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Ouachita Front Range/Arkoma Basin Field Trip Guide

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OKLAHOMA GEOLOGICAL SURVEY
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Preface

It is easy to reflect back upon many adolescent days spent in the Ouachita Mountains and the Arkoma Basin. Days spent exploring Robbers' Cave State Park and kayaking on Lake Carlton, swimming in Little River near Honobia, youth church camp at Christ's 40 Acres, and hiking around the second Queen Wilhelmina Inn, to name a few. One of the late Senator Robert S. Kerr's goals was to promote this corner of Oklahoma for its beauty and recreation. While attending the University of Oklahoma, one of my personal goals was to survive through one rainy, cold spring break while enrolled in "Introduction to Field Geology" and performing geological mapping on several sections west of Beaver's Bend.

For these and other reasons, I quickly volunteered to coordinate and organize a geological field trip to the Ouachitas and Arkoma for the geology groups at Netherland, Sewell & Associates, Inc. (NSAI). The words of the Sage ring true, "Be careful what you volunteer for." I gathered many excellent field guides from the Oklahoma Geological Survey and other sources, a multitude of articles and papers, but soon realized that no publication presented a geological chronology of the deposition and development of the Ouachitas and Arkoma Basin. Thus, this simple field trip turned into a research and guide writing exercise of which this book is a result. On the following pages of geological history, one will find the result of many others' thoughts and hypotheses plus my own concerning the formation of the Ouachita Mountains and Arkoma Basin.

There are many people to acknowledge and thank for this field guide and space limits this process to only a few. Thank you to Dan Walker of NSAI for his support and patience. For her assistance, advice, and proof-reading, I extend a special thank you to Alayna M. Miller. I owe a deep thanks and gratitude to Dr. Neil Suneson of the Oklahoma Geological Survey for his guidance, support, leadership, and suggestion to publish this guide as an Open File. I have a great respect and thank you for Dr. Charles Mankin of the Oklahoma Geological Survey who assisted and guided me during my college years. Dr. Robert L. DuBois also has my greatest respect and gratitude not only as my major professor but as someone who encouraged my desire of knowledge and thus added to this guide. More over, I must express my deepest gratitude to my wife, Maureen A. Nichols, who has come to love the rocks, fossils, and outdoors as much as me and who encouraged me during the months of writing this guide. And finally, I thank my employer, Netherland, Sewell & Associates, Inc., for allowing me to assemble and lead this field trip for the knowledge and enjoyment of all the geologists and geo-analysts at NSAI and granting me permission to submit this guide to the Oklahoma Geological Survey for publishing so that others may explore and form their own thoughts about the Ouachita Mountains and Arkoma Basin.

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DISCLAIMER

Geological History
Theory of the formation of the Ouachita Mountains and Arkoma Basin

"No rock is accidental." – J. Tuzo Wilson

Around 13.7 billion years ago, the Big Bang happened. Some time passed, during which material from the Big Bang accreted under its own gravitational attraction in space whirlpools around greater gravitational masses. Galaxies, star systems, and planetary systems were formed. Within these systems, "cold" particles merged under their gravitational pull to form stars, planets, moons, comets, etc. As the massive stars coalesced, their fusion engines started. As the terrestrial planets coalesced, their fission engines started. Depending upon the material and the Kepler radius, materials of different atomic weights accreted at different distances from the primary gravitational object (i.e., proto-star). Closer planets contained materials of greater atomic weight, while those more distant planets contained lighter-weight atomic elements. And somehow the Earth fell within the correct "mass" distance and also the correct "environmental" distance from the star known as Sol. At some point more than 4.5 billion years in the past, the Earth coalesced into a rough globe with heavier (and some radioactive) materials forming a core with a lighter-material shell gathered around it. As this spherical mass compressed under its own gravitational pull, the decaying radioactive materials began to generate fission heat. The Earth gradually began to differentiate into a (outer to inner) crust, mantle, outer core (liquid), and inner core (solid). Because of this differentiation, the Earth's spherical surface broke into moving plates gliding along a partially melted zone powered by gravity and, to a lesser extent, heat.

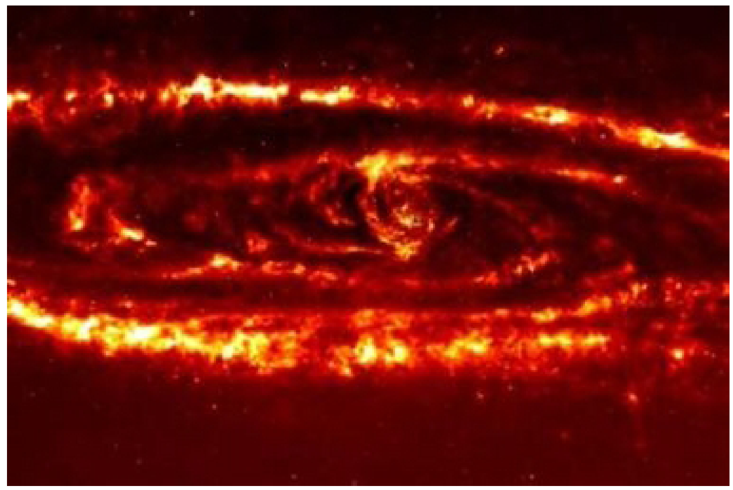

Figure 1: Andromeda Galaxy - Infrared NASA photo

We know Oklahoma (and the North American craton) existed as a crustal landmass in the long-distant past. The Tishomingo Granite (~1.37 bya), Troy Granite (~1.37 bya), and other Proterozoic igneous rocks show this landmass was intruded by magma that cooled slowly, insulated from quick cooling by long-lost surface rock. The Blue River Gneiss (~1.4 bya) shows that forces of pressure and heat acted upon unknown sedimentary and/or igneous rock. There were tectonic plates active on the Earth's surface at this time. These plates joined all the cratonic masses into one supercontinent named Rodinia approximately 2 billion years ago. There is evidence that several rift systems formed between 1.1 and 1.5 billion years ago and split Rodinia onto several tectonic plates. The Midcontinent Rift System (bisecting Kansas and extending into Minnesota and Canada), formed some 1.1 billion years ago, was one of these rift systems that failed.

The cratonic masses and tectonic plates continued to move across the Earth's surface for millions of years before coming together again at the end of the Permian Age (230 mya) to form Pangea. During the Mesozoic Age, Pangea split to form Laurasia and Gondwana, and these two supercontinents split to form what we recognize as plates and continents today.

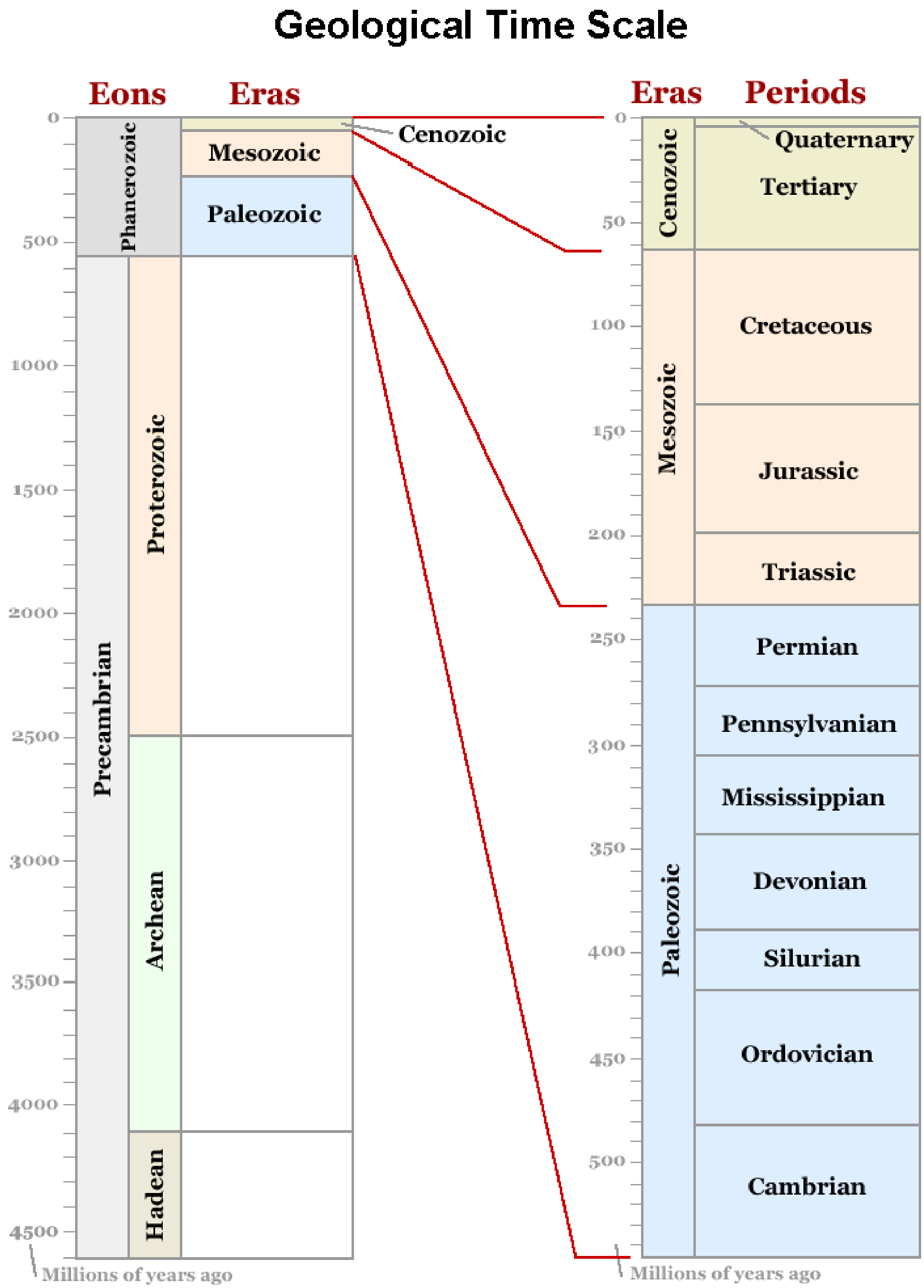

Figure 2: GEOLOGICAL TIME SCALE Copyright 2005 - GEOLOGY.COM

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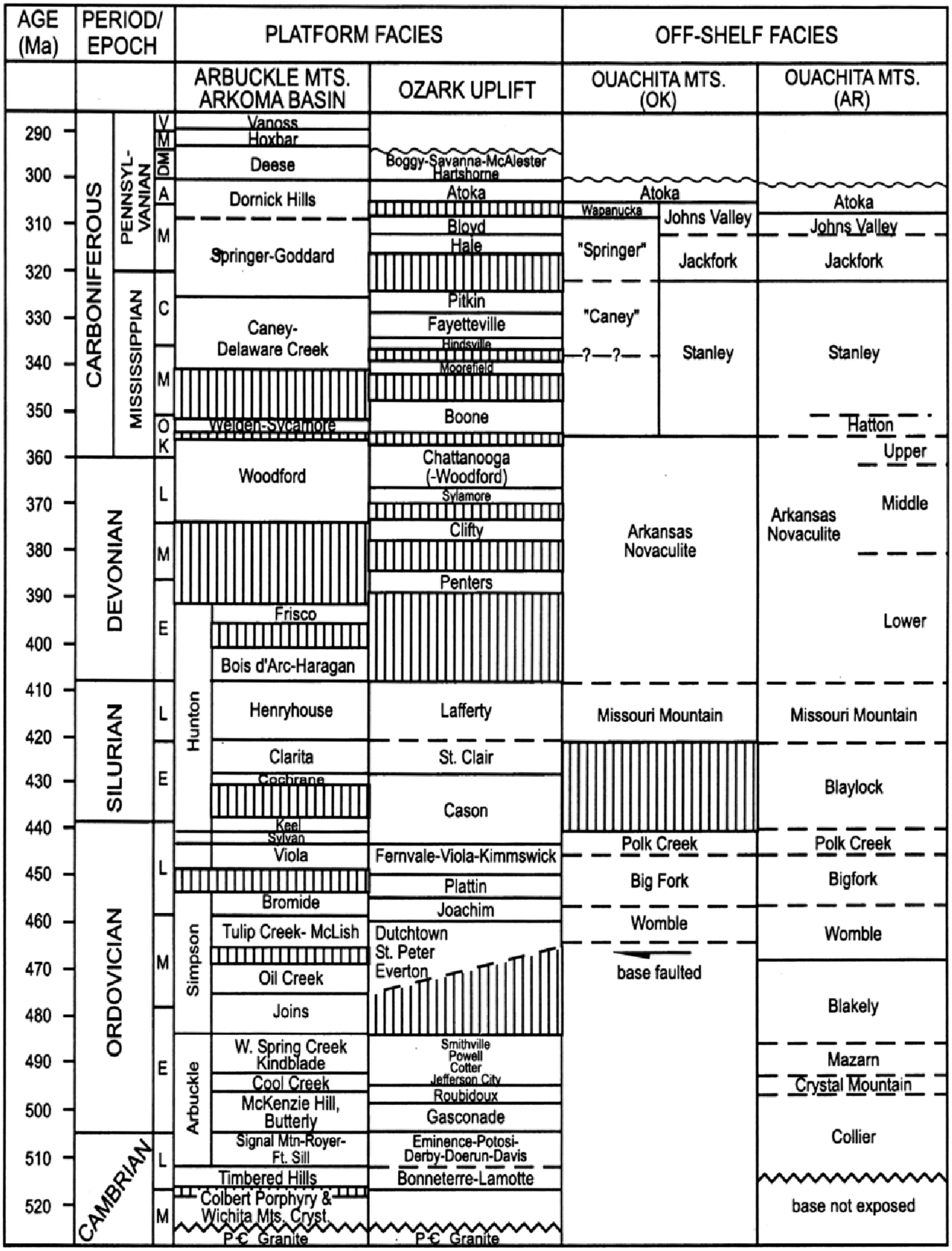


Figure 3: Generalized surface and subsurface stratigraphy in the field trip area.
(from Oklahoma Geological Survey, Guidebook 34)

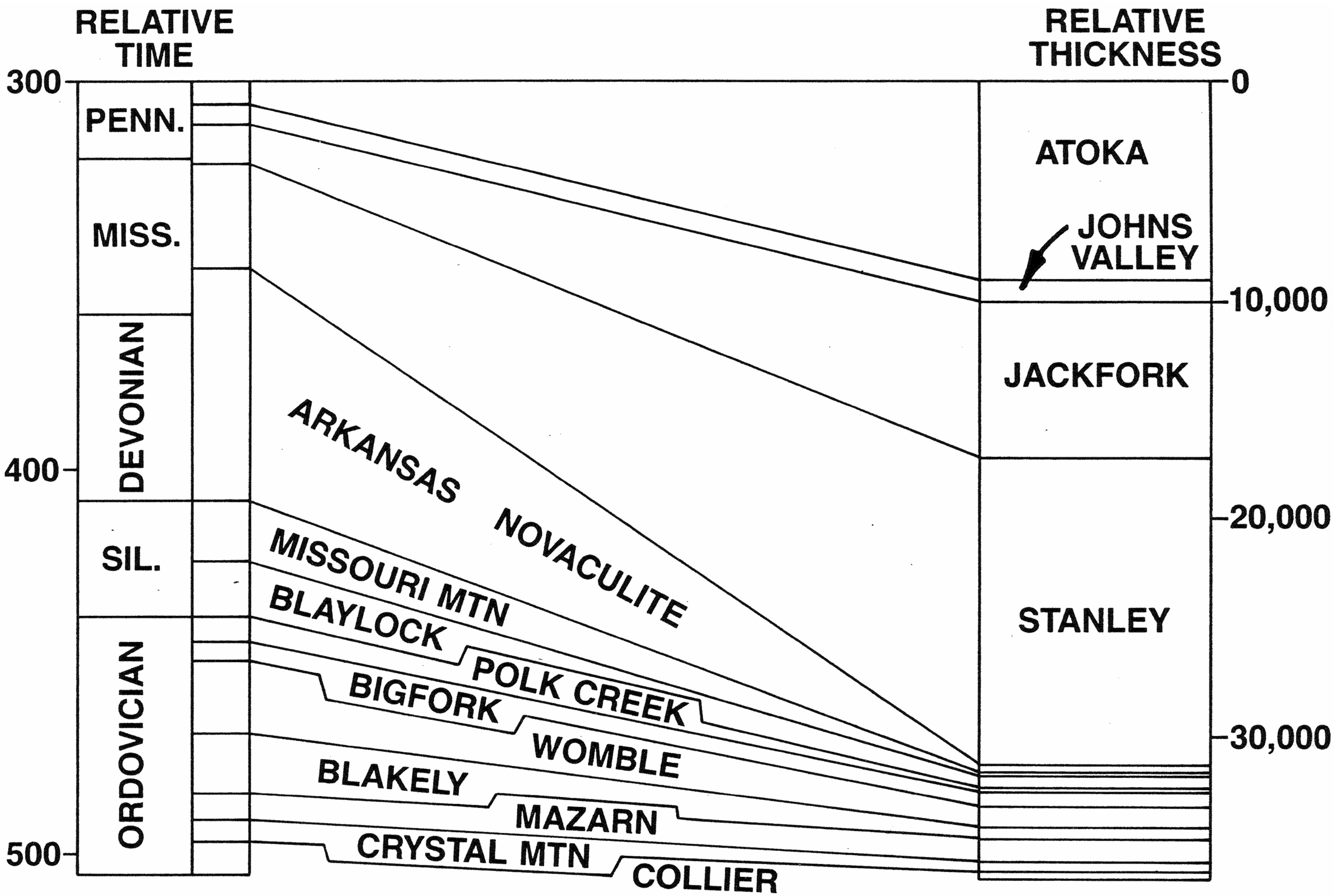


Figure 4: Generalized stratigraphy of the Ouachita Mountains, Oklahoma.
(from Oklahoma Geological Survey Open File OF-87)

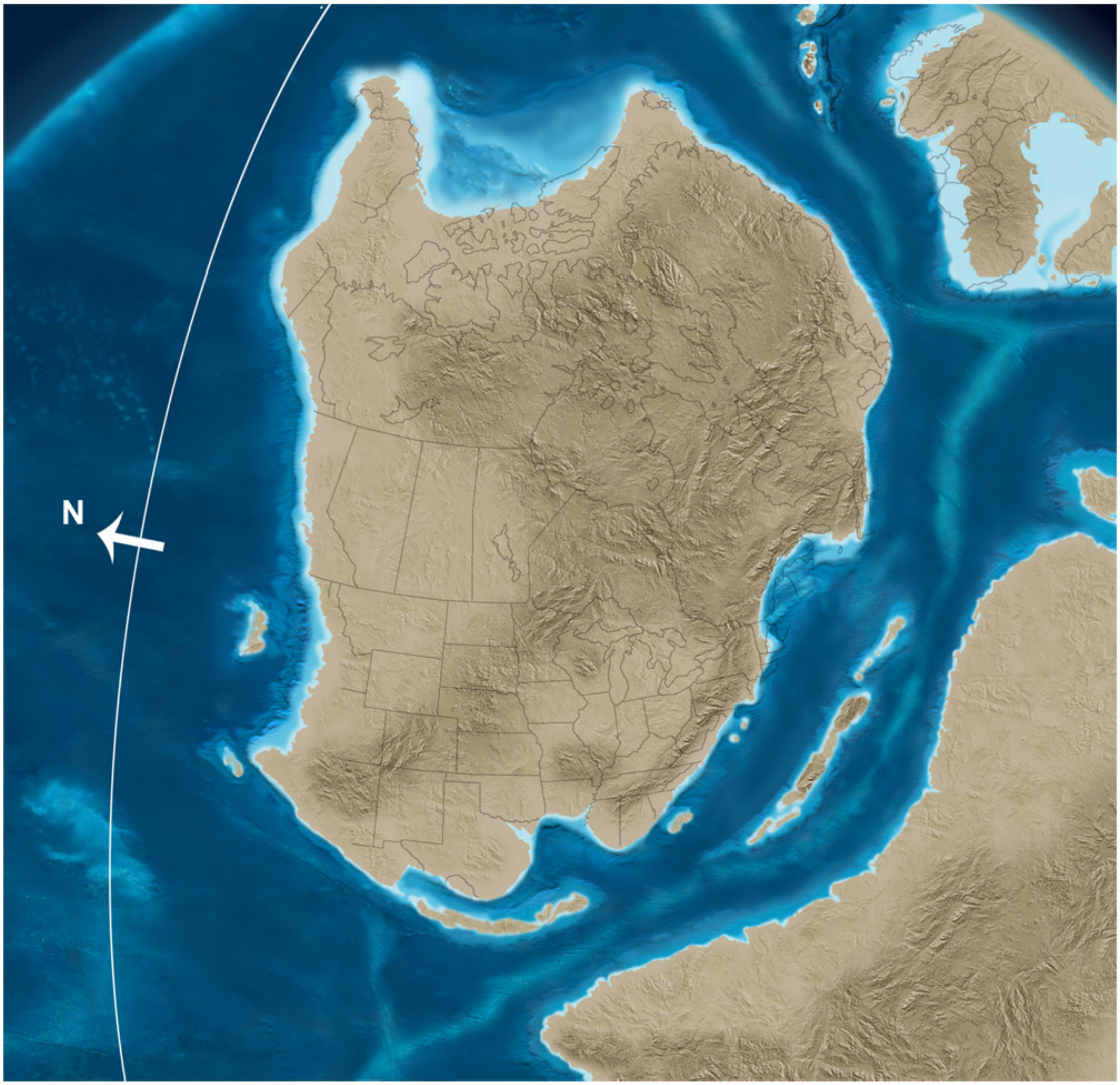


Figure 5: North America – 550 million years ago (late Pre-Cambrian)
(from Dr. R. Blakey, Northern Arizona University, Flagstaff, AZ)

But return to the <u>Cambrian Period (545 – 488 mya):</u>

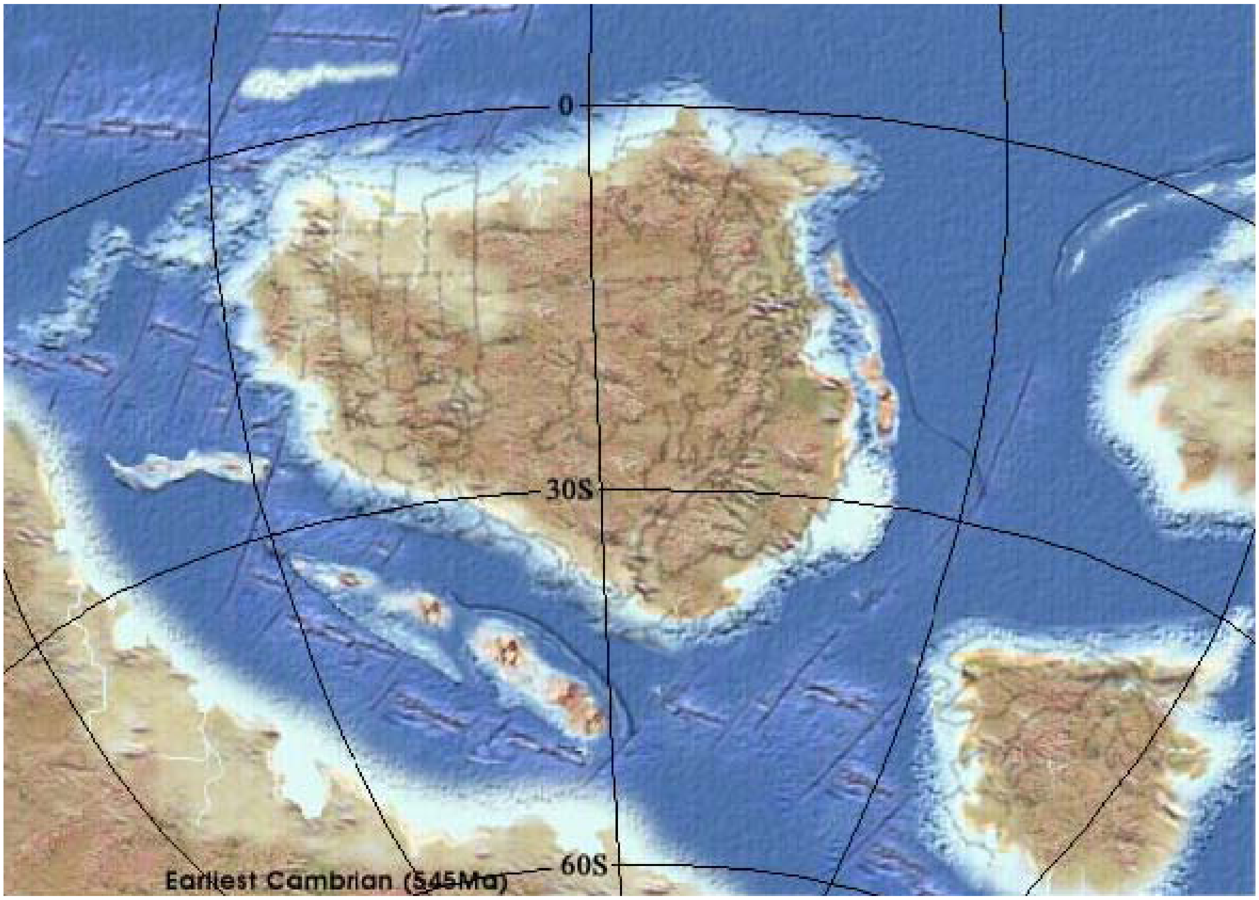


Figure 6: North America – 545 million years ago (early Cambrian)
(from Dr. R. Blakey, Northern Arizona University, Flagstaff, AZ)

Much of Oklahoma and the midcontinent were transgressed by a shallow sea during the Cambrian. As it is inferred that most of the area was quite flat (peneplain), this sea would be a shallow-water continental shelf (locally: Oklahoma basin) within the North American craton. In mid-Cambrian times (530 mya) around present-day eastern Texas/western Louisiana, a Wilson Triple Point formed. This triple point formed a successful rift that separated the North American plate from Rodinia. Offset transforms on the rift formed two promontories (Alabama and Texas Promontories) and two embayments (Ouachita and Marathon Embayments). The Reelfoot Rift (Arkansas, SE Missouri, Illinois), and the Oklahoma Aulacogen (Arbuckle basin) failed as rifts or rift/transforms. Though these rifts failed, they produced a thinning in the crust and thus a depositional basin.

On the shelf and near shore in the late Cambrian, the relatively thin transgressive (rising sea level) Reagan Sand was deposited in all but local topographic highs. This was followed by deposition of Honey Creek and Arbuckle limestone. Off the oceanic slope and in deeper water, the Collier shale was deposited from late Cambrian to early Ordovician.

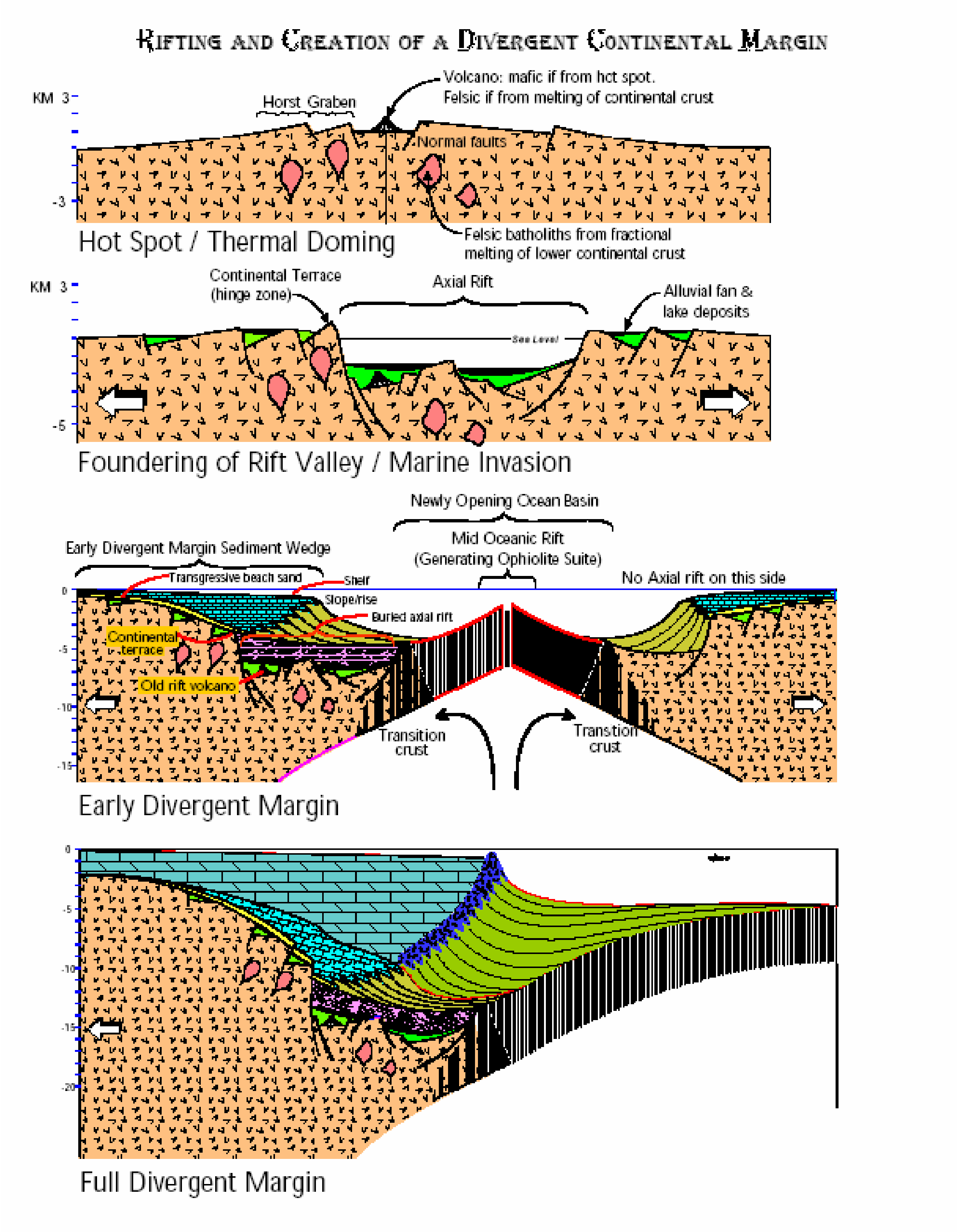


Figure 7: From "The Wilson Cycle"
(Dept. of Geology, James Madison University, Harrisonburg, VA)

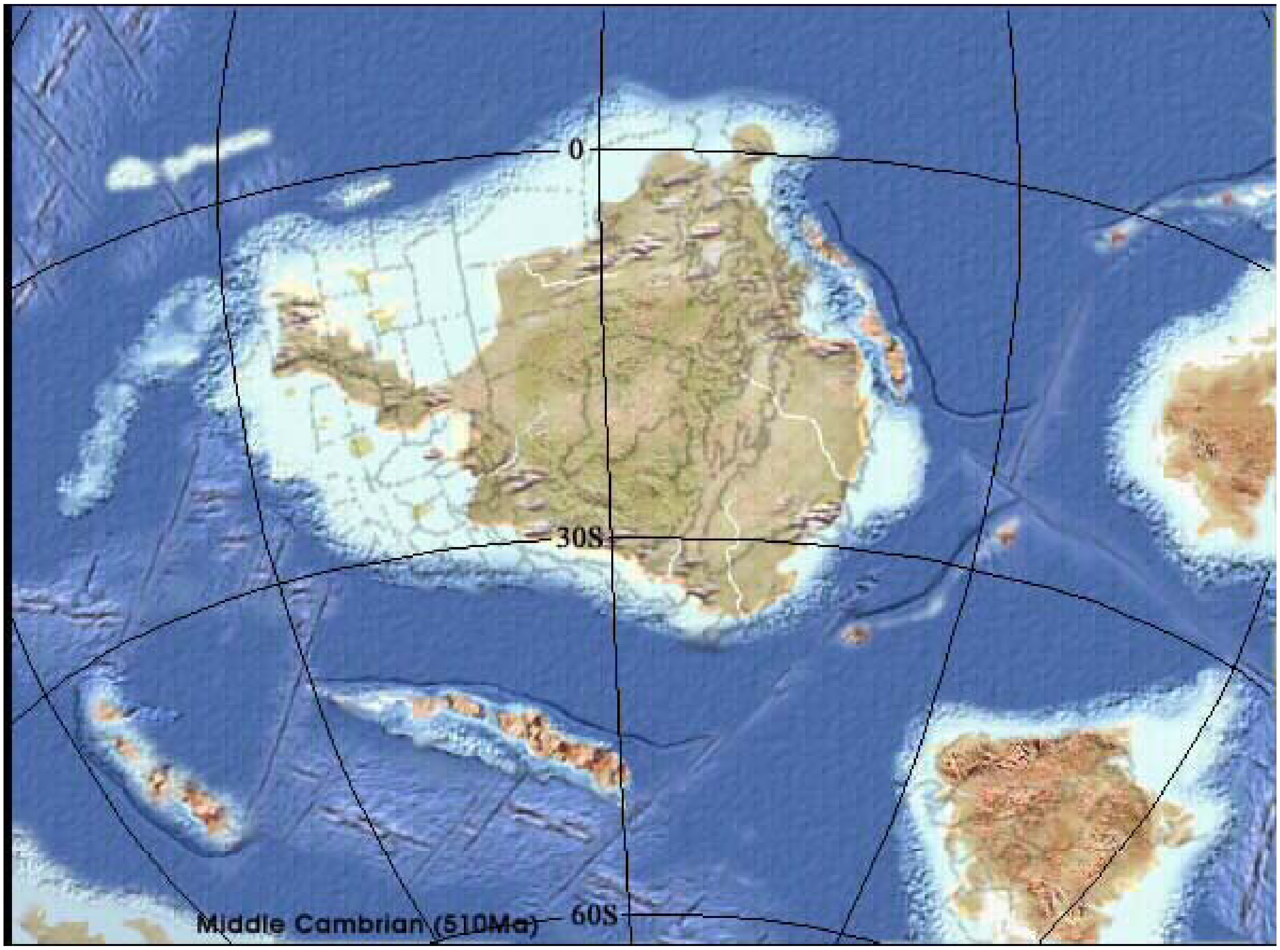


Figure 8: North America – 510 million years ago (middle Cambrian)
(from Dr. R. Blakey, Northern Arizona University, Flagstaff, AZ)

The Collier shale is a gray to black, lustrous shale containing occasional thin beds of dense black chert. An interval of bluish-gray thin-bedded limestone may be present. The Collier shale was deposited in the newly formed Iapetus Ocean basin between the rift ridge and the continental slope. This area would not be too far from the craton to receive clay- and silt-sized sediments but no sand. The chert would indicate that occasionally clay deposition waned and was replaced by siliceous ooze from Cambrian/Ordovician plankton with silica tests. As the Collier time of deposition drew to an end (early Ordovician?), sea level dropped (continental glaciation on another plate?) and limestone was sporadically deposited. Near the limestone top, it turns conglomeritic and pelletoidal with pebbles and cobbles of limestone, chert, meta-arkose, and quartz. It is estimated that the Collier shale is more than 1,000 feet thick as the base of the formation is not exposed. Fossils are rare but include trilobites and conodonts. The type locality for the Collier is Collier Creek, Montgomery County, Arkansas.

Ordovician Period (488 – 444 mya):

Deposited conformably above the Collier shale is the Crystal Mountain sandstone. This formation is a massive, coarse-grained, well-rounded, light gray sandstone with lesser amounts of light gray to gray shale, black chert, bluish-gray limestone, and gray calcareous conglomeritic sandstone.

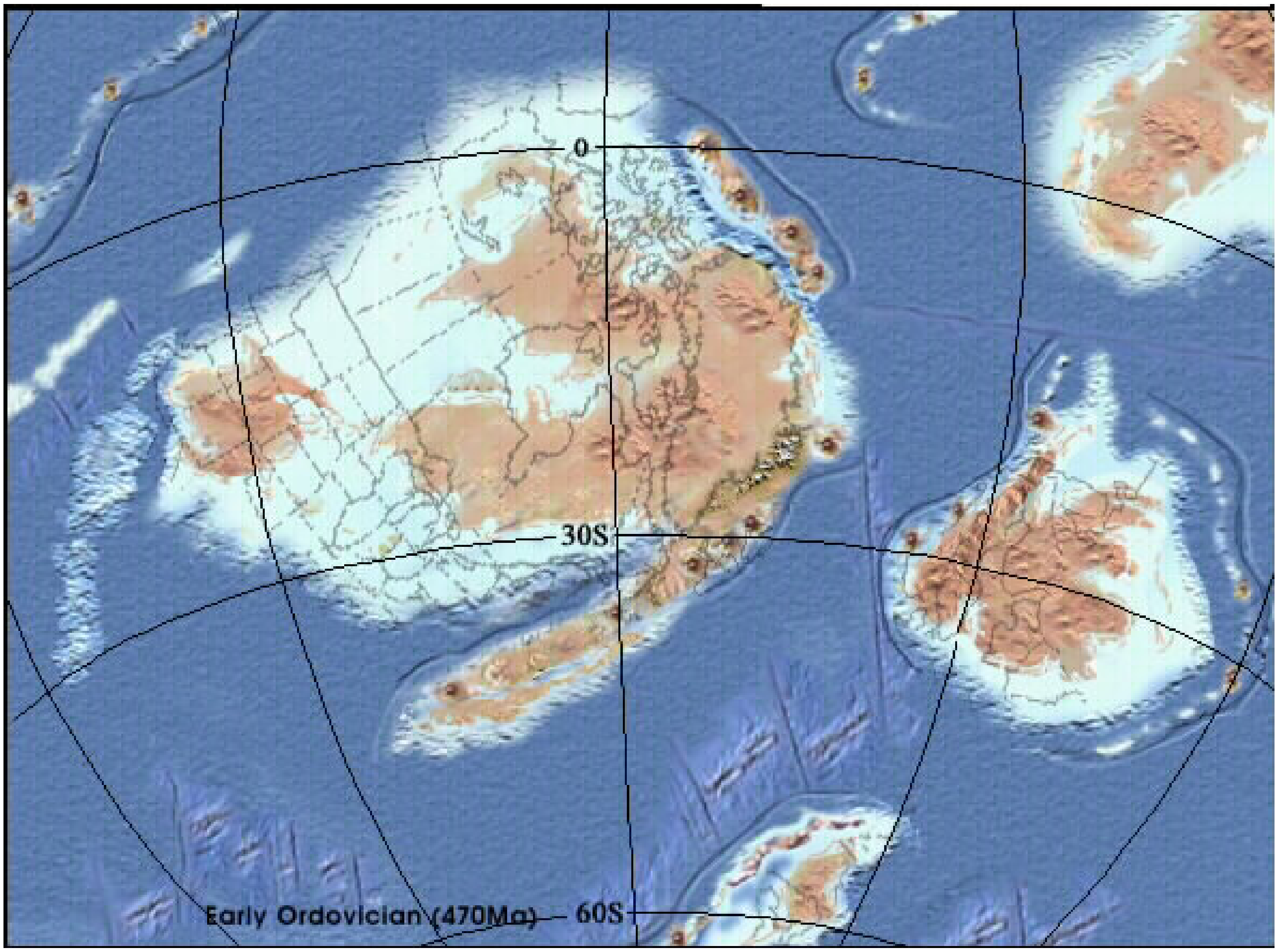


Figure 9: North America – 470 million years ago (early Ordovician)
(from Dr. R. Blakey, Northern Arizona University, Flagstaff, AZ)

In some areas, large boulders of meta-arkose and other olistoliths may be found in the conglomerate. This formation was probably deposited during a period of low sea levels. When sand sources were lacking, chert and limestone were deposited probably from siliceous and carbonaceous plankton tests. The conglomerates might represent periods of storms with an influx of eroded material washing in from the craton. During the Pennsylvanian Period, this formation developed a network of quartz veins from several inches to several feet thick. In some of these veins, clusters of quartz crystals can be found. Conodonts are the only fossils present. Typically this formation ranges from 500 to 850 feet thick, though in some areas it is less than 50 feet. The type locality is the Crystal Mountains, Montgomery County, Arkansas.

Still in early Ordovician times, the Mazarn shale was conformably deposited on top of the Crystal Mountain sandstone. The Mazarn shale is predominately gray-black shale with small amounts of quartzose siltstone, silty to conglomeritic sandstone, blue-gray limestone, and glossy black chert. When the dark and greenish shales are cleaved at an angle to bedding, they yield a ribboned surface. Sea level was probably fluctuating during the deposition period of the Mazarn. The chert is usually found near the top of the formation. Milky quartz veins are common in some areas. Only conodonts and a few graptolite fossils have been noted. The thickness ranges from 1,000 feet to over 2,500 feet. The type locality is the headwaters for Mazarn Creek, eastern Montgomery County, Arkansas.

The Blakely sandstone was deposited conformably on the Mazarn in middle Ordovician time. The Blakely is actually made up of 50 to 75 percent black and green shale, but the sandstone can be very resistant to weathering. The sandstones are light gray to blue, medium-grained, and well-cemented occurring in thin to thick beds. The cementation is either silica or calcite. Where the cement is silica, the sandstone is quartzite and is very resistant to weathering. Some of the sandstone is conglomeritic and contains erratic meta-arkose boulders and pebbles. This probably represents periods of lower sea level with storms causing the influx of material from the craton and shelf. The shales of the Blakely are sometimes ribboned much like the Mazarn shales. Only graptolites and conodont fossils have been reported. The formation thickness ranges from a few feet to around 700 feet. The type locality is Blakely Mountain, Garland County, Arkansas.

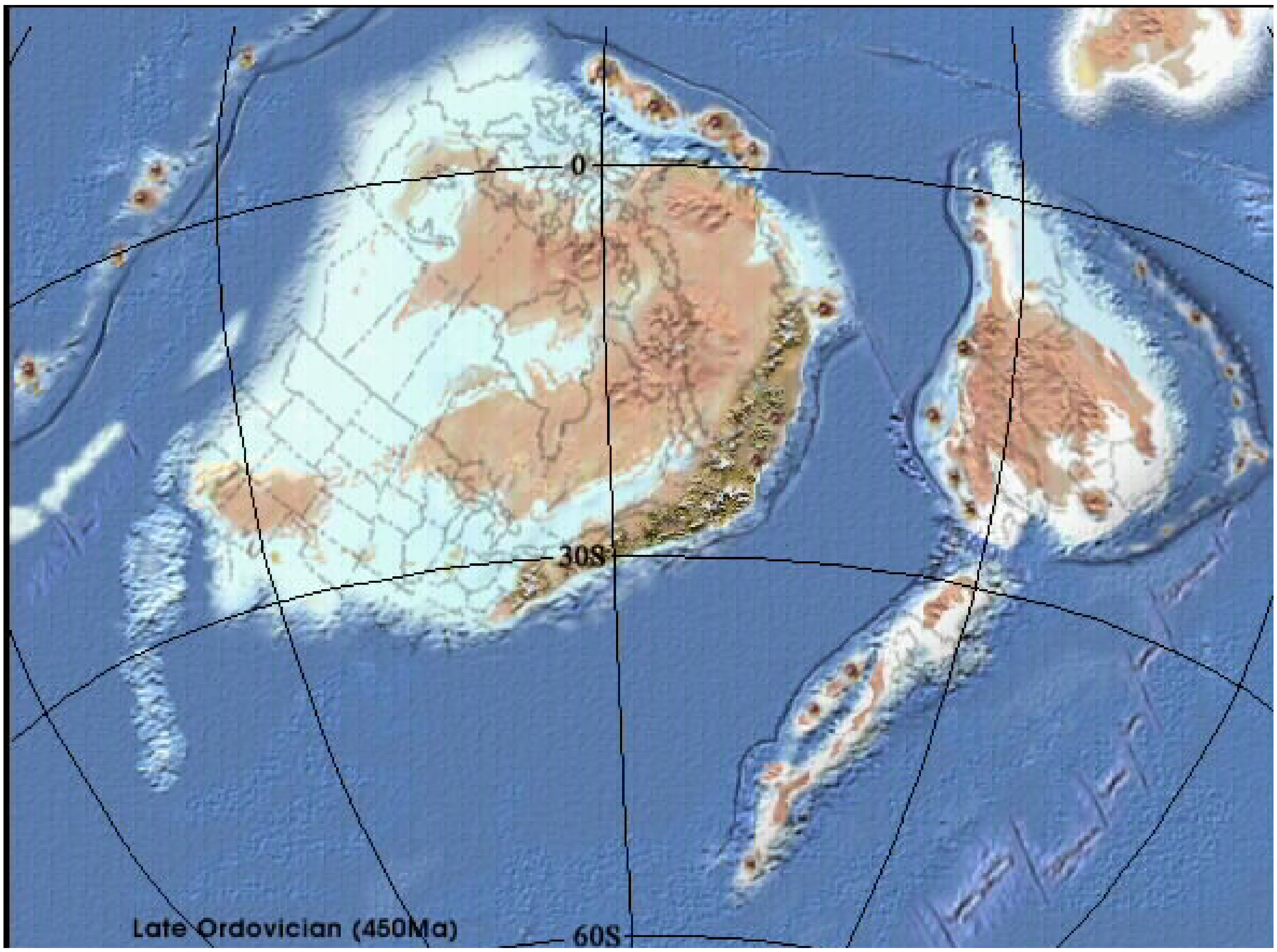


Figure 10: North America – 470 million years ago (late Ordovician)
(from Dr. R. Blakey, Northern Arizona University, Flagstaff, AZ)

The Womble shale is mostly black shale with thin layers of limestone, silty sandstone, and chert. Some green shales are interbedded with the black shales, but less so than in the Mazarn shale. As in the Mazarn and Blakely, cleavage at an angle to bedding frequently displays ribboned surfaces. The sandstones, if present, are found in the lower part of the formation and are dark gray, fine-grained, and occasionally conglomeritic or phosphatic. Perhaps the sea level was still somewhat low at the beginning of the Womble deposition, as it had been in the Blakely, but higher than it was in the Mazarn. Sea level seems to have risen during Womble times since the black and green shales may indicate an increased ocean depth and an anaerobic environment. Near the top of the Womble Formation, dense blue-gray limestone may be found in thin to medium beds. Black chert is also present in thin layers. The limestone and chert may have been deposited from plankton tests during times when clay sediments were not being transported to the basin. Graptolite and conodont fossils have been noted in the Womble but are rare. The Womble ranges from 500 to 1,200 feet in thickness. The type area is near the town of Norman, Arkansas in Montgomery County. Norman was previously named Womble, Arkansas.

In latter middle and late Ordovician times, the Bigfork chert was deposited conformably over the Womble Formation. The Bigfork chert consists of thin-bedded, dark gray, cryptocrystalline chert interbedded with varying amounts of black siliceous shale, calcareous siltstone, and dense, bluish-gray limestone. The cherts normally occur in thin to medium beds and are usually highly fractured. The interbedded siliceous shales occur in thin to thick sequences and are often pyritic (secondary feature?). Limestones occur mostly as interbeds in the chert and are more common in the northwestern exposures. Fossils are rare, but fragments of brachiopods, crinoids, sponges, conodonts, and graptolites have been reported. The oceanic basin was becoming wider, and much of the depositional basin was deepening from relatively shallow near-slope to deeper basin. Shelf down-to-the-basin faulting is evident in the shallow-water fossil fragments that fell to deeper basinal depolocations. These were probably deposited in non-turbiditic landslides and sediment slumping. The shelf-shedding deposition is offset by depositional sequences of siliceous and/or carbonaceous planktonic oozes. Basinal deepening is indicated as the formation thickness ranges from about 450 feet in the northern Ouachitas to over 750 feet in the southern Ouachitas. The type area for the Bigfork Formation is near the Bigfork Post Office, Montgomery County, Arkansas.

As the Ordovician drew to a close, the Polk Creek shale was deposited. The Polk Creek Formation consists of black, sooty, fissile shale with minor black chert and traces of gray quartzite and limestone. Graptolites are common in most of the shales. The Polk Creek rests conformably on the Bigfork chert. During Polk Creek times, the down-to-the-basin faulting/slumping seems to have almost stabilized or much of the section is missing. The Polk Creek appears to have been deposited during a time of clay particle influx that only lessened on occasion. As graptolites were oceanic floating invertebrates, they would be easily incorporated in quiet, deep basinal sediments. The Polk Creek Formation thickness varies from 50 to 225 feet, and again probably shows increasing basinal water depth away from the slope. The type area for the Polk Creek Formation is near Polk Creek, Caddo Gap Quadrangle, Montgomery County, Arkansas.

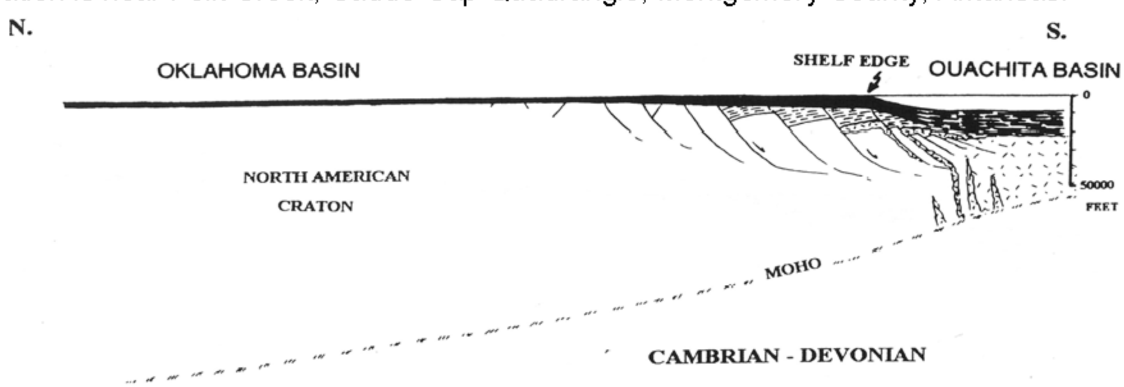


Figure 11: Oklahoma Basin – Ouachita Shelf/Slope/Basin - Cambrian through Devonian.
(from Suneson, 1995)

Silurian (444 – 416 mya):

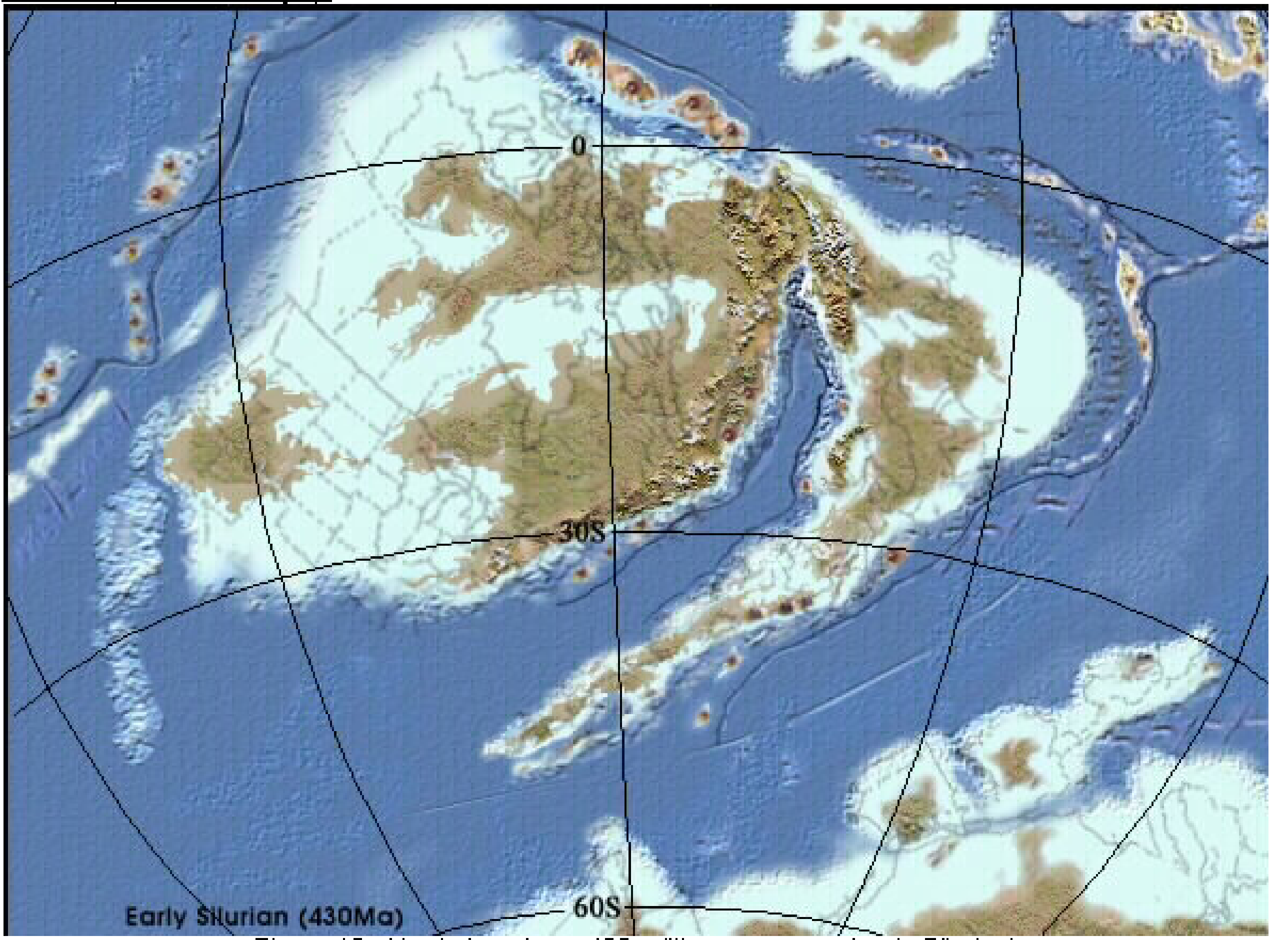


Figure 12: North America – 430 million years ago (early Silurian)
(from Dr. R. Blakey, Northern Arizona University, Flagstaff, AZ)

The Blaylock sandstone seems to have been emplaced during a low stand in sea level. To the north, down-to-the-basin faulting, wasting, and erosion (both from the shelf and from the land) deposited fine- to medium-grained sandstone that tends to be tan, dark gray, or greenish color. These sandstones are usually thin bedded and tend toward wackestones with small amounts of plagioclase, zircon, tourmaline, garnet, and mica. The sandstones are interbedded with dark-colored to black fissile shale that becomes the predominate facies to the south. Fossils are very rare. The Blaylock Formation ranges from over 1,200 feet thick in the southern Ouachitas of Arkansas to not deposited (missing) in the northern Ouachitas. The type area for the Blaylock sandstone is Blaylock Mountain, Montgomery County, Arkansas.

The Missouri Mountain Formation consists of gray, green, black, or red shale that is interbedded with conglomerates (northern Ouachitas), sandstones, and novaculite. The conglomerate is normally present at or near the base of the formation and may be up to four feet thick. It appears that sea level rose during the Missouri Mountain deposition. The quartzite sandstones are thin beds that occur throughout the unit but are more common in the upper and lower parts. Thin beds of novaculite are present in the upper part also. Very few identifiable fossils have been found. The Missouri Mountain Formation rests conformably on the Blaylock sandstone in the southern Ouachitas and conformably on the Polk Creek shale in the north. The formation reaches a maximum thickness of 300 feet. The type area for the Missouri Mountain Formation is the Missouri Mountain, Polk and Montgomery Counties, Arkansas.

It is interesting to note how, during the Silurian, the Ouachita basin seems to tilt and develop a more inclined ramp from the shallow slope to very deep water. One probable cause for this would be the development of growth faults on the continental shelf. However, along with the growth faults, there is speculation that the Silurian might be the time when the cooler, growing overburden of continental deposits caused the oceanic crust to break. This break would be the start of a subduction trench. As the trench developed and subduction began, the overall trend of the basin floor would be down towards the trench. It is important to note that the Ouachita basin (North American plate) was the subducted plate (foreland). The plate of oceanic crust with aforementioned deposited formations would be the overriding plate (hinterland). How exactly a trench develops is still unknown. Is it that the overburden finally cools a thinner area of oceanic crust enough that it begins to sink into the mantle in a manner similar to temperature spheres in a Galilean thermometer? Does it begin as a "downward bulge"? It certainly is not primarily caused by sheet-like deposition in an oceanic basin since the cratonic derived sediments would be less dense than the mafic/ultramafic oceanic crust. There has to be another contributing factor, and it makes sense that this factor might be temperature. Is it possible that this "downward bulge" starts to linearly involve the surrounding oceanic crust? As this bulge grows and becomes more linear, the oceanic crust would finally thin and rupture to produce the trenches and subduction zones that we observe today. The hinterland would start to override the foreland. The foreland, being cooler than the surrounding crust and mantle, would begin to sink. Gravity would take over and start pulling the cooler plate down. (After all, it is thought that gravity actually drives plate tectonics. The plates are actually being pulled apart at the trenches rather than pushed apart at

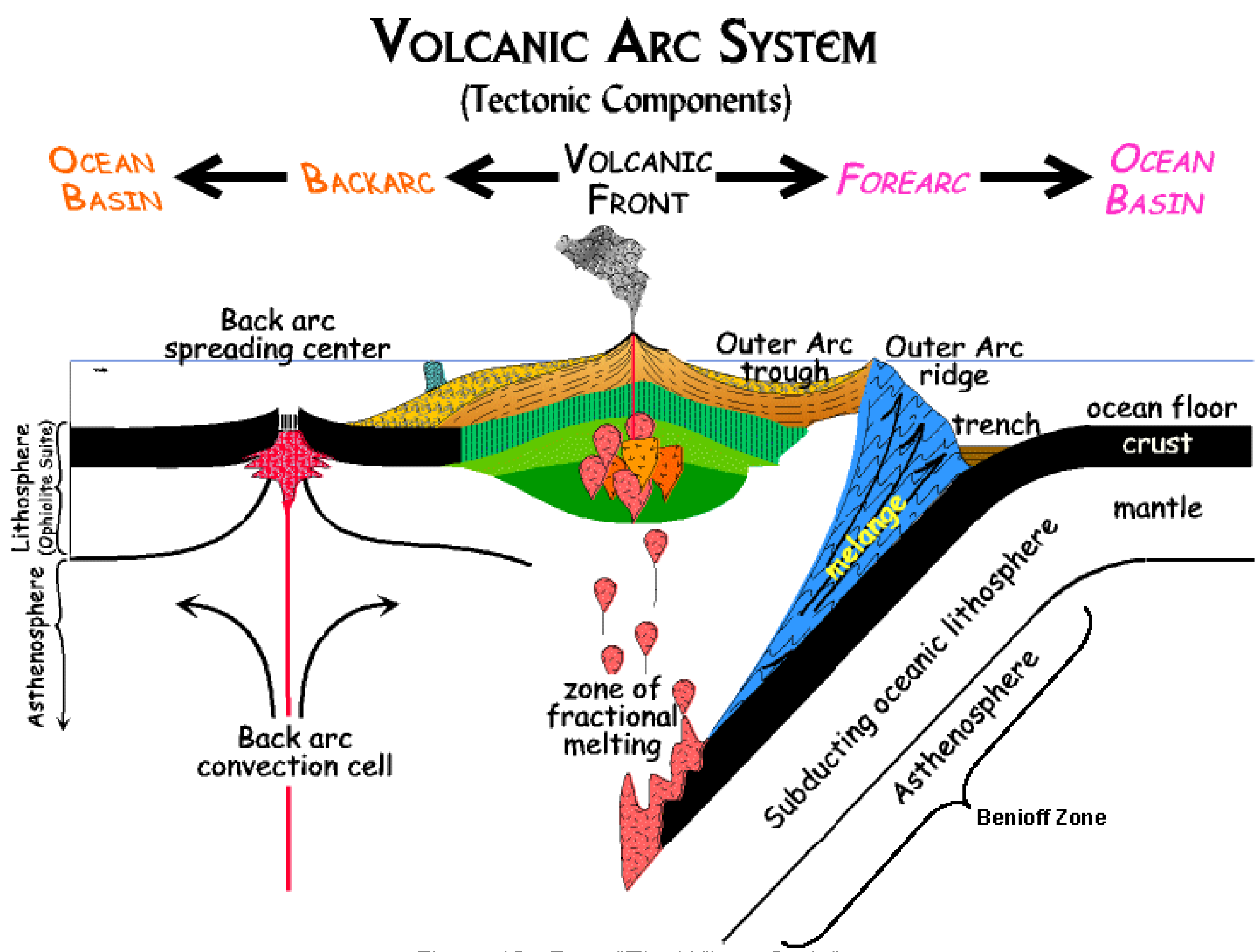


Figure 13: From "The Wilson Cycle"
(Dept. of Geology, James Madison University, Harrisonburg, VA)

the ridges.) The trench would develop and spread laterally, perhaps being offset by transform faults as it spread. And how long would it take a trench to develop? Modern day plates are observed to be moving apart at between 2.5 and 15 cm/year. Would it take 10,000 years for the foreland to move laterally a kilometer beneath the hinterland? That is not very long in geologic time.

As the foreland was subducted, some of the cratonic formations would be scraped off at the trench to form a melange, but some would be carried along with connate water below the hinterland. The subducted plate would be heated, and the cratonic formations (with connate water) and oceanic crust would begin to differentially melt. The subduction zone is much like a distillation tower in that the fractional melting refines the magma into felsic magma (the basis of continental crust). This magma migrates upward, finally building an andesitic volcanic island arc on the hinterland side of the trench.

So, how long would it take for the trench and the volcanic island arc to develop? The Silurian was only about 40 million years. How far offshore from the North American plate did the subduction trench develop? And how long did it take before this trench would impinge upon the North American plate? Some geoscientists (Blythe et al., 1988) have suggested that a subduction zone formed prior to or during the Mississippian. However, there are many unknowns that plague defining even an approximate time, such as distance between the formed subduction zone and the continental margin, time involved in developing a typical active subduction zone, rate of subduction, etc.

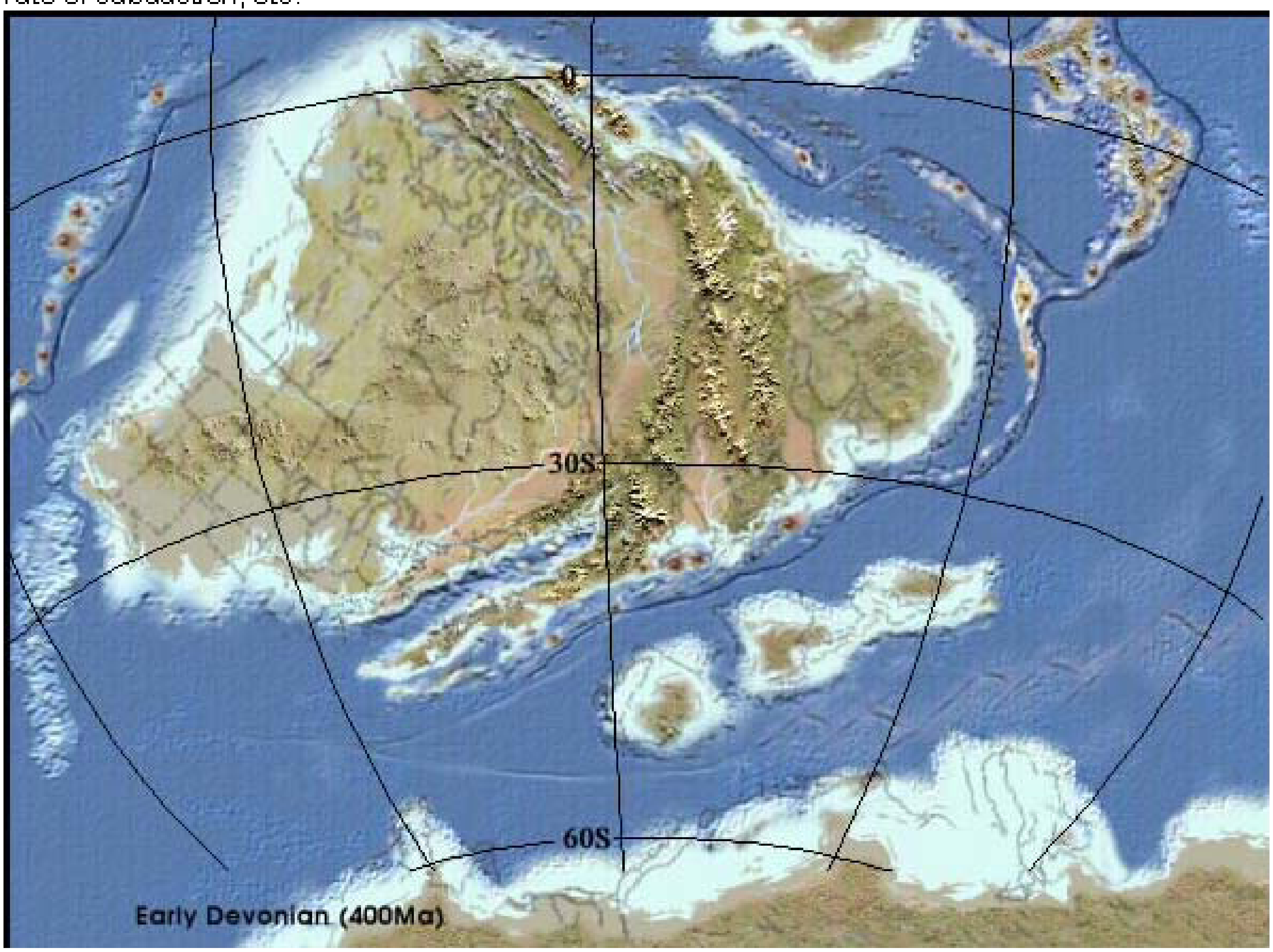


Figure 14: North America – 400 million years ago (early Devonian)
(from Dr. R. Blakey, Northern Arizona University, Flagstaff, AZ)

Devonian Period (416 – 359 mya):

The Arkansas Novaculite is deposited upon the Missouri Mountain shale conformably except where the presence of conglomerates in a few places indicates a possible minor incipient submarine disconformity. Could these places have been influenced by a young developing subduction zone? There are three recognized divisions of the Arkansas Novaculite (except in the northern exposures). The Lower Division is a white, massive-bedded novaculite with some interbedded gray shales near its base. The Middle Division consists of greenish to dark gray shales interbedded with many thin beds of dark novaculite. The Upper Division is a white, thick-bedded, often calcareous novaculite. Conodonts and other microfossils are sometimes common in the Arkansas Novaculite. The formation may attain a thickness of up to 900 feet in the southern outcrops but thins rapidly to about 60 feet to the north. The depositional environment for the novaculite is probably deep oceanic basin (although starved basin has been usually proposed in the past). In early Devonian times, siliceous oozes from plankton gathered on the ocean floor interrupted only occasionally by the introduction of clay-sized sediment. The Middle Division basically represents a time when clay-sized sediment was being introduced almost constantly. Since the clay would intermix with the siliceous ooze and contaminate it, shale was the result. The thin beds of black novaculite just represent a time of less clay sediment influx. The Upper Division shows plankton-rich, clay-sediment-starved deposition again. However, this time the plankton tests were both siliceous and carbonaceous. This may just simply be caused by changing ocean currents and water temperature and/or dissolved gasses. After all, the subduction trench was developed at this time and the volcanic arc was gradually nearing the North American plate.

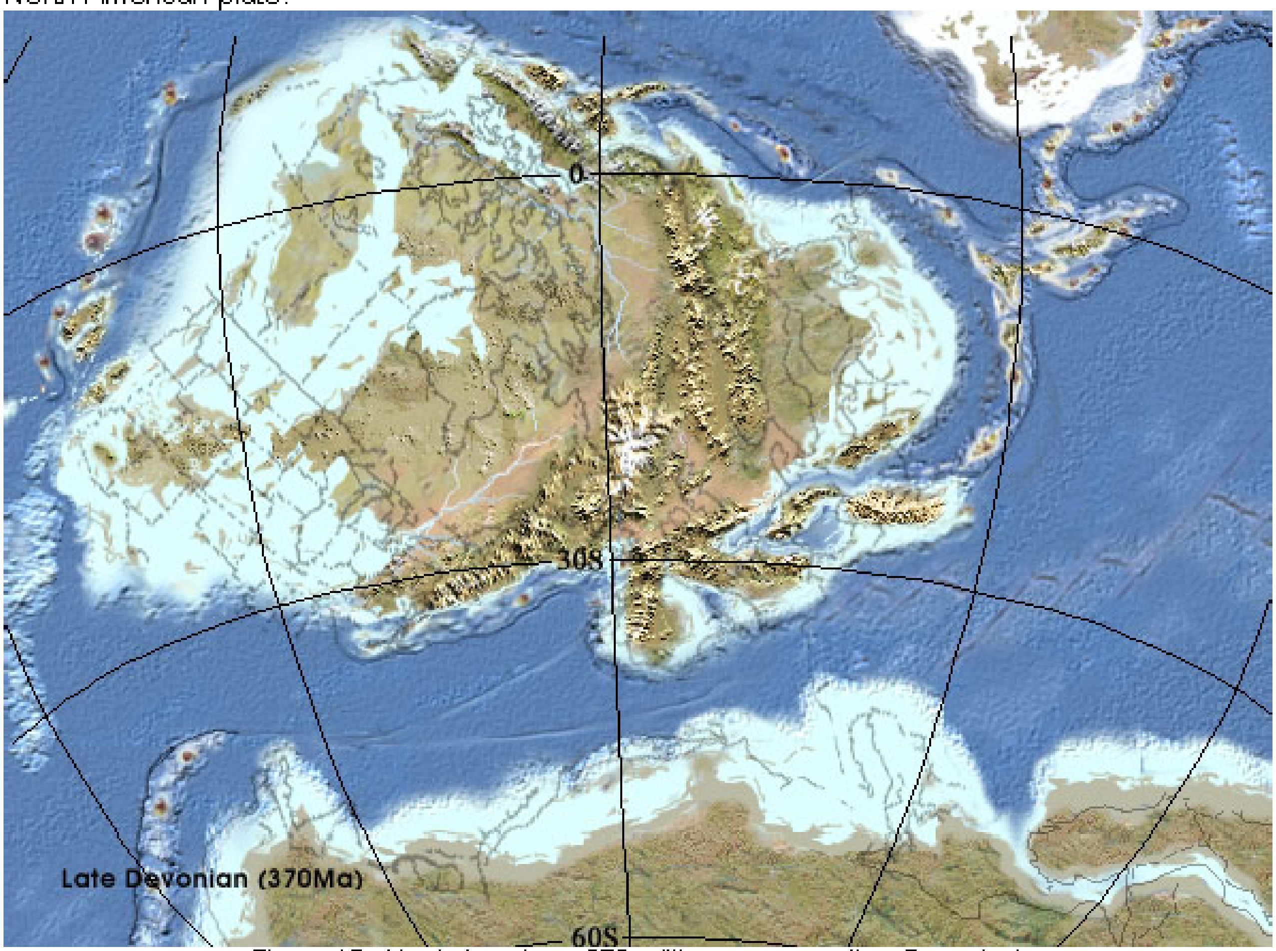


Figure 15: North America – 370 million years ago (late Devonian)
(from Dr. R. Blakey, Northern Arizona University, Flagstaff, AZ)

The type area for this formation is the quarries around Hot Springs, Garland County, Arkansas that quarry and sell this rock under the trade name of "Arkansas Novaculite".

Mississipian (Early Carboniferous) Period (359 – 318 mya):
Deposition of the Arkansas Novaculite continued into the early Mississipian Period. But soon the massive thickness (3,500 to 10,000 feet) of the Stanley shale was deposited conformably on the Arkansas Novaculite. The Stanley Shale Group is a complex of deepwater, distal, dark gray shales but with high accumulation rates. The shale is interbedded with turbidite sandstones, siliceous shale/chert, bedded and vein barite, and water lain tuffs. The type area for the Stanley shale is the townsite of Stanley, Pushmataha County, Oklahoma.

At first it was proposed that the Stanley was deposited as large, freshwater deltas on a southern margin of a geosyncline. In 1959, Cline and Shelburne proposed a significant, new interpretation of the Stanley depositional environment. They advocated that the Stanley, Jackfork, Johns Valley, and Atoka Formations were similar to the black-shale flysch and wildflysch facies of Europe. These flysch facies were deep water debris flows and turbidites. Upon further investigation, it was concluded that, in the southern Ouachitas, the sediment source was from the south or southeast. The sediments accumulated in a trough/basin via debris flow or turbidity currents flowing west-southwest. The predominate paleocurrent direction is indicated to be north to northwest. In the northern Ouachitas, the sediment source appears to have been from the north and east with the paleocurrent direction being west. Could this indicate that the basin was still fairly wide (early Mississippian) but restrained/closed to the east? Niem (1976) divided the

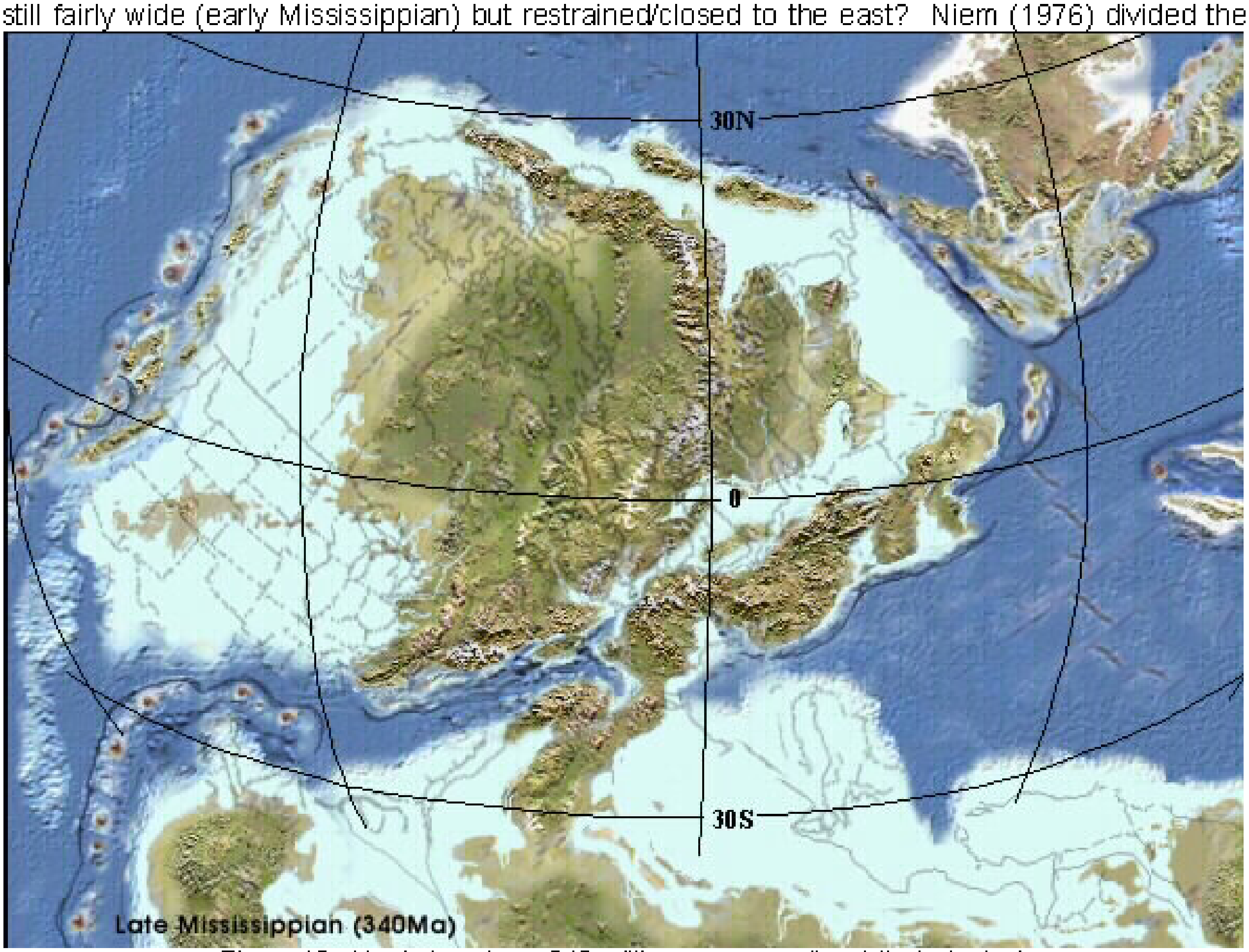


Figure 16: North America – 340 million years ago (late Mississippian)
(from Dr. R. Blakey, Northern Arizona University, Flagstaff, AZ)

lower part of the Stanley into a southern/proximal and a northern/distal flysch facies and suggested each accumulated on different parts of a deep sea fan complex and adjacent oceanic basin plain. He also showed more sand-rich proximal facies prograded over the distal facies in later Stanley time in the central Oklahoma Ouachitas. It may be possible that the deposition of these sands was influenced by a deepening trough, sand sourcing from the east, and stronger paleocurrents.

The tuffs – Hatton, Beavers Bend, Lower and Upper Mud Creek – are primarily within the lower Stanley of the southern Ouachitas. However, Niem (1971) described several thin tuff beds above the Mud Creek, as well as a tuff associated with the Upper Stanley Chickasaw Creek shale. The paleocurrent directions associated with the tuffs indicate a southern or southeastern source. These tuffs seem to indicate an early explosive eruption sequence of the developing volcanic arc opposite the newly formed subduction zone. Based upon major-, trace-, and rare-earth element abundance, it is suggested that these tuffs were felsic island-arc sourced.

A thick sandstone member, the Hot Springs sandstone, is found locally near the base of the Stanley. An equivalent thin conglomerate/breccia occurs at the base of the Stanley in many other localized places. The silty sandstones outside of the Hot Springs sandstone are normally found in thin to massive beds separated by thick shale intervals. The Hot Springs sandstone and localized conglomerates/breccias possibly indicate a submarine disconformity between the Stanley and Arkansas Novaculite. An alternative explanation could be that the Hot Springs sandstone and the localized conglomerates/breccias are a result of debris flow/slumping or turbidity flows caused by a megatsunami from an earthquake centered in the subduction trough. At least this could explain the localized nature.

The hydrocarbon potential of the Stanley is still questionable as both a source and reservoir. Perhaps the best example of this potential is the "Talihina Oil Field". The "discovery well" and only well of this field, Select No. 1 Warren, is located 0.3 mile north of the intersection of Oklahoma State Highways 1 and A63. This well produces from the Stanley Group at 156 – 164 feet. (This well is occasionally produced to preserve wooden fences and soften pig skins.) The well's oil has been geochemically analyzed and described as "moderately mature to mature, algal-based, predominately marine-type oil, generated in clastic source rocks under mildly reducing conditions". It was also concluded that the most likely source rocks for Ouachita crude oils are the Caney shale, Woodford shale, Arkansas Novaculite, and/or Polk Creek

Figure 17: Neil Suneson and Jock Campbell (Oklahoma Geological Survey) hand-operating the pumpjack on the Select No. 1 Warren, December 5, 1988. After 45 minutes of back-breaking labor, oil was recovered. This method of oil collection is not recommended. (from Suneson, 2005)

shale. If these organic-rich deposits lie beneath and down dip from the known small oil fields of the Ouachitas, then there may be a potential for unconventional shale gas to the south or southeast below these small fields.

Around Hatton, Arkansas, there is some indication that the Ordovician through Devonian units were deformed before the deposition of the Pennsylvanian strata. Blythe et al. (1988) and Welland et al. (1985) have suggested that the deformation of Cambrian to Mississippian formations commenced during the late Mississippian. They suggest that the observed and inferred deformation is analogous to the present-day subduction deformation observed in the Makran complex (Arabian plate being subducted beneath Eurasian plate). Also, the southward vergence seen in today's Ouachita pre-Mississippian formations is similar to the strong seaward-dipping anisotropy typically developed in some modern accretionary complexes (e.g., Oregon-Washington) as well as rotation along faults.

The lower Stanley contains a major detachment zone that is a boundary between two distinct and independent deformation styles observed in the central Ouachita Mountains (Titus, 1995). This lower Stanley detachment was confirmed through proprietary drilling results and seismic data performed by Sohio Production Company (now BP p.l.c.).

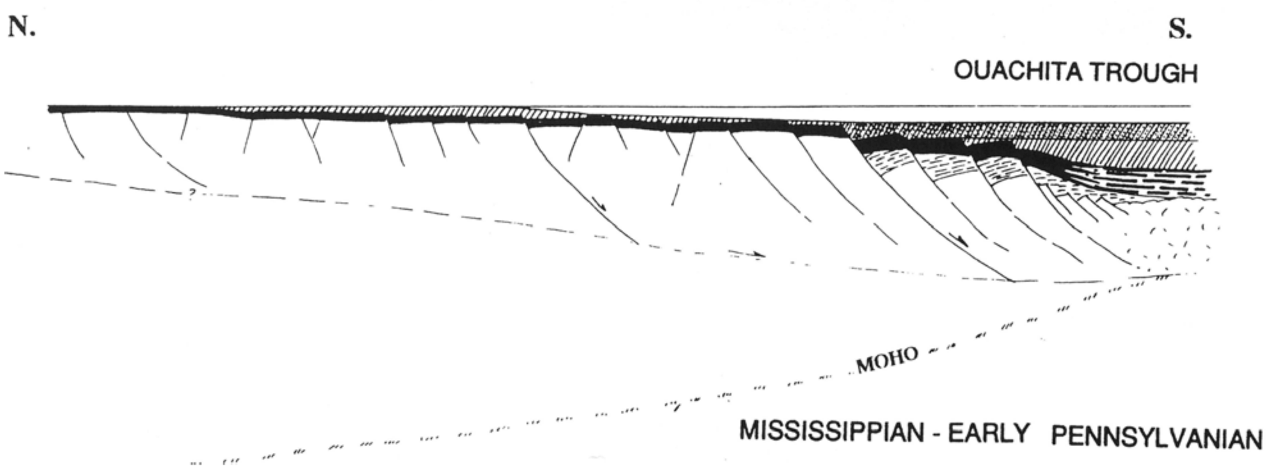


Figure 18: Ouachita Shelf/Slope/Basin - Mississippian through early Pennsylvanian.
(from Suneson, 1995)

Before continuing to the Pennsylvanian Period, it might do well to address two additional topics: "Subduction Tectonics and Tsunamis" and "Debris Flow versus Turbidites".

Subduction Tectonics and Tsunamis: Subduction is not a continuous process, rather a series of sudden, quantized movements marked with large to small earthquakes within the Benioff Zone of the subducting plate. Small subduction movements usually generate small earthquakes, while large subduction movements generate huge earthquakes along with oceanic floor changes. With any size movement/earthquake, there exists a potential for a tsunami. There does appear to be a positive correlation between large magnitude (7.5+) earthquakes and tsunami generation. Current thought places the cause of tsunamis on impulsive vertical displacement of water (USGS, 2005), submarine debris flows/slumps (Tappan, 2004), volcanic explosions (van den Bergh et al., 2003), or meteorite impacts (Bryant, 2001). An earthquake-generated tsunami may cause or be

Figure 19: Khao Lak, Thailand before and after December 26, 2004 Sumatra-Andaman earthquake (9.2 magnitude) and tsunami. Tsunami was approximately 11 meters at Khao Lak. (Satellite Imagery by GeoEye/CRISP)

caused by a submarine flow that results not only in a turbidite/debris flow within the trench but also possible flows and near-shore erosion/deposition on distant shores. A submarine flow may cause a tsunami that in turn causes another submarine flow. If one examines the present as the key to the past, during the twentieth century, some 688 tsunamis occurred in the Pacific Ocean. At that rate, one could expect nearly seven million tsunamis of varying magnitudes over a period of one million years. During the past 2,000 years, Scheffers and Kelletat (2003) reported that at least 100 megatsunamis (wave height in excess of 40 meters/130 feet) have occurred. In modern times, the greatest wave height recorded for a megatsunami occurred at Lituya Bay, Alaska on July 10, 1958, and reached a wave height of 524 meters/1720 feet.

<u>Debris Flow versus Turbidites:</u> Since the first description of turbidity flows in 1952 (based upon research concerning the 1929 trans-Atlantic telegraph cable break), Bouma's description (1962) of turbidite deposition and sequences, and through today, geoscientists have applied the term "turbidite" to any and all deepwater sand deposit. In much the same way, we used to talk about "Xeroxing a copy" and currently speak of "Googling a website". To be specific, turbidite sediments should only apply to those formations that have been transported and deposited by fluid flows in which the grains are supported by turbulence or turbulence with hindered settling. These types of sediments will usually exhibit Bouma Sequences. Debris flows and/or slump deposits are those transported by plastic laminar flows in which grains are supported by matrix strength and/or dispersive pressure. Typically geoscientists proclaim these sediments as "turbidites that lack Bouma Sequences". In fact, sediments and formations deposited via plastic flow are not true turbidites.

Lowe (1982) classified these sediment deposits into two principal types and three populations. Population 1 represents low-density turbidity currents composed of clay to medium-grained sand (turbidites with Bouma Sequences). Population 2 represents turbidites or debris flows in which the grains (population 1 along with coarse sand and pebbles) are supported by hindered settling (matrix) and turbulence. Population 3 represents debris flows in which the grains (population 2 along with cobble and boulder) are supported mainly by matrix buoyancy lift and dispersive pressure.

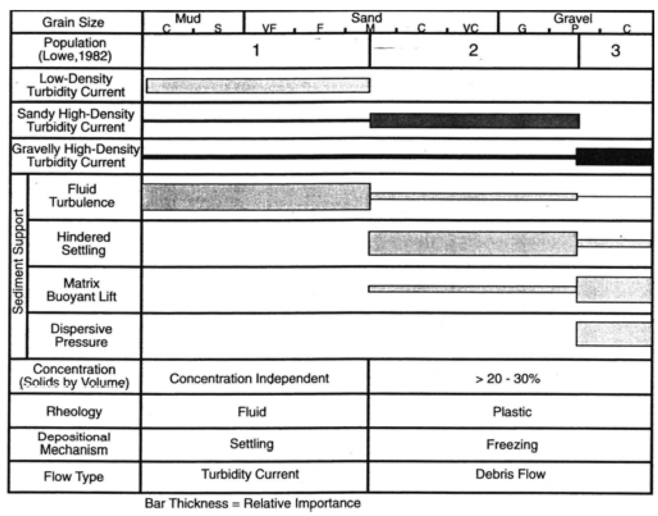


Figure 20: An illustration of Lowe's (1982) classification of turbidity currents and their grain-size populations, sediment support mechanisms, and particle concentrations. (from "An Unconventional Model for the Deep-Water Sandstones of the Jackfork Group (Pennsylvanian), Ouachita Mountains, Arkansas and Oklahoma", G. Shanmugam and R. J. Moiola, GCSSEPM Foundation 15th Annual Research Conference, 1994)

Within the Jackfork, Johns Valley, and Atoka Formations, there seems to be strong evidence of not only Bouma and non-Bouma sequence turbidites but also debris flow, especially within the Johns Valley and Atoka. Non-Bouma sequence turbidites may be influenced by spatial size of deposition basin, sea level, sediment transportation and availability, etc. Deposition history of the non-Bouma sequence turbidites may also contribute to the cementation diagenesis and reservoir quality of the formation. Though some of the theories proposed by Shanmugam and Moiola (1984) do not appear to be reasonable for the Jackfork deposition, they do have one very good point. A submarine flow (turbidite or debris) may occur as simultaneous multiple flows and transform between flow types depending upon the contained material, flow speed/turbulence, and distance from source(s). Multiple flows may come from different spatially distant sources along the same slope or different slope. These multiple flows may actually overlap or combine within the basin. Also, flows may contain different sediment materials and come from different sediment sources.

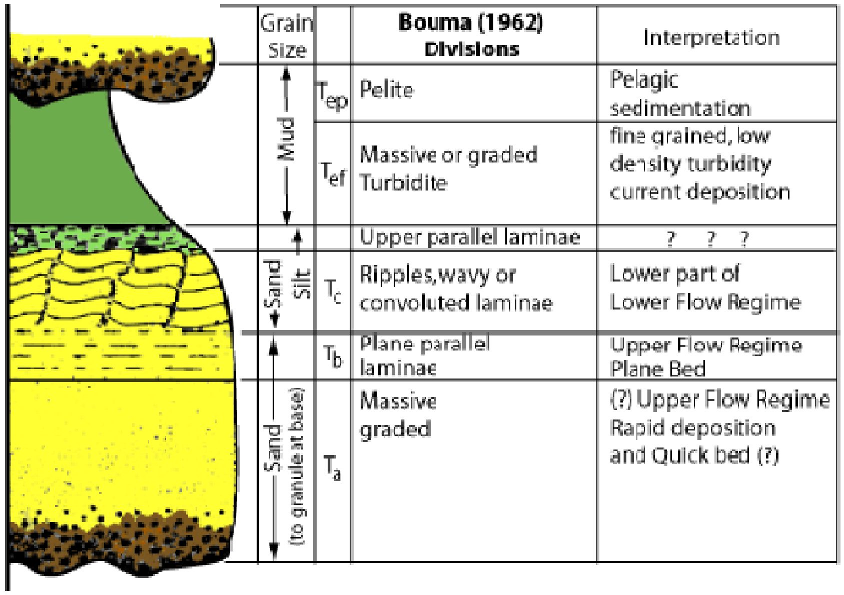


Figure 21: (from University of South Carolina Geology Department website "USC Sequence Stratigraphy Web", http://strata.geol.sc.edu/index.html)

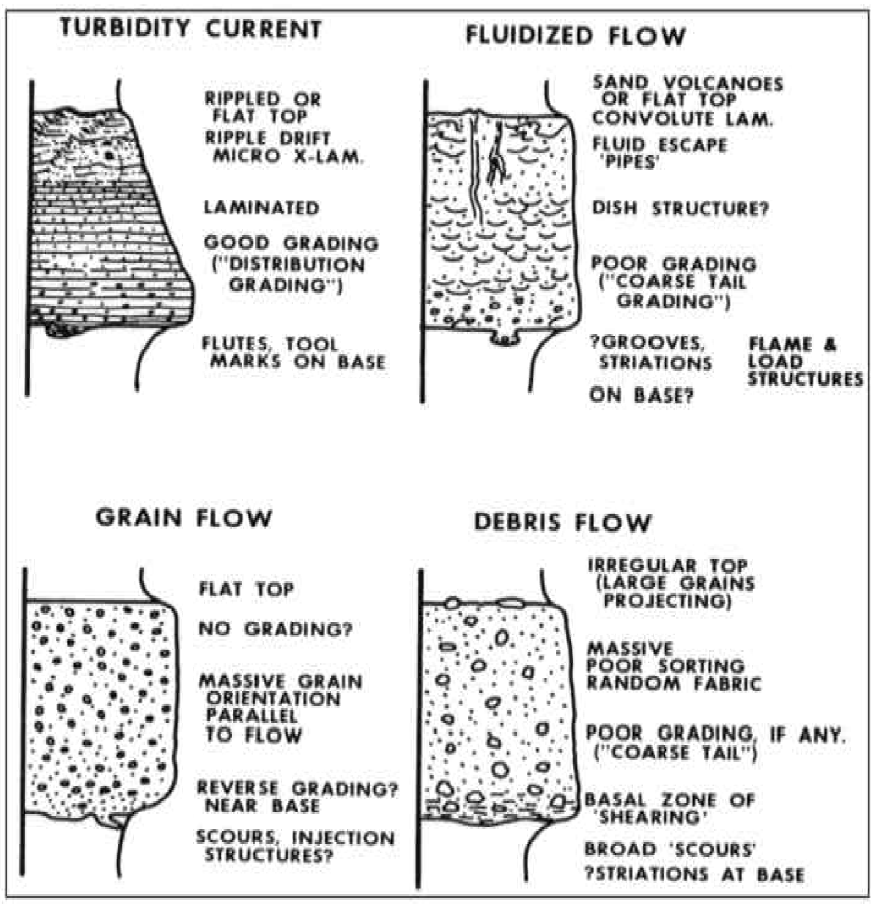


Figure 22: (from Wikipedia – subject: turbidites, date: Feb. 2, 2007)

Pennsylvanian (late Carboniferous) Period (318 – 299 mya):
The Pennsylvanian Period is a time when the remaining Iapetus Ocean was closing off from the northeast to southwest as the Laurussia plate (containing the North American craton) came closer to a southern plate. The exact identity of the colliding southern plate is unknown, but it is generally believed to have been a subduction accretion thrust front with one of the following: 1) a subduction volcanic arc, 2) Gondwana, 3) a former piece (Llanoria plate) of the North American plate removed from the craton during Cambrian rifting, or 4) unknown foreign terrain. The best answer seems to be the subduction volcanic arc. The ultimate result would be a tectonic collision with the newly developed continental crust of the volcanic arc. It also appears that the collision proceeded from northeast to southwest and was not typical of a craton-craton collision (such as the present-day India/Asia collision and Himalaya Mountains), rather a craton-arc collision. Beyond the volcanic arc was yet another subduction trough that was closing the distance between it and Gondwana. Additionally, this was a time of drastic low stands of sea level. Massive amounts of water were held as an ice cap at the South Pole resting upon Gondwana and removed from the oceanic volumes.

The Jackfork sandstone Group was deposited within the subduction trench/basin during Morrowan times of the early Pennsylvanian. The Jackfork is a thin- to massive-bedded, fine- to coarse-grained, brown, tan, or bluish-gray quartzite sandstone with subordinate brown, silty sandstones and gray-black shales. Toward the north of its Ouachita outcrop area, the shale units of the lower and middle Jackfork sandstone take up more of the section and the sandstones are

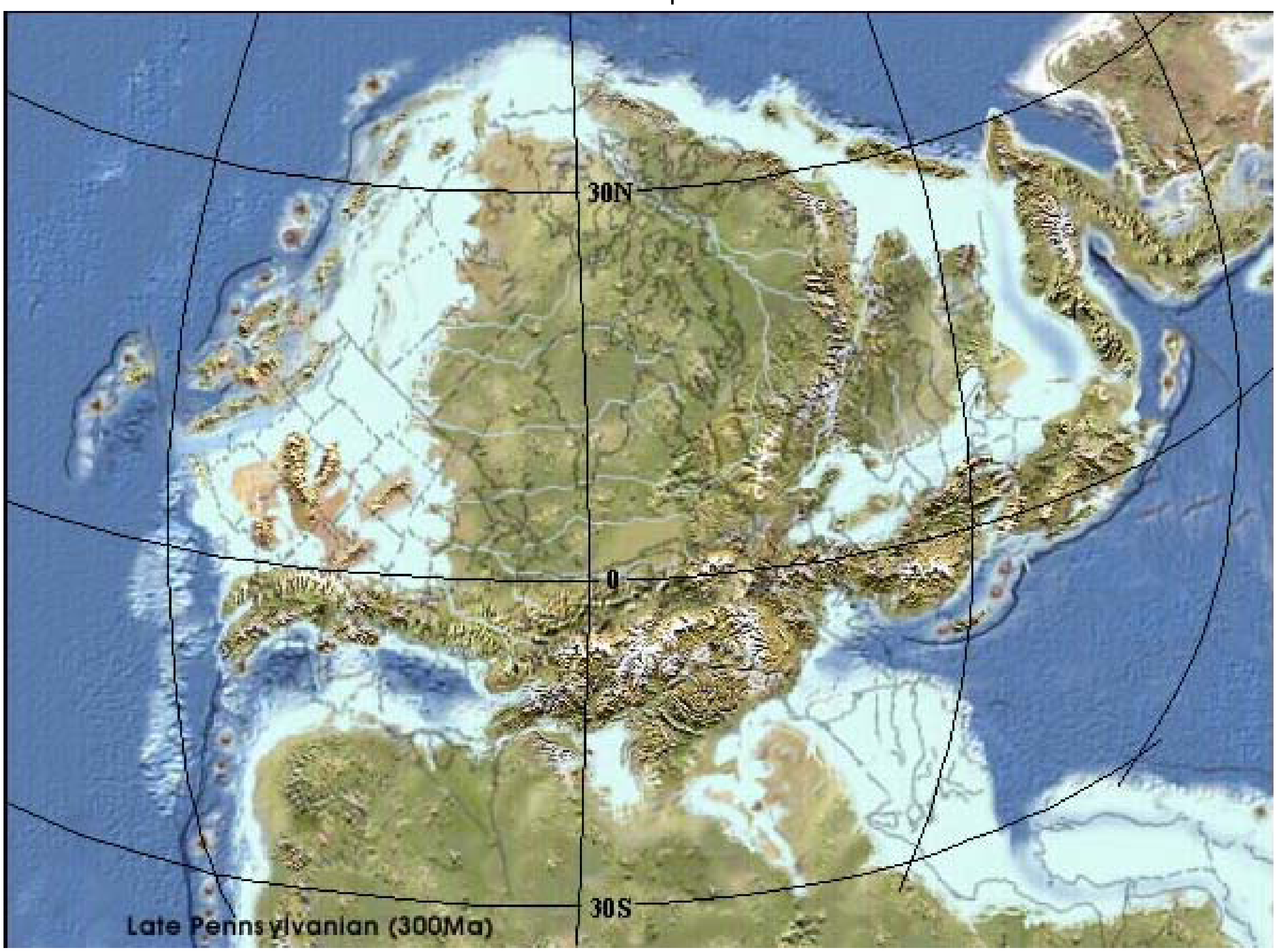


Figure 23: North America – 300 million years ago (late Pennsylvanian)
(from Dr. R. Blakey, Northern Arizona University, Flagstaff, AZ)

more lenticular, often occurring as chaotic masses in the shale. Minor conglomerates composed of quartz, chert, and metaquartzite occur notably in the southern exposures of the formation. A few poorly preserved invertebrate and plant fossils have been recovered from the Jackfork Formation. The Jackfork rests conformably on the Stanley shale and varies from 3,000 to more than 6,000 feet thick. The type area is Jackfork Mountain, Pittsburg and Pushmataha Counties, Oklahoma.

The Jackfork deposition was influenced by several factors. The above stated one is, of course, turbidite deposition within a subduction trench/basin. However, another key factor is the worldwide low stand of sea level (possibly one of the lowest in the past 545 million years). The graph on the following page illustrates the relative stand of sea level. The lower stand of sea level would make the water depth less in the trough and basin. This in turn would increase the potential affect of tsunamis, increase the channeling of the slope, allow more sediments to be directed into submarine canyons that were at that time partially exposed or in shallower water, provide a larger shelf area for sediment accumulation and sourcing for turbidity currents, and in general throw an imbalance upon the depositional system. Additionally, some studies suggest that the primary source of Jackfork sediments were from the north and east of the trough/basin. It is easy to agree with these studies since the more southern depositional areas would have been thrust over the remaining exposed Jackfork Group and have been lost to erosion. (More on this subject later.) There is also thought that the thrust faulting brought about by the craton-arc collision commenced in Jackfork times. These early thrusts were probably confined to the northern edges of the subduction trough.

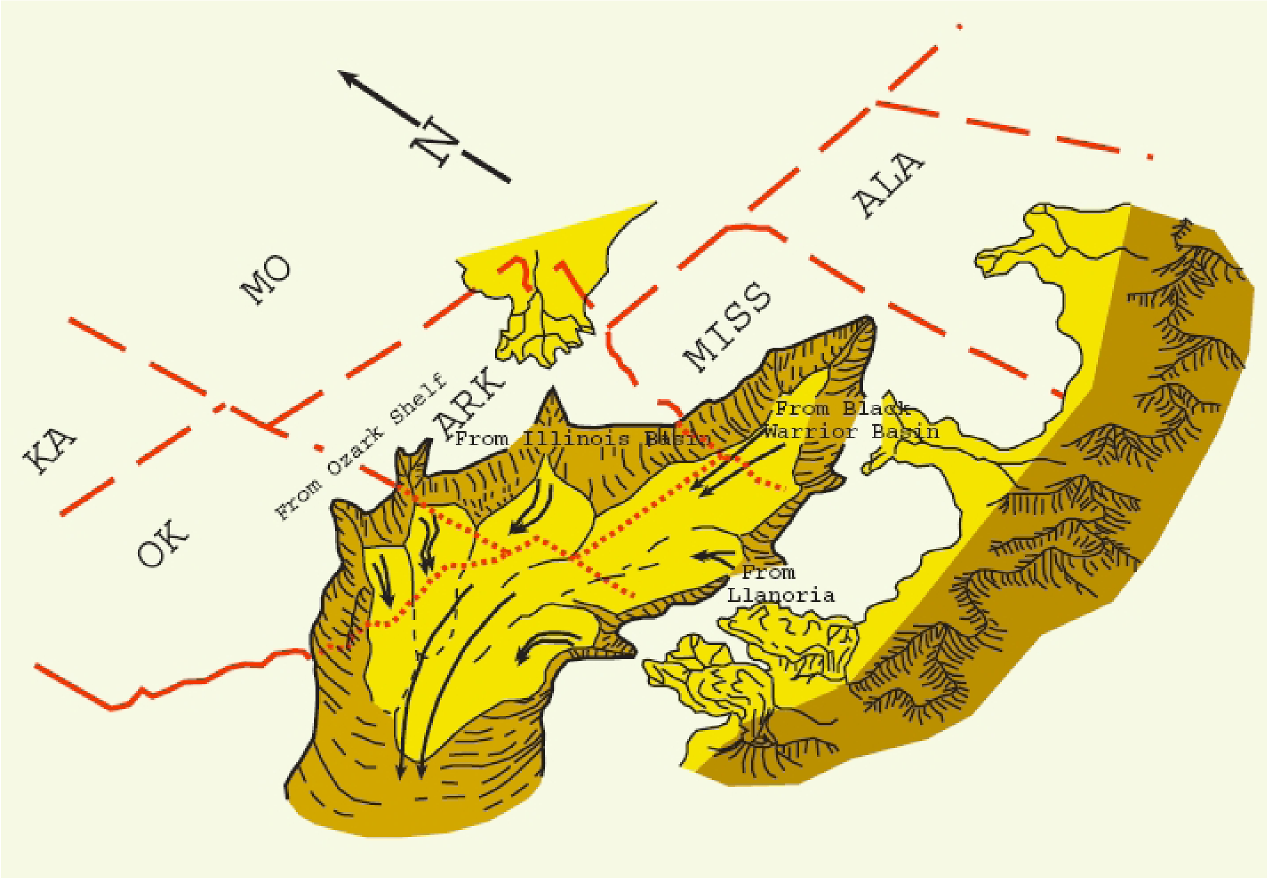


Figure 24: Ouachita Basin during deposition of the Jackfork Group. Source areas of sediments are from the northeast (Illinois Basin), north (Ozark Shelf), and south (Llanoria and Black Warrior Basin). General sediment-transport direction within the basin was from east to west, along the axis of the basin (from Slatt et al., 2000).

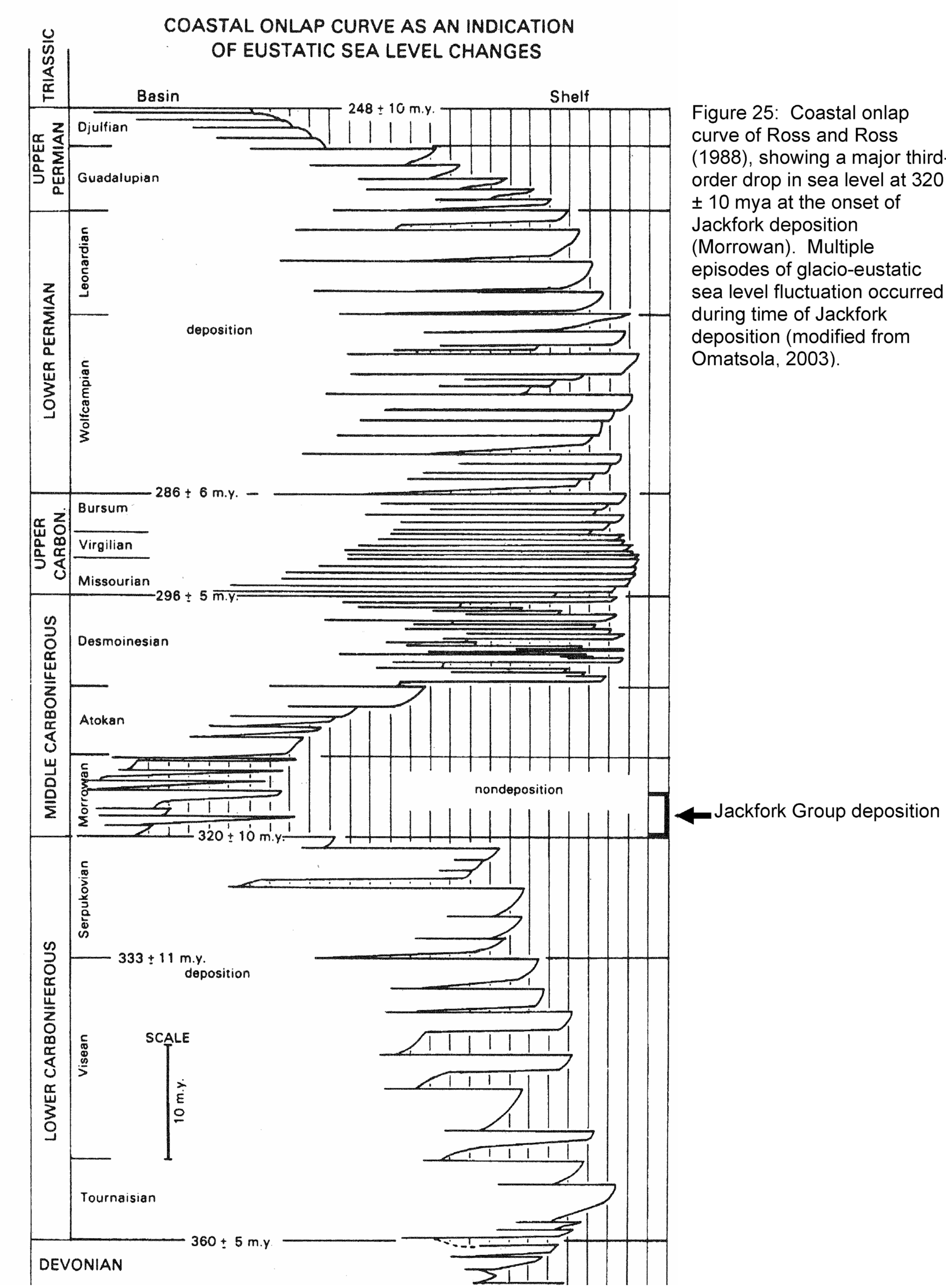
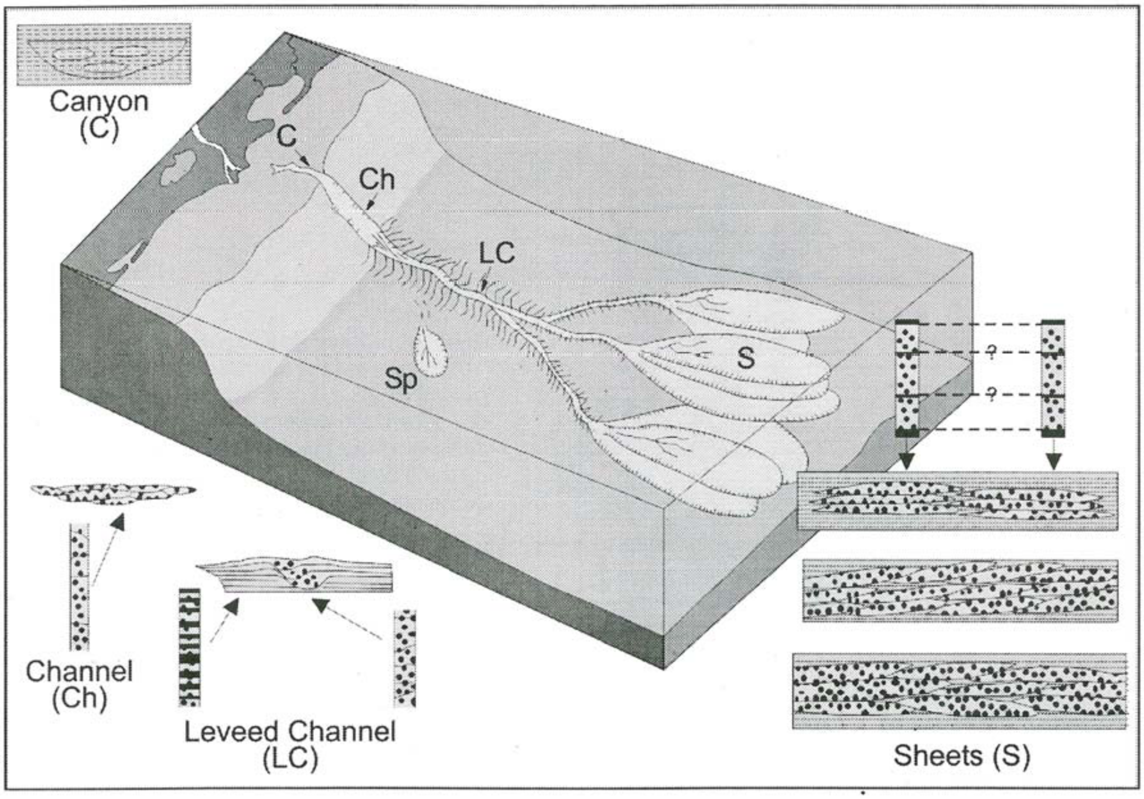
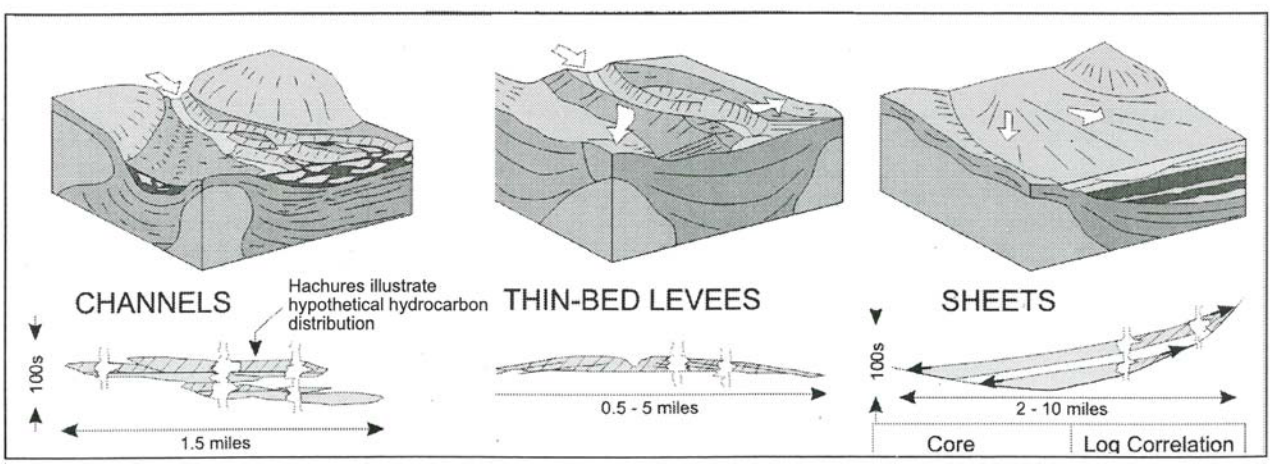


Figure 25: Coastal onlap curve of Ross and Ross (1988), showing a major third-order drop in sea level at 320 ± 10 mya at the onset of Jackfork deposition (Morrowan). Multiple episodes of glacio-eustatic sea level fluctuation occurred during time of Jackfork deposition (modified from Omatsola, 2003).

The Jackfork Group turbidites are comprised of sheet sands, channel sands, rarely levee beds, and intervening shales. These turbidites may or may not exhibit Bouma sequences. Sheet sandstones are interpreted as having been deposited in a basinal or base-of-slope setting. Channel sandstones are interpreted to have been deposited in a somewhat more proximal setting on the slope/near slope of the Ouachita trench and basin. Depending upon the "size" of the turbidity current, the resulting turbidite deposition may or may not cover the previous turbidity flow. Several factors could come into play here. Within the subduction trench/basin at low sea level stand, the weathering process would deposit large amounts of weathered material on the former (partially exposed) oceanic shelf. If this material did come to reside in shallow water,





Figures 26 and 27: Generalized diagram of deepwater sedimentary elements (after Chapin et al., 1994). Those elements that are recognized in Jackfork outcrops and in petroleum wells are principally channels and sheet sandstones. Levee deposits are rare in Jackfork strata. Lower block diagram modified from Bouma (2000). (from Suneson, 2005).

currents would work and rework the sediments. It is possible that a turbidity current could occur just from thick sediment accumulation. However, the subduction zone would be a very active seismic area. When a subduction earthquake would occur, the area around the epicenter would be subjected to violent shaking that could trigger debris flows and/or turbidity currents. A large, shallow focus quake could also generate a tsunami that would quickly span the width and length of the closing basin. When a tsunami crashed into a low-stand sea level shoreline, the material held upon the shelf both above and below sea level would be inundated, washed into channels, and fed toward the canyons incised in the slope. These turbidity currents would then flow out into the trough/basin, cover an area proportional to the amount of sediment carried in the flow, and possibly interact and/or drape over adjacent flows. This would concurrently happen not only in several to many canyons but also on both sides of the trough/basin. Thus, one earthquake's tsunami might cause small to large turbidite flows to cascade down many canyons across the length and breadth of the trough/basin. As the turbidite flows acted and interacted within the trough, it is easy to conclude that normal Bouma Sequences might not be formed.

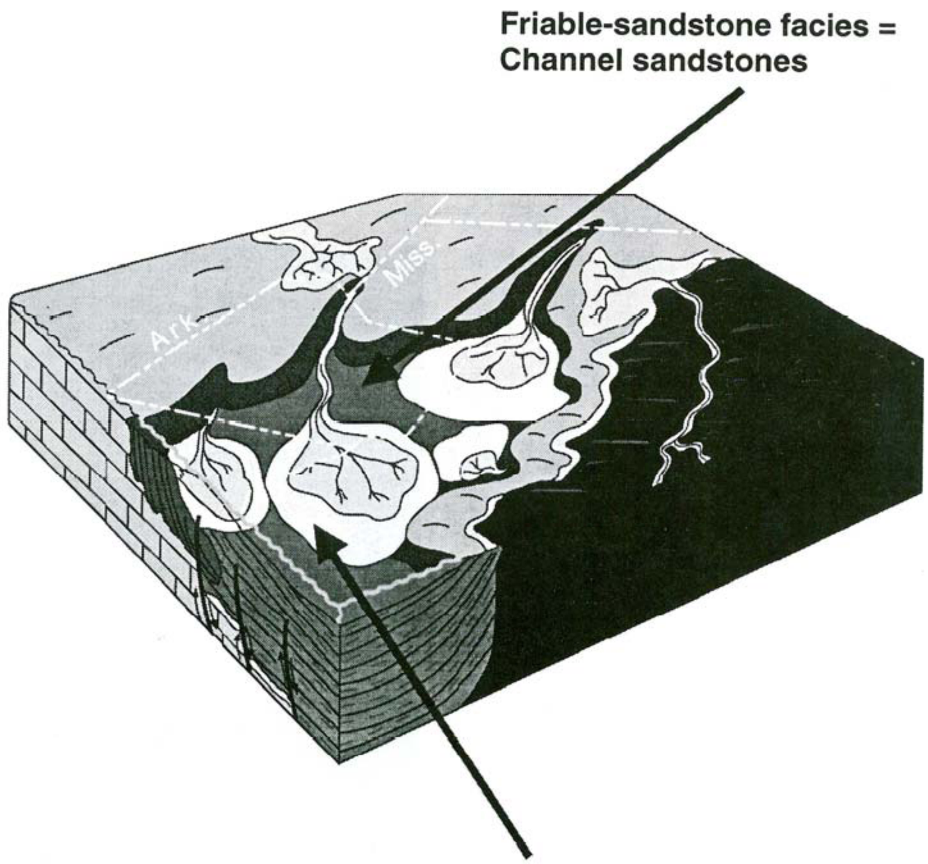


Figure 28: Depositional interpretation of friable sandstones and cemented sandstones. Based upon the sedimentary characteristics of the friable sandstones, such as lenticularity- and erosionally-based beds, they are interpreted as channel sandstones. Based on the sedimentary characteristics of the cemented sandstones, such as sharp bases and tops, and interbedding with shales, they are interpreted as sheet sandstones. (from Suneson, 2005).

The early Morrowan-time slope on the northern side of the Ouachita trough/basin would have been long and broken by many down-to-the-basin fault scarps. It has been suggested that disturbed beds within the Jackfork represent slumps and debris flows from the northern basin slope that contain platform (craton) sequence clasts from the fault scarps. There seems to be more evidence of Jackfork channel-levee complexes in the Arkansas Ouachitas, while the Oklahoma Ouachitas have more of the down-fan facies of sheet sandstones and thin-bed facies. It has been proposed that the Jackfork is a mixture of Type II and Type III Mutti (1985) fans (Coleman et al, 1994). Both types were deposited in the east-west basin/trough with a paleocurrent direction being primarily east to west. This scenario seems to agree with what is observed in the outcrops.

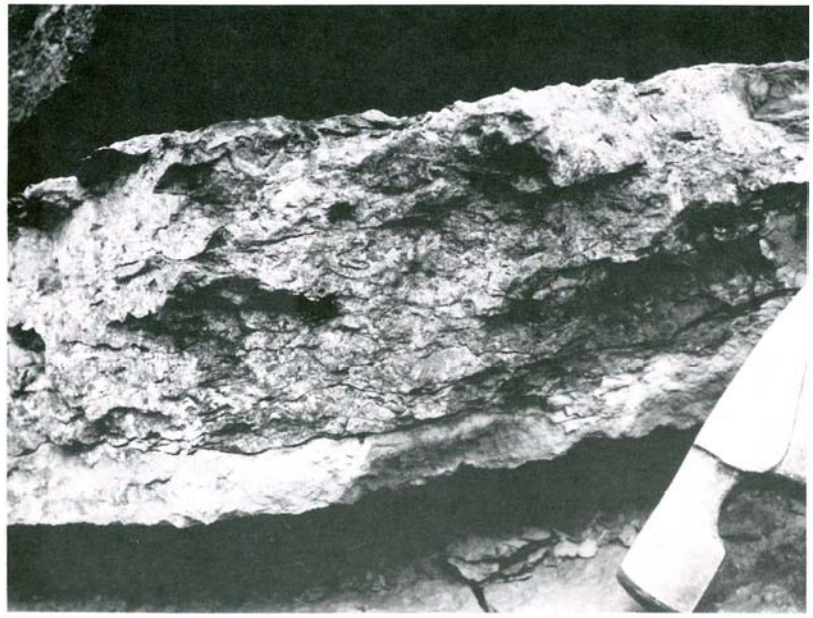


Figure 29: Slurried "turbidite" (blue-bed) containing abundant plant and wood fragments. Plant fragments are jumbled and have no preferred orientation. Located in the Wildhorse Mountain Formation of the Jackfork Group southwest of Three Sticks Monument along U.S. 259. (from Tillman, 1994).

Mutti (1985) Submarine Fans	
Type I:	Large sandy flows move away from the channel-forming lobes far away from the feeder channel.
Type II:	Single leveed valley on upper fan. Mid-fan build-up of suprafan depositional lobes at the ends of channels with these lobes switching positions periodically. Topographically smooth lower fan without channels.
Type III:	Muddy channel levees form when sea level rises.

The Jackfork sandstone is a renowned "hammer ringer". The reason for this reputation is because much of the sandstone of the Jackfork is quartz-cemented. However, there are parts of the Jackfork sandstone that are quite friable and are excellent reservoir rock. Additionally, there are the siltstone and shale sequences of the Jackfork that represent more "quiet" time periods when silt and clay settled out of suspension. The type location to study the differences in the Jackfork Group is a roadcut along U.S. 259 south of Big Cedar, Oklahoma. This portion of the Jackfork is the Wildhorse Mountain Formation. It is comprised of a lower section of interbedded, highly cemented sheet sandstones and interbedded shales. The upper section consists of more massive (i.e., no shale interbeds), friable channel sandstones. As previously mentioned, the sheet sandstones have been interpreted as being deposited in a basinal or base-of-slope setting. The channel sandstones are interpreted as being deposited in a more proximal setting on the slope of the basin. Due to the drastic sea level changes of the Jackfork time, it is quite easy to understand how both these depositional settings could occur at the same locale.

Lithologically, the sheet sandstones are very-fine- to fine-grained, moderately to well sorted, and planar-tabular bedded with characteristic sedimentary structures (tops and bases of beds are sharp and generally non-erosive). The channel sandstones are friable, fine- to medium-grained, poorly to moderately sorted, and commonly have undulating bed boundaries. Petrographic analysis shows different diagenetic features in these two sandstones. The sheet sandstones are quartz-cemented grains with quartz overgrowths and pressure solution characteristics. The channel sandstones have little to no quartz-cementation and feldspar dissolution and clay are quite common. Thus during burial and diagenesis, the sheet sands were firmly quartz cemented. But the detrital clay and clay-coated quartz grains of the channel sands prevented silica nucleation and cementation. The channel sandstones also exhibit some siderite (iron mineral) cementation in the subsurface. This siderite is oxidized in outcrops and is seen as an iron stain. The oxidation of the siderite cement would also make the outcrop of channel sandstone more friable.

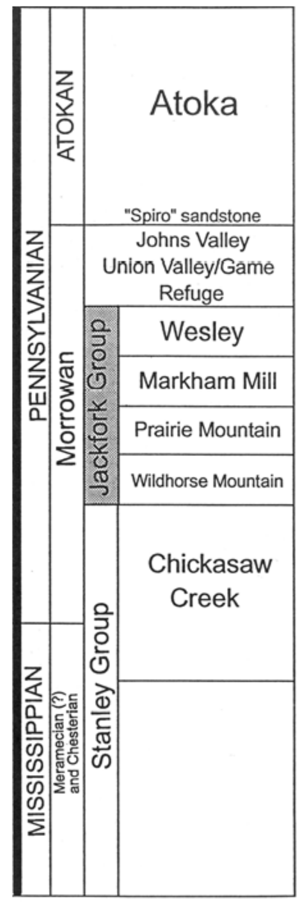


Figure 30: Jackfork stratigraphic sequence, Lynn Mountain Syncline (from T. E. Legg et al., 1990)

The sandstones of the Jackfork Group produce gas in the Potato Hills, Buffalo Mountain, and Talihina Northwest Fields. The gas production comes from both the fractured quartz-cemented sheet sands and the friable, sometimes siderite-cemented channel sands. Due to the structural complexity (highly folded and faulted) and the lateral variability of the Jackfork, well-to-well correlations within and between these fields can be quite difficult. Depositional environment interpretation from the logs is difficult as well. Geologists have used several criteria, especially gamma ray and dipmeter logs, to differentiate sheet and channel sands. The similarities between outcrop and reported subsurface observations allow Jackfork surface exposures to be used as analogues for potential subsurface reservoirs. Well log correlations are best approached using sequence stratigraphy by first identifying the faults and then using dipmeter and gamma-ray logs to develop a framework of the depositional system. In this way, a model of the subsurface may be developed and predictions of anticipated porosity areas made. Oklahoma Geological Survey Guidebook 34 figures 57 through 60 have been included on the following pages as figures 32 through 35, respectively, to illustrate these interpretations.

Just as it is difficult to measure the total thickness of the Collier shale because its lower contact with the pre-Cambrian has not been found, it is just as difficult to definitely confirm the original total thickness of the Jackfork, Johns Valley, and Atoka Formations. If the Ouachita basin/ subduction trough was narrowing during Jackfork times and if thrusting was starting to displace the northern edge of the trough, it is quite possible that the Jackfork Group we see today only represents a small percentage of the deposits channeled between the northern edge of the basin and the thrusted northern edge of the trough. Though there must have been deposition within the trough during Jackfork times, it has either not been identified or it has been lost to erosion. Due to the thrusting and uplift of the Ouachitas, what we see today of these three formations is only a minor part of their deposition. There has not been a full, intact section of these three formations found to accurately measure, as the basin was narrowing from east to west the type rock as well as the formation thickness for these formations would vary similarly.

The Johns Valley shale is generally a gray-black clay shale with numerous intervals of silty, thin to massive, brownish-gray sandstone. Small amounts of gray-black siliceous shale and chert have also been noted. In the frontal (northern and western) Ouachita Mountains, the unit contains large quantities of erratic rocks (limestones, dolostones, cherts, etc.) formed by submarine slumping of older stratigraphic units from the north. The Johns Valley shale is conformable with the underlying Jackfork sandstone. Due to the high degree of structural deformation, the total thickness of the unit is difficult to estimate, but it likely exceeds 1,500 feet in thickness. The type area for the Johns Valley Group is near Tuskahoma, Pushmataha County, Oklahoma.

The Johns Valley is a mixture of debris flow, slumps, turbidites, and possibly some quiet-water sedimentation. By the Johns Valley time (late Morrowan of the Pennsylvanian), the Ouachita basin had become very narrow and the Ouachita subduction trough very near the North American craton. The subduction movement was probably quite strong (possibly assisted by the approaching subduction associated with Gondwana) and downwarped the basin while applying great stress to the rocks of the basin, causing normal down-to-the-basin faults to form. The deep normal faults of the Johns Valley fault system are clearly defined on deep sounding seismic sections in Arkansas and projected to extend into Oklahoma (Blythe et al., 1988). The remnants of the Johns Valley fault system are seen beneath the Ouachita thrusts south of the Ross Creek thrust fault (Arkansas), and, if the system does extend into Oklahoma, it would be located south

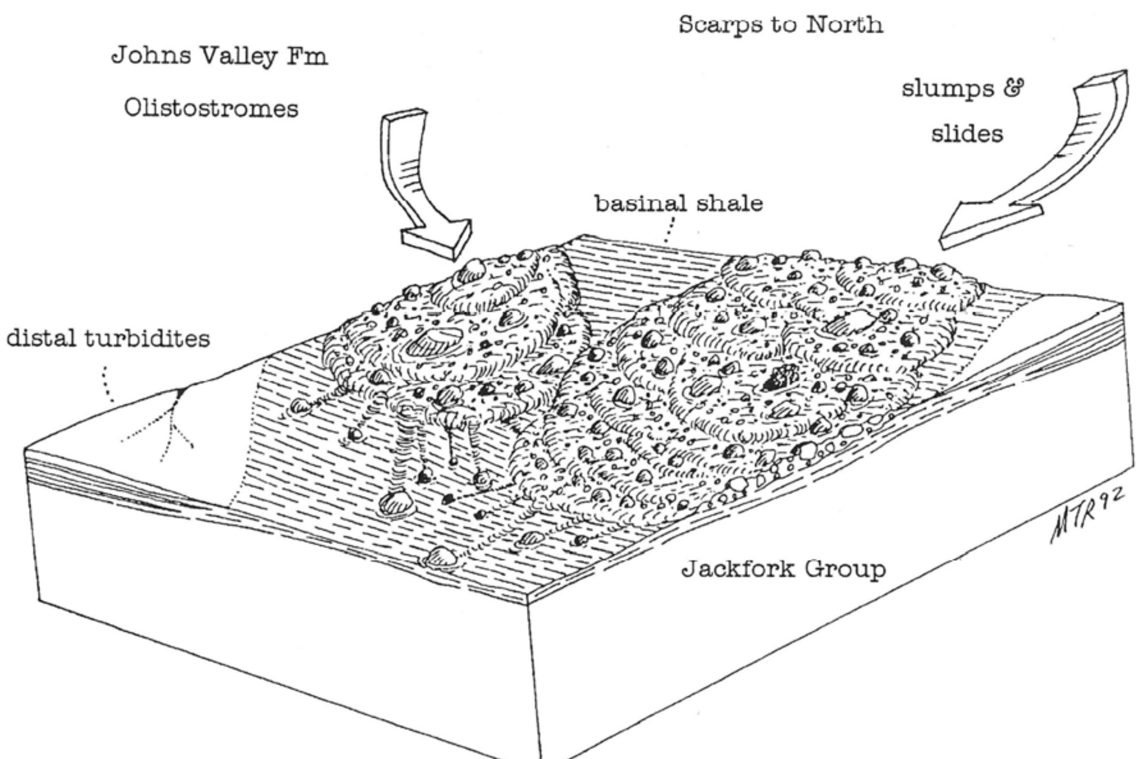


Figure 31: Depositional model, Johns Valley Formation. Fine-grained basinal facies with slumps, slides, and flows of unsorted boulder-rich masses derived from fault scarps that exposed northern platform-facies strata. (from Suneson, 2005).

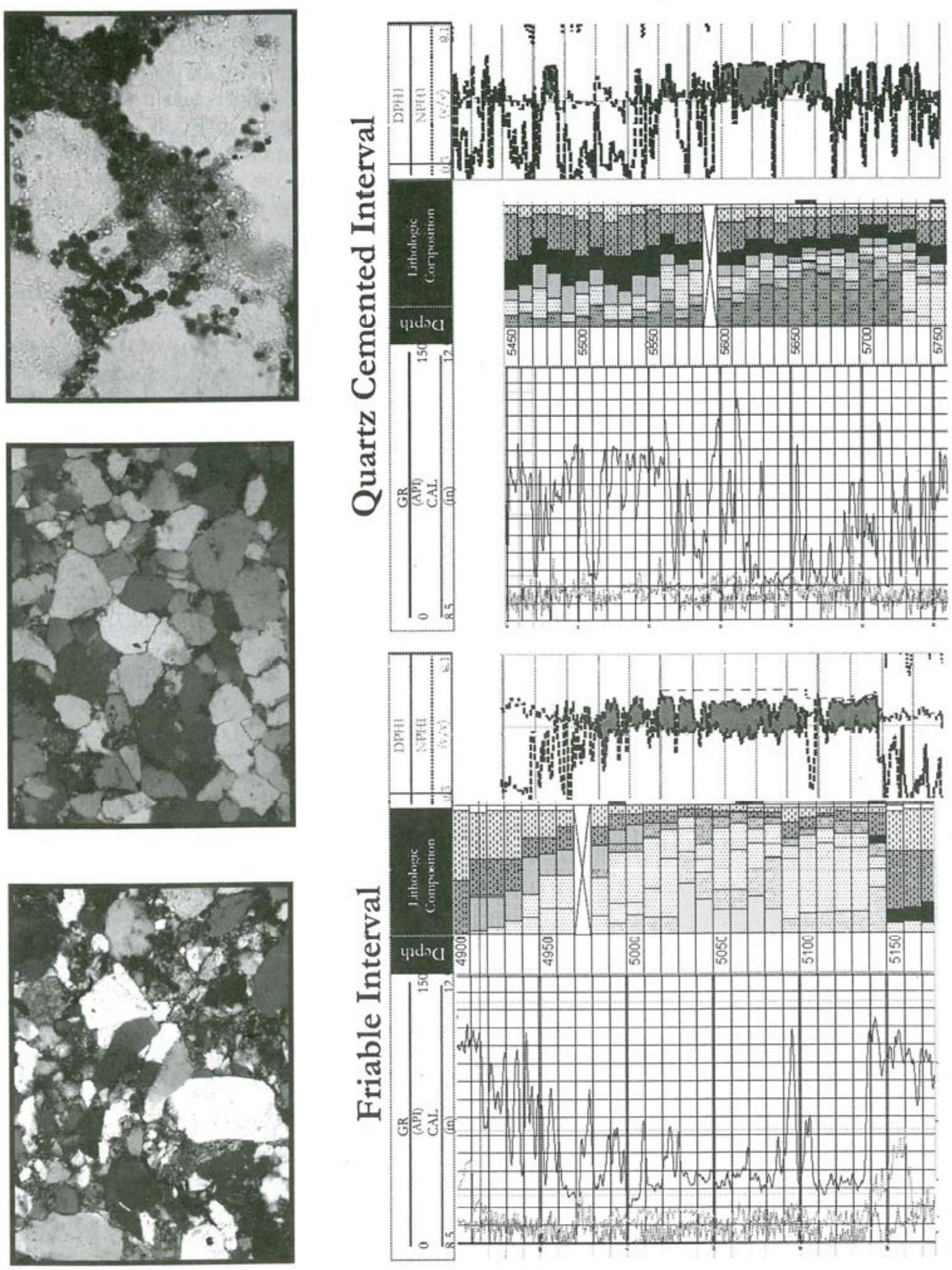


Figure 57. Thin-section photomicrographs of friable (left), quartz-cemented (center), and siderite-cemented (right) sandstone cuttings. Bottom: relationship of cuttings analysis, gamma-ray log, and density logs of Jackfork Group sandstones in the GHK No. 1-12 Edmonds well (Potato Hills field). The cuttings analysis indicates which sandstones are mostly friable and which are mostly cemented with quartz. The gamma-ray log of the friable-sandstone interval shows very few shale interbeds. By contrast, the quartz-cemented interval contains more shale interbeds. These features are diagnostic of channel- and sheet-sandstone facies, respectively. Modified from Romero (2004).

Figure 32: (from Suneson, 2005.)

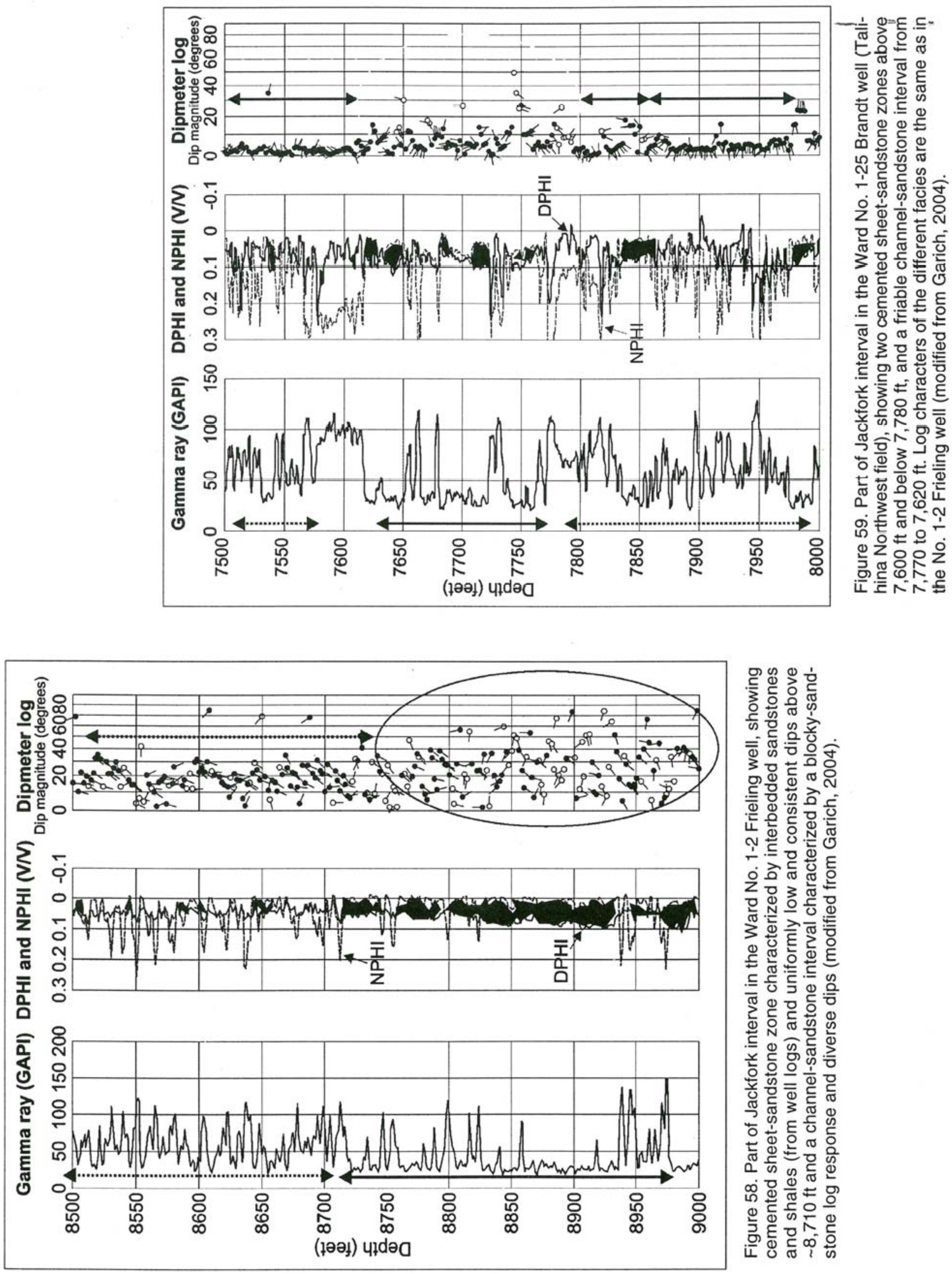


Figure 33: (from Suneson, 2005.)

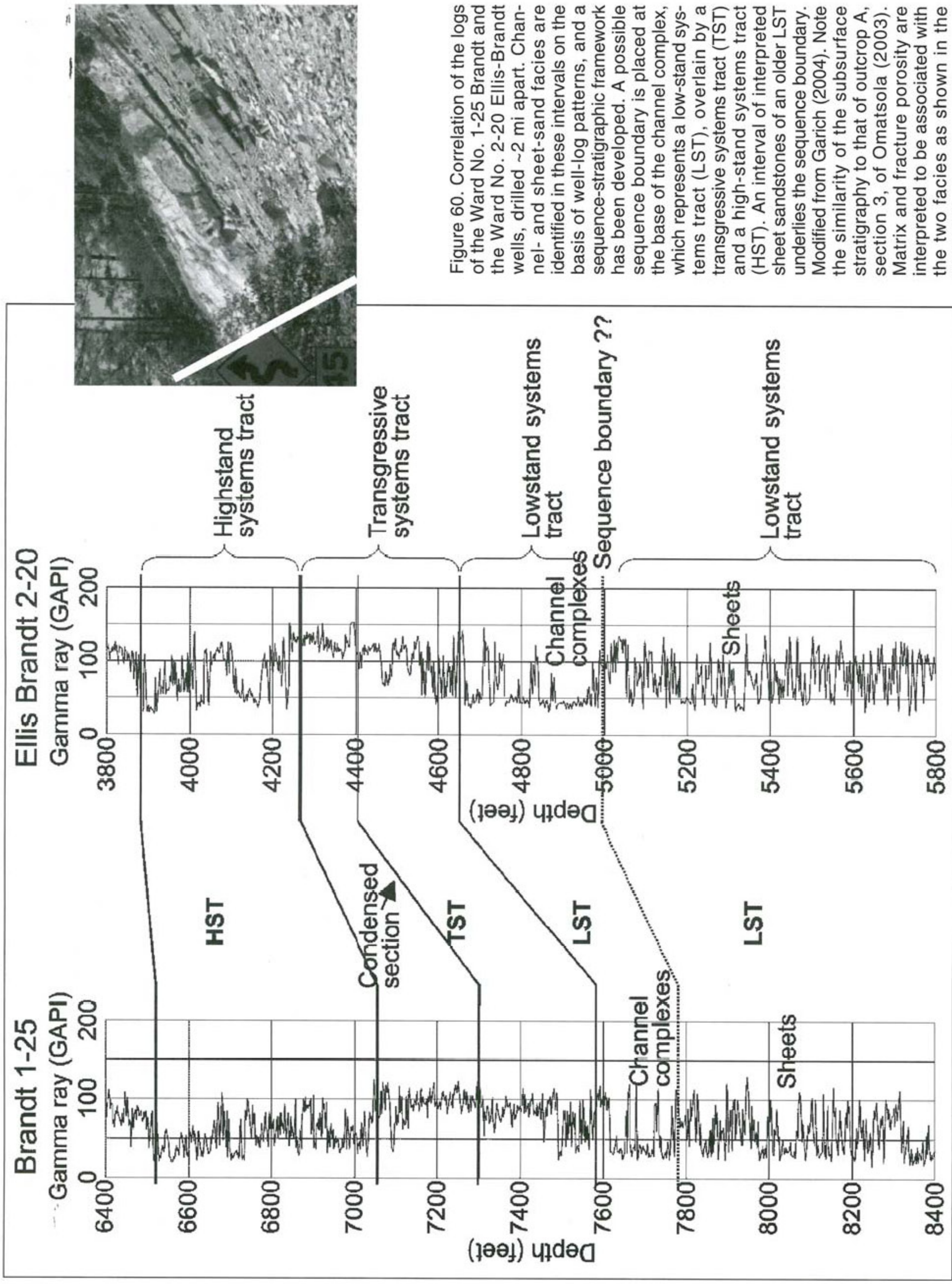


Figure 34: (from Suneson, 2005.)

of the Ti Valley thrust fault. This fault system would have exposed shelf-based Cambrian to Mississippian rocks during Morrowan times and is evidenced by the shelf-derived exotic blocks in olistostromal deposits of the Jackfork but especially the Johns Valley. Earthquakes and tsunamis were probably quite common though the sea level continued to fluctuate from higher stand to low stand. (Some geologists regard the Ouachita basin/trough as a "starved basin", but the characteristics are just as likely to be an overall low-stand sea level.) Because of wave base properties and the narrowing basin/trough seismic activity, the Johns Valley time would have probably experienced many tsunamis that caused massive slumps and debris flows. The southern volcanic arc was probably still towering above sea level and its formations were being eroded quickly, thus supplying sand and clay to the Johns Valley depositional area in addition to the sediment flowing into the basin from the north and east. The result would be a massive formation of shale matrix mixed with boulders, cobbles, gravel, and so on, turbidites, chert beds, etc.

At the end of the depositional period for the Johns Valley Formation, could the volcanic arc have been very close or even adjacent to the craton with subduction of the lower crust still active? Only a shallow sea within the basin might have remained and that would have been influenced by changing sea levels. It is quite possible, as some (Blythe et al., 1988) have suggested, that the Johns Valley Group may have exceeded 3,200 meters in thickness. This must indicate strong subduction of the basin to accommodate the pre-Pennsylvanian formations plus the thicker Jackfork and Johns Valley. Thrust faulting most certainly occurred during Jackfork and Johns Valley times, but the most active thrust sequences and basin shortening would occur during the next epoch, the Atokan.

Note: It is interesting to notice that though all the literature acknowledges the point that the combined Ouachita thrusts moved what we see today some 70+ miles north and linearly compressed the formations some 50+ percent, most all drawings depict deposition in today's locales. Refer to the Jackfork diagrams (from different sources) shown earlier. You will notice that one would think the north edge of the Jackfork would be static in its location over the past 320 million years. This is probably not the case. As the Sohio #1-22 Weyerhauser (located six miles northwest of Broken Bow, OK) shows, at around 12,000 feet in depth, the Choctaw (?) fault is crossed and Oklahoma shelf Arbuckle sequence rocks encountered. Therefore, the rocks we identify with the Ouachitas must have been thrust up over the shelf. The former basin and subduction zone would have been located much further south than most diagrams illustrate.

It has been theorized that the Ouachita orogeny did not elevate the Ouachita formations to great heights, such as we see in the Himalayas today. The geological evidence seems to support this theory. As stated before, probably the subduction process (or combined subduction process, noted below) stayed very strong and active during the continent-arc collision process. (A present-day example would be the active subduction beneath the Himalayas that still move the Himalayas and India an average of two centimeters north per year.) These combined forces would downwarp the area such that the elevation of the formations remained very near average sea level for that time and through much of the later Pennsylvanian. In fact, the downwarp process may have been responsible for this thrusting as material volume was compressed into a lesser volume. The approaching subduction zones that brought the volcanic arc, Gondwana, and Meguma (northeastern plate of today's eastern North America) together may have contributed to this downwarp. As sea level was relatively low and fluctuating (see Figure 25), the downwarped, thrusted formations and sediments would be subsea or exposed at any point in time. But even with a strong subduction, the upper part of the continental crust would not be subducted because of density differences. Basically, the upper part of the crust floats on the lower crust and mantle.

So, as the subduction process stayed strong, the lower crust subducted, the upper crust/formations sank downward and thrusted northward, and the whole process caused an extremely active seismic area. There is also evidence that the subduction forces did not abate until the beginning of the Permian. Thus the faulting and folding of the Arkoma Basin, especially the southern Arkoma formations, was probably caused by the subduction zone(s) and the collision of the continent and volcanic arc backed by the collision of Gondwana.

At the beginning of the deposition of the Atoka Formation, the Ouachita formations were near sea level backed by the volcanic arc (and Gondwana) to the south. To the north, between the Ouachitas and the Ozark Uplift, the Arkoma Basin would have formed in response to the subduction and its location between higher areas to the north, east, and south. The Arkoma Basin was a low, open area receiving drainage from the Ozarks, Ohio, and western Appalachians, and also from the low-lying Ouachitas and the remaining volcanic arc. From these areas, especially the southern part, the Atoka Formation was sourced and deposited.

The Atoka Formation is a sequence of marine, mostly tan to gray, silty sandstones and grayish-black shales, with some localized deltaic sequences. Some rare calcareous beds and siliceous shales are known. In the frontal Ouachita Mountains, the Atoka Formation has been

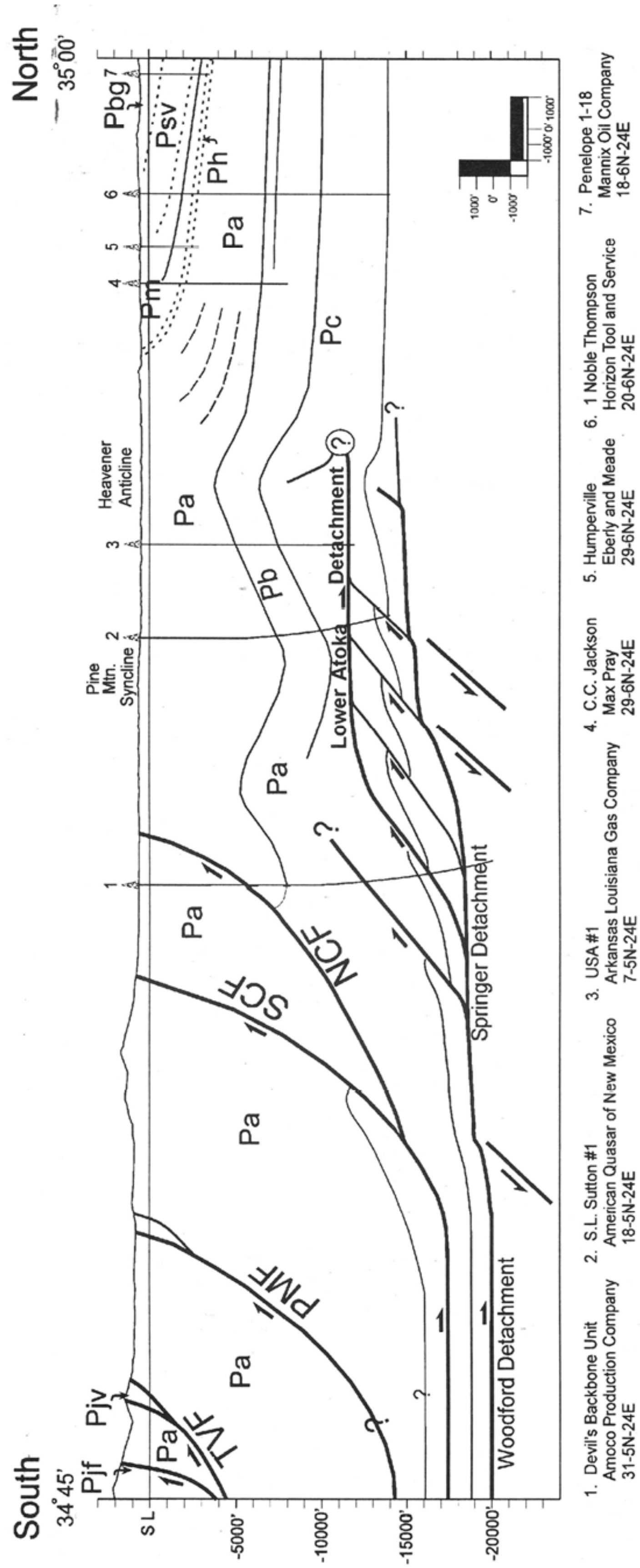


Figure 36: Balanced structural cross-section just west of Oklahoma-Arkansas border, showing subsurface geology. Faults: TVF = Ti Valley Fault; PMF = Pine Mountain Fault; SCF = Southern Choctaw Fault; NCF = Northern Choctaw Fault. Rock units: PJF = Jackfork Group; PJv = Johns Valley Formation; Pa = Atoka Formation; Pc = Cecil sandstone; Pb = Brazil sandstone; Ph = Hartshorne formation; Pm = McAlister Formation; Psv = Savanna Formation; Pbg = Boggy Formation. (from Suneson, 2005).

subdivided into upper, middle, and lower lithic members based upon regionally mappable shale or sandstone intervals. The formation has localized discontinuous streaks of coal and coaly shale. Fossil plants, generally poorly preserved, are common. Poorly preserved invertebrate fossils are much less common but have been reported from several horizons. The formation seems to be conformable with the Johns Valley shale and may be more than 25,000 feet (7,620+ meters) in thickness, although only large incomplete sections are known. The type area for this formation is Atoka, Atoka County, Oklahoma.

Due to large, and possibly rapid, changes in sea level combined with (probably) unstable "ground" elevation (it is assumed that the subduction process was acting against isostatic rebound and causing some rise/fall of the Ouachita formations), the Atoka Formation ranges from deep water turbidites and sands to near-shore bay/lagoon shales and mudstones. As the Atoka Formation was being deposited, the basin was still being compressed and shortened due to the subduction process. Combined with this shortening, the basin (and Arkoma Basin) was being pulled downward by the continued subduction process. (For example, as previously stated, the subduction zone still pulls India northward at one to two centimeters a year, and the Himalayans are still rising five millimeters a year.) The deposition was rapid and fluctuating. Overall, sea

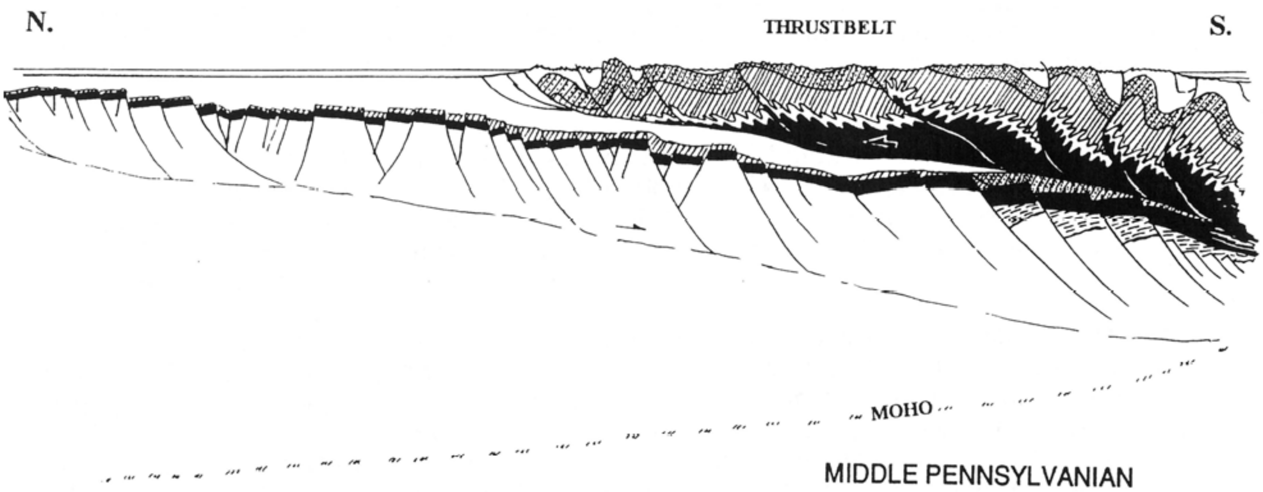


Figure 37: Ouachita Shelf/Slope/Basin. Middle Pennsylvanian.
(from Suneson, 1995)

level was rising, inundating the Arkoma Basin and Ouachita formations. What type of facies represents the Atoka depends upon the location. Over the span of a day, one can visit locations that show the Atoka to be lagoonal/deltaic (south of Heavener – conformable Hartshorne coal/sandstone), turbiditic (Spring Mountain Syncline), deltaic, channels, and arkosic slumps. Thrust faulting seems to be most active within the Atoka Formation probably caused by subduction and later isostatic rebound.

Blythe et al., (1988) proposed that the lower and middle Atoka age facies represent proximal turbidites deposited by westward-prograding submarine (or shallow-water) fans. The deposition of these turbidites and debris flows extended from the volcanic arc across the site of the present-day frontal thrust zone and into the Arkoma Basin. Keeping in mind that subduction forces were still very strong, the normal faults that offset the basement and lower Atoka Formation were the result of lithospheric flexure caused by the northward migration of the Ouachita subduction trench (Stockmal et al., 1986).

It actually is important to the Arkoma Basin that the Ouachitas in Atokan and following Pennsylvanian times were under such strong forces of subduction and kept from rising much beyond sea level. The thick accumulations of the Atoka Formation of the Ouachitas extended as thinner accumulations across the Arkoma Basin, Oklahoma, and Texas. The Ouachitas and the volcanic arc formed a higher-than-sea level barrier to the south that allowed the Arkoma to become a large, shallow-marine/deltaic basin. Within this basin, braided channels, swamps, deltas, sand bodies, etc., were deposited along with accumulations of mud- and sand-encased vegetation that would later become coal. At the end of the Pennsylvanian and the beginning of the Permian, the subduction forces would end with the joining of Laurussia, the volcanic arc, Gondwana, and Meguma. In response to the cessation of downwarping forces, isostatic rebound immediately started and the rocks and sediments of the Ouachitas rose above sea level as mountains and were eroded during the Permian. The forces of this rebound would also cause thrust faults and folding within not only the Atoka Formation but also the other Ouachita formations. Due to the complexity of the faulting, folding, and stratigraphy of the Ouachitas, it is difficult to ascertain with certainty which faults were pre-rebound and which were rebound, though there seems to be good evidence that the North Potato Hills Thrust occurred earlier than other thrusting. Additionally, if there were other formations deposited above the Atoka in the Ouachita basin, they have been lost to thrusting and erosion.

The unknown volume of the Ouachita basin rocks and sediments is quite important. These formations would rebound during the Permian and would be eroded to form a thick sediment shield over the Arkoma and the rest of Oklahoma north of the Arbuckle Mountains. These sediments were rich in iron and thickly deposited. Over the course of some 250 million years or so, even with the erosional forces present during all that time period, these sediments are still present in Oklahoma and form the red soil that distinguishes Oklahoma. These sediments would also bury, protect, and allow the Arkoma Basin formations to mature, undergo diagenesis, and also form coals.

The Pennsylvanian Era was also responsible for much of the hydrothermal waters that left quartz veins in many of the Paleozoic rocks. These hydrothermal waters were secondary to the subduction and plate collision process. As previously discussed, by Permian times, these subduction forces ceased and so did the formation of quartz veins. Thus, even if found in the Crystal Mountain sandstone, the “Arkansas Point” quartz crystals are Pennsylvanian, possibly early Permian, in age.

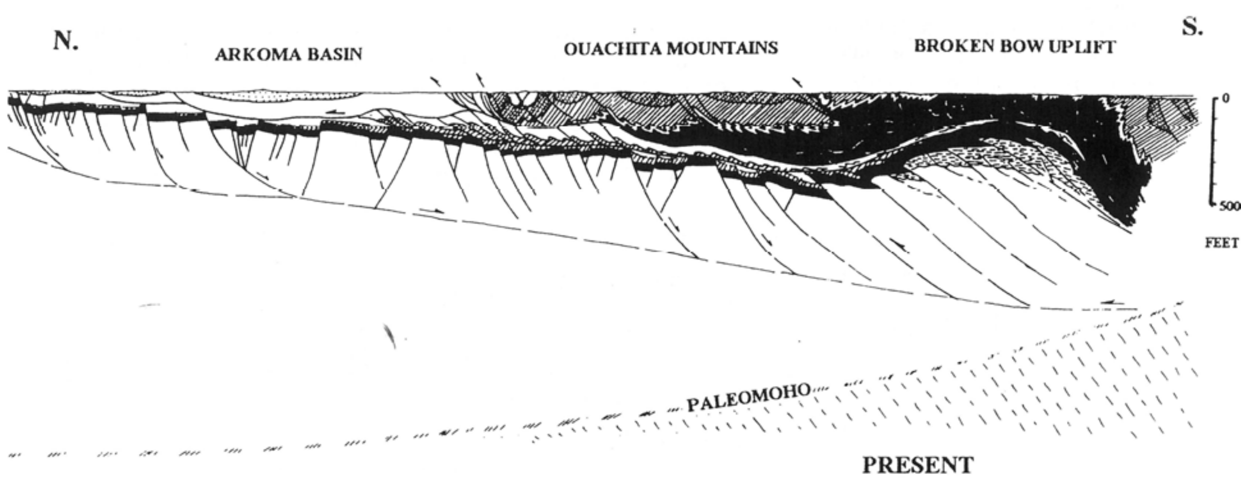


Figure 38: Ouachita Shelf/Slope/Basin. Present time.
(from Suneson, 1995)

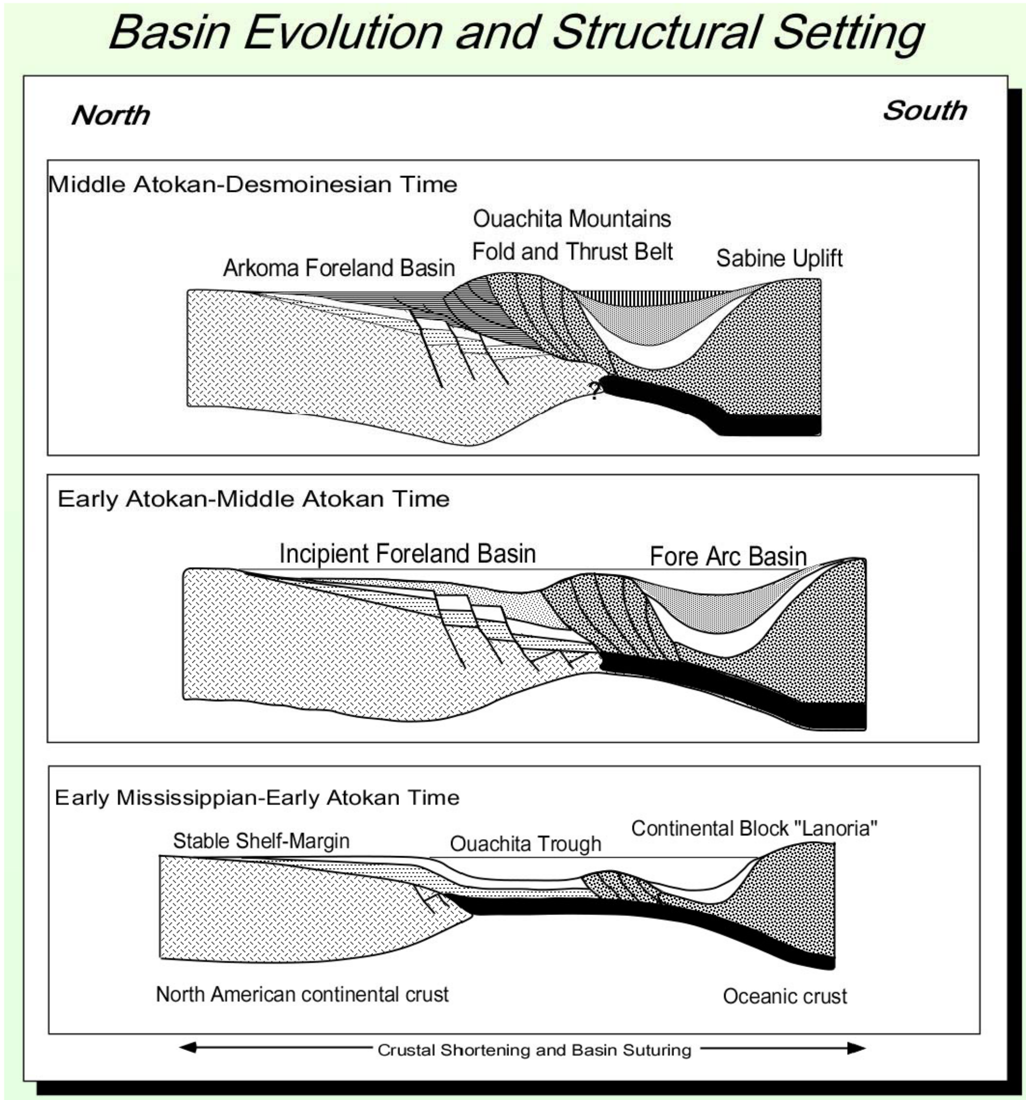


Figure 39: (from Horn, 2006)

The Arkoma Basin and the Ouachita Frontal Area:

In the western region of the Ouachita shelf, Arkoma Basin, and Oklahoma shallow seas, the Wapanucka-Spiro interval was deposited at the same time as the Johns Valley and early Atoka Formations. During Morrowan (early Pennsylvanian) times, the Wapanucka limestone was deposited within this area under fluctuating sea level conditions and an encroaching subduction trough. Suneson (2005) describes earlier work performed by Grayson that suggests the Wapanucka was deposited under low-energy lagoonal conditions. Micritic lime mud was deposited under conditions of poor circulation and low sea level stand. Spiculiferous limestones were deposited under higher sea levels and better oceanic circulation. Horn (2006) adds to this interpretation by suggesting that these limestones were deposited under lagoonal coastal conditions with a carbonate and siliciclastic shoreline divided by tidal channels fed by coastal/onshore drainage. This condition might be correlated to the modern-day deposition at Trucial Coast in the Persian Gulf or the Gulf of Gabes on the eastern coast of Tunisia in the Mediterranean. If the tidal channels were inundated by rising sea levels and fed by quartz-rich clastics, then channel sands would be found interspersed within the Wapanucka limes as evidenced in western LeFlore and eastern Latimer Counties (Horn 2006).

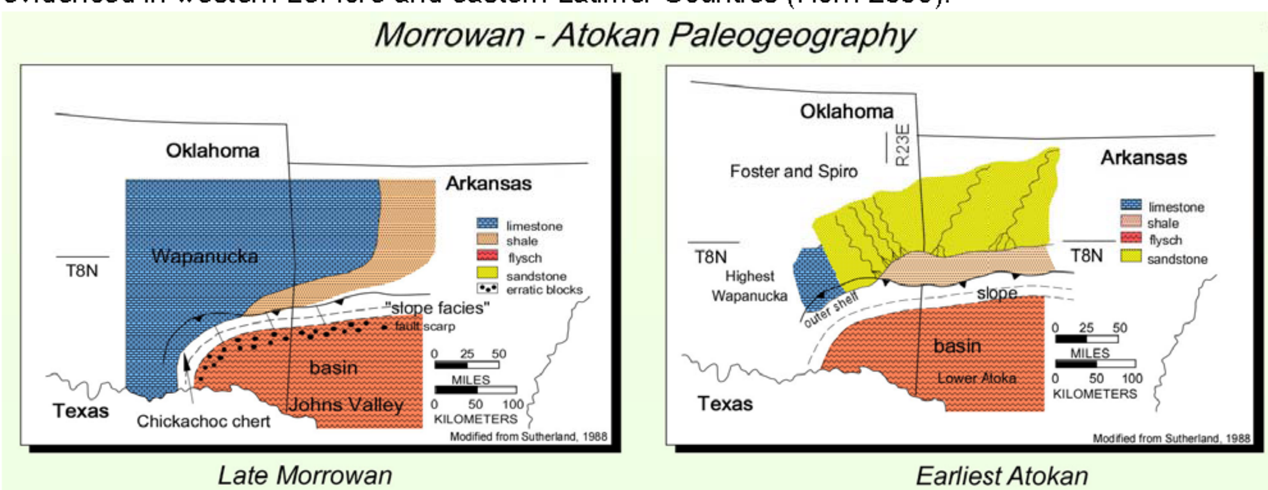


Figure 40: (Horn, 2006)

In eastern Oklahoma, the channel Foster sandstone cuts into the Wapanucka Formation and separates the sub-Spiro transgressive shale and Spiro sandstone from the Wapanucka Formation (Horn, 2006). As one moves west of this area, the sub-Spiro shale (both coastal and marine-deposited) separates the Wapanucka limestone and Spiro sandstone and finally, further west, only the Upper Wapanucka limestone is present (Horn, 2006).

The Spiro sequence indicates a shallow marine environment. Besides Spiro channel sands, the early Spiro times point toward a shallow marine environment with offshore bar deposition and tidal channels. The Spiro Formation covered intervals point toward shales deposited under quiet-water conditions, possibly in slightly deeper water than the basal sandstones (Suneson, 2005). Bioclastic sandstones may be a sign of either storm deposits or tsunami deposits (still an earthquake-prone area). There are also Spiro “lowstand deltas” present in the hanging walls of the Choctaw and Pine Mountain thrust faults (Horn, 2006) that would be across the trough from simultaneous deposition of Atoka Formation. As the craton-trough collision continued, the Atoka Formation deposition (shale?) would onlap and cover the Wapanucka-Spiro Formations. By the end of Spiro deposition, the Arkoma Basin would be fairly constrained between the Ozark Uplift and the low-rise Ouachita trough/volcanic arc. This basin would have been a shallow-water basin and influenced by rising and falling sea levels.

The next formation has a long history of interest within the Arkoma Basin and is the lower member of the Krebs Group: the Hartshorne Formation. The Hartshorne (pronounced HARTS´-horn) Formation is a brown to light-gray, massive, frequently cross-bedded, medium-grained sandstone. It is the first continuous sandstone underlying the lower Hartshorne coal. The formation is a prominent ledge-former under favorable structural conditions. A few fragmental plant fossils have been noted in the formation. The Hartshorne sandstone rests with minor unconformity on the Atoka Formation. The formation's thickness ranges from 10 to 400+ feet.

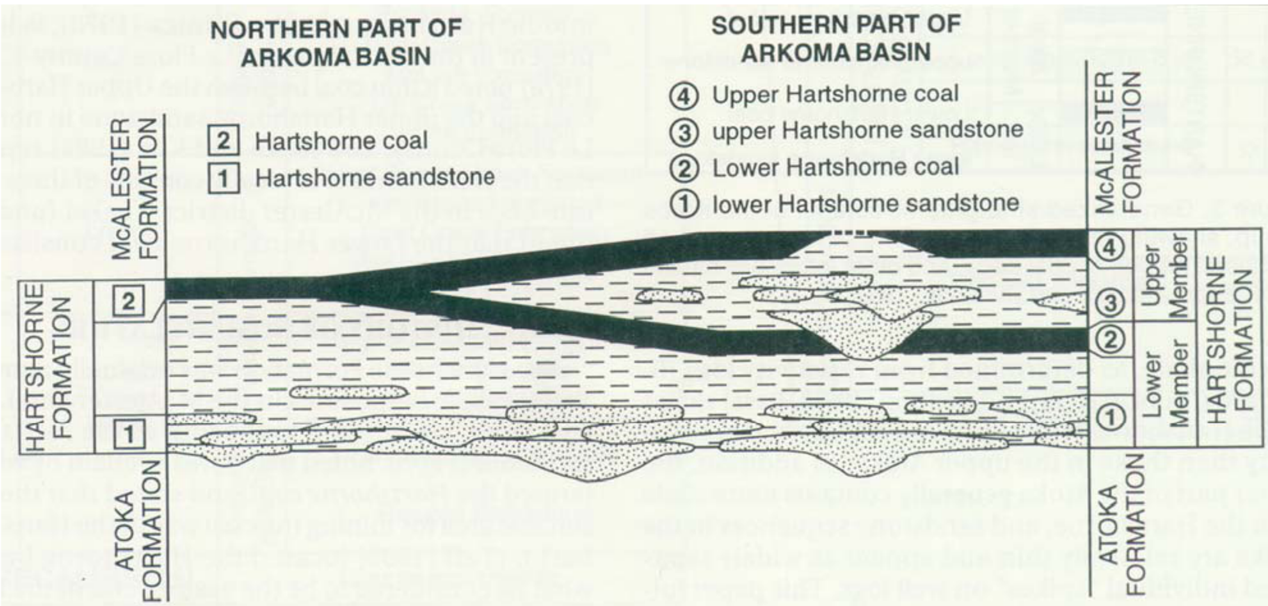
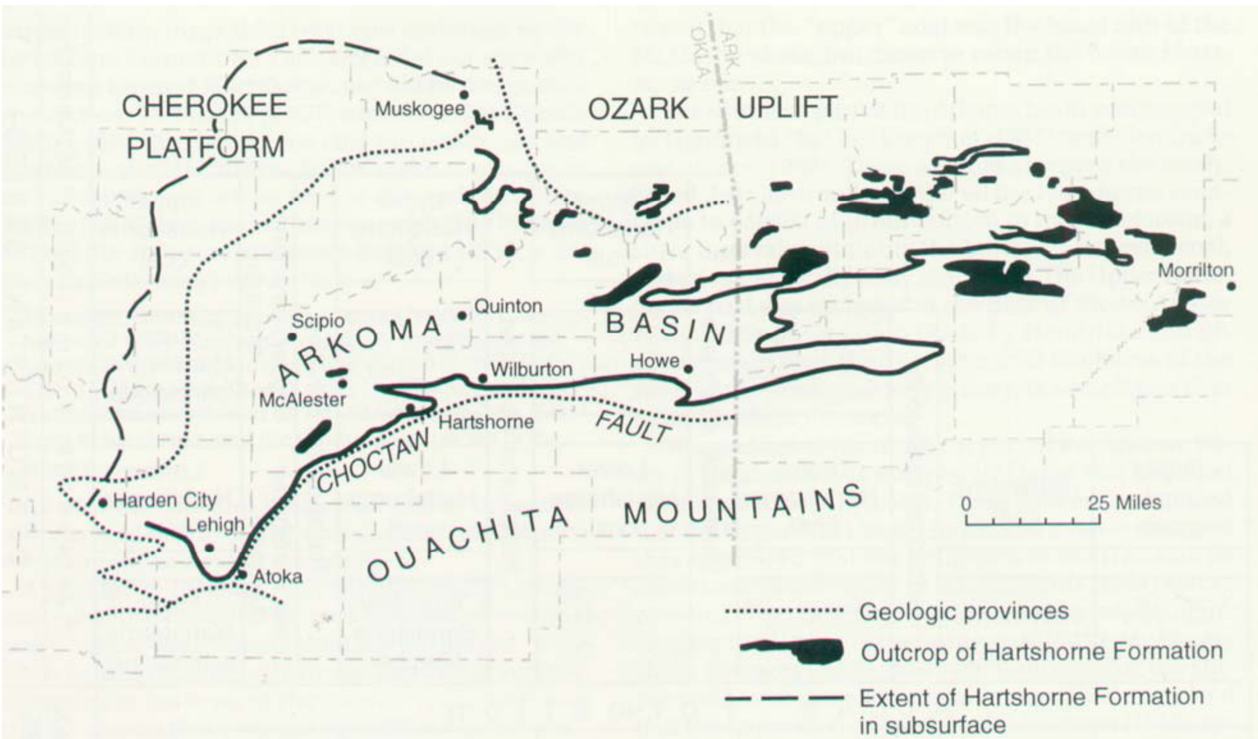


Figure 50: General relationship of different stratigraphic units (formal and informal) that constitute the Hartshorne Formation in the northern and southern parts of the Arkoma Basin in Oklahoma. Note: Locally the upper Hartshorne coal merges with the lower Hartshorne coal, or the upper member of the Hartshorne Formation appears to pinch out. (from Suneson, 2005)

In 1890, Chance named the Hartshorne sandstone the Tobucksy sandstone (Suneson, 2005). Tobucksy appears to have come from the Choctaw word *tobaksi*, meaning coal pit. However, Taft in 1899 suddenly changed the name to Hartshorne Formation for exposures in the McAlester and Lehigh coal fields and mentioned the most suitable area for mining the coal was in the Hartshorne area. In the first interpretation of the Hartshorne, Hendricks and others (1936) described the depositional environment as beneath a shallow ocean (Suneson, 2005). However, by 1950 Scruton noted the mixed continental and marine character to describe the Hartshorne as deltaic (Suneson 2005). Today it is widely accepted that the Hartshorne Formation represents two progradational sequences, both of which consist of delta-front strata in the lower part, overlain by delta-plain strata that may be overlain by flood-plain strata that correlate with thick sandstones that fill channels eroded into the underlying delta-plain and/or delta-front strata (Suneson, 2005). As accepted today, the base of the Hartshorne is characterized by the lowest mappable sandstone that is within a unit dominated by siltstone and shale. These lower Hartshorne strata seem to represent bar-transition or a lower distributary mouth-bar facies.



As sea level was still fluctuating during Pennsylvanian times (see Figure 25), these changes in sea level and local surface topography affected the pattern of deposition. Combined with this, the subduction forces deepened the southern part of the Arkoma, which favored thicker deposition along an east-west belt north of the present trace of the Choctaw fault. The delta-front deposits prograded into the basin, while the back delta swamps advanced over the former delta front. Within these swamps and marsh environments, *Calamites*, lycopods, and ferns grew in abundance, and the remains accumulated within the swamp waters and sediment. The thick organic sediments created an anaerobic environment that was eventually covered by muds and sands and became coal beds.

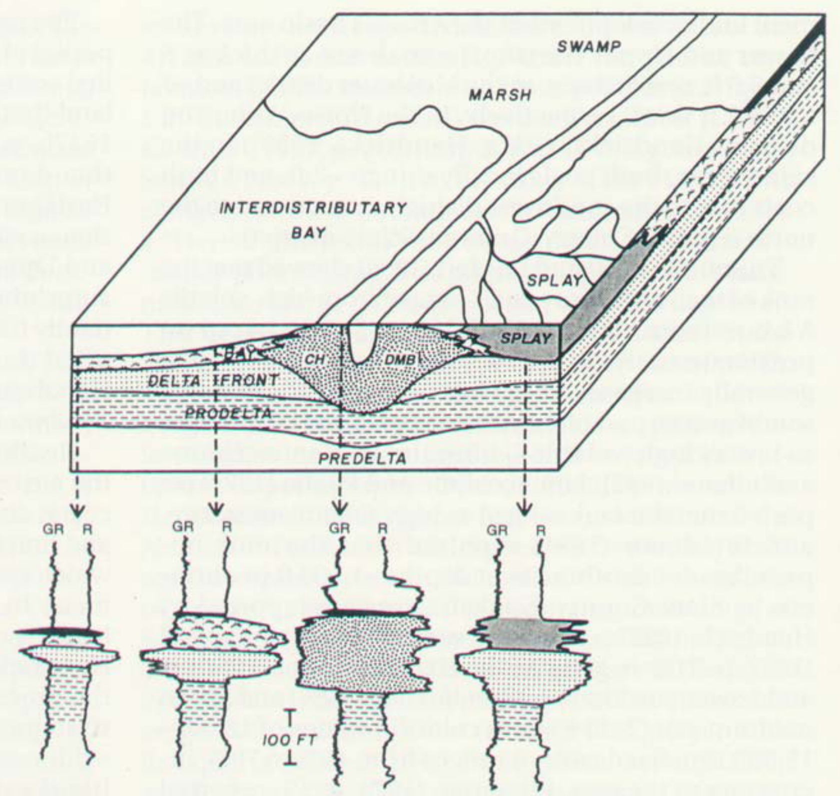


Figure 51: Top: Outcrop pattern of Hartshorne Formation in Oklahoma and Arkansas. Dashed line is western extent based on well penetrations. Bottom: Idealized block diagram of the Hartshorne deltaic environments and facies showing typical gamma-ray and resisitivity log responses. (from Suneson, 1998)

The sandstones of the Hartshorne can be grouped into three primary types: marine, fluvial, and splay deposits. The marine deposits are generally very-fine- to fine-grained, quartz-cemented, very hard, and have low porosity and permeability. They are characterized by flaggy bedding (discrete beds of several inches separated by silt/shale) with ripple marks. In areas corresponding to near-shore environments, high-angle cross-bedding is prevalent. This environment usually yields better porosity and permeability. Storm rip-up clasts are common in the marine sandstones, though these may actually be tsunami rip-up clasts. The fluvial channel deposits are generally fine- to medium-grained, poorly to moderately sorted, and commonly have good porosity and permeability. The channels typically have sharp lower boundaries with some channels exhibiting a sudden fining-upward profile. The sandstones are usually thick or massive, possibly multistory, with high-angle cross-bedding. Rip-up clasts and rafted plant debris are common at the channel base, here again possibly caused by tsunami. Channel deposits range from very shaly to very clean. The splay deposits usually have massive bedding and soft-sediment deformation. Cross-bedding is common along with lower bed boundary undulations. Plant impressions are common and are usually oriented in a single flow direction. These splay sandstones are usually fine-grained and relatively clean. Overall the depositional model for the Hartshorne is more terrestrial in the eastern Arkoma to more marine in the west. However, the major sandstone trends in the Hartshorne are predominately fluvial through the basin. The source of sediment seems to be primarily from the north, east, and southeast, with only minor areas being sourced from the near-sea level Ouachitas.

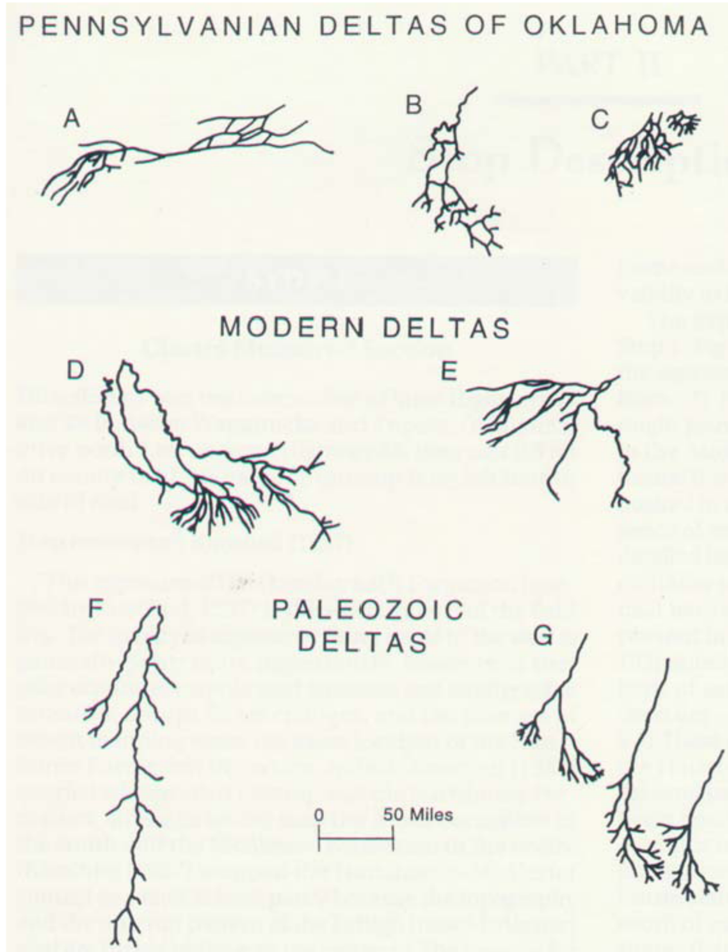


Figure 52: Diagrams of selected well-studied Phanerozoic deltas at the same scale. (A) Hartshorne. (B) Bartlesville. (C) Booch (McAlester). (D) Mississippi. (E) Orinoco. (F) Red Bedford (Ohio). (G) Catskill (New York). (from Suneson, 1998)

The McAlester Formation was deposited during the Desmoinesian Series time of the Pennsylvanian Period. Refer to the "Eustatic Sea Level Changes" (Figure 25) graph to see that this time experienced relative high and low sea levels. These changing sea levels were combined with the continued subduction beneath the Ouachita trough and the opposing force of isostatic rebound that caused the southern Arkoma Basin surface elevation to fluctuate. The Arkoma Basin was subjected to repeated oceanic transgressions followed by oceanic regressions with delta sequence deposition. The deposition seems to have primarily come from the north via deltas extending out into the shallow basin. Depending upon time and locale, one might find prodelta shales, delta front sequences and bars, delta bay fill shales and swamp (coal), and stacked channel sands. Thus the McAlester Formation is comprised of several members separated by unnamed shales. The formation thickness is generally 1,700 to 2,500 feet. The shales range from olive gray to olive black to grayish-black and are usually poorly exposed silty shales with locally thin siltstone layers. The type area is near McAlester, Pittsburg County, Oklahoma.

The McCurtain shale member at the base ranges from 200 to 600 feet thick. This shale generally is spheroidally weathering, poorly exposed, olive gray to olive black, fissile, and silty. Ironstone concretions and layers are sometimes present. In some areas, minor siltstone and sandstone beds are found.

The Warner sandstone member is two resistant, grayish orange to moderate reddish-brown, fine-grained, cross-bedded sandstones of variable thickness separated by a shale unit. The Warner member ranges from 0 to 200 feet thick.

The Lequire sandstone member is locally well exposed, fine-grained, silty sandstone that ranges from 0 to 150 feet thick. Sedimentary structures include ripple marks, parallel laminations, soft-sediment deformation features, and trace fossils.

The Cameron sandstone member ranges from yellowish-gray to dusky-yellow, fine- to very-fine-grained, non-calcareous, silty sandstone. Deposited as stacked channel sands and bars, the Cameron sandstone can be found as continuous beds to separate sand bodies separated by shales. Ripple marks, wavy bedding, cross-bedding, and sole marks are common.

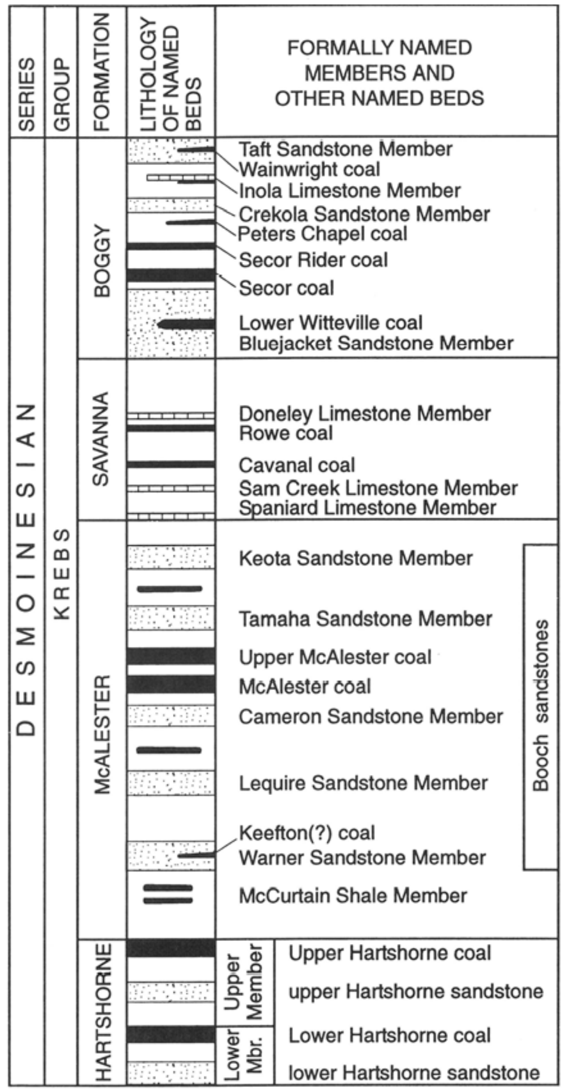


Figure 53: Generalized stratigraphic column of the Krebs Group. (from Suneson, 1998)

The McAlester coals represent a long time of low sea level stand. As the deltas prograded out into the basin, the back delta swamps would accumulate large areas of vegetation that resulted in a coal seam that ranges from 2 to 4 feet thick. Locally, a shale layer overlies the McAlester coal and a thin (<1 foot) smutty coal occurs as the Upper McAlester coal.

The distinction between the McAlester and Savanna Formations at this point depends upon the geologist. Some geologists consider the Tamaha and Keota sandstones (and deltaic sequences) to belong to the Savanna Formation, while others designate the thin Spaniard limestone to represent the base of the Savanna. This sequence is usually less than 600 feet thick and can locally contain thin coal seams.

Though Boyd (2005) makes a clear point that the Booch Formation of the Oklahoma Arkoma Basin and Cherokee platform is not equivalent to the McAlester Formation of the surface, the Booch is the common subsurface name for an internal sequence of sands, shales, and coals within the McAlester Formation. The Booch Formation consists of eight, northerly sourced progradational sequences bounded by oceanic flooding surfaces. Each of these sequences

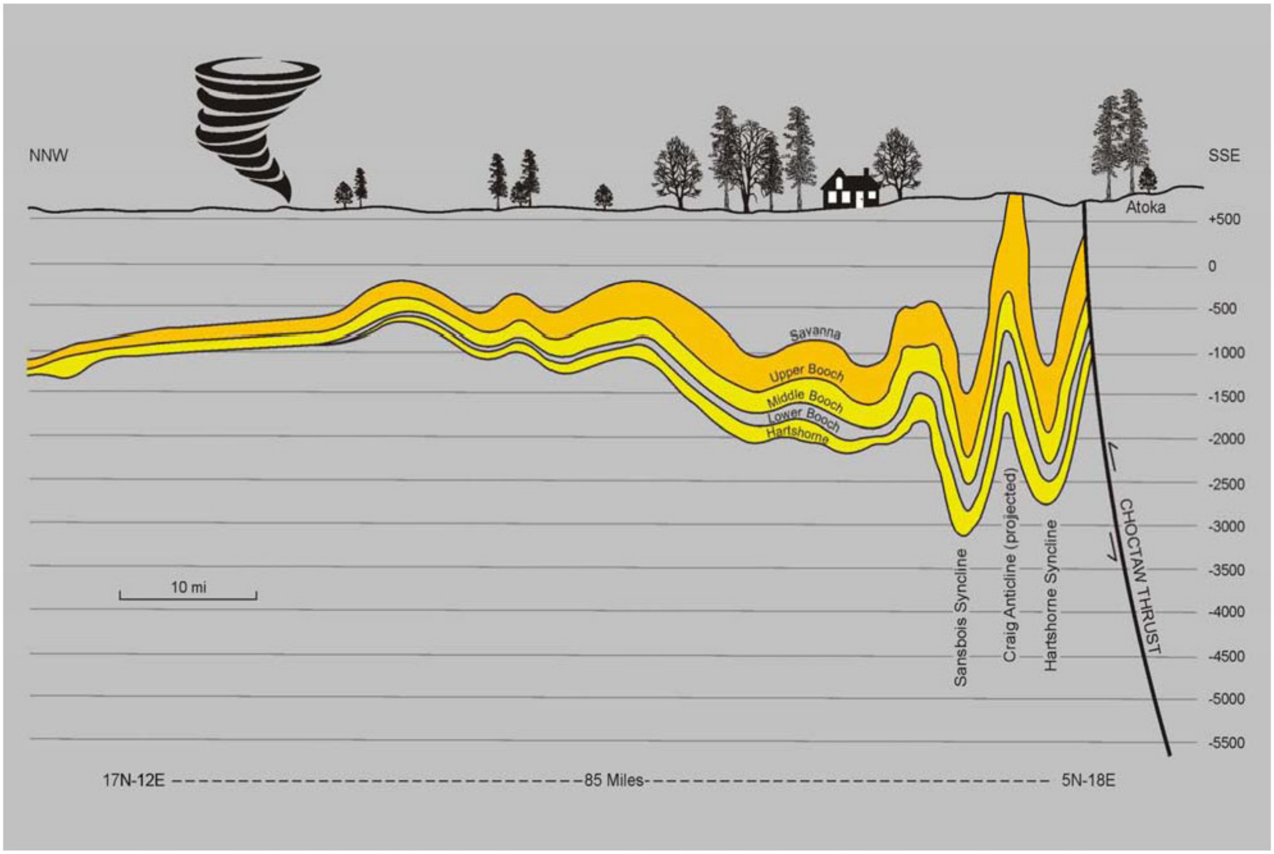


Figure 54: Regional structural cross section of Hartshorne to Savanna Formations.
(from Boyd, 2005)

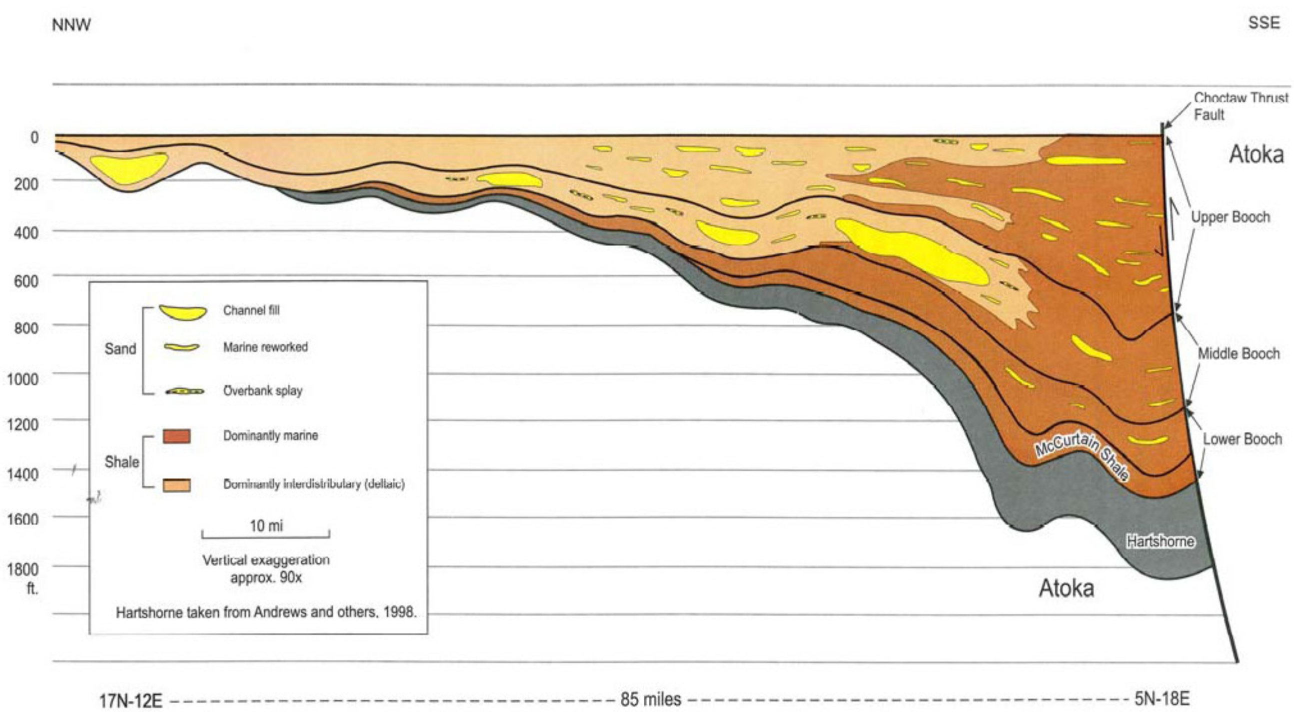


Figure 55: Regional schematic stratigraphic cross section hung from the top Booch.
(from Boyd, 2005)

exhibits a distinct coarsening-upward sequence of distal marine shale, to delta front to delta plain (swamp), and in some cases, incised valley. The sandstone members of the Booch indicate low-energy, tidally dominated deltaic deposition as distributary-mouth bars, tidal channels, distributary channels, overbank (crevasse) splays, and multiple channel fills with virtually no longshore current movements. The delta plain is represented by shales and coals. The Booch was deposited over an approximate period of two million years. This would roughly work out to be an average of 250,000 years between sea level rise and inundation.

The middle Booch consists of the third, fourth, and fifth sequence and is the period of maximum channel (valley) incision, progradation, and sand deposition. Obviously, this

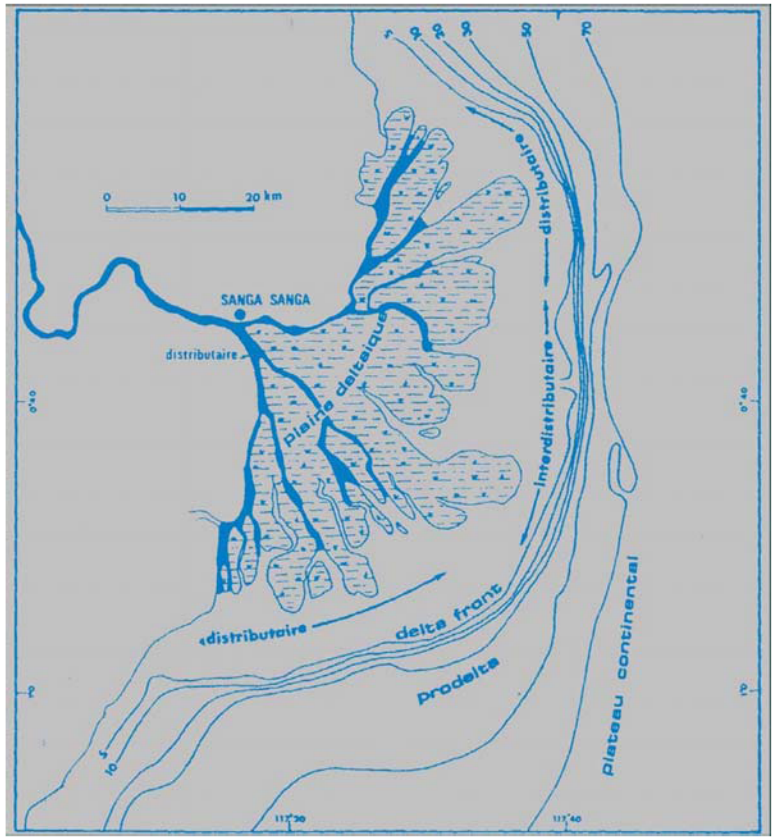


Figure 56: Mahakam delta, East Kalimantan, Indonesia. (from Boyd, 2005)

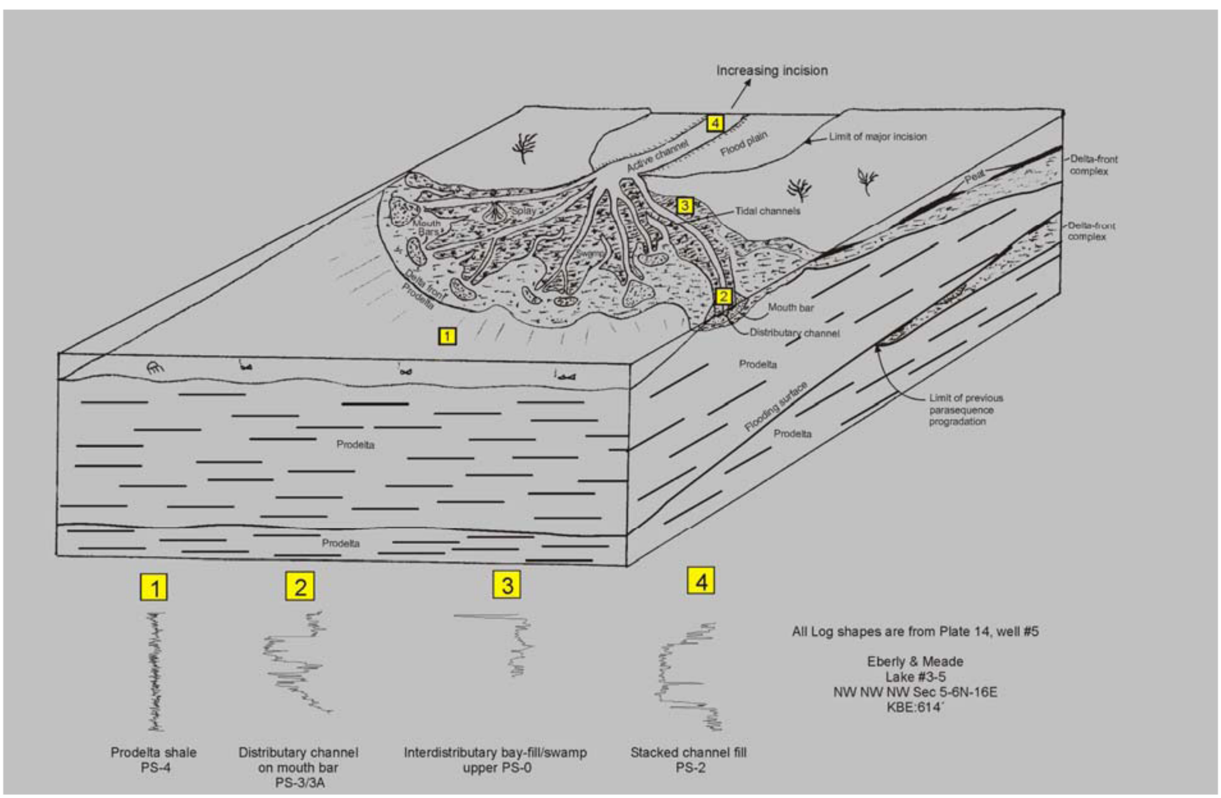


Figure 57: Idealized Booch tidal delta. (from Boyd, 2005)

would be the best time for present-day oil and gas reservoir sands. Boyd (2005) cites the present-day Mahakam delta in East Kalimantan, Indonesia as a modern analog to the Booch deltas. Boyd also described the Booch reservoirs as self-sourced with hydrocarbons generated from the marine shales and coals. (See Figures 56 through 59.)

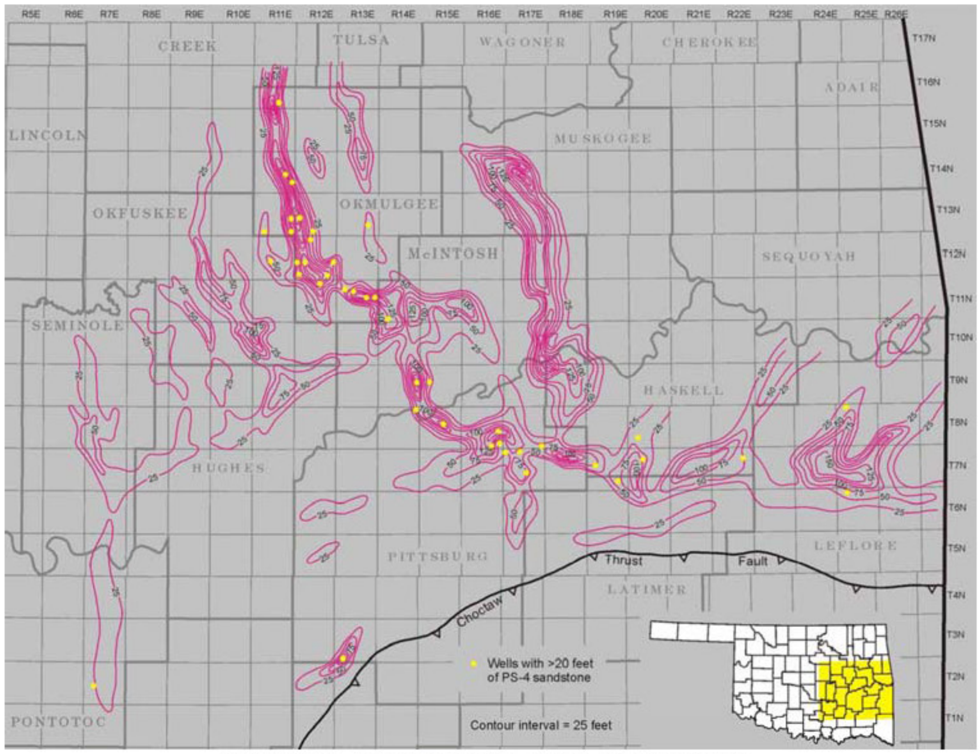


Figure 58: Middle Booch gross sand isopach.
(from Boyd, 2005)

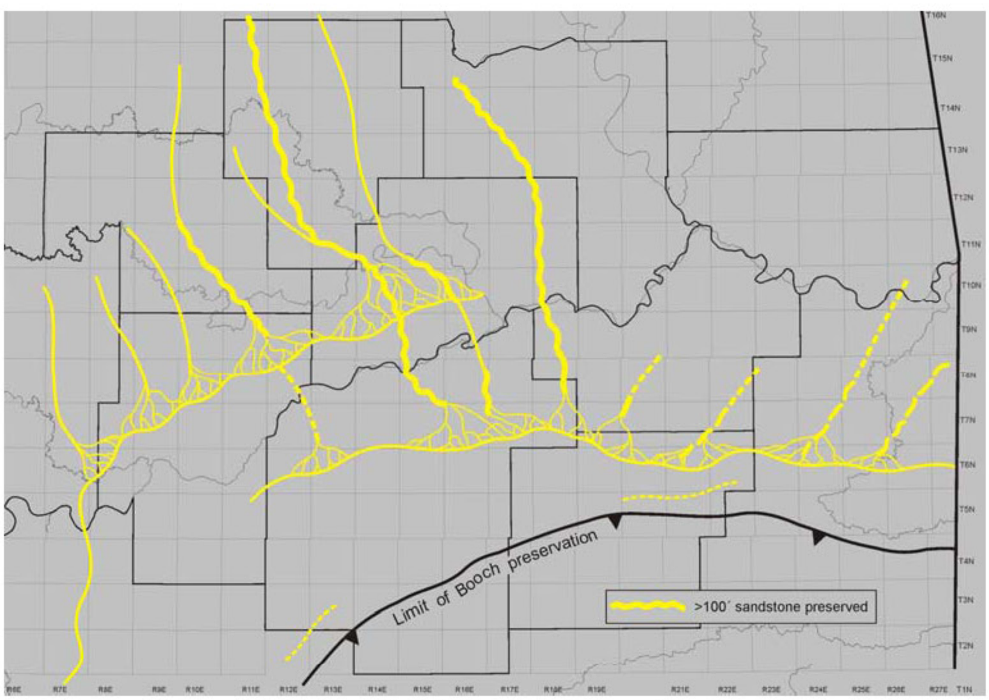


Figure 59: Schematic Middle Booch depositional systems.
(from Boyd, 2005)

The Savanna Formation exhibits much of the same depositional environment as the McAlester Formation. In northeastern Oklahoma, the base of the Savanna is the base of the shelf-deposited Spaniard limestone. In LeFlore County, there is a thin, fossiliferous marine limestone near Caston Creek that correlates stratigraphically with the Spaniard. The Savanna Formation members represent several sequences of transgressive/regressive sea levels with prodelta, delta, swamp, and channel environments. Locally, shelf limestones were deposited. The color of the sandstones ranges between yellowish-brown, light olive-gray, yellowish-gray, to dusky yellow. There are seven mappable sandstone units that occur in different areas of the Arkoma. The sandstones commonly exhibit cross-bedding, ripple marks, irregular to swaly bedding planes, soft-sediment deformation, bioturbation, and load casts. Sandstone outcrops tend to be less than 20 feet thick, though in some areas the sandstone can approach 80 feet thickness. In certain areas, coal is present. Shales are predominately olive-gray to grayish-black, silty, and well-laminated to fissile. Shale locally grades into siltstone beds and lenses. The Savanna Formation averages 1,600 feet thickness though it varies across the Arkoma. The type area is Savanna, Pittsburg County, Oklahoma.

The Boggy Formation continues the same type of depositional sequence as the McAlester and Savanna Formations. The Boggy is usually recognized as the top of the Krebs Group. However, in some areas, the Boggy contains medium- to coarse-grained sandstones with conglomerates with angular, bleached (weathered), pebble-sized chert. These areas probably represent fluvial channels. Coal beds (Secor, Secor-Rider, Lower Witteville) are present in some areas and thicker coal deposits have been mined. The Boggy Formation varies in thickness. In the Savanna area, it reaches a maximum thickness of 3100 feet though the top of the formation is eroded. The type area is the townsite of Boggy Depot near Atoka, Atoka County, Oklahoma.

The thin, locally present Thurman Formation of the southwestern Arkoma Basin is the last of the remaining Arkoma formations adjacent to the Ouachita front. It was deposited in the Pennsylvanian Desmoinesian above the Boggy Formation. The Thurman is a grayish-orange to moderate brown, very-fine to fine-grained sandstone with thick to medium bedding and locally exhibits irregular bedding and cross-bedding. Plant material is abundant, which could indicate a fluvial, lacustrine, or bay environment for deposition. It is conglomeritic in places with abundant fragments of chert and quartz. Above the lower sandstones are beds of grayish-orange shales and fine-grained sandstones. Most all of the Thurman is eroded, but the remaining thickness is estimated to be 100 to 150 feet. It has been proposed that the Thurman was sourced from the southeast, so the Ordovician and Devonian Ouachita cherts would be the source for the conglomerate. However, the Johns Valley Formation might also be a source for these same cherts. It does seem that during Thurman and possibly Boggy depositional times, the subduction forces of the Ouachita and Gondwana trenches were ending and isostatic rebound was lifting the Ouachita trough.

Boggy Depot

Boggy Depot received its name from Boggy River (Clear Boggy), the town being situated about a mile west of that stream, just out of the bottom, on the dividing ridge between the river and a little creek called Sandy Creek. The name is a translation of that given it by the French traders, of the eighteenth century, who called it "Vazzures," from the word "vaseux," meaning miry or boggy.

During the Civil War, Confederate troops were stationed at Boggy Depot (Butterfield Overland Mail station), the military quarters occupying about thirty acres in the southwestern part of town, where several rows of log cabins were erected for the soldiers, and a cannon was set that boomed forth a salute every evening at sundown.

Boggy Depot's contribution to Oklahoma outlasted its structures, for it was the source of the state's name. Boggy Depot was home to Chief Allen Wright, principal chief of the Choctaw Nation, who suggested the word "Oklahoma" ("Home of the Red Man") in 1866 as the name for the proposed Indian Territory. In 1907, the word was made the official state name.

Permian Period (299 – 251 mya):

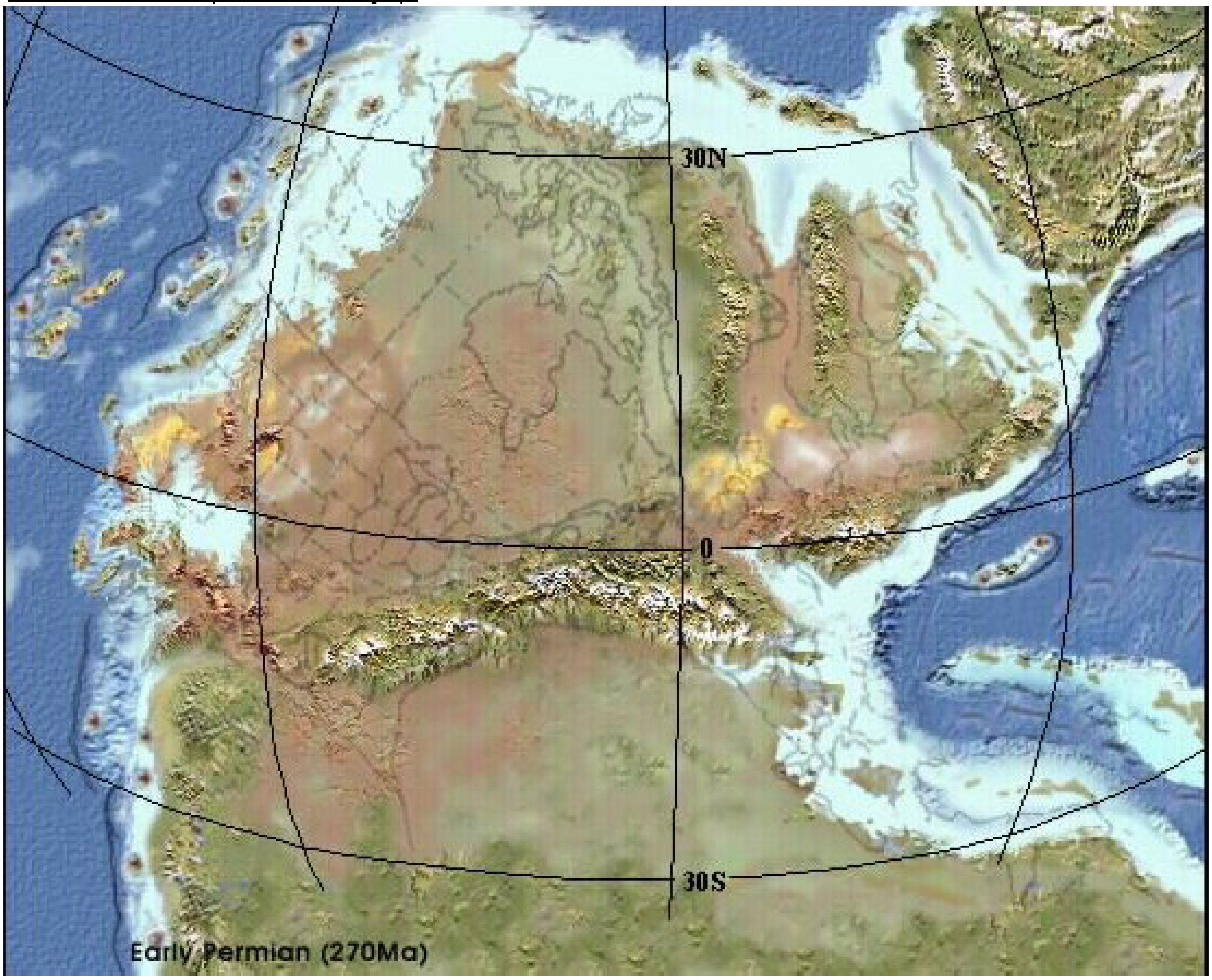


Figure 60: North America – 270 million years ago (middle Permian)
(from Dr. R. Blakey, Northern Arizona University, Flagstaff, AZ)

By the early Permian Period, the subduction forces that formed the Ouachita trough/trench and the Arkoma ended. The North American craton was sutured to Gondwana and parts of Laurasia as Pangea was formed. As noted before, the less-dense crustal deposits downwarped by the subduction started rising due to isostatic rebound. The Ouachitas slowly rose as a mountain chain overlooking the Arkoma. The land to the west and immediate north of the Ouachitas was still covered by shallow seas. Erosion from the Ouachita, Arbuckle, and Wichita Mountains deposited thick layers of sediment within this shallow sea. It has been estimated that most of Oklahoma north of the Arbuckles was covered by several thousand feet of sediment with the majority of that sediment sourced from the Ouachitas.

Plate tectonics (as predicted by the Wilson Cycle) once again gathered most of the continental masses together as one huge landmass, Pangea. The single super-ocean was called Panthalassa. The Earth's climate changed during the Permian, and by late Permian most of Pangea (including Oklahoma) was very arid. There was a corresponding drop in sea level (Figure 25). The end of the Permian was marked by a severe extinction event (actually two extinction episodes spaced apart by 9 million years), informally called the "Great Dying", in which 70 percent of the land species and 90 percent of the marine species became extinct. There are many theories as to why the “Great Dying” occurred. Most likely, it was a combination of several causes that contributed to the extinction. One notable theory is a large meteor or comet that may have struck the Earth off the northwest shelf of Australia that exacerbated other causes of the extinction. Another theory concerning the extinction of marine species states that as the oceans warmed and any ice caps vanished, the ocean water would become the same temperature from the surface to the deepest depths. At that point, the oceans would have “turned over” bringing hydrogen sulfide and other anaerobic toxins to the surface waters and death to most marine species. Two notable classes of animals that survived the extinction are the Sauropsida (dinosaurs and birds) and Synapsida (proto-mammals).

The southernmost belt of the Ouachitas, the Benton – Broken Bow uplift, may represent the area updip of where the subduction zone finally ended. There would be a thickening of the lower crust due to subduction, so the rebound of this thicker lower crust would elevate the deformed and thrusted upper crust. Thus the shelf (Arbuckle) sequences would be closer to the surface in the uplift as seen in the Sohio #1-22 Weyerhauser well at approximately 12,000 feet depth.

The Maumelle chaotic zone, near the town of Maumelle, Arkansas (central Arkansas), is thought to be the thrusted, displaced remains of the subduction mélange zone (Coleman, 1997). The Athens Plateau of south central Arkansas, and south of the Benton uplift, is thought to be the deformed, vertically oriented strata from the southern portion of the subduction trench. This would indicate that the isostatic rebound would have been responsible for some of the lateral thrusting of the Ouachitas given the distance between the two locations of Maumelle and Athens.

Jurassic Period (200 – 146 mya):

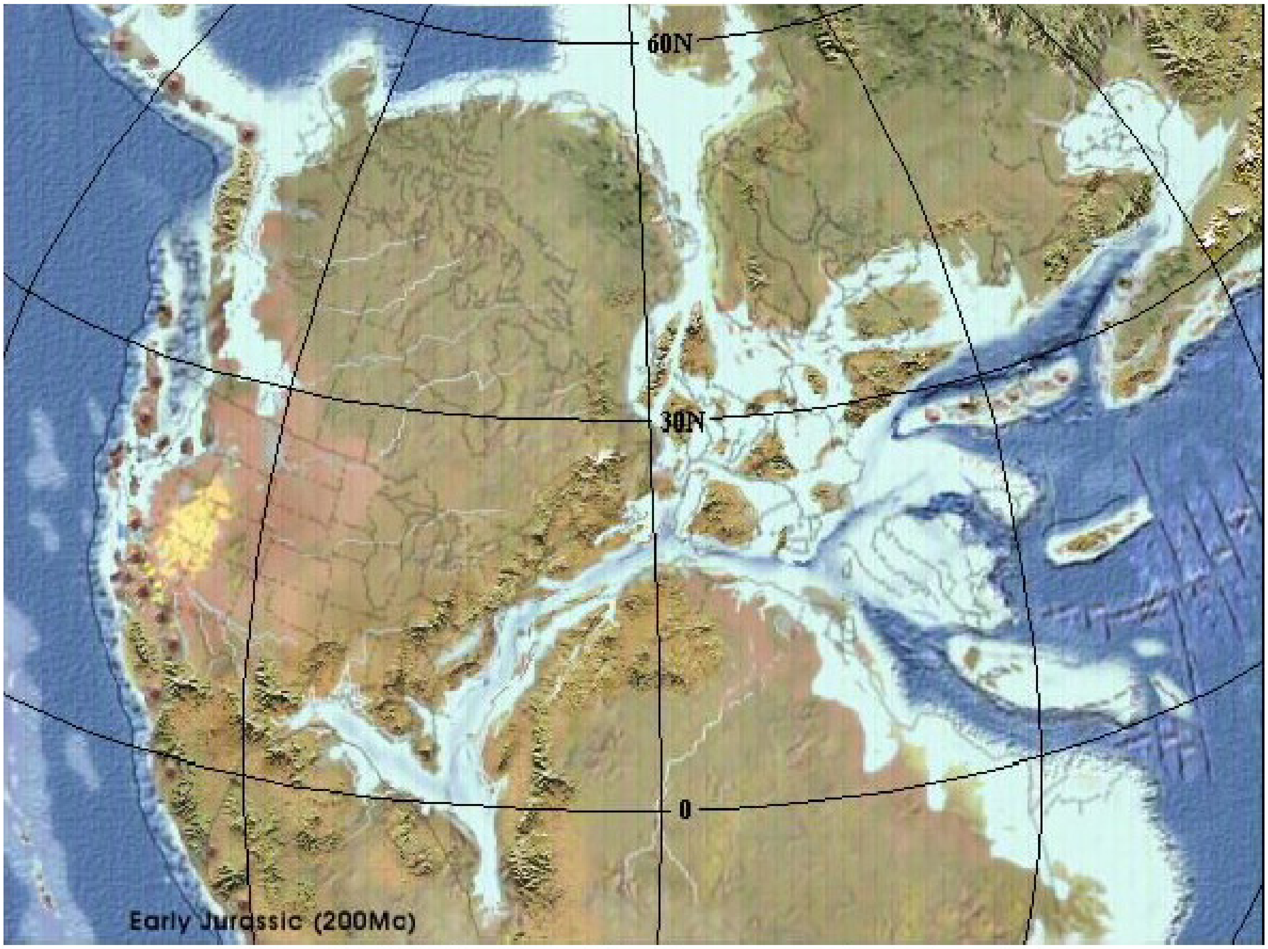


Figure 61: North America – 200 million years ago (early Jurassic)
(from Dr. R. Blakey, Northern Arizona University, Flagstaff, AZ)

A Wilson Triple Point formed in western Laurasia that resulted in a rift forming. This rift was the beginning of the Atlantic Ocean and split North America from Laurasia.

Cretaceous Period (146 – 65 mya):

Figure 62: North America – 115 million years ago (early Cretaceous)
(from Dr. R. Blakey, Northern Arizona University, Flagstaff, AZ)

The North American plate continued to drift west relative to the European plates. Sea level rose and formed the Cretaceous sea shelf along the southern limits of the Ouachitas. Carbonate sediments, sand, and mud deposits accumulated to form the "Cretaceous onlap" on the southern side of the Ouachitas.

Pleistocene Epoch of the Quaternary Period (1.8 million – 11,550 years ago):

Figure 63: North America – 1 million years ago (Pleistocene)
(from Dr. R. Blakey, Northern Arizona University, Flagstaff, AZ)

Stone and McFarland (1979) have noted more than 100 rock-glacier deposits within the northern regions of the Ouachita Mountains, some of which are active. They have suggested that these boulder fields are evidence of periglacial conditions and/or semi-permanent ice fields in the higher elevations of the Ouachitas during the Illinoian and Wisconsinan glacial stages.

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Road Log and Stop Descriptions

Thursday

0.0mi 2pm: Leave Thanksgiving Tower, Pacific Street side, downtown Dallas, TX. Proceed northeast on Pacific to Central Expressway. Turn left to North Central Expressway. Go north 6.1 miles to Walnut Hill Exit. Stay on the frontage road through the intersection and turn right into the parking for the Centennial "Formation". After evaluating this phenomenon, return to vehicles and back-track to northbound Central Expressway (U.S. 75).

78.3mi Cross Red River and enter Oklahoma.

89.5mi Choctaw Casino Complex. At the stop light, turn right, proceed to the Phillips Station for a break.

112.5mi East of the highway is the village of Caney, OK. I am not aware if there is a good exposure of Caney shale at this location or not.

116.0mi South of Tushka, OK is a right – left curve combination on U.S. 75. This is a renowned speed trap. Please strictly observe the posted speed limit as it does change on the curve. North of Atoka is the town of Stringtown – another personally known speed trap area.

125.2mi North side of Atoka, OK, continue straight on U.S. 69 towards Stringtown and McAlester.

135.9mi Yes, that is one of the Oklahoma State Prison Facilities on the left. This is the Stringtown Unit.

Historically, it is interesting that Stringtown was originally named "Springtown" for the abundant water springs present in the ridge that can be seen west of the highway. However, when the Postmaster sent the paperwork in to Washington, D.C. to establish a post office, a clerk in Washington misread the handwritten form. The post office was registered as "Stringtown" and the name remains to this day. West of this point on the west side of the Atoka Ridge is Atoka Lake that was constructed by Oklahoma City in 1959. In the early 1960's, a five-foot-diameter concrete pipeline was laid from Atoka Lake to Lake Stanley Draper southeast of Oklahoma City (over 100 miles away). The purpose was to supply potable water to Oklahoma City for the future.

147.5mi If you do not blink, the area and ridge to the west of the highway is Chockie, Oklahoma. This area is the hometown of Reba McEntire.

151.9mi Kiowa, OK. Notice State Highway OK 63 intersection. This is the road on which we will return on Saturday.

165.7mi Continue on U.S. 69 – George Nigh Expressway. Do not take Business 69 into McAlester.

169.6mi At the southeast edge of McAlester, take the U.S. 270 East exit (Carl Albert Expressway) towards Krebs/Wilburton.

170.0mi Almost immediately after merging onto U.S. 270, there will be an exit on the right for OK 31 (W. Washington Avenue). Take the OK 31 exit. Cross over U.S. 270.

170.6mi First cross street will be 8th Street. Turn right on 8th Street. Go one block to Pete's Place.

Pete's Place

Pietro Piegari traveled with his family from San Gregorio Magno, Italy, to the coal mining community of Krebs, Oklahoma, in 1903. Three years later the boy officially changed his name to Pete Prichard when he signed on to work in the mines. He was eleven years old.

Pete grew from boy to man in the mines, and was twenty-one when a cave-in almost took his life, crushing one of his legs so badly that he was unable to return to work.

Taking any odd jobs he could find, the enterprising young immigrant soon began making and selling Choc beer from his home. The home brew originated in Indian Territory, and the recipe had passed from the Indians in the area to the Italian immigrants.

Soon men began gathering in Pete's home to buy and drink Choc. It seemed a natural progression for Pete to begin fixing food to accommodate the men's appetites. Old timers recall that Pete began his food preparation by fixing lunches for the English, Irish, Scot, Welsh and Italians who swarmed into the area to work jobs available in the rich coal mines.

In 1925, Pete officially opened a restaurant in his home. His customers were accustomed to going to "Pete's Place," so the name, too, was a natural evolution. The menu included homemade spaghetti, meatballs, ravioli, sausage, and other Italian dishes served family style, along with the Choc beer that was outlawed by the Federal prohibition act.

Eventually, Pete expanded his menu, adding salad, lamb fries, veal, chicken and steak. And he began making a red wine, an appropriate beverage for his Italian dishes. The wine, like the Choc, was also a violation of Federal law.

Old timers recall that in the late nineteen thirties and forties, when Japanese Americans were interned during World War II, first generation citizens from nations like Germany and Italy, countries which were America's enemies at the time, were not allowed to have weapons in their possession. During that period, Pete had a new challenge: operating an eating establishment with no knives.

Other old timers in the area recall that for several years, Pete provided a special reward to those who attended Christmas mass. As they came from church after the midnight service, Pete opened his restaurant to serve supper.

In 1964, Pete turned operation of the restaurant over to his son Bill, but the man who began Pete's Place continued to make ravioli by hand every day to feed an ever-increasing clientele, which included U.S. senators, governors, congressmen, legislators, sports and movie stars, and celebrities from every field, many of whom sampled the still illegal home-brewed beer and wine.

In 1984, Bill and Catherine Prichard turned the business to the next generation of Prichards: Joe and Kathy, who continue to operate the restaurant today.

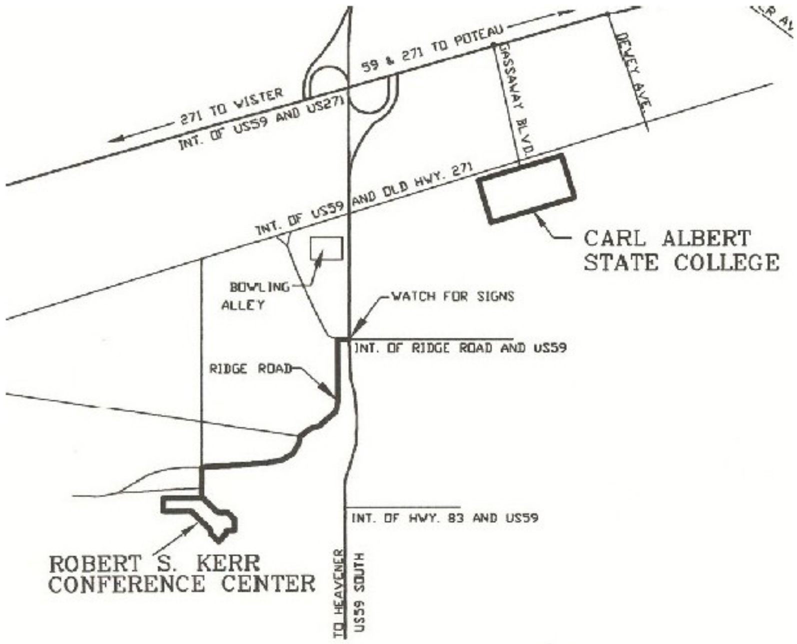
After dinner, drive south on 8th Street and **carefully** turn left on to U.S. 270 East. We will pass through several towns and areas to which we will return, including Hartshorne and Wilburton.

181.1mi Haileyville, OK. Notice the intersection with State Highway 63 on the right. This is the road we will take Saturday on our return.

182.4mi Hartshorne, OK

234.0mi In the town of Wister, continue straight on U.S. 271 towards Poteau.

240.3mi Turn south (left turn) on U.S. 59 on the southwest side of Poteau. Proceed south on U.S. 59 1.7mi to Ridge Road. Turn right on Ridge Road (watch for signs) and follow the signs to Kerr Conference Center.



End of Thursday's trip. (244.4 miles)

Kerr Conference Center

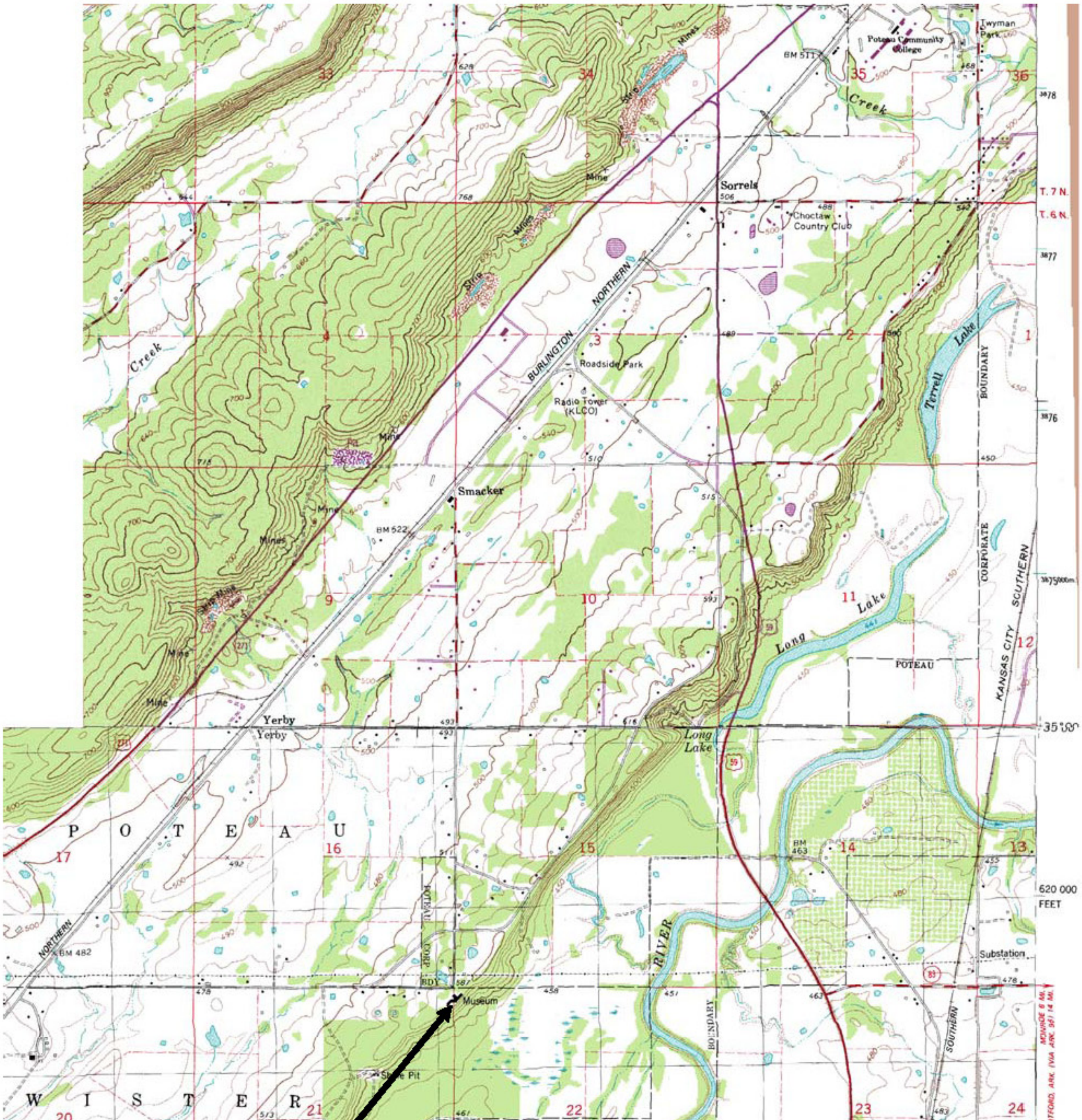
The Kerr Conference Center was built originally as a home for the late Senator Robert S. Kerr and his family. Construction started in 1957 and was completed in 1960.

Senator Robert S. Kerr unquestionably was one of Oklahoma's most prominent and well-known citizens. He was born in 1896 in a log cabin southeast of Ada, Oklahoma, and went on to serve as governor of the State. He was elected to the U.S. Senate in 1948 and was serving his third term when he died on January 1, 1963, at the age of 66. At the time, he was considered by some to be the leading possibility for the U.S. presidency.

The Kerr home was presented as a gift from the Kerr family to the Oklahoma State Board of Regents for Higher Education in 1978. It was remodeled for its current use in 1983 at a cost of $500,000. Since 1968, the Kerr Center has housed the Kerr Museum, which now is located in the former carport, remodeled for its present use. The museum is operated by the Eastern Oklahoma Historical Society.

Visitors to the Kerr home and Center have included such famous people as Presidents John F. Kennedy, Lyndon B. Johnson, Gerald Ford, George H. Bush, former Speaker of the House Carl Albert, and before he was known outside of the military, General Norman Schwartzkopf.

A short biographical sketch of Senator Kerr is included in the Appendix.



Topographic map showing location of Kerr Conference Center

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Friday

The writer acknowledges the hard and enduring work of the Oklahoma Geological Survey and, in particular, the work of Dr. Neil Suneson, Dr. Brian Cardott, Dr. LeRoy Hemish and Dr. Robert O. Fay. These four learned men, along with their colleagues past and present, have assembled a great deal of knowledge of the Ouachitas and Arkoma Basin. The planned stops, the majority of the stop descriptions, and most of the historical side notes are well-documented in many of the Oklahoma Geological Survey publications. The writer also acknowledges the excellent work from the Arkansas Geological Commission and Dr. Charles Stone. Thank you all for sharing your work and knowledge.

Cavanal Hill

Cavanal Hill is the large topographic high immediately north of the Kerr Conference Center and northwest of the intersection of U.S. 59 and 271.

Before World War II, members of an English class in a LeFlore County high school exchanged letters with students in a similar class in England. The British class discovered from a Boy Scout manual that Cavanal Hill, west of Poteau, was "The World's Highest Hill". Subsequent investigation revealed that the British Geological Society defined a hill as less than 2,000 feet above the surrounding terrain, and a mountain as 2,000 feet or more. Cavanal Hill measured 1,999 feet above the local area (base taken from near the Arkansas River).

0.0mi Start trip at Kerr Conference Center parking lot. The Center is located on the basal sandstone of the Savanna Formation. Exit parking lot and turn left on blacktop road.

There are two separate routes that may be taken to the first stop depending upon road conditions and weather. Route 1 descends onto the Poteau River flood plain, passes oxbow lakes and abandoned meanders, and requires permission from Kerr Center for Sustainable Agriculture. Route 2 remains on the paved roads through the town of Wister and across Wister Lake Dam.

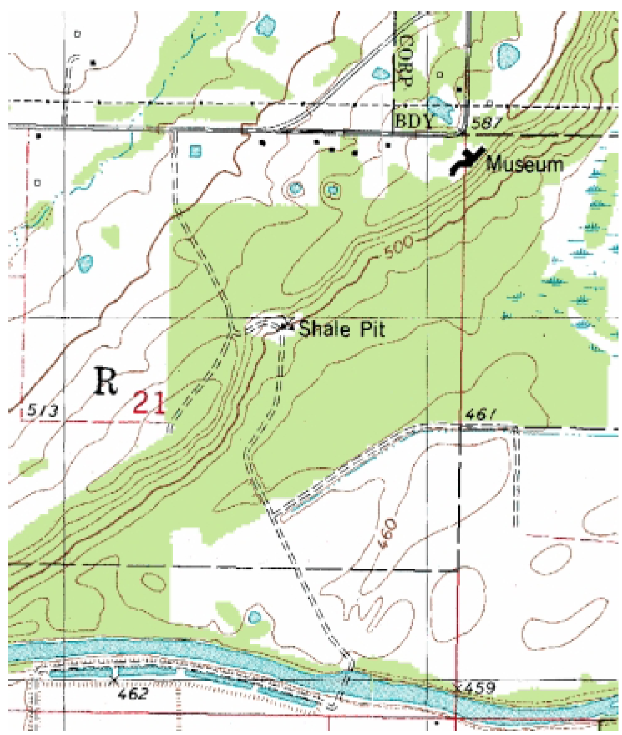
Route 1:

0.5mi Turn left (south) on gravel road. In 0.4 mile, intersection with gravel road. Turn left (east).

0.9mi Gully and shale pit to left of road has outcrops of Spaniard limestone and McAlester Formation. Proceed south on winding road across flood plain of Poteau River. During the drive, notice the abandoned meandering channels of the Poteau River (see map).

1.6mi Proceed south on winding gravel road across the Poteau River flood plain and cross concrete low-water bridge. On the south side of the low-water bridge is an outcrop of the Keota sandstone member of the McAlester Formation.

Pass Beaver Lake, an oxbow lake, on left. Turn right at next gravel road intersection.

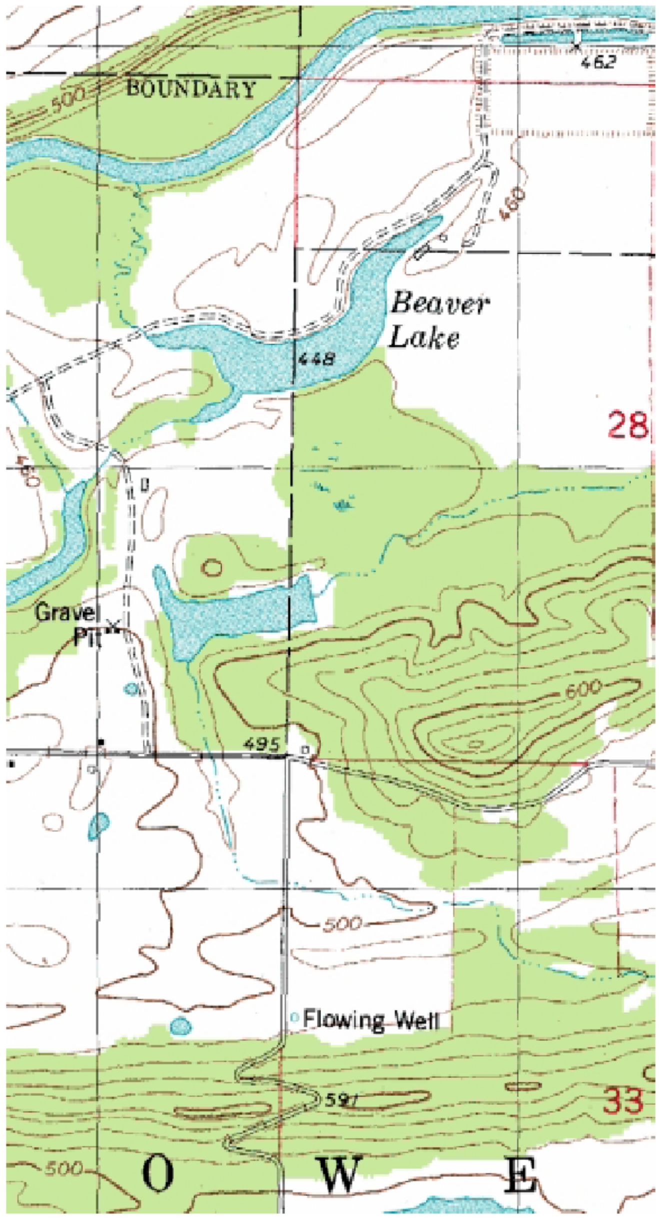


Depending upon slope and vegetation, all streams and rivers will meander or become braided. In this particular case, the Poteau River is meandering. Actually, the bends (meanders) of the river do "behave" as described by a solution of an elliptical integral though it has been found that a sine-generated curve does serve as a good approximation. As the river erodes and deposits sediments, its "work" in turning changes, thus the meanders change and the course will change with the resulting abandonment of meanders and channels. Beaver Lake is one of those abandoned channels. Along the river from here to the Arkansas River, there are abandoned meanders (also known as "oxbow lakes") and channels. Submerged channels, such as those associated with turbidites, will behave in a similar manner. River plains that are near level or different vegetation will produce braided streams, such as the North Platte River in Nebraska or the Hartshorne channels in the Pennsylvanian.

1.0mi Pass gravel pit on right. The ridge to the left is formed by the Cameron sandstone member of the McAlester Formation. At intersection turn left, go east about a quarter mile to the next intersection and turn right (south). The ridge to the south is the Warner sandstone member of the McAlester Formation. Proceed up switchbacks across the Warner ridge.

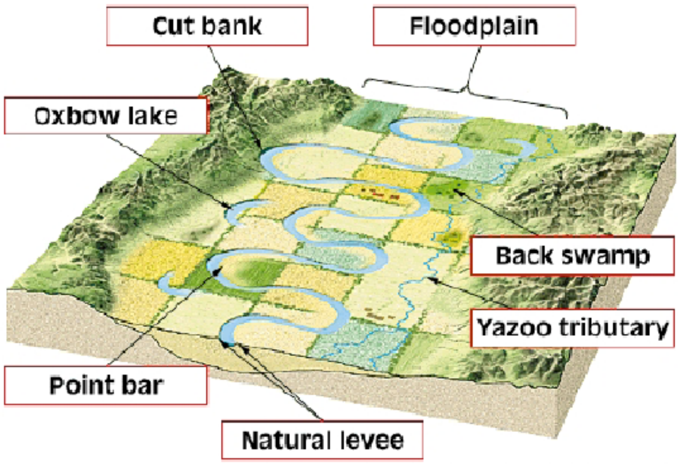
5.1mi Cross railroad. Turn right at second right (asphalt road). Proceed in a south and southwesterly direction. The ridge is the Hartshorne Formation. As you pass a small saddle on the right, there is an abandoned coal mine in the Upper Hartshorne Coal on the opposite side of the saddle. Proceed past Victory Church. The ridge to the right is the Atoka Formation. Cross a bridge. Proceed straight to intersect U.S. 270 immediately east of the Wister spillway.

Abandoned meander and Beaver Lake



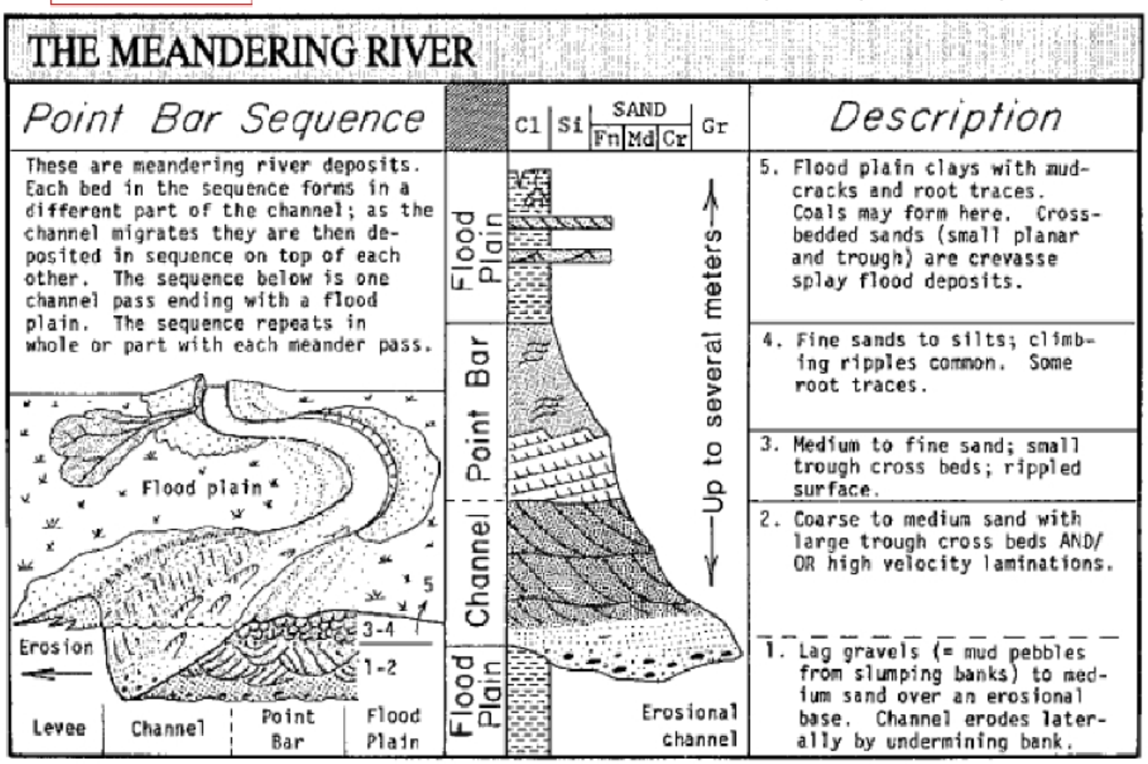
Long Lake and U.S. 59 south of Poteau, OK

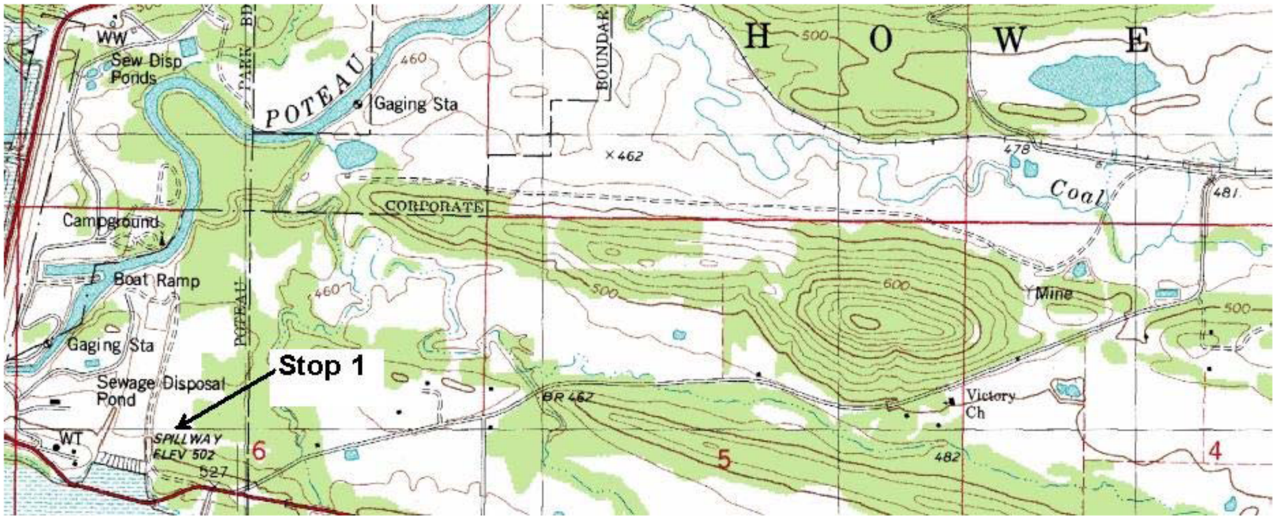
Oxbow lakes and abandoned channels south of Wister Lake



Common features of streams and rivers.

Description of point bar deposition.

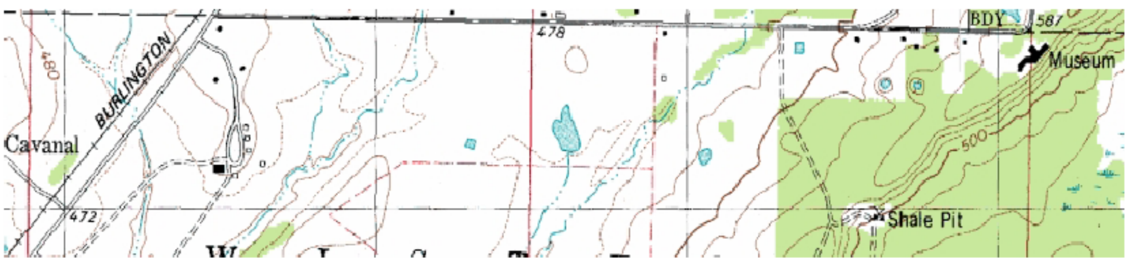




7.6mi Turn right (west) on to U.S. 270.

7.7mi Turn right (west) at U.S. Army Corps of Engineers' "Lake Wister" sign and drive to parking area at east side of spillway.

Route 2:

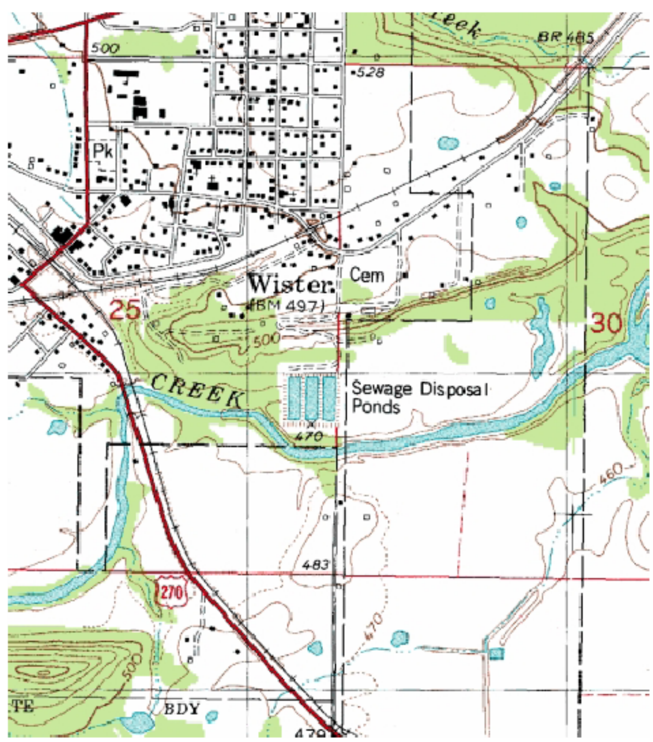


1.6mi Turn left on old U.S. 271 and continue due southwest on Savanna shale and Quaternary alluvium towards the town of Wister.

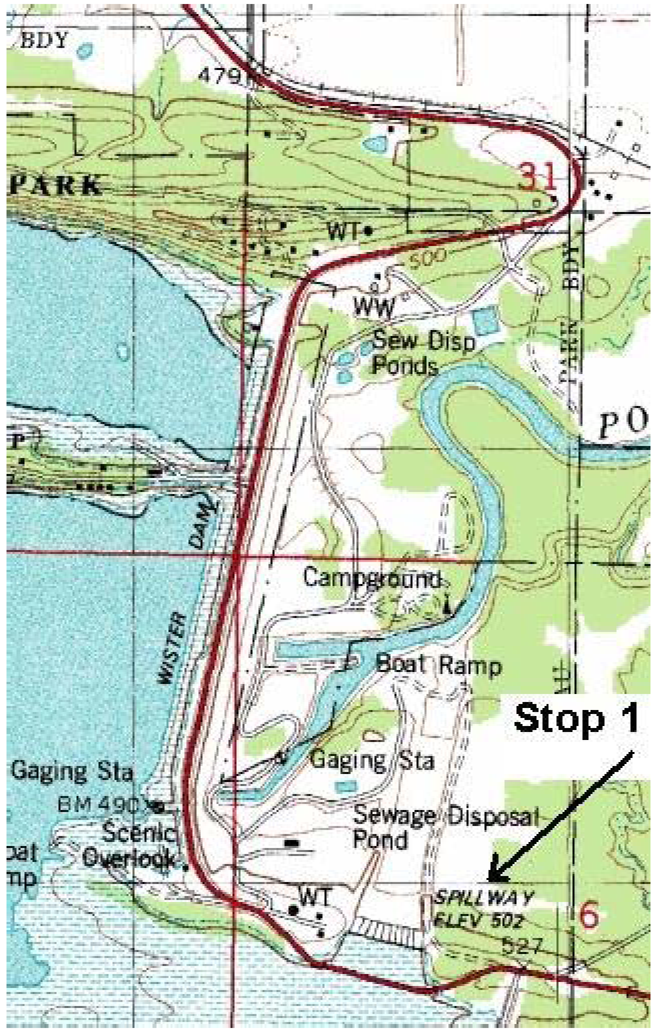
4.4mi Turn left (south) in downtown Wister onto U.S. 270 and proceed through town, crossing railroad tracks and following the bends of the road.

4.9mi Cross Caston Creek and drive southeast on its flood plain. The ridges to the right are formed by the Cameron and Warner sandstone members of the McAlester Formation.

5.9mi Dip-slope outcrop of the upper unit of the Warner sandstone on the side of the road. Continue around broad curve in the road, enter Wister State Park and ascend to the crest of the Wister Dam. McCurtain shale



member of the McAlester Formation crops out in ditch on the northwest side of the highway.



6.7mi North end of Wister Dam. Turn left (south) and cross dam.

7.0mi Quarry Isle and Wister State Park Headquarters on the right (west). Quarry Isle is formed by a hogback of moderately dipping sandstone in the Hartshorne Formation. Dips here are approximately 25º north, increasing to the south towards the axis of the Heavener Anticline. Continue south across the dam.

7.5mi Control tower and lift gates on the right (west); discharge chute to the left (east) with outcrops of steeply dipping, dark gray shales of the upper part of the Atoka Formation visible in channel walls downstream.

7.6mi Entrance to rest stop and scenic overlook at south end of the embankment. Continue on U.S. 270 and drive due east. The dam's 600-feet-wide spillway is to the left (north) and ahead to the right (south) is the 2,400-feet-long, 40-feet-high dike.

8.1mi Turn sharply left (west) at U.S. Army Corps of Engineers' "Lake Wister" sign and drive to parking area at east side of spillway.

Stop 1
Northern Leg of Heavener Anticline and Sedimentology of the Upper Part of the Atoka Formation, Wister Lake Spillway, LeFlore County, Oklahoma.

(Permission to enter the spillway must be obtained at the U.S. Army Corps of Engineers' office located within Wister State Park.)

Wister State Park is located in the southern part of the Arkoma Basin. The most prominent structural feature within the park is the Heavener Anticline, which trends westerly across the area and extends well beyond the park boundaries. Wister Dam is located on the northern flank of the Heavener Anticline where beds have a northward dip averaging approximately 26º north and an average strike of N68ºW. The Heavener Anticline is broken on both flanks by numerous tear faults. One of these faults can be observed at this stop on the west side of the spillway where surface rocks are offset approximately 10 feet.

Rocks that outcrop in the Wister State Park are assigned to, in ascending order, the Atoka Formation (approximately 11,000 feet exposed in the vicinity of the park), the Hartshorne

Formation (250-300 feet exposed), and the McAlester Formation (900-950 feet exposed). Lithologically, the succession is composed primarily of dark gray to medium gray, noncalcareous, silty shale and subordinate amounts of ripple-marked, locally cross-bedded, very fine grained sandstones. Some sandstones are fairly discontinuous.

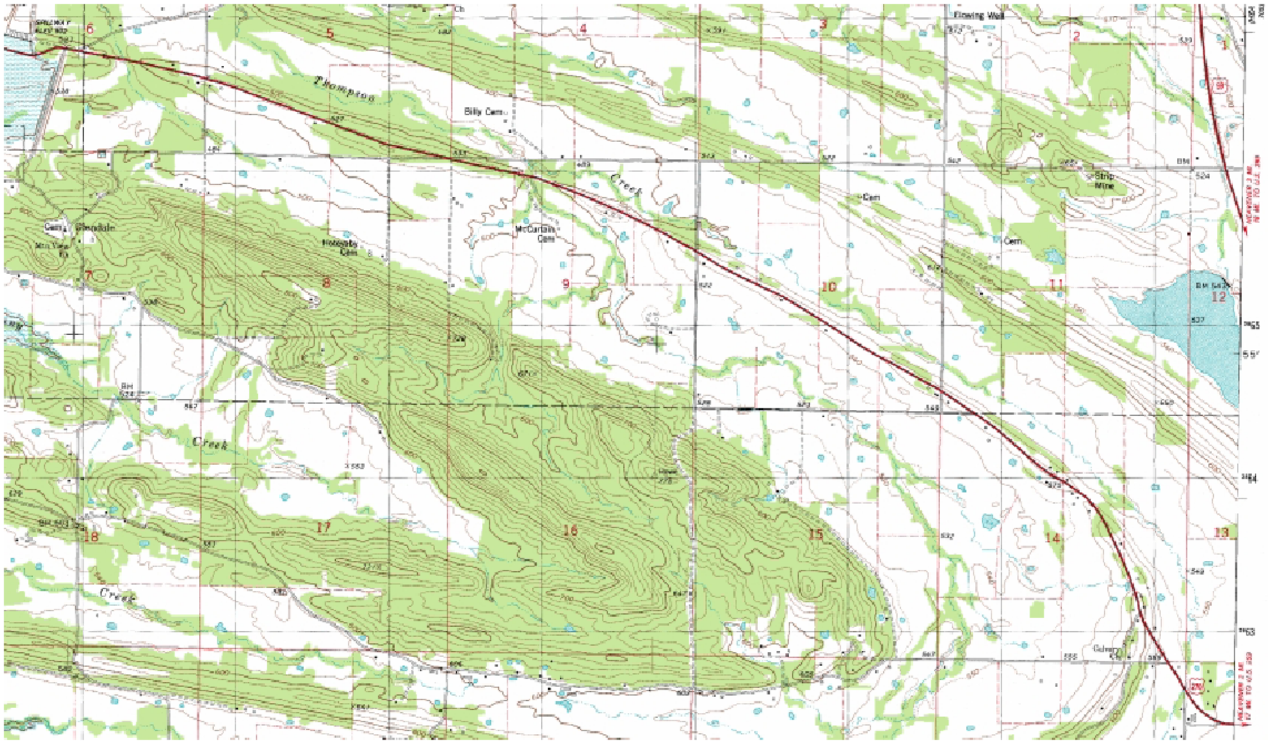
The Atoka Formation contains a variety of current and wave ripple marks. Some ripple patterns suggest the combined influence of waves and currents. In some cases, thin mud drapes occur on ripple foresets, or ripples have a more symmetrical form, which suggests wave and, possibly, tidal influence. Both symmetrical and asymmetrical wave ripples are present. Symmetrical wave ripples are essentially straight-crested and show, in part, a tuning-fork-like bifurcation. This type of ripple typically is produced by slow-moving waves on the margins of a water body with a depth of only a few inches. Asymmetrical ripples are similar to straight-crested current ripples in possessing a steep lee side and a gentle stoss side. These wave ripples may develop as climbing ripples or ripple laminae in-phase if sufficient sediment is available in suspension. Crests of both symmetrical and asymmetrical wave ripples show repeated bifurcation in the shape of tuning fork, and the profile of the crest is rather regular.

Other sedimentary features at this stop are soft sediment deformation, scours, shale/mud clasts, pyrite/siderite nodules and replacement in shells, comminuted plant material, some shell and crinoid fossils, and bioturbation. There is evidence of deposition by infrequent (episodic) high-energy events of short duration (storms or tsunami) characterized by coarsening-upward sandstone lithofacies. Some evidence for storm- or tsunami-influenced, episodic sedimentation include: (1) laminated siltstone/sandstone lenses in silty shale intervals; (2) alternating flow-velocity characteristics of vertical-bedding sequences; (3) asymmetrical ripple laminations with flasher and thin, wavy shale beds; (4) rip-up clasts in cross-bedded sandstone facies; (5) sharp-based sandstone beds separated by shale interbeds; (6) rapid lateral variation in stratification; (7) horizontal trace fossils common but restricted to rippled surfaces in upper part of sandstone facies; and (8) alternating vertical variations in grain size.

Storm and tsunami activity influenced transportation and deposition of sediment on the shelf within the basin. One possible mechanism of sand transportation, induced geostrophic flows, would be consistent with the evidence of oscillatory currents. Periodic flooding (storm and tsunami events) during which sediments were transported seaward out of brackish, marginal-marine bays and marshes is indicated by: (1) the presence of crinoid stems and disarticulated brachiopod and bivalve shells, (2) wood fragments, and (3) organic fish hash in sandstones.

An inferred chronological development of succession might include: (1) an initial transgressive event with a relative rise in sea level and simultaneous moderate reworking of sand in shallow-marine setting; (2) major transgression with subsequent flooding of the mud-dominated shelf and deposition of thick, open-marine shales; and (3) periodic interruption of background shale deposition by regressive events with relative sea level falls and deposition in certain intervals of coarsening-upward sandstone lithofacies by storm- or tsunami-influenced transportation of sand across a mud-dominated shelf.

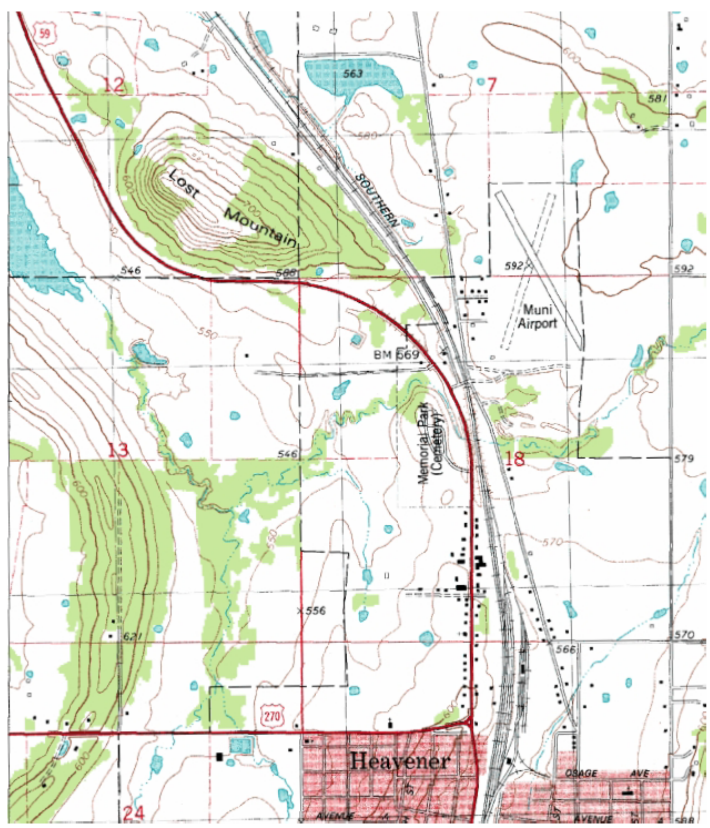
The key to effective exploration and to production and ultimate recovery of hydrocarbons from these sandstone reservoirs is the recognition of depositional controls and facies. Deep-sea fan deposits, deltaic sequences, and shelf deposits result from very different processes. They also have vastly different paleogeographic significance. But because the three share a wide variety of common sedimentary features, distinguishing among these depositional environments may be difficult. Therefore, the ability to identify the differences between turbidite-sandstone facies, deltaic-sandstone facies, and storm-/tsunami-influenced shelf sandstones will be a significant aid in predicting the occurrence and trend of sandstones that have hydrocarbon-production potential.



Return to the vehicles. Reset mileage to 0.0 since the beginning trip routes might vary according to weather and other circumstances. Exit the parking and turn left (east) on U.S. 270 to Heavener. U.S. 270 follows along a ridge of Potts Mountain sandstone of the Atoka.

7.1mi Enter Heavener from the west and intersect with U.S. 59. Turn left (north) on U.S. 59.

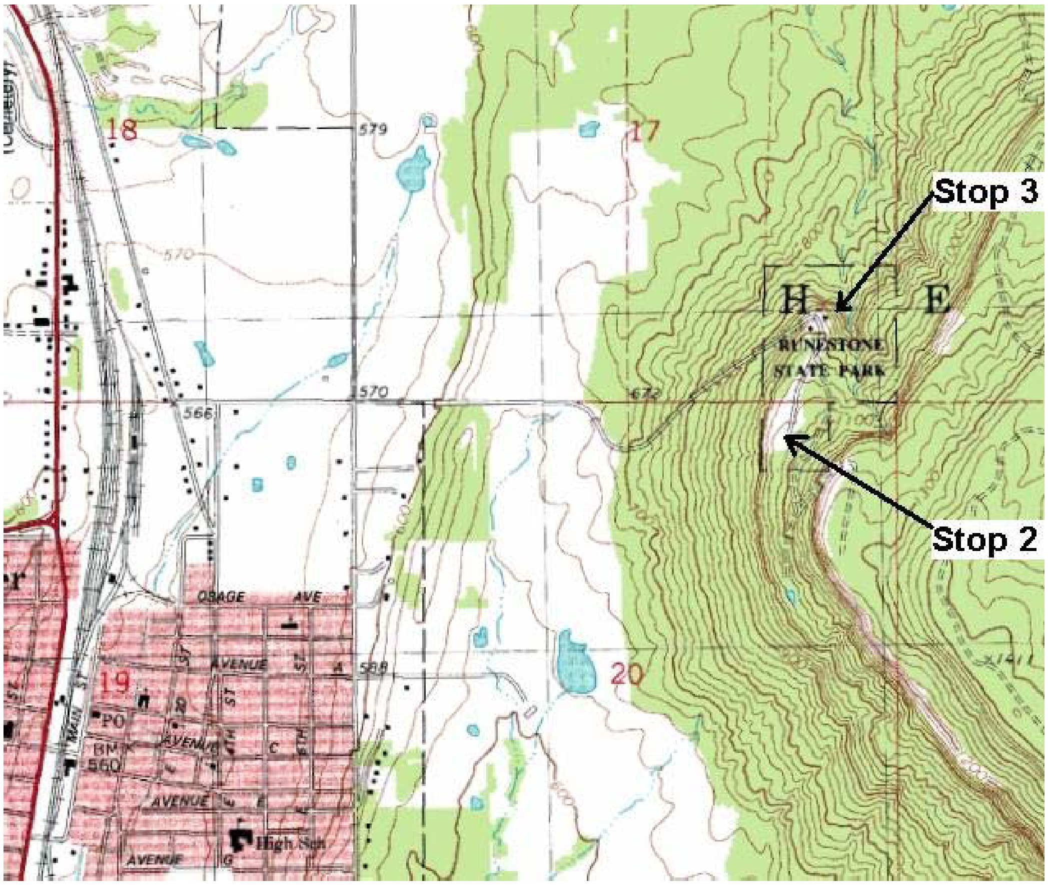
The low mountain just ahead to the slight left is Lost Mountain. At the top is a thick, channel-fill facies of the upper Hartshorne sandstone. The mountain and nearby area are honeycombed with abandoned underground mines. An approximate 4-foot exposure of lower Hartshorne coal is visible at the southeast end of the mountain. This area and much of Section 18 make up the Dawes Coal Company Problem Area that has been reclaimed under Oklahoma's Abandoned Mine Land Program.



8.0mi Turn right (east) and cross Kansas City Southern Railroad tracks. At first intersection (0.1mi) turn right (south).

8.8mi Turn left (east) and follow road to Poteau Mountain and Heavener Runestone State Park.

9.3mi Heavener water tower, on north side of road, sits on a resistant ridge of Warner sandstone. Proceed up the mountain, past the park office, community building, and to the southern parking lot.



Stop 2

Heavener Anticline and Arkoma Basin-Ouachita Mountains Transition Zone

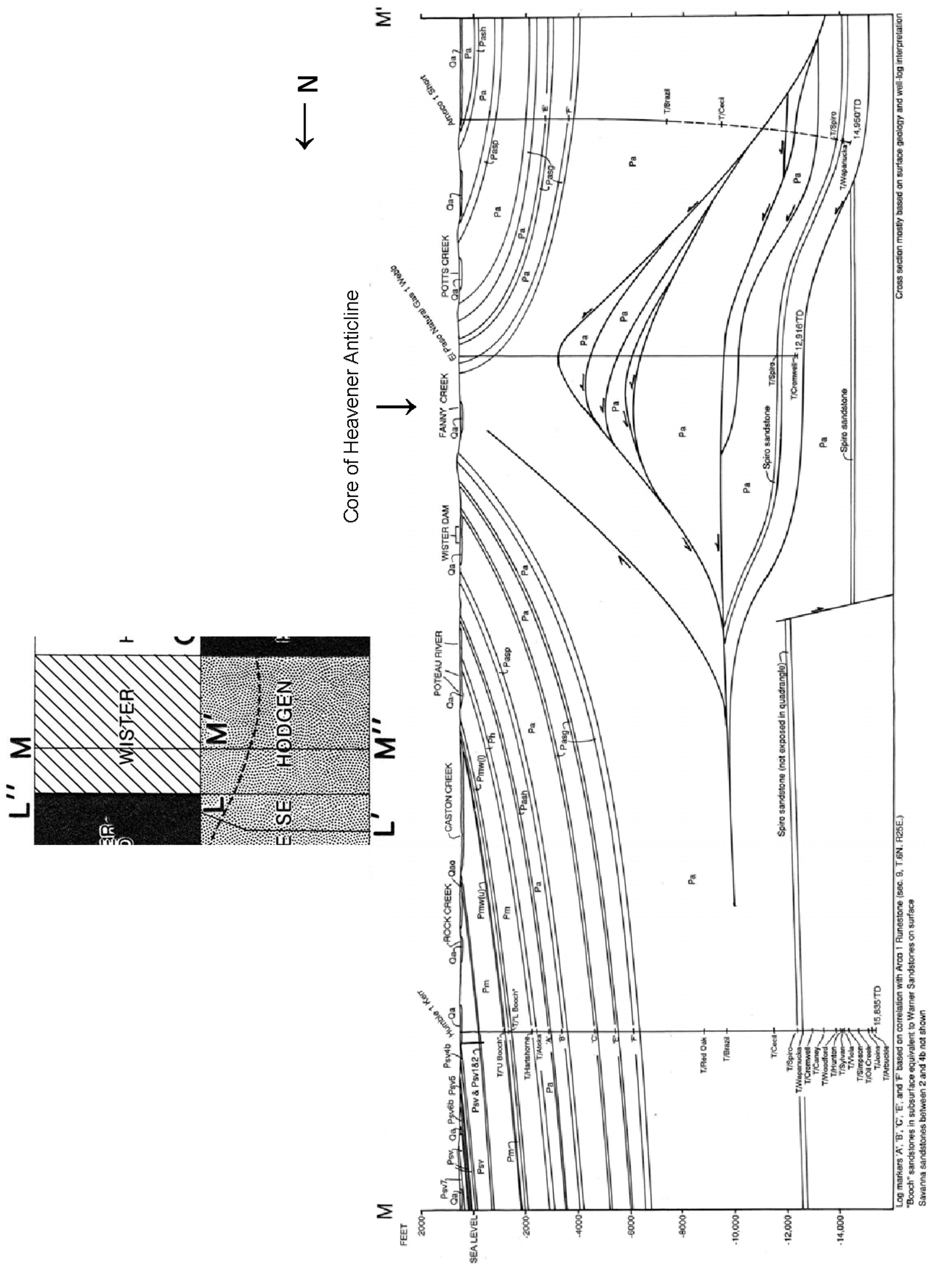
Two of the most spectacular folds of the Ouachita-Arkoma area – the Pine Mountain Syncline and the Heavener Anticline – are easily visible from this overlook. The two folds plunge to the west and involve the Atoka and Hartshorne Formations. The sandstone ridges of the anticline are tree-covered, while the shale intervals have weathered to soil and are mostly cultivated valleys between the ridges. The core of the anticline exposes the informally named Glendale sandstone, which is the oldest Atoka sandstone exposed in the southern part of the Arkoma Basin. The second and third ridges are the Potts Mountain and Horseshoe Ridge sandstones, respectively. The outermost curved ridge is the Hartshorne Formation. The "Heavener Road Cut" can be seen to the south on the highway on the southern limb of the Pine Mountain Syncline. The northern thrust fault boundary of the Ouachita Mountains can be inferred by the sudden change from cultivated fields to forested mountain terrain. This is easily seen on the cover of this guide at the top of the picture. Poteau Mountain and the Heavener Anticline are visible at the upper right of that picture.

The footwall of the Choctaw Fault contains a basal detachment fault within the Devonian Woodford shale, which is well recognized as the Woodford Detachment Fault. In southern LeFlore County (approximately 35 miles south of Heavener), this fault is approximately 20,000 feet below sea level. By approximately 27 miles south of Heavener, the detachment fault rises about 1,000 feet. At that point, the detachment fault turns up-section, leaves the Woodford shale, and rises into the Morrowan Springer shale to become the Springer Detachment. The Springer Detachment serves as the floor thrust of a duplex structure that has a base at approximately 16,000 feet below sea level (see Figure 36). There is another detachment that branches off the Springer Detachment and forms the Lower Atoka Detachment. This Lower Atoka Detachment acts as a roof thrust for a large duplex structure and rises to approximately 12,000 feet below sea level and continues horizontally for some distance.

Between the Lower Atoka Detachment and the Springer Detachment are numerous south-dipping thrust faults. Several wells have been drilled into the core of the Heavener Anticline including the El Paso No. 1 Webb (18-5N-25E). This well shows an interval between 5,700 and 7,100 feet of multiple repetitions of beds that suggest thrusting. Tectonic thickening in this interval and the apparent absence of major thrust faults at the surface lead Hemish and Suneson (1993) to interpret a duplex structure within the Atoka beneath the Heavener Anticline. These imbricate thrusts create a series of horses that are hinterland-dipping and decrease the displacement to the north. Some data (Hemish and Suneson, 1993) also suggest that there may be a triangle zone set up by these horses beneath the Heavener Anticline (see Figure 36).

Besides the geology and the view, this overlook provides a visual representation of a contour map. The treed ridges of the Heavener Anticline are representative of "lines of constant depth", while the cultivated valleys are representative of the distance between contours.

Heavener Anticline. Upper left is Wister Lake. The town of Heavener is easily seen in the lower right center. Heavener Runestone State Park can be seen right of north Heavener. Ponds north and south of Heavener are located on reclaimed coal mining areas.



Core of Heavener Anticline
N
L''
M
L'
M'
M''
WISTER
HODGEN
FEET
SEA LEVEL
M
M'
FANNY CREEK
POTTS CREEK
WISTER DAM
POTEAU RIVER
CASTON CREEK
ROCK CREEK
Spiro sandstone (not exposed in quadrangle)
Cross section mostly based on surface geology and well-log interpretation

Return to the vehicles and drive to the parking area near the Park office.

10.7mi Heavener Runestone State Park office. Park and proceed down walkway south of the office. Take the upper trail. Please leave all rock hammers in the vehicles.

Stop 3
Savanna #2 Sandstone, Basal Shale and Heavener Runestone

The Savanna Formation includes all the strata from the top of the youngest unnamed shale unit of the McAlester Formation to the base of the Bluejacket sandstone Member (known as the Bartlesville sand in the subsurface) of the Boggy Formation. The Savanna sandstone that forms the cliff here at Runestone Park is stratigraphically the same that underlies Kerr Conference Center – Savanna #2 sandstone. Though there has not been a comprehensive study of the depositional environment of the Savanna, it is generally agreed that the Savanna was deposited in a deltaic environment. It appears that the Savanna was sourced from the south (Ouachita "High" during Pennsylvanian) in the western Arkoma and from the east in the eastern Arkoma. The formation thickens to the east. There appear to be seven transgressive/regressive events during Savanna times. These repetitive cycles are called cyclothems.

This valley is cut into a deltaic (shallow marine) sand deposit of the Savanna #2. Along the upper path, the sandstone is composed of fine- to very-fine-grained sand with quartz cementation and is moderate reddish-brown to moderate yellowish-brown on weathered surfaces. One can find wavy to lenticular bedding, obscurely ripple-marked bedding surfaces with some trace fossils and black comminuted plant material. Generally, the unit coarsens upward. Look for indications of deltaic deposition. Descend into the valley and through the Runestone house.

There will be a trail that leads uphill to the right. Take that trail.

This trail dead-ends at a bay/marine siltstone inclusion within the sandstone. The siltstone is very-fine-grained sand and shale that weathers to a brownish gray. It is very thin bedded, friable, and obscurely ripple-marked. Trace fossils and comminuted plant material may be found on bedding surfaces.

Return to the vehicles. Retrace the route to Seventh Street.

The Heavener Runestone

On Poteau Mountain near the small town of Heavener, Oklahoma, near the Arkansas line, stands a slab of stone which is 12 feet tall, 10 feet wide, and 16 inches thick, like a billboard. There is writing on this billboard, consisting of 8 deeply pecked letters, whose edges have eroded to smoothness, even though the stone's hardness on the Moh's Hardness Scale is 7, where a diamond is 10.

In the 1830s, the Choctaws of Indian Territory saw the writing but could not read it. Various citizens in the 1800s saw the stone and named it "Indian Rock", although the Indians had no alphabets. In 1923 the lettering was submitted by Carl Kemmerer of Heavener to the Smithsonian Institution, who identified the letters as Norse runes.

In 1948, research to find out what the letters said, when they were made, and by whom, was begun by Gloria Stewart Farley, who had seen the inscription as a child. She has spent a total of 38 years finding the answers to these questions. She renamed it The Heavener Runestone in 1951. Based on her research, the Runestone State Park came into existence to preserve this stone in 1970.

By 1967 the runes were believed to represent the date of November 11, 1012, with the runes used as numbers in a Norse cryptopuzzle, according to Alf Monge, a cryptanalyst who was born in Norway. The authenticity of the stone being made by ancient Vikings was supported by the finding of two more runestones in the vicinity of Poteau Mountain, another smaller inscription of eight runes at a foothill, Cavanal Mountain, 14 miles away, and another stone bearing five runes at Shawnee, Oklahoma. In 1986, it was found that these five runestones had apparently been made even two or three centuries earlier, before 800 A.D. Translations were made in words, not numbers, by Dr. Richard Nielson, whose doctorate was obtained at the University of Denmark. By making an in-depth study of the ancient literature and hundreds of Scandinavian runestones, he determined that the second and eighth runes are actually variants of the letter L, which permitted him to say that the Heavener runes are G-L-O-M-E-D-A-L, meaning Glome's Valley, a land claim. The similar Poteau runes are a memorial to the same man, meaning, "Magic or protection to Gloie (his nickname)". The Shawnee runestone is the name MEDOK, and was probably a gravestone but had been moved because of construction work. The other two runestones on or near Poteau Mountain do not have enough runes for a translation, but the four stones were placed in a straight line, miles apart. These five inscriptions are all from the oldest 24-rune FUTHARK, used from 300 until 800 A.D. in Scandinavia.

It is believed that these Norse explorers crossed the Atlantic, rounded the tip of Florida into the Gulf of Mexico, found the Mississippi River, and sailed into its tributaries, the Arkansas and Poteau Rivers, around 750 A.D. This date is indicated by the grammar used on the Poteau Runestone.

There is much evidence that many Old-World cultures visited America centuries before Columbus, discovered by Gloria Farley and her colleagues, and presented in her book, "In Plain Sight: Old World Records in Ancient America". One chapter of her book is devoted to the Oklahoma Runestones. For more information, visit URL http://www2.privatei.com/~bartjean/chap9.htm.

Another, possibly more plausible, explanation is not well-accepted by the Heavener locals. Wycoff (1973), a State Archeologist, reviewed evidence for the antiquity of the six runestones found in Oklahoma. He suggests that two were probably carved by prehistoric or early historic Native Americans. Based on the character of the inscriptions and the hardness of the stone into which they were carved, Wycoff believes two others were probably cut about ten years before they were found. Another stone was not present in the 1920s, as reported by a man who grew up near where it was found. Therefore, using other Oklahoma runestones to support the view that the Heavener runestone was carved by Vikings is inadequate. Wycoff admits that there is no evidence against a Viking origin for the Heavener Runestone. However, he suggests that it was carved in the 1800s possibly from two different sources. Fort Smith, Arkansas (35 miles to the north) was an active trading center and military post visited by people with European education that included “the study of runic alphabets”. An even-more-plausible suggestion of the source comes from one of our later stops. In the 1890’s, the Queen Wilhelmina Inn was built just a few miles to the south and east on Rich Mountain. This resort was built to cater to wealthy Dutch and German families. It is possible that the Heavener Runestone might have been carved during an outing and climbing of the hill just north and west of the inn. The coal mining industry was well established in this area at the time, so chisels, hammers, and other tools would have been readily available. And, if it was carved by a (possibly young) European tourist, it certainly would not have been the first time people of European descent left graffiti for those arriving later to ponder.

Wycoff, D. G., 1973, No stone unturned; differing views of Oklahoma’s runestones: Popular Archaeology, August 1973, p. 16-31.

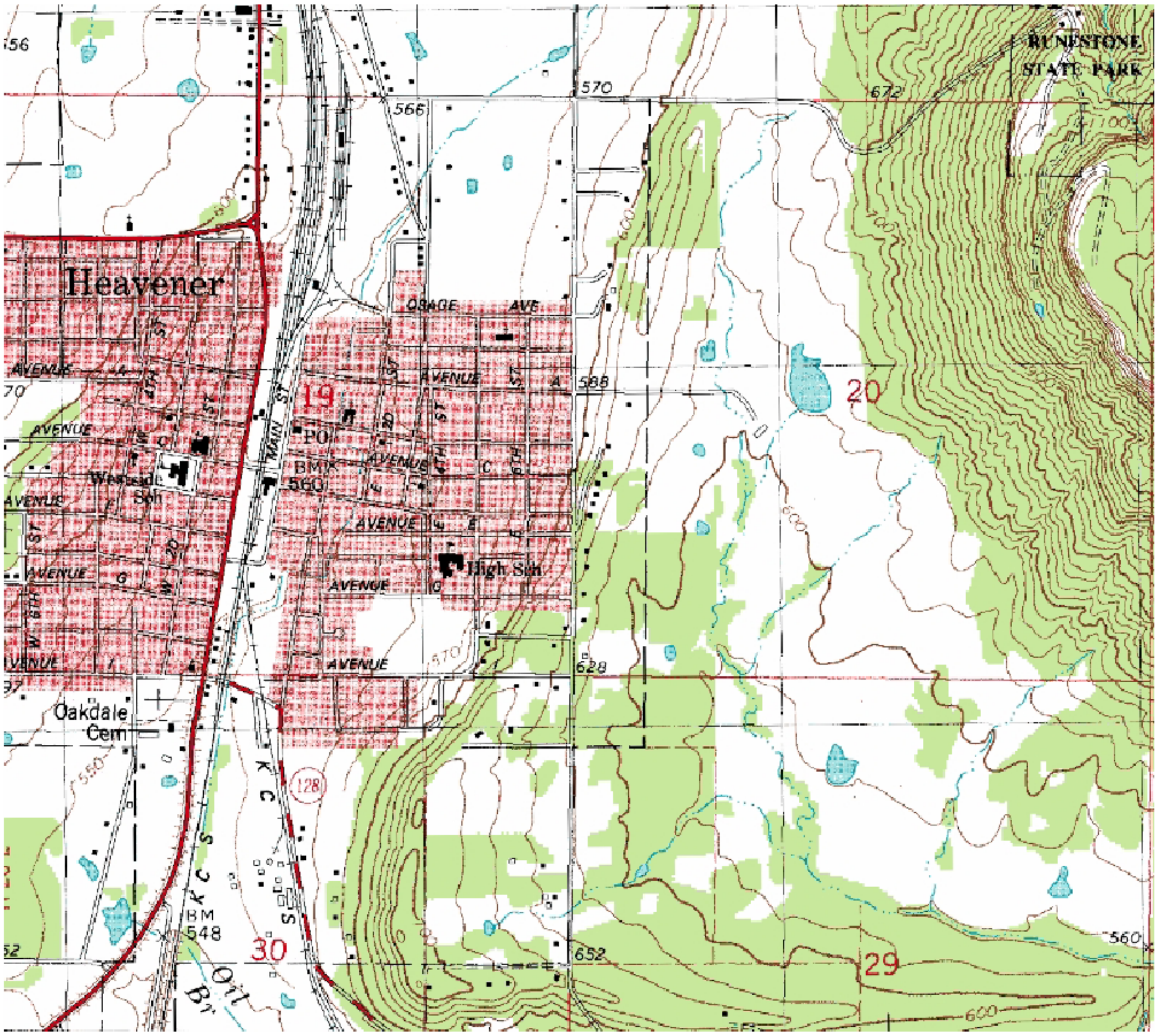
11.7mi Turn left (south) on Seventh Street.

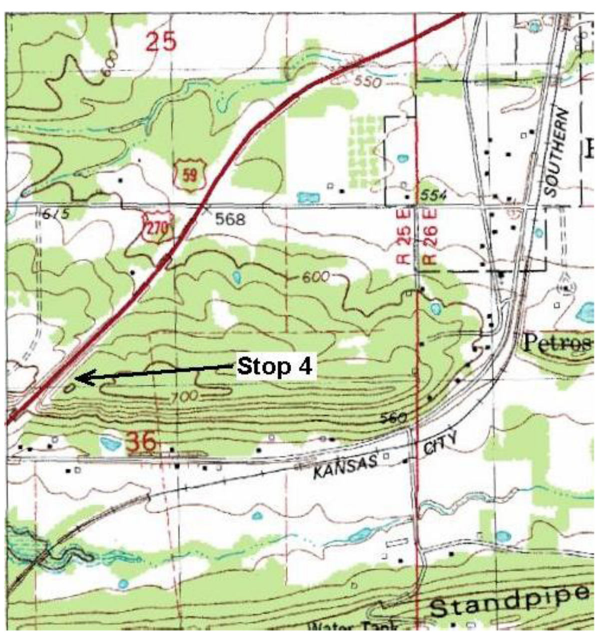
12.3mi Turn right (west) on C Street.

15.4mi Turn left (south) on Main Street and in about 250 feet, turn right (west) and cross the Kansas City Southern Railroad tracks.

12.8mi Intersection with U.S. 59/270. Turn left (south).

15.0mi Heavener road cut.


RUNESTONE
STATE PARK
Heavener
19
20
PO
High Sch
Oakdale
Cem
30
29
128
OSAGE AVE
MAIN ST


25
Stop 4
36
KANSAS CITY
SOUTHERN
R 25 E
R 26 E
Petros
Standpipe
Water Tank

Stop 4

(drive-by or optional stop)

Upper Atoka Formation and Hartshorne Formation

This road cut into the Hartshorne Formation probably has been visited by more geologists than all other Hartshorne outcrops and road cuts in the state combined.

Though an excellent example of delta plain sediments, it is atypical of most exposed Hartshorne strata in the southern part of the Arkoma Basin. It is this outcrop that causes most geologists to think of the Hartshorne deposition as a delta model. This outcrop also causes different thoughts about the deposition of the upper Atoka.

Elsewhere, the upper Atoka Formation is typically marine with distal-marine, prodelta, bar-transition, and marine-bar environments. Here at this road cut, the upper Atoka is bay-fill shale and marsh coal deposits. Suneson (1998) describes the Atoka in this cut as two fining-upward transgressive sequences consisting of laminated sandy siltstones grading into black organic-rich shales with abundant siderite nodules and ending with a layer of coal. The environment for this deposition was possibly an interdistributary bay in a delta-margin environment. The uppermost zone of the Atoka at this cut is another sandy siltstone distal crevasse-splay zone. In the Mobil No. 1 Ann Lyons well, approximately 7.1 miles north-northeast of this cut, the log interpretation of the upper Atoka is more typical – that being one of marine shale and shoreface-transition strata.

The Hartshorne strata exposed in this cut were deposited in interdistributary marshes and swamps of a delta-plain environment, much like the upper Atoka. The coal beds represent periods of little to no sediment influx and peat accumulation. The sandstones are overbank and/or crevasse-splay deposits that are probably a result of flooding. At this road cut exposure, no Hartshorne fluvial channels are present.

16.7mi Enter Hodgen, Oklahoma

17.5mi Cross trace of the Choctaw Fault. We are now in the Ouachita Mountains.

→

17.7mi Highway bends to the right (west). Outcrops on the right are turbidites in the Atoka Formation. For the next 3 miles, the highway crosses steeply dipping, imbricately thrust-faulted Atoka Formation turbidites.

24.2mi The village of Stapp, Oklahoma was located here.

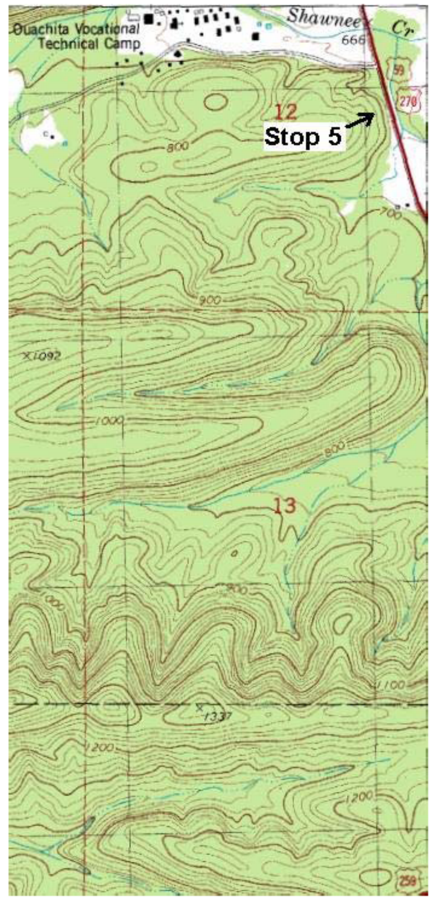
24.9mi Road to Ouachita Vocational Technical Camp to right (west).

25.0mi Excellent outcrop of Johns Valley Formation on right.

Stop 5
Johns Valley Shale at Stapp

This outcrop and the one along the Kansas City Southern Railroad 0.25 mile to the southeast have fueled many arguments about the origin of the Johns Valley Formation. Early geologists thought this was the Caney shale, far east of its type section on the Tuskahoma syncline. Ulrich in 1927 first proposed the name Johns Valley shale "for the Pennsylvanian black shale" that "rests on the Jackfork sandstone and is overlain by . . . the Atoka Formation." Ulrich also recognized that the Johns Valley contained erratics from older formations. Powers in 1928 believed this to be basal Atoka and claimed that boulder-bearing Caney shale was near by. Powers also believed the boulders were glacial dropstones and added a high landmass near the present-day Ouachita Mountains. This high landmass was later named "Bengalia" by Kramer in 1933. Basically, this high landmass was an attempt to explain observed formations without assuming any large-scale thrusting. Finally, McDonald studied this area in 1986 and interpreted it in terms of the Mutti and Lucchi turbidite facies classification scheme.

McDonald suggested a boulder conglomerate surrounded above and below by chaotic debris-flow deposits. The remainder of the outcrop is turbidites. Suneson (1994) examined this outcrop again. In his examination, Suneson describes a turbidite facies approximately 70 feet south of the boulder bed where adjacent and steeply dipping sandstone turbidites face in opposite directions indicating an isoclinal syncline. He also describes that the shale immediately adjacent to the boulder bed appears to be "squeezed" into the spaces between adjacent boulders and into cracks of some of the large boulders some 170 feet north of the boulder bed. These features were probably caused by burial and differential compaction of the incompetent shale around competent cobbles and boulders. The matrix between the boulders is shale, but the boulders are clast-supported. In 1938, Harlton described pitted surfaces on the boulders and cobbles probably to justify transportation by glaciers. Suneson did not

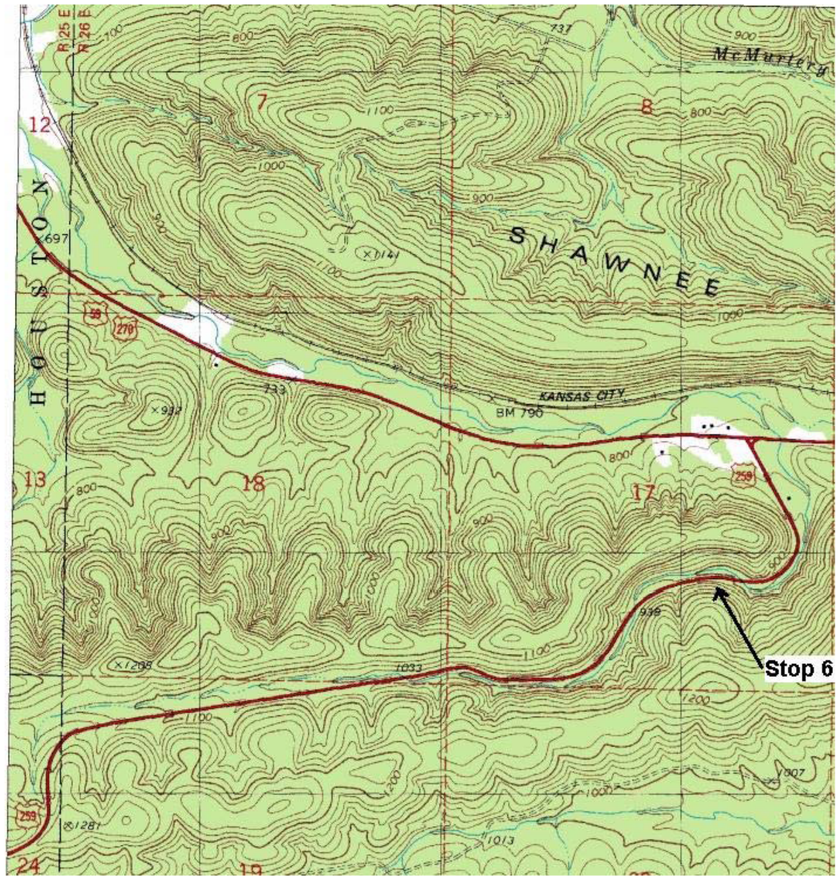


Stapp, Oklahoma

The village of Stapp was founded in 1897 (originally called Thomasville). A post office was maintained from 1918 to 1944. The town originally was a thriving lumber town with a population of 1,000. Nothing remains of the old town. The highway passes through what used to be the lumber yards and single-bandsaw mill of the Buschow Lumber Company. In contrast to present-day conservation practices in lumbering, the Buschow operation was "the ultimate in devastation . . . one of the bad ones . . . a cut-out-and-get-out operation.

(Smith, K. L., 1986, Sawmill: the story of cutting the last great virgin forest east of the Rockies: University of Arkansas Press, Fayetteville, 246p.)

observe any pitted surfaces. Most of the boulders are rounded, with the planar surfaces on some resulting from breakage along bedding planes and/or fractures. Most turbidite strata face north and are overturned. Paleocurrent directions are indicated to be mostly south-southwest and southwest.



27.4mi Intersection of U.S. 259 with 59/270. Turn right (south) on U.S. 259.

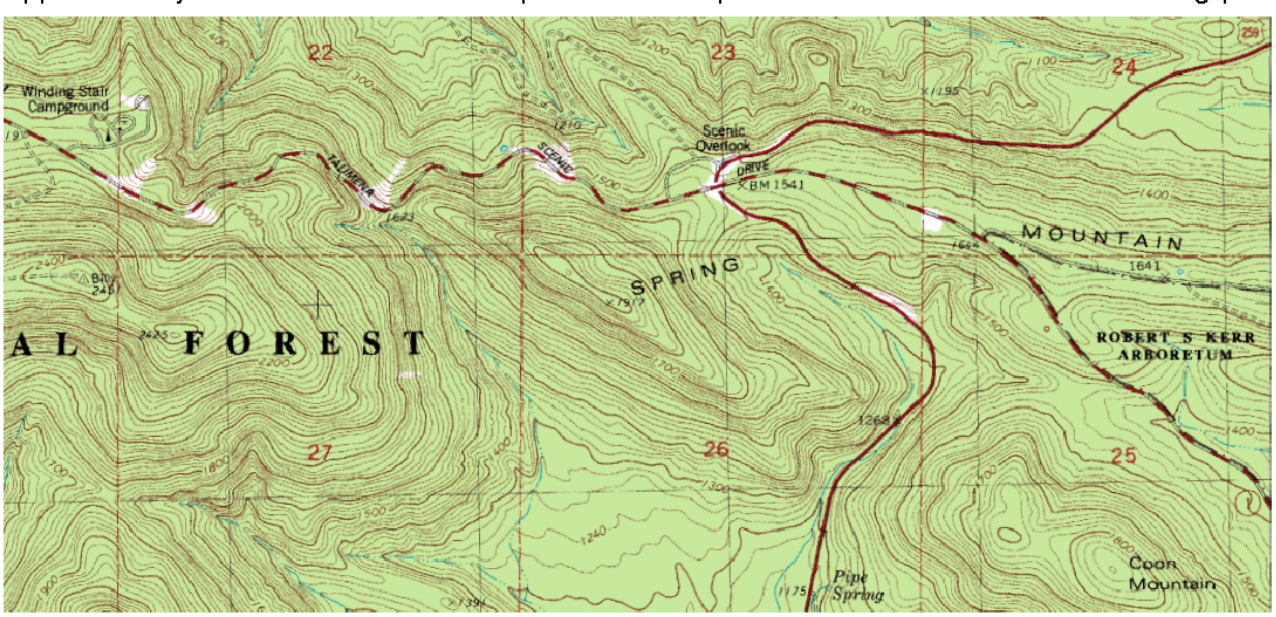
28.0mi Park on side of road and walk back to outcrop.

Stop 6

(optional stop)

Atoka Formation

The strata here at this outcrop are more typical of the Atoka Formation in the frontal belt of the Ouachita Mountains. The shales and mudstones that constitute some 80 percent of the Atoka are rarely so well-exposed. Many features characteristic of turbidites are exposed in this outcrop: graded bedding, sole marks, and complete and incomplete Bouma sequences. This outcrop was probably deposited in an outer-fan environment. Paleocurrent directions are mostly to the west-northwest. Another sequence of Atoka turbidites is well exposed in the stream bed to the north, just on the other side of the road. Approximately 120 feet of section is exposed with 20 percent sandstone and the remaining part



mostly shale. Paleocurrents based upon sole marks are to the west-northwest while paleocurrent directions based upon ripple cross-stratification (Bouma sequence Tc) are to the north-northwest. This stop has a measured section description in the Oklahoma Guide Book 29, Stop 20.

29.5mi Creek on the north side of the road marks the axis of the Spring Mountain syncline.

31.1mi McDonald (1986) also measured several sections of the Atoka Formation on the left (south) side of the highway. Overall, McDonald considered this to be a sandstone-rich part of the Atoka Formation.

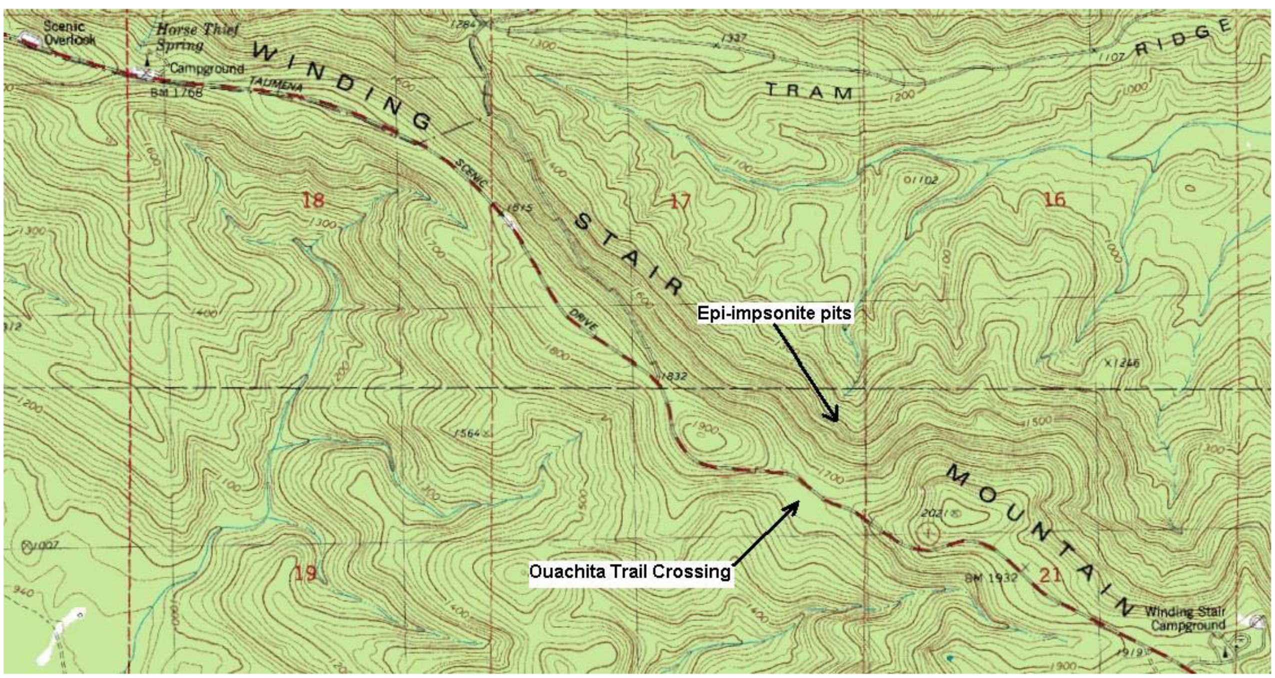
31.6mi Intersection U.S. 259 and OK 1 (Talimena Scenic Drive). Turn right onto on-ramp of Talimena Drive if it is around noon for lunch. Otherwise, skip and continue below at *.

31.8mi Talimena Drive. Turn right (west). There are two near campgrounds/picnic areas. Follow directions as to group's decision.

32.9mi Good outcrop of stacked sandstones in Jackfork Group on left (south).

33.2mi Good outcrop of shale in Jackfork Group strata.

33.6mi Entrance to Winding Stair Campground and Picnic Area (probable lunch site).
34.8mi (Alternative lunch spot) Cross Ouachita Mountain Trail at saddle. The trail is 192 miles



Ouachita National Recreation Trail

This is the longest trail in the Ouachita National Forest spanning 192 miles across its entire length. In the west, the trail begins at Talimena State Park on Highway 271 near Talihina, OK. The eastern boundary is south of Perryville, AR on Highway 9. Elevations range from 600 to 2,600 feet above sea level as the trail passes through forested mountains, across sweeping valleys, and near clear-running streams. The trail is open to foot traffic only for 55 miles and both foot and mountain bike traffic for 137 miles.

http://www.fs.fed.us/r8/ouachita/recreation/documents/TR-01_Ouachita_National_Rec_Trail.pdf long and extends from near Little Rock, AR, to Talimena State Park, OK. On west side of the creek, approximately 300 feet below this saddle on the north side of Winding Stair Mountain, are two small asphaltite pits. Cardott and others (1993) determined that the material is epi-impsonite, and Finkelman and Cardott (1993) report unusually high vanadium content. The asphaltite was mined and used in blacksmith's forges prior to 1936.

37.0mi Entrance to Horse Thief Spring Campground/Picnic Area. The spring was frequented in the late 1800s by a number of horse thieves and bank/train robbers, including the illustrious Belle Starr. Cedar Lake Vista is another 0.4mi west. The vista offers an excellent view to the north of Canaval Hill, Heavener, Cedar Lake, Sugarloaf Mountain, Poteau Mountain, Walker Mountain, and Shawnee Ridges. After lunch, retrace route to U.S. 259.

* If lunch was taken at this time at Winding Stair Campground, follow the same mileage. If lunch was taken at Horse Thief Spring Campground, add 6.8 miles to the following mileage.

36.1mi Intersection with U.S. 259 and Talimena Drive. Turn right (south) on U.S. 259.

36.6mi Contact between Atoka Formation and Johns Valley Formation. Here, the Johns Valley contains numerous blocks of Mississippian Caney shale.

37.4mi Pipe Spring on left (east) side of road is on the trace of the Briery Fault. This is one of the large faults of the Ouachitas. It is at least 60 miles long. At this location, it is one of the few faults to be exposed in the Ouachitas, and this is an especially good exposure. The fault brings Stanley shales up against the Jackfork Group. The stratigraphic displacement is at least 6,500 feet. The horizontal displacement is probably more but unknown.

39.9mi Cross trace of Windingstair Fault. North of this fault is the Ouachita frontal zone.

41.1mi Big Cedar, OK. A monument on the southwest side of the intersection of U.S. 259 and OK 63 notes that President John F. Kennedy, as a guest of Senator Robert S. Kerr, on October 29, 1961 dedicated U.S. 259 as the U.S. highway over the Ouachita Mountains.

**PINE VALLEY TRAM –
FOREST SERVICE ROAD 6029-2**

At the western base of Rich Mountain is Forest Service Road 6029-2. This road travels part of the historic route taken by the Pine Valley Tram as it made its way up the south side of the pass between Spring and Rich Mountains. The road ends at Pipe Spring, a small roadside picnic area on Highway 259.

In the 1920s, a thriving lumber town called Pine Valley developed in the Kiamichi valley. The Oklahoma Rich Mountain Railroad constructed the 15-mile spur over Rich Mountain to the new, state-of-the-art sawmill built by the Dierks Company. The tram line carried logs to the mill and lumber from the mill to Page on the north side. At Page, cargo was transferred to the Kansas City Southern for transport to northern markets. Residents rode the passenger car on the tram line, making the connection in Page, usually traveling on to Mena, Arkansas, for shopping and socializing.

Big Cedar, Oklahoma

Big Cedar, located in the valley of the Kiamichi River between Kiamichi Mountain to the south and Winding Stair Mountain to the north, occupies one of the truly picturesque sites in Oklahoma. The hamlet is said to have derived its name from either a very large cedar tree that grew nearby or from an enormous grove of large cedars that grew in the vicinity. The settlement may have been located where it was because of the cedars, for most were soon cut and marketed. Records indicate that until the 1940s there was a small sawmill in operation most of the time.

The hamlet probably had its greatest population, about fifty persons, in 1910. One general store in which a post office was located, a blacksmith shop, a gristmill, a sawmill, and a cotton gin formed the commercial activities. Three years later only the store and sawmill remained. Because of the lack of good roads, the area was sparsely populated and isolated.

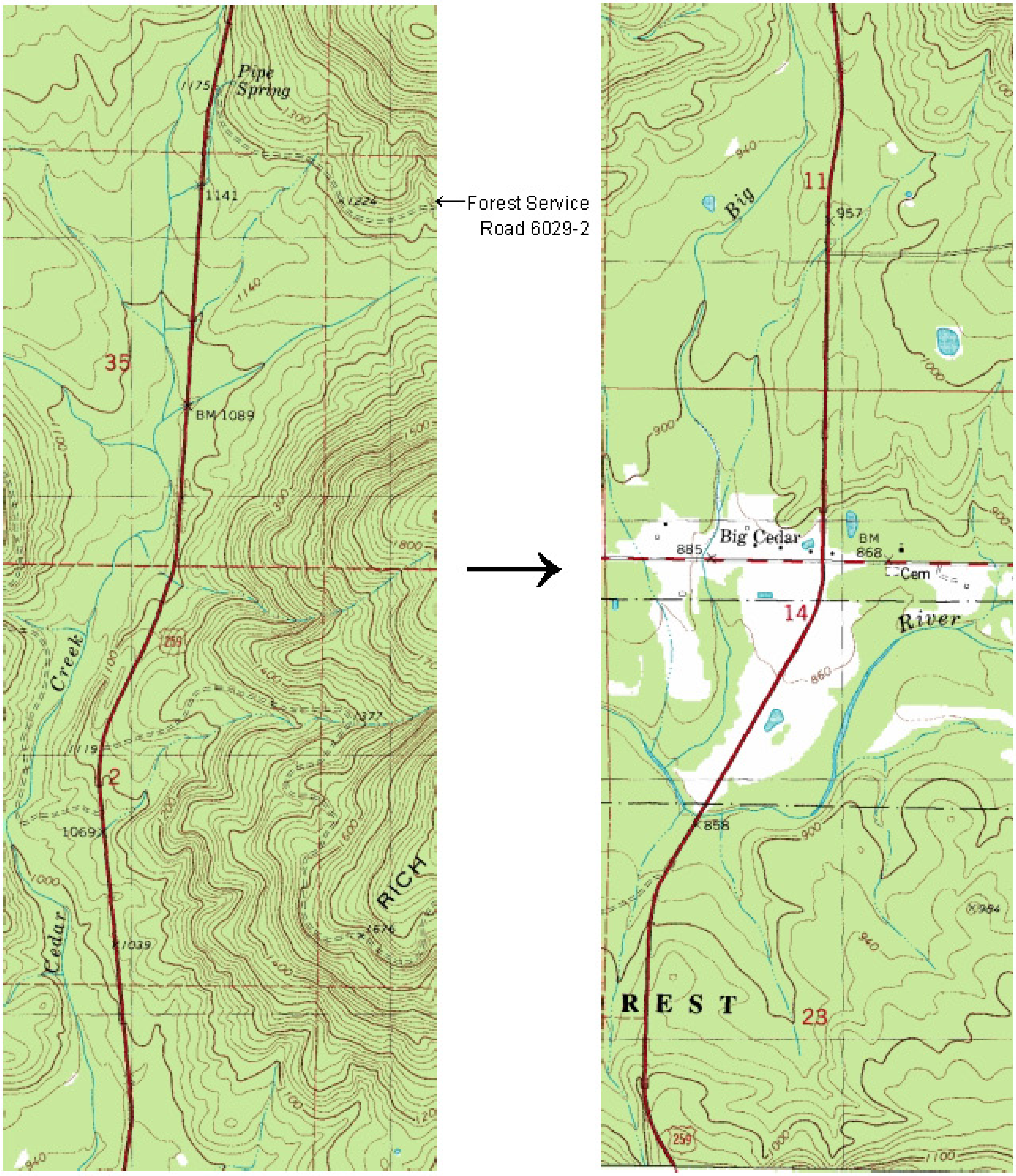
In the late 1930s activity increased when (after the repeal of Prohibition) the white oaks of the area were being cut and made into barrel staves, the stave mill being located in Big Cedar. The staves were dried in the open and sent to a finishing mill in Arkansas. By 1940 the stave mill was closed, and only the same store remained.

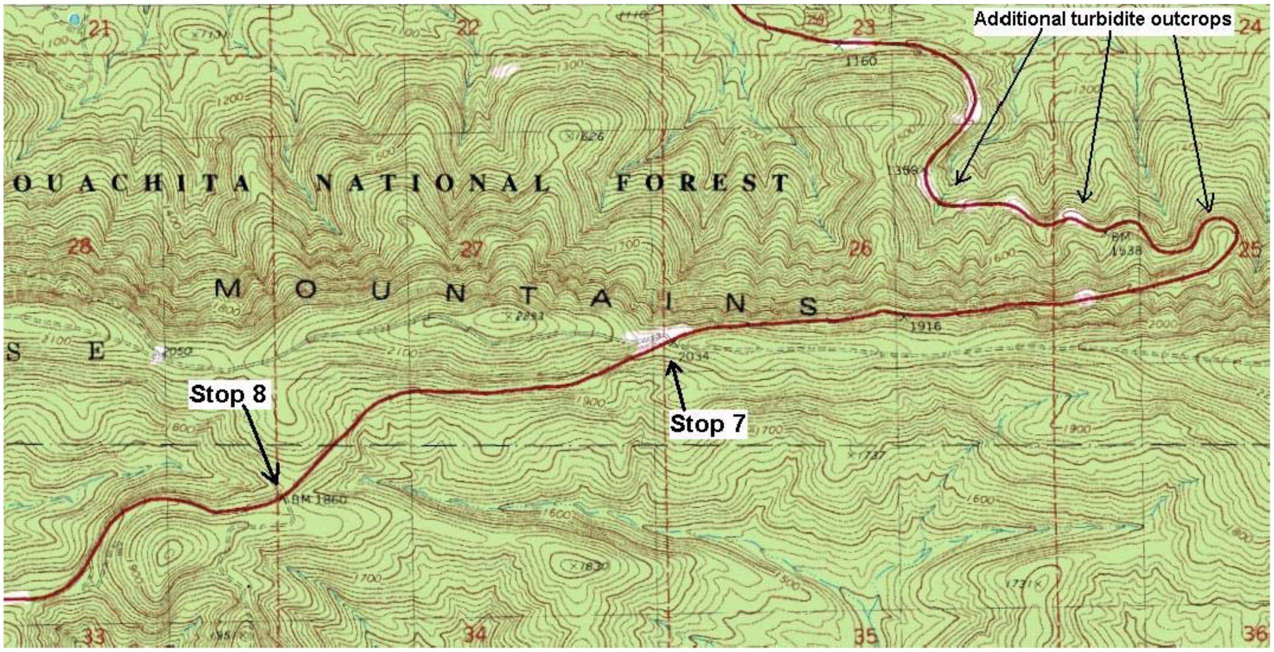
Following World War II, State Highway 63 from Talihina to Mena, Arkansas, through the Kiamichi Valley, was paved. In 1961 U. S. Highway 59 (259), extending from Monterrey, Mexico to Winnipeg, Canada, was completed through the mountains of eastern Oklahoma. Big Cedar then had its "day in the sun." President John F. Kennedy delivered the address that officially opened the highway on Sunday, October 29, 1961, at Big Cedar. At that time this ghost hamlet had at least twenty thousand visitors. Its natural beauties were shown on television to all parts of the nation. During his talk the President said "A sympathetic understanding and sound evaluation of present-day conditions in Oklahoma necessitates knowledge of the salient facts of the state's history, for the historical development of any locality determines in large measure the present social conditions of the given region and furnishes a key to an understanding of its peculiar characteristics. The history of Oklahoma has been a unique one, romantic, and some respects tragic."

The humorous side of the dedication: President Kennedy almost forgot to cut the opening ribbon. Rep. Carl Albert called Kerr's attention to the Secret Service man holding the scissors. Kerr told the President, "Mr. President, we have come here to dedicate a highway." Kerr handed JFK the scissors who clipped the ribbon officially opening the new U.S. highway.

Big Cedar today is identified by a roadside monument dedicated to President Kennedy. One small convenience store is located across the intersection to the north. The area is sparsely populated. Most motorists speed past without realizing the historic importance of the place.

41.8mi Cross Kiamichi River.





43.4mi Outcrop of Chickasaw Creek Siliceous shale, the uppermost formation in the Stanley Group, on the right (west) side of road. Road for the next several miles passes through the Wildhorse Mountain Formation of the Jackfork Group.

44.5mi Hairpin curve.

47.2mi Three Sticks Monument at top of Kiamichi Mountain. Elevation, 2,034 feet.

47.5mi Park on turnoff on left (south) side of road to examine large dip-slope outcrop of sandstone in the Jackfork Group. **Please be careful! This highway is <u>the</u> major north-south highway through the Ouachitas and is very busy!**

<u>Stop 7</u>

Friable and Cemented Sandstones of the Jackfork Group – Lynn Mountain Syncline

As stated in the geological history section, the Jackfork was deposited in the east-west trending Ouachita Basin during Morrowan times when this was a tectonically active area and with fluctuating low sea levels. The sandstones of the Jackfork Group produce gas in the Potato Hills, Buffalo Mountain, and Talihina Northwest fields. The gas production is believed to be primarily from fractures since much of the Jackfork is quartz-cemented sandstone and a real "hammer-ringer".

Three Sticks Monument

The Three Sticks National Forest Monument honors the five people who were primarily responsible for the construction of the original state highway and/or the promotion of the area to bring about the highway construction. The three "sticks" represent Kerr's "Land, Wood, and Water."

A dedication sign reads:

In Appreciation of the Leadership in the
Rapid Development of Our State Roads,
Water, Recreation, Forests
"LAND — WOOD —-WATER"
We, the Grateful Citizens of McCurtain and
LeFlore Counties Contribute and Dedicate
This Monument to the Following:
SENATOR ROBERT S. KERR
SENATOR MIKE MONRONEY
CONGRESSMAN CARL ALBERT
GOVERNOR RAYMOND GARY
R.G. MILLER (Daily Oklahoman).

Contrary to some beliefs, President Kennedy did not dedicate U.S. 259 from this location. As Raymond Gary was governor of Oklahoma from 1955-59, this monument's honorees predate Kennedy's visit. This monument was formerly known as "Mount Kiamichi Monument" and "Recognition Monument and Park" on Oklahoma State Highway 103. Money for the construction of the monument was donated by public-spirited citizens of LeFlore and McCurtain Counties.

However, some of the Jackfork is weakly cemented and has substantial porosity and permeability. This stop and two more of the day will examine the relationship between the cemented (fracture porosity) and weakly cemented (matrix porosity) sandstones. **Carefully cross the highway** and walk west of the Three Sticks Monument along the highway.

Approximately 110 feet of the upper part of the Wildhorse Mountain Formation is well-exposed here. The lower part of this section consists of interbedded, highly cemented sheet sandstones and interbedded shales. The upper part of the section consists of more massive (no shale interbeds), friable channel sandstones. This interpretation is based upon a number of criteria developed for the Jackfork by Slatt et al. (2000), such as the nature of the bed boundaries, the presence or absence of shale clasts in sandstones, and stratification style. Sheet sandstones are interpreted as being deposited in a basinal or base-of-slope setting. Channel sandstones are interpreted to have been deposited in a more proximal setting on the slope of the basin.

Outcrop measurements have identified two dominant fracture sets oriented orthogonal to one another and normal to bedding. The attitude of the primary set of fractures is N71°W, 59°N. The strike of this set is approximately parallel to the strike of the bedding planes. The attitude of the second set of fractures is N13°E, 87°W. The strike of this set is approximately parallel to the dip of the bedding planes, and, in general, these fractures terminate against the primary set.

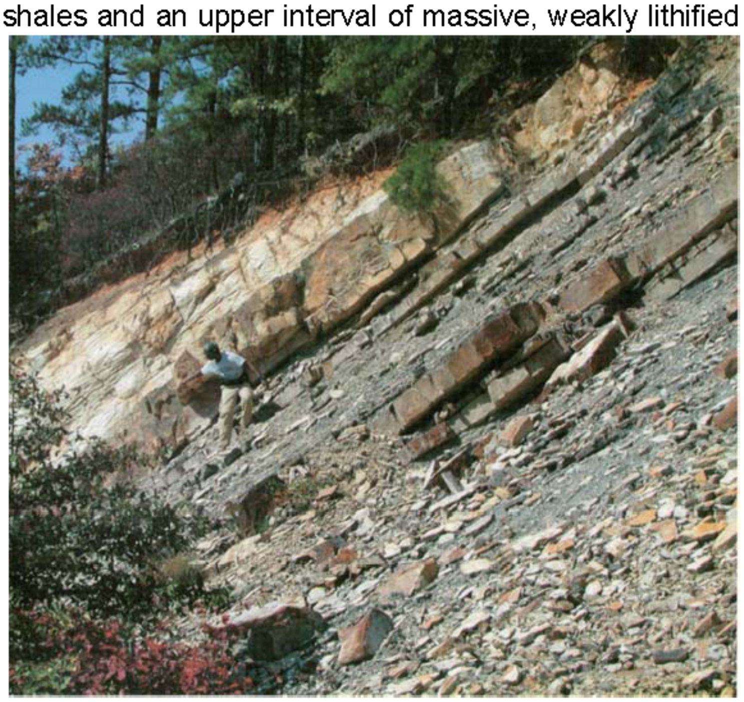
Return to the vehicles. **Be very careful when crossing the highway.** Continue south for a short distance on U.S. 259.

48.4mi Turn left (south) on dirt road and park. Walk back to examine large outcrop of Jackfork. **Please watch for traffic as you cross the highway to the north side!**

Stop 8

Friable and Cemented Sandstones of the Jackfork Group – Lynn Mountain Syncline

Approximately 175 feet of the upper part of the Wildhorse Mountain Formation is exposed at this stop. The base of this outcrop is approximately 321 feet above the top of the previous stop. Similar to the previous stop, the Jackfork here consists of a succession of lower, interbedded, quartz-cemented sheet sandstones and shales and an upper interval of massive, weakly lithified channel sandstones.



The contact between the cemented and friable sandstones is sharp. Lithologically, the quartz-cemented sandstones are very fine to fine grained, moderately to well sorted, and planar-tabular bedded with characteristic deep water sedimentary structures. The bases and tops of beds are sharp and generally non-erosive. By contrast, the friable sandstones are medium to fine grained, poorly to moderately sorted, massive, and commonly have undulatory bed boundaries. Petrographic studies show different diagenetic features in the two sandstone types. Quartz overgrowths and pressure solution characterize the quartz-cemented sandstones, and feldspar dissolution and clay are common in the friable sandstones.

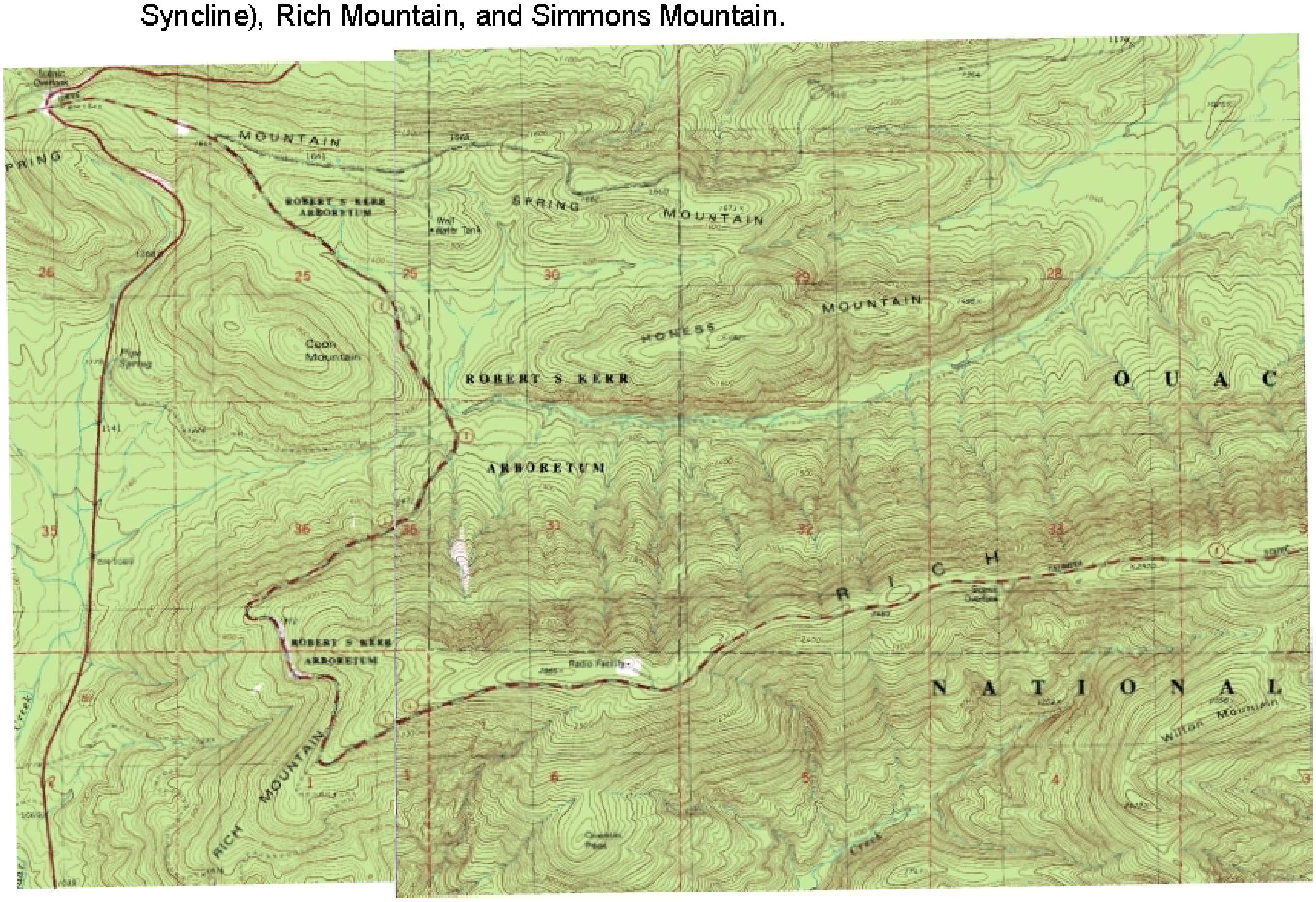
The relation between cementation and depositional environment can be explained in terms of sedimentary processes and burial diagenesis. Quartz cementation is restricted to the sheet sandstones as a result of long-distance transport via turbidity currents. These turbidity currents sorted the sands and removed most of the clay fraction (Omatsola, 2003). During burial diagenesis, silica-rich fluids migrated through the sands, and quartz precipitated out around sand grains. However, the more poorly sorted, clay-rich channel sandstones were not transported as far, and more detrital clay was deposited within the sand. During diagenesis, this clay would serve as a coating around the quartz sand grains thus preventing silica nucleation and cementation. As discussed at the previous stop, the weakly cemented sandstones typically are iron-stained in the outcrop. Siderite cement occurs in this type of sandstone in the subsurface but is not present in the outcrop. Probably the iron stain of the channel facies outcrop is derived from the siderite cement. This also would explain the apparent lack of cementation in outcrop exposure.

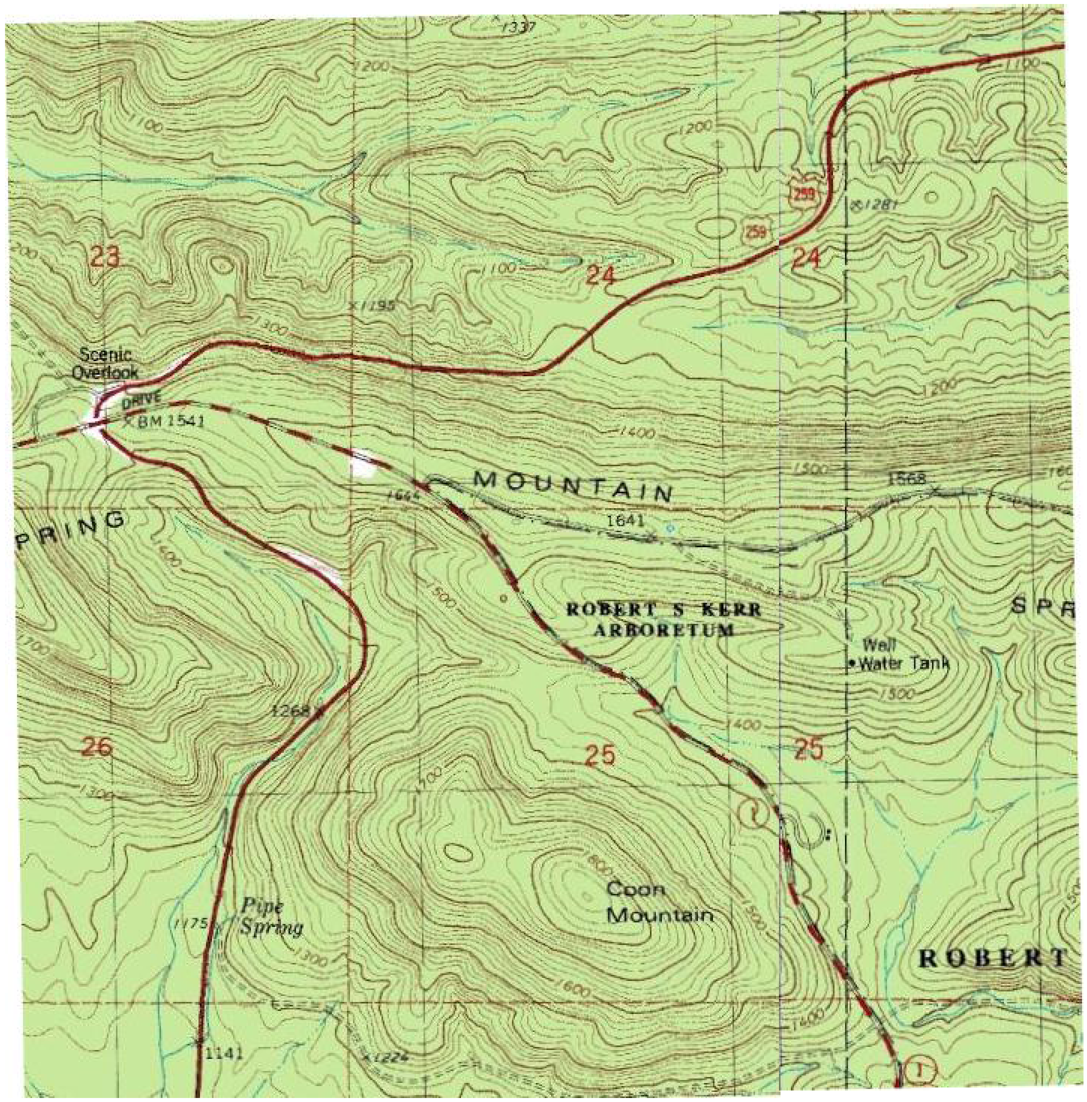
Carefully return to the vehicles and retrace the route back to Talimena Drive.

60.7mi Intersection of U.S. 259 and Talimena Drive (S.H. 1). Turn left (west) onto access road to Talimena Drive.

60.9 mi Intersection with Talimena Drive. Turn left (east).

61.6mi Big Cedar Vista. Good view of Kiamichi Mountain (north flank of Lynn Mountain Syncline), Rich Mountain, and Simmons Mountain.





61.7mi Forest Service Road 6007 to left (east).

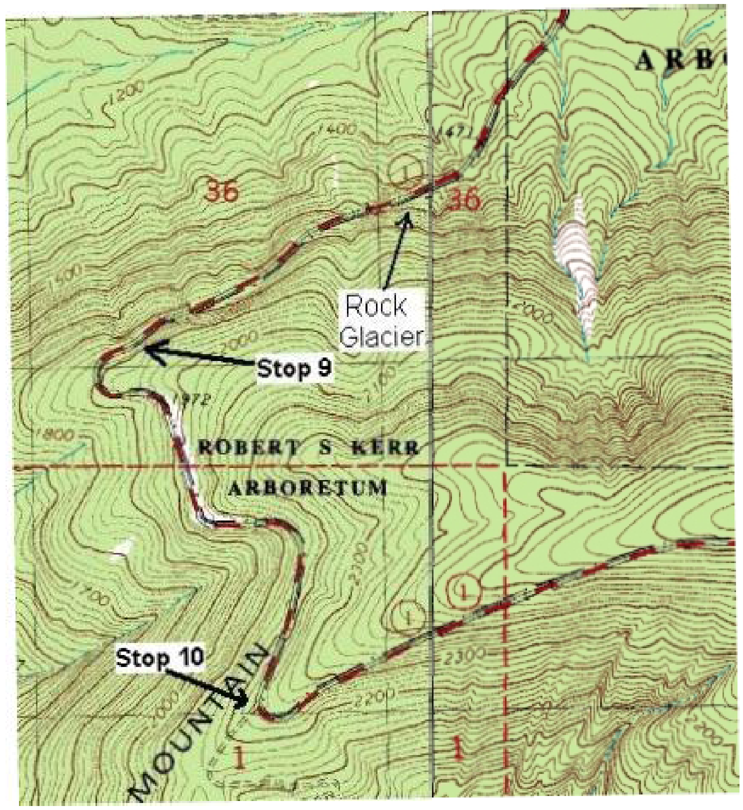
62.1mi Excellent outcrops of northeast-facing Atoka Formation sandstones on south flank of Spring Mountain Syncline. A wide variety of sole marks and soft-sediment-deformation features occur in these strata. Paleocurrent directions based on sole marks are mostly south-southeast to north-northwest; some indicate a current direction to the west-northwest.

62.6mi Forest Service Road 6029-2 on right (west).

63.1mi Rock glacier on left (south).

Stone and McFarland (1979) note that more than 100 similar rock glaciers are present in the northern part of the Ouachita Mountains in Arkansas and Oklahoma, some of which are active.

63.3mi Several large outcrops of Stanley Group strata (Moyers Formation) on the left (south).



63.4mi The large outcrop on the left (south) exposes the Chickasaw Creek Siliceous shale and the lower-most part of the Wildhorse Mountain Formation (Jackfork Group) at the top. Pull off the road for stop.

Stop 9
Stanley/Jackfork Contact and Chickasaw Creek Siliceous Shale

Unlike the siliceous shales of the Tenmile Creek and Moyers Formations, the Chickasaw Creek siliceous shale appears to be present throughout most of the Ouachita Mountains in Oklahoma and Arkansas. At this locality, the approximately 3 foot thick siliceous shale is the only siliceous shale separating the Stanley Group strata and the Jackfork Group sandstones.

The age of the Chickasaw Creek has not been determined directly despite the abundant radiolarians and conodonts. There is no evidence for unconformities within the Stanley Group and the Chickasaw Creek is conformably overlain by the Jackfork Group. The upper part of the Stanley below the Chickasaw Creek appears to be Chesterian (late Mississippian). Plant fossils from the lower part of the Jackfork Group in the Buffalo Mountain Syncline west of Talihina are Chesterian, and marine invertebrates from several localities in Arkansas of the stratigraphically similar Jackfork are early Morrowan (early Pennsylvanian). Thus, the top of the Chickasaw Creek marks the Mississippian/Pennsylvanian boundary, but it is possible that the boundary lies somewhere in the lowermost Jackfork.

Return to vehicles for short drive.

64.7mi Forest Service road to the right (south). Turn off and park on Forest Service road. We will walk back to Stop 10.

Stop 10
(optional or drive-by)
Friable and Cemented Sandstones of the Jackfork Group – Rich Mountain Syncline

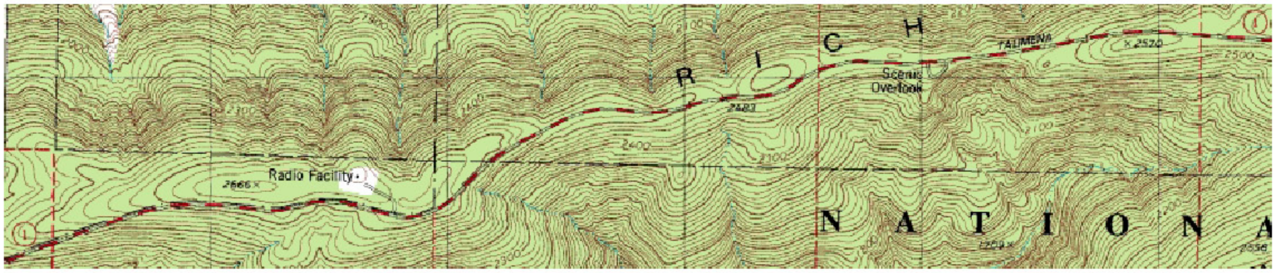
This outcrop within the Wildhorse Mountain Formation is an unusual and uncommon type of Jackfork strata. The Jackfork here consists of 280 feet of poorly consolidated sandstone that appears to be more feldspathic and siltier than those exposed on Kiamichi Mountain. The weakly consolidated strata, however, are stratified and contain some lithified shale beds, including one that is conspicuously maroon. Perhaps the most interesting aspect of this outcrop is that quartz-cemented fractured sandstones are present at the top and bottom of the overall poorly consolidated section. If a section such as this were discovered in the subsurface (possibly, as in the Potato Hills Field), the positive aspect of it would be that of a thick section of unconsolidated, moderately porous, potentially gas-bearing Jackfork. The negative aspect would be that the high silt content would decrease the porosity and permeability and might plug the wellbore and/or pore throats. This poorly consolidated section also contains fractures, suggesting that it might have once been lithified. The diagenetic history of this section is as yet not fully understood.

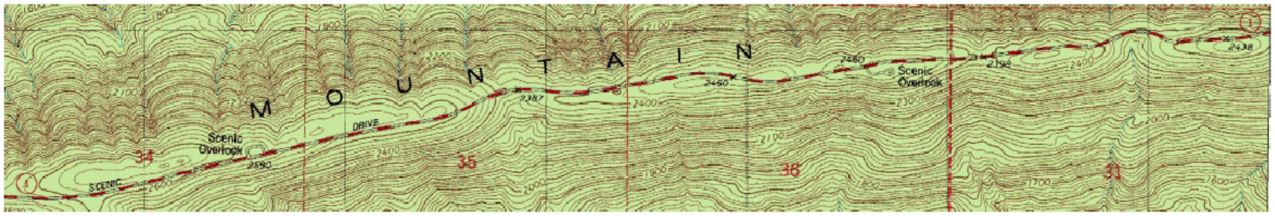
Cuttings analysis and facies analysis (mainly from dipmeter logs and cuttings) of the Jackfork Group sandstones from six wells in Potato Hills, Talihina Northwest, and Buffalo Mountain gas fields reveal the presence of all three types of Jackfork sands – highly quartz-cemented, friable, and siderite-cemented. This may have implications for gas production in the area. The structural complexity and the lateral variability in the turbidite facies make well-to-well correlations and interpretation of depositional environments from logs difficult.

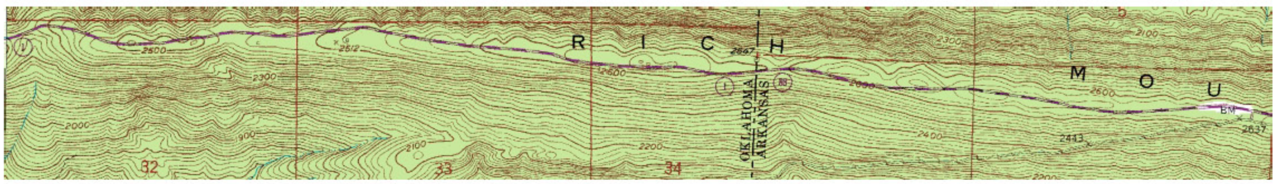
In all three fields, fault zones were first identified by using cumulative-dip and dip-vector azimuth plots derived from dipmeter logs. Borehole image logs were used where available. Dips affected by faults were not used in the facies analysis. The dipmeter information was combined with conventional well logs and cuttings analysis provided information to build a facies classification for the Jackfork sandstones. Several criteria (but especially gamma-ray and dipmeter logs) differentiate the sheet and channel sandstones on the logs. Friable and siderite-cemented sandstones appear to be associated with channel facies (from the logs), and quartz-cemented sandstones appear to be associated with the sheet facies. This association agrees with what is observed in the outcrop.

The similarity between outcrop and subsurface observations is evidence that the surface exposures of parts of the Jackfork Group are excellent analogs to potential subsurface Jackfork gas sands. It may be possible to improve well-log correlations by using a sequence stratigraphic approach. To use such an approach, faults must be identified from the well logs. Then, dipmeter logs and gamma-ray log shapes can be utilized to develop a framework between faults that relate the stratigraphic positions of depositional systems and thus allow prediction of the anticipated porosity type. (Suneson, 2005) Also see Figures 32 through 34.

Return to the vehicles. Depending upon time of day, etc., we may proceed east along Talimena Drive to Queen Wilhelmina Inn to not only visit this historic and interesting site but to also examine several additional Jackfork turbidite outcrops located around the inn. However, if the time is late, etc., we may turn around and proceed west along Talimena Drive back to U.S. 259 and north to the Kerr Conference Center.


R I C H
TALIMENA
Scenic Overlook
Radio Facility
N A T I O N A


M O U N T A I N
Scenic Overlook
SCENIC
DRIVE
34
35
36
31


R I C H
M O U
OKLAHOMA
ARKANSAS
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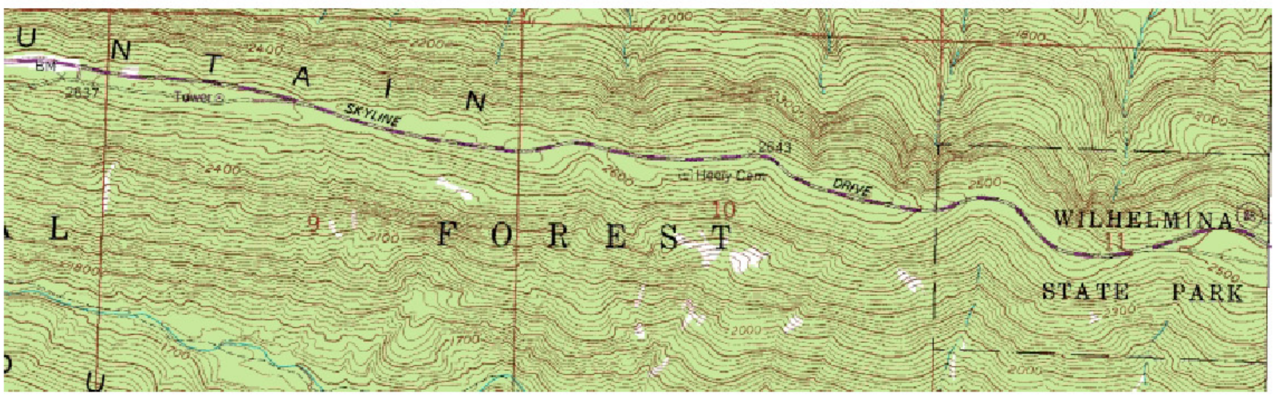
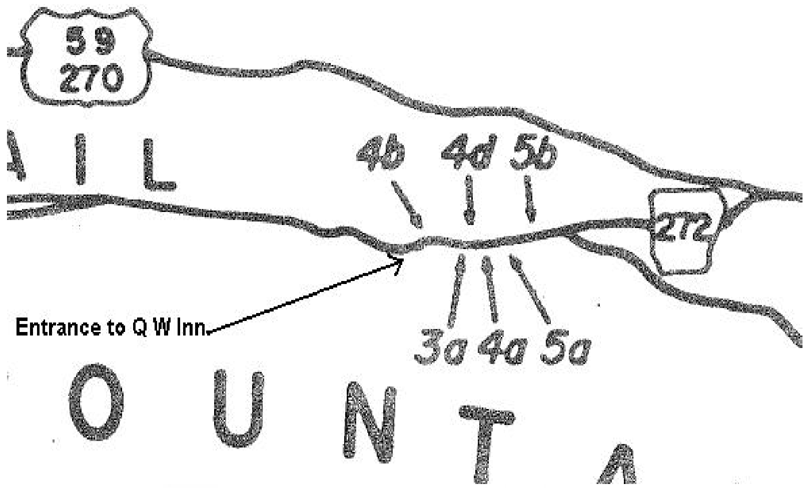

U N T A I N
Tower
SKYLINE
DRIVE
F O R E S T
WILHELMINA
STATE PARK
9
10
11


Stop 11
Howard
Creek
OUNTAIN
QUEEN WILHELMINA
STATE PARK
Ruins
Rich Mountain
Middle

79.6mi Proceed east to Queen Wilhelmina State Park, Arkansas. At the entrance to Queen Wilhelmina Inn is a parking area. Park and we will walk east along Talimena Drive. Again – be careful and watch for traffic.

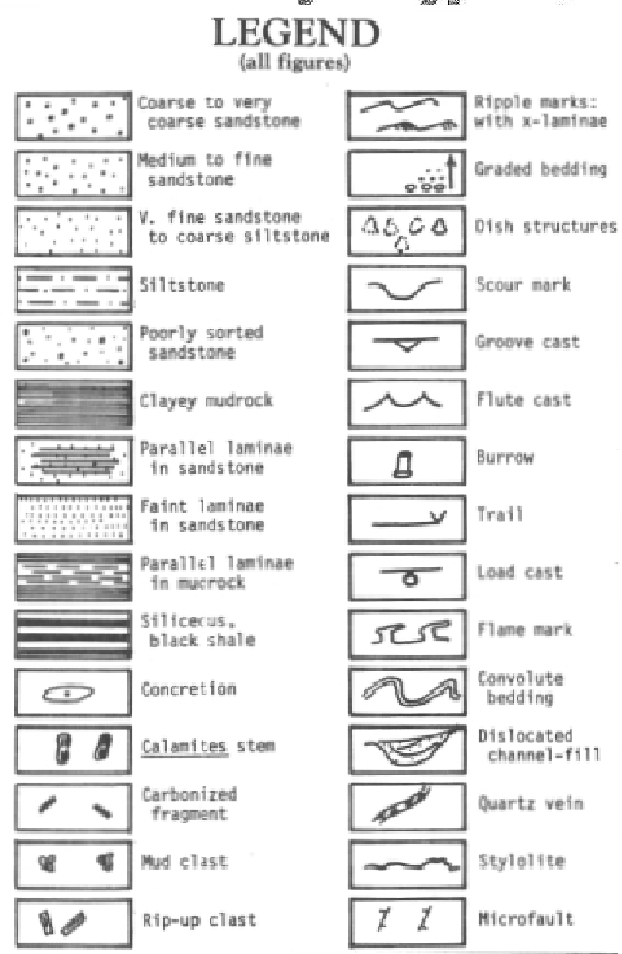
Stop 11
(optional or drive-by)
Friable and Cemented Sandstones of the Jackfork Group –
Queen Wilhelmina State Park

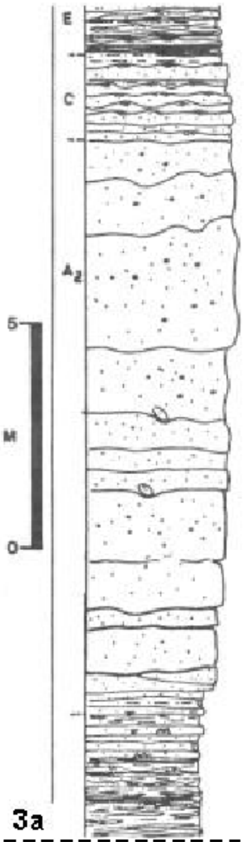
The road cuts between the entrance to Queen Wilhelmina Inn and Arkansas S.H. 272, a distance of approximately one-half mile, offer a variety of depositional environments for the Jackfork.



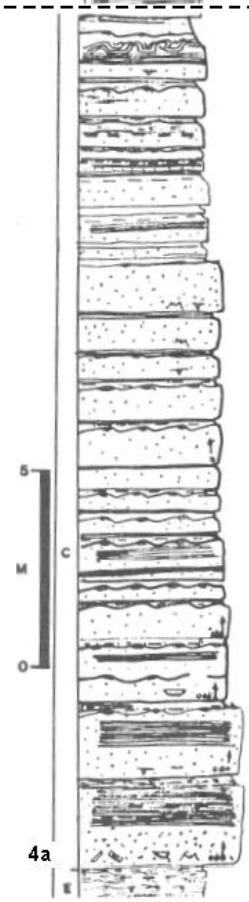
Naz and Mansfield (1986) provide descriptions for the annotated locations. These sections nearly parallel the west-southwesterly paleocurrent trend shown by contained sedimentary structures. Thus, these sections provide an excellent, current-parallel view of Jackfork turbidites and associated deposits.

It is probably best to address each of the annotated locations separately with Naz and Mansfield's columns. The legend on this page applies only to those stratigraphic columns. The letter/number annotations on the left of the columns and descriptions based on lithofacies (adapted from Mutti and Ricci Lucchi) refer to Table 1 from Naz and Mansfield (1986), which is included at the end of this section.

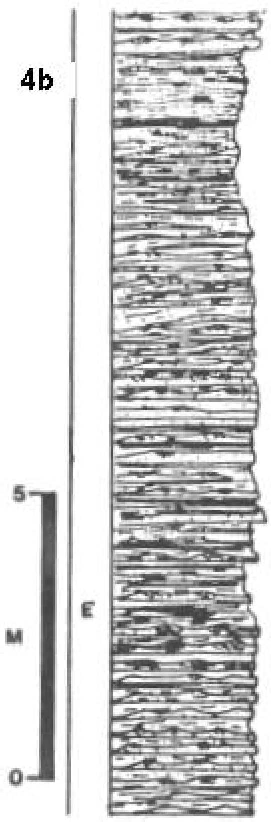




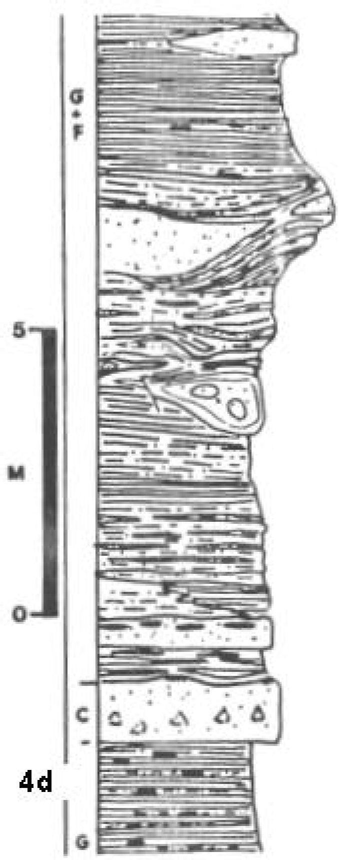
The majority of this section comprises Lithofacies A-2 that is medium to very thickly bedded, fine- to medium-grained, well-sorted, quartz-cemented sandstone. It is distinguished from the sandstones of Lithofacies B, C, and E by its thicker bedding, somewhat coarser grain size, locally sparse granules and mud clasts, absence of interleaved mudrock, and general absence of sedimentary structures. The beds are about 3 to 6 feet thick and bedding contacts are mostly sharp and flat. Some bedding contacts are irregular due to amalgamation and local scour-and-fill structures up to 3 feet wide and almost 2 feet deep. Basal beds include randomly scattered, very coarse, quartz sand grains and granules along with rare, angular mud-clasts up to 8 inches across. Naz and Mansfield report that this lithofacies appears to be deposited by grain-flow currents. It is better described by Lowe (1982) as a “sandy high-density turbidity current” and would represent the previously mentioned sheet sand deposits.



The local 4a is primarily Lithofacies C. It contains medium to very thick beds of sandstone to mudrock lithologic couplets composed of lower sandstone and upper mudrock. The sandstone is generally well- to very-well-indurated, fine- to medium-grained, normally graded, and well laced with sedimentary structures including abundant scour marks. The upper fine-grained part (mudrock) is mostly thinner than the lower sandstone. The mudrock is also normally graded and contains clayey to silty mudrock with intercalated siltstone. The internal boundary between the sandstone and the mudrock can be either sharp or gradual. Most beds are laterally continuous and traceable for several hundreds to thousands of feet. Thickness ranges from 2 to 5 feet and mostly does not change markedly across outcrops. A few beds, however, vary in thickness because of local scour marks up to 2 feet deep and tens of feet across. Some beds coalesce. These beds were deposited by turbidity currents and have nearly complete Bouma sequences (a through e) with only the a or e interval missing from a few beds.

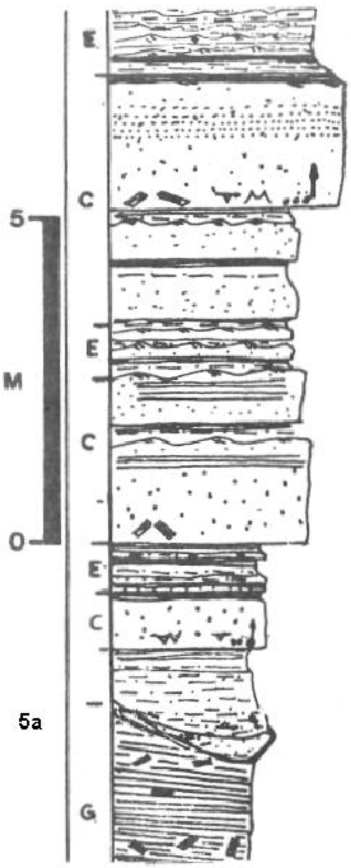


Locale 4b corresponds with Lithofacies E and is associated with thicker and sandier beds of Lithofacies C (locale 4a). This lithofacies is also composed of two types of beds: 1) thin- to medium-bedded, normally graded, lithologic couplets of fine-grained sandstone or siltstone with overlying mudrock and 2) relatively pure, nongraded siltstone. The lower sandstone or siltstone is generally well quartz-cemented, moderately to poorly sorted, and poorly graded to not graded. The upper part contains clayey mudrock and intercalated siltstone. Beds are 4 to 8 inches thick. Most beds are irregular and do not persist laterally more than 300 feet. Bedding contacts are sharp, flat, and erosional with the soles displaying scour marks. These beds are probably "low-density turbidity current" deposits (Lowe, 1982). They are usually associated with Lithofacies C, F, and G at Rich Mountain.

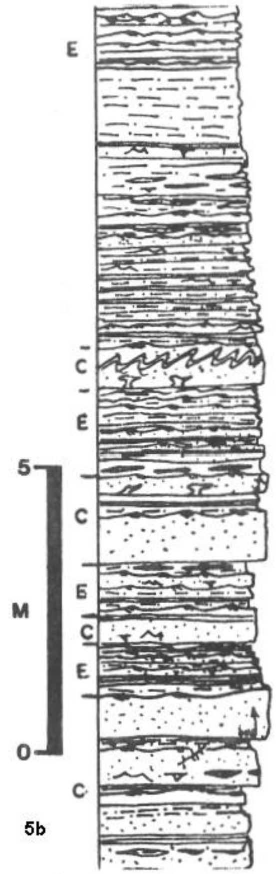


The locale of 4d contains two of the lithofacies in combination and separate. Lithofacies F comprises those deposits of other lithofacies that have undergone post-depositional, soft sediment deformation. Volumetrically these are of minor importance and include disrupted sandstone blocks and dislocated channel-fill deposits. The disrupted sandstone blocks are angular, up to 15 feet across, and generally sharply surrounded by mudrocks of Lithofacies G. The dislocated channel-fill deposits are well-amalgamated and show no internal sedimentary structures. Several display characteristic semicircular, scoured bases. These deposits apparently underwent gravity-induced sliding and deformation shortly after deposition because the overlying beds are undeformed.

Lithofacies G comprises thick sequences of laminated to bedded shale and associated mudrock that, in some localities, have been mapped as members. These mudrocks generally separate the different submarine fan lobe sequences.



Both locales 5a and 5b are distal lobe turbidite deposits. Locale 5a represents a sandy distal lobe, while locale 5b represents a silty distal lobe. They are down-current of and peripheral to the proximal lobe deposits. They consist of Lithofacies C and E in reverse – E-C sequences (there is an upward increase in grain size and bed thickness) and symmetrical E-C-E sequences. The E-C sequences may identify prograding distal lobes that were suddenly abandoned. Conversely, the E-C-E sequences may identify a prograding then slowly abandoned lobe or a series of laterally migrating, interfingering lobes.



Though we will not visit this particular outcrop on this trip, the geological sketch below illustrates sand-filled channels within a silty, clayey sequence along the southwest side of Talimena Drive (SE¼, Sec. 25, T1S, R31W, Arkansas). Note this sequence is perpendicular to the paleocurrent direction.

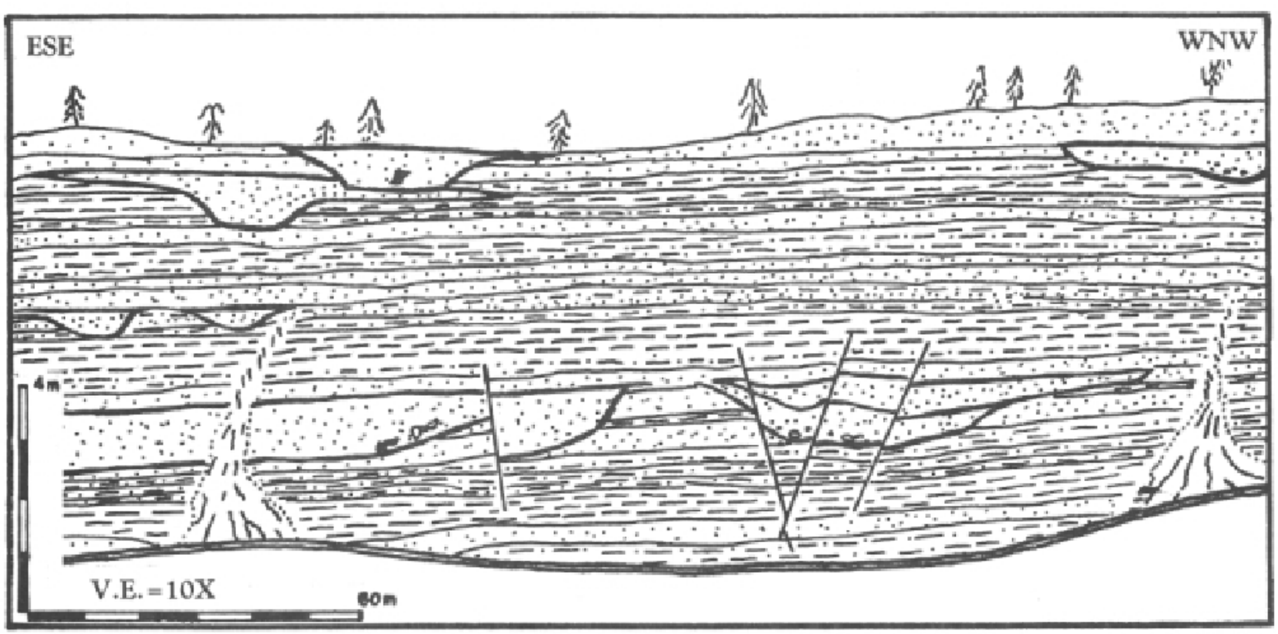


TABLE 1. CHARACTERISTICS OF COMMON LITHOFACIES ALONG THE TALIMENA TRAIL. ADAPTED FROM MUTTI AND RICCI LUCCHI (1978).

	A-1	A-2	B	C	E
LITHOLOGY	Sandstone-mudrock	Sandstone	Sandstone	Sandstone to mudrock (L.C.)[1]	Sandstone, siltstone to mudrock (L.C.)[1]
TEXTURE	Sandstone: fine to medium, granule and rip-up clasts, poorly sorted, weakly indurated. Mudrock: clayey.	Locally sparse granules, rip-up clasts, well sorted, well. indurated.	Fine to medium, well sorted, well to moderately indurated, rip-up clasts.	Sandstone: fine to medium, well sorted, well indurated; pebbles and rip-up clasts. Mudrock: clayey to silty; siltstone intercalations.	Sandy part: fine-grained sand to silt, sorting variable (poorly to well), moderately to well indurated. Muddy part: silt to clay. Pure siltstones: coarse silt.
BED THICKNESS	Sandstone: thick to very thick, (mostly 1 m) Mudrock: intervals up to 2 m.	Thick to very thick (mostly 0.90–2m).	Thick to very thick (mostly 0.65–1m).	Medium to very thick (mostly 60–150 cm). Lower sandstone part generally thicker.	L.C.: thin to medium (mostly 10–20 cm). Pure siltstones: thin to medium.
BED GEOMETRY	Even-parallel at outcrop; erosional truncation of mudrocks prevalent but no channeling.	Continuous at outcrop; flat, parallel; wavy diffuse, convex basal contacts; channels not deeper than 3 m; sole markings rare to absent; load casts rare.	Continuous at outcrop; sharp, flat-parallel base, wavy top. Scour marks predominate.	Continuous at outcrop; sharp, flat-parallel base and top. Scour marks predominate; load casts present.	L.C.: discontinuous at outcrop; sharp, flat base and top; wedging, lensing, pinching, swelling common. Tool marks predominate; some beds are truncated; trace fossils common. Siltstone: discontinuous to parallel.
SAND:MUD RATIO	High; average 70:30	Indefinite, amalgamated.	Very high; 95:5	High; generally 60:40. Some beds coalesce.	L.C.: 40:60. Siltstones: indefinite.
INTERNAL SEDIMENTARY STRUCTURES	Sandstones: structureless. Mudrocks: thin to thick, parallel laminated.	Structureless	Thick horizontal laminae, dish structures, parting lineation, current ripples.	Step grading, diffuse current laminae, ripples and dish structures present; convolute bedding common.	L.C.: normal grading, step grading, current laminae of transition and lower flow regime. Siltstones: structureless.
BOUMA SEQUENCES	Not applicable (or T_{ae})	Not applicable (or T_a)	T_{abc}, T_{bc}	T_{abcde}, T_{abce}, T_{ace}, T_{bcde}, T_{bce}, T_{ae}	T_{acde}, T_{abde}, T_{ade}, T_{ae}
DEPOSITIONAL MECHANISM	Slurry-like mass flow or grain flow.	Grain-flow	High- to moderate-energy turbidity flow.	High- to moderate-energy turbidity flow.	Low-energy turbidity flow.

[1] L.C.: Lithologic couplet.

Queen Wilhelmina Inn

The beginning of this grand lodging tradition high atop Arkansas' second highest mountain is rooted in the 1890s when railroad expansion was big business in this country. Arthur Stilwell, vice president of the Kansas City, Pittsburg and Gulf Railroad (KCP&G), decided to build the first north-south railroad, a route from Kansas City, Missouri to Port Arthur, Texas, to provide rail access to the Gulf of Mexico. This brought the railroad's route through Arkansas, and inevitably the Ouachita Mountains. During the routing of the tracks through the valleys of the rugged Ouachitas, a flat area near the top of 2,681-foot Rich Mountain was discovered. This windswept, mountaintop location was brought to the attention of the investors of the KCP&G, many of whom were Dutch, as a site to build a resort retreat featuring a grand hostelry to entice railroad patrons to travel the rails.

The luxurious hostelry of Victorian splendor was constructed of native stone and timber at a cost of $100,000. The building was illuminated by carbide lights and made for a glorious site as carriages topped Rich Mountain from the train stop at the base of mountain's north side. Thirty-five guest rooms graced the second floor with at least four "water closets" to serve their guests. Maids and cooks were housed on the third floor. The glorious first floor was used as a place to socialize. The especially beautiful dining room, when converted to a ballroom, would seat 300 people.

Queen Wilhelmina of the Netherlands was to be crowned in September 1898. To honor the young Queen, the magnificent structure was called "Wilhelmina Inn." A suite of rooms was located in the southeast corner of the second floor and named for Queen Wilhelmina in the vain hope she would visit.

The grand opening of the inn came on June 22, 1898. Soon, Wilhelmina Inn became known as the "Castle in the Sky." The grandeur of this renowned mountaintop inn with its breathtaking scenery, fine accommodations and exquisite service, however, was to last only a few short years.

Less than three years after the opening of the lodge, the Kansas City, Pittsburg and Gulf Railroad, facing enormous financial troubles, was sold to what is now the Kansas City Southern Railroad. With the new owners in place, the lodge was abandoned by its former owners and languished into disrepair. In 1905, the inn was given away in a drawing where chances where sold for thirty dollars. E.A. Cotham won this drawing. Later, from 1906 to 1910, M. Maxwell ran the hotel. Not much was documented about the hotel during this time.

Although the lodge did not close permanently until 1910, its heyday had too quickly come to a close. The building fell into decay. In the 1920s the Shelton family (parents and their ten children) used the inn as their home for a short time. As the inn became more and more dilapidated, it became known as "Dutchman's Folly" and the "Ghost Hotel". A photograph shows sheep standing in what was once the grand ballroom where elegantly dressed ladies and gentlemen danced.

By the 1930s, only remnants of the original structure's stone fences and fireplaces remained standing, starkly silhouetted against the sky. The year 1940 brought a brief respite and renewed hope for the now desolate building. Earnest Rolston, a professor from Centenary College in Shreveport, Louisiana, decided to create a summer music school using a portion of the inn. The idea was good, but unfortunately the timing was not. The beginning of World War II in 1941 ended any further attempt to restore the old ruins.

After the decade of the 40s, the 1950s brought renewal into sight. The war years had brought travel awareness to the many men and women who had served in the Armed Forces. The growth of America's travel and tourism industry was now on the horizon. In light of this, State Senator Landers Morrow and other community leaders started discussions to create a new state park on the site where Wilhelmina Inn reigned over the Ouachita Mountains.

On Thursday, March 21, 1957, Gov. and Mrs. Faubus, Winthrop Rockefeller, and KCS President William N. Deramus met in Mena to discuss the establishment of the Queen Wilhelmina State Park. It was created when the Arkansas legislature passed Concurrent Resolution No. 17 on March 7, 1957. The resolution appropriated roughly $70,000 for the purchase of the original 460-acre site. The park was officially dedicated in October 1957. The Tulip Queen of Holland, Agustia de Zoete, was present and stood on the front steps while officially naming it "Queen Wilhelmina State Park". The park opened to the public in 1958. On June 2, 1959, H. C. Walker Construction Co. of Mena began restoration of the Queen Wilhelmina Inn, using the remaining walls of the original inn and working as money became available. The first to open, in the spring of 1961, were the single story kitchen and dining room. The slow pace of funding delayed the dedication of the second inn until June 21, 1963, the 65th anniversary of the original inn. Governor Faubus gave the dedicatory speech. In 1971, the state spent $183,000 on renovation of the inn.

Like a phoenix rising from the ashes, the second inn opened its doors on June 22, 1963. Although less grand than the original hostelry, this lodge contained 17 guest rooms and a restaurant. Occupying the same site as the first inn, the second structure was built with some the of rockwork still remaining from its predecessor. Operated for 10 years by the State of Arkansas as an Arkansas State Parks lodge, the facility was a popular travel attraction until on the evening of November 10, 1973, a fire that began in the kitchen area destroyed it. Thankfully, there was no loss of life, but the building was totally destroyed.

To carry on this grand lodging tradition atop Rich Mountain, Arkansas State Parks lost no time in constructing a new lodge on the site, opening a new $3 million dollar state park lodge in 1975. Today, this lodge is the crowning attraction of Queen Wilhelmina State Park. Within walking distance of the lodge are a park amphitheater, playground, campground with 40 sites and a modern bathhouse, and hiking trails. To add to the park's summer season offerings, two private concessions operate a miniature train ride and a rehabilitation center for species native to Arkansas.

All Queen Wilhelmina Inn photographs (pages 102 – 104) and Inn history have been furnished by the Arkansas Department of Parks and Tourism.

The above easterly facing aerial photograph of Rich Mountain and the Queen Wilhelmina State Park illustrates the long mountain ridges of the Ouachitas. Talimena Drive (foreground) parallels the ridge of the mountain from its eastern edge to western edge. Stop 11 is located directly below the Inn on the upslope side of the road. The crest of Rich Mountain is a continuous exposure of proximal and distal turbidite lobes along with lobe-fringe deposits, outer-fan channels, and hemipelagic or starved-basin deposits. These types of deposits have been described as suprafan-lobe and lower fan deposits. The turbidite flows were primarily from east to west, parallel to the crest of Rich Mountain, so this photograph would be oriented looking toward the source of the flow.

If time allows, we will visit Queen Wilhelmina Inn. This is the end of Day 1. Exit onto Talimena Drive by going right (east). In about one-half mile, Arkansas S.H. 272 will intersect Talimena Drive. Turn left and follow S.H. 272 for about one and one-half steep miles to U.S. 59/270. Turn left onto U.S 59/270 and return to the Kerr Conference Center. End of day mileage: 105.4mi.

We will visit the Kerr Museum this evening after dinner.

Preview of Tomorrow
Units 1 through 4 of the Savanna Formation, Lequire road cut. Notice coal located mid-Unit 2 above the group's heads and mid-Unit 4 above the head of the upper student at right.
(Photo courtesy of Dr. Neil Suneson, Oklahoma Geological Survey)

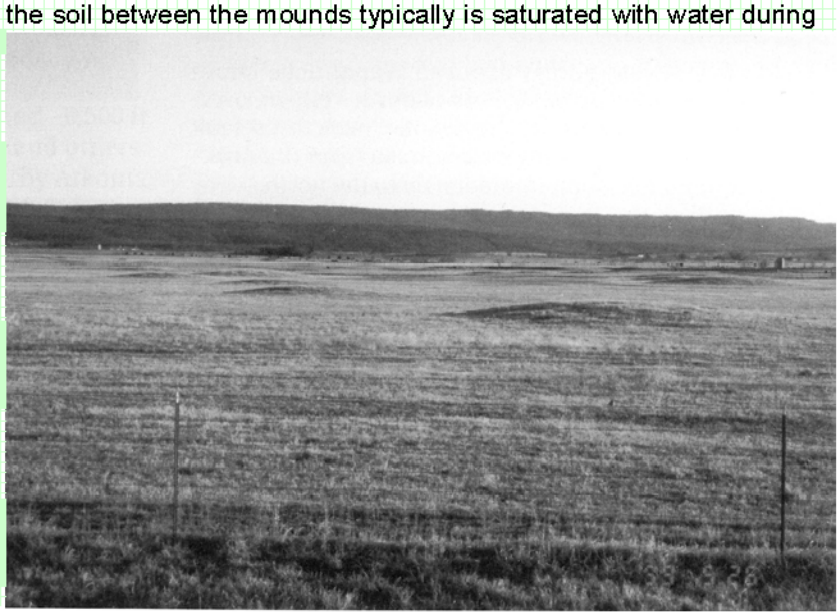
Mima Mounds

During the drive across U.S. 270/271 last night, it was probably too dark to notice the mima mounds that are present through the valleys in this area. Mima mounds are also called hogwallows, prairie mounds, pimple mounds, prairie pimples, or silt mounds. They also occur in a number of other areas throughout North America and the world. Mima mounds are enough of a geological curiosity that they are the feature attraction at Mima Mounds Natural Area Preserve south of Olympia, Washington. The mounds can be most striking in cold weather when light snow or frost is accumulated around them and they are "mountains" in a white background.

The origin of mima mounds is controversial, and a single origin may not apply to all places. However, areas with mima mounds share several characteristics: they are treeless to partially vegetated, consist of thin unconsolidated material overlying coarser or harder material, occur on a land surface of considerable age, and are present in a former or current non-permafrost climate.

Over 30 different hypotheses in nine categories have been put forth to explain mima mounds. 1) The *gilgai* hypothesis suggests that mima mounds form as a result of the shrinking and swelling of expansive clays in the soil, including the infilling of desiccation cracks and subsequent swelling and diapiric rise. 2) The *fluvial deposition alone* hypothesis likens mima mounds to accretion ridges on point bars in an alluvial deposit. 3) *Fluvial deposition with vegetation anchoring* requires that small clumps of vegetation stabilize and serve as the loci for sediments in an alluvial deposit. 4) A popular and widely accepted origin suggests that *fossorial rodents* (typically pocket gophers) tunneling outward from nest sites cause the backward displacement of the soil toward the center. 5) The *runoff erosion alone* hypothesis suggest that the mounds are formed as a result solely of fluvial, slopewash, and other unorganized erosional processes. 6) Two ideas suggest that the mounds may have formed as a result of thermal-contraction cracking of soil: 6a) Several versions of the *runoff erosion with polygonal permafrost cracking* hypothesis all require the growth of ice wedges in permafrost cracks and subsequent thawing of the wedges. 6b) *Runoff erosion with polygonal seasonal-frost cracking* is similar to 6a but does not require the cold temperatures necessary for permafrost. 7) *Runoff erosion with desiccation cracking* was originally proposed in 1952 for the mounds of eastern Oklahoma. It was suggested that the low intermound areas are the sites of desiccation cracks, enhanced by erosion. 8) The *erosion runoff with vegetation anchoring* hypothesis requires clump vegetation and trees. 9) The *seismic* hypothesis requires a veneer of unconsolidated fine sediment over a hard substrate and the occurrence of earthquakes. There are other more fanciful explanations for mima mounds, including, in Oklahoma, old bison wallows. For those interested, check out www.intersurf.com/~chalcedony/pimple2.html.

The mima mounds of eastern Oklahoma were studied in the early 1970s. It was noted that the mounds are closely associated with the 40+ inch rainfall belt, that most form on dense substrates with perched water tables in the spring, and that the soil between the mounds typically is saturated with water during the rainy season. Compared to intermound soils, those of the mounds are more friable, less dense, have thicker soil horizons, and are less leached. All of these characteristics ascribe to the high density of organisms in the mounds, especially pocket gophers, moles, and earthworms. It has been suggested that the mounds form because of the large volume of material added to the mounds to make nests, the increase in soil volume from earthworm activity, and sheet erosion in the intermound areas.



Saturday

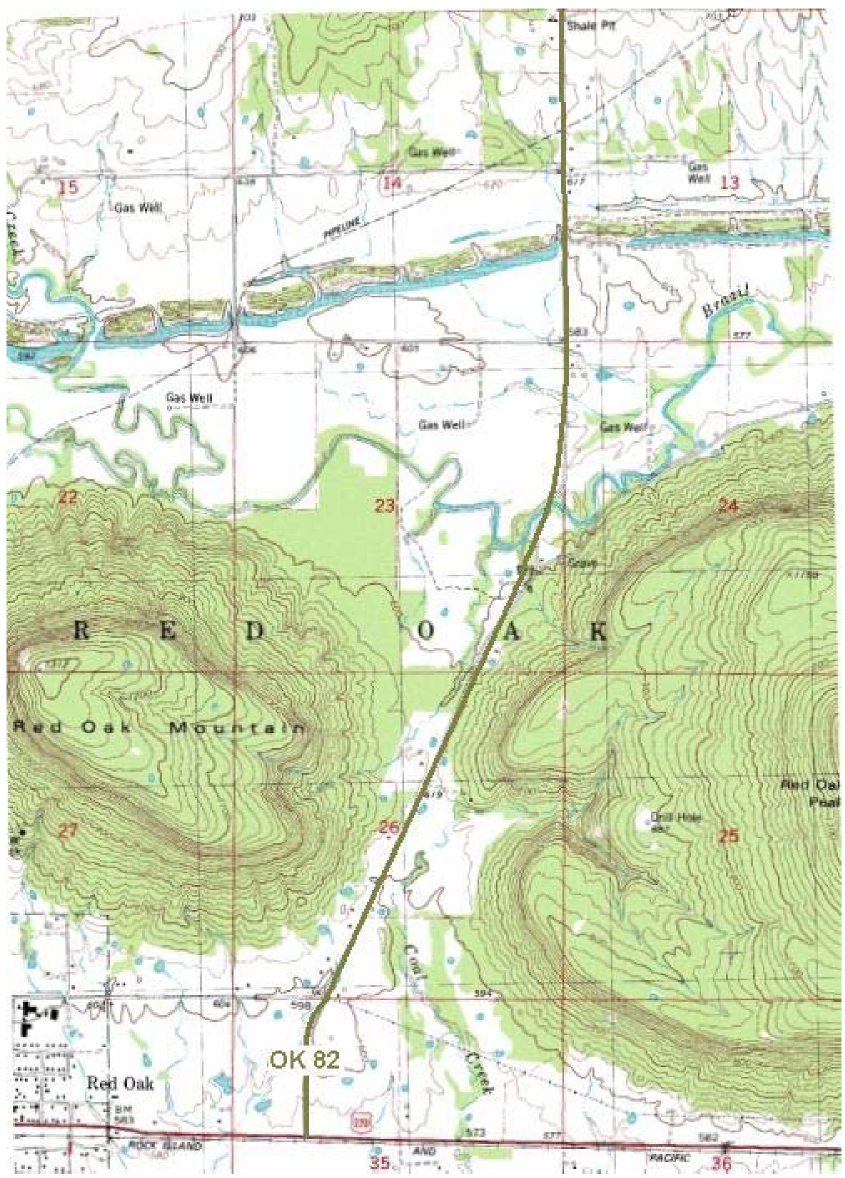
0.0mi Start trip at Kerr Conference Center parking lot. The beginning of today's trip will follow Friday's beginning Route 2. As we will have a distance to travel along U.S. 271 and 270 before the first stop, the topographic location maps will commence with the first stop. Exit parking lot and turn left on blacktop road.

1.6mi Turn left on old U.S. 271 and continue due southwest on Savanna shale and Quaternary alluvium towards the town of Wister.

4.0mi Turn right (north) in downtown Wister onto U.S. 270 and proceed through town.

4.2 mi Turn left (west) on U.S. 270/271.

22.9mi Before the town of Red Oak, turn right (north) on OK S.H. 82 (approximate location on maps).

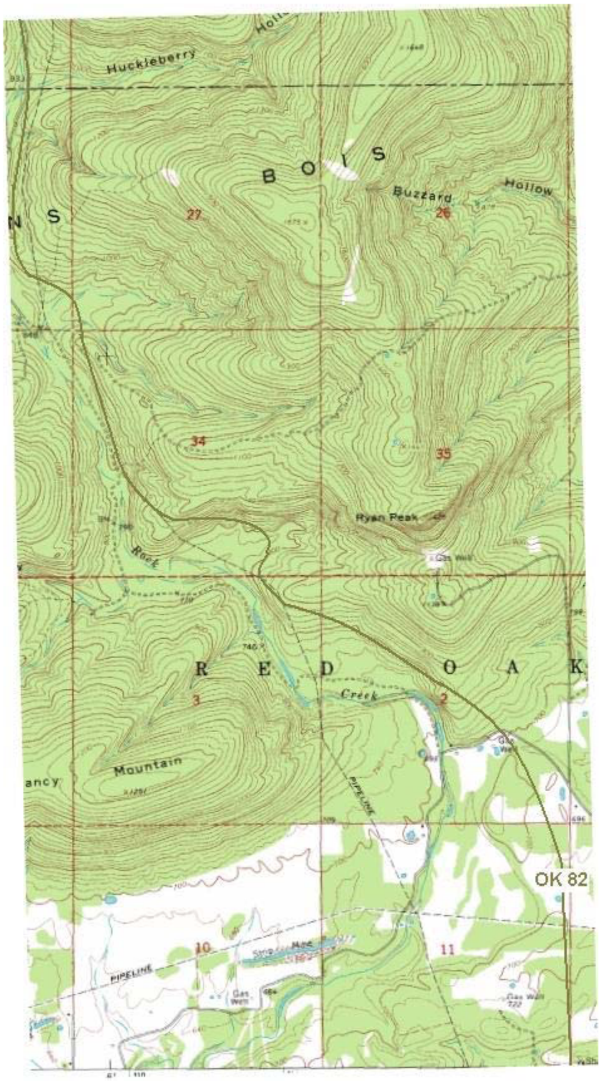


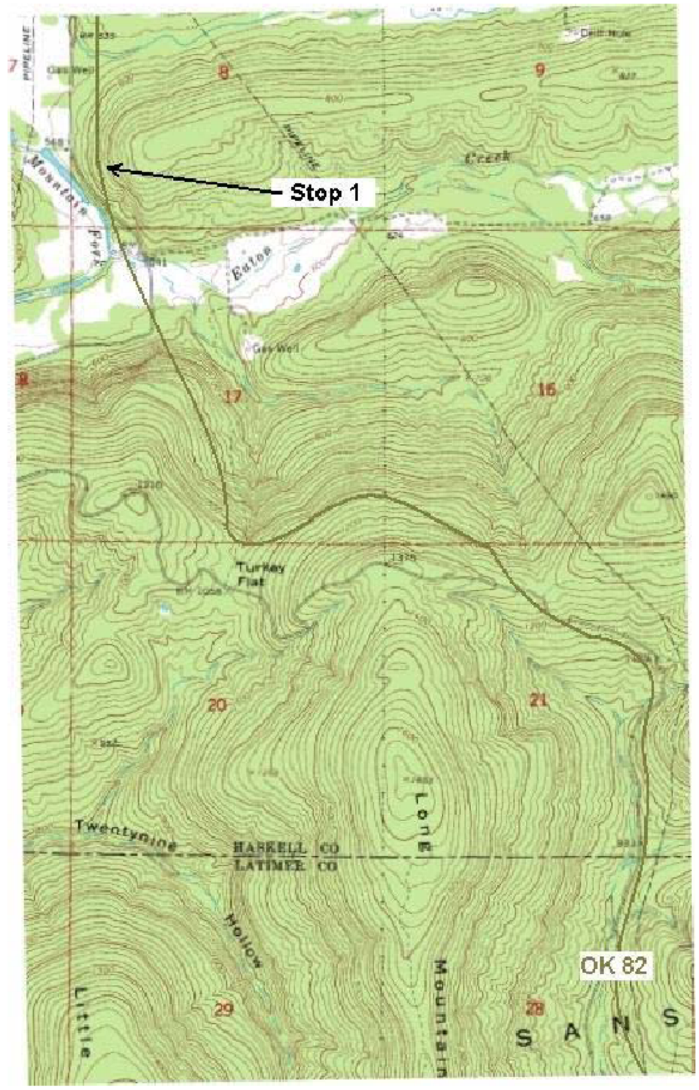
This road from U.S. 270 north to Brazil Creek follows closely the old Butterfield Overland Stage route (1857-1861). Historical note is after Stop 1 description.

23.9mi Pass between Red Oak Mountain (left) and Red Oak Peak (right). Various sequences of the Savanna Formation make up these mountains. Red Oak Peak is topped by Savanna sandstone #6. Red Oak Mountain is topped by Savanna sandstone #3. The terraces on the sides of these mountains are the intervening Savanna shales between the separate Savanna sandstone.

24.9mi Cross Brazil Creek.

25.7mi Pass reclaimed strip mining pits in the McAlester coal and dragline.





27.6mi Enter the San Bois Mountains. The pass was formed by Rock Creek on the south flank.

33.8mi Several hundred feet to the east of the highway is the Gose No. 1 Madden gas well.

34.4mi The Lequire road cut in the Savanna Formation. Pull off side of the road.

Stop 1
Delta-Plain Environment: Savanna Formation, Lequire Road Cut

This outcrop is subdivided into nine major units based on exposed rock types, sedimentary structures, fossils, and contact relations between rock types. Most of the units were deposited in a mid- to lower-delta-plain environment and include distributary bay-fill and crevasse-splay sediments, as well as organic material deposited in marshes and/or swamps. Evidence that supports such an interpretation includes interbedded sandstones and shales, common fining-upward textures of the sandstones, and the presence of coal. In contrast, the basal unit probably was deposited in a delta-fringe environment, and the upper part of the outcrop contains evidence for subaerial exposure.

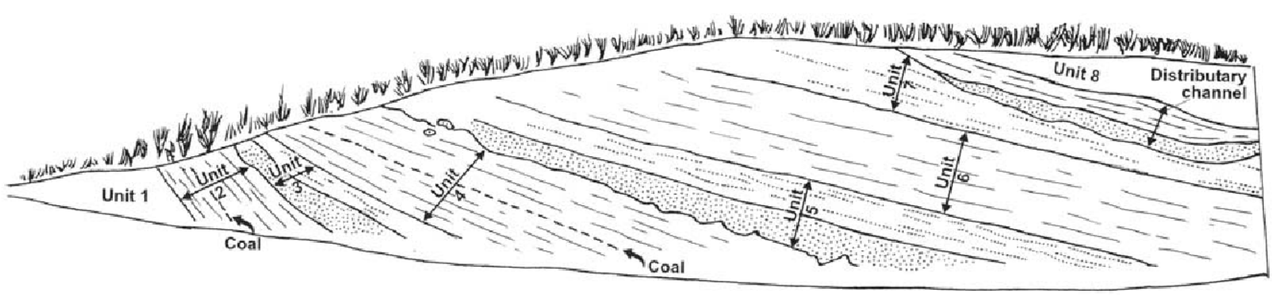
This is one of the best examples of delta-plain strata in Oklahoma. As we examine this road cut, notice that plant fossils are abundant in some units and include conspicuous, large, erect, in-situ *Calamites* and lycopods. Also, as shown in the Heavener road cut, the depositional environment can change in just a short distance. Approximately 5 miles to the southeast near the village of Lodi, the Savanna appears to be a subaqueous, delta-front environment (similar to the Savanna at Runestone State Park) – the basinward equivalent of the delta-plain exposed here.

This road cut focuses on the identification and characterization of mid- and lower-delta-plain deposits of the Savanna Formation. In particular, sediments deposited in crevasse splay, distributary channel, and interdistributary (including bays, marshes, and swamps) environments. These deposits include sandstones, siltstones, shales, and coal beds.

In overbank deposits (crevasse splays), sandstone beds commonly are relatively thin but widespread. In contrast, sandstones in distributary channels are restricted spatially and may be thick. Siltstones and shales commonly occur in bay-fill environments, but may also occur in abandoned channels. Coal beds are diagnostic of marsh or swamp environments. Interdistributary bay and marsh/swamp sequences commonly are interbedded with crevasse splay sandstones.

In the spring of 2002, an article entitled "Interpretation of Depositional Environments of the Savanna Formation, Arkoma Basin Oklahoma, from Outcrops and Surface Gamma-Ray Profiles" by Richard D. Andrews and Neil H. Suneson was published in the Oklahoma Geology Notes, v. 62, no. 1. Much of the description for this stop was taken from this article. As this article is one of the few that discusses the Savanna Formation, it has been included in the Appendix.

Andrews and Suneson divide the Savanna in the Lequire road cut into nine major units with Unit 1 on the north and Unit 9 on the south.



Unit 1: Sandstone Unit 1 is interpreted to be dominantly marine and probably represents a delta-fringe facies. Sedimentary features include small-scale stratification and local ripple-cross-stratification with thin shale drapes. Plant fossils and trace fossils are absent.

Unit 2: Unit 2 is mostly shale with a 4-inch thick coal bed in the lower half. The shale below the coal contains ostracodes which implies a brackish to fresh water environment. Some beds are highly calcareous and may grade into muddy limestone. The shale above the coal contains abundant coaly laminations and siderite concretions containing plant compressions along bedding planes. Unit 2 is interpreted to be alternating marsh/swamp with interdistributary bay facies deposited in brackish to fresh water.

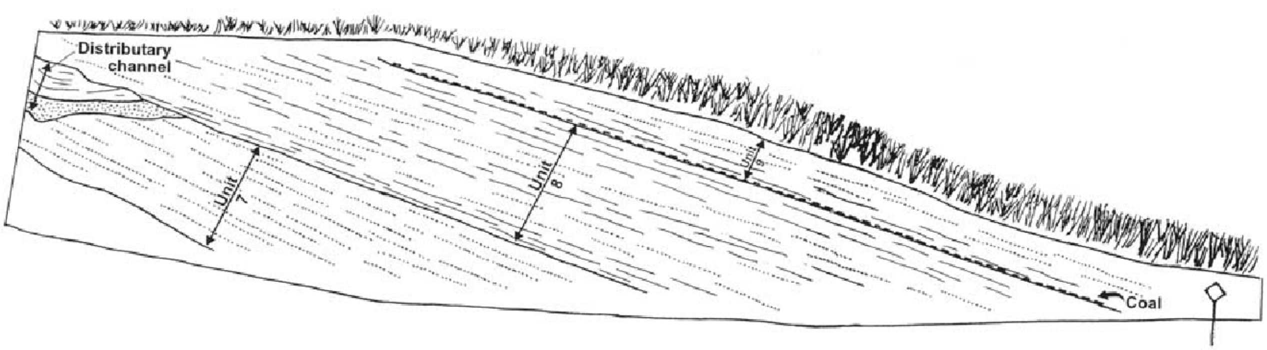
Unit 3: The sandstone of Unit 3 fines upward as evidenced by the increasing number and thicknesses of shale and siltstone layers and decreasing thicknesses of sandstone layers from the base to the top of the unit. All the sandstones are fine grained to very fine grained and relatively clean. Bedding planes are marked by shale rip-up clasts and plant debris. The basal sandstone was deposited during a single event, probably a flood. A 6-foot thick channel filled with massive, soft-sediment deformed sandstone locally erodes into the sandstone beds in the upper part of Unit 3. Unit 3 is interpreted to be a fining-upward crevasse-splay sequence.

Unit 4: Shale Unit 4 consists of shale, siltstone, sandstone, and coal, in decreasing order of abundance. Depositional features include abundant plant fossils, burrows, and siderite nodules that are evidence for a bay-fill sequence of dominantly fine-grained rocks. The presence of coal near the middle of the unit is evidence for a period of low sedimentation rates.

Unit 5: Unit 5 is similar to Unit 3 in many respects and consists of multiple sandstone beds that become thinner higher in the section. Shale and siltstone beds increase in abundance and become thicker higher in the section. The sandstones are very fine grained and are quartz-cemented. The base of this unit is a massive sandstone whose base is undulatory and contains numerous upright carbonized tree trunks up to 6 feet high and 14 inches in diameter. Most of the tree trunks appear to be leaning generally south. This bed also contains abundant shale rip-up clasts and plant fragments. The overlying sandstone beds range from 1 inch to 1 foot thick and show many pinch and swell features along with large-scale crossbedding, macerated carbonized plant material, and rarely small burrows. Each sandstone bed is interpreted to have been deposited by rapidly moving water during a single event such as a flood. The abundant plant material is evidence for a nonmarine to brackish water depositional environment. Unit 5 probably represents a series of crevasse splay sandstones deposited during floods.

Unit 6: Shale Unit 6 is similar to shale Unit 4. However, in Unit 6, plant fossils are relatively rare except for *Calimites* stems in the upper part. Siderite concretions are abundant throughout the unit. A single, thin, ripple-bedded, very-fine-grained sandstone containing trace fossils is present. A thin discontinuous coal bed is present approximately 12 feet from the top of the unit. This shale was deposited mostly in an interdistributary-bay environment and more rarely in a marsh.

Unit 7: The sandstone of Unit 7 is similar to the sandstones of Units 3 and 5. However, Unit 7 differs because it is eroded by a channel some 20 feet deep near the top of the outcrop. The channel is filled with approximately 10 feet of very soft-sediment deformed sandstone containing small shale rip-up clasts and an overlying shale and thin siltstone beds that are laminated but not crossbedded. The predominance of shale and silt is evidence that the channel was abandoned



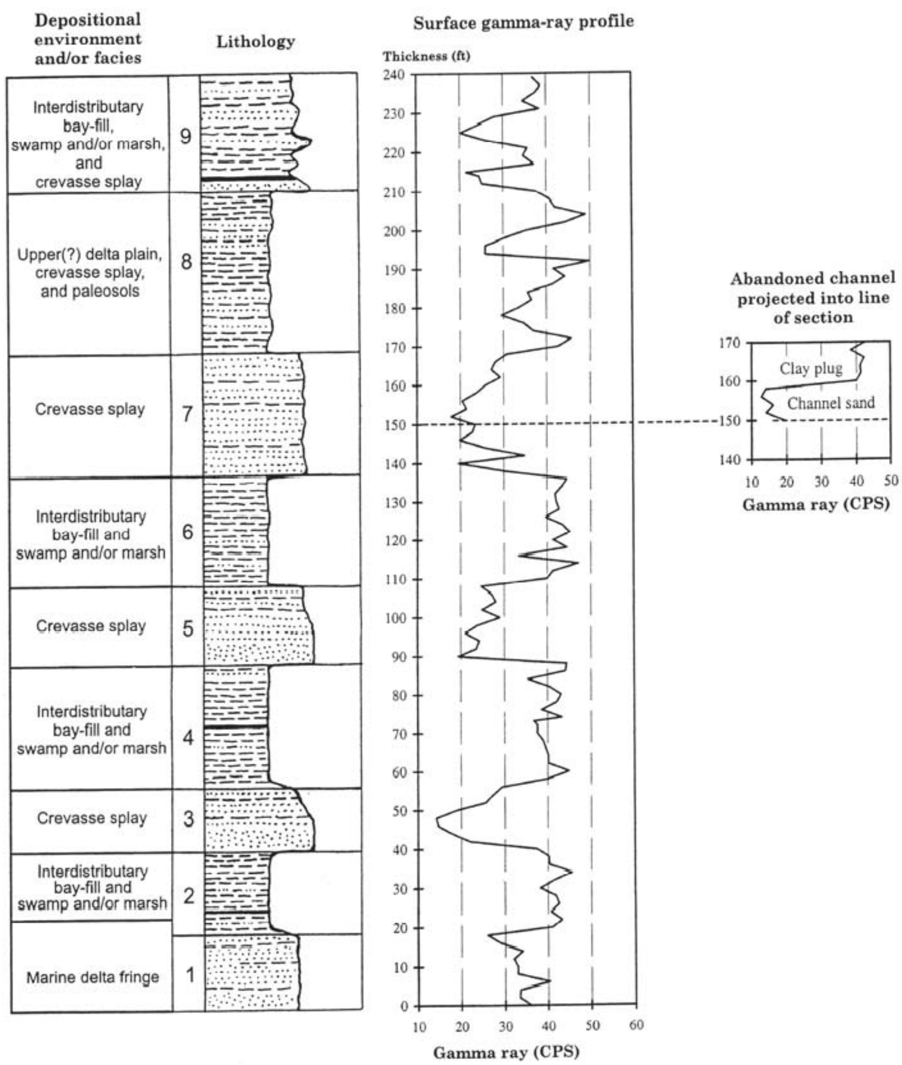
prior to being completely filled. As the other units, the sandstone of Unit 7 is a series of crevasse splay sandstones.

Unit 8: Shale Unit 8 is heterolithic and consists mostly of shale with two sandstone-rich intervals. The shale intervals at the base, middle, and top of the unit differ slightly from the shale of Units 4 and 6. Carbonized plant impressions are common, but coaly layers and siderite concretions are absent. Additionally, shales locally contain isolated soft-sediment deformed sandstone masses as long as 4 feet. The most distinctive feature of the shales is their color – the typically dark gray shales grade irregularly to a maroon color parallel to and highly oblique to the stratification. This color change plus calcareous nodules and root casts imply extensive paleosoil development within the shales of Unit 8.

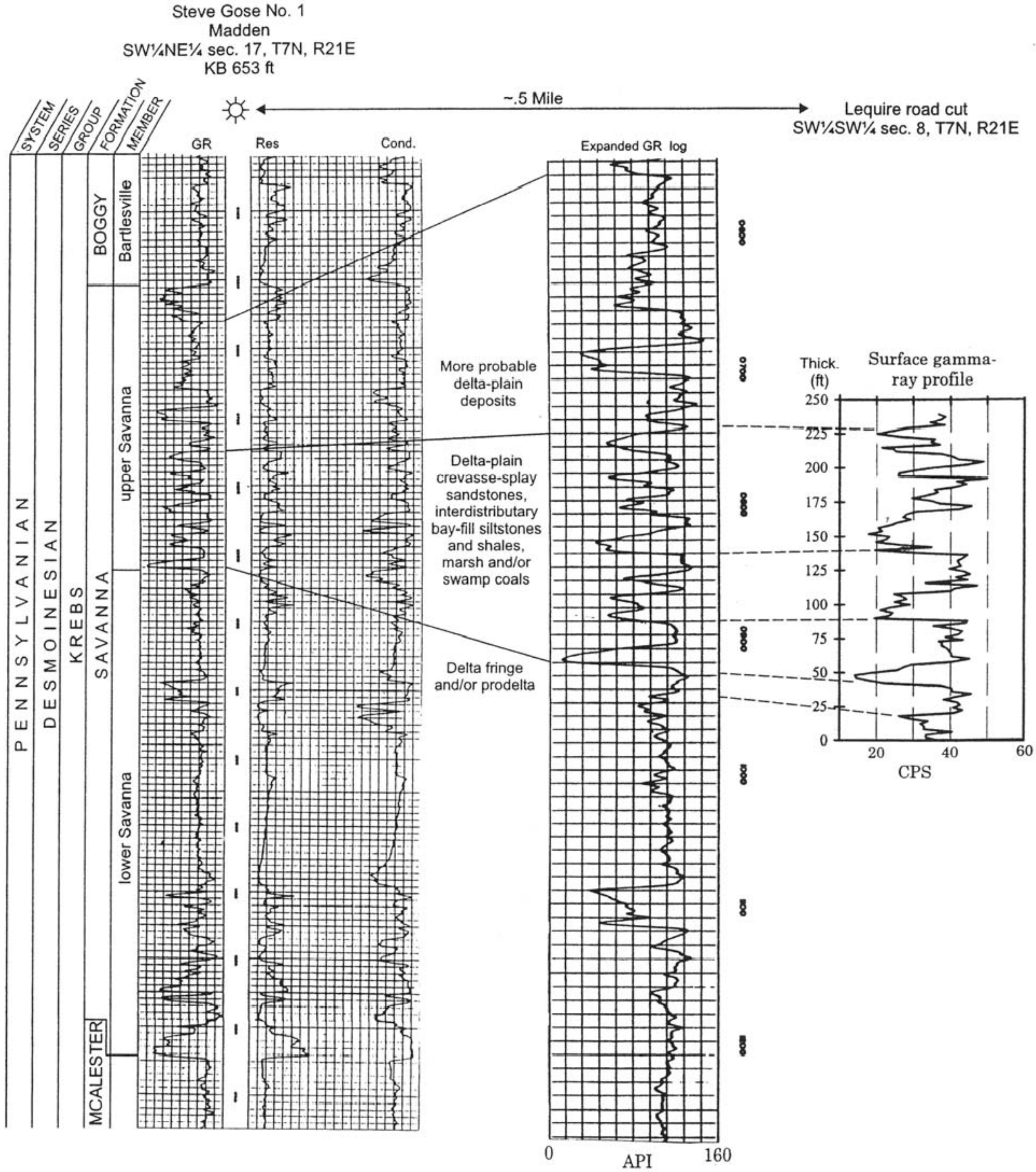
Unit 9: Like Unit 8, the sandstone Unit 9 is heterolithic and consists of sandstone, shale, siltstone, and coal. Key environmental features include compressed carbonized logs as long as 7 feet and burrows in the basal sandstone. Plant fossils in siderite nodules are commonly found in the shale overlying the coal. The upper strata is a medium-bedded, sandstone-rich zone with common cross-stratified, soft-sediment deformed, and lenticular sandstone beds. The depositional environment was probably an interdistributary-bay environment with crevasse splay sandstones.

One of the goals of geologists in studying wireline logs is to interpret the depositional environment of the strata in the wellbore. Where cores have not been retrieved, this interpretation must be accomplished without examining any rocks. In outcrops - where rock types, sedimentary structures, contact relations between different beds, and fossils can be observed directly and studied – interpretations of depositional environments are more straightforward. A surface gamma ray log can be a valuable tool to interpreting wireline gamma ray logs.

Andrews and Suneson measured a surface gamma-ray profile for the entire Lequire outcrop. Their gamma-ray profile clearly illustrates the major sandstone and shale dominated units with gross rock textural characteristics. Unit 1, as a marine delta-fringe sequence, is different from the other sandstone dominated units. Shale Units 2, 4, and 6 have similar profiles and are from similar depositional environments. The sharp bases and fining-upward characteristics of the crevasse splay sandstone Units 3, 5, and 7 can be observed both in the outcrop and in the profile. The heterolithic character interpreted as bay-fill and crevasse splay of Units 8 and 9 are also evident.



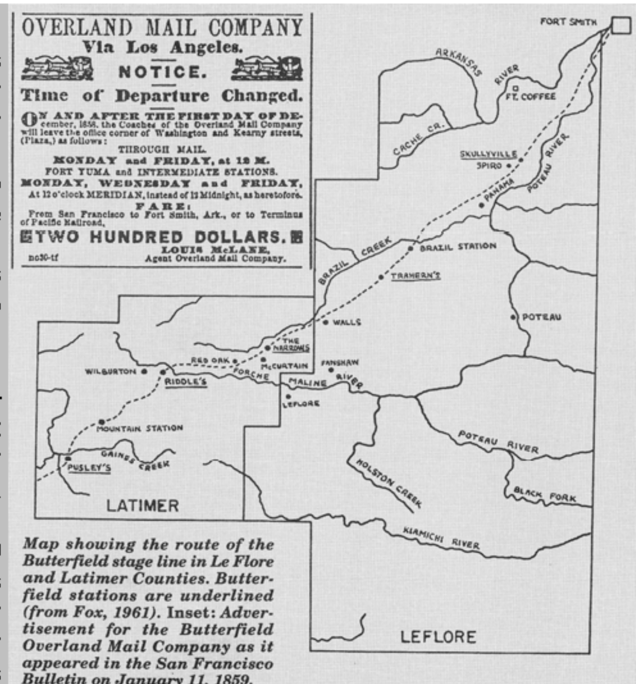
To determine whether the surface gamma-ray profile was similar to a typical wireline gamma ray log, Andrews and Suneson compared the profile to the Steve Gose No. 1 Madden well located approximately 0.5 mile south of the outcrop and mentioned in the road log. The results are remarkable - the logs are quite similar.



As mentioned, the complete article describing this road cut from "Oklahoma Geology Notes" has been included in this field guide in the Appendix.

The Butterfield Overland Mail

As the population of the western United States increased during the 1840s and 1850s, particularly after the discovery of gold in California, the need for better east-west communications grew. In April 1857, the postmaster-general advertised for bids to operate an overland stage line between the Mississippi River and San Francisco. In September, John C. Butterfield (of Utica, NY) and associates were awarded the contract. The route they chose to follow started at Tipton, MO (western rail head) and extended west to Ft. Smith, AR; Jacksboro, TX; El Paso, TX; Ft. Yuma, CA; and on to San Francisco – a trip of 2,800 miles. The terms of the contract required that mail and passengers be carried safely to and from San Francisco twice a week and that a one-way trip not exceed 25 days. For this, Butterfield and his associates were paid $600,000 per year. An additional stipulation was that stations were to be built along the route (approximately every 13 miles) that would serve as "restaurants" for the passengers on the stage line, and also as stables, blacksmith shops, and local post offices. In Indian Territory, these stations were run by citizens of the Choctaw and Chickasaw Nations.



Map showing the route of the Butterfield stage line in Le Flore and Latimer Counties. Butterfield stations are underlined (from Fox, 1961). Inset: *Advertisement for the Butterfield Overland Mail Company as it appeared in the San Francisco Bulletin on January 11, 1859.*

The stage ran 24 hours a day. The one-way fare was $200, not including meals, and passengers were allowed 40 pounds of luggage at no extra charge. A letter from Missouri to California cost 10¢.

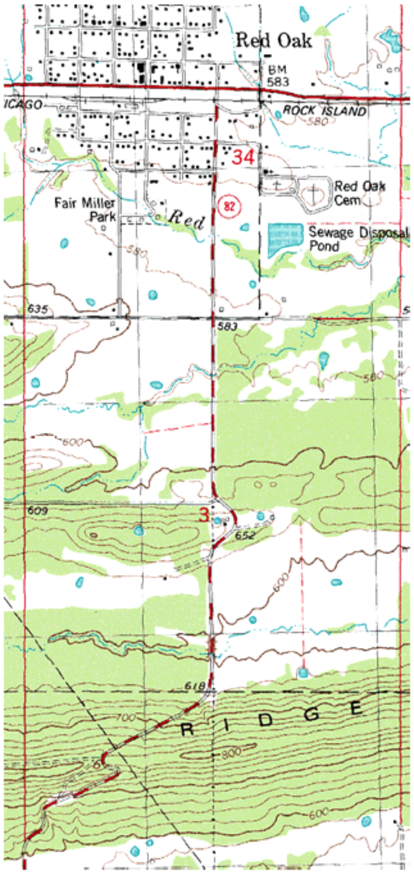
The Butterfield Mail operated in Oklahoma between 1858 and 1861. The 192-mile trip though Indian Territory started at Ft. Smith, AR and ended at Colbert's Ferry, Indian Territory (near present day Colbert and U.S. 75 at the Red River). The operation of the Butterfield stages through Indian Territory was of such importance that the Choctaw and Chickasaw Nations each granted eight toll-gate privileges along the route. The tolls were collected by citizens of the Choctaw and Chickasaw Nations who guaranteed to build bridges over the larger streams and maintain roads over the more difficult parts of the route.

Holloway's Station, three miles northeast of Red Oak maintained "The Narrows". This was the area where the upper Brazil Creek skirts Red Oak Peak and between Red Oak Peak and Red Oak Mountain. The route to Stop 1 approximately follows this route between U.S. 270 and Brazil Creek.

The route south of Red Oak to the west was no accident. The geology of this area determined the route. The line of east-west hills, rising to a height of more than 850 feet would have been real "horse-killers" to cross. The Butterfield Overland Mail took advantage of the fine engineering work of nature and crossed these hills where Fourche Maline Creek had laboriously cut through the hills at Riddle's Station (near Wilburton).

Riddle's Station was a two-room log cabin with a breezeway (known as a "dog-trot") and stone chimneys. The seams of good coal in the area were mined for the fuel and for the blacksmith forge. It is known that the coal was so abundant that it was mined and shipped to other Butterfield stations. Riddle Station was completely demolished after his son's death. Rumors of buried gold on the premises caused a local "rush" and the "searchers" let nothing stand in their way.

After the Civil War, the Butterfield Overland Mail changed its name to Wells Fargo Express Company and new routes were established. The company became known as the American Railway Express Company when railroads replaced stagecoaches. Later, it was split into the American Express Company (credit cards, traveler's checks, etc.) and the Railway Express Agency (no longer in existence.) And, of course, the banking part of Wells Fargo is still around in one form or another.



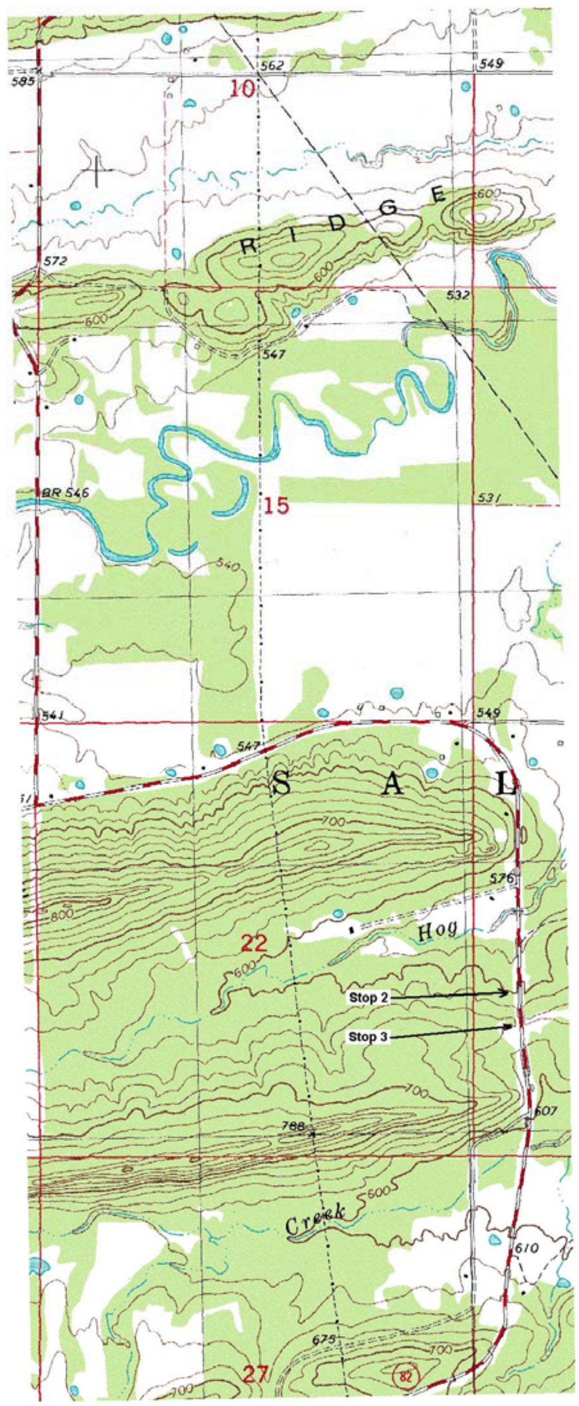
Return to the vehicles. Retrace the route south on OK 82 to U.S. 270.

46.1mi Intersection with U.S. 270. Turn right (west).

46.7mi Intersection with OK 82 South. Turn left (south) onto OK 82.

47.1mi Cross poorly exposed McAlester coal beds.

The lower bed of the McAlester Coal was surface mined approximately 0.4 mile to the east at some unknown time in the past but since 1931. A small underground mine, active before 1931, is present approximately 0.4 mile west of the highway on the southwest side of Red Oak



47.9mi Cross ridge of Warner sandstone.

48.3mi Road turns right (southwest) and begins to climb ridge of Hartshorne Formation. Covered upper Hartshorne coal located at top of Hartshorne Formation at bend in road.

48.7mi Top of Red Oak Ridge.

48.9mi Excellent outcrop of uppermost Atoka Formation on the right.

49.2mi This flat area, known as Long Prairie, is underlain by shale in the upper part of the Atoka Formation.

49.7mi Cross low ridge known as Little Ridge comprised of an extensively ripple-marked sandstone in the Atoka Formation. This sandstone is approximately 3,200 feet below the top of the Atoka.

50.2mi Cross Fourche Maline Creek.

50.3mi Cross buried trace of Choctaw fault.

50.9mi Turn left (east) on OK 82. Ridge immediately to the south is Limestone Ridge, which is capped by Spiro sandstone.

51.9mi County road to Salonia and Leflore continues straight (east). OK 82 to Talihina bends to the right (south). Follow OK 82.

52.2mi Large outcrop of massive, fractured Spiro sandstone on the right (west). A thrust fault that ramps up-section to the east terminates the Spiro outcrop; as a result, the Spiro does not crop out at the road.

52.7mi Outcrop of folded lower Atoka Formation on both sides of the road.

Stop 2

(optional stop)

Folds in the Atoka Formation

This is the first well-exposed outcrop of the turbidite sandstones and shales in the Atoka Formation south of the Choctaw Fault in this area. The turbidites exposed represent mostly incomplete Bouma sequences lacking transport features on the base and are probably distal. Although complicated at first glance, most of the structure is out-of-the-syncline flexural-slip folds and small thrust faults. The axis of the syncline is exposed at the north end of the outcrop on the east side of the road.

In an unpublished Masters thesis (Poole, 1985, University of Missouri), interpreted this exposure in terms of mélange formation and recognized contrasting styles of deformation (ductile versus brittle). If this is true, this area is probably the only other place in the Ouachitas that the subduction mélange may be found.

There is a high degree of structural complexity in this outcrop; nevertheless, most of the strata were lithified during folding (support for mélange hypothesis). Soft-sediment deformation features related to dewatering of sand beds are common. There is some evidence that some sandstone beds behaved less coherently than others during folding.

Return to the vehicles for a short drive south.

52.8mi Outcrop of Spiro sandstone on the right. This is an optional stop. If taken, please park and stay on the side of the road. Watch for traffic.

Stop 3

(optional stop)

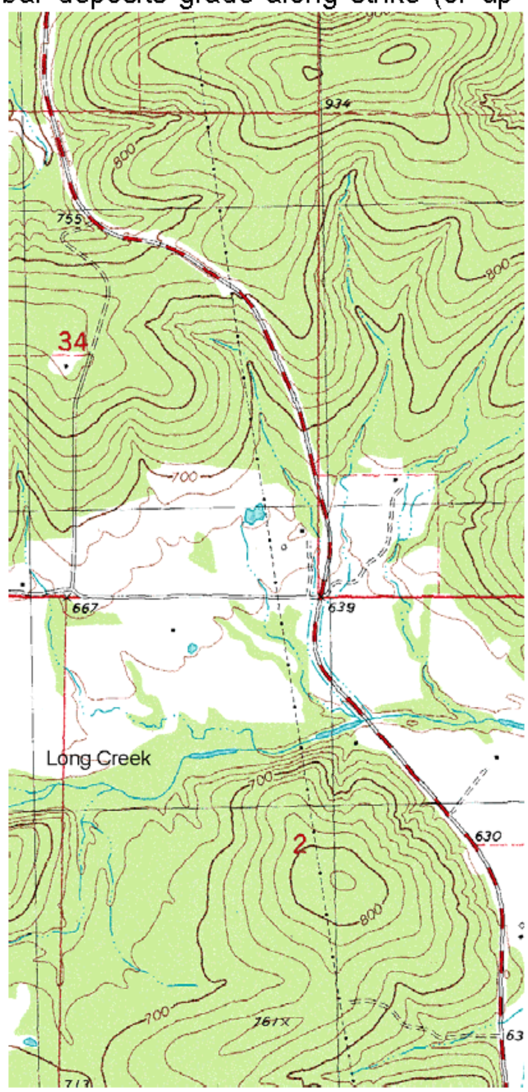
Facies changes in the Spiro Sandstone and Frontal-Belt Structure

This outcrop is approximately 6 miles south of Red Oak on the west side of OK 82. The strata strike at N80°E, dip 75°S, and are overturned. Although the Spiro in this outcrop is composed predominately of sandstone, it does contain a limestone bed near the top. The Spiro has a gradational basal contact with the sub-Spiro shale. The underlying Wapanucka does not occur at this outcrop. The Spiro sandstone is 228 feet thick and can be divided into six intervals at this outcrop.

Quartz is the primary detrital constituent in the sandstones. Fossil fragments are common in some intervals with Echinoderm fragments the most common. At this locality, the porosity of the Spiro is characteristic of the formation.

The occurrence of burrows, bioturbation, fossils, and glauconite suggest that the Spiro sandstone at this outcrop probably was deposited in a shallow marine environment. The cross-bedding and coarser grain size at the base of the uppermost interval in the third unit from the top, and in the second interval from the base suggest possible channeling. The limestone in the second interval from the top apparently represents a period when the sand source was cut off.

Suneson (2005) notes that the Spiro at this location is very different from the Spiro sandstone exposed immediately to the north, yet both outcrops are part of an overturned, north-vergent syncline. If these two outcrops are not separated by a thrust fault, then there is an abrupt facies change from thick, massive, very poorly stratified Spiro sandstone in the north to the well-stratified Spiro sandstone at this outcrop. Earlier examination has suggested that much of the Spiro sandstone in the Arkoma of Latimer County consists of barrier-island deposits separated by tidal channels. The channel deposits have been described as stacked, crinoidal, and bioclastic – what is seen in the northern outcrop. In contrast, the sandstone here was probably deposited in a marine-bar environment. It is possible that the marine-bar deposits grade along strike (or up-section) into barrier-island deposits. If the Spiro of the northernmost thrust sheets of the fold-and-thrust belt are similar to those studied by Gross et al. (1995, AAPG Bulletin, v. 79, p. 159-182) in the Arkoma, then there would be evidence that either the Spiro depositional shelf was very wide or the Choctaw Fault has relatively little displacement at this locale. Alternatively, the stratified Spiro sandstone here may be a marine-bar deposit such as proposed by Grayson and Hinde (1993, Oklahoma Geological Survey Circular 95, p. 216-224.) that is closely associated with a tidal (?) channel deposit.



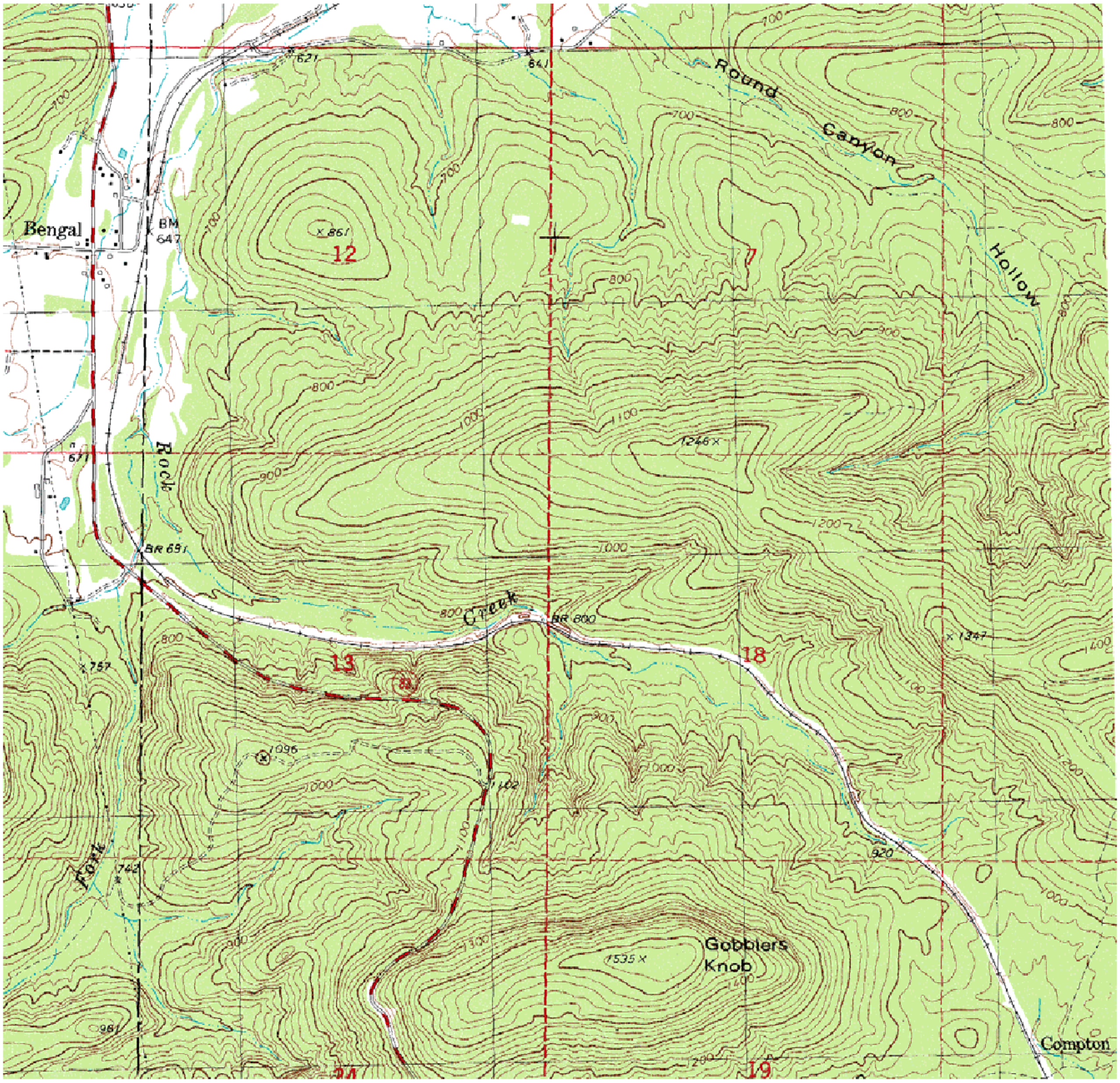
Return to the vehicles and proceed south on OK 82.

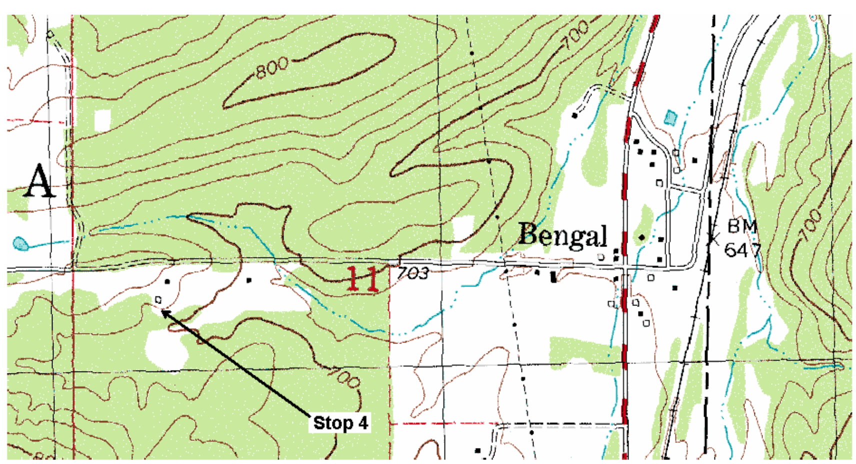
53.2mi Good exposure of "Springer" Formation in the borrow ditch on the left (east) side of the road.

53.4mi Fair exposure of Spiro sandstone to the right (west) of the road. This is structurally the highest and, presumably, most basinward outcrop of Spiro sandstone in this part of the Ouachita frontal belt. However, a very Spiro-like sandstone is present in the Atoka Formation in several thrust sheets to the south.

54.8mi Excellent outcrop of steeply south-dipping Atoka Formation turbidites on the left (east) side of the road.

55.9mi Cross Long Creek.





57.2mi Bengal (ben-GAL), OK. The imaginary ancestral mountain range of "Bengalia" is named for this small town. This ancestral mountain range was necessary in pre-plate tectonic days to fill the geosyncline. Turn right (west) on the paved county road.

57.9mi Stop 4. Behind the

farm house and barn on the left (south) side of the road in a shallow creek bed. This exposure is on private land – please leave all gates as you find them. To visit this site, you must obtain permission from the owners.

Stop 4
Woodford Chert – Caney Shale Olistolith In the Johns Valley Shale

This outcrop was first described in 1933 as Arkansas Novaculite. The "bedrock" outcrop is approximately 400 feet long with its eastern and western ends covered by alluvium and float blocks. However, local accumulations of Woodford float blocks imply that the outcrop is at least 2,000 feet long. Based upon geological mapping by Suneson and Ferguson (1990), this outcrop is a large olistolith within the Johns Valley shale and not a thrust slice surrounded on all sides by faults.

This exposure is the easternmost of several large outcrops of Woodford chert – Caney shale that extend from here to near Wesley, OK. These outcrops may represent slide blocks or debris flows initially derived from the north and subsequently moved north within thrust sheets. The smaller fragments of Woodford chert and Caney shale that are common in the more typical Johns Valley outcrops to the south may represent the more broken, basinward equivalent of the large, coherent blocks similar to this one at this stop.

The Woodford chert and its equivalent units have been identified as possible petroleum source rocks in this region. Therefore, the different interpretations of the Woodford-Caney outcrops here and in other parts of the Ouachitas have significant implications for hydrocarbon exploration. If the interpretation that the Woodford-Caney outcrops are large olistoliths in the Johns Valley shale is correct, then the extent of the Woodford beneath the thrust sheets is unknown and would depend upon where the Woodford olistoliths were derived. To determine this, it would have to be known how far south the olistoliths were carried as parts of slides/debris flows and then how far north they were subsequently thrusted.

Return to the vehicles and retrace route to Bengal.

58.6mi Bengal. Turn right (south) on OK 82.

58.7mi Cross trace of "Ti Valley Fault". This is only approximate due to the difficulty (if not impossible) to map and name individual thrust faults in this part of the Ouachita Mountains (Suneson, 1988).

59.4mi Cross West Fork of Rock Creek.

59.5mi Dirt road to the left (east) and then immediately right (south). This is not one of our stops but is of historical significance.

This dirt road follows the old St. Louis-San Francisco railroad grade and is passable for most cars, pickups, and SUVs but not buses. A field trip in 1994 examined the Johns Valley Formation at the Compton Cut approximately 2 miles to the south. The exposure at Compton Cut probably was visited by most, if not all, of the early geologists who worked the Oklahoma Ouachita Mountains and fueled arguments about the age and origin of the Johns Valley.

The Saint Louis – San Francisco Railway

The St. Louis-San Francisco Railway (or “Frisco”) was one of the largest railways in Oklahoma until the 1990s. Its period of greatest growth in Oklahoma was 1900-1904, but in 1886-87, it constructed one of its earliest and longest lines (144.4 miles) between the eastern border of Oklahoma near Ft. Smith to the Red River south of Hugo. Part of this line crossed Winding Stair Mountain between Bengal and Talihina. The history of this railroad is particularly interesting because it reveals the changing attitudes of the Indians in the Choctaw Nation toward the white settlers and vice versa, following the Civil War.

In 1866, the U.S. Government and the Five Civilized Tribes signed the Peace Treaties of 1866 that stated all past treaties between the Indian Nations and the U.S. Government were null and void because the Indian Nations had fought on the side of the Confederacy. Two railroads were to be built across Indian Territory. The north-south route was granted to the Missouri, Kansas, and Texas Railway (“Katy”). The east-west route was awarded to the Atlantic and Pacific Railway Company (John Fremont was principal organizer). In an 1871 pamphlet entitled *The Atlantic and Pacific Railway and the Indian Territory*, C. Hillyer (A&P Railway attorney) set forward a defense of “Manifest Destiny” of white industrialized civilization which was so representative of a large portion of the climate of opinion of the times that it eventually became the essential position of the U.S. Congress. The railway system in Indian Territory was necessary for the well-being of the country and “any resistance to this policy should be dealt with severely whether one Indian or five thousand be killed in the operation.”

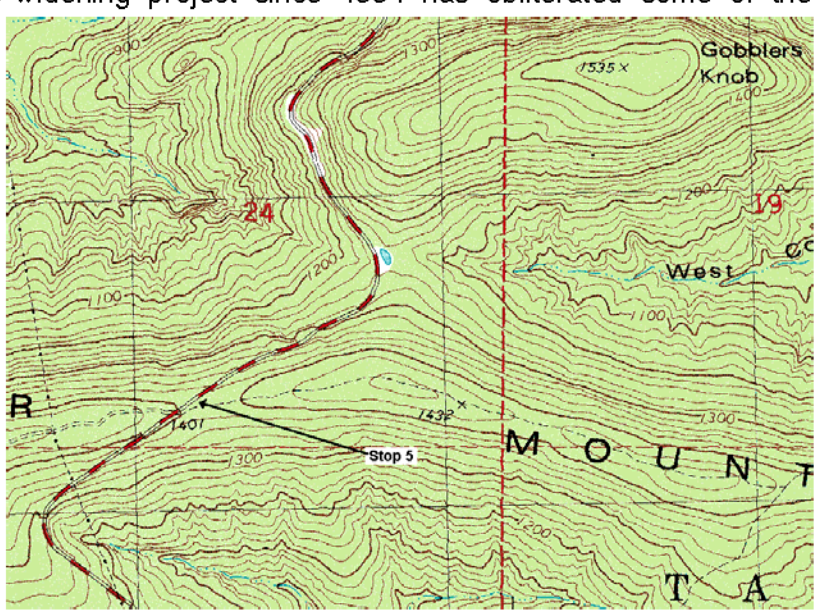
In an attempt to thwart Hillyer and A&P Railway’s attempts, the Indians demanded exorbitant prices for railroad ties, telegraph poles, roadbed material, etc. These high prices, poor business practices, etc., finally drove the A&P Railway into receivership in 1875. It was bought by the Frisco Railway that made an honest effort to correct some of the problems of the A&P and resolve some of the Indian claims.

During this time period, the Congress designated Indian Territory as a U.S. territory. In 1881, the Frisco negotiated an agreement with the Choctaw (somewhat underhandedly) to build a railroad across the Choctaw territory. In 1885, Congress approved the Frisco to build its railway from Ft. Smith, AR to Paris, TX. Construction began in 1886 and completed the following year.

From 1887 until 1919, the Frisco Railway was the least difficult access to the small missionary settlement now known as Talihina. “Talihina” is a Choctaw word meaning “iron road”. It was not until 1919 when convict labor constructed OK 82 from Red Oak that access to Talihina became less difficult.

60.2mi Outcrop of Johns Valley Formation on the uphill (right, south) side of highway. Unfortunately, a highway-widening project since 1994 has obliterated some of the outcrop.

61.2mi OK 82 turns left. This area has been a field trip stop to look at the deepwater Atoka Formation and the “Spiro Equivalent” at the area of Gobblers Knob Syncline. In the literature, this outcrop is often mentioned. If you come back to visit this outcrop, please be aware and watch the traffic.

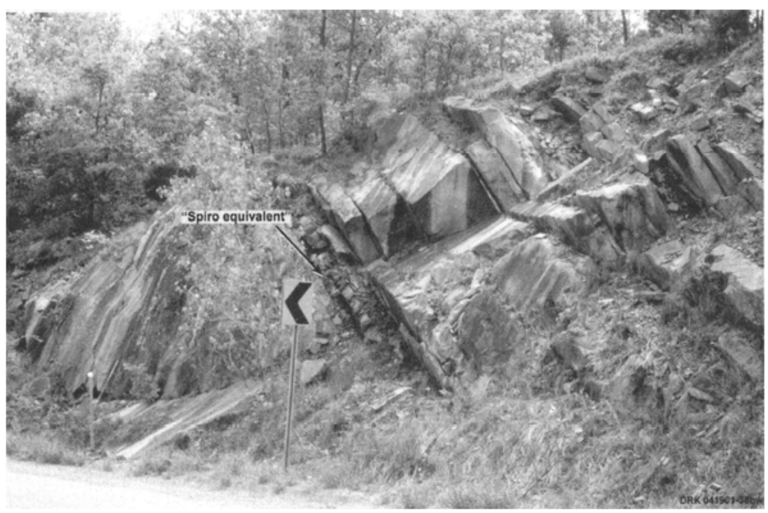


62.1mi Top of Winding Stair Mountain. Pull off on right side of the highway and stop. We will walk back down the highway a few hundred yards. Please be careful! This highway is a very busy state highway with many blind curves, and many drivers drive faster than they should.

Stop 5
Deep-Water Atoka Formation and "Spiro Equivalent", Northern Slope of Winding Stair Mountain

According to Suneson and Ferguson's geological mapping of the Talihina 7.5' Quadrangle (1990), the Atoka Formation along OK 82 is a structurally intact section southward for approximately 1.5 miles to where it encounters the overriding thrust block of the Windingstair Fault. As at Gobblers Knob, the Johns Valley Formation is poorly exposed, thinner sandstone-and-mudrock-dominated sections of the Atoka are poorly to moderately exposed, and the sandstone-dominated Atoka is well exposed.

A distinctive bituminous, skeletal-moldic sandstone occurs near the base of the Atoka Formation at localities along OK 82 and OK 1 and 2. Kerr (2003, AAPG Mid-continent Section Program, p. 36) referred to this unit as "Spiro Equivalent" believing it to be correlative with the lower Atoka Formation Spiro sandstone which crops out between the Choctaw and Pine Mountain Faults in the frontal Ouachitas. At the Gobblers Knob and Winding Stair Mountain sections, the "Spiro Equivalent" is approximately 1 foot thick and is found 102 and 136 feet, respectively, above the base of the Atoka Formation. At both of these locations it is included in the deep-water channel-levee deposits. At the hairpin curve exposure (today's Stop 7), the "Spiro Equivalent" is 71 feet above the base of the Atoka and is part of the 15-foot-thick succession of sandstones that includes dispersed molds of skeletal detritus.



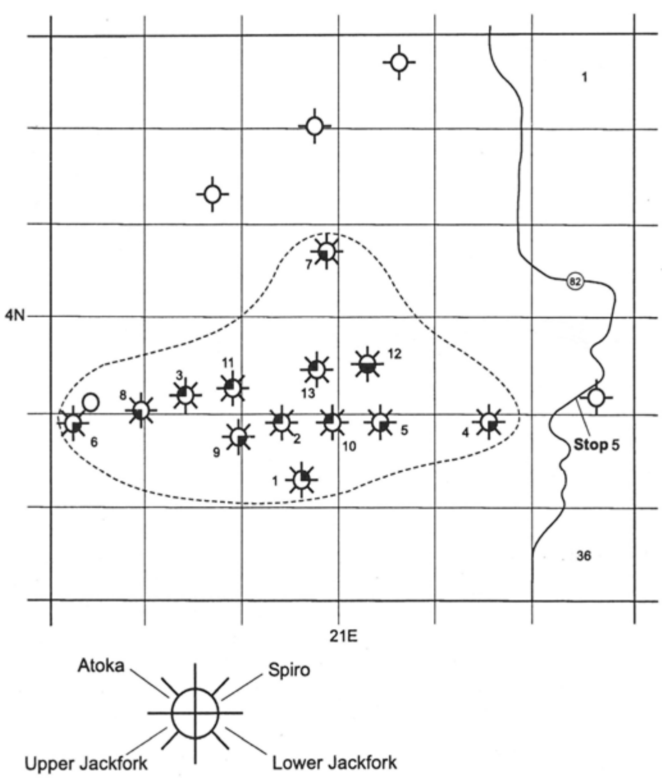
There are two noteworthy differences here compared with the exposures at Gobblers Knob. First, the "Spiro Equivalent" occurs 136 feet above the lithostratigraphic base of the Atoka. Second, a well-exposed, 28-foot-thick channel-fill sequence is present beneath the "Spiro Equivalent". This channel-fill succession is made up mostly of lithofacies organized into thinning-upward amalgamated beds that also show westward lateral shifting of cut and fill.

The character of the lower Atoka at Gobblers Knob and Winding Stair Mountain is interpreted to be the record of mud-rich, submarine-fan, channel-levee deposition. The type of incomplete Bouma sequences, the presence of thick fluidized/liquefied and trough-cross-stratified beds in channel-fill successions, and the development of starved-ripple-cross-stratified sandstones in addition to paleocurrent patterns are the principal evidence for this interpretation. The Gobblers Knob section subjacent to the "Spiro Equivalent" consists predominately of levee deposits on the west side of a submarine channel. The western edge of a sandstone lens 820 feet east of the road cut exposures at about the same stratigraphic position relative to the base of the Atoka (Suneson and Ferguson, 1990). Relative to the "Spiro Equivalent", thick channel-fill successions are exposed along OK 82 above this marker at Gobblers Knob and below at Winding Stair Mountain. These channel-fill deposits trend southeast in the lower Atoka exposures. Although the exposures in the frontal Ouachitas are largely two dimensional, the presence of the "Spiro Equivalent" as a marker bed provides geographic constraints on detailed facies-architecture reconstruction. At Stop 8, this same lower Atoka interval is interpreted to be deposits of submarine-fan lobes.

The Talihina Northwest Gas Field extends for 5 miles west of here. It is noteworthy that the discovery well for this field is the only well that produces from the Spiro (?).

Talihina Northwest Gas Field

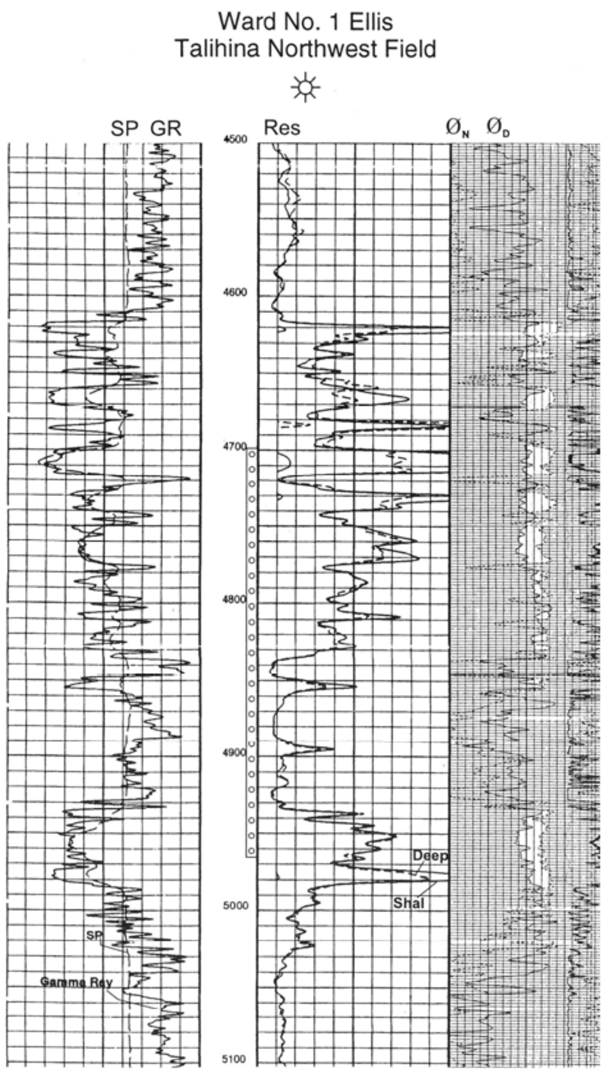
The Talihina Northwest Gas Field was discovered in 1992 by the H&H Star No. 1-28 Lady Luck. This well was completed in the Spiro(?) sandstone at 8,946-9,032 feet and tested 4.59MMcf/day. The field consists of 13 producing gas wells producing from the Atoka, Jackfork, and one possibly from the Spiro. Some of the wells listed as Atoka producers probably produce from the Jackfork. As interpreted, some of the wells produce from fractured Jackfork sheet sands while others produce from Jackfork channel sands.
(Following figures from Suneson et al., 2005.)



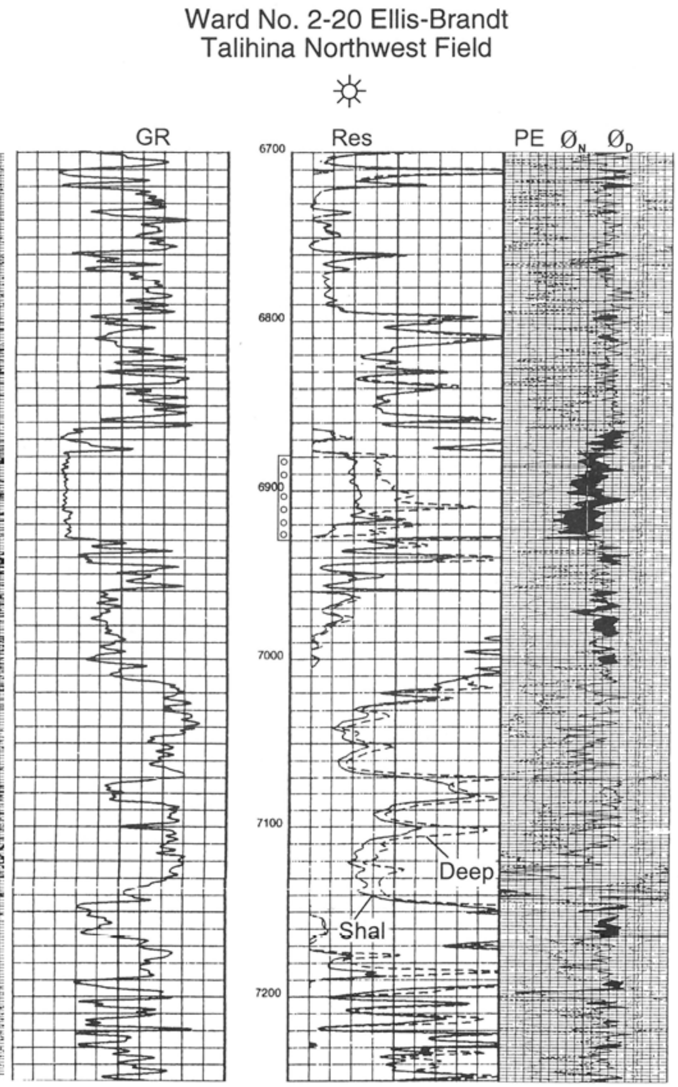
Producing Wells in Talihina Northwest Gas Field by Spud Date

Operator, number, farm, spud date, total depth, producing formation, depth of producing formation (data from NRIS as reported by operator to Oklahoma Corporation Commission on Form 1002A).

1. H&H Star Energy 1-28 Lady Luck; 12/30/91; 9,976 ft; Spiro; 8,946–9,032 ft
2. Ward Petroleum 1-21 Secor; 6/16/94; 8,600 ft; Atoka Lower; 7,702–7,953 ft
3. Ward Petroleum 1-20 Ellis-Brandt; 2/24/95; 6,700 ft; Atoka Middle; 3,975–4,320 ft; Atoka Lower; 6,056–6,465 ft
4. Ward Petroleum 1-23 Sara; 5/20/95; 8,239 ft; Jackfork; 6,104–6,307 ft
5. Chesapeake Operating 1-22 Weyerhaeuser; 5/27/95; 9,500 ft; Lower Jackfork; 5,640–9,368 ft
6. Ward Petroleum 1-30 Lyons; 8/27/95; 7,905 ft; Lower Jackfork; 5,220–7,742 ft
7. Chesapeake Operating 1-16 Bear Mountain; 11/25/95; 9,992 ft; Upper Jackfork; 7,476–8,256 ft
8. Ward Petroleum 1 Ellis; 2/5/96; 10,052 ft; Upper Jackfork; 4,698–6,718 ft
9. Ward Petroleum 1-29 Ford; 8/28/97; 8,850 ft; Lower Jackfork; 8,656–8,698 ft
10. Ward Petroleum 1-21 Mary Grace; 1/1/99; 8,000 ft; Atoka Lower; 7,163–7,455 ft; Atoka Middle; 5,115–6,818 ft
11. Ward Petroleum 2-20 Ellis-Brandt; 10/8/01; 7,304 ft; Atoka Lower; 6,878–6,928 ft; Atoka Lower; 6,436–6,607 ft
12. Chesapeake Operating 2-22 Weyerhaeuser; 7/14/02; 7,500 ft; Upper Jackfork; 4,600–5,694 ft; Lower Jackfork; 6,282–7,122 ft
13. Ward Petroleum 1-21 Blake; 6/5/03; 8,100 ft; Atoka Upper; 5,539–5,588 ft; Atoka Upper; 5,302–5,388 ft



Part of log from Ward No. 1 Ellis showing the spontaneous potential, gamma-ray, resistivity, and porosity log patterns for typical Jackfork sheet sandstones. Many of the sandstones show neutron – density crossover.



Part of log from Ward No. 2-20 Ellis-Brandt. The well is listed by the OCC as an Atoka producer, but the log character of the producing intervals resembles that of the Jackfork Group. The perforated interval has a distinctly blocky character with an abrupt base, suggestive of a channel sandstone. The blocky sandstone shows significant neutron – density crossover.

Return to the vehicles and proceed south on OK 82. For the next approximately 1.4 miles, the road descends the south side of Winding Stair Mountain and ascends through approximately 4,000 feet to moderately (30-60°) south-dipping, south-facing Atoka Formation.

63.5mi Cross trace of Windingstair Fault. This fault probably has among the largest throws of any of the thrust faults in the Ouachita Mountains, and here it juxtaposes the Stanley Group in the hanging wall to the south against the Atoka Formation in the footwall to the north.

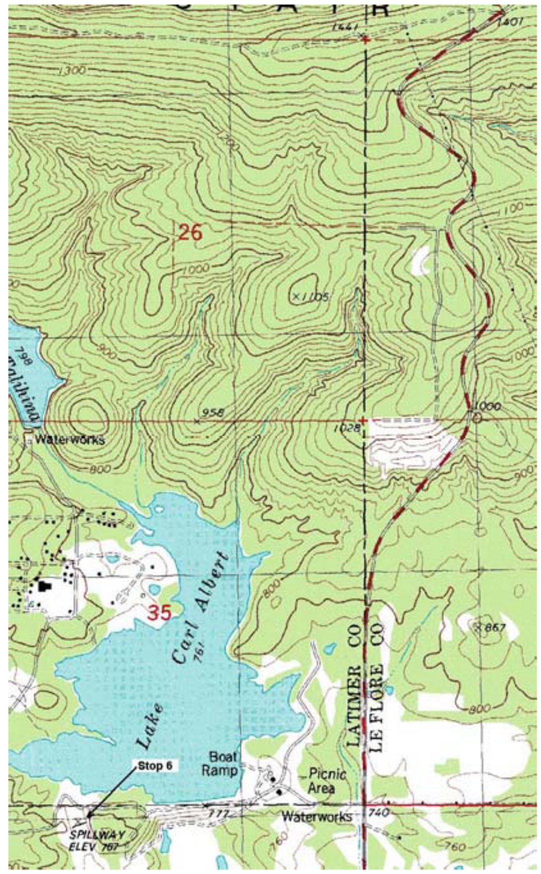
63.6mi Entrance to the Talihina city dump on the right (west). The Windingstair Fault zone is exposed in the dump.

64.5mi Turn right (west) on gravel road toward Lake Carl Albert.

64.7mi Bear left to go over dam.

64.9mi Cross Lake Carl Albert Dam.

65.2mi Large outcrop on east side of spillway of Lake Carl Albert Dam. Park the vehicles and walk up the low hill on east side of spillway and descend into spillway near the east abutment of the low dam. Be careful, much of the floor of the spillway typically is muddy.



<u>Stop 6</u>
Stanley Group Strata

This outcrop is one of the best exposures of the Stanley Group in this part of the Ouachita Mountains. Reasons for looking at this outcrop are 1) to compare the Stanley sandstones and shales with those of the Atoka and Jackfork Formations and 2) to investigate whether or not these turbidite-appearing strata are, in fact, turbidites.

Many features of the Stanley strata at this location are similar to those observed in the turbidite strata of the Atoka and Jackfork Group, including sole marks, dewatering structures, and convolute stratification. Other features, however, are distinctive of the Stanley: 1) many of the sandstone beds are graded and contain matrix-supported, subrounded, coarse-grained-sized grains in a muddy, fine-sand-size matrix at the base, 2) shale rip-up clasts are common locally, and typically are concentrated in bedding-parallel zones within the sandstone beds, 3) trace fossils are rare, 4) some beds are cemented with calcite, and pyrite occurs locally in trace amounts, 5) shales typically contain discoidal siltstone masses and show pencil structure, and 6) cone-in-cone structures and sandstone and siltstone dikes characterize some strata.

Many of the sandstone beds in this outcrop of the Stanley Group do not have typical Bouma-sequence structures. It is possible that some may not have been deposited by turbidity currents, but by mass-flow mechanisms. Niem (1976) divided the lower part of the Stanley into a southern/proximal and a northern/distal flysch facies and suggested each accumulated on different parts of a deep-sea fan-complex and adjacent basin plain. He also showed that the more sandstone-rich proximal facies prograded over the distal facies in later Stanley time in the central Oklahoma Ouachitas.

Return to vehicles. Retrace route to OK 82.

65.9mi Turn right (south) on OK 82. At this point, OK 82 follows the county line. Latimer County is to the right (west) and LeFlore County is to the left (east).

67.0mi Intersection with OK 1 and 63 on west side of Talihina. Turn right (west) on OK 1/63. OK 82 ends.

67.2mi Leave LeFlore County and enter Latimer County.

67.3mi Cross Rock Creek. The bouldery material on either side of the highway probably represents debris flow deposits that flowed out of Devils Hollow just north of Buffalo Mountain.

68.2mi OK State Highway A63 to the right (north). Continue straight on OK 1/63. About 0.3 mile north of this point is the one-well “Talihina Oil Field”. See Figure 17.

For the next 10 miles the road crosses over very low topography, underlain by the Stanley Group. Poorly documented faults and folds occur within the Stanley, but little (nothing?) is known about their location or origin.

72.3mi Highway turns slightly to the right and heads due west. The Potato Hills are to the left, and Buffalo Mountain is on the right (north). A welded tuff is present about two-thirds of the way up Buffalo Mountain near the top of the Stanley Group.

77.0mi Turn left (south) on to gravel road. (If you cross Buffalo Creek, turn left immediately after the bridge and ignore next two turns.)

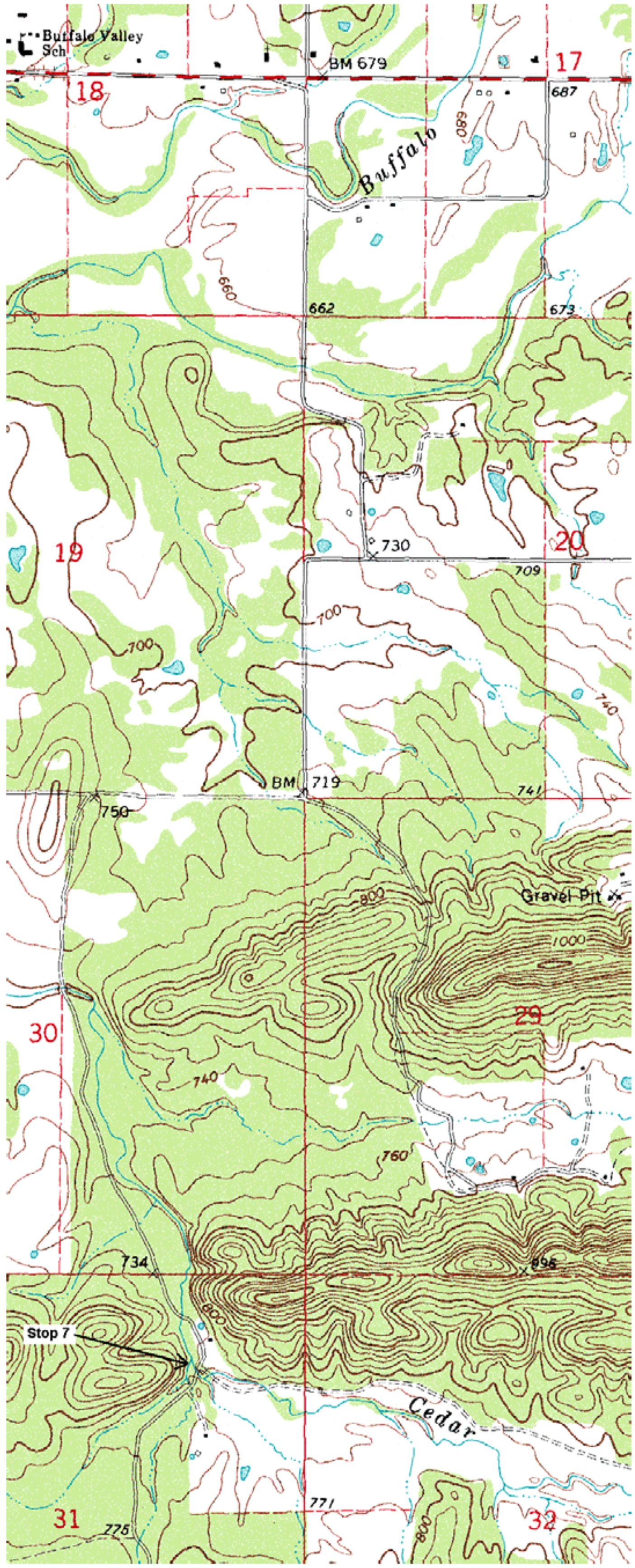
77.2mi Turn right (west).

77.7mi Turn left (south).

78.0mi Cross Little Buffalo Creek. Then turn left, then right.

78.5mi Turn right (west) at T intersection.

78.6mi Turn left (south).



79.1mi Turn right (west) at T intersection.

79.5mi Turn left (south).

79.9mi Cross Cedar Creek. An excellent, although highly deformed, outcrop of Stanley sandstone and shale, is present immediately up the creek.

80.7mi Fork in road. Left fork crosses Cedar Creek. Stop at fork.

Stop 7
Early and Middle Paleozoic Stratigraphy in Potato Hills And Potato Hills Jackfork Play

This stop is one of the best exposures of the lower and middle Paleozoic strata in the Ouachita Mountains. The outcrop is on the southern limb of an overturned, north-vergent anticline that is bounded on the north by the Cedar Creek Thrust Fault. The Cedar Creek Fault juxtaposes the Ordovician Womble shale in the hanging wall to the south against Mississippian Stanley Group shales and sandstones in the footwall to the north. The Womble shale is not exposed along the road and is poorly exposed along the creek just east of the road. The Bigfork chert conformably overlies the Womble shale and is well-exposed in the creek. The Upper Ordovician Polk Creek shale conformably overlies the Bigfork and consists of a dark gray shale with chert stringers. An unconformity separates the Polk Creek from the overlying Lower Silurian Missouri Mountain shale. The Missouri Mountain shale is a platy green shale that is typically mapped with the Polk Creek shale. The Arkansas Novaculite is Early Devonian to Early Mississippian and consists of chert that has a distinctive blue to green color.

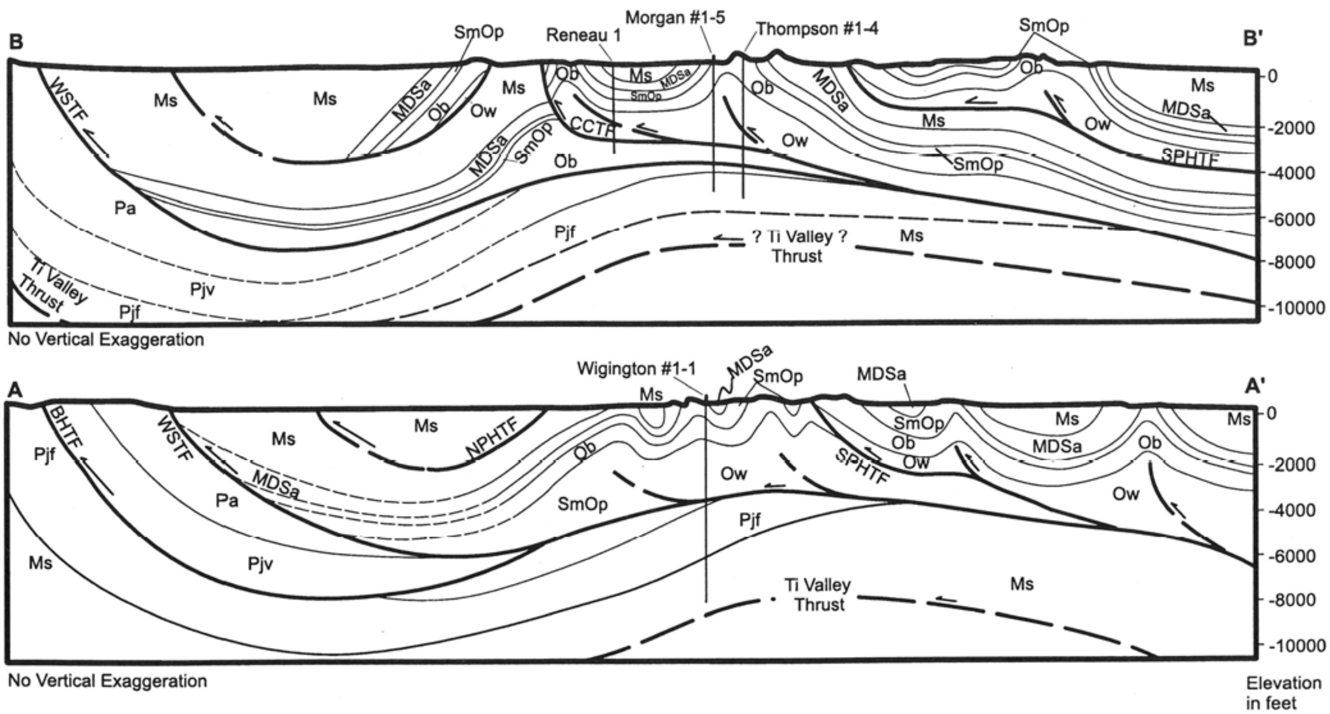
The Potato Hills are located in an antiformal valley (Kiamichi Valley) between the Buffalo Mountain Syncline to the north and the Lynn Mountain Syncline to the south. They consist of a series of low, well-rounded ridges, said to resemble a sack of potatoes from a distance. The hills form a roughly elliptical exposure of Ordovician through Mississippian shale and chert units. The Potato Hills are the only place in the central Ouachitas of Oklahoma that exposes these units. The two other Oklahoma locales for these units are Black Knob Ridge near Atoka and the Broken Bow Uplift near Stevens Gap and Beavers Bend.

The Potato Hills have provided geologists with much fuel for a variety of different structural interpretations. The most compelling interpretation of the structural origin of the Potato Hills is that they are a window through a single-folded thrust fault – the Potato Hills Thrust. This interpretation has implications for the relative timing of the movement on the major Ouachita thrusts. If correct, the Potato Hills Thrust was emplaced prior to movement on the deeper and more foreland-ward Windingstair, Ti Valley, and Choctaw Thrusts. Movement on and subsequent folding of the Windingstair Fault would have folded the Potato Hills Thrust. The window interpretation also requires a break-forward style of thrusting as has been suggested by Çemen et al. (2001) for areas in the frontal belt of the Ouachitas and the Arkoma Basin.

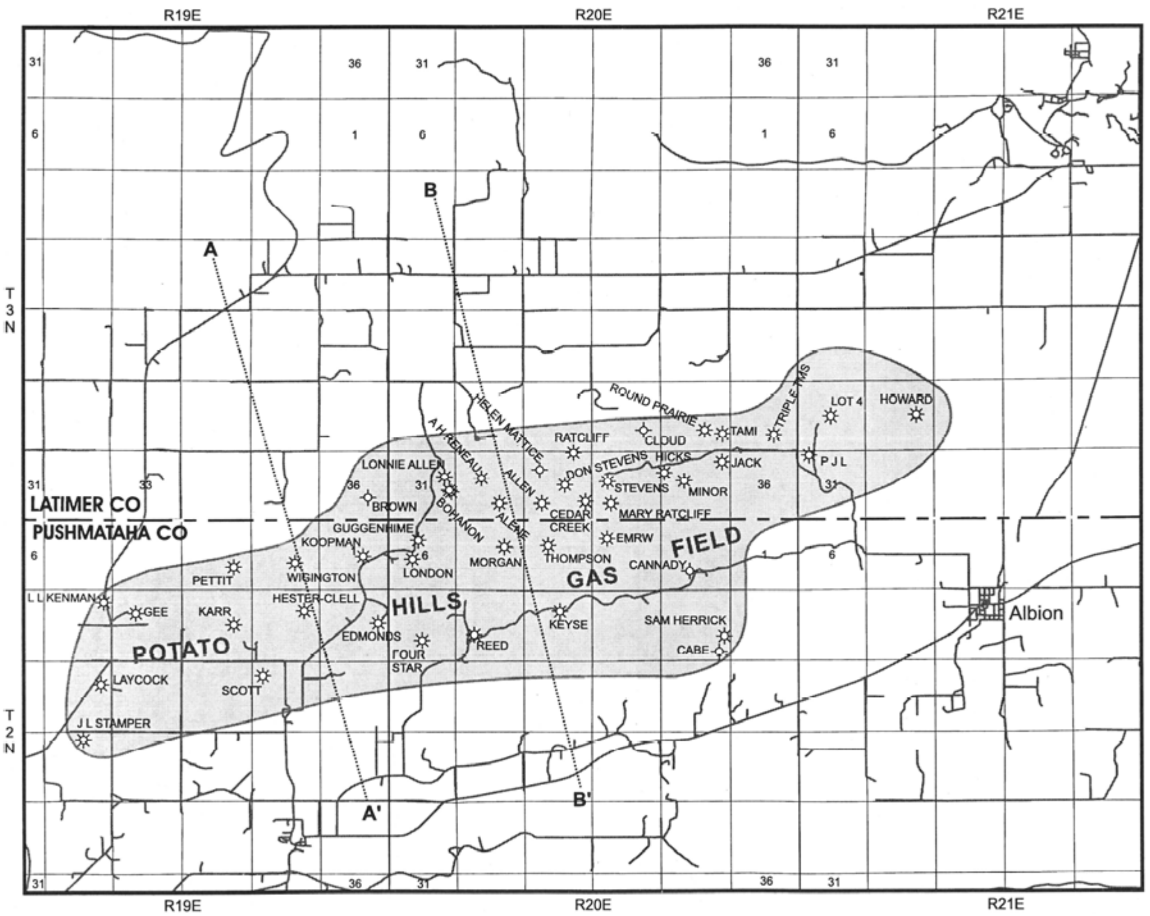
The Potato Hills gas field was discovered in 1960 by Sinclair Oil Company. The discovery well was the Sinclair No. 1 Reneau (immediately east of the Stop location). The total depth was 7,097 feet and it was completed in the Bigfork chert at 2,340-2,410 feet with an open-flow potential of 1.8MMcf/day. The well may have produced from the lower overturned limb of an anticline or a thrust repeated Bigfork section. A few more wells were drilled in the 1960s yielding a total production of a few thousand Mcf per month. The gas was used locally in Clayton and Albion.

The late 1990s brought a "rediscovery" of the Potato Hills Field by GHK. Gas production peaked in July 2000 when almost 4Bcf of gas was produced. Approximately 35 wells are active (2004) in the Potato Hills gas field, mostly completed in the Jackfork. Most wells are drilled along the trend (N85°E) of the subsurface antiformal trap created by the movement of the Ti Valley and/or Choctaw Fault.

Speculation on the origin of the deeper structures in the Potato Hills area for the folding of the Potato Hills and deeper thrust sheets continues. Interpretation of a recently acquired, low-altitude, high-resolution aeromagnetic survey suggests that variations in rifted basement topography may be related to the Potato Hills structure. The aeromagnetic data suggest that a north-northeast-trending lineament cuts across the Potato Hills in an area where geologic mapping demonstrates that a detachment fault ramps up from the Womble shale to the Stanley Group. Thus, deeper structures may be folded in response to this irregular basement configuration. (Following figures from Suneson et al., 2005.)



NPHTF	North Potato Hills Thrust fault	Pa	Atoka	SmOp	Missouri Mtn./Polk Creek
SPHTF	South Potato Hills Thrust fault	Pjv	Johns Valley	Ob	Bigfork Chert
CCTF	Cedar Creek Thrust fault	Pjf	Jackfork Group	Ow	Womble Shale
WSTF	Windingstair Thrust fault	Ms	Stanley Group		
BHTF	Boggs Hollow Thrust Fault	MDSa	Arkansas Novaculite		



Wells in Potato Hills Gas Field by Spud Date

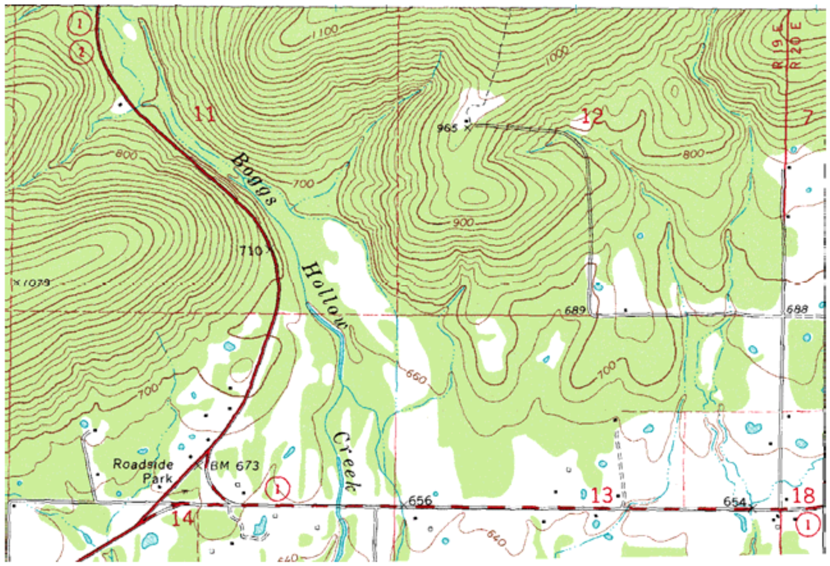
Operator, name, producing unit, total depth, spud date (data from NRIS as reported by operator to Oklahoma Corporation Commission on Form 1002A).

1. Sinclair Oil & Gas Co.; A. H. Reneau; Big Fork; 7,097 ft; 5/9/1959
2. Sinclair Oil & Gas Co.; H. H. Coussens; not reported; 2,500 ft; 10/7/1960
3. Sinclair Oil & Gas Co.; Helen Mattice; not reported; 3,000 ft; 2/14/1961
4. GHK Co.; 1-33 Ratcliff; Jackfork; 12,597 ft; 12/29/1996
5. GHK Co.; 1-34 Stevens; Jackfork; 6,115 ft; 6/5/1998
6. GHK Co.; 1-32 Bohanon; Jackfork; 6,974 ft; 7/24/1998
7. GHK Co.; 1-31 Alene; Jackfork; 6,955 ft; 9/25/1998
8. GHK Co.; 1-35 Minor; Jackfork; 5,410 ft; 11/9/1998
9. GHK Co.; 1-30 P J L; Jackfork; 7,235 ft; 5/24/1999
10. GHK Co.; 1-26 Round Prairie; Jackfork; 7,058 ft; 6/6/1999
11. GHK Co.; 1-25 Triple Tms; Jackfork; 8,905 ft; 6/18/1999
12. GHK Co.; 1-6 Guggenhime; Jackfork; 14,268 ft; 9/14/1999
13. GHK Co.; 1-4 Thompson; Jackfork; 4,918 ft; 10/4/1999
14. GHK Co.; 1-5 Morgan; Jackfork; 4,736 ft; 12/18/1999
15. Gothic Production Co.; 27-1 Cloud; Jackfork; 7,000 ft; 12/21/1999
16. GHK Co.; 2-32 Allen; Jackfork; 5,672 ft; 1/21/2000
17. GHK Co.; 1-1 Wigington; Jackfork; 8,000 ft; 1/21/2000
18. GHK Co.; 1-3 Emrw; Jackfork; 5,560 ft; 3/2/2000
19. GHK Co.; 1-2 Koopman; Jackfork; 7,220 ft; 4/2/2000
20. GHK Co.; 2-35 Hicks; Jackfork; 7,516 ft; 4/15/2000
21. GHK Co.; 2-6 London; Jackfork; 5,981 ft; 6/16/2000
22. GHK Co.; 1-3 Pettit; Arkansas Nov.; 7,546 ft; 6/20/2000
23. GHK Co.; 3-35 Jack; Jackfork; 9,824 ft; 8/6/2000
24. GHK Co.; 1-7 Four Star; Jackfork; 21,143 ft; 9/1/2000
25. GHK Co.; 2-33 Mary Ratcliff; Jackfork; 6,903 ft; 10/22/2000
26. GHK Co.; 3-33 Cedar Creek; Jackfork; 5,824 ft; 1/4/2001
27. KCS Medallion Resources Inc.; 1-26 Tami; Jackfork; 5,800 ft; 1/11/2001
28. GHK Co.; 1-12 Edmonds; Jackfork; 6,625 ft; 1/11/2001
29. GHK Co.; 1-11 Hester-Clell; Jackfork; 5,569 ft; 3/2/2001
30. GHK Co.; 1-8 Reed; Jackfork; 6,715 ft; 1/27/2001
31. GHK Co.; 1-9 Keyse; Jackfork; 7,247 ft; 3/12/2001
32. GHK Co.; 4-33 Don Stevens; Bigfork; 13,350 ft; 4/20/2001
33. GHK Co.; 1-10 Karr; Jackfork; 7,244 ft; 4/28/2001
34. GHK Co.; 2-12 Edmonds; Jackfork; 7,550 ft; 5/9/2001
35. GLB Expl. Inc.; Brown; Jackfork; 7,482 ft; 5/24/2001
36. GHK Co.; 1-2 Cannady; not reported; 7,685 ft; 6/21/2001
37. GHK Co.; 1-9 Gee; Bigfork; 8,676 ft; 7/5/2001

Return to the vehicles and retrace the route back to OK 1/63.

85.4mi Turn left (west) on OK 1/63.

86.0mi Buffalo Valley School on the right (north). Buildings are faced with beautiful pieces of turbidite sandstones from the Atoka Formation, showing a wide variety of sole marks including scours and trace fossils.

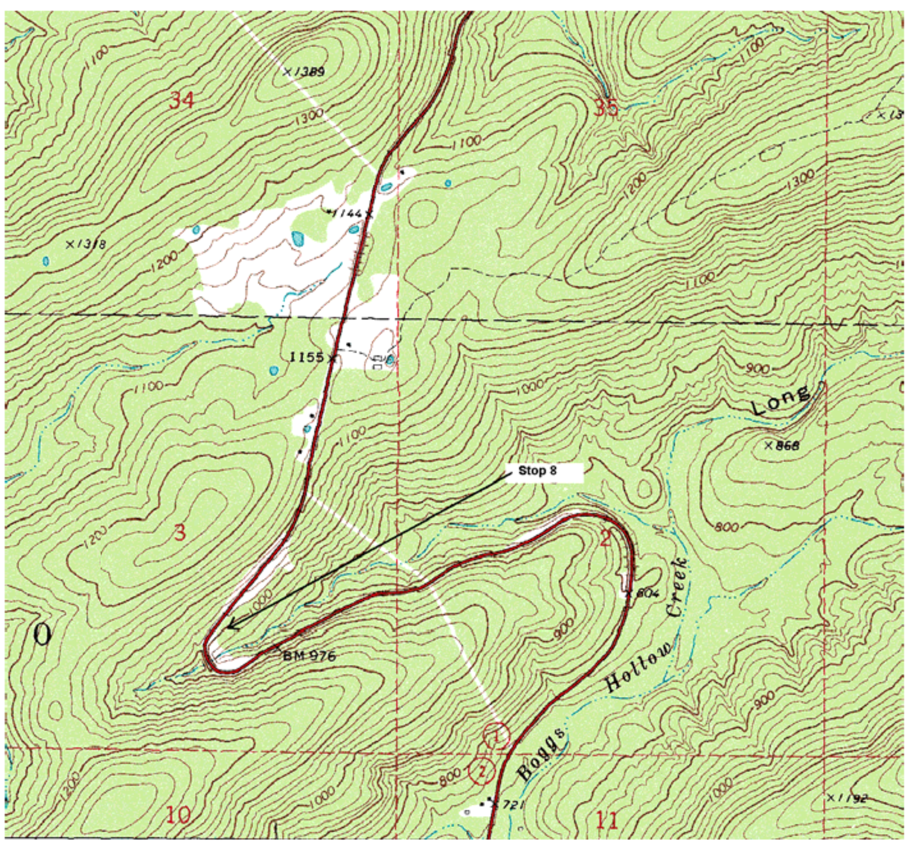


88.0mi Intersection with OK 2. Turn right (north) on OK 1/2/63 toward Wilburton. (Note: Travel is from bottom to top of map graphics!)

88.6mi Cross trace of Windingstair Fault. Here the fault juxtaposes the Stanley Group in the hanging wall to the south against the Atoka Formation in the footwall to the north.

91.1mi Sandstones in the upper part of the Jackfork Group on the left (south).

91.3mi Hairpin curve. The upper part of the Jackfork Group, the Johns Valley Formation, and the lower part of the Atoka Formation are exposed here. Just above the curve there is a wide shoulder on the right (east) side of the road. This is an optional stop. If we do decide to stop, pull off onto the shoulder. Outcrop is on the north side of the highway. **Please be careful crossing the road!**



Stop 8

(optional stop)

Deepwater Atoka and "Spiro Equivalent",
Hairpin Curve Locality

This locality probably has been visited by every geologist who has ever worked in the Ouachita Mountains and by most geologists who have ever taken a field trip to the Ouachitas. Highway construction in the 1940s removed the soil and slope debris that typically cover the Johns Valley Formation. Over the years the exposure has deteriorated to the point where only a resistant sandstone interval and exotic boulders as float are evidence for the existence of the Johns Valley outcrops. However, the Atoka Formation is still relatively well-exposed here, although the shale-rich intervals typically are covered.

The lithostratigraphic base of the Atoka Formation is made of up interstratified 1-foot-thick sandstones with mostly incomplete Bouma successions and 3- to 10-foot thick dark gray clay-shale interbeds. These turbidites are crudely organized into upward-thickening sandstone beds and upward-increasing sand/mud-ratio successions 100 to 130 feet thick. A prominent 15-feet thick sandstone 61 feet above the base of the Atoka Formation is made up of amalgamated T_a sandstones, each of which is 3 to 10 feet thick and has scoured basal contacts. This interval also contains scattered skeletal molds as part of the framework constituents. Near the top of the interval is a 1-foot-thick bituminous, skeletal-moldic sandstone that represents the "Spiro Equivalent".

The deepwater lower Atoka section at this locality contrasts in a number of important respects with the exposures seen along OK 82 some 14 miles to the east (Stop 5). The incomplete Bouma successions here contain more of the finer-grained, more dilute fraction of turbidity currents. Hemipelagic deposits are thicker and make up more of the section here. Biogenic structures as sole markings on sandstone beds are much more abundant here than at Stop 5. Finally, the "Spiro Equivalent" here occurs within a succession of sandstone beds containing dispersed fossil molds. At Stop 5, OK 82, it is a discrete bed.

Paleocurrent measurements, integrated with lithofacies, define four lobe deposits in the lower Atoka at this site; a fifth lobe deposit is present at the top of the exposure on the north limb of the syncline. The first (oldest) lobe indicates southwest sediment transport. The second indicates west transport; the third and fourth west-southwest transport, and the fifth west-northwest transport. Typically the standard deviation about the mean azimuth of paleocurrent measurements within each lobe is less than 10°.

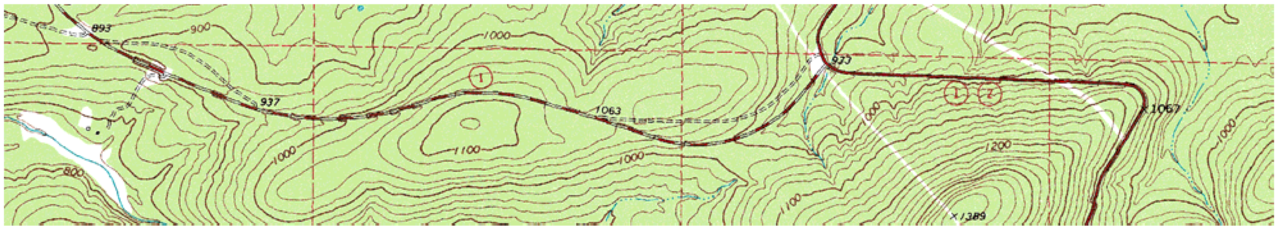
Watch the traffic and carefully return to the vehicles. Use extreme caution when pulling on the roadway. Continue north on OK 1/2/63. For the next ¾ mile the strata face north and dip steeply north (upright) or south (overturned) on the south flank of the Anderson Creek Syncline.

92.1mi Cross axis of Anderson Creek Syncline. For the next mile the sandstones in the Atoka Formation face south and dip about 45°SSE on the north flank of the syncline.

93.3mi Thick sandstone outcrops on left (south) are basal Atoka Formation. Dispersed sparse molds are present in some sandstone beds. The "Spiro Equivalent" occurs 98 feet above the base of the Atoka.

93.4mi A large (several hundred feet by several hundred feet) olistolith of Woodford shale is present in the Johns Valley Formation immediately south of the highway. The outcrop is similar to the Caney shale, but the presence of phosphate nodules is evidence that it is Woodford.

94.1mi Intersection with OK 2 straight (north) to Wilburton and OK 1/63 left (west) to Hartshorne. Turn left (west).

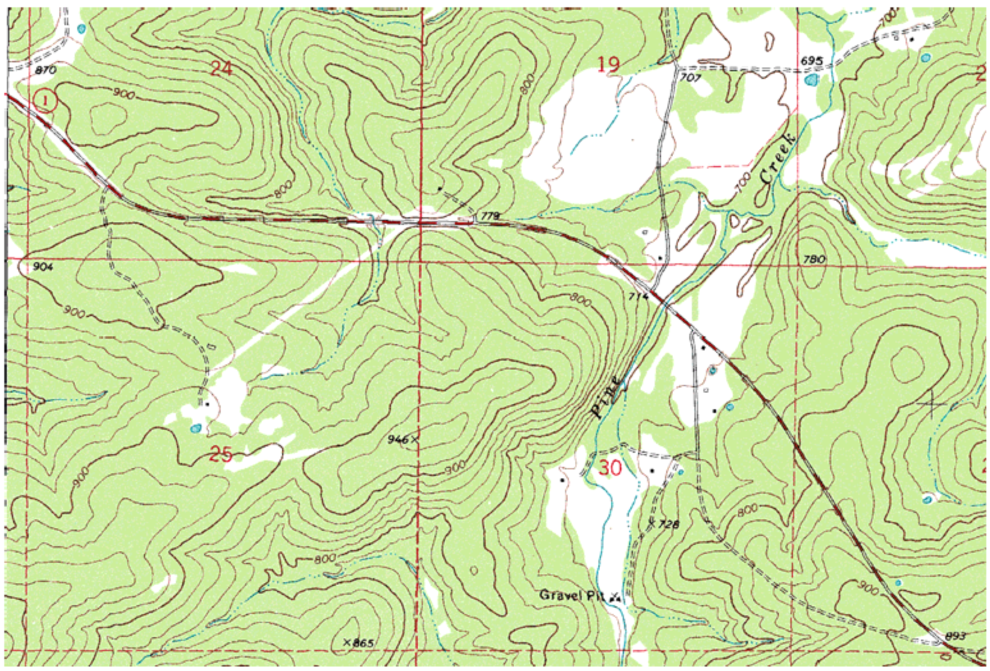


94.8mi Cross trace of thrust fault that juxtaposes Johns Valley Formation to the south against Atoka Formation to the north.

97.1mi Cross trace of "Ti Valley Fault".

97.4mi Cross Pine Creek.

98.0mi Enter Veterans Colony West gas field. Most of this gas field is north of the highway.

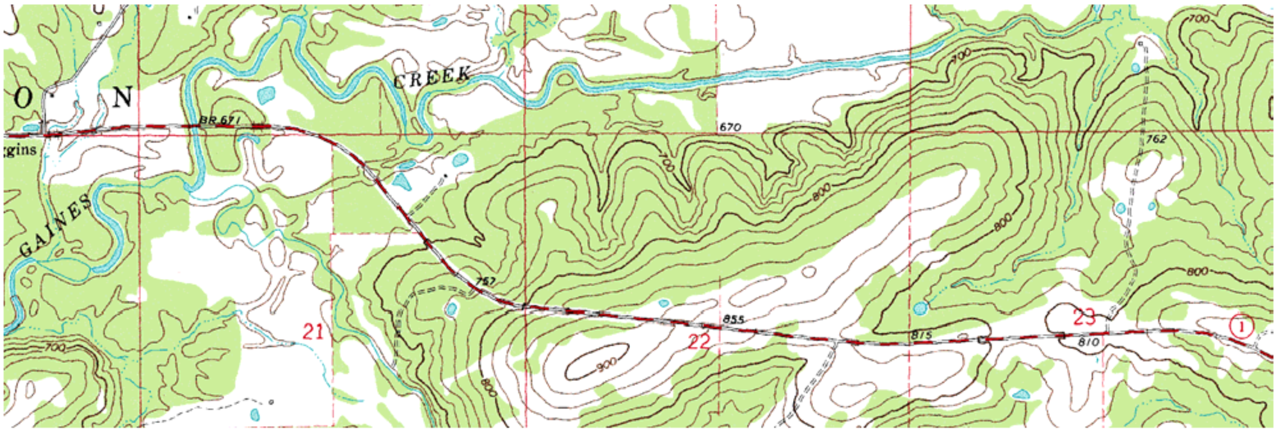


Veterans Colony West Gas Field

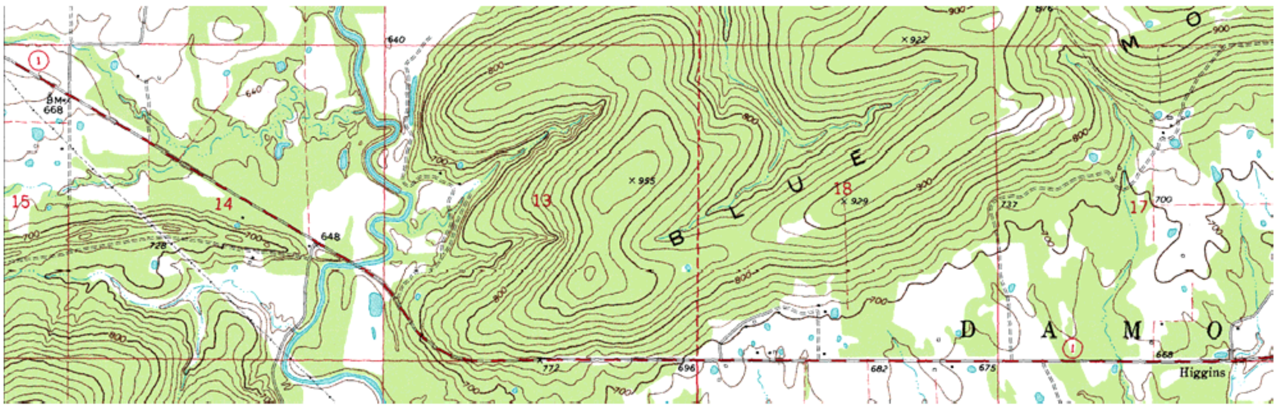
The Veterans Colony West Gas Field covers approximately 7 square miles. The discovery well for the field is the BTA No. 1 9001 JV-P Amason drilled in 1990 and completed in the Spiro sandstone. At the present time, there are 11 active wells in the field. Nine produce from the Spiro sandstone, one produces from the Atoka, and one is commingled Atoka and Spiro. The principal reservoir is the Spiro sandstone. The structural geology of the field at the Spiro reservoir level is several blind anticlines overlying blind thrust in the footwall of the Choctaw Fault. The thrusts are splays off the Woodford detachment.

99.2mi Leave Veterans Colony West gas field. For the next several miles, OK 1/63 crosses turbidites in the Atoka Formation.

102.2mi Cross Gaines Creek.



102.6mi Small "village" of Higgins, Oklahoma.



103.6mi Butterfield Overland Stage Line crossed the highway near here.

105.0mi Ridge to right (north) is Blue Mountain. It is underlain by south-facing, south-dipping turbidite shales and sandstones of the lower Atoka Formation.

105.5mi Recross Gaines Creek.

105.6mi Long ridge of Wapanucka limestone – Spiro sandstone ends abruptly just to the east of the road.

Some kind of north-south trending transverse structure follows Gaines Creek at this location. The strata on the east side of the creek consist mostly of the steeply south-dipping Atoka Formation, whereas the south- to west-dipping folded Wapanucka limestone and lower Atoka Formation occurs on the west side. It has been suggested that a right-lateral tear fault separates these two areas. An alternative

Pusley Station

Approximately 1½ miles southwest of the Gaines Creek crossing was the site of the Butterfield Station operated by Silas Pusley. Pusley was a member of an old Choctaw family that settled in the areas shortly after the Choctaw removal and by 1858 there were many members of the family living in this area.

Pusley's home was the usual two room log house with a dog trot and tall stone chimneys. The stable and corral were near the home in the well watered creek valley which provided excellent forage in summer and hay in the winter for the Butterfield teams for which Pusley tended. In the first year of operation, the stages forded Gaines Creek but were often bogged down and stuck which delayed the mails. In 1859, the Choctaw Council gave Pusley a permit to build a toll bridge across the creek. This he did and travel for the stages and also for the freighters was improved and speeded up.

explanation, largely based on the folded strata west of Gaines Creek, is that the structure is a north-striking, west-dipping thrust ramp in which the west side has moved relatively up and over the east side.

107.2mi Ridge of Wapanucka limestone dipping 45° south. Park on right side of highway for Stop 9. As always, watch for traffic.

<u>Stop 9</u>
Wapanucka Limestone and Structure of the Arkoma Basin – Ouachita Transition Zone

The Wapanucka limestone here is exposed along Limestone Ridge in the northernmost thrust sheet in the Ouachita fold and thrust belt. The Wapanucka exposure that we passed west of Gaines Creek is contained within a higher thrust sheet. This outcrop is in the hanging wall of the Choctaw Fault, the trace of which is approximately one mile north-northeast of here.

The yellow painted numbers that may be seen along the northeast side of the highway are from work performed by R. C. Grayson for his Doctoral dissertation in 1980. His measured section has been included here. Grayson used this outcrop and others along-strike to show the interbedded nature of micritic and spiculiferous limestones in the Wapanucka. He suggested that both were deposited under low-energy lagoonal conditions. The micritic limestones predominated under conditions of poor circulation, and the spiculiferous limestones predominated under conditions of better circulation. He also used this outcrop to suggest that the interbedded limestone-pebble conglomerates, oolites, and bioclastic calcarenites (rare in this outcrop) record the transition from subaerial exposure to intertidal to shallow subtidal conditions. Most of the section consists of bioclastic spiculiferous limestone. Though we will primarily examine the newer outcrop on the southwest side of the road, Grayson's unit 11 (shale) can be easily recognized on either side.

Of particular interest in the new exposure of the Wapanucka on the southwest side of the road are

Measured Section of Wapanucka Limestone

Top of measured section	*Thickness (ft)*
Spiro sandstone	
17. Spiculiferous chert	1.8
Sub-Spiro shale	
16. Covered	99.0
Wapanucka Limestone	
15. Spiculiferous limestone, rare bioclasts	10.0
14. Spiculiferous limestone, rare bioclasts, chert layers	22.0
13. Conglomeratic limestone, large bioclasts and intraclasts	1.4
12. Spiculiferous limestone, commonly replaced by chert	10.5
11. Shale, uncommon siliceous shale, locally spiculiferous	5.0
10. Spiculiferous limestone, rare bioclasts, abundant chert nodules	30.5
9. Micritic limestone, common algal debris, rare bioclasts	12.0
8. Spiculiferous limestone, locally common bioclasts, chert nodules and thin beds	2.8
7. Conglomeratic limestone, common bioclasts and chert nodules	4.2
6. Micritic limestone, common algae and spicules, common chert nodules, argillaceous partings	4.9
5. Bioclastic limestone, common oolites	1.4
4. Micritic limestone, common algae, common spicules and bioclasts, argillaceous partings	3.5
3. Bioclastic limestone, common chert nodules	1.0
2. Spiculiferous limestone, fine skeletal debris, rare chert nodules	1.5
Total thickness	211.5

Modified from Grayson (1980).

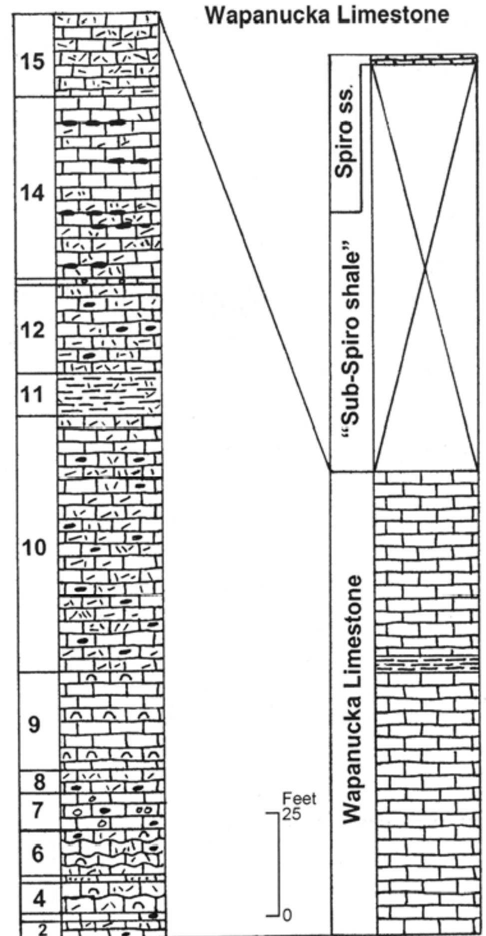
the fractures, bedding planes, and vugs that are filled with solid hydrocarbons. Grayson noted “common carbonaceous matter and plant debris” in many of the units on the northwest side of the highway. However, numerous hydrocarbon-filled veins perpendicular to the bedding planes are clear evidence that the “carbonaceous matter” is post-depositional. The origin of this material and its relation to fracturing, diagenesis, and hydrocarbon generation and migration is unknown.

Structural Geology of the Frontal Ouachitas – Arkoma Basin Transition Zone

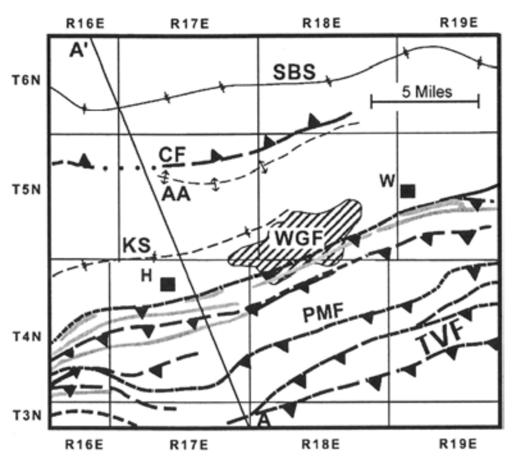
The frontal belt of the Ouachita Mountains contains imbricated thrust faults with tight to overturned folds typical of a fold-thrust belt. The Choctaw Fault usually is considered the boundary between the frontal Ouachitas and the Arkoma foreland basin. The Arkoma Basin is characterized by the broad to open folds and minor faults generally found in the foreland basins. The transition zone is that part of the Arkoma just north of the Choctaw Fault.

Suneson et al., have constructed balanced cross sections along the frontal Ouachita Mountains – Arkoma Basin transition zone from Hartshorne to the Wister Lake area. These studies were started in 1992 as part of the Oklahoma Center for Advancement in Science and Technology (OCAST) project to examine overthrusted natural gas reservoirs in the Wilburton gas field area of the Arkoma Basin. They constructed eight balanced structural cross sections to determine detailed configuration and geometry of the thrust faults. The cross sections were based upon surface geologic maps published by the Oklahoma Geological Survey, wireline well log data, and OGS interpretation of many seismic profiles furnished to them by ExxonMobil Corporation.

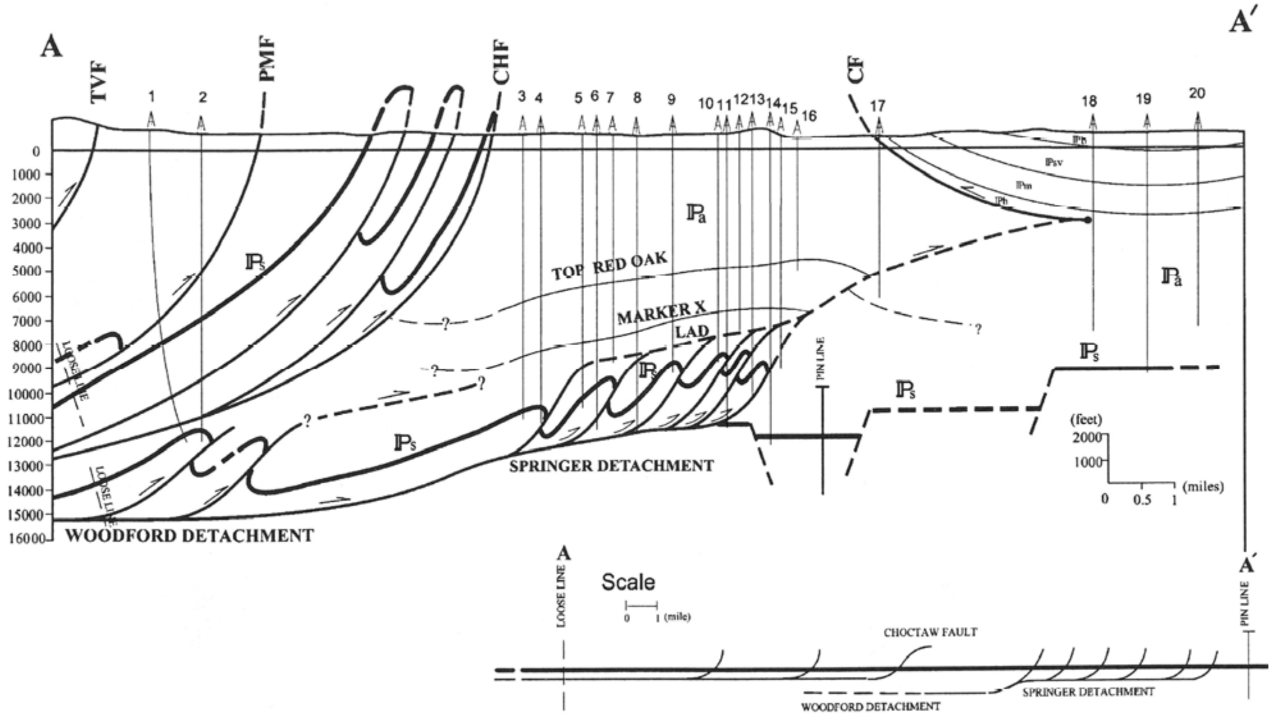
The map and balanced cross section are from Suneson (2005). The balanced cross section A-A’ passes close to this stop. It shows about 60 percent shortening when restored to the time of Spiro sand deposition, using key-bed balancing techniques. The cross section is constructed perpendicular to the tectonic-transport direction. Therefore, it shows displacements along the thrust faults where appropriate piercing points are located in the hanging wall and footwall. The Spiro sandstone is used as the key bed to determine the structural geometry. The Wapanucka Formation and the Spiro sandstone are not divided. The unit is referred to as the *Spiro* and is assumed to have uniform thickness in the study area.



short lines = spicules;
small, blackened ellipses = chert beds and nodules;
circles = conglomerates;
inverted U = algal mass.



Simplified map of the Wilburton gas field and surrounding areas (modified from Çemen and others, 2001a), showing (a) major structural features, (b) outcrops of the Spiro sandstone (shaded pattern), and (c) the line of cross section A–A′. H = Hartshorne; W = Wilburton; AA = Adamson Anticline; CF = Carbon Fault; KS = Kiowa Syncline; PMF = Pine Mountain Fault; SBS = Sans Bois Syncline; TVF = Ti Valley Fault; WGF = Wilburton gas field.



Balanced structural cross section A–A′ (see map for line of section) and its restoration (from Çemen and others, 2001). The cross section shows the presence of the Wilburton triangle zone, the duplex structure, and other structural features. The restored cross section suggests ~60% shortening along the original length of the Spiro sandstone owing to Pennsylvanian thrusting. Note that the scale of the restored section is 2 times smaller than the deformed cross section. See text for explanation. CF = Carbon Fault; CHF = Choctaw Fault; LAD = Lower Atoka Detachment; PMF = Pine Mountain Fault; TVF = Ti Valley Fault; Ps = Spiro sandstone; Pa = Atoka Formation.

In the cross section the hanging wall of the Choctaw Fault contains many south-dipping listric thrust faults, splaying both from the Choctaw Fault and the main detachment surface within the Woodford. Suneson (2005) suggests that a triangle zone is present along the line of cross section A-A'. The triangle zone is bounded by the Choctaw Fault on the south and the Carbon Fault on the north. It is floored by a possible detachment surface in the Atoka Formation. Below the triangle zone is a duplex structure that contains hinterland-dipping imbricate thrust faults splaying from a detachment surface within the Springer Formation (the floor thrust known as the Springer Detachment). The hinterland-dipping faults join the Lower Atoka Detachment in the Atoka Formation (the roof thrust). The detachment continues in the Atoka Formation northward and displaces the Red Oak sandstone before reaching a shallower depth and forming the Carbon Fault as a north-dipping back thrust below the Sans Bois Syncline and involving Pennsylvanian Desmoinesian strata. Suneson interprets the duplex structure in the Wilburton area as having been formed by a break-forward sequence of thrusting.

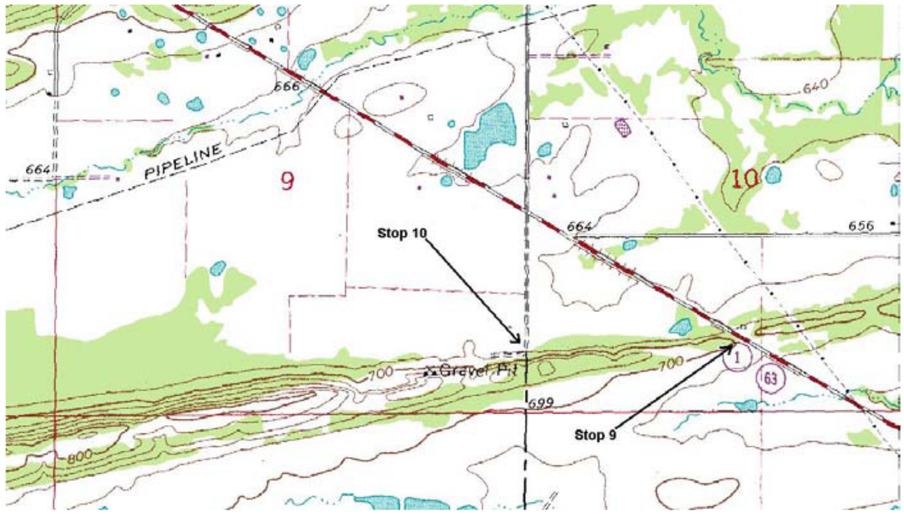
The pin lines for the restored cross section are north of the leading duplex, or the blind thrust, where the Spiro sandstone is not affected by shortening of the frontal belt. The loose lines are to the south, where there is no piercing point for the thrusted Spiro sandstone. Calculations suggest about 60 percent shortening for the Spiro sandstone in this area.

Return to the vehicles and proceed west on OK 1/63.

107.6mi Enter Wilburton gas field.

107.7mi County road to the left (south) follows Latimer – Pittsburg County line. Turn left (south) on county road.

108.0mi Top of Limestone Ridge - excellent exposure of Spiro sandstone. Park near the top of the ridge.



Stop 10
Spiro Sandstone

The Spiro sandstone is one of the principal reservoir rocks in the Arkoma Basin and frontal Ouachita Mountains. It is the primary producing formation in the Veterans Colony West gas field, the Hartshorne South gas field, and the Wilburton gas field. The Spiro produces gas from both thrusted and subthrusted positions.

Approximately 60 feet of the lower part of the Spiro sandstone is exposed at this outcrop. About 75 feet of sub-Spiro shale (covered) underlies the Spiro, and the top of the Wapanucka limestone is exposed beneath the covered interval. The Spiro sandstone consists of four lithofacies at this outcrop (from bottom to top): ripple-bedded sandstone, probable shale (covered interval), limey bioclastic sandstone, and spiculitic sandstone. The basal sandstone is medium- to fine-grained, well-sorted, and well-stratified. Burrows are common on bedding planes and also occur oblique to bedding. Ripple-bedding is wide spread, but cross-bedding, channeling, and pinch-and-swell structures are absent to poorly developed. The sequence does not appear to fine or coarsen upward, nor do the beds appear to thin or thicken upward. Rather the sandstone appears to have a relatively sharp base and top although neither is well exposed. The bioclastic sandstone is relatively thin and shows poorly developed low-angle cross-stratification. The spiculitic sandstone is well-stratified but highly irregularly bedded.

The Spiro sequence at this outcrop was deposited in a shallow-marine environment. The basal sandstone probably represents an offshore-bar deposit. Low-energy wave action probably caused the good sorting and abundant ripple marks. Abundant burrows also are evidence that the energy was low. The absence of channels is evidence for deposition in a dominantly constructional setting as opposed to deposition and reworking as might be found in a tidal channel. The "ideal" marine-bar sequence would coarsen or thicken upward, but the apparent sharp base of this unit is not strong evidence against a marine-bar origin.

The covered units, presumably shale, probably were deposited under quiet-water conditions, possibly in slightly deeper water than the basal sandstone. The thin, bioclastic sandstone is interpreted to be a storm deposit. The low-angle cross-stratification may be hummocky cross-stratification or a cut-and-fill structure. However, this also is too poorly exposed to determine which it may be. The spiculitic sandstone clearly is marine, but again too poorly exposed to identify a depositional environment. The depositional environment for the Spiro at this locale was probably marine-bar as mentioned. Spiro sandstones that were deposited in a barrier-island environment are subthrust and more like shelf-deposited Spiro sandstone, whereas Spiro marine-bar deposits are thrusted and therefore probably had a depositional location farther out on the shelf than the barrier islands.

This concludes our trip. Please return to the vehicles and return to OK 1/63.

108.3mi Turn left (west) on OK 1/63.

108.7mi Low ridge is highly deformed Atoka Formation. The trace of the Choctaw Fault is between the outcrop and the base of the Hartshorne ridge ahead.

109.3mi Ridge is underlain by Hartshorne Formation. Numerous adits into the Hartshorne coal are present on the north side of the ridge.

109.9mi Intersection with U.S. 270. Continue west on U.S. 270 / OK 1/63.

110.8mi Intersection of Pennsylvania and 9th Street. Beneath this intersection is the eastern edge of the Rock Island No. 8 coal mine. The western edge of the mine is under Lindley's Grocery on the west side of Hartshorne. Approximately one mile north of this intersection is Elmwood Cemetery and the grave of Warren Spahn.

113.3mi Intersection with U.S. 270 and OK 63. Turn left (south) on OK 63.

OK 63 is one of those "blue line" roads on maps that have AAA warnings. This road starts out as a block-by-block winding road in Haileyville. Below the road are extensive abandoned coal mines (see map next page). Once Blue Creek has been crossed, the road straightens to some extent and basically parallels ridges of Atoka and Hartshorne Formation. Be extra careful on the curves and always be on the right side of the road when topping a hill. The ridge seen most of the way on the left (south) is Limestone Ridge (Wapanucka limestone) south of the Choctaw Fault.

Warren Spahn

Warren Edward Spahn (April 23, 1921 – November 24, 2003) was an American left-handed pitcher in Major League Baseball who played for 21 seasons, all in the National League. Although never quite as dominating as some, he was both astonishingly consistent and durable.

Spahn was born in Buffalo, New York. In 1940 he signed with the Braves organization. His major league career began in 1942 with the Braves and he spent all but one year with that franchise. He finished his career in 1965 with the New York Mets and the San Francisco Giants. Spahn won more games than any other lefty (363) and is the fifth-winningest pitcher in MLB. Spahn also threw two no-hitters, won 3 ERA titles, appeared in 14 All-Star games, and holds the National League record for career home runs by a pitcher with 35. He was elected to the Baseball Hall of Fame in 1973, his first year of eligibility.

Spahn served in the United States Army in World War II and was wounded in Europe. He was awarded the Bronze Star for bravery and a Purple Heart. He saw action in the Battle of the Bulge and at the Ludendorff Bridge (the famous bridge at Remagen) as a combat engineer for which he was awarded a battlefield commission. He was the only one of major league baseball's military who has earned a battlefield commission.

Spahn died at age 82, apparently of natural causes, at his home in Broken Arrow, Oklahoma. He is interred in the Elmwood Cemetery in Hartshorne.

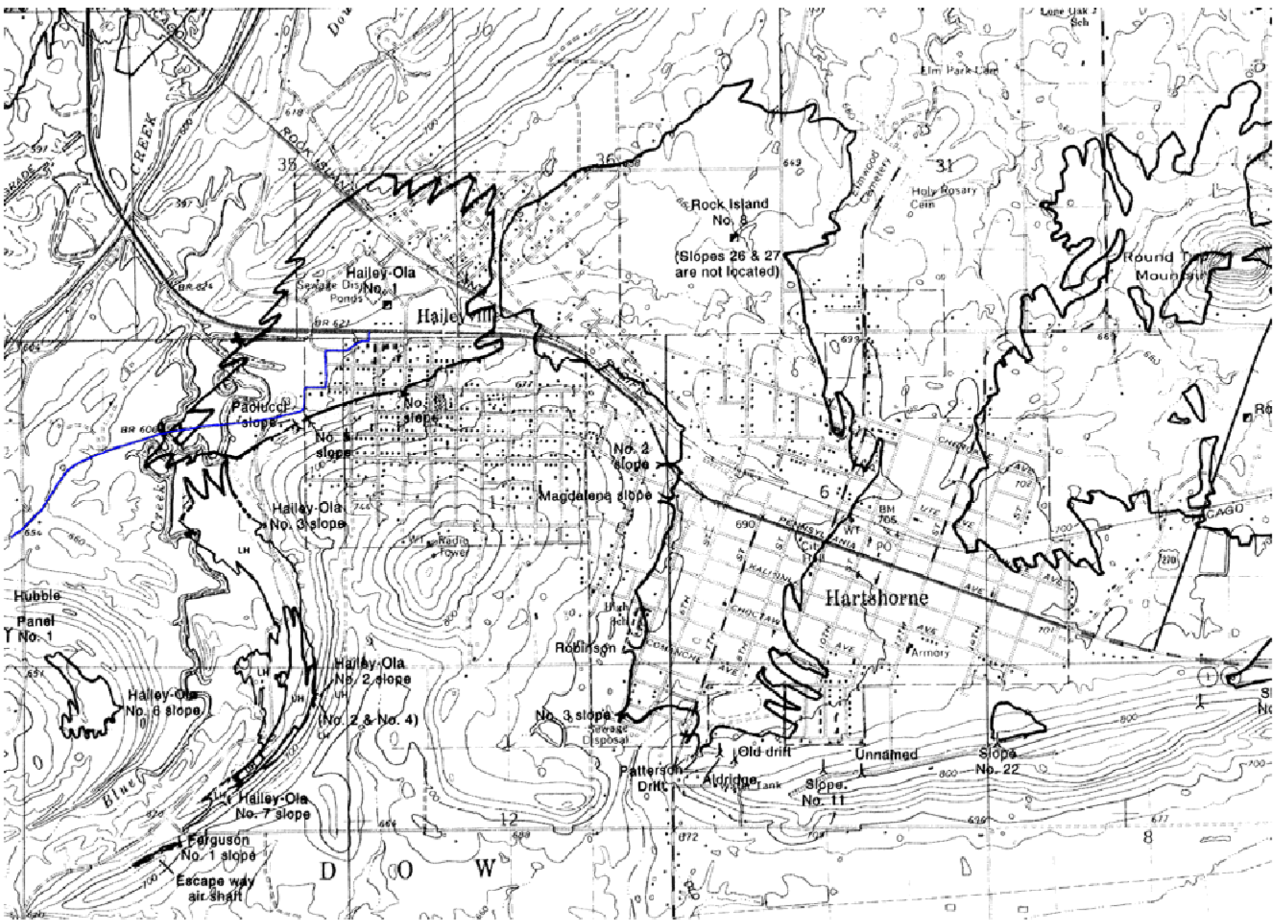
Quote: "Hitting is timing. Pitching is upsetting timing."

128.5mi Pass under Indian Nation Turnpike.

133.5mi Apparently some old mine apparatus on right side of road.

136.9mi Kiowa, OK. Intersection with U.S. 69. Turn left (south) onto U.S. 69 to return to Dallas. This is a heavily traveled road (as we experienced on our way up) that has heavy truck traffic. **Be very careful while turning left! Drive safely!**

288.8mi Total mileage to downtown Dallas and end of trip.



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Appendix

A. – The Wilson Cycle (from Dr. Lynn Fichter, James Madison University, Harrisonburg, VA)

B. –Senator Robert S. Kerr – Comments and a URL link to the Internet exhibit commemorating Senator Kerr from The Carl Albert Center, University of Oklahoma.

C. – Oklahoma Geological Notes, 2002, v. 62, no. 1 – Interpretation of Depositional Environments of the Savanna Formation, Arkoma Basin, Oklahoma, from Outcrops and Surface and Subsurface Gamma-Ray Profiles.

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And A Plate Tectonic Rock Cycle

The Cyclical Opening and Closing of Ocean Basins

No rock is accidental. No idea in geology is more profound than this; it runs from the center to the whole of geology and influences every subdiscipline of the field. Genuine understanding of the science of geology begins with one's ability to understand and explain why no rock is accidental.

Tectonics is concerned with deformation in the earth and the forces which produce deformation. Plate tectonics is the theory that the earth's lithosphere (outer rigid shell) is composed of several dozen "plates", or pieces, which float on a ductile mantle, like slabs of ice on a pond. In plate tectonic theory earth history, at its simplest, is one of plates rifting into pieces diverging apart and new ocean basins being born, followed by motion reversal, convergence back together, plate collision, and mountain building. This cycle of opening and closing ocean basins is the *Wilson Cycle*.

Plate tectonics is one of the great unifying theories in geology. Virtually every part of the earth's crust, and every kind of rock and every kind of geology can be related to the plate tectonic conditions which existed at the time they formed. *Nothing in geology makes sense except in terms of plate tectonic theory*.

One of the most important messages of modern understanding of plate tectonics and the Wilson cycle is that beginning with a parent igneous rock of mafic/ultramafic composition all the other rocks now on the earth can be generated. The most important message of the plate tectonic rock cycle is that each and every rock forms only under a specific set of tectonic conditions.

Most geologic activity occurs at the three kinds of plate boundaries:
(1) *divergent boundaries* where plates are moving apart and new crust is being created,

Craton

Other Related Links

A Plate Tectonic Rock Cycle
Page of all cross sections
Igneous Home Page
Sedimentary Home Page
Metamorphic Home Page
Plate Tectonic Primer

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James Madison University,
Harrisonburg, VA 22807
Spring, 1999

(2) *convergent boundaries* where plates are moving together and crust is being destroyed, and

(3) *transform boundaries* where plates slide past one another.

Very interesting geology occurs along transform boundaries, as all the faulting along the San Andreas fault system in California attests to, but this model does not include transform boundaries.

We have two models summarizing earth evolutionary processes.

(1) The Wilson Cycle, explored below, and . . .

(2) The *Tectonic Rock Cycle*, a more theoretically abstact model of how rocks and the earth evolve.

The following Wilson Cycle model follows the series of cross sections constituting the Wilson cycle. It begins with a hypothetical geologically (tectonically) quiet continent. The model is divided into nine stages, but the stages are arbitrary and do not exist naturally. The earth is an ongoing series of processes so it is much more important to understand the processes, how they are related, and how one process leads naturally to the next process.

Also note that this Wilson Cycle is a *simple*, ideal model. The earth has many continents, which migrate across its spherical surface in very complex ways. Just about any scenario you can think of, and any exception you can imagine is quite possible - and has probably happened during some point in the earth's history.

- *Go to Stage A*
- *PDF version of illustrations for all stages*
- *The Plate Tectonic Rock Cycle*

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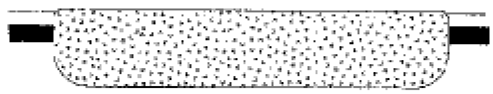
Stage A

(Go to next stage) (*Return to Previous Stage*)

A Stable Continental Craton



Imagine a very simple situation - a tectonically stable continental craton bordered by ocean basins all around. The continent is eroded down nearly to sea level everywhere (a peneplain); it is dead flat from edge to edge and corner to corner and there is no tectonic activity anywhere. On the surface is a blanket of mature quartz sandstone (*QFL*, yellow field), the result of millions of years of weathering and erosion and sorting. Limestones are probably also well developed, if the climate is warm, but most shales (clays) have been wind blown or washed off the continent into the surrounding ocean basins.

The continent is in perfect isostatic equilibrium; by itself it will not rise or sink. Nothing exciting is happening; no earthquakes or volcanic activity - unrelenting boredom, perhaps for tens or hundreds of millions of years.

Continents are composed of relatively light weight felsic igneous rock (*granites*, *granodiorites*, etc.). Light enough that when eroded to a peneplain, and "floating" in isostatic equilibrium, it's surface is a few hundred feet above sea level. Thus, granite gives us the dry land we live on.

Ocean basins are composed of mafic igneous rocks (*basalt* and *gabbro*), and because these are relatively heavy rocks they isostatically "float" on the underlying mantle a little over 5 miles below sea level. Continents and oceans are thus natural divisions on the earth, not only because they are composed of very different rocks, but also because one lies naturally above sea level, and the other naturally far below sea level.

Go to Stage B - Hot Spot and Rifting
Return to Home

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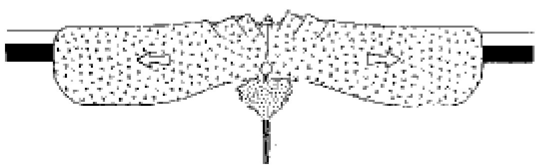
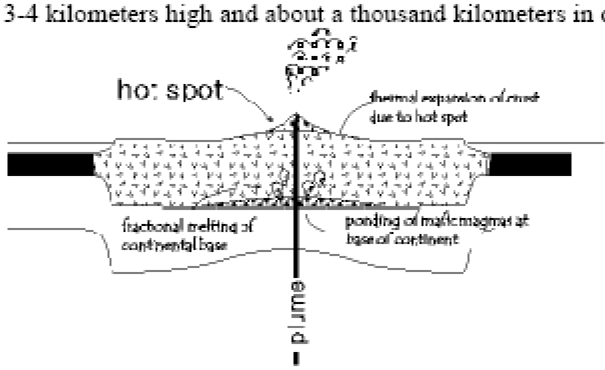
Stage B

(Go to next stage) (Return to Previous Stage)

Hot Spot and Rifting



Into the peaceful stable continent of *Stage A* comes a disturbance. From deep in the mantle a plume of hot *mafic or ultramafic magma*, rises toward the surface and ponds at the base of the continent creating a hot spot. Heat from the hot spot warms the continental crust causing it to expand and swell into a dome 3-4 kilometers high and about a thousand kilometers in diameter. As the dome swells it thins and stretches like pulled taffy (or silly putty) until the brittle upper surface cracks along a series of three rift valleys radiating away from the center of the hot spot. These form a triple junction. *Details of early rifting*. Ideally the three rift valleys radiate from the center at 120º, but often the triple junction is not symmetrical and arms may diverge at odd angles. Rifting is splitting the original continent into two pieces, west and east, although they are still connected at this stage.



Mafic volcanism is normal and appears as intrusive sills, or vent volcanos and/or flood basalts from fissure volcanos rising along feeder dikes. The volcanics may be mostly volcaniclastic, or lava flows of vesicular and columnar-jointed basalt. Subaqueous pillow basalts are not unusual in later stages.

Mafic (hot spot) volcanoes are common and appear as vent volcanos and/or flood basalts from fissure volcanos in the rift. Commonly the intense heat of the hot spot will *fractionally melt* the lower continental crust composed of *granodiorites* or *plagiogranites*. The results are *alkali granitic* magmas that rise to emplace as *batholiths*, frequently sending conduits to the surface to create large felsic volcanoes. The simultaneous formation of these two very different rock types (one from the bottom and one from the top of *Bowen's Reaction Series*) is called a ***bimodal distribution***.

Active Rifting

Axial rifts are typically tens of kilometers across, and the elevation from the rift floor to the mountain crests on either side are as much as 4-5 km. Structurally, rift valleys are block-fault graben bordered by horst mountains on either side (see *Hot Spot/Thermal Doming* cross section). The edges of the major horsts bordering the axial graben are the continental terraces (also called hinge zones) (see *Foundering of Rift Valley/Marine Invasion* cross section).

The major axial graben contains numerous smaller horsts and graben. The normal faults are listric type. The fault surfaces are curved so that the graben blocks rotate as they subside, trapping small basins between the down faulted-block and the wall behind the fault. It is also typical for numerous, smaller lateral graben to form for several hundred kilometers on either side of the axial graben. Initially the axial valley floor is subareal, that is above water (except for lakes), but in time the axial graben subsides and the sea invades creating a narrow marine basin (making it subaqueous).

A diversity of sedimentary rocks are deposited in the graben, mostly in short system environments where facies changes are very rapid. The horst mountain highlands are composed of felsic and high grade metamorphic continental basement which erode rapidly to coarse, subareal arkosic breccias and conglomerates (fanglomerates) (red field on the *QFL diagram*). All around the basin edges, at the base of the fault scarps, these accumulate in steep-faced alluvial fans. Away from the alluvial fans, toward the basin axis, the fans give way to braided rivers and then often lakes. See reconstructions for the *Rifting of Pangaea*.

The lakes are trapped depressions created when the graven floors drop and pond the water. Many of the lakes are very deep and, based on modern rift lakes, may be extremely alkaline with salt crusts floating on the surface. In the lake bottoms black, organic rich, anoxic clays accumulate because there is no circulation or oxygen in the deep water.

After the sea invades the rift, fan deltas develop. Here alluvial fans still form next to the mountains but now turbidity currents rather than braided rivers transport sediment toward the basin center. The basin center is still frequently deep and anoxic, and thinly laminated black clays and silts are deposited. Thousands of meters of sediment may accumulate during this stage.

In a geologically short time (~ 10 million years) the basin finishes filling. As the former great relief of the horst mountains and deep graben smooth out, shelf and near-shore deposition takes over. Sands now dominate and abundant cross beds and ripples indicate shallow water processes. By this time the *Early Divergent Margin* stage is beginning (*Foundering of Rift Valley*).

- *Go to Step C - Creation of New Oceanic Crust: Early Divergent Margin*
- *Return to Stage A*
- *Return to Home*

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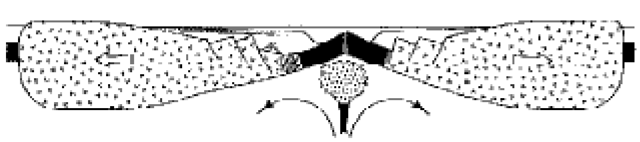
The Wilson Cycle

Stage C

(Go to next stage) (Return to Previous Stage)

Creation of New Oceanic Crust: Early Divergent Margin



A hot spot may form, be active for a while, and then just die. But sometimes a string of hot spots joint together to create convection cells. These turn the hot spot into a rifting system poised to create a new ocean basin (the four layers that compose oceanic lithosphere are the *ophiolite suite*).

The process of ocean basin formation begins with a great surge of mafic volcanic activity along one side of the axial rift. Axial rifts do not usually split in two, down the middle, but separate along one side or the other (*detailed drawing*). In this model the activity is on the east (right) side of the rift and so the axial rift will remain with the western continent. At first the magma is injected as a large number of basaltic dikes into the now thinned and stretched granitic continental crust. So many dikes form in fact that it is finally hard to decide looking at them what the original rocks were, *granite* invaded by *basalt*, or basalt invaded by granite. This mixture of continental granite and injected basalt is called ***transition crust*** (principally because the speed of seismic (earthquake) waves traveling through it is transitional between the slower granite and the faster basalt.)

The mafic volcanic activity is concentrated at the rifting site, but is not confined there. Feeder dikes cut through the crust at many places, sometimes hundreds of miles to the sides of the axial rift. This magma may emplace as sills or laccoliths, or may surge to the surface to form fissure volcanos and lava flows.

As the volcanic activity continues, the two pieces of the original continent begin to drift apart and the gap between them fills with mafic igneous rock. Surge after surge of magma rises from the convection cells in the mantle into the continuously spreading gap as the continents move farther and farther apart. Within a few million years the two continents can be separated by thousands of kilometers.

Because all this new igneous rock is mafic and ultramafic in composition (basalt/gabbro near the surface and dunite/peridotite at depth), and high in density, it "floats" about 5 km below sea level. These layers of rock that form the oceanic lithosphere are the *ophiolite suite*.

The final result is that beginning with only one tectonic plate in *Stage A*, rifting has created a new divergent plate boundary and two plates, one on the west (containing Westcontinent) and one on the east (containing Eastcontinent).

Sedimentary Record

As the new ocean basin begins to form the edge of the continent cools and subsides below sea level. And as the continental edge subsides below sea level the sea begins to ***transgress***, or migrate across, the edge of Westcontinent (and Eastcontinent too). This is the beginning of deposition of Divergent Continental Margin (DCM) sediments, which will become much more prominent in the next few stages (see *Early Divergent Margin*). But initially, as the sea begins its transgression a layer of quartz sandstone is laid down as a beach deposit by the transgressing sea. Off shore from it is shallow shelf deposition. Its composition may be dominantly shale if there is a clastic source on the continent. But if the continent is stable, as Westcontinent is, and the climate is warm, then carbonate (limestone) deposition will dominate.

- *Go to Stage D - Full Divergent Margin*
- *Return to Stage B*
- *Return to Home*

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THE WILSON CYCLE

Stage D

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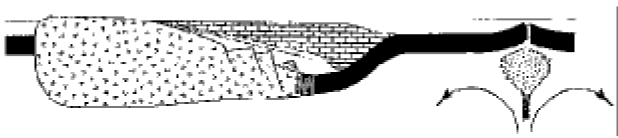
Full Divergent Margin



Eastcontinent has now drifted off the eastern side of the cross section, and only Westcontinent and the new ocean basin with its rifting center (mid oceanic ridge) remain. Heat rising to the surface from the convection cells remains concentrated at the rifting site in the center of the new ocean basin, so as the ocean basin widens the newly formed continental margin (now called a ***divergent continental margin*** [DCM], or a passive continental margin because it is geologically passive) moves away from the heat source, and cools. Cool crust is denser than warm crust and as the DCM cools it sinks, rapidly at first, but ever more slowly with time (a process called thermal decay). Thus, in about 5-10 million years the horsts which once were 3-5 kilometers above sea level sink below the waves. Ultimately it will take about 110 millioin years for the DCM to cool completely and stabilize (*detailed cross section*), at which point it will be about 14 kilometers below sea level (*Stage E*).

Meanwhile a great wedge of sediment is deposited on the DCM, expanding and thickening from a feather edge on the continent side toward the ocean basin. These sediments are derived from the eroding continent in the case of clastics, and by chemical and biological activity in the case of carbonates. It consists mostly of shallow-water marine deposits because subsidence and deposition go on at about the same rate.

When next to a stable craton, the wedge of sedimentary rocks is dominated by mature sandstone, limestones, and dolomites, but if the continent has some tectonic activity many kinds of less mature sedimentary rocks are possible, such as along the east coast of North America today where sublithic sandstones and shales are common. The Virginia coastal region today is a modern DCM, at this point stabilized since the rifting which opened the Atlantic ocean occurred nearly 250 million years ago.

- Go to Step E - Creating a Convergent Boundary: Volcanic Island Arc Mountain Building
- Return to Stage C
- Return to Home

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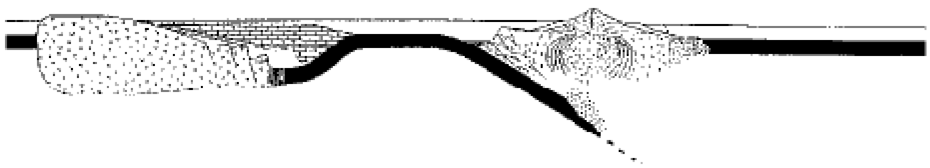
The Wilson Cycle

Stage E

(Go to next stage) (*Return to Previous Stage*)

Creating a Convergent Boundary: Volcanic Island Arc Mountain Building



Divergence, and the creation of new oceanic lithosphere, can go on for tens or hundreds of millions of years. At some point, however, divergence stops and the two continents begin to move back toward each other, initiating the second, closing, half of the Wilson Cycle. This is ***convergence*** and a new plate boundary must be created for it. Convergence begins when oceanic crust decouples, that is, breaks at some place and begins to descend into the mantle along a subduction zone.

It is always oceanic crust which decouples and descends into a subduction zone; continental crust is too light to subduct. Subduction zones can form anywhere in the ocean basin. In the Stage E cross section subduction is dipping east, but it could have been west, or any direction. For example, in this *detail* subduction is toward the west.

There are just two kinds of *locations for subduction zones*, however, one within an ocean basin (Island Arc type), the other along the edge of a continent (Cordilleran type). Both kinds of subduction cause volcanic mountain building and they are extremely important. Things are heating up now compared to the boredom of Stage A. The island arc type is described below; the Cordilleran type in *Stage G*.

At a subduction zone oceanic crust dives into the mantle. When oceanic crust subducts it sets in motion a chain of processes which creates several new *structural features*, and generates a wide range of new kinds of rocks (*detail*) each reviewed separately below.

Structural Features

At the site of subduction, part of the oceanic crust is dragged down into a trench 1-2 km below the normal ocean floor which is about 5 km deep. The subducting oceanic crust begins its descent cold but heats up as it slides into the mantle. At about 120 km deep rock begins melting to form magma. The magma, hot and of low density, rises toward the surface, forms batholiths, breaks onto the ocean floor as lava and builds a volcano which eventually rises high enough to form an island.

The location of the volcano is called the *volcanic front* (in three dimensions it is a *string of volcanoes* all rising above the subduction zone). The area on the trench side of the volcanic front is the *forearc*, and the area on the back side of the volcanic front is the *backarc*. A new convergent boundary has been created along the zone of subduction. The ongoing subduction and magma generation eventually builds a volcano perhaps 7-8 km off the ocean floor, and its center (mobile core) is made of *many batholiths*. All of this has set in motion several more processes.

Fractional Melting and the Creation of New Igneous Rocks:

The mantle rock above the subducting plate selectively melts, and *fractionates* (or see *Igneous Rock Evolution*). In fractional melting an igneous rock of one composition is divided into two fractions each of a different composition.

The original rock descending into the subduction zone is the oceanic lithosphere (*ophiolite suite*) composed of cold basalt and gabbro of the oceanic crust, and peridotite of the upper mantle (*detail*). As it descends into the mantle it gradually heats because of the geothermal gradient and friction of subduction. But the descending slab also carries a lot of sea water with it and at about 120 km down the water and heat lead to fractional melting of the mantle material just above the subducting slab. As heating progresses only the lower temperature *phases* (lower on Bowen's Reaction Series) in the rock melt to produce magmas of intermediate composition. And since these are fluid and hot they rise up through the crust to eventually emplace and solidify as intermediate rocks (e.g. *diorites*, *granodiorites*, etc). The second fraction is the unmelted residue with a composition more mafic/*ultramafic* than the original rock. That is, its composition is higher in Bowen's Reaction Series than the original rock.

If time and conditions allow, the fractionation process can continue and the intermediate magma fractionate into *felsic magma* (typically *plagiogranites*), leaving behind a magma more mafic than the original intermediate starting rock. Thus, beginning with one (mafic) igneous rock many new igneous rocks can be generated, including ultramafic, intermediate, and felsic (*model*). Or, felsic continental crust is created from the fractional melting of mafic oceanic crust.

In our subduction zone, the ultramafic residue, being very dense, stays in the mantle, while the hot, less dense, melt rises to the surface where it forms first intermediate and later felsic batholithic magma chambers. From the chamber the magma reaches the surface as lava and forms explosive composite volcanoes, which are dominated by *andesite*, although it can evolve from mafic, to intermediate, to felsic as the magma fractionates. Hydrothermal metamorphism also occurs when hot lava spills out onto the ocean floor and reacts with cold sea water to form pillow basalts (*detail*).

Sedimentary Processes:

As soon as the volcano breaks the surface weathering/erosion processes attack it and form lithic rich sediments (*detail*) (becoming more feldspar rich as erosion exposes batholiths, or as rhyolites and andesites with feldspar phenocrysts weather) that wash into the sea on all sides. Sediments on the backarc side just spill onto the ocean floor as turbidity currents and stay there undisturbed. On the forearc side, however, the sediments pour into the trench as turbidity currents (underwater avalanches). A trench is like the mouth of a conveyor belt and sediments do not stay there long. Instead they are scraped off the subducting oceanic crust into a melange deposit, or they are partially subducted and metamorphosed. A melange is a chaotic mixture of folded, sheared, faulted, and blueschist metamorphosed blocks of rock formed in a subduction zone. It is also normal, if the climate is right, for reefs to grow around the island. These limestones typically interbed with the coarse-grained lithic breccias and conglomerates eroding from the volcano, and the volcanic sands on the beach. During a volcanic eruption, then, lavas and pyroclastics may interbed with limestones to form a very unusual association of rocks.

Paired Metamorphism:

Two major kinds of metamorphism are common in a volcanic arc forming a *Paired Metamorphic Belt*. The first is Barrovian metamorphism (low to high temperature, and medium pressure) formed inside the volcano by heat from the batholiths, accompanied by intense folding and shearing. Because the batholiths are invading mafic oceanic crust these rocks are converted into greenschist (chlorite and epidote rich), amphibolite (amphibole rich), and granulite (pyroxene rich) facies rocks as we get closer to the batholiths and deeper in the crust. Also earlier, now crystallized, intermediate and felsic batholiths may be converted into gneisses and migmatites.

The second metamorphism is high pressure-low temperature Blueschist metamorphism formed in the melange of the trench. It is high pressure because this is a convergent boundary and the trench sediments are being rapidly subducted between two plates. The low temperature is because cool surface rocks are rapidly subducted and do not have time to heat up. These belts of Barrovian and blueschist metamorphism form a *Paired Metamorphic Belt*, which is always the result of subduction.

Other kinds of metamorphism are also associated with the volcanic arc. At depth along the subduction zone the ultramafic layers of the ophiolite suite undergo eclogite metamorphism, and contact and hydrothermal metamorphism would be common along the volcanic pipes and dikes coming off the batholiths (*detail*).

Ancient and modern volcanic island arcs are very common. Modern examples are Japan, the Aleutian Islands of Alaska, and the Malaysian archipelago including the islands of Java, Borneo, and Sumatra. Ancient examples are not as obvious because they eventually collide with another island arc or a continent and are hidden, but that is Step F in the model.

Remnant Oceans:

Now, step back and look at the whole of *Cross Section E*. Notice that the ocean basin to the west of the volcanic arc is trapped between the divergent continental margin and the subduction zone. Clearly, if subduction continues the ocean basin between the two will become smaller and smaller until the Westcontinent and the volcano collide. Also the more the continent and volcanic arc move together the more oceanic crust is subducted and destroyed. These ocean basins which will soon disappear in a subduction zone are called ***remnant oceans***.

The fact that subduction zones always create remnant ocean basins means that no ocean basin can survive long in geologic history (see these examples). In fact, the oldest ocean basins we know of are only around 200 million years old (compared to the 4 *billion* year age of the earth). In contrast, continental crust, because it is too light to subduct, tends to remain around just about forever, excluding weathering and erosion.) Many parts of the continents are three to four billion years old.

- *Go to Step F - Island Arc-Continent Collision Mountain Building*
- *Return to Stage D*
- *Return to Home*

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THE WILSON CYCLE

Stage F

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Island Arc-Continent Collision Mountain Building

Westcontinent and the volcanic island have now converged and collided, creating a large mountain, and the remnant ocean basin is reduced to a suture zone. Eastcontinent has also come onto the cross section, but it is still far away. Collision mountain building is of two basic kinds: (1) Island arc-Continent collision, and (2) Continent-Continent collision. The island arc-continent collision is described here, the continent-continent collision later.

Observe the geometry in the Stage F cross section. Because the subduction zone dips east, the island arc has attempted to slide up over the edge of the former divergent continental margin. We can generalize this: in every collision orogeny one plate is going to ride up onto the edge of the other. The overriding plate is called a ***hinterland***. The overridden plate is called a ***foreland***.

It does not matter what is on the edge of the plate (volcanic arc, hot spot volcano, continent), or which way the subduction zone dips, the overriding piece is always the hinterland, the overridden piece always the foreland.

Suture Zone:

During the collision the first part of the volcanic arc to be affected is the trench melange. The melange has been accumulating for a long time as it was scraped from the descending oceanic crust, and now it is thrust up over the hinterland along a major thrust fault where it is smeared out and sheared even more. In the end the melange belt will go from being a hundred or more kilometers wide to maybe only 10 kilometers wide, or maybe even a single thrust fault plane. This narrow zone of ground up, smeared out rock is the suture zone and it is the boundary zone which separates the two blocks which have collided and are "sutured" together. It is also all that remains of an ocean basin that may have been thousands of kilometers wide.

Hinterland mountain:

The volcanic island arc may have been a few kilometers high before the collision but now it is dramatically thrust up even higher into snow capped mountain peaks. Along the way very large thrust faults dipping back toward the hinterland carry rock toward the foreland. Behind the major mountain peaks some volcanic activity may continue from the last magmas rising from the subduction zone. It is the last gasp, however, because with the collision subduction stops, volcanic activity stops, mountain building stops, and the only thing remaining is for the mountain to erode.

Foreland:

Several things happen in the foreland. The first is that the ancient thick wedge of DCM sediments accumulated on Westcontinent gets compressed, folded into anticlines and synclines, and thrust faulted toward the foreland. Second, the DCM sediments closest to the island arc are depressed down into the earth by the overriding arc, where they are Barrovian metamorphosed forming marble, quartzite, slate, and phyllite. Deeper rocks may metamorphose all the way to amphibolite or granulite facies.

Third, inland from the mountain a foreland basin rapidly subsides into a deepwater basin which fills with a thick clastic wedge of sediments. Foreland basin clastic wedges are common in the geologic record, although their individual features vary depending on local circumstances.

One of the things we are interested in is the composition of these sediments filling the foreland basin. Because an island arc has formed the hinterland mountain the sediments eroded from it are dominantly lithic in composition (volcanic and plutonic igneous as well as metamorphic rock fragments), with varying amounts of sodic plagioclase feldspar from the *intermediate* igneous rocks . However, since some of the parent rocks likely include Westcontinent DCM sedimentary rocks which have already been through one cycle of weathering and and erosion, they will generally be more quartz rich than those from a pure arc (*QFL diagram*, sediment is evolving along path of red arrow).

The foreland basin depositional environments the sediments are deposited in typically begin with black deep water shales. But the large volume of sediment eroding from the mountain will quickly (geologically) fill the basin in. Depositional environments typically begin with submarine fans which shallow upward to shelf environments, and then eventually terrestrial deposits (meandering and braided rivers.) Inland toward the craton the foreland basin shallows and the clastic wedge thins and becomes finer grained until it merges with sediments being deposited on the craton. (Observe that there are two different kinds of sedimentary wedges in the Wilson cycle. The first are the DCM wedges which begin thin on the craton and thicken toward the ocean basin. The second are the foreland basin clastic wedges, which begin thick next to the mountains and thin toward the craton.

Denouement of the Mountain Range:

In time, the hinterland mountains will erode to sea level (a peneplain). But by that time the hinterland (that is, the island arc) is permanently sutured to the Westcontinent (*Stage G cross section*, left side). Westcontinent is now larger because of the island arc-continent collision, but this was possible only because subduction and fractionation created the *intermediate and felsic* batholiths which compose the core of the volcanic arc, and which have now become part of a larger, sutured continental crust.

- *Go to Step G - Cordilleran Mountain Building*
- *Return to Stage E*
- *Return to Home*

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Stage G

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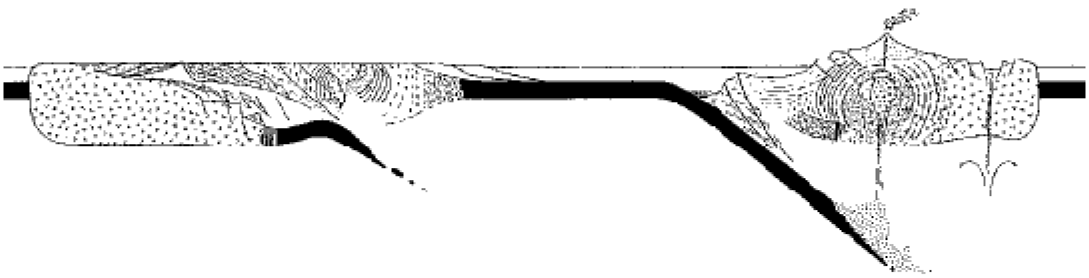
Cordilleran Mountain Building



The subduction zone under the island arc is now dead, and the mountain on the edge of Westcontinent peneplaned, but Eastcontinent and Westcontinent are still being driven together by forces outside the cross section. Therefore, another subduction zone has to begin. It could begin anywhere within the ocean basin and form another island arc, and it could dip in any direction. But in this model, decoupling occurs dipping east under the edge of the Eastcontinent, forming a Cordilleran (volcanic arc) type of mountain building.

The processes of trench formation, subduction and fractional melting of the oceanic crust, melange deposition, and Blueschist metamorphism are the same here as for an *island arc orogeny*. Observe, however, that all this tectonic activity is occurring along an old divergent continental margin which, like all rifted margins (see in *Stage C*), has accumulated a thick wedge of DCM sedimentary rocks. Thus, the rising *intermediate to felsic* batholithic magmas now inject into the thick wedge of continental margin sediments heating them to very high grade Barrovian metamorphism (amphibolite to granulite facies). If the sediments are limestones and quartz sandstones the metamorphic rocks will be marbles and quartzites. Less mature sandstones and shales will form slates, phyllites, schists, and gneisses. It is also quite likely that the basement batholiths under the divergent continental margin will be metamorphosed into gneisses and migmatites.

Along with the metamorphism, the old divergent continental wedge of sediments and invading batholits plus superposed volcanoes are uplifted along major thrust faults until they form towering mountains. The Andes in South America and the Cascades in Washington, Oregon, and northern California are mountains of this type.

Inland from the volcanic front, in the backarc region, backarc spreading occurs. Heat rising from above the subduction zone creates a small convection cell which stretches the continental crust so that normal faults develop into deep graben. Superficially this may seem like an axial rift but it forms under very different conditions and processes.

The graben fills with a great complex of deposits including coarse clastic sediments in alluvial fan and braided rivers and intermediate to felsic volcanics rising from the subduction zone. Because the source land composition is so variable (divergent margin rocks, suture zone rocks, metamorphics, volcanics, and, when erosion is deep enough, felsic and intermediate batholithic rocks) the sediments eroded from it are rich in quartz and (many kinds of) lithics, plus lesser amounts of feldspar (sodic plagioclase and orthoclase - *QFL diagram*, blue field).

The volcanics in the backarc basin begin mafic (*basalt*, *scoria*, etc.), but slowly turn into intermediate (*andesite*), and finally felsic (*rhyolite*) rocks. In the latter stages granite *dikes or stocks* (small batholiths) may invade the now mostly filled graben.

- *Go to Step H - Continent-Continent Collision Mountain Building*
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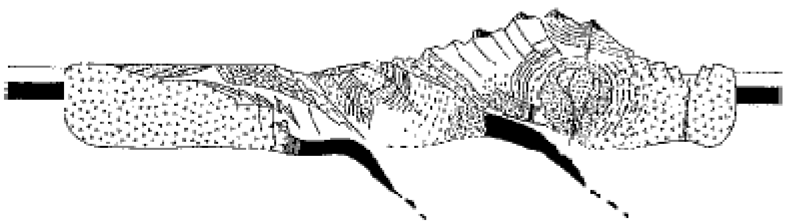
Stage H

(Go to next stage) (Return to Previous Stage)

Continent-Continent Collision Mountain Building



By Stage H the remnant ocean basin separating East- and Westcontinents has closed and they have collided to form a *continent-continent collision orogeny*. This mountain building has many of the same elements as the *island arc-continent collision*: a hinterland, foreland, suture zone, foreland basin, and a towering mountain range, most likely Himalayan size (*detailed cross section*; observe this is a mirror image; the hinterland is on the left not right).

One major difference between this collision orogeny and the Stage F arc-continent collision is that because the hinterland began as a DCM with a thick wedge of sediments it is these DCM rocks that are being thrust toward the foreland (observe that the Eastcontinent DCM of *Stage F* has been invaded by batholiths in *Stage G*; after metamorphism the DCM rocks are not symbolized in the drawing.) In the arc-continent collision it is pieces of ocean lithosphere (ophiolite suite) and the volcanic arc that are tbrust toward the foreland. But with the Westcontinent DCM rocks, we would expect ramp and flat thrust faulting to be common, stacking up the sedimentary pile to great thicknesses, as well as large nappe structures.

Also observe that the hinterland is overriding not the edge of Westcontinent, but the eastern side of the volcanic arc that collided with Westcontinent in *Stage F*. But as a result the hinterland is using its weight to shove the arc deep into the earth, resulting in Barrovian metamorphism of the arc rocks. But this is probably not the first time these rocks have been Barrovian metamorphosed, since during the arc's formation much of its deeper portions were metamorphosed by the invation of batholits.

[Note, by the way, that in the *detailed cross section* it is the DCM of a hinterland continent that is being overridden, not a volcanic arc, and it is this sedimentary wedge that would be depressed into the earth and metamorphosed. Many variations are possible on the theme.]

Sediments:

The sediments eroding from this mountain and filling the foreland basin would also be different in composition from those eroding from an island arc, even if they are deposited in very similar depositional environments. The hinterland rocks consist of large volumes of DCM sedimentary rocks undergoing a second (or third, or fourth) cycle of weathering and erosion. They are quartz rich, as shown in the *QFL* (blue field). Also, because the source land is complex, the diversity of lithic fragments is great, including sedimentary, metamorphic and igneous rock fragments. Also, feldspar is present due to the weathering and erosion of metamorphic schists and gneisses (most likely Na plagioclase), and eventually exposed batholiths (Na plagioclase and orthoclase).

All this is in contrast to the sediments filling the foreland basin of Stage F. Because the hinterland in *Stage F* was a volcanic arc, the sediments entering the foreland basin were much more volcanic-lithic rich and more quartz poor (*QFL, green field*), in contrast to the much more quartz rich sediments filling the continent-continent collision foreland basin (*QFL blue field*).

Foreland Basin:

Foreland basins are common in the geologic record since much of the earth's history is of volcanic arcs and continents colliding in endless Wilson cycles. So a brief examination of their nature.

Foreland Basins develop very rapidly geologically. Just before the collision the foreland is tectonically stable with quartz rich sandstones and limestones being deposited (*Stage G* or *detail of DCM*). Then the collision occurs and within a few million years the foreland basin subsides hundreds and then thousands of feet (*series of stages*). The shape of the basin is usually asymmetrical with the deepest portion closest to the mountain and shallowing toward the foreland continent (*detail, Stage II*).

It is not unusual for the total sedimentary thickness in the basin to be two miles thick. A lot of subsidence, and a lot of sediment. The speed of subsidence can be seen in the rock record. The rocks before the collision are often quartz rich sandstones and limestones, both indicative of tectonic stability. But then right on top of them will be black shales deposited in water hundreds of feet deep. The sediments start to fill in the basin, but for a time basin subsidence and deposition are racing with each other. But as the hinterland overthrust grinds to a halt the subsidence slows and then stops. Now the sediment has a chance to catch up and fill in the basin (*detail Stage III*, and *detail, Stage IV*).

And fill it in it does, all the way to the top, and beyond. Typically after the deep water black shales come avalanches (turbidity currents) of sediment building submarine fans out onto the basin floor. These may reach several thousand feet thickness, and are largely responsible for filling in most of the basin. But as the water shallows upward the turbidity currents give way to shelf environments.

Meanwhile closer to the mountain, thick wedges of terrestrial sediments build out toward the coastline. These begin with alluvial fan and braided river deposits, which eventually give way to meandering rivers that work their way down to the coast. The rivers dump sediment into the shoreline region building land where there was once water. This building of the shoreline out across the basin is called ***progradation***, or a prograding shoreline. In time the shoreline will prograde all the way across the basin, filling it in completely, while the terrestrial sediments will pile up another couple of thousand feet (*detail, Stage V*).

By this time the mountain is mostly gone, eroded down to low hills, most of its rock transferred to the foreland basin. And over the next few million years even these low hills will disappear and the land will be reduced to a peneplain (*Wilson Stage I*). If you could walk across this land it would look flat and featureless, but underneath lies a lot of historical record. To the east the eroded roots of the mountains exposing their batholith and metamorphic rocks, and to the west a thick wedge of foreland basin sediments, but now all buried in the subsurface.

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THE WILSON CYCLE

Stage I

(Go to next stage) (*Return to Previous Stage*)

Stable Continental Craton

The cycle which began in Stage A now comes to an end. The original continental craton of *Stage A* which was rifted into two pieces in *Stage C* is now back together, and stabilized once more.

Note, however, that this new continent is quite complex compared with the Stage A craton, and that the basement rocks exposed at the surface are very diversified. In the *enlarged and detailed drawing* you can see that in addition to the original Westcontinent and Eastcontinent blocks there is a volcanic arc trapped between then, and there are now two foreland basin clastic wedges (probably filled with quite different sediments since one was eroded from a volcanic arc and one from a cordilleran mountain). There are two suture zones of melange and a host of different igneous and metamorphic rocks. Nonetheless, when everything is finally weathered to completion and the continent is eroded to a peneplain the simple ideal model for sedimentary rocks will be in force and this continental craton will be dominated by a veneer of quartz sand (*QFL diagram*, yellow field) and limestones. Shales may also be present at first, but with enough time, these are eventually washed off the continental edge into the surrounding oceans.

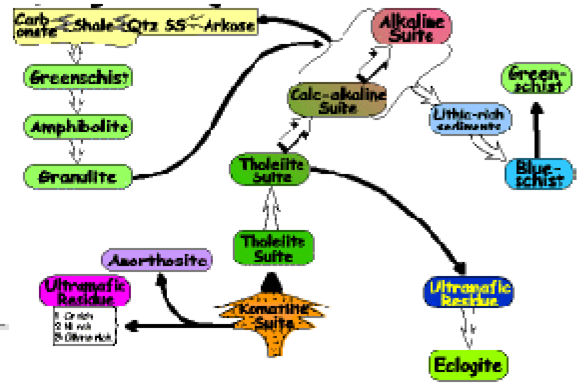
In *Stage A* we began with an ideal continent, assuming it was homogeneous in structure and composition. In light of the Wilson cycle history you have just reviewed, it should be clear that the original continent was not homogeneous. Over, and over, and over, since the first crust solidified, the processes of subduction have been making new continental crust. Collisions have been welding them together, and rifting has been fragmenting them.

It is the work of geologists to read great events in the rocks of the earth's crust, but it is also something like a flea trying to understand the great dog it is living on. Many geologists spend their time walking the earth, looking at the rocks at their feet, trying to understand the ancient meanings they have. Endlessly fascinating, endlessly frustrating, and immensely satisfying when we glimpse a little of the greatness of it.

The Wilson Cycle is a relatively simple model

of how the earth works and evolves. But is there an even simpler or more theoretically abstract model of how the earth works? A single model that incorporates everything in the Wilson Cycle?

There is, and it is the Tectonic Rock Cycle. Click on the drawing for an enlarged version, or click this *Tectonic Rock Cycle* to go to the description of the model.



How Much Do You Understand?

The *Stage I enlarged drawing* contains evidence of all the events and processes occurring during the Wilson Cycle. The question is, can you reconstruct them? Can you go through the final cross section and identify specific rock types, or specific tectonic regimes, or specific tectonic stages in the Wilson Cycle?

Q Try This Tectonic Recognition and Identification: Without going back to the labeled cross section, go to *this lettered drawing* where different parts of the cross section are identified by letters. Do one of two things with these locations, either:

» Identify the stage of the Wilson cycle they formed in, or . . .

» Identify what tectonic regime they represent; e.g. DCM, volcanic arc, axial rift. etc. (All the letters are hot and will take you to an answer)

Q Try This Two (Too) Rock Identification and Interpretation: Can you identify the various rock types in the Stage I cross section? Go to *this numbered drawing* where different rock units are identified with a number.

» Identify the rock type (igneous, sedimentary, metamorphic) and specific rock (e.g. greenschist, arkose, etc.) that would reasonably be found at each location.

» Describe the processes by which each rock formed. If the rock is altered from a parent identify the parent.

» Identify the tectonic regime and/or Wilson Cycle stage each rock formed in.

- *Go to A Plate Tectonic Rock Cycle*
- *Return to Stage H*
- *Return to Stage A - Stable Continental Craton*
- *Return to Wilson Cycle Home*

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Senator Robert S. Kerr

Senator Robert S. Kerr was born in a log cabin south of Ada, OK on September 11, 1896. From these humble beginnings came a brilliant oil businessman, Oklahoma's first native born governor, and a powerful force in the United States Senate. Throughout his life, Senator Kerr always had Oklahoma's best interests at heart.

Senator Kerr was in many ways an early environmentalist long before the concept of Earth Day and the controversies concerning the environment. He constantly advocated the careful use of natural resources. One of his themes, "Land, Wood, and Water" became the title of his book on the environment published in 1960.

Senator Kerr enjoyed life and could disarm a foe with his charisma. He would smile and say, "I'm just a simple country boy," and his foes would most often retreat from an attack. He was always quick with a joke, a "down home" quote, or humorous story. It has been reported that when Senator Kerr suffered a fatal heart attack on the morning of January 1, 1963, he was in the midst of telling a humorous story to some friends.

After his death, Senator Kerr was interred at his birthplace homestead on a hilltop east of the cabin near Ada. His gravestone was a piece of Oklahoma granite carved with the cover art of his book, "Land, Wood, and Water." In 2006, Senator Kerr's grave and granite marker were moved from his homestead in Ada to Oklahoma City.

Immediately west of Kerr's homestead site in 1966, the Robert S. Kerr Environmental Research Laboratory was dedicated and remains one of the Environmental Protection Agency's six research divisions on National Risk Management. Senator Kerr's ranch outside of Poteau, OK is now "The Kerr Center for Sustainable Agriculture" and is responsible for leading research to benefit Oklahoma's and the Nation's farmers and ranchers.

At the Kerr Conference Center (see page 66), Poteau, OK, there is an excellent museum dedicated to Senator Kerr's life and political career and also exhibits pertaining to eastern Oklahoma. The museum is well worth a visit.

Another excellent and brief source about Senator Kerr's life is the Internet exhibit commemorating the centennial celebration of Senator Kerr's birth created and maintained by the Carl Albert Center, University of Oklahoma. The URL for this exhibit is: http://www.ou.edu/special/albertctr/archives/kerr/KERRPN1.HTM.

Kerr Cabin – Ada, Oklahoma
Senator Robert S. Kerr's Birthplace and boyhood home
February, 2007

Interpretation of Depositional Environments of the Savanna Formation, Arkoma Basin, Oklahoma, from Outcrops and Surface and Subsurface Gamma-Ray Profiles

Richard D. Andrews and Neil H. Suneson
Oklahoma Geological Survey

ABSTRACT.—The upper part of the Desmoinesian Savanna Formation is well exposed in a new road cut along Oklahoma State Highway 82 just south of Lequire in southern Haskell County. The outcrop is subdivided into nine major units based on exposed rock types, sedimentary structures, fossils, and contact relations between the rock types. Most of the units were deposited in a mid- to lower-delta-plain environment and include interdistributary bay-fill and crevasse-splay sediments, as well as organic material deposited in marshes and/or swamps. Evidence that supports such an interpretation includes interbedded sandstones and shales, common fining-upward textures of the sandstones, and the presence of coal, all characteristic of mid- to lower-delta-plain deposits. In contrast, the basal unit probably was deposited in a delta-fringe environment, and the upper part of the outcrop contains evidence of subaerial exposure.

Gamma-ray values measured on the outcrop closely reflect rock types. Sandstone-dominated intervals have low gamma-ray values; shale-dominated intervals have high values; and intervals of muddy sandstones and/or interbedded thin sandstones, siltstones, and shales have intermediate gamma-ray values. A gamma-ray profile of the entire outcrop was constructed from the measured values. The sharp basal contacts of thick sandstones overlying shales that are observed in outcrop are recorded on the profile, as are units that contain decreasing amounts of sandstone upward. The presence of coal also is reflected on the surface gamma-ray profile.

The surface gamma-ray profile is very similar to a subsurface gamma-ray wireline log for the same stratigraphic interval from a petroleum well ~0.5 mi southeast of the outcrop. The similar profiles illustrate what delta-plain deposits look like on wireline logs and demonstrate the usefulness of surface gamma-ray profiles for interpreting the depositional environment of strata encountered in a wellbore.

INTRODUCTION

This paper has two primary purposes. The first is to describe and interpret a new and exceptionally well exposed outcrop of the Pennsylvanian Savanna Formation near Lequire in Haskell County, Oklahoma. The second is to show the similarity of the gamma-ray profile of the outcrop to the gamma-ray log of the same part of the Savanna Formation from a nearby petroleum well. The goals of this paper are to document that surface gamma-ray profiles accurately reflect the rock types present in a sequence of strata and that certain depositional environments result in particular surface gamma-ray profiles and subsurface gamma-ray logs.

An exposure in the upper part of the Savanna Formation (Desmoinesian) in the Arkoma Basin just south of Lequire (Fig. 1) is one of the best examples of delta-plain strata in Oklahoma. The strata were exposed between 1994 and 1996 during construction of an addition to Oklahoma State Highway 82. The exposure is essentially unweathered and consists of ~240 ft of mostly nonmarine sandstone, siltstone, shale, and thin coal beds that represent multiple crevasse-splay and interdistributary bay-fill, swamp, and marsh deposits. Plant fossils are abundant and include conspicuous, large, erect, in situ *Calamites* and lycopods. (See Lupia and others, 2002 [this issue, p. 19–26], for a preliminary survey of the flora from the outcrop.) Common sedimentary structures in the sandstones that are characteristic of episodic and rapid deposition on a delta plain include soft-sediment deformation features, cross bedding, and load casts.

The Savanna Formation near Lequire also is important for reconstructing the formation's paleogeographic environment of deposition in southeastern Oklahoma. Much of the Savanna Formation ~5 mi to the southeast described by Hemish (1996) (e.g., Lodi section) appears to be marine and probably was deposited in a subaqueous delta-front environment, the basinward equivalent of the delta plain exposed at Lequire. The different depositional setting of the Savanna Formation at Lequire compared to that near Lodi requires further study; such detailed paleoenvironmental reconstructions are important for resource assessment of coal, natural gas, and coalbed methane, all of which are present in the Savanna.

Gamma-ray profiles of surface exposures—where rock types, textural variations, and sedimentary structures provide visible evidence for interpreting depositional environments—are useful for interpreting subsurface strata for

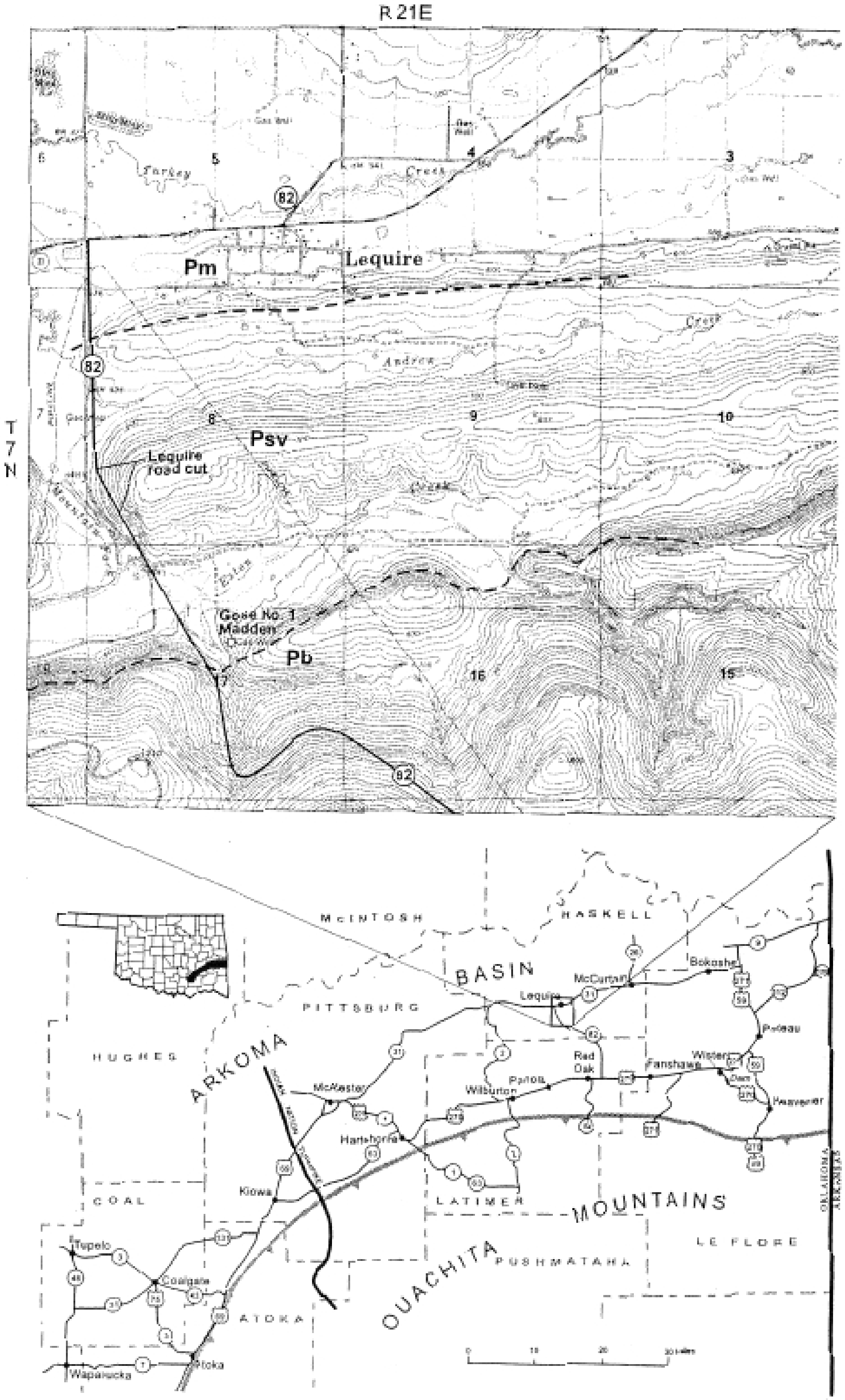


Figure 1. Map showing the locations of the Lequire road cut (SW¼ sec. 8, T. 7 N., R. 21 E.) and the Steve Gose No. 1 Madden well. (Geologic map modified from Hemish, 1998; location map modified from Suneson, 1998, inside front cover.) Pm—McAlester Formation; Psv—Savanna Formation; Pb—Boggy Formation; dashed lines—geologic contacts.

which only wireline logs are available. Gamma-ray profiles generally measure the relative abundance of shale or interstitial clay, both of which produce relatively large amounts of gamma radiation compared to other common sedimentary rocks such as sandstone, limestone, or coal. Therefore, a gamma-ray profile (or a wireline log) can be used to distinguish between these rock types. Generally speaking, sandstone with little interstitial clay or interbedded shale exhibits low gamma-ray values and is called "clean." Sandstone or siltstone having larger amounts of interstitial clay and/or interbedded shale have gamma-ray values between those of a clean sandstone and a shale and may be called "dirty." A wireline log, therefore, records the relative amounts and thicknesses of shale and of clean and/or dirty sandstone in a wellbore; it also records the nature of the contacts (sharp vs. gradational) between the sandstones and shales.

This study is similar to Andrews and Suneson's (1999) study of the Desmoinesian Hartshorne Formation, and the delta-plain origin of the Savanna at Lequire is similar to that of the Hartshorne at Heavener (p. 54–56). In this paper, however, we more carefully describe those outcrop features that support our interpretation for a delta-plain environment of deposition. In addition, the outcrop gamma-ray profile and the wireline log of the Savanna are far more strikingly similar than are the Hartshorne profiles. Both studies, however, confirm the general log signature of delta-plain deposits as described by Brown (1979) and Coleman and Prior (1982).

PREVIOUS STUDIES OF THE SAVANNA FORMATION

The Desmoinesian Savanna Formation is within the Krebs Group, which consists (from bottom to top) of the Hartshorne, McAlester, Savanna, and Boggy Formations (Fig. 2). It is exposed along the eastern side of the Cherokee Platform area from the Kansas state line in Craig and Ottawa Counties (Branson and others, 1965) south to Muskogee (Oakes, 1977) (Fig. 3). The Savanna is not recognized as a separate formation in Kansas, where its stratigraphic equivalent is within the Krebs Formation (Brady and others, 1994). The Savanna Formation also is widely exposed in the Arkoma Basin of Oklahoma and Arkansas (Hart, 1974; Marcher and Bergman, 1983; Haley, 1976; Hemish and Suneson, 1997; and references cited therein).

The geology of the Savanna Formation in southeastern Oklahoma was summarized recently by Hemish (1996) and Hemish and Suneson (1997). Those studies focused on the history of nomenclatural changes; thickness variations, particularly from the platform area in the north to the Arkoma Basin in the south; lithologic variations; and resources. The depositional environment of the Savanna Formation is poorly understood (Hemish and Suneson, 1997, p. 27), but its numerous coal beds and widespread limestone beds containing marine, invertebrate fossils are evidence that the Savanna includes continental and marine strata. The Savanna probably consists of a variety of offshore marine, marine bar, deltaic, and alluvial facies; however, an understanding of the distribution of these facies and an accurate picture of Savanna paleogeography await future study.

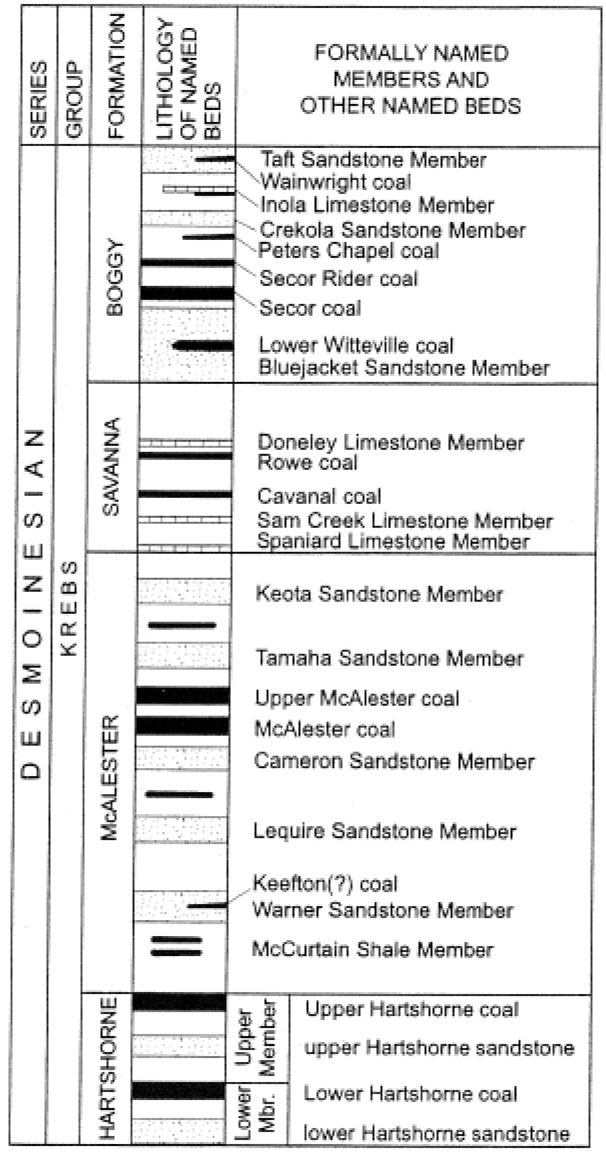


Figure 2. Generalized stratigraphic column of the Krebs Group showing the relative positions of formally named members, names of coal beds, and other informally named beds. Of the members of the Savanna Formation, only the Rowe coal has been tentatively identified in the Lequire road cut. (Modified from Hemish and Suneson, 1997, fig. 3).

MID- AND LOWER-DELTA-PLAIN DEPOSITS

Deltas generally consist of a distinctive sequence of rock types, and the different deltaic environments can be interpreted from outcrops and from surface and subsurface gamma-ray profiles (e.g., Brown, 1979; Coleman and Prior, 1982) (Fig. 4). This study focuses on the identification and characterization of mid- and lower-delta-plain deposits of the Savanna Formation, in particular, sediments deposited in crevasse-splay, distributary-channel, and interdistributary (in-

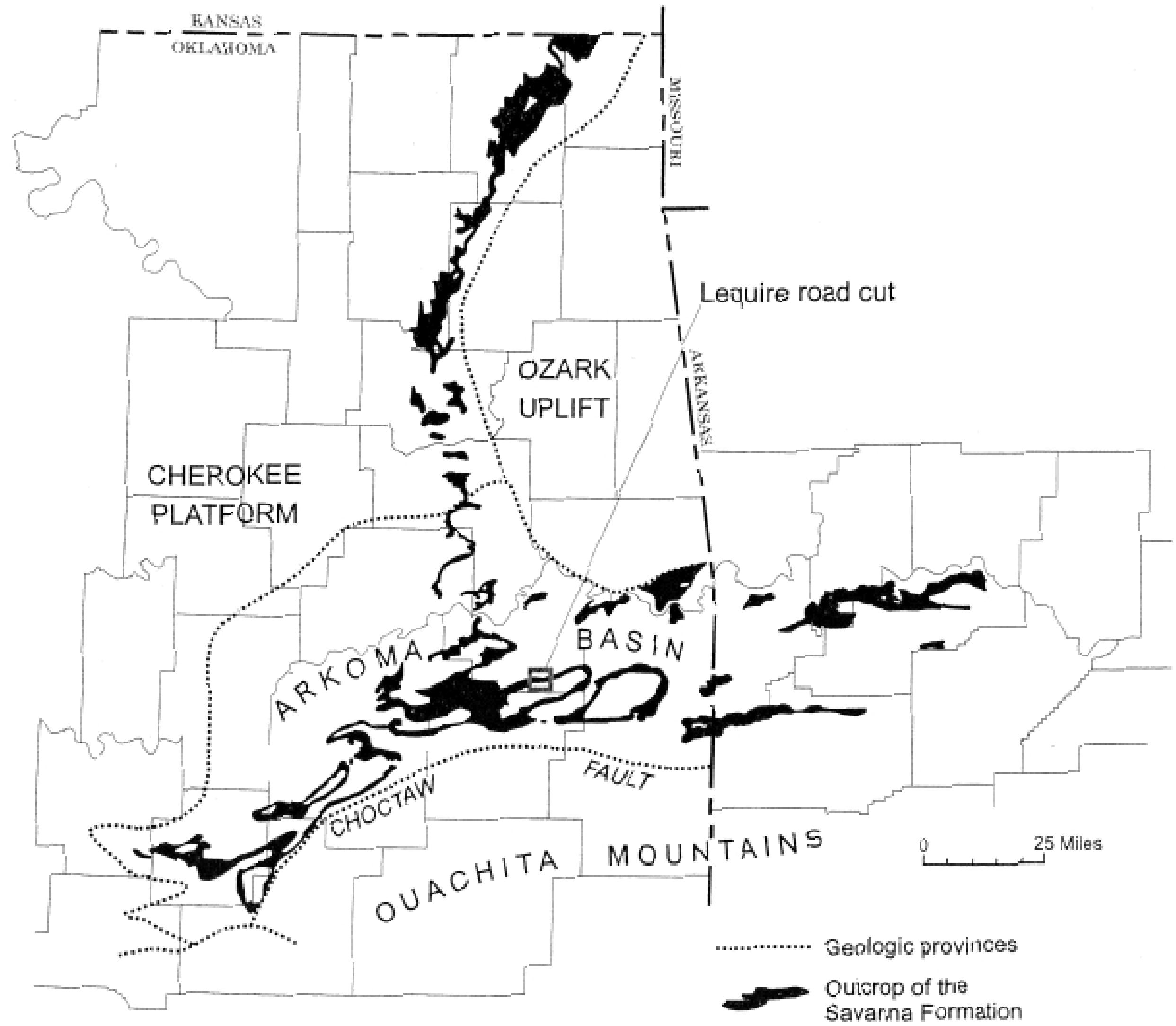


Figure 3. Map showing the outcrop belt of the Savanna Formation in Oklahoma and Arkansas and the location of the Lequire road cut. (Modified from Hemish and Suneson, 1997, fig. 15; outcrop of Savanna Formation in Cherokee Platform area from Miser, 1954).

cluding bays, marshes, and swamps) environments (Fig. 4). These deposits include sandstones, siltstones, shales, and coal beds. In overbank deposits (crevasse splays), sandstone beds commonly are relatively thin but widespread; in contrast, sandstones in distributary channels are restricted spatially and may be thick. Siltstones and shales commonly occur in bay-fill environments, but may occur also in abandoned channels. Coal beds are diagnostic of marsh or swamp environments. Interdistributary-bay and marsh or swamp sequences commonly are interbedded with crevasse-splay sandstones.

Crevasse-Splay Deposits

Crevasse-splay sandstones typically are thinner than the depth of the interdistributary bay in which they are deposited. In most of the Pennsylvanian deltas of Oklahoma, bays rarely exceeded depths of a few tens of feet. However, the lateral extent of crevasse-splay sandstone beds is large and reflects the area of the receiving bay and the amount of sand available. Crevasse-splay sandstones may have either a coarsening-upward or a fining-upward textural profile, and both patterns are common in a single stratigraphic sequence in which more than one splay event occurred.

Textural profile is a function of depositional energy. (Textural profile in this article refers to sediment grain-size distribution, or specifically, the number and thickness of siltstone and/or shale beds interstratified with sandstone beds.) Proximal splay sands are deposited close to the distributary channels from which they were derived, and depositional energy in a proximal splay environment typically is high, as it is in a break-out channel. In a vertical profile, therefore, the sand body resembles that deposited in a river or channel. Proxi-

CURRENT STUDY

This study focuses on a well-exposed road cut through part of the Savanna Formation on the east side of State Highway 82 just south of Lequire in southern Haskell County, Oklahoma (Fig. 1). The outcrop, located in the SW¼ sec. 8, T. 7 N., R. 21 E., was initially described by Hemish (1998) during highway construction (October 1994). At that time, ~100 ft of section, dipping south at 18°, was exposed. Hemish (1998, appendix) measured ~70 ft of exposed section. Since Hemish's work, the road cut has been cut back further and ~240 ft of strata now are exposed (Fig. 5).

Based on gamma-ray correlation with the Steve Gose No. 1 Madden well located ~0.5 mi southeast of the outcrop (Fig. 1) (discussed below in the section on correlation of surface and subsurface gamma-ray profiles) and mapping by Hemish (1998, fig. 9A), the base of the outcrop is ~645 ft above the base of the Savanna Formation, which is ~1,085 ft thick in the study area. In this area, the Savanna is underlain by the McAlester Formation (Fig. 2), which underlies the north-facing slope of the ridge immediately south of the town of Lequire. (The Keota Sandstone Member of the McAlester Formation is exposed in the town [Hemish, 1998, fig. 9A].) The exposed section is ~240 ft thick; therefore, the top of the outcrop is ~200 ft below the top of the Savanna, which is the base of the Bluejacket Sandstone Member of the Boggy Formation (Fig. 2).

Depositional Environments

We subdivide the Lequire outcrop into nine major units based on exposed rock types, sedimentary structures, fossils, and contact relations between rock types. Five sandstone-dominated zones (units 1, 3, 5, 7, and 9) separated by siltstone- and shale-dominated zones (units 2, 4, 6, 8) (Fig. 6) are exposed at the outcrop. We interpret the Savanna Formation exposed in the Lequire outcrop to have been deposited mostly in a mid- to lower-delta-plain environment. The interpretation is supported by the features emphasized in the general descriptions of the units in this section. (Detailed descriptions of the units are given in the Appendix.)

Unit 1

Sandstone unit 1 is interpreted to be dominantly marine and probably represents a delta-fringe facies. Distinctive sedimentary features that contrast with the other sandstones include excellent small-scale stratification and local ripple-cross-stratification with thin shale drapes. Plant fossils and trace fossils are absent.

Unit 2

Unit 2 is mostly shale with a 4-in.-thick coal bed in the lower half. The shale below the coal contains ostracodes, which are either Carbonita sp. or Darwinula sp. (Faye Simms, Northwestern State University, personal communication, 1999). Both genera are evidence for a brackish- to fresh-water environment (e.g., Kietzke and Kaesler, 1992). Some beds are highly calcareous and may grade into muddy limestones. The shale above the coal contains abundant coaly laminations and siderite(?) concretions containing plant compressions. The siderite(?) occurs as isolated nodules, nodules concentrated along bedding planes, and discrete beds. A discontinuous, 1-in.-thick coal bed is present ~6 ft below the top. Unit 2 is interpreted to be alternating marsh or swamp and interdistributory-bay facies deposited in brackish to fresh water.

Unit 3

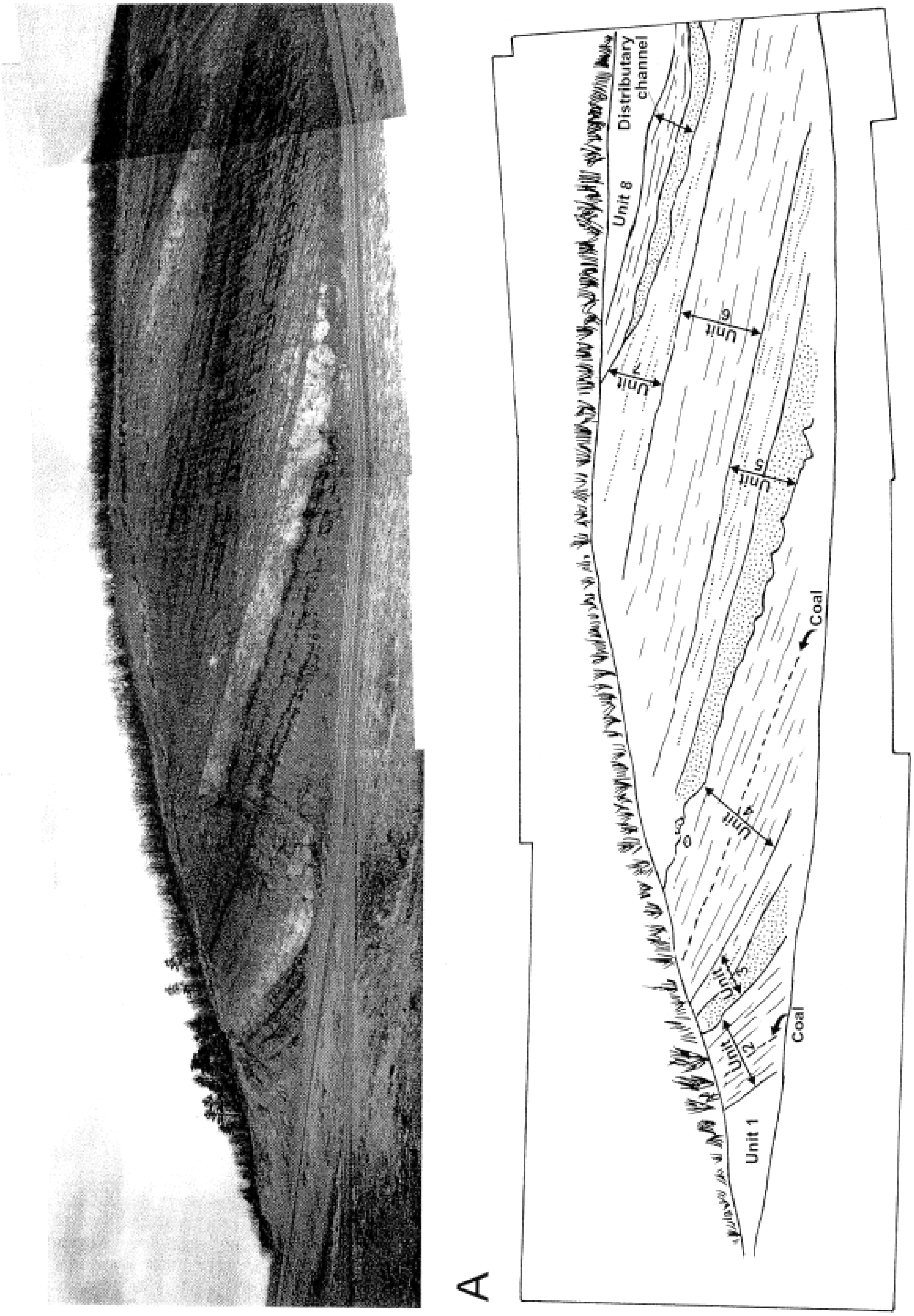
Sandstone unit 3 (Fig. 7) fines upward as evidenced by the increasing number and thicknesses of shale and siltstone layers and decreasing thicknesses of sandstone layers from the base to the top of the unit. All of the sandstones are fine-grained to very fine grained and relatively clean. The basal sandstone is ~9 ft thick and contains abundant soft-sediment-deformation features. Bedding planes are marked by shale rip-up clasts and plant debris. The base is slightly irregular and the underlying shale (unit 2) has locally squeezed up into the sandstone, but there is no evidence for channeling or erosion. The basal sandstone was deposited during a single event, probably a flood. Stratigraphically higher sandstone beds in unit 3 range from 1 ft to 1 in. thick, are discontinuous, show much pinch and swell, and locally erode into underlying beds. Like the massive basal sandstone, the thinner sandstone beds also contain shale rip-up clasts and plant fragments. The sandstone beds are separated by thin laminated shales and siltstones. A 6-ft-thick channel filled with massive, soft-sediment-deformed sandstone locally erodes into the sandstone beds in the upper part of unit 3. Unit 3 is interpreted to be a fining-upward crevasse-splay sequence.

Unit 4

Shale unit 4 consists of shale, siltstone, sandstone, and coal, in decreasing order of abundance. Key environmental features include abundant plant fossils, burrows, and siderite(?) nodules, which are evidence for a bay-fill sequence of dominantly fine-grained rocks. The presence of coal near the middle of the unit is evidence for a period of low sedimentation rates.

Unit 5

Unit 5 is similar in many respects to unit 3 and consists of multiple sandstone beds that become thinner upward (Fig. 8); shale and siltstone beds increase in abundance and become thicker upward. The sandstones are very fine grained and quartzose. The base of this unit is marked by a massive sandstone, the base of which is undulatory and marked by numerous upright carbonized tree trunks as much as 6 ft high and 14 in. in diameter (Fig. 9). Most of the trunks appear to be leaning generally south (Hemish, 1998, p. 109). The basal sandstone is soft-sediment deformed (Fig. 10) and contains abundant shale rip-up clasts and plant fragments. Overlying sandstone beds range from 1 in. to 1 ft thick, show much pinch and swell, and locally exhibit large-scale crossbedding. Macerated carbonized plant debris is common; small burrows are rare. Each sandstone bed is interpreted to have been deposited by rapidly moving water during a single event, such as a flood. The abundant plant debris, some in growth position, is evidence for a nonmarine to brackish environment. Most


A
Distributary channel
Unit 8
Unit 7
Unit 6
Unit 5
Unit 4
Coal
Unit 3
Unit 2
Coal
Unit 1

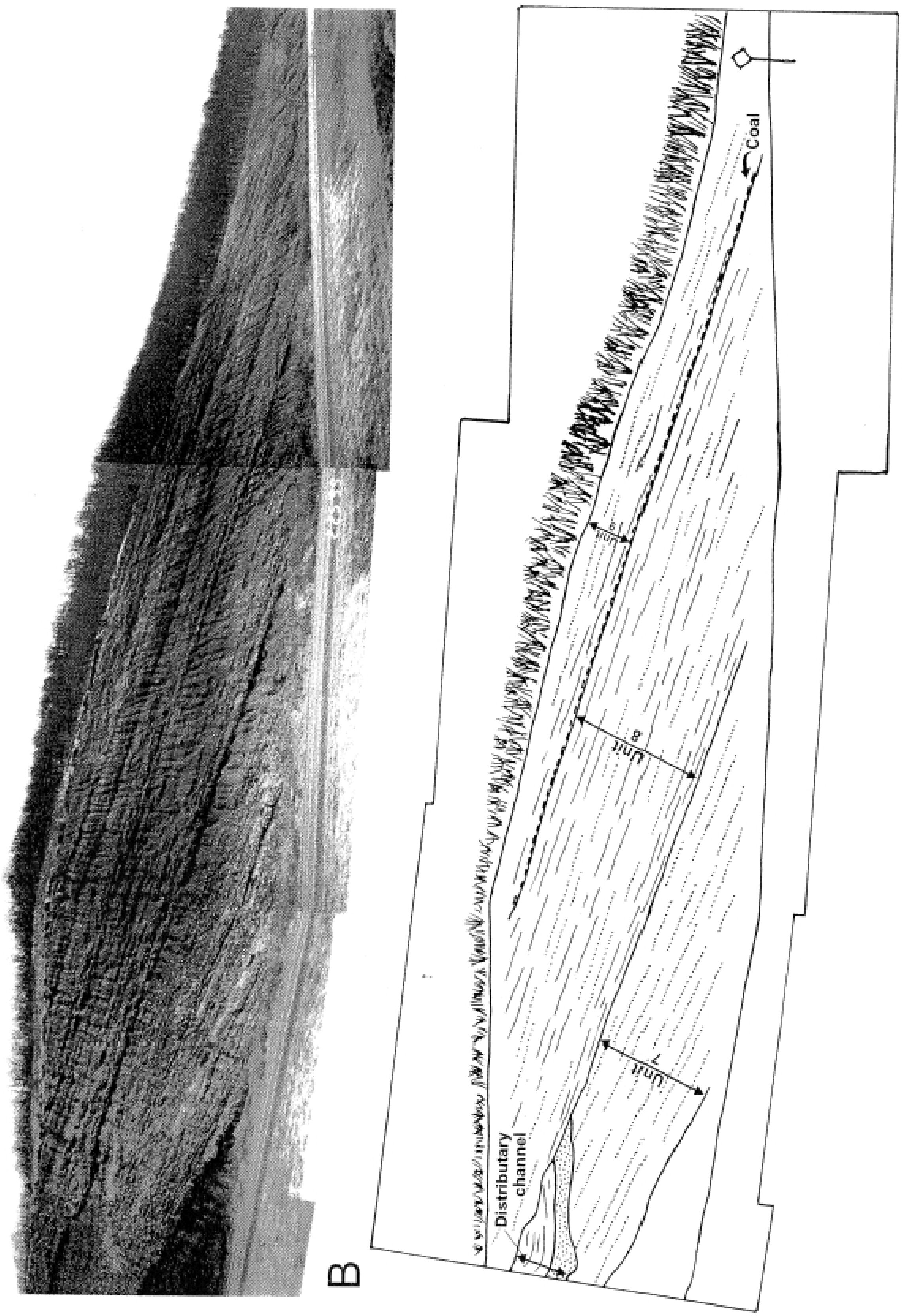


Figure 5. Photographic panorama of the Lequire road cut on the east side of Oklahoma State Highway 82 (SW¼ sec. 8, T. 7 N., R. 21 E.) and a sketch of the road cut showing the numbered units in the section. The road cut is ~900 ft long and ~60 ft high. (*A*, *facing page*)—North end of the road cut. (*B*, *above*)—South end of the road cut.

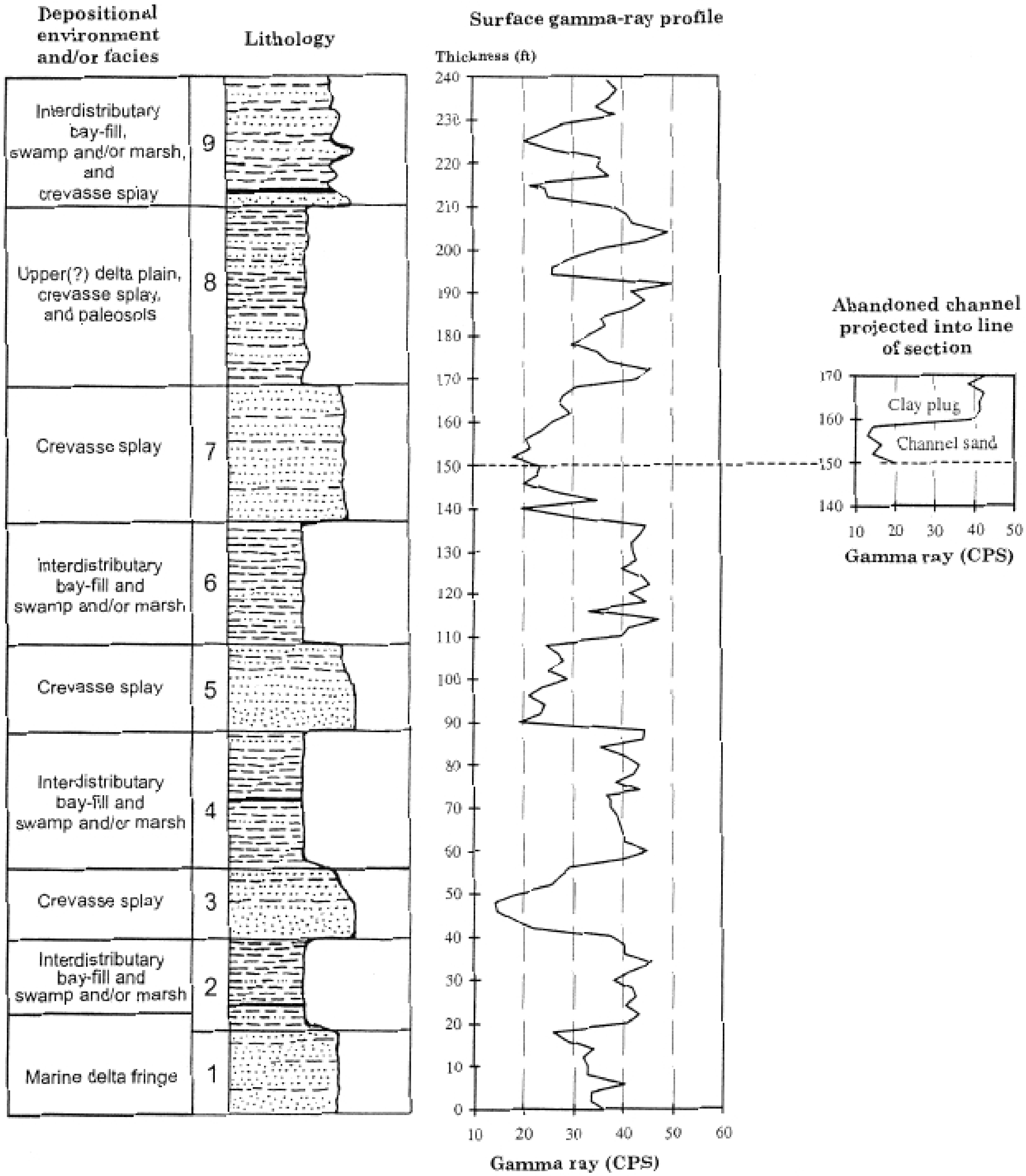


Figure 6. Graphic columnar section of the Lequire road cut showing the generalized distribution of rock types. Units are described by number (1 through 9) in the text and in the Appendix. Interpretation of the depositional environment is shown on the left, and the gamma-ray profile of the outcrop is shown on the right. Lithologic symbols: Dots—sandstone; dashes—shale; dots-dash—siltstone; heavy solid line—coal.

likely, unit 5 represents a series of crevasse-splay sandstones that were deposited during floods.

Unit 6

Shale unit 6 is similar to shale unit 4; however, plant fossils are relatively rare except for *Calamites* stems in the upper part. Siderite(?) concretions are abundant throughout the unit and a single, thin, ripple-bedded, very fine grained sandstone contains trace fossils. A thin, discontinuous coal bed is present ~12 ft from the top of the unit. Like unit 4, this shale probably was deposited mostly in an interdistributary-bay environment and more rarely in a marsh.

Unit 7

Most of sandstone unit 7 (Fig. 11) is similar to sandstone units 3 and 5. Similarities include multiple sandstone beds that generally become thinner upward (although the trend is less pronounced in unit 7 than in those lower units); are fine-grained to very fine grained quartzose sandstone; contain soft-sediment-deformation features and cross-stratification; exhibit much pinch and swell; contain abundant upright *Calamites* (molds) in growth position and uncommon trace fossils; and are interbedded with siltstone and shale. Unit 7, however, is distinctive from the other sandstone units because it is eroded by a channel ~20 ft deep near the top of the outcrop (Fig. 11). The channel is filled with ~10 ft of very soft-sediment-deformed sandstone containing uncommon, small shale rip-up clasts, and an overlying shale and thin, continuous siltstone beds that are laminated, but not crossbedded. Like sandstone units 3 and 5, unit 7 is a series of crevasse-splay sandstones. Unlike the lower sandstone units, however, unit 7 contains a distributary channel that is partly filled with sandstone, and partly with a plug of siltstone and shale. The absence of current indicators (such as crossbedding) and the predominance of shale in the plug are evidence that the channel was abandoned prior to being filled completely.

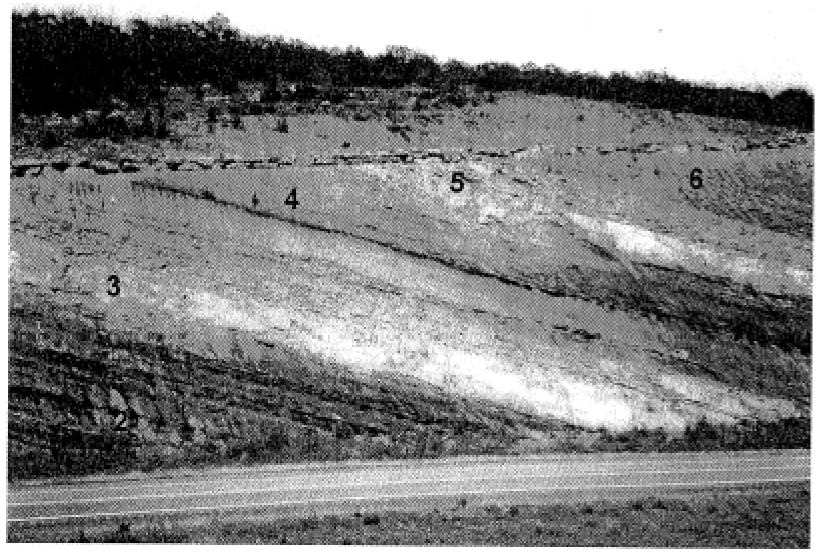


Figure 7. Photograph of sandstone unit 3 (center of photograph). The top of unit 2, weathered units 4 and 5, and the base of unit 6 also are visible. Note the thinning-upward character of the sandstone beds in unit 3. The prominent white sandstone in the lower part of unit 3 is ~9 ft thick.

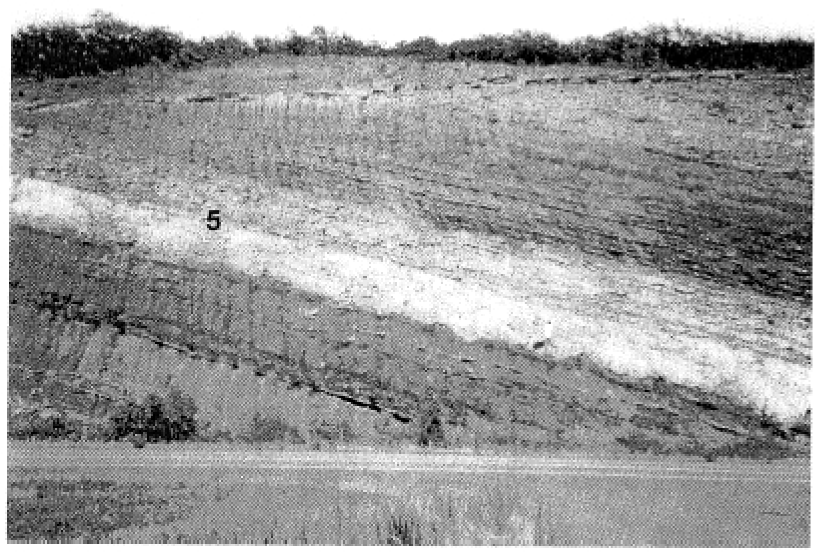


Figure 8. Photograph of sandstone unit 5 (center of photograph). The base of the massive, basal sandstone is sharp, but undulatory. Note the thinning-upward character of the sandstone beds. Geologist for scale.

Unit 8

Shale unit 8 is heterolithic and consists mostly of shale with two sandstone-rich intervals. The shale-rich intervals at the base, middle, and top of unit 8 differ slightly from shale units 4 and 6; carbonized plant impressions are common but coaly layers and siderite(?) concretions are absent. In addition, the shales locally contain isolated soft-sediment-deformed sandstone masses as long as 4 ft. The most distinctive feature of the shales is their color—the typically dark gray shales grade irregularly to a maroon color parallel to and highly oblique to the stratification. The color, the presence of irregularly

Figure 9. Carbonized tree trunk in growth position at the base of sandstone unit 5. The fossil tree is tilted slightly to the right (south). Like this large trunk, most of the upright fossil trees (mostly *Calamites*) in unit 5 are tilted to the south. This unidirectional tilting is a paleocurrent indicator that shows the direction of flood-water movement associated with deposition of the crevasse-splay sandstones. The flood waters probably inundated a forested marsh or swamp, partially knocking the trees over. Hammer for scale.

shaped calcareous nodules in the upper shale, and what Hemish (1998, p. 114, units 1, 4, 6, and 7) identified as root casts and pedogenic slickensides, are evidence for extensive paleosol development throughout the shales of unit 8.

The sandstones in unit 8 are similar to those in units 3, 5, and 7, except that there are no thick, massive beds. Some of the sandstone beds have load casts on their bases, and several are cross-stratified and vary in thickness. Unit 8 probably was deposited in a delta-plain environment, possibly higher on the delta than the underlying units. The sediments were exposed subaerially, which suggests that they were deposited above mean high tide. However, the sandstone layers are similar to the crevasse-splay sandstones described in units 3, 5, and 7.

Unit 9

Like unit 8, sandstone unit 9 is heterolithic and consists of sandstone, shale, siltstone, and coal. Key environmental features include compressed carbonized logs as long as 7 ft and burrows in the basal sandstone; common plant fossils in siderite(?) nodules in the shale overlying the coal; and an upper, medium-bedded, sandstone-rich zone with commonly cross-stratified, soft-sediment-deformed, and highly lenticular sandstone beds. Hemish (1998) suggested that the coal may be the Rowe coal, but he was unsure. Our interpretation of the sediments of unit 9 is that they were deposited in an interdistributary-bay environment and as crevasse-splay sandstones.

Summary of Depositional Environments

In summary, the sedimentary structures, rock types, and fossils support our interpretation that the Savanna Formation exposed in the Lequire road cut was deposited mostly in a mid- to lower-delta-plain environment. The evidence for this interpretation includes the repetitive series of sandstone- and shale-dominated units believed to represent overbank crevasse-splay sandstones and interdistributary-bay shales and swamp or marsh coals, respectively. These deposits comprise the vast majority of sediments in the outcrop, and they overlie marine strata of unit 1 that are interpreted as delta-fringe deposits.

The sedimentary structures that are key to our interpretation that most of the sandstones are crevasse-splay deposits include ubiquitous soft-sediment deformation (flowage displaying convolute bedding), load casts at the base of thicker sandstone beds, abundant shale rip-up clasts, plant debris ranging from large casts to macerated carbonized hash, and engulfed *Calamites* in growth position. Evidence for shale deposition in interdistributary bays includes abundant siderite(?) concretions; common carbonized plant fossils; and the several coal beds, which probably represent marsh or swamp deposits. The bay-fill deposits of unit 8 appear to have been exposed subaerially, as evidenced by the presence of poorly developed paleosols.

Thus, we conclude that the Lequire outcrop represents a progradational sequence. Mostly marine sediments (unit 1) are overlain by deposits of mid- to lower-delta-plain origin.

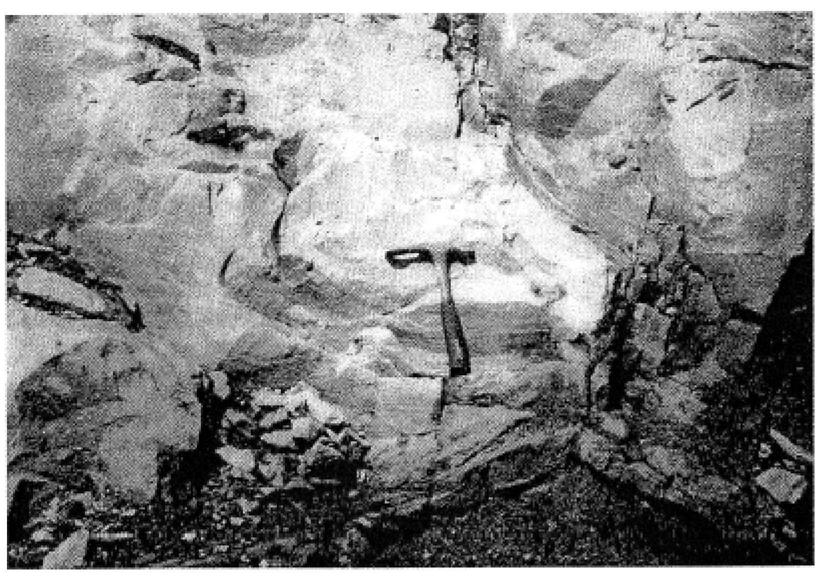


Figure 10. Convolute bedding (soft-sediment deformation) typical of crevasse-splay sandstones in unit 5. Such deformed bedding is characteristic of sand deposited rapidly during a single event. Hammer for scale.

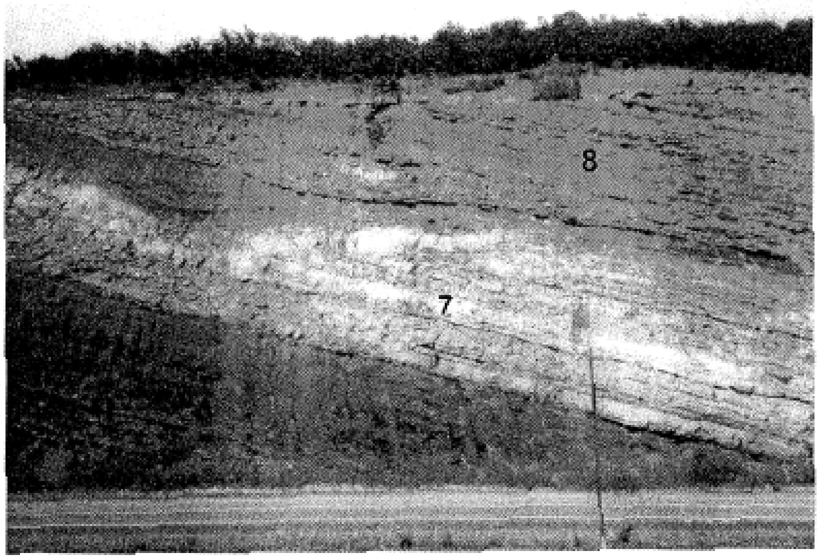


Figure 11. Photograph of sandstone unit 7, which is ~30 ft thick. In the upper left part of the photograph, a distributary channel erodes about two-thirds of the way through the sandstone sequence. Sandstone forms the base of the channel, but most of it is filled with shale. Shale unit 8 overlies unit 7 and consists mostly of dark gray and maroon-colored beds.

Correlation of Surface and Subsurface Gamma-Ray Profiles

One of the primary goals of geologists who study subsurface wireline logs is to interpret the depositional environment of the strata in a wellbore and thereby predict depositional trends and characteristics of petroleum reservoir rocks. Where cores have not been retrieved, this interpretation must be accomplished without examining any rocks. In outcrops—where rock types, sedimentary structures, contact relations between different beds, and fossils can be observed directly and studied—interpretations of depositional environments are more straightforward. By measuring the gamma-ray profile of an interpreted outcrop, a geologist can characterize a particular depositional environment. This surface log can then be used to interpret subsurface logs. However, to be useful for interpreting wireline gamma-ray logs, the surface profile should be compared to the subsurface profile of the same stratigraphic interval.

A gamma-ray profile for the entire Lequire outcrop was constructed from measured gamma-ray values. All field measurements and graphing were completed by the authors. We used a Scintrex GRS-500 gamma-ray spectrometer/scintillometer. The GRS-500 utilizes two time constants (sampling rates), 1 second and 10 second. For better statistical results, we used a 10-second time constant, measuring total gamma radiation (uranium plus thorium plus potassium) above 400 keV. Readings from an analog display were recorded in a field notebook.

The gamma-ray intensity of the outcrop strata was measured according to a set procedure. We checked the batteries to be sure they were fresh and adjusted the instrument to the proper spectral and time-constant settings. We placed the instrument against the outcrop where there were no significant overhangs or other rock protrusions that would partially surround the instrument (such as in a small gully or rock cavity) and cause the gamma-ray values to be enhanced or attenuated. Covered intervals were avoided. We took readings 2 ft apart stratigraphically and five readings per station.

To construct the surface gamma-ray profile, we entered the five gamma-ray values from each station into an MS Excel spreadsheet, where they were numerically averaged. Using a scatter plot, we graphed the average gamma-ray values (CPS), adjusting the vertical scale to fit the graphic columnar section of the Lequire outcrop (Fig. 6).

Surface gamma-ray measurements on the Lequire outcrop ranged from ~15 CPS to 50 CPS. Correlation of the gamma-ray profile with the outcrop rocks indicates that values greater than approximately 35–40 CPS represent shale-dominated intervals and values of less than ~35 CPS represent increasingly cleaner sandstones. Very clean sandstones always have values of less than 25 CPS.

The surface gamma-ray profile clearly depicts the major sandstone- and shale-dominated units and their gross textural characteristics (Fig. 6). Unit 1, interpreted as a marine, delta-fringe facies, is different from the other sandstone-dominated units; it contains more siltstone and shale, as reflected in its higher gamma-ray values. Shale units 2, 4, and 6 have similar profiles and are from similar depositional environments. The sharp bases and fining-upward characters of crevasse-splay sandstone units 3, 5, and 7 can be observed in outcrop and are evident on the profile. The heterolithic character of units 8 and 9, interpreted as bay-fill and crevasse-splay sediments, are also evident on the profile. However, evidence for subaerial exposure, observed in outcrop, is not apparent on the profile.

To determine whether the surface gamma-ray profile is similar to a typical subsurface well log, we compared the surface profile to the gamma-ray log from the Sieve Gose No. 1 Madden well (SW¼NE¼ sec. 17, T. 7 N., R. 21 E.) (Fig. 12), which is located ~0.5 mi southeast of the Lequire road cut. Based on the dip of the beds and the base of the Savanna Formation as mapped by Hemish (1998), and on the position of the base of the Savanna Formation on the wireline log (1,645-ft drilled depth), the interval between ~730 ft and ~980 ft in the well corresponds to the surface outcrop.

The three clean-sandstone-dominated units can be seen on the well log (Fig. 12). The base of unit 3 is ~922 ft deep; base unit 5 is ~890 ft deep, and base unit 7 is ~840 ft deep. The wireline log profiles of the other units also are similar to those on the surface gamma-ray profile. Therefore, based on our interpretation of the Lequire road cut, the gamma-ray profile of the road cut, and our correlation of the surface

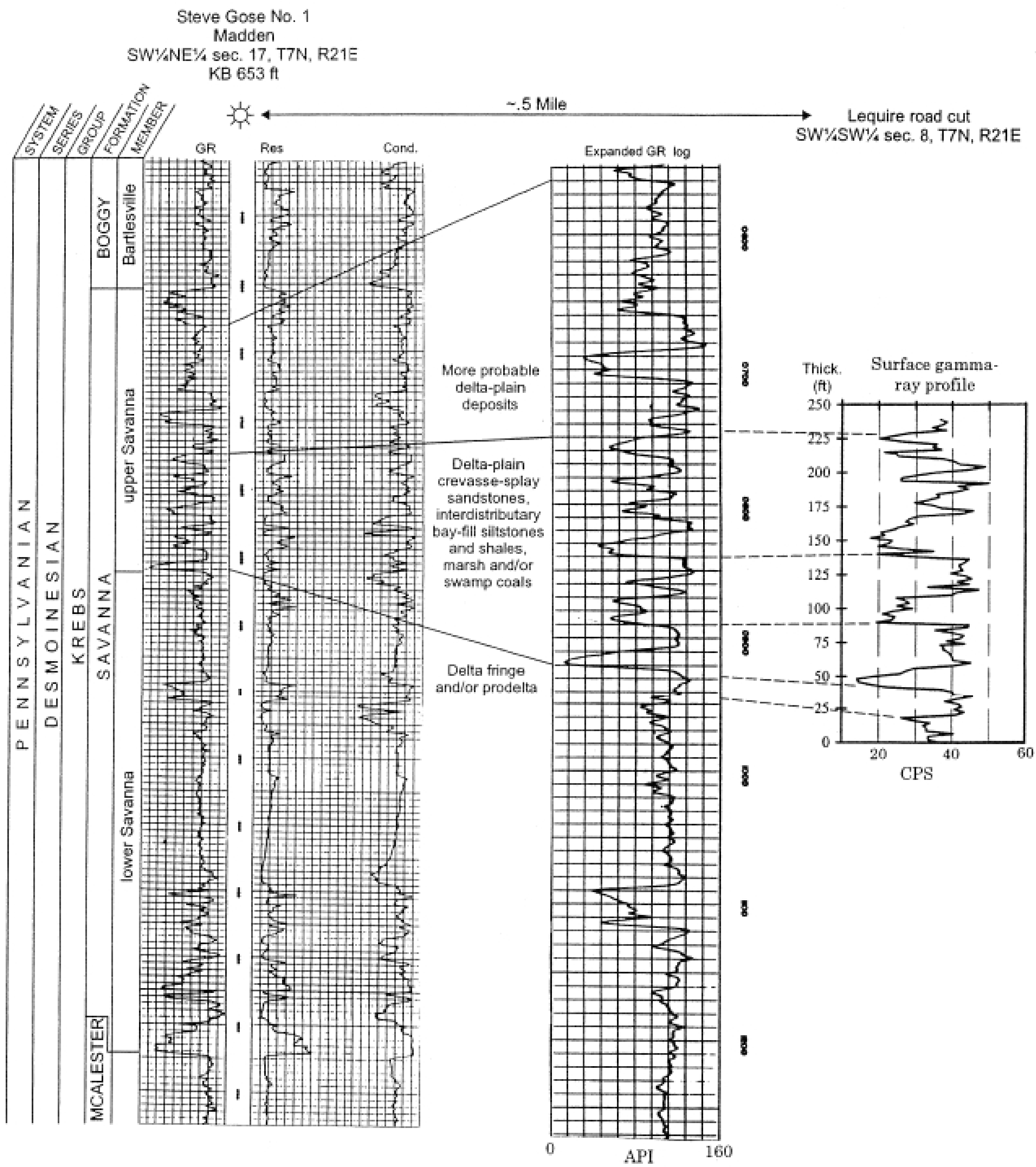


Figure 12. Part of the wireline well log from the Steve Gose No. 1 Madden well (located ~0.5 mi southeast of the Lequire road cut). The wireline gamma-ray (GR) log is expanded in the center of the figure. The surface gamma-ray profile of Lequire road cut, plotted at the same vertical scale as the expanded subsurface gamma-ray profile, is shown on the right. The log signature of the upper Savanna sandstone interval in the Gose No. 1 well correlates well with the surface gamma-ray profile of the Lequire outcrop, and the subsurface interval is interpreted as delta-plain strata. Res = resistivity; Cond. = conductivity.

gamma-ray profile with the subsurface gamma-ray log of the Gose well, we interpret the sandstone and shale interval within the Gose well to be a mid- to lower-delta-plain sequence composed of crevasse-splay sandstones, interdistributary-bay fill, and swamp and/or marsh deposits. The strata beneath the correlated interval of delta-plain deposits probably are marine (delta-fringe or prodelta) deposits and those above the interval probably are more delta-plain sediments.

CONCLUSION

By examining surface outcrops, measuring their gamma-ray profile, and correlating that profile with the gamma-ray track on wireline logs, the depositional environment of subsurface strata can be interpreted more accurately. Our study of the Lequire road cut and comparison with a nearby wireline log confirm that mid- to lower-delta-plain sediments have a distinctive log character. Interbedded fine-grained shale and siltstone (interdistributary bay-fill), coal (marshes and swamps), and coarser-grained sandstone (crevasse-splays) results in a very irregular gamma-ray profile. As recorded on the outcrop and in the Gose well, surface and subsurface logs show that the sandstone-dominated units commonly have sharp bases and, in some cases, fine upward. This character contrasts sharply with that of delta-front deposits such as those described in most of the Hartshorne Formation by Andrews and Suneson (1999).

ACKNOWLEDGMENTS

We would like to thank Faye Simms (Northwestern State University) for identifying the ostracodes in unit 1 for us. Rick Lupia (University of Oklahoma) identified the flora throughout the section. Roger Slatt (University of Oklahoma) kindly reviewed the manuscript and made many very helpful suggestions. The paper was greatly improved as a result of his efforts. We also thank Frances Young and Christie Cooper, OGS editorial staff, for carefully reading the paper, editing it, and making welcome improvements.

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