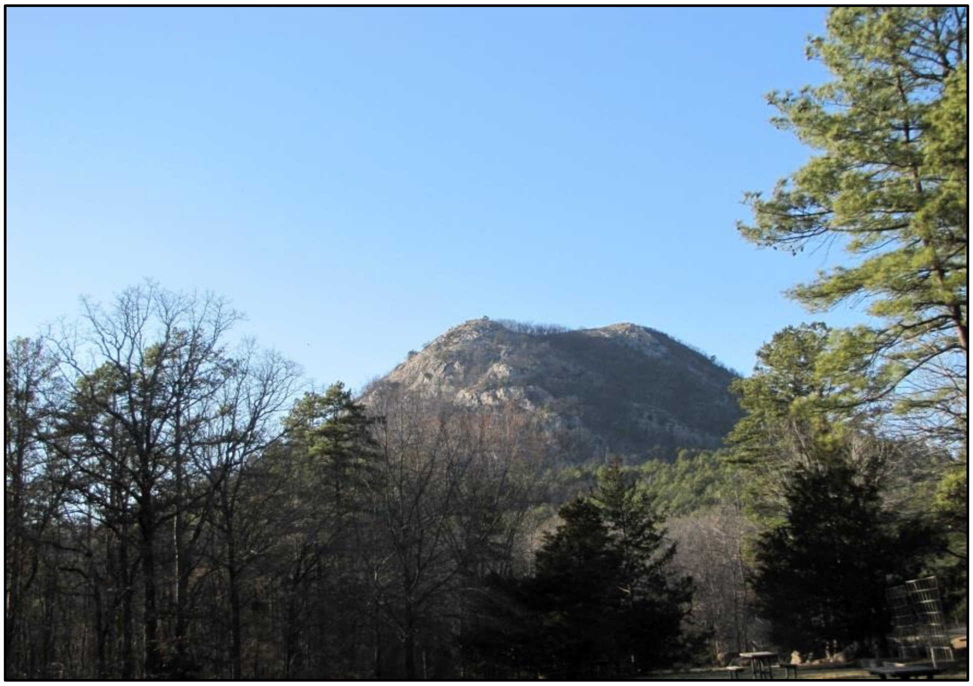


Figure 3. Pinnacle Mountain

There are several trails in the area including one that goes to the top of Pinnacle Mountain for those of you that enjoy hiking and have the time to look around. You can pick up a pamphlet titled “The Geologic Story of Pinnacle Mountain” at the Visitor's Center. “The Geologic Story”, prepared by the Arkansas Geological Survey, will make your hike more informative and enjoyable.

Return to SH-10 and continue west toward Lake Maumelle.

Road Guide - Lake Maumelle to Williams Junction
(Refer to Map 3)

Between west Little Rock and Lake Maumelle the road traverses the Morrowan-aged (Lower Pennsylvanian) Jackfork Formation (quartzitic sandstone, silty sandstone, and shale) exposed between the Panther Creek and Y-City regional thrust faults, as previously mentioned. The Jackfork is broken by numerous northwest-southeast-trending thrust faults resulting in an *imbricated* complex of fault plates that moved from the southwest to the northeast.

Road cuts exposed along AR-10 provide an excellent opportunity to study the results of soft-sediment and structural deformation of the Jackfork. This region has been named the Pennsylvanian-Mississippian Turbidite Sandstone Belt by Arbenz (refer to Map 2). Previously, this region was referred to as the "Maumelle Chaotic Zone" by G. W. Viele (Hatcher, 1988, Vol. F-2, Plate 11) due to the presence of numerous soft-sediment and submarine slide deformation features.

Figure 4A. **Figure 4B.**

Sandstone olistoliths in the Jackfork Formation

The geologic structure in this area is dominated by steeply-dipping (20^o to 75^o north) sandstone and shale units that are repeatedly fractured by east-west-trending thrust faults. Evidence indicates that the overriding thrust sheets were forced northward during the Ouachita Orogeny (Middle to Late Pennsylvanian, 315-299 mya). The Jackfork in this area contains exotic boulders (olistoliths) of fossil-bearing, somewhat *calcareous* sandstone. The boulders may have originated in a shallow-water (continental shelf) depositional environment. It has been proposed that they were transported to their present location by gravitationally-induced sliding down the slope of a submarine fan (Stone, 1981, p. 29).

Approximately 2 miles (3.4 kilometers) west of the Maumelle Harbor Road (sign for Jolly Roger Marina) a large road cut exposes the middle Jackfork Formation which is composed of black shale containing olistoliths of light-gray sandstone (Fig. 4 A). The outcrop also contains thrust faults that display slickensides and milky quartz veins. Some of the veins contain trace amounts of lead, zinc, copper, and silver minerals (Stone, 1981, p. 29). This type of mineralization, caused by element-rich, hydrothermal solutions rising toward the surface during an orogenic episode, is responsible for many of the world's mineral deposits. Only 0.8 miles (1.3 kilometers) west of the last road cut there is another excellent exposure of olistoliths of quartzitic sandstone interbedded within black shale of the Jackfork (Fig. 4 B).

A Cretaceous-aged igneous *dike* is present in the shale on the north side of the AR-10 road cut approximately 700 feet (210 meters) west of West Hundley Road. The Road joins AR-10 just east of a bridge over an inlet from Lake Maumelle. The dike is severely weathered and its presence is indicated by a clay-rich soil zone containing biotite mica flakes (cleavage plates). The temperate-humid climate of Arkansas causes some igneous minerals, especially those composed of *feldspars* (orthoclase and plagioclase), feldspathoids (nepheline), and ferromagnesian minerals (pyroxene and hornblende), to be rapidly weathered into clays and iron oxides *(limonite* and hematite). So instead of dikes standing out as ridges as found in dry climates, they are often deeply eroded in Arkansas.

From the dike location, AR-10 crosses the western end of Lake Maumelle. Two east-northeast-trending thrust faults are crossed before the road curves to the west at the junction with AR-113. The southernmost fault of this pair brings the Jackfork into contact with the younger Johns Valley Shale. The Johns Valley, like the Jackfork, contains olistoliths that may have originated elsewhere and traveled as exotic masses down a submarine fan slope into deeper water sediments. The lower Jackfork is intensely folded to the north, but movement was to the south forming *backthrusts* (Arbenz, 2008, Plate 4, Cross Section). AR-10 traverses the Johns Valley Shale for approximately 7.75 miles (12.5 kilometers) from the AR-113 junction to Williams Junction where State Highway 9 (AR-9) joins AR-10. The highway parallels the Maumelle River and five east-west-trending thrust faults before reaching Williams Junction. At Williams Junction, the road turns northwest and crosses three of the faults before encountering the generally north-dipping lower Atoka Formation.

Road Guide - Williams Junction to Perry

(Refer to Map 4)

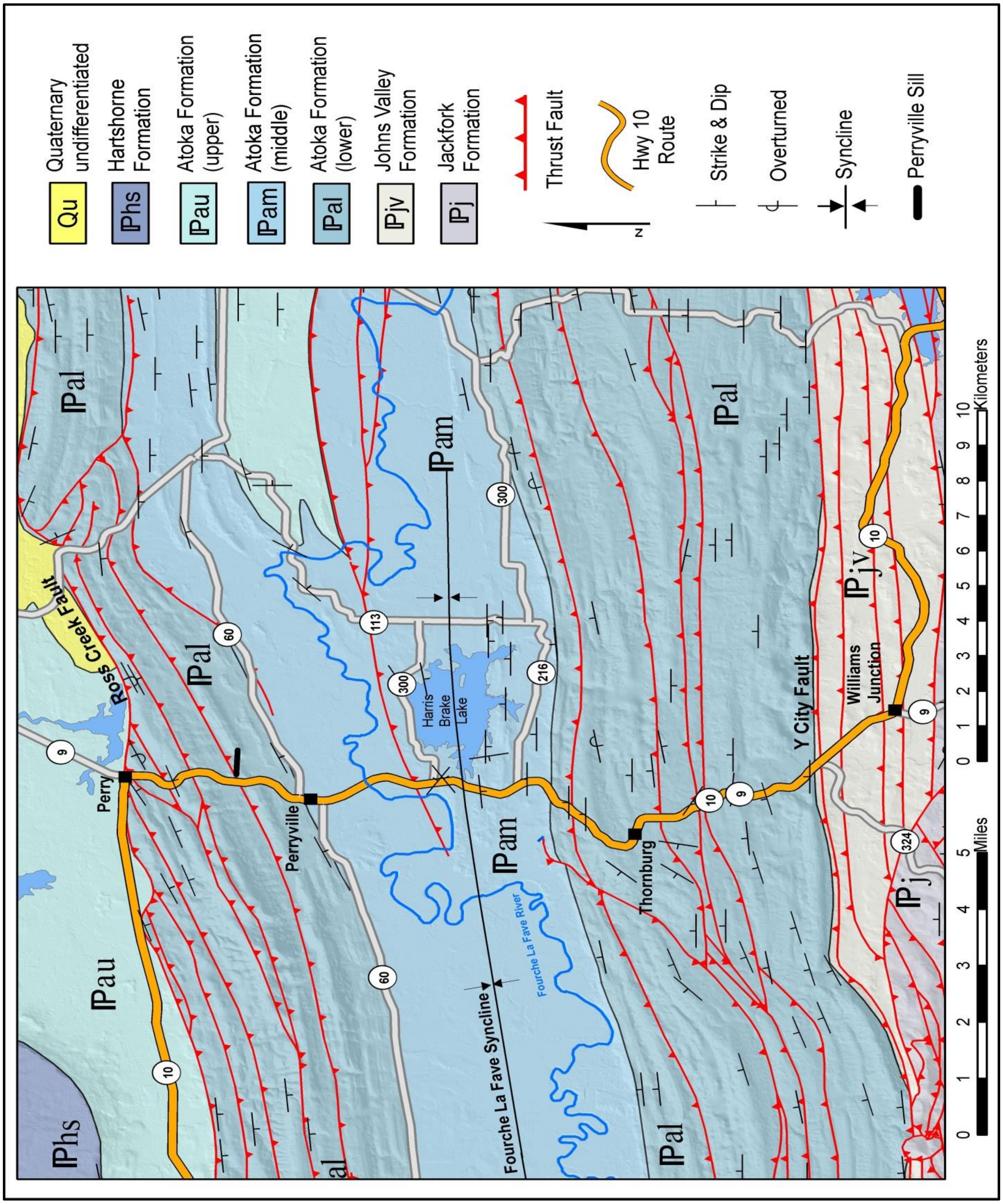
The Johns Valley is brought into contact with the lower Atoka Formation by the Y City Fault approximately 1.5 miles (2.4 kilometers) northwest of Williams Junction (very close to the junction of AR-9/10 and AR-324). According to Arbenz, the Y City Fault is the "most important tectonic boundary of the entire Ouachita Mountains." The Y City Fault dips north at the base of the Fourche La Fave Syncline. Therefore, the foreland and orogenic foredeep depositional provinces of the Pennsylvanian-aged (299-323 mya) North American Continent are located north of the fault. South of the Y City Fault are the deep-water marine (*geosynclinal*) sediments ranging in age from Late Cambrian to Middle Pennsylvanian (501 to 315 mya). These sediments (Ouachita facies) were tectonically transported northward during the Ouachita Orogeny (Middle to Late Pennsylvanian, 315-299 mya) resulting in the foredeep becoming a tectonic melange zone. The distance of tectonic transport between the Y City Fault and the Ross Creek Fault is 43 to 93 miles (70 to 150 kilometers), depending on location of measurement (Arbenz, 2008, p. 12).

The lower Atoka Formation dips north between 10^{o} and 80^{o} after crossing the fault. However, some dip reversals are present, as is to be expected in a faulted region. Three mapped thrust faults are present between the contact and the community of Thornburg. The upper plates of the thrust faults are interpreted to have moved north during the Ouachita Orogeny.

Continuing northward from Thornburg to Perryville, AR-9/10 crosses two more thrust faults in the lower and middle Atoka Formation. Two miles (Three and two-tenths kilometers) north of Thornburg, AR-9/10 enters the valley of the Fourche La Fave River. The River, which is crossed before entering the town of Perryville, flows east parallel to the axis of the Fourche La Fave Syncline which exposes the middle Atoka. The Syncline lies between the Y City Fault on the south and the Ross Creek Fault on the north. These thrust faults are regional in scale, extending from near Atoka, Oklahoma to the overlapping sediments (Tertiary-Quaternary) northeast of Little Rock (Arbenz, 2008, Plate 2). In Oklahoma, the Y City is equivalent to the Ti Valley Fault and the Ross Creek is named the North Ti Valley Fault.

The Johns Valley Shale underlies the Y City Fault at a depth of approximately 6500 feet (1980 meters). The ductility of the shale in the subsurface probably facilitated the development of the Fault. The unnamed faults paralleling the Y City appear to dip north while the upper plates are interpreted to have moved south as backthrusts (Arbenz, 2008, Plate 4, Cross Section AR-2).

Arbenz offers an interesting analysis of the tectonic development of this region, suggesting the following sequence of events: (1) northward advancing Ouachita thrust sheets came in contact with very thick, Atokan-aged turbidite sediments positioned on the downthrown side of a basement *growth fault* (Ross Creek Fault), (2) advancing thrust sheets were not able to overthrust the massive volume of Atoka flysch sediments, (3) therefore, the potential overthrust became an *underthrust* which lifted the south limb of the Fourche La Fave Syncline, and (4) thus, a very large triangle zone was formed with the Y City Fault in Arkansas serving as the *conjugate shear zone* of the Ti Valley Fault in Oklahoma (see Glossary page 42 for a diagram) (Arbenz, 2008, Plate 5B).



Map 4. Williams Junction to Perry. Data from reference map 4 (see p. 39). Structural axes added for clarity

Continuing north from Perryville, the highway climbs Perry Mountain, a lower Atoka ridge (elevation 736 feet, 224 meters). Approximately 1.1 miles (1.8 kilometers) north of the AR-60 intersection in Perryville, an *igneous breccia* (Perryville *Sill*, also known as the Perryville Breccia or Perry Mountain Breccia) crops out near the house on the east side of the road. The highly weathered igneous rock was earlier reported to crop out on both sides of the road (Croneis, 1930, p. 153-155).

This exposure of igneous rocks is thought to be part of a cluster of sills and igneous breccias (reported by Croneis) including: Arkansas River Sills, Opello Breccia, and Brazil Branch Breccia. Considering the location of these intrusions, they may be related to a northeast-trending, covered basement fault. The intrusions are generally classified as *carbonatites* based on chemical analyses. The carbonatite matrix includes biotite crystals, a few glassy pyroxene grains, and rounded to angular *xenoliths* of *granite*, *syenite*, *magnetite-apatite* rock, *sovite*, shale, and sandstone (McCormick and Heathcote, 1987). These rocks were dated by fission-track methods and determined to be Late Cretaceous age (94-101 mya) (Eby and Vasconcelos, 2009).

Figure 5. Lower Atoka Formation exposed between Perryville and Perry

Drive another six-tenths of a mile (one kilometer) north and park in the Perry Mountain summit parking area. Walk downhill on the east side of the road for a closer examination of this rock sequence (Fig. 5). Please be mindful of the heavy traffic along the road.

The south-dipping lower Atoka Formation, situated on the north limb of the Fourche La Fave Syncline, is well exposed for the next 1600 feet (490 meters). On your walk, you will see a well-exposed example of a flysch depositional sequence. Flysch is a pre-orogenic deposit of *subgraywacke*, clay-rich sandstone, mica-rich siltstone with zones (blue beds) containing fossil plant fragments that have been partially converted to coal, and black shale. Also, sideritic (iron carbonate) concretions have been found. These sediments (now rocks) are interpreted to have been deposited in the mid-fan portion of a deep-water, submarine fan in a channel and lobe turbidite environment. Many unique sedimentary features are present which support this interpretation such as: variations in *strata* thickness, *graded bedding*, *load casts*, *convolute bedding*, *bottom marks*, and *trace fossils* (Stone, 1981, p. 37).

See Appendix for additional information and an extended walking tour in this location. Return to your vehicle and continue driving north on AR-9/10.

Road Guide – Perry to Ola

(Refer to Map 5)

At the base of Perry Mountain, you enter the small town of Perry. Here, AR-9/10 diverges with AR-10 turning left (west) to parallel the Ross Creek Fault. AR-9 continues north to Morrilton crossing Quaternary alluvium of Cypress Creek and terraces and alluvium of the Arkansas River.

Turn left on AR-10 and continue driving west.

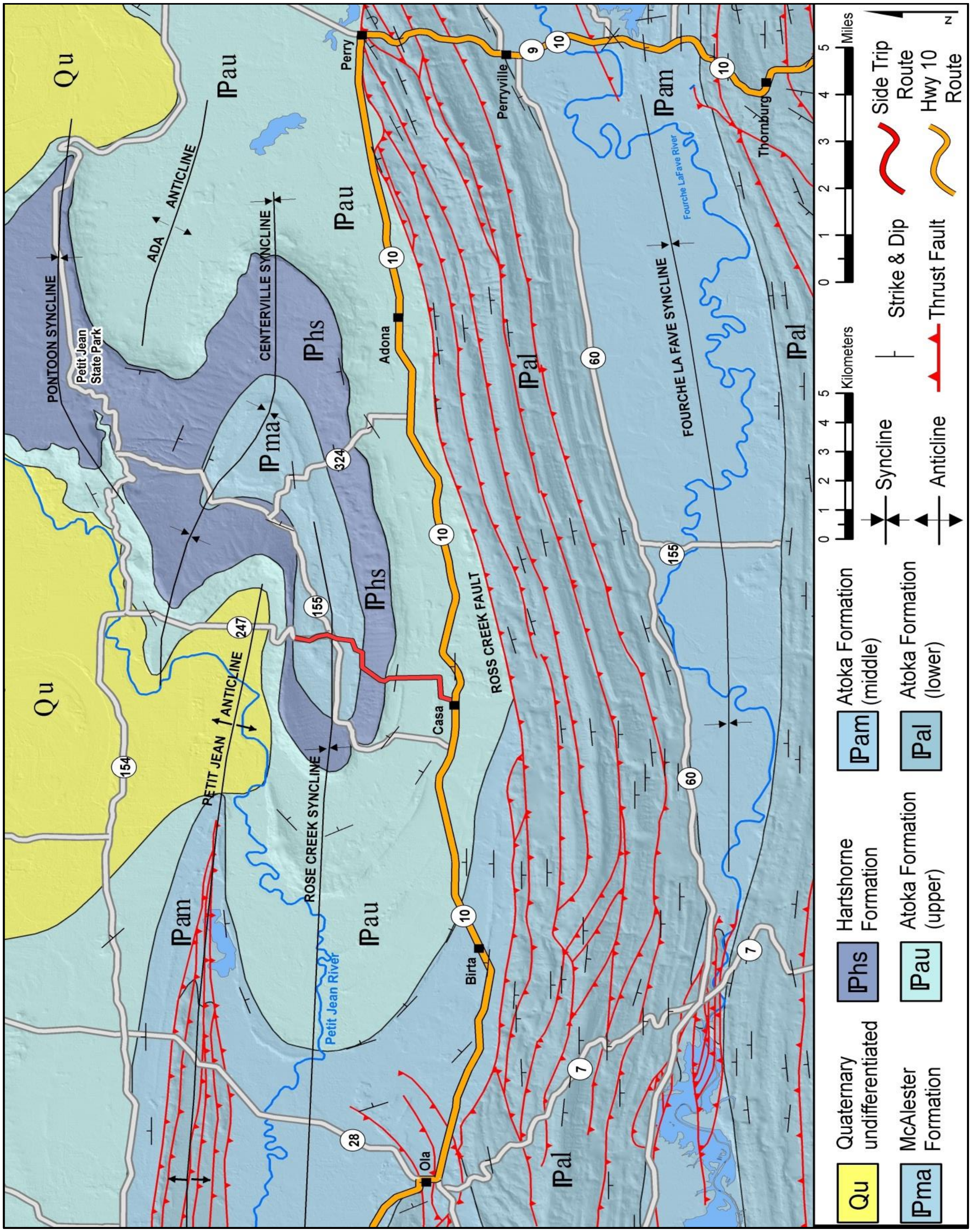
The Ross Creek Fault is the northernmost fault of a parallel series of four or more imbricate thrusts that can be mapped for approximately 80 miles (129 kilometers) to the west before merging with the North Ti Valley Fault of Oklahoma. This marks the northern boundary of the Frontal Ouachita Fold Belt. The Southern Arkoma Fold Belt (Arkoma Basin) lies to the north of the Ross Creek Fault (refer to Map 2).

Traveling west on AR-10 and looking to the right (north), you will see Rose Creek Mountain which is the north-dipping, southern limb of the Rose Creek Syncline. The south-facing *escarpment* is composed of Hartshorne Sandstone that dips as much as 30^{o} north. AR-324 turns to the north approximately 2.2 miles (3.5 kilometers) west of Adona and travels across Rose Creek Mountain and a portion of Round Mountain located on the axis of the Centerville Syncline. Round Mountain is capped by sandstone and shale of the McAlester Formation.

Petit Jean Mountain's north-facing escarpment is formed by the northern limb of the Pontoon Syncline. Petit Jean State Park is in that area. ***An excellent detailed geologic report, SPS-02 "The Geologic Story of Petit Jean State Park", is available from the Arkansas Geological Survey's website: www.geology.arkansas.gov/geologic_maps/dgm_sps002.htm.***

The town of Casa is approximately 9 miles (14.5 kilometers) west of Adona. AR-10's route remains parallel to the Ross Creek Fault. The upper Atoka Formation is exposed between the Fault and Rose Creek Mountain. To the south, you will see ridges of the lower Atoka with structural dips as much as 70^{o} south-southeast, because of *overstepping* thrust faults.

See Appendix for additional information and an extra side trip in this area.



Map 5. Perry to Ola. Stratigraphic order: younger on the left.
Data from reference map 4 (see p. 39). Structural axes added for clarity

Approximately 4.5 miles (7 kilometers) west of Casa, AR-10 crosses the contact between the upper and middle Atoka Formation. The contact trends northwest because of the synclinal fold that forms Rose Creek Mountain (Rose Creek Syncline). Also, the fold is expressed topographically, north of the Birta community, as the Santa Fe Ridge which is formed by a sandstone unit in the upper Atoka. From Birta to Ola the road runs on the middle Atoka. Approximately 1.5 miles (2.4 kilometers) southeast of Ola, the Ross Creek Fault's strike changes direction to approximately 30^{o} to the northwest.

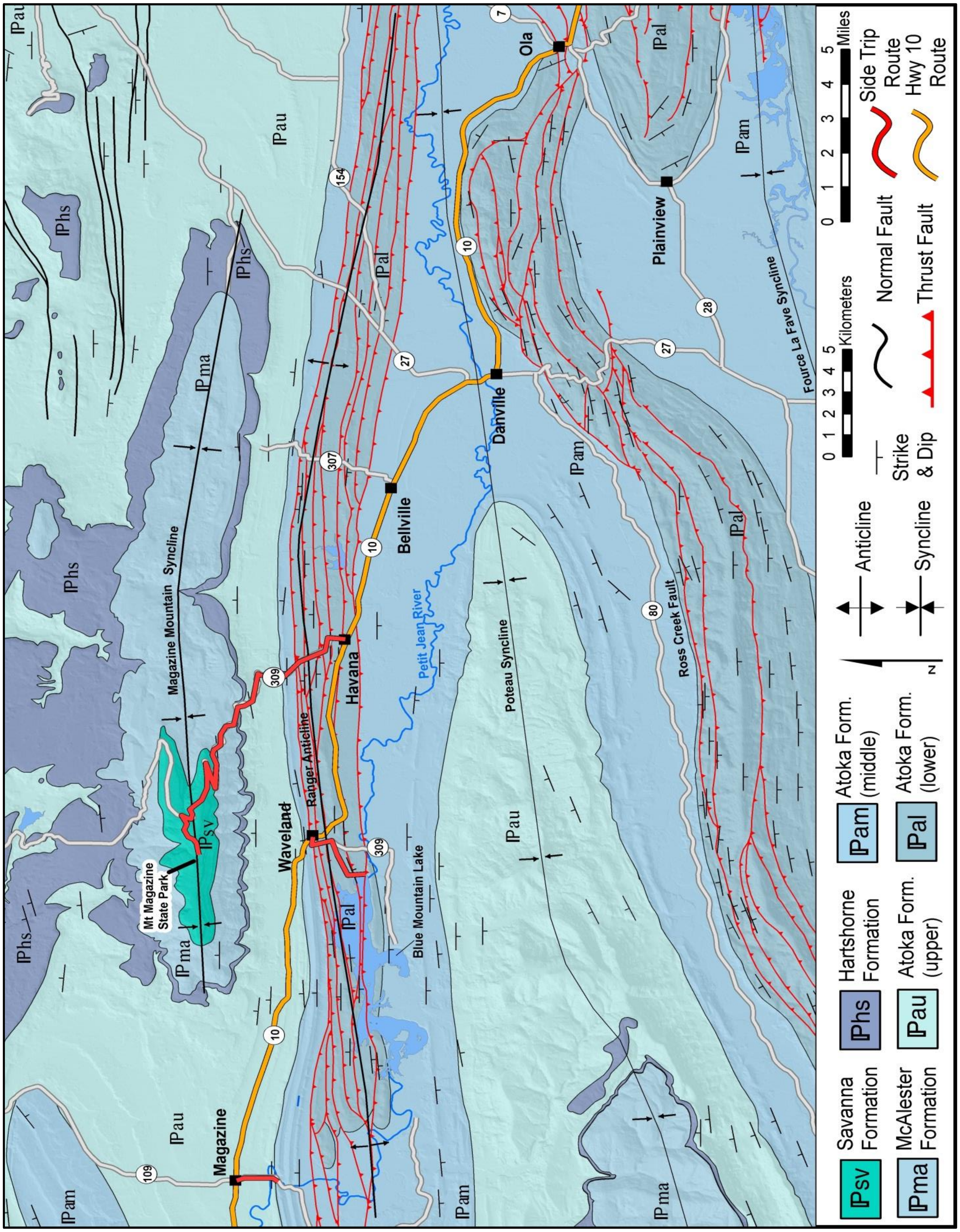
Road Guide - Ola to Danville

(Refer to Map 6)

Figure 6. Looking west toward Danville, Danville Mountain, and Dutch Creek Mountain

From Ola, AR-10 continues west toward Danville (Fig. 6). The road generally parallels the southern edge of the Petit Jean River Valley which is located within the Poteau Syncline. The Ross Creek Fault curves to the northwest around the northern edge of Danville Mountain (elevation 1269 feet, 387 meters above sea level at Bunker Hill). Before reaching Danville, the Fault makes a broad 45^{o} turn toward the southwest. The highland south of the Ross Creek Fault in this area is known as Dutch Creek Mountain which is the southern limb of the Poteau Syncline.

The northward-arching trend of the Ross Creek Fault between Ola and Danville reflects a subsurface structure that was the drilling target for Arkansas' deepest wildcat gas exploration well, the Danville Oxy USA Number 1. The well, located approximately 2.5 miles (4 kilometers) east of Danville, was drilled in 1991-92 to a depth of 20,661 feet (6297 meters). The target formation, the Cambro-Ordovician Arbuckle Group (510-485 mya), was reached. However, the well was a dry hole. Many drilling problems were encountered due to faults, fractures, and the hardness of quartz-rich sandstone at great depth. Additional technical problems were related to the elevated temperatures encountered in the deeper part of the borehole.



Map 6. Ola to Magazine. Stratigraphic order: younger on the left
Data from reference map 4 (see p. 39). Structural axes added for clarity

The Ross Creek Fault in this region is interpreted to be the surface expression of a *decollement* horizon (see Glossary p. 42 for a diagram) in the lower Atoka Formation above normal faults in Cambro-Ordovician basement rocks (Arbenz, 2008, Plate 5, Cross Section AR4). According to Arbenz's interpretation, rocks of the Fourche La Fave Syncline were thrust northward, as were rocks of the Poteau Syncline. Associated thrust faults were also products of this major tectonic movement.

Since crossing the Frontal Ouachita Thrust and Fold Belt between Williams Junction and Perry, AR-10 has paralleled the Ross Creek Thrust Fault (refer to Map 2). At Danville, the road turns more northwesterly and diagonally crosses the Southern Arkoma Fold Belt. This Belt, as mentioned before, consists of compression-produced, large-scale folds detached from basement rocks along ductile middle Atoka shale. *Growth faults* in the Atoka often extend upward into the folds.

The northern edge of the Petit Jean River Valley is host to six east-west-trending parallel thrust faults along the axis of the Ranger Anticline for approximately 45 miles (72 kilometers). These backfolding faults bring the lower Atoka to the surface, while the Petit Jean Valley is floored by the middle Atoka.

Gas Producing Regions

Southern Arkoma Fold Belt

For the remainder of the trip, AR-10 will pass through important gas-producing areas of the Arkoma Basin. Major gas fields are sited on three large, east-west-trending, faulted anticlines. They are from east to west the Ranger, the Washburn, and the Hartford. The gas fields in the following counties: Yell, Logan, Sebastian, Franklin, and Scott Counties are known collectively by the Arkansas Oil and Gas Commission as Area B-44. Significant individual fields in B-44 are the Waveland, Chismville, and Booneville in Logan County, and the Gragg, Greenwood, and Bonanza in Sebastian County. These fields produce from various horizons in the Atoka Formation. Gas production from B-44 was 51,449,628 Mcf (thousand cubic feet) in 2015 (AOGC Annual Report, 2015, p. 34). Cumulative production, since the fields were developed, is 566,090,365 Mcf.

Waveland and Mansfield Gas Fields

Gas production in the Waveland Gas Field extends for 12 miles (19 kilometers) along the Ranger Anticline's crest in the area centered near Waveland. The asymmetric anticline's interior is broken into slices by numerous stacked (imbricated) thrust faults along shale units in the Atoka which form decollement horizons. This results in repetition of the major gas-producing sandstone zones in the middle Atoka Formation-Upper Borum unit (Butler, 2004, Powerpoint, slide 2).

The oldest gas field in Arkansas, the Mansfield in Scott County, lies approximately 11 miles (17.7 kilometers) southeast of Greenwood. This field also produces from the Atoka Formation, here folded into the Hartford Anticline (Refer to Map 7).

See Appendix for a more complete discussion of the Arkoma Basin's gas production.

Road Guides

Road Guide - Danville to Havana

(Refer to Map 6)

At Danville, AR-10 turns northwesterly heading toward Belleville, which is 3.6 miles (5.8 kilometers) from the junction of AR-10 and AR-27. Be sure to notice the scenery to the south where there are excellent views of the frontal Ouachitas across the Petit Jean River Valley (Fig. 7). The Petit Jean River flows across the middle Atoka. These distant ridges (Dutch Creek Mountain), south of the Ross Creek Fault, are composed of sandstone in the lower Atoka.

Over 300 gas wells are in Yell County, and you will see several wells on either side of AR-10 between Belleville and Havana. The easternmost wells in the County are located north of Danville and approximately 3 miles (4.8 kilometers) east of Belleville. These wells produce dry methane natural gas from Atoka sandstone that was folded and faulted into hydrocarbon traps associated with the Ranger Anticline.

Approximately 0.6 miles (1 kilometer) southeast of Havana, the road crosses the southernmost thrust fault of the Ranger Anticline complex. The 53-mile (85-kilometer)-long Ranger Anticline parallels AR-10 for 33 miles (53 kilometers) between Danville and Booneville. It lies between the Mount Magazine and Poteau synclines. The lower Atoka is exposed in this thrust-faulted and northward-overturned structure from approximately 8.5 miles (13.7 kilometers) northeast of Ola to an area south of Booneville.

At Havana, AR-309 leads to the summit of Arkansas' highest mountain, Mount Magazine, which has an elevation of 2753 feet (839 meters) on Signal Hill (Fig. 8). ***An excellent geologic map of Mount Magazine and vicinity, including the State Park, is available from the Arkansas Geological Survey's website: www.geology.arkansas.gov/geologic_maps/dgm_sps001.htm.***

See Appendix for a side trip road guide to the summit of Mount Magazine via AR-309 from Havana.

Figure 7. Ouachita Mountains south of Petit Jean River Valley

Figure 8. Mount Magazine – a view from near Havana

Road Guide - Havana to Waveland
(Refer to Map 6)

From Havana toward Waveland, AR-10's route is superposed on an east-west-trending thrust fault for a distance of approximately 5 miles (8 kilometers). The road then turns northwest, crossing two thrust faults in the lower Atoka (Ranger Anticline fault complex) before reaching Waveland. Dips of the strata range from 70^{o} to the south to 87^{o} to the north in this zone of faulting.

Figure 9. Blue Mountain Lake

Turn left from AR-10 onto AR-309 and follow the signs to Blue Mountain Dam. The short drive (2.4 miles, 3.8 kilometers) to Blue Mountain Dam is well worth your time. Drive across the dam and park at the southern end (Fig. 9).

Blue Mountain Lake is a reservoir on the Petit Jean River. The 2800 foot (9184 meter)-long, 115 foot (377 meter)-high earthen dam was built by the U.S. Army Corps of Engineers in 1947. The Lake has a surface area of approximately 4.5 square miles (7.2 square kilometers) and approximately 50 miles (80 kilometers) of shoreline.

The lower Atoka Formation, exposed at the south end of the dam, consists of a turbidite sequence of "alternating brownish-gray, micaceous, fairly clean to silty sandstone, gray siltstone, and black shale and are considered to be of proximal deep-water origin." (Stone, 1981, p. 55). Several sedimentary features, typical of *turbidites*, may be seen including: graded bedding, *bottom marks*, convolute bedding, load features, channels, contorted structures, and trace fossils, along with small to large lenticular sandstone and shale submarine slump and slide masses (Stone, 1981, p. 55).

A prominent contact can be seen to the right (west) of the dark-colored rocks (Fig. 10). The light-colored sandstone is interpreted to have been formed by a *turbidity current* that incised a channel into the underlying dark-colored, finer-grained sediments. This shale and siltstone could have been deposited as a submarine fan or part of a deep-water slope deposit (Stone, 1981, p. 59).

See Appendix for additional information concerning this location.

Figure 10. Lower Atoka turbidite sequence, south end of Blue Mountain Lake Dam

Return from Blue Mountain Lake to Waveland.

Road Guide - Waveland to Magazine

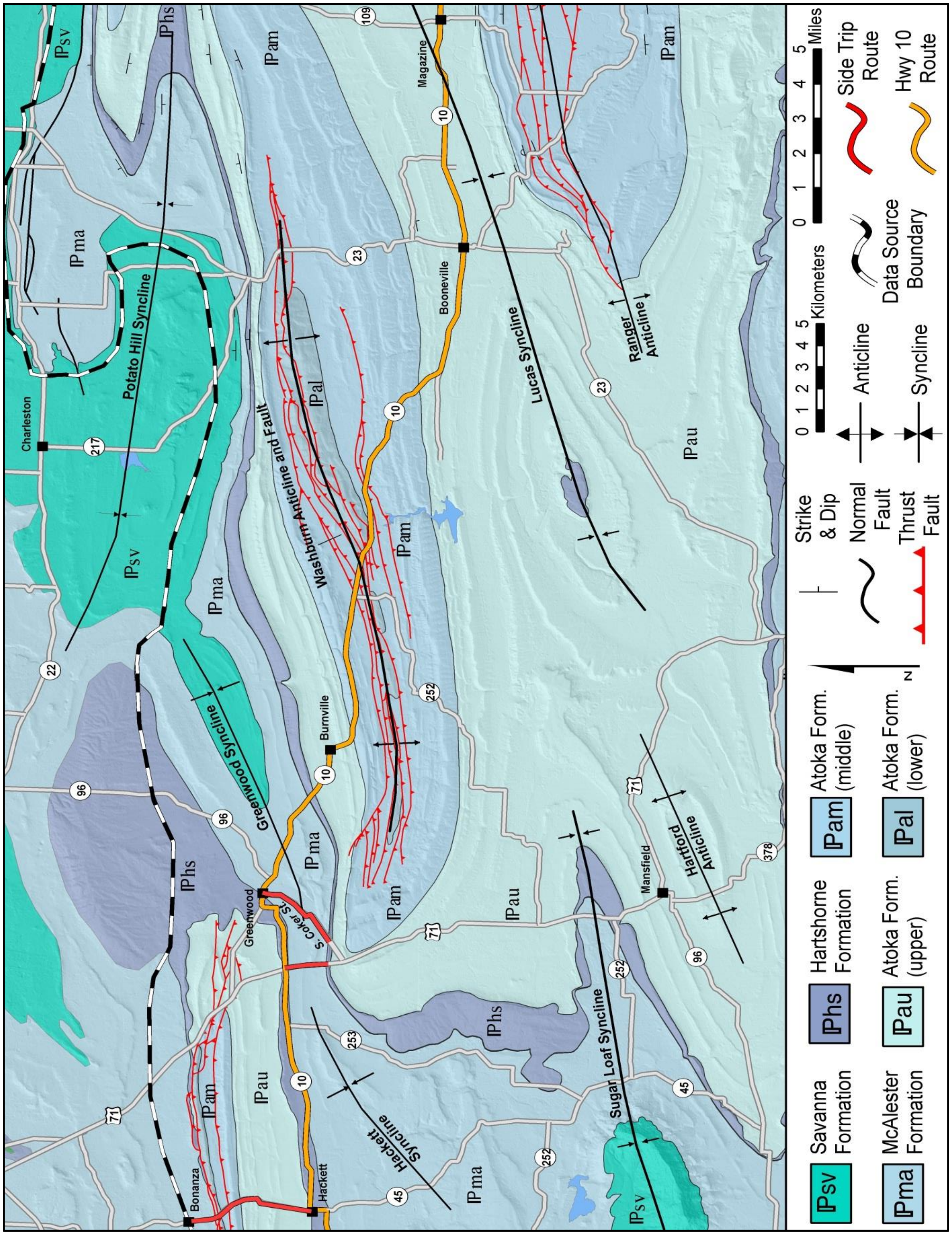
(Refer to Map 6)

Continuing westward from Waveland on AR-10, you will be crossing the upper Atoka exposed on the northwest flank of the westward plunging nose of the Ranger Anticline. Dips in the Atoka range from 30º to 40º when not affected by thrust faulting which produces dips in the 60º to 80º range.

Approximately 4.5 miles (7.25 kilometers) from Waveland, AR-10 intersects AR-109 in the town of Magazine. A short trip (1.1 miles, 1.77 kilometers) south on AR-109 brings you to a quarry where the middle Atoka Formation is well exposed (Fig. 11). The quarry is in a water gap, known locally as the "Narrows", that was eroded across east-west-trending Potts Ridge by north-south-trending Revilee Creek. Here the middle Atoka consists of light-gray, fine- to medium-grained sandstone and thin beds of siltstone. Iron staining (limonite) is present on numerous fractures *(joints)* and bedding planes.

Figure 11. Middle Atoka Formation, south of the town of Magazine

Return to Magazine and continue west on AR-10.



Map 7. Magazine to Hackett. Stratigraphic order: younger on the left. Data north of "Data Source Boundary" from reference map 3; south of Boundary from reference map 4 (see p. 39). Structural axes added for clarity

Road Guide - Magazine to Greenwood
(Refer to Map 7)

Three and one-half miles (Five and six-tenths kilometers) west of the junction with AR-23 in Booneville, AR-10 turns northwest at the junction with AR-60 and begins a climb toward a collection of ridges, namely Booneville Mountain, Pleasant Ridge, and Pine Ridge. Approximately 0.75 miles (1.2 kilometers) northwest of the AR-60 junction, AR-10 crosses from upper Atoka to middle Atoka which is exposed on the southern flank of the Washburn Anticline (Fig. 12). The thrust-faulted Washburn Anticline extends approximately 30 miles (48 kilometers) in an east-west direction with a slight northeast trend. The Chismville Gas Field lies approximately 5 miles (8 kilometers) north of Booneville, while the Booneville Gas Field is approximately 6 miles (9.7 kilometers) northwest of Booneville. The gas traps formed by the Washburn Anticline and associated faults are present in various Atoka Formation horizons.

Figure 12. Middle Atoka Formation on Washburn Mountain

The first fault in the Washburn Fault Complex is crossed in the valley of Pigeon Creek approximately 3.75 miles (6 kilometers) from the AR-60/AR-10 junction. This is one of many south-dipping thrust faults in the lower Atoka which developed above a series of north-dipping normal faults in basement rocks approximately 8000 feet (2438 meters) below the surface (Arbenz, 2008, Plate 5, Cross Section AR 5).

The Washburn Anticline continues west-southwest into Sebastian County and several additional gas fields (Greenwood, Gragg, Witcherville, Excelsior) are associated with the structure. Also, another anticlinal structure, the Hartford, is located approximately 11 miles (17.6 kilometers) southeast of Greenwood. This smaller structure is responsible for the oldest gas wells (Mansfield Field) in the State.

Figure 13. Hartshorne Sandstone on Devil's Backbone Ridge

The road continues westward across the fault complex, Devil's Backbone Ridge, and the Greenwood Syncline. The upper Atoka is exposed in the area surrounding the community of Burnville. Approximately 0.75 miles (1.2 kilometers) northwest of Burnville, the Hartshorne forms Devil's Backbone Ridge. The Hartshorne is exposed in a small roadside quarry to the south of AR-10 at the crest of the Ridge (Fig. 13). Once across the Ridge, the McAlester Formation is exposed along the axis of the Greenwood Syncline or Washburn Mountain. The city of Greenwood is located on the Hartshorne Sandstone.

Figure 14. McAlester Formation, south of Greenwood

Road Guide - Greenwood Area
(Refer to Map 7)

In Greenwood, AR-10 divides; AR-10 Spur turns northwest, while AR-10 turns south on Coker Street and then west on Excelsior Road. To see an excellent exposure of the McAlester Formation, turn left (south) on Coker Street.

Coker Street crosses Quaternary alluvium and terrace sediments in Adamson Creek's valley. A quarry exposing the McAlester Formation is located on Coker Street approximately 1.5 miles (2.4 kilometers) south of the Excelsior Road turn-off. The quarry is located on the east side as the road begins an uphill run (Fig. 14). The McAlester consists of an upper unit of shale, siltstone, and thin beds of silty sandstone and a lower unit that is more sandy, silty, and less shale rich (Haley, 1966, Plate 1).

Continuing uphill to the summit of Devil's Backbone Ridge, you will see the nearly vertical (dip is 89^0 to the north) Hartshorne Formation composed of sandstone and silty sandstone. This exposure is on the southern flank of the Greenwood Syncline (Fig. 15).

Figure 15. Vertical Hartshorne Sandstone, south of Greenwood

After examining the Hartshorne, retrace the route north to Excelsior Road (AR-10) and turn left (west) to continue on AR-10 approximately 1.8 miles (2.9 kilometers) to U.S. Highway 71 (US-71). To examine an excellent cross section of the Hartshorne and upper Atoka contact, turn south on US-71 and go approximately 1 mile (1.6 kilometers) to a large road cut through Devil's Backbone Ridge. There, an exposure of steeply-dipping Hartshorne Sandstone and an erosional contact with the silty marine shale of the upper Atoka Formation can be seen (Fig. 16).

Figure 16. Devil's Backbone Ridge, Hartshorne Sandstone and upper Atoka Formation contact south of Greenwood on US-71

Structurally, Devil's Backbone Ridge is on the north-dipping (89º) southern flank of the Greenwood Syncline - northern flank of the Washburn Anticline. According to M.T. Roberts' interpretation, the Washburn Anticline is the result of several northward-directed imbricate thrust faults and conjugate southward-directed thrust faults resulting in a structural triangle zone of lower Atoka above a *sole thrust fault* over the ductile Morrowan strata (Suneson, 2005, Fig. 17).

The Hartshorne Sandstone at this locality is approximately 215 feet (65.5 meters) thick and consists of cross-bedded and ripple-marked light-brown to tan sandstone. According to Rufus LeBlanc and Lloyd Yeakel's interpretation of the depositional environment, the Hartshorne Formation developed as an overlapping *point-bar* sequence deposited by a regional-scale, west-flowing, meandering river. The bar deposits are intermixed with channel deposits (LeBlanc and Yeakel, unpublished report for Shell Oil Company).

An alternative interpretation of the depositional environment is that the Hartshorne was deposited in numerous sub-environments related to a major river delta. The sub-environments included the following: *pro-delta*, delta-front, distributary-channel, interdistributary-bay, *crevasse-splay*, marsh-swamp, and *fluvial* facies. The Hartshorne channels were eroded into pro-delta marine sediments of the upper Atoka Formation (Houseknecht, 1983, p. 82).

The Hartshorne is overlain by the delta-plain deposits of the McAlester Formation (Suneson, 2005, p. 22). The McAlester includes the Lower and Upper Hartshorne Coal beds which are the major coal-producing deposits in the Arkoma Basin (See Fig. 4A in the Appendix, p. 8A, for a stratigraphic column diagram).

Upon completion of your study of the road cut, return to the junction of US-71 and AR-10. Park your vehicle in the lot on the southeast corner of the intersection.

Hike across AR-10 into the abandoned quarry on the northeast corner of the intersection. Quarrying has removed most of the Hartshorne Sandstone exposing the upper Atoka. However, on the north face of the quarry there is an excellent exposure of the Hartshorne and upper Atoka contact (Fig. 17). Here you may study the lithology of each formation in detail.

When finished, return to the parking lot and proceed west on AR-10 toward Hackett and the Oklahoma State Line.

Figure 17. Hartshorne Sandstone – upper Atoka Formation contact in quarry, junction AR-10 & US-71

Road Guide - Greenwood to the Oklahoma State Line
(Refer to Map 7)

From Greenwood to Oklahoma, AR-10 lies on the east-west-striking Hartshorne Sandstone. The upper Atoka crops out north of the road along Hester Creek and Hackett Creek. To the south, the McAlester Formation crops out along Adamson Creek and Elder Branch.

Hartshorne Sandstone is quarried at several locations in this area, especially near the Oklahoma State Line west of Hackett, for use as dimension stone and in other applications. The variety of stone colors, finishes, and dimensions is quite large. For an illustration of the various stone products produced in the area, see the following website: http://ibisonstonesupply.com.

From the vantage point of the Ibison Stone Quarry entry on AR-10, there is an excellent view of the Ouachitas to the south (Fig. 18). The Savanna Formation forms the caprock of Sugar Loaf Syncline. Sugar Loaf Mountain, 2564 feet (785 meters) in elevation, and Midland Peak, 2102 feet (641 meters) in elevation, are the prominent peaks visible. They are approximately 12 miles (19.3 kilometers) and 10 miles (16 kilometers) away, respectively.

Figure 18. Ibison Stone Supply storage area, looking south toward Sugar Loaf Mountain (to the left) and Midland Peak (to the right)

Figure 19. Hartshorne Sandstone "columns", Ibison Stone Quarry

Several structural and lithologic features are present in the Hartshorne Sandstone that make quarrying more efficient. The intersecting north-south and east-west-trending vertical joint sets and bedding plane fractures facilitate the removal of large slabs and massive sandstone "columns" (Fig. 19). These "columns" are used in river control structures to stabilize channels and prevent bank erosion, among other construction applications.

Also, there are many well-developed sedimentary structures present, such as interference *ripple marks* (Fig. 20), *cut-and-fill channels* (Fig. 21), and *cross-bedded* stratification. These features indicate the Hartshorne originated as point-bar deposits in paleostream channels or in ancient deltas as distributary channels.

Figure 20. Jointed and ripple-marked Hartshorne Sandstone, Ibison Stone Quarry

Figure 21. Channel deposit in Hartshorne Sandstone, Ibison Stone Quarry

Upon returning to Hackett, turn left (north) on State Highway 45 (AR-45) for an interesting side trip to Bonanza.

Road Guide - Hackett to Bonanza
(Refer to Map 7)

This route takes us across Backbone Ridge (Backbone Anticline and thrust fault complex). Approximately 1.5 miles (2.4 kilometers) north of the AR-10 and AR-45 intersection, there are two road cuts exposing the upper and middle Atoka Formations. The Hartshorne-upper Atoka contact is present where AR-10 and AR-45 join. Proceeding north on AR-45, the road crosses into the upper Atoka after crossing Hackett Creek. Just north of Sebastian Lake, the upper Atoka contact with the middle Atoka is dramatically exposed in a relatively new, deep road cut (Fig. 22). The Hartshorne is not present due to east-west-trending thrust faults.

Figure 22. Middle Atoka Formation, road cut north of Hackett on AR-45

The upper Atoka is approximately 5000 feet (1524 meters) thick, on average, and is mostly black shale, with some silty shale, siltstone, and fine-grained sandstone. The sandstone may contain soft-sediment flow and slump features (distorted bedding and variations in strata thicknesses). Channel sandstone and thin coal seams have also been noted (Stone, 1968, p. 8).

The middle Atoka, in this part of the Arkoma Basin, has a thickness of approximately 4000 feet (1219 meters) and consists of four or five sandstone units separated by shale. The fine- to medium-sized grains in these rocks contain a significant percentage of *metamorphic* rock fragments (Zachry, 1983, p. 47). A paleogeographic map for early to middle Atokan-aged sediment proposes an Ouachita orogenic highland located in southern Arkansas and central Mississippi as source areas for the fragments (Houseknecht, 1983, p. 22). However, don't expect to find grains that can be identified in the field as metamorphic rock fragments, since the grains are less than 1 millimeter in diameter and must be studied in thin section with a petrographic microscope.

This stop marks the end of the Geotour. Fort Smith may be reached by continuing north on AR-45 and State Highway 253 for approximately 5.5 miles (8.8 kilometers).

Conclusion

In 2010, the U.S. Geological Survey assessed the undiscovered natural gas resources present in the Arkoma Basin's Post-Ouachita Successor Belt (Southern Arkoma Fold Belt) and the Ouachita Thrust Belt (Frontal Ouachita Thrust and Fold Belt) (U.S.G.S. Fact sheet 2010-3043, June 2010). This assessment arrived at the following estimates:

Natural Gas …................ 38 Tcf (trillion cubic feet)

Natural Gas Liquids ….. 159 million barrels

Oil …............................. 0.5 million barrels or less

According to these estimates, shale-gas-containing formations have 70 percent of the total, while basin-centered, tight-sandstone formations include 18 percent, and coal beds carry 9 percent, amounting to a 97 percent total. The remaining 3 percent is not related to shale-gas-containing formations, and is estimated to be present in conventional traps such as sandstone, limestone, and fractured chert.

On March 7, 2012, the Oklahoma City Geological Society and the Oklahoma Geological Survey conducted a workshop to examine the "Arkoma Basin Petroleum Past, Present, and Future". One of the most interesting statements about the future for natural gas exploration in the Arkoma depends on "Two Killers" which are (1) awful (low) gas prices, and (2) lack of infrastructure (collection systems, pipe lines, and distribution systems) (Suneson, 2012).

In a recent article in the AAPG Explorer, it is noted that the Independent Potential Gas Committee stated that "the nation's available gas . . . resource-base estimate (is) 1,836 Tcf – the nation's highest in the Committee's 44-year history". Assuming these estimates are accurate, the Arkoma's potential future production could represent 2 percent of the nation's total available gas resource.

This excursion from Little Rock to the road cut north of Hackett has exposed you to the geological complexity of the Arkoma Basin (an orogenic foreland basin) and its adjacent regions (the Frontal Ouachita Fold Belt and the Pennsylvanian-Mississippian Turbidite Sandstone Belt of the Ouachita Mountains). Hopefully, the trip has been interesting, educational, and has provided you with an understanding of the challenges exploration geologists face as they search for additional hydrocarbon energy resources.

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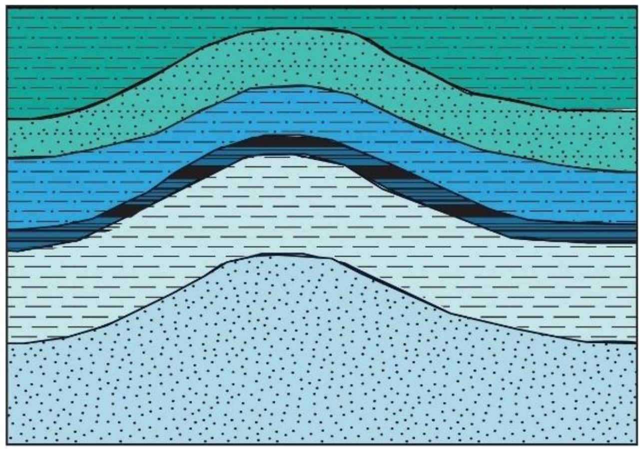
Glossary of Terms

Note: All diagrams are cross-section views

Anticline - an upfold (arch) in sedimentary strata formed by structural deformation forces (compression or vertical uplift)

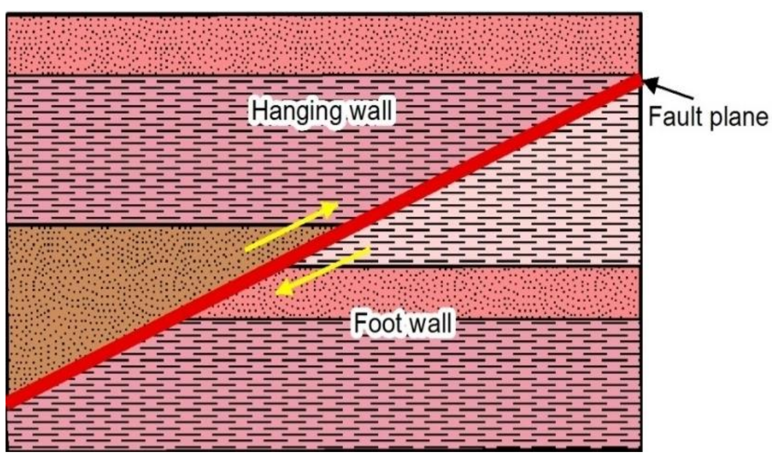


Alluvium - the sediment (gravel, sand, silt, clay) deposited by a modern stream or river

Apatite - a group of calcium phosphate minerals that may contain fluorine, chlorine, hydroxyl or carbonate in differing amounts

Basement rock - the igneous or metamorphic rock that underlies sedimentary rock sequences

Backfolding - the folds that are overturned toward an orogenic core region



Backthrust - a thrust fault in which the hanging wall moved toward the orogenic core region (positioned to the right in this diagram)

Bathyal - a deep-water zone in the ocean (650 to 12,500 feet or 200 to 2000 meters deep)

Bottom marks - (sole markings) include scour marks, flute casts, tool marks, groove casts, and load casts found on the bottom of some sedimentary strata, especially turbidite deposits; such sedimentary features are used to determine the bottom of a stratum, especially where structural overturning is suspected

Calcite - a mineral composed of calcium carbonate ($CaCO_3$) which is the major component of limestone

Calcareous - indicates that the composition of a rock includes calcium carbonate, usually as the cement holding grains together

Carbonates - a group of minerals composed of various metals (calcium, magnesium, etc.) combined with carbon and oxygen (see calcite as an example)

Carbonatite - an intrusive igneous rock with a carbonate-rich matrix, associated with alkaline igneous intrusions, such as dikes or sills

Chaotic sedimentary structure - a large-scale (ranging in size from tens to hundreds of feet/meters), complex mixture of sedimentary depositional structures; for example turbidity flow lobes, submarine fans or slumps, debris flows, and deep, sea fan channel deposits

Chert - a microcrystalline form of silicon dioxide, SiO^2 (quartz)

Clastic - the sediments or rocks composed of rock, mineral, or organic fragments that were transported from their place of origin

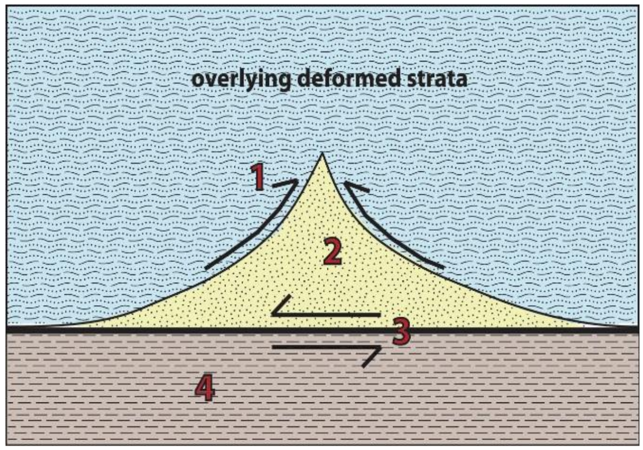
Clay - a group of very fine-grained minerals (hydrous aluminum silicates) produced by weathering of igneous and metamorphic rocks, especially those containing feldspars; the term is often used to mean a fine-grained earthy material that becomes plastic when mixed with a small amount of water

Coal - a combustible, brown to black sedimentary or metamorphic rock; the following coal ranks are arranged in order of increasing heat value per pound: Lignite > Bituminous > Semi-anthracite > Anthracite

Cookeite - a lithium-containing, mica-like mineral formed by hydrothermal alteration of feldspar and/or mica

Note: All diagrams are cross-section views

Conjugate shear zone - (backthrust) a thrust fault which developed above a tectonic triangle zone and displays evidence of movement toward the direction from which the compressive forces originated



1 – Conjugate shear fault

2 – Triangle zone

3 – Major thrust fault

4 – Highly ductile strata

Continental shelf - a portion of the continent covered by shallow sea water (maximum depth 600 feet or 183 meters)

Convolute bedding - the sedimentary bedding that is distorted, not planar, as a result of soft-sediment slumping or flow

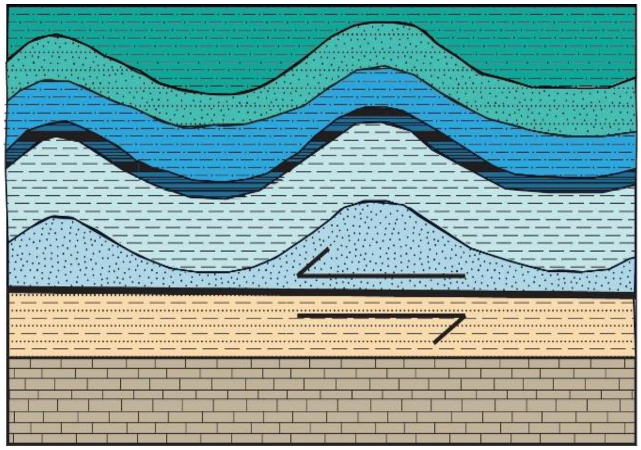
Crevasse splay - a river or stream deposit formed when a stream erodes across a natural levee on a floodplain creating a deposit of sediment that is physically distinct from the surrounding sediments

Cross-bedding - an arrangement of sediment layers that are at an angle to the horizontal plane of stratification

Cut-and-fill channels - a sedimentary structure resulting from erosion of previously deposited sediment and the filling of the channel with another sediment

Note: All diagrams are cross-section views

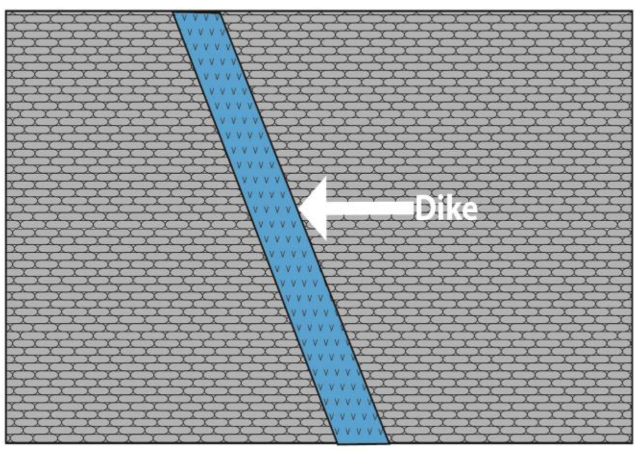
Decollement - a deformation structure in sedimentary rocks where there are unique structural styles in rock above and below a distinct horizon, usually a thrust fault



Delta - a deposit of sediment formed at the mouth of a river upon entry into an ocean or lake

Dickite - a hydrous, aluminum silicate clay mineral often associated with hydrothermal alteration in fault zones

Dike - an igneous rock intrusion that cuts across the enclosing rock's structure or position



Dip - the angle of inclination (tilt) of a bed of sedimentary rock as measured from a horizontal plane to the surface of the bed; the positions of other geologic features (fault planes, veins of mineral matter, etc.) may also be described in the same manner

Dolostone - a sedimentary rock composed of the mineral dolomite (calcium-magnesium carbonate)

Down-to-the-south normal fault - a normal fault where the rock mass above the fault plane (hanging wall) moved downward in a southerly direction

Drape fold - a fold in sedimentary rocks overlying a normal or thrust fault in basement rocks

Escarpment - a steep slope, often vertical, at the edge of a flat-topped highland area, usually composed of layered sedimentary rocks

Facies - a change in the physical and/or chemical characteristics of a mappable stratigraphic unit (formation) due to variations in the depositional environment

Fault - a fracture or group of fractures with rocks on one side showing displacement (offset) relative to the other

Feldspar - the most abundant mineral family in igneous and metamorphic rocks; includes orthoclase to albite (potassium to sodium aluminosilicate) and plagioclase (sodium to calcium aluminosilicate)

Fissile - a thinly-bedded (laminated) rock, usually shale, that splits into numerous layers less than two millimeters thick

Flame structure - a load cast that has some of the underlying layer squeezed upward into the overlying stratum

Foot wall - the rocks below a fault plane

Foredeep - a linear depression in the Earth's crust next to a folded mountain (orogenic) belt

Foreland - a resistant mass of basement rocks and sediments (continental edge) against which geosynclinal sediments are compressed during an orogeny

Formation - a term applied to a group of sedimentary strata (sandstone, shale, etc.) that were deposited at approximately the same time

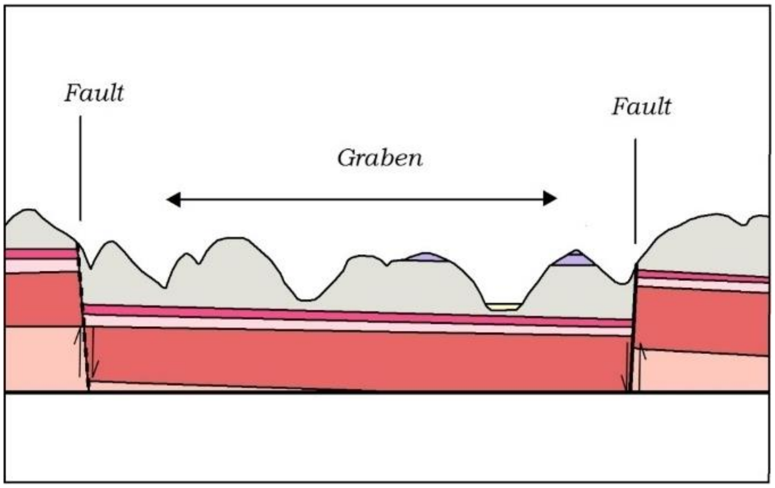
Fluvial sediments - the sediments transported by flowing water (streams or rivers) that were deposited when flow ceased

Flysch - the deposits of sandstone, marl, and shale derived from sediments eroded from a rising landmass during an early stage of an orogeny

Geosyncline - a large-scale, elongated trough adjacent to a continent or island arc that sinks several thousand feet while accumulating sediments during the orogenic process

Note: All diagrams are cross-section views

Graben - a down-dropped block of the Earth's crust between two normal faults that dip toward each other

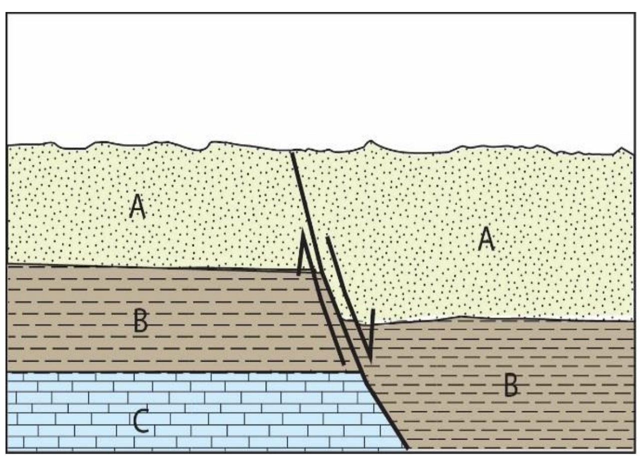


Graded bedding - the stratification in sediment or sedimentary rocks having coarse clastic sediments at the bottom of a sequence that becomes progressively more fine-grained upwards

Granite - a medium- to coarse-grained plutonic igneous rock composed of quartz, potassium and sodium feldspars, and minor amounts of other minerals

Graywacke - a type of sandstone with quartz and feldspar grains surrounded by a matrix of clay

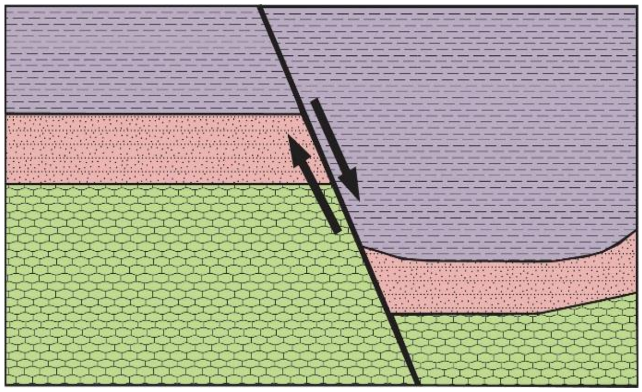
Growth fault - an active normal fault that develops thicker deposits of sediment on the down-thrown block due to continually increasing accommodation space as fault movement progresses



Hanging wall - the rocks above a fault plane

Note: All diagrams are cross-section views

Half-graben - a mass of rock bounded on one side by a normal fault and on the other side forms a fold



Hydrothermal fluid - a hot (100^0 to 500^0 C) water-rich solution released from magma late in the crystallization process

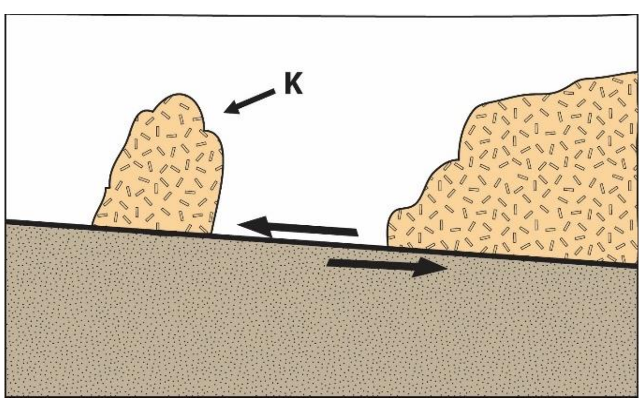
Igneous - the rocks that crystallized from molten material (magma in the subsurface or lava on the surface) upon cooling

Igneous breccia - an igneous rock consisting of broken angular fragments surrounded by a fine-grained matrix; generally related to some form of eruptive activity; however, not necessarily related to a volcano

Imbricate - an overlapping arrangement of sedimentary rock particles due to current action; or the overlapping "shingle-like" arrangement of structural elements (for example, thrust faults)

Joint - a planar fracture in rock along which there has been only minor movement, often only a slight "pull-apart"

Klippe (Klippen, pl.) - an "island-like" mass of rocks separated from underlying strata by a thrust fault



K = Klippe

Note: All diagrams are cross-section views

Limestone - a chemically precipitated sedimentary rock composed of the mineral calcite (calcium carbonate) often containing fossils (shells or other hard parts) of invertebrate marine organisms

Limonite - a non-crystalline variety of hydrous iron oxide (yellowish brown in color) that may form during the weathering of iron-rich rocks and minerals

Lenticular - a body of sediment that has the shape of a lens or lentil; a biconvex shape

Load cast - a sedimentary depositional structure caused when sand layers overlie a bed of wet clay and compaction caused by gravitational forces results in dewatering of the clay and the downward movement of the sand resulting in an irregular, “lumpy” sandstone/shale contact

Magnetite - a slightly magnetic mineral composed of iron and oxygen

Magma - a molten igneous rock-forming material located below the Earth's surface

Marl - a sedimentary rock that is a mixture of clay and calcite

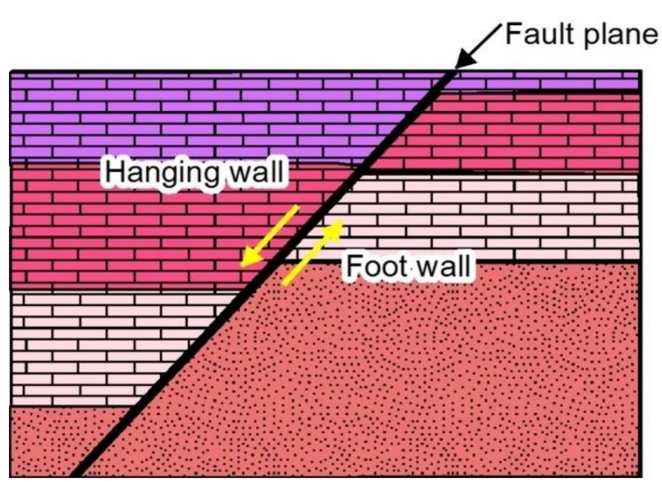
Melange - a mappable rock unit that contains rock fragments of all sizes from local or remote sources, enclosed in a crushed and sheared matrix

Metamorphic - the family of rocks that develops after earlier-formed rock is exposed to increased heat, pressure, and chemically active fluids, resulting in changes in composition, texture, and structure

Neritic - the shallow water portion of oceans that overlies the continental shelf with water depths from 0 to 600 feet (0 to 183 meters).

Novaculite - a very fine-grained sedimentary rock composed of silicon dioxide, SiO_2 (quartz)

Normal fault - a fracture in rocks along which the rock mass above the inclined fracture (hanging wall) moves downward in response to tensional forces and gravity



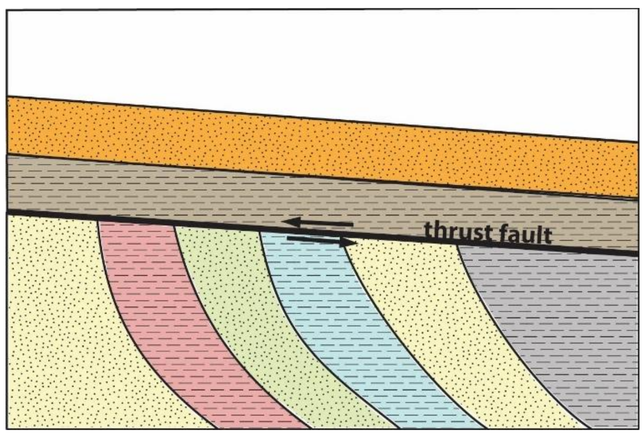
Note: All diagrams are cross-section views

Orogenic - an adjective for the word “orogeny”

Orogeny - (orogenesis) the long-term (millions of years) group of processes, usually involving intense compressive forces being applied to thick masses of sediments, leading to the formation of folded and thrust faulted mountains of massive scale (for example the Rocky Mountains or the Alps)

Orogenic foredeep - (molasse basin) a region between the undeformed continental platform and the main orogenic fold and fault belt which contains a thick sequence of clastic sediments

Overstepping - a structural relationship where a thrust fault truncates (cuts off) several upturned strata below the thrust sheet (mass)



Overthrust - a thrust fault having a low dip angle and a large distance (miles/km) of displacement

Paleocurrent - a water current direction at the time of sediment deposition as determined by sedimentary rock structures (such as ripple marks, and cross beds)

Plate tectonics - a theory developed in the 1960's that explains the structure of the Earth's crust and phenomena such as earthquakes, volcanoes, and folded and faulted mountains as the result of the crust being composed of massive plates of solid rock that move across a hotter, less rigid, underlying rock; heat flow from the Earth's core drives the process

Point-bar - the sediment deposited on the inside portion of a developing meander curve of a stream or river

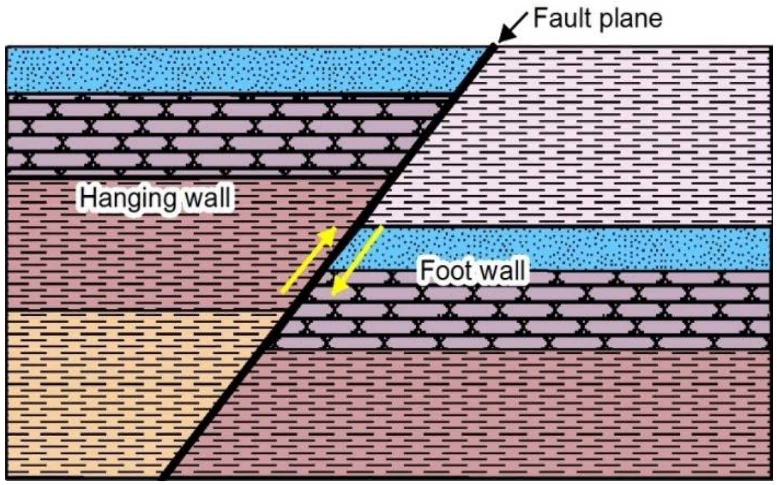
Pro-delta - the part of a delta far enough offshore to no longer be affected by wave erosion

Quartz - a mineral composed of silicon dioxide (SiO_2) which is a major component of igneous, sedimentary (especially siltstone, sandstone, and conglomerate), and metamorphic rocks

Rectorite - a mica-like mineral formed as a hydrothermal alteration of feldspar or muscovite mica

Note: All diagrams are cross-section views

Reverse fault - a fracture in rocks caused by compression resulting in the rock mass overlying the fracture (hanging wall) moving upwards in comparison to the rock mass that underlies the fracture (foot wall)



Ripple marks - the wave-like structures of sand and/or silt caused by wind, water currents, or wave action which may be preserved as depositional features in clastic sedimentary rocks

Sandstone - a sedimentary rock composed of detrital grains of chemically and physically resistant minerals (often quartz); grain sizes may range from 1/16 millimeter to 2 millimeters in diameter

Sediment - loose mineral grains or rock fragments that are weathered from rock, transported by wind, flowing water, and/or glacial ice, and deposited a distance from their source

Sedimentary - the family of rocks that form from weathered rock residue (gravel, sand, silt, clay) or are chemically precipitated from water (calcite, dolomite, chert, gypsum) and which usually display bedding or layering

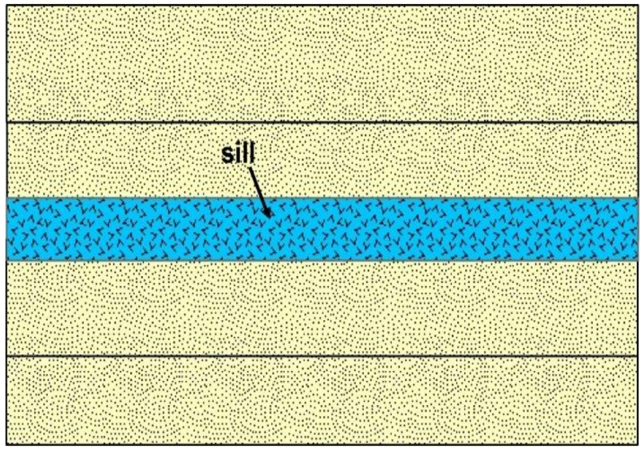
Shale - a sedimentary rock composed of clay that often contains organic matter which causes gray to black coloration; often displaying fine laminations (fissility)

Shale-gas - the natural gas (methane) that is trapped within shale deposits

Siliceous - an adjective that means containing silica (silicon dioxide) as a cementing agent in sedimentary rocks

Note: All diagrams are cross-section views

Sill - a tabular-shaped igneous intrusion that is parallel to the enclosing sedimentary rocks or metamorphic rock foliation structures



Silt - a durable sediment that is finer than sand; grain sizes may range from 1/16 millimeter to 1/256 millimeter

Siltstone - a sedimentary rock composed of silt

Slickensides - a polished surface, often with ridges and grooves, on a fault plane which may indicate the direction of movement of the fault blocks

Sole thrust fault - the lowest thrust fault in a shingle-like stack of thrust faults

Sovite - a coarse-grained variety of carbonatite

Strata - the layers of sedimentary rocks

Strike - the compass direction indicated where a sedimentary bed or fault intersects a horizontal plane

Subduction - a process that results in a plate of the Earth's crust, usually ocean basin crust, being drawn down below another plate of the crust, usually continental crust

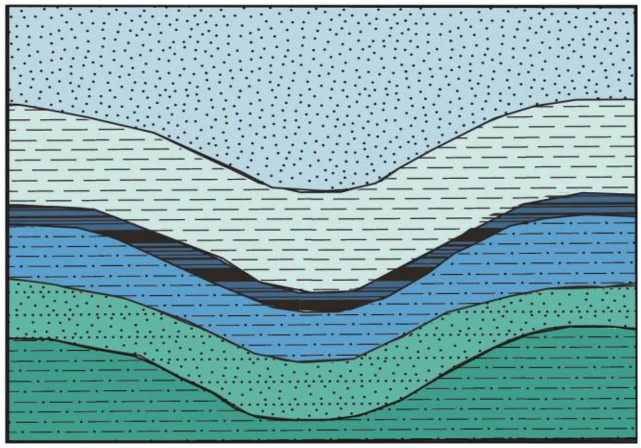
Subgraywacke - a hard, dark sandstone containing minor amounts of feldspar, angular rock fragments, and clay; formed during orogenic activities

Submarine fan - a fan-shaped deposit of marine sediment carried down a continental slope by a turbidity flow of water and sediment of mixed grain sizes

Syenite - a coarse- to medium-grained plutonic igneous rock related to granite in overall appearance, but lacking the quartz content characteristic of granite. Syenite is the rock type quarried in central Arkansas at Little Rock and Magnet Cove

Note: All diagrams are cross-section views

Syncline - a downfold (trough) in sedimentary strata caused by structural deformation forces



Tectonic - the forces or processes that alter the structure of the Earth's crust

Terrace - an elevated flat area of alluvium situated above the present-day floodplain, formed as a previous floodplain prior to the river eroding its channel to a lower level

Thrust fault - a reverse fault that has a low angle of dip (30^0 or less) where the overlying rock mass (hanging wall) has moved up and over the underlying rocks (foot wall); caused by extreme compression

Trace fossils - the sedimentary structures, present in some sedimentary rocks, which were caused by burrowing or bottom-feeding organisms

Triangle zone - a crustal structure formed where a master thrust fault moved over a very ductile rock (usually shale) resulting in a triangular-shaped (wedge-shaped) mass of rock being formed above the fault; the “wedge” is bounded on either side by a higher angle thrust and a higher angle backthrust – *see conjugate shear fault* (p. 42)

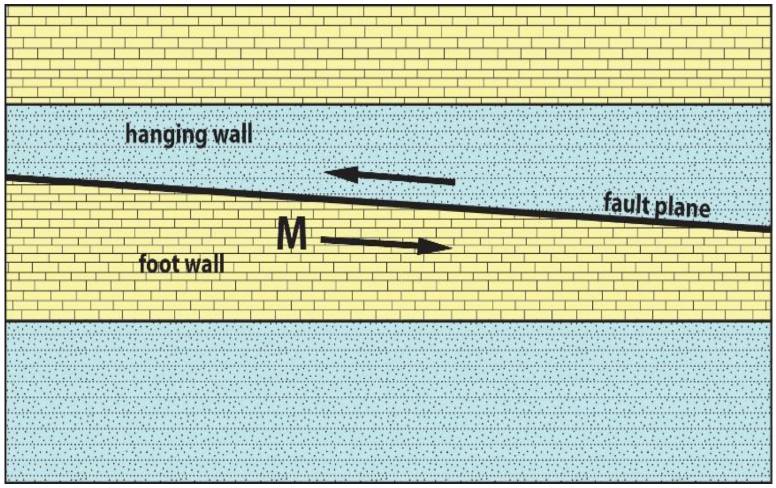
Tuff - a rock composed of compacted volcanic ash

Turbidite - a sedimentary rock formed by the flow of water and sediment down a submarine fan slope

Turbidity current - a flow of mixed sizes of sediment and water (a “slurry” like fresh cement) that, due to its higher density, will stay in contact with the bottom and not significantly mix with water being displaced by the flow

Note: All diagrams are cross-section views

Underthrust - a thrust fault with the mass of rock below the fault plain (foot wall) being the moving mass instead of the rock mass above the fault plane (hanging wall) moving



M – lower plate moves

Xenolith (strange rock) - a rock that was surrounded by magma or lava and thus was included in the newly-forming igneous rock

Appendix

Additional Discussion of Selected Road Guide Stops and Side Trips to Nearby Locations of Interest

by Victor Vere

Perryville – Perry

(Refer to Map 4, p. 16)

At 1.7 miles (2.7 kilometers) north of the intersection of AR-10 and State Highway 60 on the north edge of Perryville, there begins a large exposure of the lower Atoka Formation. The road cut begins at the crest of the hill where there is a picnic area with off-road parking on the right (east) side of the road. Three distinct outcrop areas are exposed here, however, only the upper two will be discussed. The outcrops are separated by wooded, shallow intermittent stream valleys oriented perpendicularly to the highway. Such an angular indentation in a landform is known as a "reentrant" by geologists. These weathered and more easily eroded areas are likely indicative of faults, joints, or shale units in the bedrock.

The outcrops seen as you go downhill are located on the extensively-faulted north limb of the east-west trending Fourche La Fave Syncline. The uppermost rock exposure borders the parking area and extends downhill to the north. This exposure is approximately 365 feet (111 meters) long, ending where overhead power lines cross the road. The beds in this area dip 45^{O} to the southeast with a $N60^{O}E$ strike. These units are interpreted to be a classic turbidite sequence of sandstone beds, up to 10 feet (3 meters) thick, that alternate rhythmically with thinner shale-siltstone beds.

Along the first 50 feet (15.3 meters) of the exposure the sandstones are up to 2 feet (0.6 meters) thick, with most beds being from 6 to 12 inches (15 to 30 centimeters) thick. The stratigraphic thickness of this first exposure, measured perpendicularly to the bedding plane, is 31 feet (9.4 meters). At 83 feet (25 meters) along the road, a prominent 5 foot (1.5 meter)-thick reentrant or weathered-out section of thin-bedded sandstone and shale-siltstone occurs. At 109 feet (32 meters), another reentrant occurs. At 118 feet (36 meters), a massive-bedded, 10 foot (3-meter)-thick sandstone is quite prominent. A third reentrant occurs at 247 feet (75 meters) from the parking area. A probable fault zone displaying crushed and contorted beds occurs at 279 feet (85 meters). Another reentrant has formed in the weathered and eroded material below the zone. A substantial fracture at 321 feet (99 meters) dips 42^{0} to the northwest with a $N62^{0}E$ strike. Scattered on the bottoms of some sandstone beds are sedimentary structures characteristic of turbidity current deposits including load casts, flutes, groove casts, and flame structures. This upper part of the turbidite sequence shows no recognizable channeled beds nor cross beds.

Approximately 250 feet (76 meters) farther downhill, past a vegetated/wooded area, the second outcrop of interest begins. The uppermost part of the outcrop, adjacent to the wooded area, shows a heavily fractured region possibly related to faulting. This more easily eroded, sloping surface contains an intermittent stream. Overall, this outcrop exhibits thinner, more regularly bedded and lenticular sandstone, interspersed with shale-siltstone. Such irregularities and lenses are interpreted to be features of the original channeling processes. These features are best seen in the middle of the outcrop where thin-bedded sandstone occurs in thick sequences of shale-siltstone supporting the growth of small trees. Overall, this portion of the outcrop shows both a thinning of beds and a fining of grain sizes going down section, or what is known as a "coarsening upward sequence". These features are typical of a submarine fan lobe or interchannel depositional setting.

This completes our downhill excursion, please hike back uphill and continue to follow AR-10 to Perry.

Rose Creek Syncline
(Refer to Map 5, p. 19)

The southern flank of the Rose Creek Syncline is well exposed, both topographically and in outcrop, southwest of Petit Jean State Park. Just before entering the town of Casa from the east, County Road 30, also named Main Street, turns right (north) off AR-10. Over the next 4.6 miles (7.4 kilometers), you will traverse the south then the north limb of the Rose Creek Syncline.

At mile 1.3 (kilometer 2.1) from AR-10, the road begins to climb up the scarp slope of the south limb. At mile 1.8 (kilometer 2.9) at the crest of the hill, there is a well-exposed outcrop of the Hartshorne Sandstone. The Hartshorne dips 21^0 north-northeast and strikes N70^0W. As County Road 30, now named Casa Mountain Road, crosses the crest of Rose Creek Mountain, it trends northeast on the undulating dip slope of the Hartshorne.

Where the topography flattens, the road traverses the younger McAlester Formation in the valley of Rose Creek. At mile 3.5 (kilometer 5.6), the road intersects State Highway 155 (AR-155). Turn right on AR-155 and go 0.1 miles (0.2 kilometers) and turn left onto State Highway 247. At mile 4.1 (kilometer 6.6) from Casa, a shale in the McAlester Formation is exposed in a gravel pit on the right (east) side of the road.

From this outcrop, go on to mile 4.6 (kilometer 7.4) where a prominent ridge of the Hartshorne is exposed. This ridge is the north limb of the Rose Creek Syncline and dips 55^0 to the south and strikes east-west. Before reaching the ridge crest, there is a straight 310 feet (994 meters) of outcrop on the left (west). At the ridge crest, the Hartshorne is massively bedded with intermittent, thinner, light-colored, weathered zones. These zones are 99% quartz sand and silt which is unusual in the Hartshorne. There is a probable thrust fault on the north side of the

Figure A1. Hartshorne Sandstone on the north limb of the Rose Creek Syncline ridge that dips 60^0 south and strikes east-west. This fault, as well as associated fractures, may have affected the usually durable Hartshorne by allowing groundwater leaching to remove the iron oxide cement common in the Formation. The possible fault-induced grinding (crushing) may have produced the fine-grained sandstone and much finer quartz silt "dust".

This traverse from south to north across the Rose Creek Syncline illustrates the effect of differing dip values on outcrop width on each limb of the syncline. Map 5 (p. 19) shows a relatively wide Hartshorne outcrop width on the south limb that has a 22^0 north dip. This contrasts with the much narrower outcrop width on the north limb that has a 55^0 south dip. These differing dips create an asymmetric synclinal structure.

This 4.6 mile (7.6 kilometer) drive illustrates the effect of geologic structure and rock type on land use. You should note that where slopes are steepest and rocks hardest, trees predominate. On low slopes and less resistant rocks, the land is suited for agricultural purposes such as growing crops and hay, grazing cattle, and hog and chicken raising. This connection between structure, rock type, and land use is commonly evident along AR-10.

Return to Casa along the same route to continue the westerly AR-10 trip.

Mount Magazine Area

(Refer to Map 6, p. 21)

The east-west-trending mountain ridges on the north and south sides of the Petit Jean River Valley, at Danville and west to Mount Magazine, are examples of how intense folding and subsequent thrust faulting on the south margin of the Petit Jean River contrasts with the broad, open folds and lack of thrust faults on the north side. This contrast is shown in the topographic expression of the landforms. To the south, the ridges have lower elevations and are narrow, with small valleys between each ridge. To the north, mountains are higher in elevation, flat-topped (mesa-like), and separated by broad valleys.

Mount Magazine, north of the Petit Jean River, is the highest mountain in the state at 2753 feet (839 meters). Magazine is an erosional remnant formed on a broad, low-dipping synclinal structure with an east-west axis of folding. Magazine's high elevation may be attributed to several factors including: (1) lack of thrusts or other types of faults in its entire extent; (2) sedimentary rocks of varying degrees of resistance to weathering, from erosion-resistant sandstone to softer shale and siltstone that alternate in their stratigraphic placement; and (3) broad, open folding that created a low-dipping synclinal structure. The topmost formation on the mountain, the Savanna Sandstone, is a hard, erosion-resistant bed that forms a vertical cliff (>100 feet, >30.5 meters) around the summit of the mountain. When viewed from AR-10, the cliff is obvious as a light-colored band just below the beautiful tourist lodge in Mount Magazine State Park (refer to Fig. A2).

The sloping topographic surface below the Savanna is formed on the more easily eroded shale-siltstone and sandstone of the McAlester Formation. A narrow, bench-like topographic feature develops on the Hartshorne Sandstone immediately below the McAlester. The Hartshorne crops out at a sharp turn along State Highway 309 (AR-309), 4.3 miles (6.9 kilometers) north of its junction with AR-10 in Havana. Here, a large stream flows on top of the Hartshorne and prominent rock beds dip 14^0 north-northwest indicating that you are on the south limb of the synclinal structure of the mountain.

Below the Hartshorne, the Atoka Formation, especially the sandstone units, crops out sporadically in the slope along AR-309. For the first 3 or 4 miles (4.8 to 6.4 kilometers) north of Havana, the road crosses the Ranger Anticline. At 2.1 miles (3.4 kilometers) from AR-10, there is an outcrop of thick-bedded, resistant sandstone beds with almost vertical dip. This represents the most northerly occurrence of tightly folded and thrust-faulted strata in the area.

The upper slopes of Mount Magazine, in addition to showing prominent vertical cliffs in the Savanna Formation, also exhibit two striking features: (1) large rock blocks (pillar-like) have separated from the main cliffs; and (2) substantial areas of loose boulders (rock streams) have formed tongue-like masses that extend downward, covering the slope of the underlying McAlester Formation. These rock streams are up to several hundred feet (meters) long, many tens of feet (meters) wide, and several feet (meters) thick. Because they are so thick and porous, no soil forms or accumulates on top of them. Therefore, no trees or other vegetation grows on them. It is hypothesized that the rock streams formed by the periodic catastrophic collapse of large rock pillars as softer base layers were eroded away.

Continue uphill to where the road makes a sharp (hairpin) turn toward the west as it gains the top of the Savanna Formation. From this turn go 0.5 miles (0.8 kilometers) west to a south-facing overlook; the view of the Petit Jean River Valley and the distant Ouachita Mountains is spectacular. You can look east to see much of the terrain you crossed before turning onto AR-309, and to the west there is a preview of the rest of the trip.

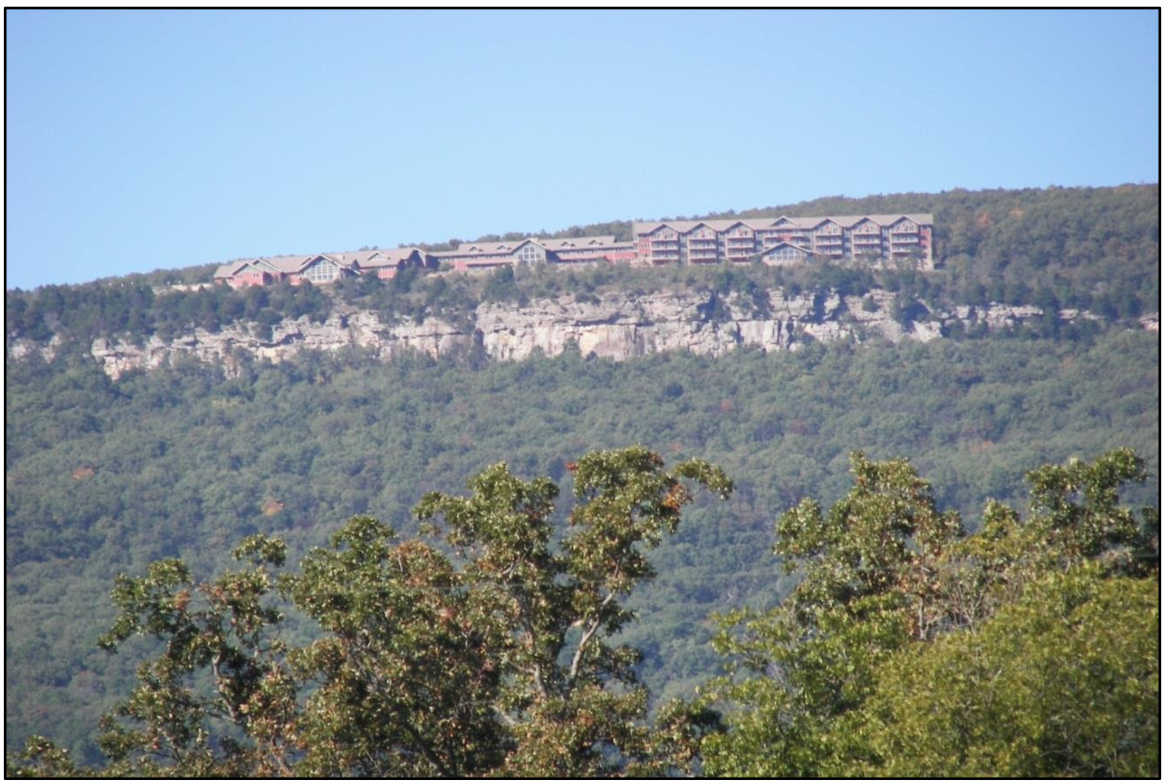


Figure A2. Mount Magazine State Park Lodge on top of the Savanna Formation

When finished viewing the scenery and taking pictures, return downhill to Havana on AR-309 and continue your westward journey on AR-10.

Blue Mountain Lake Dam
(Refer to map 6)

Figure A3. Lower Atoka turbidite sequence, south end of Blue Mountain Lake Dam

This outcrop extends from the south end of the dam westward along the edge of the lake. At this location, the lower Atoka Formation preserves a sandstone-filled channel deposit that cut into surrounding thin-bedded sandstone and siltstone. However, much of the rock exposure is inaccessible due to the steep slope, vegetative overgrowth, and fencing.

The outcrop has been interpreted to be a proximal, deep-water sequence of turbidity current deposits (Stone, 1981). The turbidite sequences one is accustomed to seeing elsewhere, at the Perryville location for example, are not readily apparent here. The sandstone, siltstone, and shale is thin-bedded, up to 6 inches (15 centimeters) thick, and lacks the massive-bedded sandstone alternating with thick shale and siltstone units present in other turbidite sequences. Only the massive-bedded sandstone of the apparent channel fill and the channel itself, with its adjacent slumped beds, are very evident. The sedimentary structures normally associated with turbidity current deposits, such as flute casts, groove casts, and graded bedding, are either inaccessible here or poorly developed and rather subtle. The bedding is highly fractured and possibly faulted, resulting in pencil-like shards of shale, siltstone, and sandstone collecting at the base of the outcrop.

The channel, with its surrounding thin-bedded shale and siltstone slump features, indicates that as it was being eroded by a high-energy turbidity current, the surrounding beds collapsed into the channel as their lateral support was removed. The sands in the channel were deposited rapidly, as evidenced by the massiveness of the resultant sandstone and the lack of internal sedimentary structures usually associated with an extended period of slowing down of the current flow. Note also that both above the channel and to the west, thicker sandstone units are continuous along the outcrop. This configuration seems to indicate that the turbidity current migrated laterally, either toward the channel, eroding it with a “last gasp” of energy, or as energy waned, the channel filled and migrated laterally toward the west.

Return to AR-10 and continue driving west toward Booneville.

Additional Discussion of the Characteristics and Energy Resources of the Arkoma Basin

by Richard Cohoon

Geologic Characteristics of the Arkoma and Peripheral Foreland Basins (PFBs)

(Suneson, 2012, p. 39-41)

(1) There is *overstepping* and faulting of the continental slopes due to north-moving thrust faults loading the slope. This caused sedimentary-slide and slump features to develop (olistrostromes in the Johns Valley Shale in Arkansas).

(2) PFBs often contain evidence of several phases of clastic sediment deposition (Stanley, Jackfork, and Atoka Formations in Arkansas).

(3) Basin-filling sequences of sediments are typical. These are indicated by progressive changes from deep- to shallow-water deposits. In the Arkoma, this is illustrated by the change from middle Atoka Formation, deep-water turbidites (flysch) to upper Atoka and Hartshorne Formation, shallow-marine and fluvial-deltaic sediments.

(4) PFBs often display sediment dispersal patterns parallel to the axis of the basin. This is the case in the Arkoma where paleocurrent direction is generally east to west during deposition of the sandstone in the upper Atoka and the Hartshorne.

(5) Typically, PFB sedimentary patterns indicate that foredeeps migrate toward the continent as time progresses. The foredeeps of the Stanley, Jackfork, and Atoka Formations demonstrate a south to north migration pattern.

Tectonic Development of the Basin

(Based on J.K. Arbenz's 2008 analysis, as summarized in Suneson, 2012, p. 42)

Stage 1 - Cambrian-Devonian (542-359 mya): deposition of shallow-water marine sediments on a continental shelf at the southern edge of the Ozark Dome, and continental slope to deep-water basin deposition in the forming Ouachita geosyncline to the south.

Stage 2 - Upper Mississippian (359-318 mya): accelerated sinking of the Arkoma Basin (Ouachita Foreland Basin) because thrusting from south to north formed a wedge zone which caused sediment to spread along the east-west-trending axis of the Basin.

Stage 3 - Early Pennsylvanian (Morrowan Series, 318-312 mya): deepening of the Jackfork Sandstone Foreland Basin north of the Stanley Shale Basin due to continued northward-directed thrusting.

Stage 4 - Middle Pennsylvanian (Atokan Series, 312-310 mya): subsidence of the Atoka Foreland Basin north of the Jackfork Basin due to ongoing northward thrusting and down-warping caused by the weight of massive amounts of sediment being deposited.

Stage 5 - Late-Middle Pennsylvanian (Desmoinesian Series, 310-307 mya): orogenic activity in the Ouachita tectonic belt reached a climax due to extreme compressive forces, directed from the south to the north, which caused the development of east-west-trending, asymmetric overturned folds, regional-scale thrust faults, and down-to-the-south normal growth faults along the southern margin of the Ozark Plateaus.

Arkoma Basin Coal Production

Before the Arkoma Basin was known as a gas-producing region, it was a well-known coal-producing area. The first recorded coal mine output, 220 short tons, was in 1848. The extension of railroads into the area between 1873 and 1887 brought sharp increases in coal mining in the following counties: Crawford, Franklin, Johnson, Pope, Yell, Logan, Sebastian, and Scott. This coal-mining region is approximately 33 miles (53 kilometers) wide (north-south) and 60 miles (102 kilometers) long (east-west).

Over twenty, vertically-separated coal beds have been identified. However, only four have been commercially mined (see Figure A4.). They are: the Lower and Upper Hartshorne (Lower McAlester Formation, Desmoinesian Series, Pennsylvanian Period), the Charleston (Lower Savanna Formation, Desmoinesian Series, Pennsylvanian Period), and the Paris (Upper Savanna Formation, Desmoinesian Series, Pennsylvanian Period).

The most widespread commercial coal horizon is the Lower Hartshorne. It underlies an area of 1360 square miles (3522 square kilometers). The Upper Hartshorne coal is present over an area of 28 square miles (75 square kilometers) in southwestern Sebastian County and has only been mined at one location: between Hartford and Huntington. The Charleston Coal, a semi-anthracite, was mined at numerous locations in an area of approximately 120 square miles (311 square kilometers). The Paris low-volatile coal has the least aerial extent with only 18 square miles (49 square kilometers) (Suneson, 2005, p. 17-19). The rank of the coal changes from semi-anthracite to low-volatile bituminous between Clarksville and Ozark (see figure A5.).

In 2015, Arkansas coal mines produced 91,000 short tons (short ton = 2000 pounds) placing the State in 25th place among coal-producing states in the U.S. (U.S. Energy Information Administration, February 2017). Remaining coal reserves are estimated to be approximately 2 billion short tons. Using modern mining techniques, the amount of recoverable reserves could be greater than 50% of the estimated reserves (Arkansas Geological Survey website).

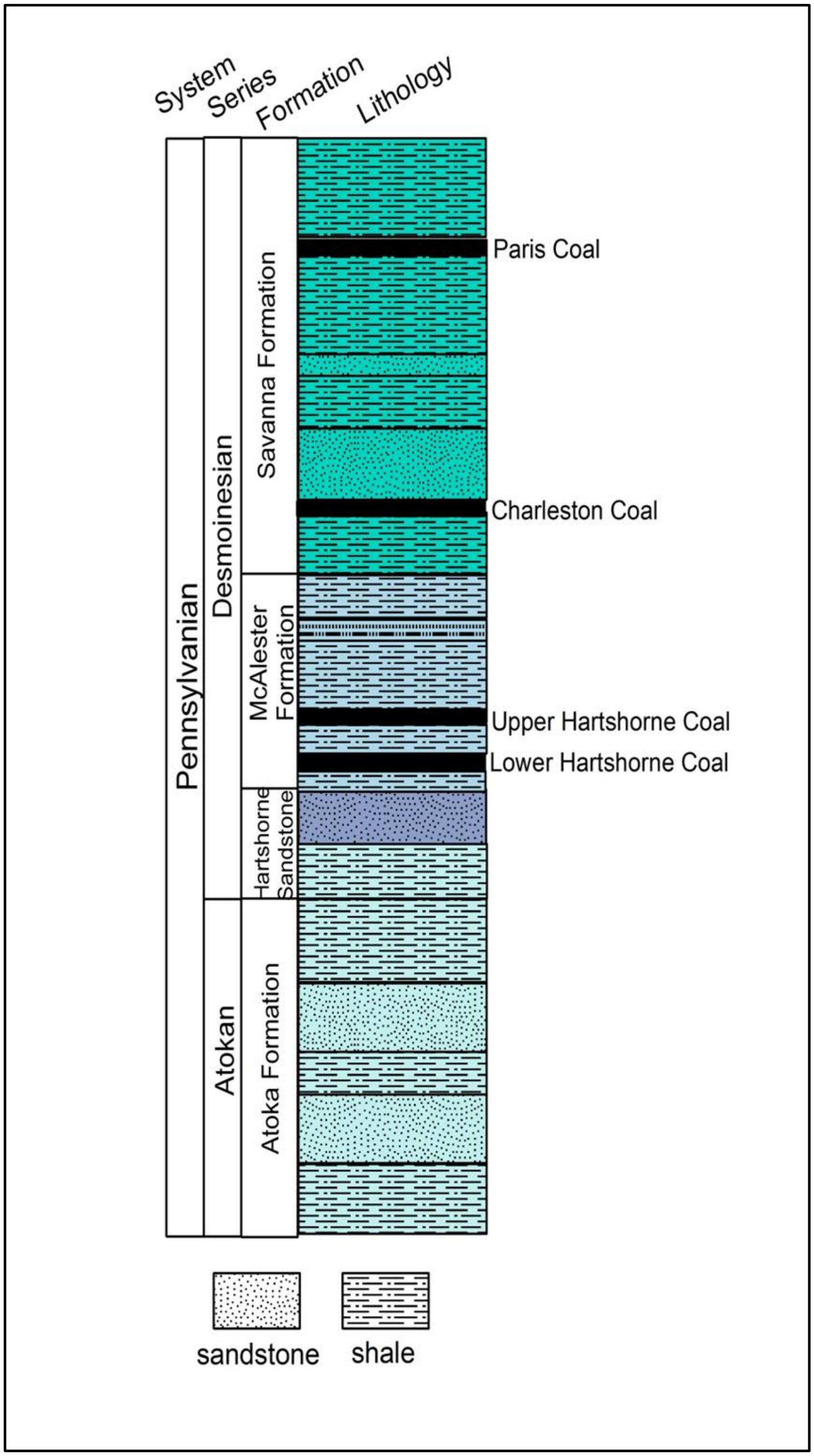


Figure A4. Stratigraphic column of coal-bearing strata in the Arkoma Basin (Source: Arkansas Geologic Survey)

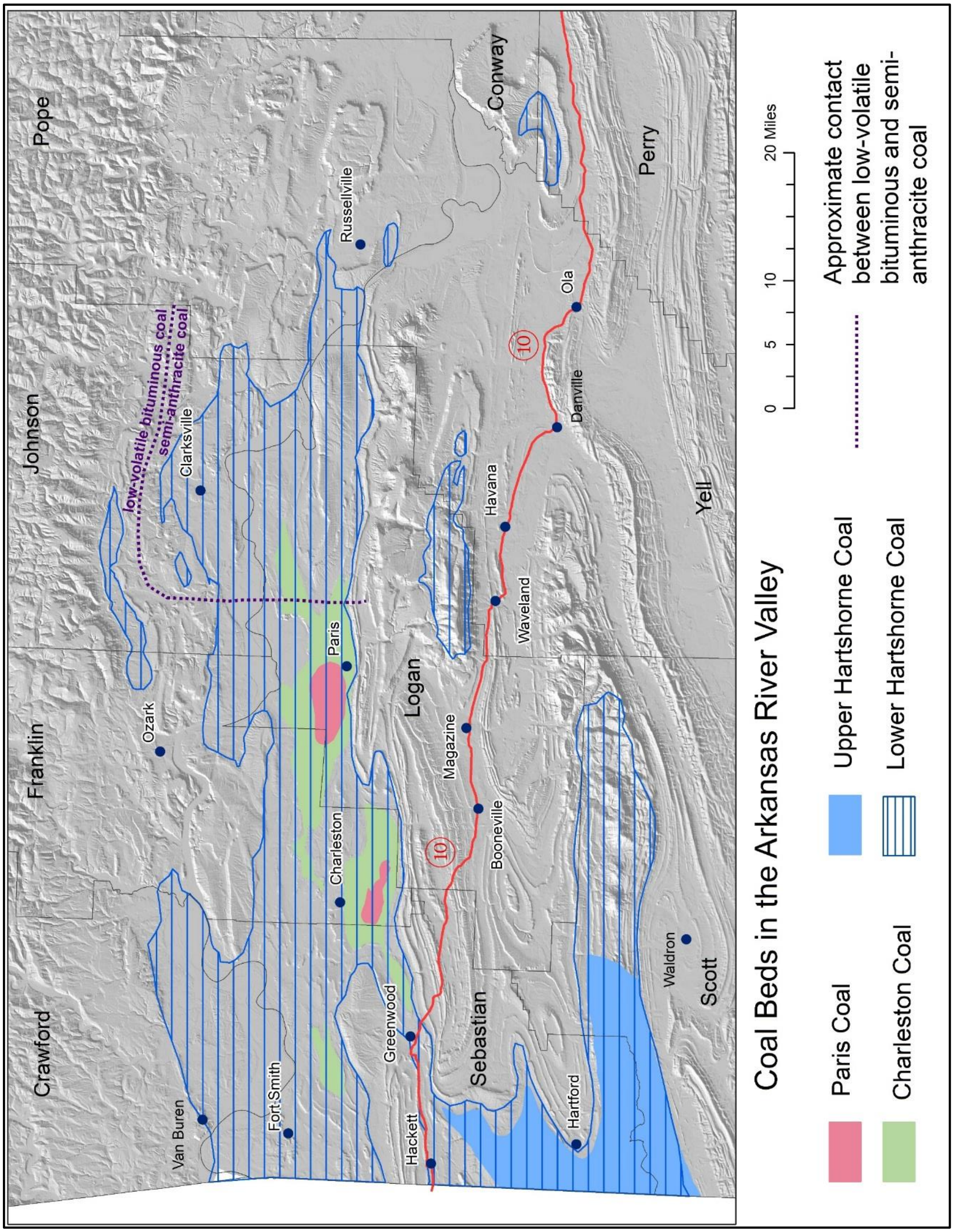


Figure A5. Map of Coal Beds in the Arkansas Valley
(Source: Arkansas Geological Survey)

Arkoma Basin Natural Gas Production

Dry natural gas (lacking liquid hydrocarbons) was discovered near Fort Smith in 1877 and the first commercial wells were drilled near Mansfield (Scott County) in 1901-02 by the Choctaw Oil and Gas Company. Some of the wells in this 3000-acre field produced as much as 5 MMcf (million cubic feet) of gas per day and was distributed to the town of Mansfield. Because of a geologic study commissioned by the Arkansas Geological Survey in 1927, Dr. Carey Croneis prepared "Geology of the Arkansas Paleozoic Area". The study attracted the interest of many speculators, and thousands of mineral deeds were bought and sold during the Great Depression.

As of January 2014, there were 145 gas fields established in the Arkoma Basin in Arkansas. These fields have produced 6.751Tcf (trillion cubic feet) of gas since accurate records have been kept (Arkansas Geological Survey website). In 2015, annual production from northern Arkansas gas fields (Arkoma Basin), including the Fayetteville Shale region, was 1,006 Bcf (billion cubic feet) (Arkansas Oil and Gas Commission, Annual Report, 2015).

The Basin has been the site of conventional, vertical-drilling plays, horizontal-drilling plays (Fayetteville Shale), and coalbed methane (CBM) drilling. Most of the conventional production is from sandstone and shale of the Atoka Formation. Some production also comes from the older Bloyd and Hale Formations, and Formations as old as Ordovician have been tested. Most of the vertically-drilled gas accumulations are trapped by a combination of folds, faults, and complex stratigraphic variations characteristic of ancient stream channels and deltas.

Gas production from conventional vertically-drilled wells occurs in the following counties: Conway, Crawford, Faulkner, Franklin, Johnson, Logan, Madison, Pope, Scott, Sebastian, Washington, and Yell. The largest conventional-well production in the Arkoma Basin is from the Cecil Field in Franklin County. Also, the Aetna Field in Logan County is a major producer. There are approximately 4100 conventional producing wells in the Basin compared to approximately 5900 horizontal wells in the Fayetteville Shale producing area.

At the eastern end of the Arkoma Basin, there are seven counties where the Fayetteville Shale has been productive since 2004. The Fayetteville is a Mississippian-aged shale, 50 to 550 feet (15 to 168 meters) thick, that produces dry methane gas through the application of vertical and horizontal-drilling combined with subsurface fracturing techniques. Currently, production lies in the following counties: Van Buren, Conway, Cleburne, Faulkner, White, Independence, and Jackson. Between January 1 and October 31, 2016, the Fayetteville Shale Field (B43) produced 632 Bcf of gas. The Field has produced approximately 7.4 Tcf of gas since 2004, and there are other potentially productive areas to be explored. However, such a projection assumes a profitable price (>$3 per thousand cubic feet) for gas in the future (Shelby, 2017). Cumulative production by 2050 could reach 18 Tcf (John Browning, et al., Oil and Gas Journal, January 6, 2014).

Natural gas as coalbed methane is present in many coal seams. It has often been the cause of disastrous coal mine explosions. In the past few years, this trapped gas has been captured through a sophisticated drilling technology known as "horizontal pinnate lateral". A few wells of this type have been drilled in the Lower Hartshorne coal bed in Arkansas since 2001. To date, this type of drilling has yielded 27 Bcf of gas. Estimated annual production is approximately 1.4 Bcf (Arkansas Geological Survey website).

According to the U.S. Energy Information Administration, Arkansas ranks 10th in natural gas production among the states with an annual production of at least 1.01 Tcf. This constitutes 3.5 % of the total production in the U.S.