PS Geological Characterization of the Upper Mississippian Fayetteville Shale in Northern and Eastern Arkoma Basin, and Mississippi Embayment Regions, Arkansas*

Carlos Ceron[1] and Roger Slatt[1]

Search and Discovery Article #10376 (2011)
Posted November 30, 2011

*Adapted from poster presentation at AAPG Mid-Continent Section meeting, Oklahoma City, Oklahoma, October 1-4, 2011

[1]Institute of Reservoir Characterization, School of Geology and Geophysics, University of Oklahoma, Norman, Oklahoma (ceroncr@ou.edu)

Abstract

The Upper Mississippian (Chesterian) Fayetteville Shale is the main source of natural gas production in the Arkoma Basin, Arkansas. The most productive area is located in central and northern Arkansas, in a region with a general east-west orientation, limited to the south by the Frontal Ouachita Thrust Belt, and to the east by the Mississippi Embayment. As of February 2010, the cumulative production of the Fayetteville Shale totaled approximately 900 Bcf. However, there is little to no commercial gas production from the Fayetteville Shale in the west-central portion of the Arkoma Basin (Li et al., 2010). The purpose of this study is to establish a correlation between surface data obtained in outcrops of Upper and Lower Fayetteville Formation in Searcy and Stone counties in northern Arkansas, with subsurface data obtained from wells located in the Embayment, and to differentiate the geological and geochemical settings that cause unequal gas production in this region.

To achieve this goal we have rock samples for thin sections and geochemical analysis from both locations, well log data, and outcrop data including hand samples, gamma ray scintillometer profiles and outcrop descriptions. Nine lithological facies have been described in the field which show vertical variations related with gamma ray response and physical features in outcrops. High contents in TOC have been obtained from samples of Upper and Lower Fayetteville. According to XRD analysis results, the most common clay is illite. From thin sections analysis, several features have been identified which will be useful for environmental and lithological interpretations.

GEOLOGICAL CHARACTERIZATION OF THE UPPER MISSISSIPPIAN FAYETTEVILLE SHALE IN NORTHERN AND EASTERN ARKOMA BASIN, AND MISSISSIPPI EMBAYMENT REGION, ARKANSAS

Carlos Ceron and Roger Slatt
Institute of Reservoir Characterization
ConocoPhillips School of Geology and Geophysics, University of Oklahoma, Norman, Oklahoma

1-. Abstract

The Fayetteville Shale was analyzed and correlated between outcrops in north-central Arkoma Basin with subsurface data from the east Arkoma Basin and Mississippi Embayment areas. Outcrop locations included Searcy and Stone counties in north Arkansas. Wells were located in the east Arkoma Basin and Mississippi Embayment area.

The Fayetteville Shale in this area contains eight major lithofacies due to variations in depositional setting. These facies are laminated black shale, black shale with some concretionary elliptical septarian limestones, dark gray shale, phosphatic dark gray shale, gray shale interbedded with dark gray limestones, cherty limestones and chert nodules at the top. Parallel lamination, planar to slightly undulatory bedding, cross bedded stratification, hummocky cross stratification, ripples and climbing ripples are the most common sedimentary structures; trace fossils include *Teichichnus, Planolites* and possibly *Skolithos*.

High amounts of pyrite as framboids or crystals indicate that the Fayetteville Shale was deposited under anoxic conditions and restricted water circulation as a Transgressive System Tract (TST). Organic matter sometimes is poorly preserved in flaky shapes, showing some partial or full chert replacement.

Organic matter (TOC) for outcrop samples is mature and kerogen is Type III (Gas Prone) and Type II/III (Oil and Gas Prone). Some samples correspond to Dry Gas. In the other hand, samples from wells show that dominant kerogen is Type III but with a low Oxygen Index perhaps due to diagenetic conditions from which all gas was generated or overcooked. Comparisons between facies and TOC distribution show that facies affect the oil or gas generation in north-central Arkoma Basin.

2-. Objective and Scope

The main objective of this research is to analyze and correlate the geological characteristics among outcrops in north central Arkoma Basin with subsurface data from east Arkoma Basin and Mississippi Embayment, to establish the differences in geological settings that affected gas generation in both locations.

Specific objectives include:

- Lithofacies descriptions of samples from outcrops and subsurface sidewall cores.
- Integrate these results with geochemical data to interpretate which facies are prone to produce gas and which facies are not able to and why.
- Compare and integrate these results with other studies for the Fayetteville Shale if possible.

3-. Background

Handford (1986), established a model for facies and bedding sequences for the Fayetteville Shale and Pitkin Limestone in Arkansas; the Upper Fayetteville Shale and Lower Pitkin Limestone correspond to storm deposits on a shelf that sloped southward at 0.08 to 0.14°. Water depth 30 km from the paleoshoreline was estimated to be 40 to 70 m. The paleolatitudinal position of northern Arkansas (5-15°S) indicates that strong tropical storms or hurricanes, rather than intense winter storms, were responsible for eroding carbonate sediments from lower-shoreface environments and depositing them as much as 30 km offshore on the muddy shelf (Hanford, 1986).

Sutherland (1988) established the Late Mississippian and Pennsylvanian depositional history of the Arkoma Basin area in Oklahoma and Arkansas, describing the Arkoma Basin as part of a broad, stable shelf along a passive margin during much of its history. During the Chesterian (Fayetteville Shale time), Morrowan, and early Atokan times, the depositional patterns on the shelf varied greatly, depending on the inconsistent development of carbonate environments and the intermittent introduction of terrigenous clastics (quartz arenites) from the north. Mississipian Chesterian Series consists of interbedded shallow-marine limestones and shales that rarely exceed 200 meters in thickness (Sutherland, 1988).

Ratchford and Bridges (2006) characterized the geochemistry and thermal maturity of the Fayetteville Shale in the eastern Arkoma Basin and Mississippi Embayment regions of Arkansas. According to the authors, the middle to lower stratigraphic section of the Fayetteville Shale is an organic-rich, black and pyritic shale, with subordinate amounts of interbedded, siliceous chert and siltstone. The most-prolific gas production from the Fayetteville Shale is associated with horizontal wells that have been completed with multi-stage fracs in the middle to lower portions of the formation. Statistical interpolation and superposition of various aspects of the geochemical data yielded important information pertaining to the identification of prospective areas for natural gas exploration in Arkansas (Ratchford and Bridges, 2006).

Since 2008, the Fayetteville Shale has been considered as one of the Top 10 gas reservoirs in the U.S. According to the Energy Information Administration (EIA) website, is one of the most important gas reservoirs in the United States.

According to Arkansas Geological Commission, the Fayetteville Shale is the current focus of a regional shale-gas exploration and development program within the eastern Arkoma Basin of Arkansas. Approximately 2.5 million acres have been leased in the Fayetteville Shale gas play with a cumulative production of 350.2 BCF since drilling began in 2004.

4-. Regional Setting

4.1-. Arkoma Basin Regional Geology

The Arkoma Basin is an arcuate structural feature that extends from the Gulf coast plain in central Arkansas westward 400 km to the Arbuckle Mountains in south-central Oklahoma (Figure 1). It ranges from 32 to 80 km wide. It is bounded on the north and northwest by the Ozark uplift and the Northeast Oklahoma Platform. Its southern margin is marked in Oklahoma by the Choctaw fault and in Arkansas by the Ross Creek fault, both of which define the cratonward margin of the Ouachita fold belt (Sutherland, P. K., 1988).

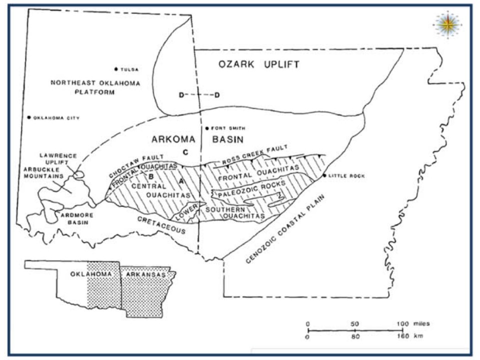


Figure 1. Arkoma basin of Oklahoma and Arkansas, and surrounding geologic provinces. Ouachita Mountains are indicated by diagonal lines. From Sutherland, P. K. 1988

The Arkoma basin was a depositionally part of a stable shelf (Arkoma shelf) along a passive continental margin during much of its history. Deep water deposits accumulated in the basin south of the shelf. In Cambrian to Early Mississippian time a thick sequence of mostly shallow-water black shales and cherts accumulated in the basin. Conditions changed dramatically in middle Mississippian time with the beginning of deposition of thick turbidites (Stanley Group) in the basin (Ouachita trough), but there was no significant change in depositional pattern on the shelf to the north except for the intermittent introduction of terrigenous clastics from the northeast. Turbidites were fed longitudinally into the deepening and narrowing Ouachita trough (Graham and others, 1975 cited by Sutherland, P. K., 1988) (Figures 2 and 3).

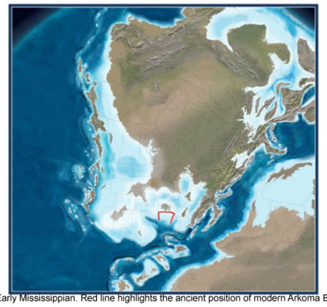


Figure 2. Palaeomap of Early Mississippian. Red line highlights the ancient position of modern Arkoma Basin. Modified from Blakey. R., 2011

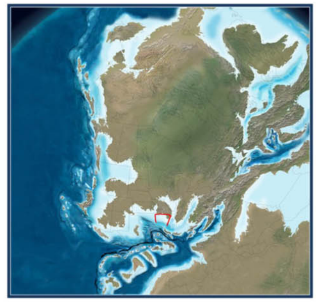


Figure 3. Palaeomap of Late Mississippian. Red line highlights the ancient position of modern Arkoma Basin. Modified from Blakey. R., 2011

4.2-. Geology of the Reelfoot Rift Region

The geologic history of the Reelfoot rift region is poorly understood because the basement rocks are largely buried beneath Phanerozoic sediments, including Mississippi River alluvium (Csontos, R. et al. 2008) (Figure 4). The Reelfoot rift is part of the Reelfoot rift– Rough Creek graben–Rome trough intracratonic rift zone that formed during the disassembly of Rhodinia and opening of the Iapetus Ocean (Thomas, 1976, 1983, 2006 cited by Csontos, R. et al. 2008). Several authors have proposed that the Reelfoot rift may have formed along the boundary between adjacent Precambrian terranes beneath the Eastern Granite Rhyolite Province (Kane et al., 1981; Hildenbrand, 1985; Hendricks, 1988; Nelson and Zhang, 1991; Dart and Swolfs, 1998 cited by Csontos, R. et al. 2008).

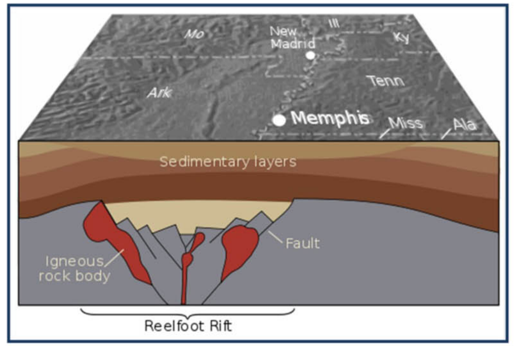


Figure 4. Reelfoot Rift, Mississippi Embayment, east Arkansas. From Smith, R.M, 1989

Initiation of Reelfoot rifting may have been due to mantle plume upwelling that occurred along terrane boundaries (Dart and Swolfs, 1998 cited by Csontos, R. et al. 2008). Alternatively, the Reelfoot rift may be a consequence of right-lateral strike-slip motion along a northwest-oriented transform fault that formed the Paleozoic continental margin of southeastern Laurentia (Thomas, 1985, 1991 cited by Csontos, R. et al. 2008).

During rifting the Reelfoot graben accumulated a maximum of 7 km of sediment, while outside the rift only 1.5 km of contemporary sediments accumulated (Howe and Thompson, 1984; Howe, 1985 cited by Csontos, R. et al. 2008). Howe and Thompson (1984) cited by Csontos, R. et al. 2008, suggested that faulting occurred syndepositionally within and along the Rift margins up to Middle Cambrian time.

From Middle Ordovician to Pennsylvanian time, subsidence and uplift alternated due to distal effects of the Taconic, Acadian, and Alleghanian orogenies (Howe, 1985 cited by Csontos, R. et al. 2008). Structural reactivation within the Reelfoot rift began during the late Paleozoic with the assembly of Pangaea (Thomas, 1985; Howe, 1985 cited by Csontos, R. et al. 2008). Middle Ordovician to mid-Cretaceous rocks are largely missing above the rift, partly due to nondeposition (Permian–Late Cretaceous) and partly due to late Paleozoic and/or mid-Cretaceous uplift and erosion, which produced a major unconformity at the top of the Paleozoic section. Many normal faults within the central United States were inverted during the Paleozoic collisional processes (Howe and Thompson, 1984; Howe, 1985; Marshak and Paulsen, 1996 cited by Csontos, R. et al. 2008).

4.3-. Regional Stratigraphy

The regional stratigraphy for the Arkoma Basin is defined for a rock succession with ages from the Cambrian to Pennsylvanian, as is shown in figure 5. Fayetteville Shale was deposited over the Hindsville Limestone and Batesville Sandstone (Lower Chesterian), and is overlain by the Pitkin Limestone (Upper Chesterian).

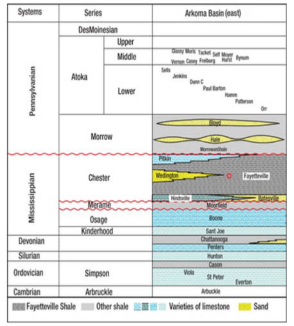


Figure 5. Stratigraphic Column for the Arkoma Basin (From Limerick et al., 2008)

5-. Location of Study Area

The area selected for this research is located in the Fayetteville Shale outcrop belt in Searcy and Stone counties, north Arkansas. Four locations were selected because of the good quality outcrops for the Fayetteville Shale. They are located in the Ozarks foothills in a general east-west trend outcrop belt. Some of the best exposures are along the road cuts, such as Highway 65 north near Marshall and Highway 66 between Oxley and Alco; some others are in county roads or private lands, such as Granny Mountain in a gravel pit for the Lower Fayetteville Shale, located along the County Road 274 south of Snowball, and Campbell Road Cut along the County Road 73 near Oxley; two continuous outcrops along the Highway 65 North near Marshall; and along the Highway 66 between Oxley and Alco, these last three locations show excellent exposures of the lower and upper Fayetteville Shale. Besides these locations, three wells, located in White and Woodruff counties of east Arkansas and Mississippi Embayment were selected to compare the geological settings in these areas (Figures 6 and 7). The distance from Granny Mountain to Marshall is about 11.5 miles; from Marshall to Campbell Road is 8 miles; from Campbell Road to Alco is 5 miles; from Alco to White County well location is 52 miles; and from this point to Woodruff County well location is 31 miles. The total distance between extreme points, Granny Mountain and Woodruff County well, is around 100 miles.

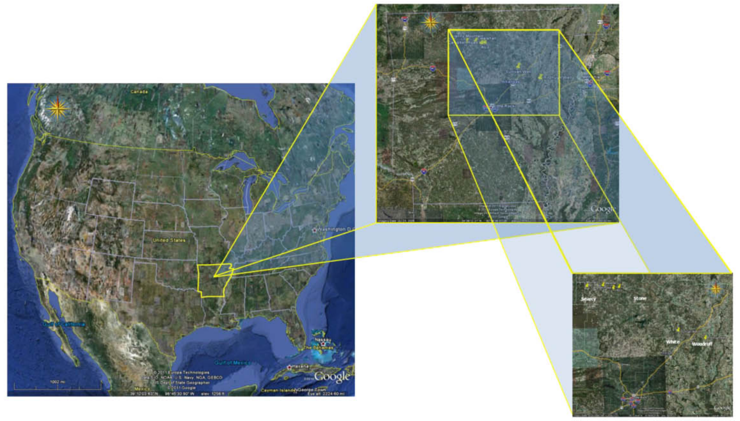


Figure 6. Location of the study area, showing outcrops and well locations . Images modified from Google Earth, 2011

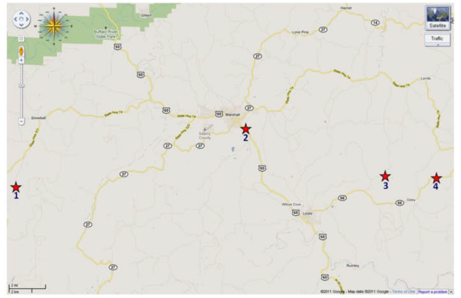


Figure 7. Location of outcrops. Image modified from Google Maps, 2011

6-. Data Available

To pursue the objectives of this research, I have the following information as is shown in Table 1.

Table 1. Available Data

OUTCROPS	**Five outcrops: Granny Mountain, Marshall (2), Campbell Road Cut and Alco, located in the Fayetteville Shale outcrop belt, north Arkansas.**
WELLS	**3 wells from the Mississippi Embayment region, east Arkansas.**
LOGS	**Scintillometer Gamma Ray logs from outcrops. Wireline Gamma Ray and Resistivity logs from wells.**
THIN SECTIONS	**62 thins sections: 27 from sidewall well cores. 35 from field hand samples.**
XRD and SEM ANALYSIS	**Each selected sample for thin section has XRD analysis. SEM from some sidewall cores.**
GEOCHEMICAL ANALYSIS	**Each selected sample for thin section and XRD has geochemical analysis.**

7-. WorkPlan

Field work was conducted from Summer and Fall 2010 to Spring 2011. Four locations were selected for outcrops descriptions and measurements: Granny Mountain near Snowball, Marshall and Campbell Road Cut. All of them are located in Searcy County and Alco in Stone County.

To complete the field descriptions, such as, lithology, bedding characteristics, thicknesses, and sedimentary structures among other significant rock features, four composite stratigraphic sections was measured for the Fayetteville Shale.

Field work consisted of detailed description and measuring with tape measure and hand-held scintillometr, taking samples for further analysis such as XRD and geochemical (Rock-Eval and Thermal Maturity) analysis, and petrography (thin sections) for each one. From wells samples the same analyses were made as well.

On each outcrop face, a GR log was run using a hand-held scintillometer with measures of counts per second (cps) taken each foot, or less when necessary, according to vertical changes in lithology.

For each selected sample from outcrops and side wall cores, 62 thin sections were prepared and analyzed using a petrographic microscope, which allowed characterizing some of the microscopic features for the Fayetteville Shale.

GEOLOGICAL CHARACTERIZATION OF THE UPPER MISSISSIPPIAN FAYETTEVILLE SHALE IN NORTHERN AND EASTERN ARKOMA BASIN, AND MISSISSIPPI EMBAYMENT REGION, ARKANSAS

Carlos R. Ceron and Roger Slatt
Institute of Reservoir Characterization
ConocoPhillips School of Geology and Geophysics, University of Oklahoma, Norman, Oklahoma

8-. Field Work

The Fayetteville Shale crops out in north Arkansas in the Ozarks foothills in a general east-west trend outcrop belt. The predominant lithology of the Fayetteville Shale is dark gray to black, fissile, carbonaceous clay shale. The shale is present across the entire area of Northern Arkansas, where it is most typical of the lower half of the formation. The character is quite uniform over most of the area, commonly weathering to dark gray or black flakes or irregular, thin plates (Ogren, D. E., 1961).

Some of the best exposures are along the road cuts, such as Highway 65 North near Marshall and Highway 66 between Oxley and Alco; some others are in county roads or private lands, such as Granny Mountain, located in a gravel pit along the County Road 274 south of Snowball, and Campbell Road Cut along the County Road 73 near Oxley (Figures 8, 9, 10, 11).

These four locations, were selected to describe the main field characteristics for the Fayetteville Shale outcrops in north Arkansas, taking measurements with measuring tape and hand-held gamma ray scintillometer in outcrop faces, and sampling for further analysis such as XRD, geochemical analysis (Rock Eval and Thermal Maturity) and thin sections.

In general these outcrops are composed by a rhythmical succession of black to dark gray shales interbedded with limestones, some horizons of black shales, phosphatic shale, cherty limestones with thin interbedded shales, limestones, and limestones with interbedded shales. Some of the sedimentary structures identified are: parallel bedding and lamination, hummocky cross stratification, ripples and some bioturbations as *Teichichnus, Planolites* and possibly *Skolithos*.

Even though fracture analyses and characterization was not considered in this research, the fracture pattern observed in outcrops is mainly vertical to sub-vertical going through the entire section from base to top having the overlying Pitkin Limestone as a natural fracture barrier in this area.

Lower Fayetteville Shale, Granny Mountain, Snowball area, Arkansas

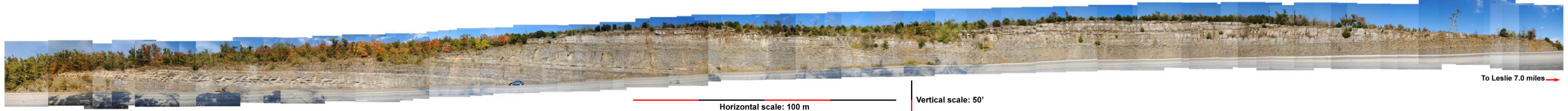
Horizontal scale: 50 m
Vertical scale: 20'

Figure 8. Lower Fayetteville Shale outcrop located in Granny Mountain, near Snowball, Searcy County, Arkansas.

Upper Fayetteville Shale, Outcrop 1, Marshall, Arkansas

To Leslie 6.5 miles
Horizontal scale: 100 m
Vertical scale: 50'
To Marshall ~0.7 miles

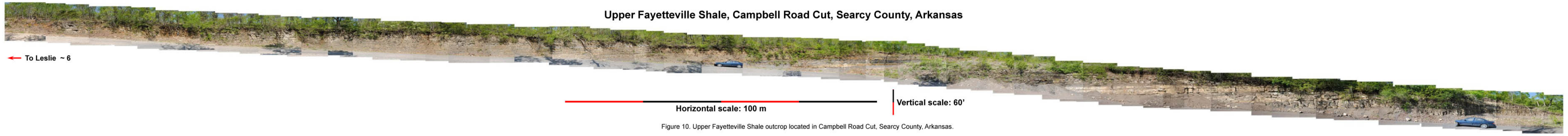
Upper Fayetteville Shale, Outcrop 2, Marshall, Arkansas



To Leslie 7.0 miles
To Marshall 0.5 miles
Horizontal scale: 100 m
Vertical scale: 50'

Figure 9. Upper Fayetteville Shale outcrops located in Highway 65 North near Marshall, Searcy County, Arkansas.

Upper Fayetteville Shale, Campbell Road Cut, Searcy County, Arkansas



To Leslie ~ 6
Horizontal scale: 100 m
Vertical scale: 60'

Figure 10. Upper Fayetteville Shale outcrop located in Campbell Road Cut, Searcy County, Arkansas.

Upper Fayetteville Shale, Alco, Highway 66, Stone County, Arkansas

To Alco ~ 3.5
Horizontal scale: 25 m
Vertical scale: 30'
To Leslie ~10.5

Figure 11. Upper Fayetteville Shale outcrop located in Highway 66 near Alco, Stone County, Arkansas.

9-. Facies Descriptions

Eight major lithofacies have been identified in the field, which show the vertical variation and changes in depositional settings of the Fayetteville Shale in the Arkoma Basin of north Arkansas.

Facies 1: Laminated black shales: Finely laminated, fissile black shales, which weather tan colors (Figure 12).

Facies 2: Laminated dark gray to black shale, with elliptical concretionary and septarian limestones: Dark gray to black laminated shales with elliptical concretionary and septarian limestones (Figure 13).

Facies 3: Slightly laminated fissile gray shale: Dark gray to gray slightly laminated hard shales, sometimes calcareous (Figure 14).

Facies 4: Phosphatic laminated dark gray shale: Dark gray finely laminated hard phosphatic shales (Figure 15).

Facies 5: Laminated gray shale interbedded with limestones: Gray laminated shales interbedded with hard limestones (Figure 16).

Facies 6: Limestones (L): Hard limestones with variable thickness laterally extended along the outcrops, with wavy or flat bedding shapes (Figure 17).

Facies 6a: Limestone with parallel lamination (LPL): Limestones with parallel laminations. Some bioturbations such as *Planolites* and *Cruzianas* can be observed at different levels (Figure 18).

Facies 6b: Limestone with cross bedding lamination (LXL): Limestones with cross bedding laminations and ripples marks. Some bioturbations such as *Planolites* and *Cruzianas* can be observed at different levels (Figure 19).

Facies 6c: Limestone with hummocky cross-stratification (LHCS): Limestones with hummocky cross-stratification, ripples and climbing ripples. Some bioturbations such as *Planolites, Cruzianas* and possible *Skolithos* can be observed at different levels (Figure 20).

Facies 6d: Fossiliferous Limestone (FL): Fossils rich limestone, some identified fossils are brachiopods, pelecypods, and shell fragments in general (Figure 21).

Facies 7: Cherty Limestone with interbedded shale (ChLS): Cherty limestones or limestones with chert nodules and thin interbedded shales (Figure 22).

Facies 8: Couplets of Chert or Cherty Limestone – Limestone - Chert or Cherty Limestone (ChL): Couplets of chert or cherty limestone – limestone – chert or cherty limestone rhythmically interbedded (Figure 23).

Figure 12. Facies1: Laminated black, fissile shale.

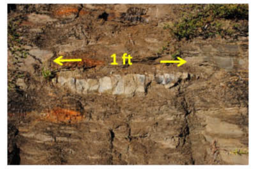


Figure 13. Facies 2: Laminated black shale, with elliptical concretionary and septarian limestones.

Figure 14. Facies 3: Slightly laminated, fissile gray shale.

Figure 15. Facies 4: Phosphatic laminated dark gray shale.

Figure 16. Facies 5: Laminated gray shale interbedded with limestones.

Figure 17. Facies 6: Limestones.

Figure 18. Facies 6a: Limestone with parallel laminations (LPL).

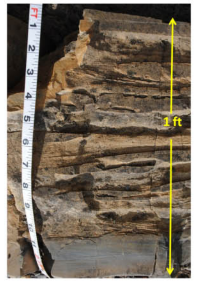


Figure 19. Facies 6b: Limestone with cross-bedding laminations (LXL).

Figure 20. Facies 6c: Limestone with hummocky cross-stratification (LXL).

Figure 21. Facies 6d: Fossiliferous (FL).

Figure 22. Facies 7: Cherty limestones.

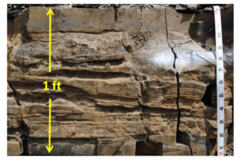


Figure 23. Facies 8: Couplets of chert or cherty limestone—limestone– chert or cherty limestone.

GEOLOGICAL CHARACTERIZATION OF THE UPPER MISSISSIPPIAN FAYETTEVILLE SHALE IN NORTHERN AND EASTERN ARKOMA BASIN, AND MISSISSIPPI EMBAYMENT REGION, ARKANSAS

Carlos R. Ceron and Roger Slatt
Institute of Reservoir Characterization
ConocoPhillips School of Geology and Geophysics, University of Oklahoma, Norman, Oklahoma

10-. Facies Distribution

The Fayetteville Shale in north-central Arkoma Basin, shows important vertical variability, which goes from black laminated shale (F1) in the Granny Mountain outcrop, to facies 2, 3, 4 and 6 in the Marshall Outcrop, while Campbell Road Cut shows shale facies at the bottom (F1), and an increase of limestone and cherty facies (F5, F6, F7, F8) toward the middle and top. Alco outcrop shows more cherty limestone (F7 and F8) facies than any of the others outcrops. Some hard ground and scour surfaces were observed in the middle section of the Campbell Road Cut outcrop and near the top in the Alco outcrop, which indicates possible subaerial exposure and stormy conditions during the Upper Fayetteville Shale deposition

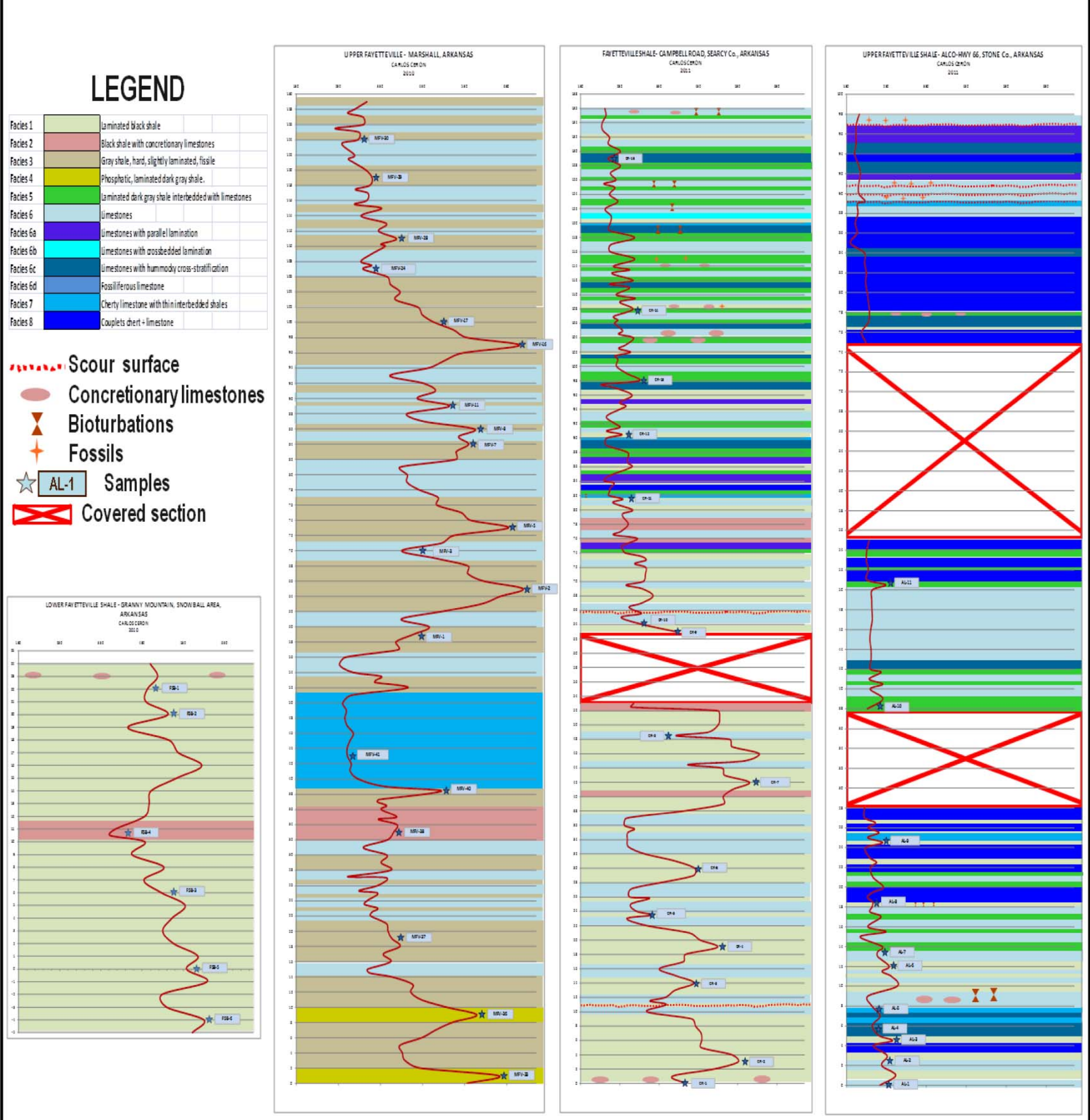


Figure 24. Scintillometer Gamma Ray logs and vertical facies distribution for all described outcrops for the Fayetteville Shale, north-central Arkoma Basin, Arkansas.

11-. Petrographical Descriptions

For each selected sample from outcrops and well side wall cores, 62 thin sections were prepared and analyzed using a petrographic microscope which allowed characterizing some of the microscope features for the Fayetteville Shale, Arkoma Basin. During the description and analysis process several features have been identified, such as brachiopod shell fragments, spores, spicules, intraclasts and conodonts among others, that are very useful during the lithofacies, source and environment interpretation . Figures 25 to 28 show some of the described petrographic features.

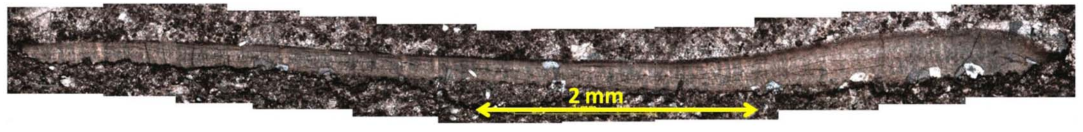


Figure 25. Photo mosaic of a brachiopod shell fragment. Parallel Nichols 10X. Depth: 4465' Well 3.

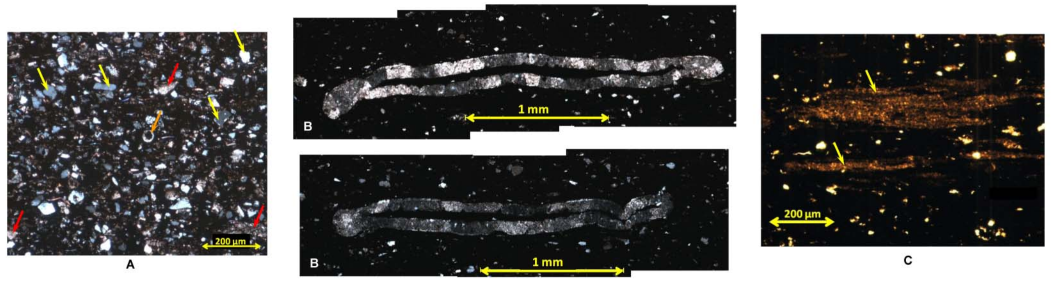


Figure 26. **A)** Quartz grains (yellow arrows), chert (red arrows), spicules (orange arrows) and matrix. Crossed Nichols 10X. Depth: 4037'. Well 1. **B)** Photo mosaics of spores replaced by chert. Parallel Nichols, 10X. Depth: 7025'. Well 2. **C) Well preserved** organic matter (yellow arrows) in dark clay matrix . Parallel Nichols, 10X. Depth: 7175'. Well 2.

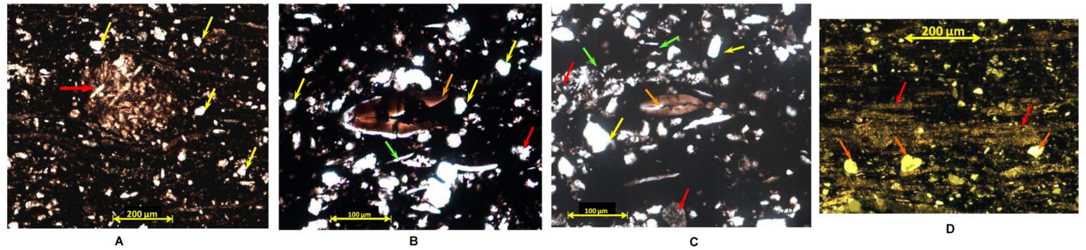


Figure 27. **A)** Intraclast with calcareous material (red arrow) and quartz grains (red arrow) embedded in matrix. Parallel Nichols 10X. Depth: 3837'. Well 3. **B)** and **C)** Conodonts (orange arrow), quartz grains (yellow arrows), chert (red arrow) and spicules (green arrow) embedded in clay matrix. Parallel Nichols 20X. Depth: 4037'. Well 1. D) Organic matter partially replaced by chert (red arrows) and quartz grains. Parallel Nichols, 10X. Depth 7175. Well 2.

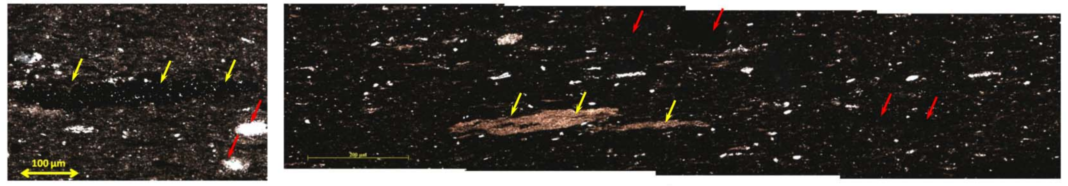


Figure 28. **A)** Framboidal pyrite (yellow arrows), pellets (yellow arrows). Parallel Nichols 10X. Depth: 3135'. Well 1. **B)** Photo mosaic of laminated organic matter (yellow arrow), framboidal pyrite (red arrow) embedded in dark clay matrix. Parallel Nichols 10X. Depth: 3320'. Well 1.

12-. Geochemical Analysis

A set of 36 samples from outcrops were selected for geochemical analysis (Rock-Eval and Thermal Maturity) to evaluate type of kerogen and thermal maturity. Results show that kerogen type for most of the samples is Type III: Gas Prone, with variable content of organic matter (TOC) which ranges from 2.6 to 13.1 %wt (average 6.35 %wt). In the other hand, results from samples of wells located in east Arkoma Basin and Mississippi Embayment show kerogen Type III: Gas Prone, but with a very low remaining hydrocarbon potential, which means that all gas has already been generated or expelled from the rock. These results are summarized in figure 29 A and B, and Table 2 (A and B).

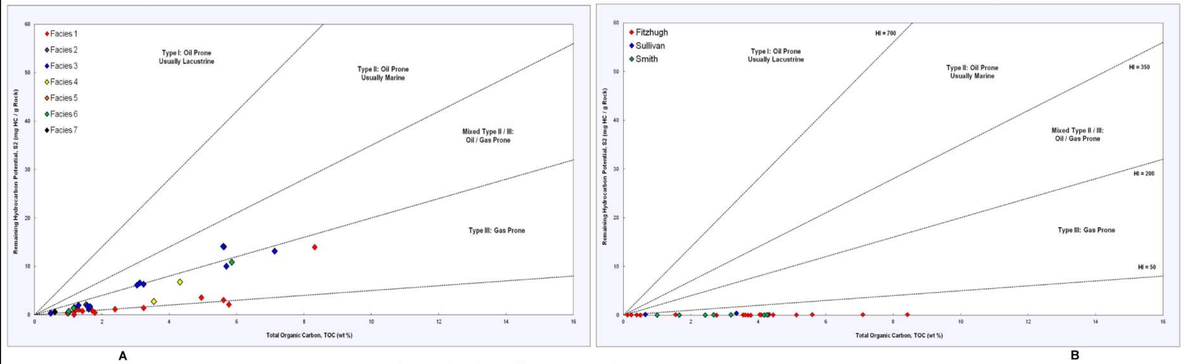


Figure 29. Kerogen Quality Plot for A) Outcrops facies, and B) Wells from east Arkoma Basin and Mississippi Embayment.

Table 2. Summarized results for A) Outcrops facies, and B) Wells from east Arkoma Basin and Mississippi Embayment.

A

Project / Sample ID	Rock ID	Upper Depth (ft)	Median Depth (ft)	Percent Carbonate (wt%)	Leco TOC (wt% HC)	Rock-Eval S1 (mg HC/g)	Rock-Eval S2 (mg HC/g)	Rock-Eval S3 (mg CO2/g)	Tmax (°C)	Calculated %Ro (RE-TMAX)	Hydrogen Index (S2x100/TOC)	Oxygen Index (S3x100/TOC)	S2/S3 Conc. (mg HC/mg CO2)	S1/TOC Norm. Oil Content	Production Index (S1/(S1+S2))
Facies 1	FSB-1	1.00	1.00	7.16	5.77	0.25	2.15	1.16	443		37	20	2	4	0
	FSB-3	2.00	2.00	7.83	5.61	1.11	3.08	0.59	444		55	11	5	20	0.26
	FSB-5	3.00	3.00	24.15	8.32	3.79	13.90	0.31	439		168	4	45	46	0.21
	FSB-6	4.00	4.00	7.37	1.17	0.02	0.04	0.30	0		3	26	0	2	0.33
	CR-1	5.00	5.00	7.13	4.95	0.33	3.59	1.19	441	0.78	73	24	3	7	0.08
	CR-2	6.00	6.00	12.46	3.24	0.15	1.41	0.91	441	0.78	44	28	2	5	0.10
	CR-4	7.00	7.00	31.31	1.71	0.28	0.92	0.54	438	0.72	54	32	2	16	0.23
	CR-6	8.00	8.00	32.41	1.79	0.09	0.46	0.77	435	0.67	26	43	1	5	0.16
	CR-7	9.00	9.00	32.43	2.39	0.15	1.15	0.87	438	0.72	48	36	1	6	0.12
	CR-8	10.00	10.00	34.30	1.42	0.28	0.75	0.42	428	0.54	53	30	2	20	0.27
	CR-12	11.00	11.00	32.52	0.97	0.19	0.40	0.27	451	0.96	41	28	1	20	0.32
	AL-3	1.00	12.00	32.65	1.17	0.18	0.59	0.34	448	0.90	50	29	2	15	0.23
	AL-6	2.00	13.00	19.42	1.31	0.40	1.10	0.28	454	1.01	84	21	4	31	0.27
	AL-8	4.00	14.00	30.25	1.27	0.34	1.01	0.18	449	0.92	82	15	6	28	0.25
Facies 2	MFV-38	38.00	1.00	29.56	1.53	1.15	2.07	0.17	455	1.03	135	11	12	75	0.36
Facies 3	MFV-1	1.00	1.00	8.53	1.61	0.54	1.19	0.20	455		74	12	6	34	0.31
	MFV-2	2.00	2.00	14.06	7.13	3.65	13.12	0.33	440		184	5	40	51	0.22
	MFV-5	5.00	3.00	6.59	5.70	2.11	9.99	0.35	442		175	6	29	37	0.17
	MFV-7	7.00	4.00	18.19	3.24	3.58	6.31	0.30	439		195	9	21	110	0.36
	MFV-8	8.00	5.00	44.67	3.13	3.12	6.55	0.33	436		209	11	20	100	0.32
	MFV-11	11.00	6.00	37.07	3.05	3.13	6.13	0.32	442		201	10	19	103	0.34
	MFV-16	16.00	7.00	22.27	5.63	4.11	14.02	0.38	439		249	7	37	73	0.23
	MFV-17	17.00	8.00	14.26	5.60	4.07	14.13	0.32	438		252	6	44	73	0.22
	MFV-28	28.00	9.00	42.47	1.16	0.69	1.34	0.28	455	1.03	116	24	5	59	0.34
	MFV-29	29.00	10.00	37.33	1.18	0.80	1.52	0.29	448	0.90	129	25	5	68	0.34
	MFV-30	30.00	11.00	34.25	1.31	1.10	1.95	0.16	448	0.90	149	12	12	84	0.36
	MFV-37	37.00	12.00	38.64	1.57	1.16	1.91	0.23	454	1.01	122	15	8	74	0.38
	MFV-39	39.00	13.00	78.90	0.48	0.10	0.33	0.16	433	0.63	69	33	2	21	0.23
	MFV-40	40.00	14.00	19.85	1.65	0.82	1.68	0.28	445	0.85	102	17	6	50	0.33
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

B

Formation Name	Upper Depth (ft)	Median Depth (ft)	Percent Carbonate (wt%)	Leco TOC (wt% HC)	Rock-Eval S1 (mg HC/g)	Rock-Eval S2 (mg HC/g)	Rock-Eval S3 (mg CO2/g)	Hydrogen Index (S2x100/TOC)	Oxygen Index (S3x100/TOC)	S2/S3 Conc. (mg HC/mg CO2)	S1/TOC Norm. Oil Content	Production Index (S1/(S1+S2))
Well 1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Well 2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Well 3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Potential (quantity)	TOC (wt.%)
Poor	<0.5
Fair	0.5–1
Good	1–2
Very good	2–4
Excellent	>4

Kerogen (quality)	Hydrogen index (mg hydrocarbon/g TOC)	Main product at peak maturity
I	>600	Oil
II	300–600	Oil
II/III	200–300	Oil/gas
III	50–200	Gas
IV	<50	None

13-. Conclusions

- The Fayetteville Shale in north Arkoma Basin is mainly composed by black laminated shale, gray shale, limestones and mudstones, with some beds of cherty limestones .
- Vertical changes in lithofacies identified in outcrops show environmental changes during deposition from "deeper" to "shallow" shelf.
- The presence of some scour surfaces and hard grounds besides hummocky cross stratification in the upper sequence, are indicatives of some sub-aerial exposure and storm events during Chesterian time while the Upper Fayetteville Shale was being deposited
- The most common bioturbations in the Upper Fayetteville Shale are *Skolithos*, *Planolites* and *Teichichnus*, which are common in shoreface shallow environments.
- TOC range from 2.6 to 13.1 % (average 6.35 %) for outcrops samples, and 0.3 to 9.6 % (average 3.48 %) for wells in the Mississippi Embayment.
- Organic matter (TOC) for outcrops samples is mature and kerogen is Type III (Gas Prone) and Type II/III (Oil and Gas Prone) with some samples corresponding to Dry Gas.
- Samples from wells show that dominant kerogen is Type III but with a low Oxygen Index perhaps due to diagenetic conditions from which all gas was generated or overcooked.
- The most common clays are Illite and Muscovite, while Smectite and Kaolinite are less common but present.
- The presence of Ankerite in samples from the Mississippi Embayment is indicative of an intermediate diagenesis from calcite to dolomite, maybe influenced by tectonically driven hydrothermal fluid circulation. Ankerite exists as a late diagenetic cement or replacement of pre-existing carbonate (Middleton, G. 2003).

14-. Selected References

- Caplan, W. M., 1957, Subsurface Geology of Northwestern Arkansas: Arkansas Geological and Conservation Commission, Information Circular 19.
- Handford, C. R., 1986, Facies and Bedding Sequences in Shelf-Stormed-Deposited Carbonates – Fayetteville Shale and Pitkin Limestone (Mississippian), Arkansas: Journal of Sedimentary Petrology, v. 56, p. 123-137.
- Li, P., Ratchford M. E., Jarvie, D. M., 2010, Geochemistry and Thermal maturity analysis of the Fayetteville Shale and Chattanooga Shale in the western Arkoma Basin of Arkansas: Arkansas Geological Commission, Information Circular 40.
- McFarland, J. D., 2004, Stratigraphic Summary of Arkansas, Arkansas Geological Commission, Information Circular 36.
- Ratchford M. E. and Bridges, L. C., 2006, Geochemistry and Thermal maturity of the Upper Mississippian Fayetteville Shale Formation, eastern Arkoma Basin and Mississippi Embayment regions, Arkansas: Gulf Coast Association of Geological Societies Transactions, v 56, p. 717-722.
- Sutherland, P. K., 1988, Late Mississippian and Pennsylvanian depositional history in the Arkoma Basin area, Oklahoma and Arkansas: Geological Society of America Bulletin v 100, p. 1787-1802.
- United States Energy Information Administration in http://www.eia.doe.gov (accessed July 2010).

15-. Acknowledgements

Dr. Roger Slatt, for his constant support and help during this research.
Dr. Michael "Ed" Ratchford, from the Arkansas Geological Commission for his support in providing data and helping us to get access to find the outcrops through contacts with landowners.
Dr. Paul Philp for his help with the geochemical analysis.
Thanks to all people who have helped me during this project.