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Structural and Stratigraphic Transition from the Arkoma Shelf into the Arkoma Basin during Basin Subsidence; Arkoma Basin, Northwest Arkansas

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by

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ABSTRACT

The Arkoma basin is an arcuate Paleozoic structural feature in the Ouachita foreland that extends from central Arkansas and westward into southeastern Oklahoma. The Arkoma shelf lies immediately north of the basin and is comprised of Cambrian to Pennsylvanian age sedimentary rocks. In northwestern Arkansas, the stratigraphic and structural transition from the shelf into the northern portion of the Arkoma basin is poorly defined.

Wireline logs were used to construct a series of three north to south cross sections, as well as two along-strike west to east cross sections to examine Morrowan and lower Atokan age strata. In addition to cross sections, isopach and structural contour maps were constructed from wireline log correlation. North to south cross sections display thickening to the south, particularly with sandstone and shale units. West to east cross sections exhibit thickening to the east due to proximity to an eastern terrigenous sediment source. Morrow and lower Atoka strata document the initiation of Arkoma basin subsidence during early Pennsylvanian time and reflect an eastern source of terrigenous sediment to the Arkoma shelf.

ACKNOWLEDGEMENTS

I would like to thank Brian Hedrick for helping me get started with Petra and for answering my questions early on in this process. Many thanks go to Dr. Davis and Dr. Dumond for serving on my committee. I would like to thank Dr. Zachry for his encouragement and guidance throughout my time at the University of Arkansas. Special thanks to my family and friends for their unending support, inspiration, and encouragemnt.

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INTRODUCTION

The Arkoma Basin is a peripheral foreland basin associated with the Ouachita orogenic belt, which functions as its southern boundary. The Ozark uplift and the Northeast Oklahoma platform serve as the northern boundary of the basin (Sutherland, 1988). The basin is 20 to 50 miles wide, is bounded to the east by the Gulf Coastal Plain, and extends 250 miles west to the Arbuckle Mountains in Oklahoma. The Arkoma Shelf, immediately north of the basin, is composed of Paleozioc sedimentary rocks ranging from Cambrian to Pennsylvanian in age. The shelf was an important depositional feature during the Chesterian, Morrowan, and early Atokan Epoch (Sutherland, 1988).

The structural and stratigraphic transition from the central portion of the Arkoma Basin to the northern shelf is poorly defined in Arkansas. Previous studies have suggested that the transition involves significant changes in structural style, stratal thickness, and sedimentary facies (Sutherland, 1988). Basin subsidence began in the late Mississippian and early Pennsylvanian in northwestern Arkansas (Zachry, 1983), affecting the Morrow section stratigraphically and structurally. Normal faulting facilitated south to north subsidence in the Morrow section as sedimentation occurred.

Purpose of Investigation

The objective of this study is to document the stratigraphic and structural changes that occurred during basin subsidence and formation in northwestern Arkansas. Timing of these changes in western Arkansas were determined by constructing detailed north to south and east to west structural and stratigraphic cross sections based on wireline logs. Isopach maps and structural contour maps were created to evaluate stratigraphic variations that occur from the shelf into the basin.

Wells were selected from the following: Townships 10N-13N, Ranges 23W-29W in Franklin and Johnson Counties in northwestern Arkansas (Figure 1). These areas define the transition between the Arkoma Shelf, to the north, and the Arkoma Basin to the south.

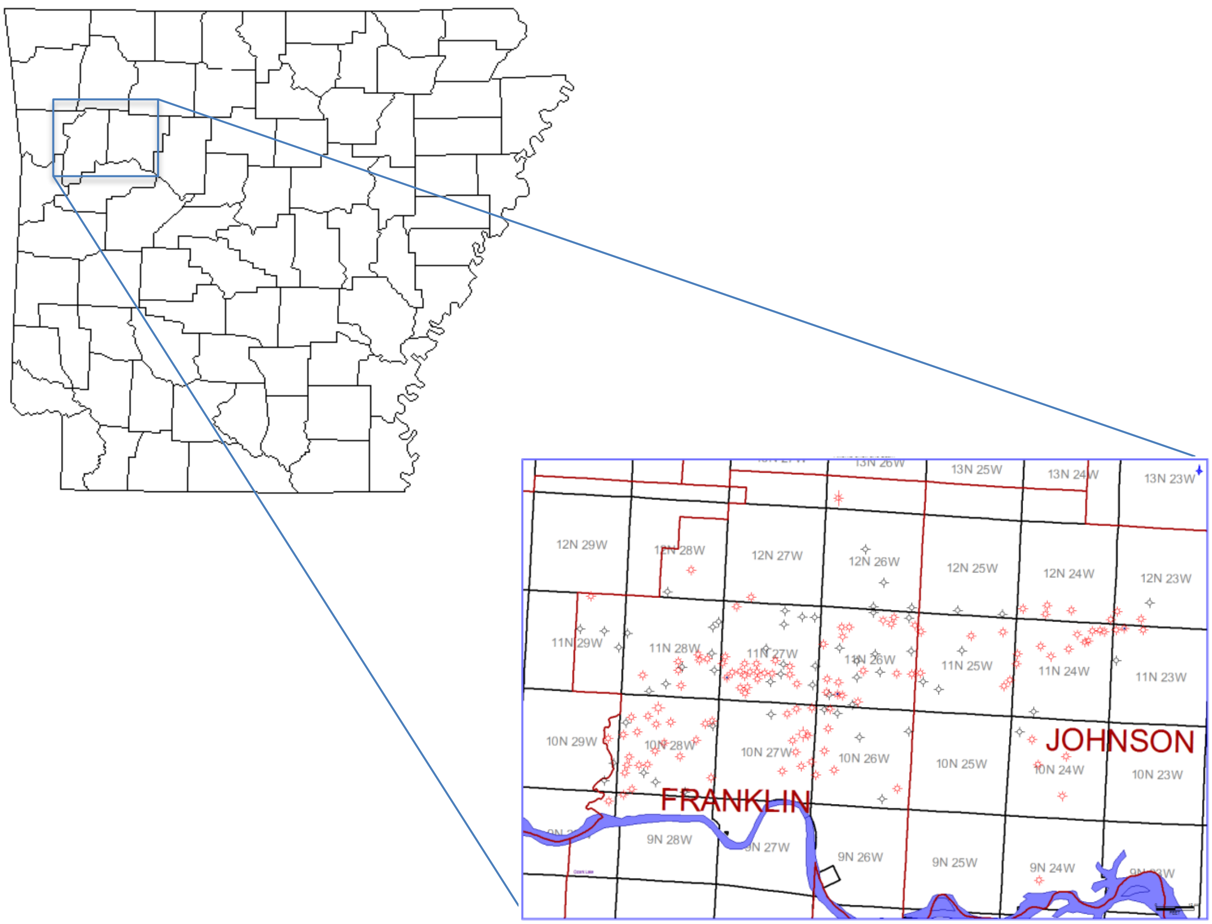

Figure 1. Location map of study area with well locations.

Previous Investigations

Lower Atoka and Morrow strata of the Arkoma Basin in northwestern Arkansas have been examined in numerous publications and theses. Publications include but are not limited to: Houseknecht and Kacena (1983), Houseknecht (1986), Sutherland (1988), Zachry (1983), McGilvery and Houseknecht (2000), and Cardot (2012). Houseknecht described a tectonic model for the Arkoma Basin. Sutherland examined the depositional history of the basin in

Arkansas and Oklahoma. Zachry defined the depositional framework of the Atoka Formation and described the structural evolution of the Atoka in the Arkoma Basin. McGilvery and Houseknecht examined the depositional facies of the lower and middle Atoka. The Oklahoma Geological Survey (Cardot, 2012) has compiled an exhaustive list of all publications through the end of 2012 discussing the Arkoma Basin.

Many theses have examined elements of the northern portion of the Arkoma Basin in Arkansas. Pontiff (2007) studied Morrowan rocks at the surface and subsurface in Franklin, Johnson, and Pope Counties. She determined the stratigraphic position of the middle Bloyd sandstone across the northern part of the basin, as well as the source of sediment from an eastern conduit. Delavan (1985) examined the Morrowan in the subsurface in Pope, Johnson, and Franklin Counties in Arkansas in T8-12N and R20-27W. He concluded that Morrowan strata thicken from the northeast to the southwest.

Methodology

Well data and raster logs were acquired from the Arkansas Oil and Gas Commission and from the Arkansas Geological Survey E-Log Database. Initially, over 1,000 well logs were examined. Approximately 342 wells were selected based on location, log type, appropriate drilling depth, and curve quality (Figure 2). Wells with the Sells, Kessler, and Pitkin were selected for use (Figure 7). Many of the wells in this area have excellent coverage of the Atoka but were not drilled deep enough to penetrate all of the Morrow strata, which is necessary in order to construct accurate cross sections and maps. Data from the Arkoma Quarterly Service disc (Herndon, 2013) were utilized to pick tops and calculate stratal thickness. Stratal thickness was calculated for the lower Atoka in the by subtracting the depth of the top pick for the Kessler from the depth of the top pick of the Sells. Stratal thickness for the Morrow was calculated by subtracking the top pick depth of the Mississippian Pitkin from the Kessler top. Gamma ray and resistivity logs were reviewed and correlated in IHS Petra® to construct a series of north to south and west to east cross sections, as well as isopach and structure maps. Cross section well information is listed in Appendix A.

Twenty-three wells were selected from the initial 342 wells to construct five cross sections across the study area (Figure 3, 4). The Mississippian Pitkin was used as a marker for the base of the Morrow and tops were selected for the purposes of examining the structure of the Morrow and constructing isopach maps. Isopach maps were created with a contour interval of 25 feet. Hot colors represent increasing thickness and cool colors represent thinner thicknesses on the isopach maps. The isopachs for the Morrow (Figure 17) and the lower Atoka (Figure 18) do not have the same coverage area due to the lack of wells that were drilled deep enough to include all Morrow units. Structural contour maps were generated with a contour interval of 100 feet for the maps of the top of the Pitkin, the top of the Morrow, and the top of the lower Atoka. Zero represents sea-level in each of the structural contour maps.

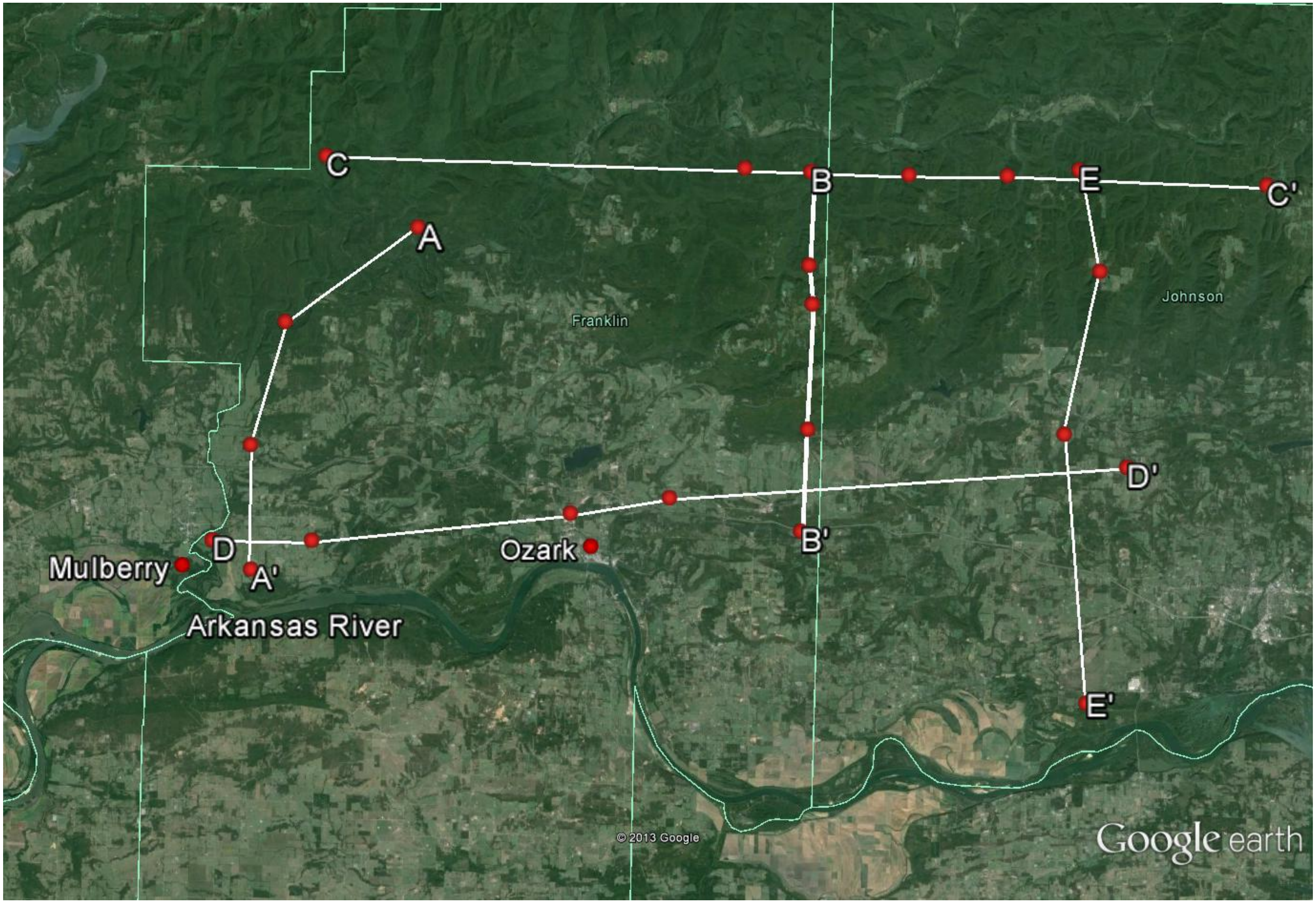

Figure 2. GoogleEarth image of study area with cross section lines A-A’, B-B’, C-C’, D-D’, and E-E’.

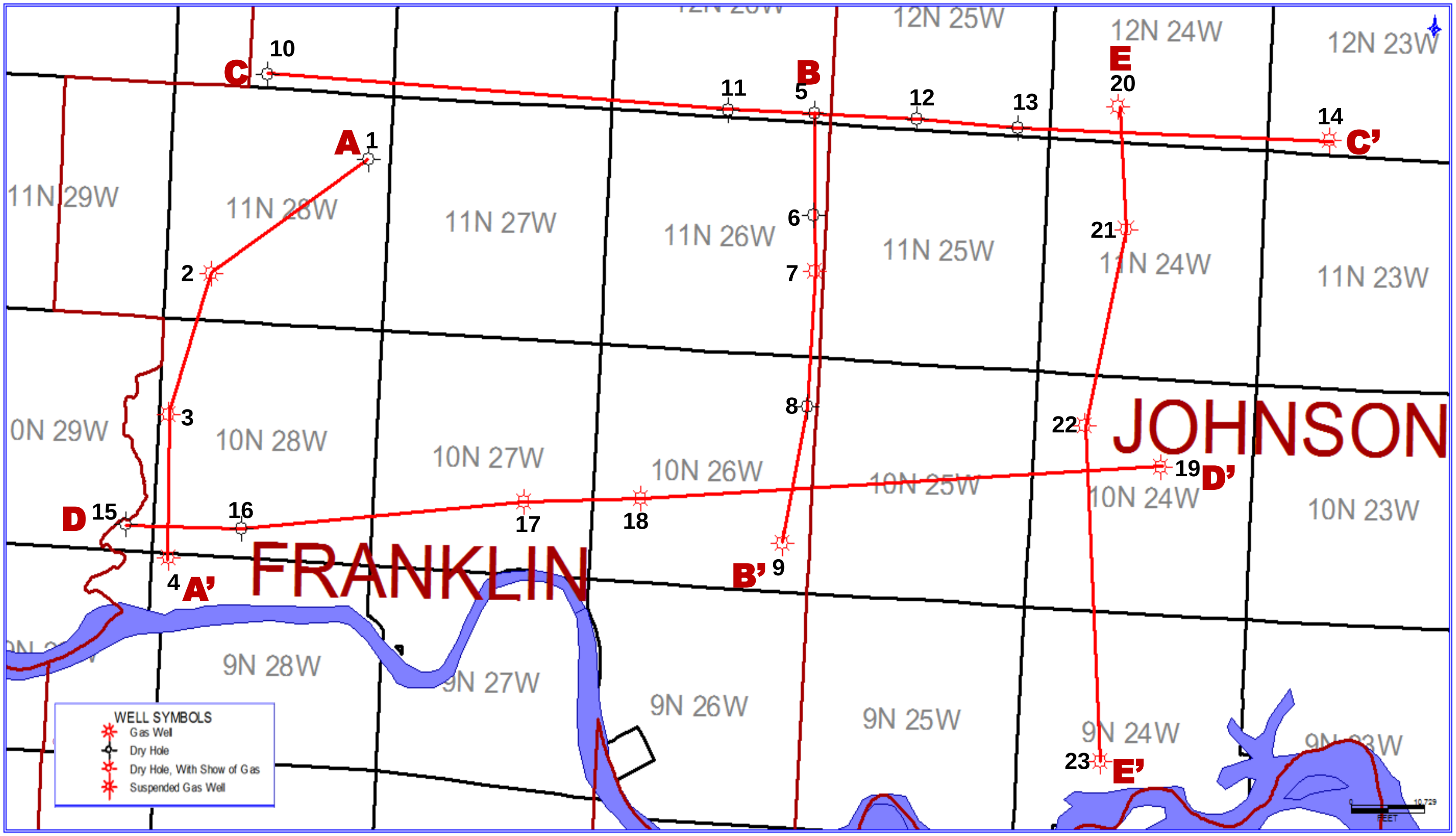

Figure 3. Petra image of study area with cross section lines A-A', B-B', C-C', D-D', and E-E'.

GEOLOGIC SETTING

The regional geology is composed of four provinces including: the Ozark uplift, the Ouachita fold and thrust belt, and the Arkoma Basin. The geologic provinces are illustrated in Figure 4.

The Ozark Dome is a broad asymmetrical structure that includes portions of northwest Arkansas, extreme northeast Oklahoma, and much of southern Missouri. Paleozoic strata dip gently away from the core of the Ozark dome and form a concentric pattern of successively younger strata to the south and southwest (Hanford and Manger, 1990). The dome is divided into three plateau surfaces that extend away from the Precambrian granite core: the Salem – underlain by lower Ordovician dolomites and limestones, the Springfield – underlain by lower Mississippian limestones and cherts, and the Boston Mountains – capped by Atokan strata (Cherry, 2012). The southern margin of the Ozark uplift contains a part of the Arkoma shelf.

The Ouachita fold and thrust belt is the southern boundary of the Arkoma Basin. It is an intensely deformed structure that is characterized by numerous anticlines, synclines, and thrust faults. The Ouachita fold and thrust belt extends at the surface approximately 100 miles from west-central Arkansas to southeast Oklahoma. In Arkansas, the orogen is 50 to 60 miles wide. The northern margin of Ouachitas is defined by the Ross Creek fault in Arkansas and the Choctaw fault in Oklahoma (Sutherland, 1988). The Arkoma is one of several basins that formed in association with the Ouachita orogenic belt.

The Arkoma Basin is an elongate, arcuate structure that formed during the Paleozoic. The basin is a structural low that extends from central Arkansas into Oklahoma (Long, 1997). The Arkoma Shelf is a broad structural platform just north of the basin that is inclined gently to the

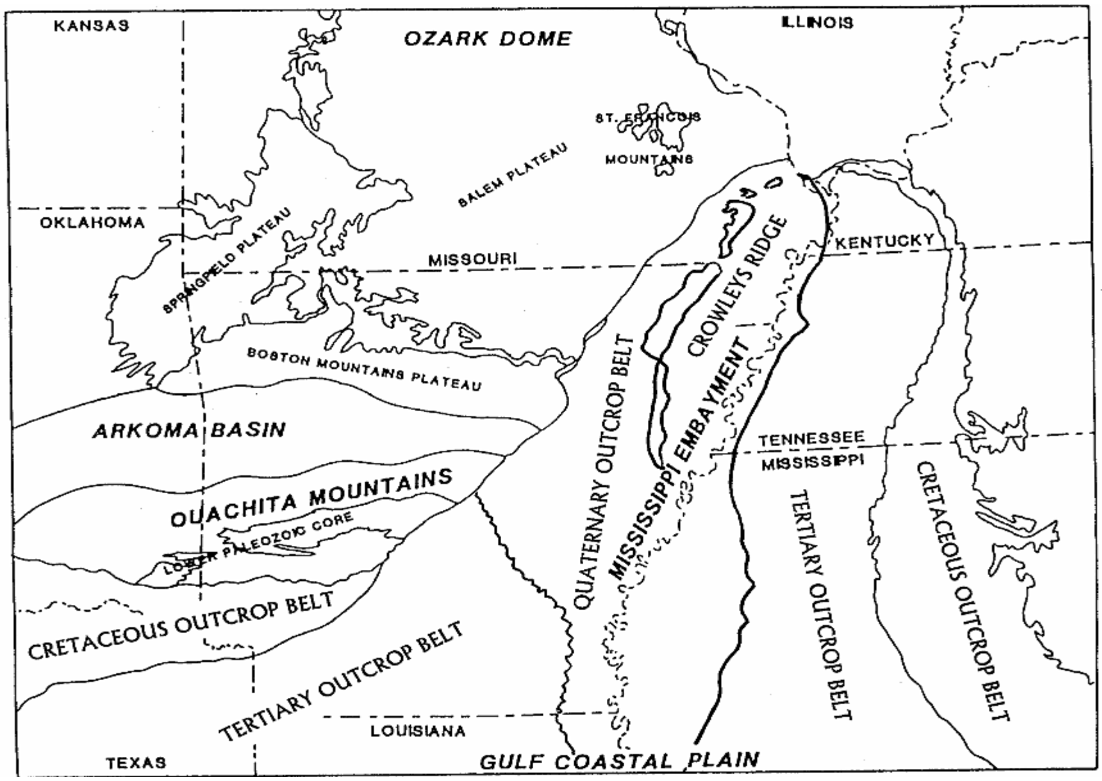

Figure 4. Geologic provinces of Arkansas and surrounding areas. (Manger, Zachry, and Garrigan, 1988)

south. Carbonate rocks replace sandstone and shale in the western part of the basin in Oklahoma. Sand content increases from west to east in Arkansas.

Numerous models have been created to explain the tectonic development of the Ouachitas and the synchronous formation of the Arkoma Basin. Houseknecht (1986) and Houseknecht and Kacena (1983) constructed a widely accepted model for the tectonic development of the Arkoma Basin. During the late Precambrian and through the early Paleozoic, major rifting occurred, opening an ocean basin. Shelf facies accumulated during this time and were dominated by carbonates with quartzose sandstone and shale. By the early Mississippian, the ocean basin began to close as southward subduction began. An accretionary prism formed in association with the subduction zone that would later become the Ouachita orogenic belt. Slow sedimentation occurred during the Mississippian and early Atokan on the southern margin of

North America in shallow marine and non-marine environments. Throughout this time, flysch accumulated in the deep remnant ocean basin. Convergence during the early Atokan facilitated formation of large down to the south growth faults during sedimentation, creating accommodation space for the middle and upper Atoka. These faults strike parallel to the Ouachita orogen which was uplifted during this period. Uplift of the Ouachitas was complete by Late Atokan time and the structure of the Arkoma Basin was much as it is today (Houseknetch, 1986).

STRATIGRAPHY

Regional Stratigraphy

The Morrowan Series in northwestern Arkansas is composed primarily of sandstone, shale, and some carbonate units. These reflect the transitions from the marine environment that existed in the Mississippian, to the terrestrial and shallow marine setting that characterizes the Pennsylvanian. From west to east, Morrow strata increase in thickness along structural strike. Sand content of the Morrow increases eastward as well. Outcrops of Morrowan and Atokan strata occur throughout northwestern Arkansas in the Boston Mountains. Morrowan outcrops are located only in the northern part of the study area because of down to the south normal faults (Figure 5).

Thick alternating intervals of sandstone, siltstone, and shale are characteristic of the Atoka. Atokan strata record the transition from passive margin sedimentation to foreland basin sedimentation (Houseknecht, 1986). Thickness increases southward into the basin.

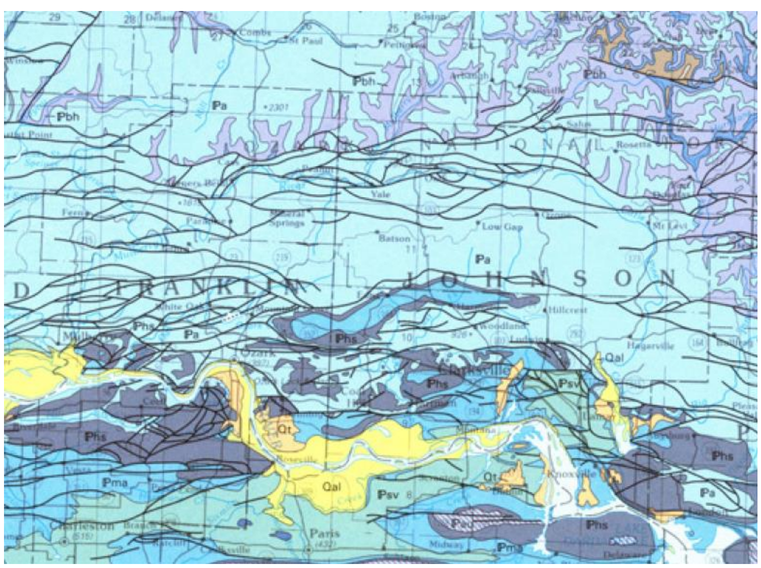

Figure 5. Geologic map of the study area illustrating normal faults displacing Morrowan units (purple) in the north and Atokan (blue) strata in the south. (Modified from Haley and others, 1993)

Local Stratigraphy

The Morrowan Series (Pennsylvanian) in northwest Arkansas is around 320 feet in thickness. The Morrowan Series consists of the Hale and Bloyd Formations (Table 1, Figure 6). These formations produce dry gas. The Hale and the Bloyd are located in west-central to western Arkansas and extend 15 miles into eastern Oklahoma before their lithologic distinction is unidentifiable (Sutherland, 1988). The Hale Formation, the oldest Pennsylvanian unit in the study area, is divided into two sandstone units: the Cane Hill Member below and Prairie Grove Member above. Dark gray, silty shale interbedded with siltstone and thin bedded, fine-grained sandstone are typical of the Cane Hill Member, the base at which marks the Pennsylvanian – Mississippian boundary in Arkansas (McFarland, 2004). The Cane Hill unconformably overlies the Mississippian Pitkin Formation. The Prairie Grove Member is a sandstone that is often cross bedded, contains fossil fragments, can be a light-gray to dark brown color, contains lenses of highly fossiliferous limestone as well as oolitic limestone, and often appears mottled in outcrops (McFarland, 2004). Honeycomb weathering is very typical of the Prairie Grove.

The Bloyd Formation is composed of alternating layers of limestone and shale in northern Arkansas and eastern Oklahoma. The members of the Bloyd in vertical succession are the: Brentwood Limestone, Woolsey Shale, middle Bloyd sandstone, Dye Shale, and Kessler Limestone. The Brentwood Limestone is composed of intervals of limestone separated by thick intervals of dark shale (McFarland, 2004). Fissile, dark grey shale interbedded with thin siltstone comprise the Woolsey (McFarland, 2004). In Washington and Crawford counties, a coal member, the Baldwin Coal, is included in the Woolsey. Eastward, in Madison County, the Woolsey is interfingered with a fine to medium-grained, highly cross-bedded sandstones referred to as the middle Bloyd sandstone (Figure 7). The Dye Shale overlies the sandstone and is dark gray in color and contains calcareous concretions (McFarland, 2004). Bioclastic, oolitic

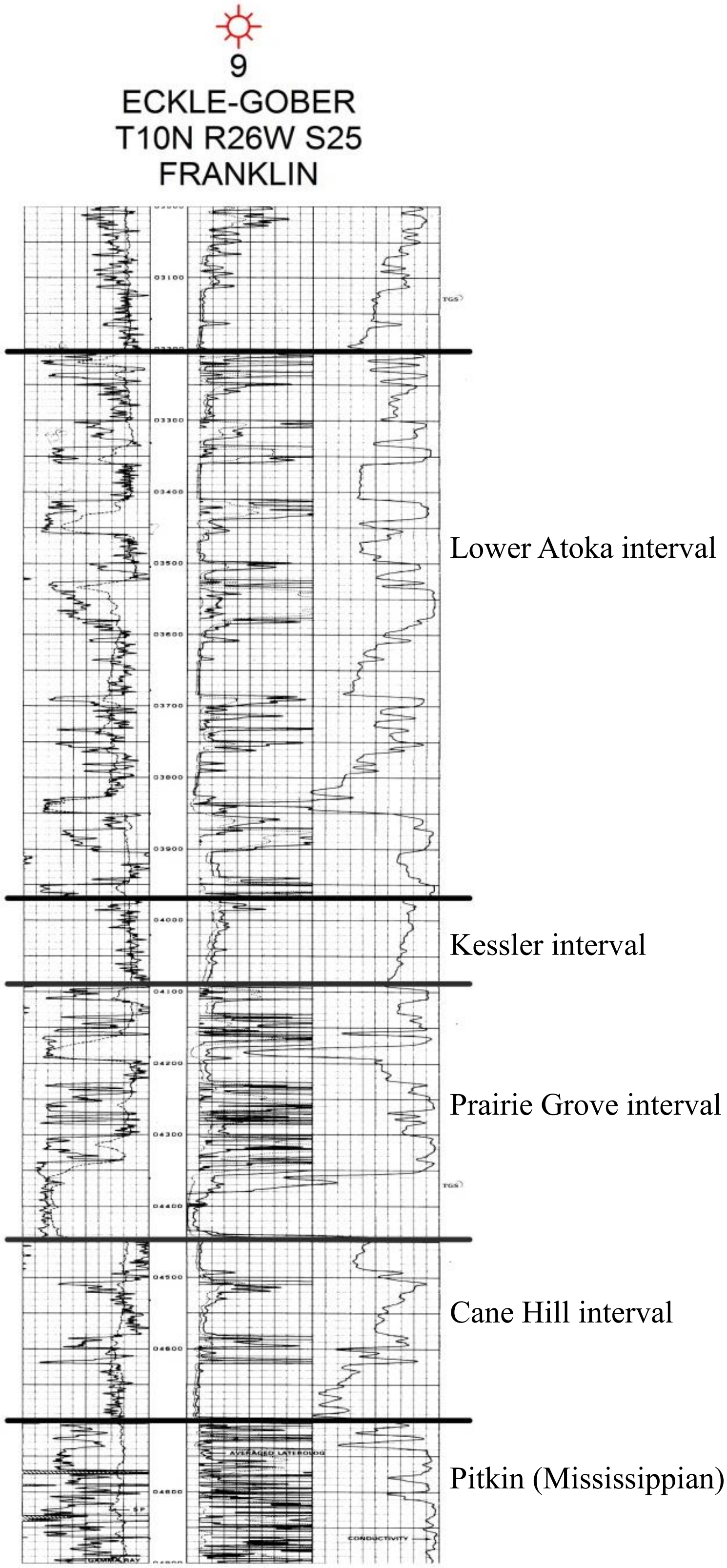

Figure 6. Type log of Lower Atoka and Morrow section

limestones that are sometimes a sequence of interbedded shale and limestone, make up the Kessler Limestone (McFarland, 2004). The top of the Kessler marks the Morrowan – Atokan boundary.

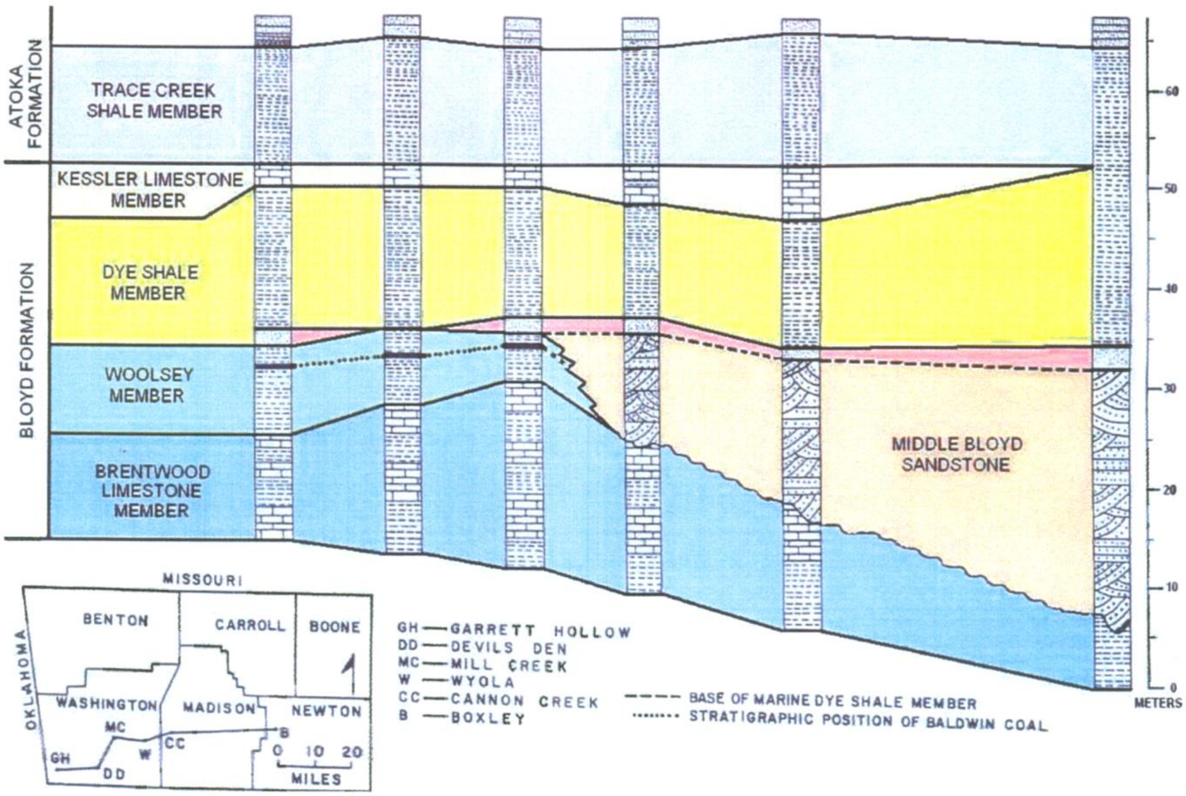

Figure 7. Regional cross section depicting stratigraphic relationships within the Bloyd Formation (Zachry, 1979).

Resting unconformably on top of the Morrow, the lower Atoka, named for Atoka County, Oklahoma, ranges in thickness from 500 feet at the northern edge of the basin to 1000 feet at its southern margin. The lower Atoka consists of several sandstone units that are separated by intervals of shale. All sandstones within the lower Atoka are composed predominantly of quartzarenite (Sutherland, 1988, Zachry, 1987). The lower Atokan sands are the: Spiro, Patterson, Cecil Spiro, Dunn C, Lower Jenkins, Upper Jenkins, and Sells (Table 1). South in the basin, units above the Spiro thin and are replaced by shale. Sandstone units in the middle and upper Atoka are not included in this study.

Table 1. Generalized stratigraphic column depicting the Morrowan formal names and Atokan Series informal names and members. (Modified from Cherry, 2012)

<table>
<tr><th>System</th><th>Series</th><th colspan="2">Formation</th><th>Unit</th><th>Commonly Used Names</th></tr>
<tr><td rowspan="3">Pennsylvanian</td><td>Atokan</td><td>Atoka</td><td>Lower</td><td>Sells
Upper Jenkins
Lower Jenkins
Dunn C
Paul Barton
Hamm
Patterson
Spiro</td><td>Dunn A, McGuire, Hudson 2
Ralph Barton, Upper Allen, Jenkins
Dunn B
Dawson , Dawson A, Allen
Dawson B, Russell, Lower Allen, Lower Dawson
Cecil Spiro, Cecil
Orr, Kelly, Barton, Basal Atoka</td></tr>
<tr><td rowspan="2">Morrowan</td><td colspan="2">Bloyd</td><td>Kessler Limestone
Dye Shale
Woolsey Member
Middle Bloyd
Brentwood Limestone</td><td>Wapanucka</td></tr>
<tr><td colspan="2">Hale</td><td>Prairie Grove Member
Cane Hill Member</td><td>Upper
Middle
Lower</td></tr>
</table>

STRATIGRAPHIC ANALYSIS

During early Pennsylvanian time, Morrow and lower Atoka sedimentary rocks were deposited on a stable shelf in northwest Arkansas. Stratigraphic relationships within this succession were influenced by (1) initial subsidence in the northern portion of the basin and (2) by the influx of terrigenous sediment from the east. Subsidence provided accommodation space for the development of additional units to the south and an increase in interval thickness. Terrigenous sediment from an eastern source caused the cessation of carbonate sedimentation and the loss of the Brentwood and Kessler members of the Bloyd Formation.

Map Analysis

Three structural contour maps and two isopach maps were generated from the stratigraphic tops of the Pitkin, Kessler, and Sells. Zero denotes sea level, with negative values representing depths below sea level and positive values representing above sea level. The Pitkin structural contour map (Figure 8) represents the base of the Morrow section. The base steadily descends and dips southward into the northern part of the basin. A few anomalies are present in the Kessler structure map (Figure 9); however, the overall structure is very similar to that of the base of the Morrow. Southward, the top of the Morrow descends rapidly into the basin (Figure 9). The lower Atoka structure map has a similar structural pattern to that of the Kessler and the Pitkin (Figure 10). A major west to east trending fault can be observed on each of the maps at the intersection of Townships 10N and 11N where the contour lines touch.

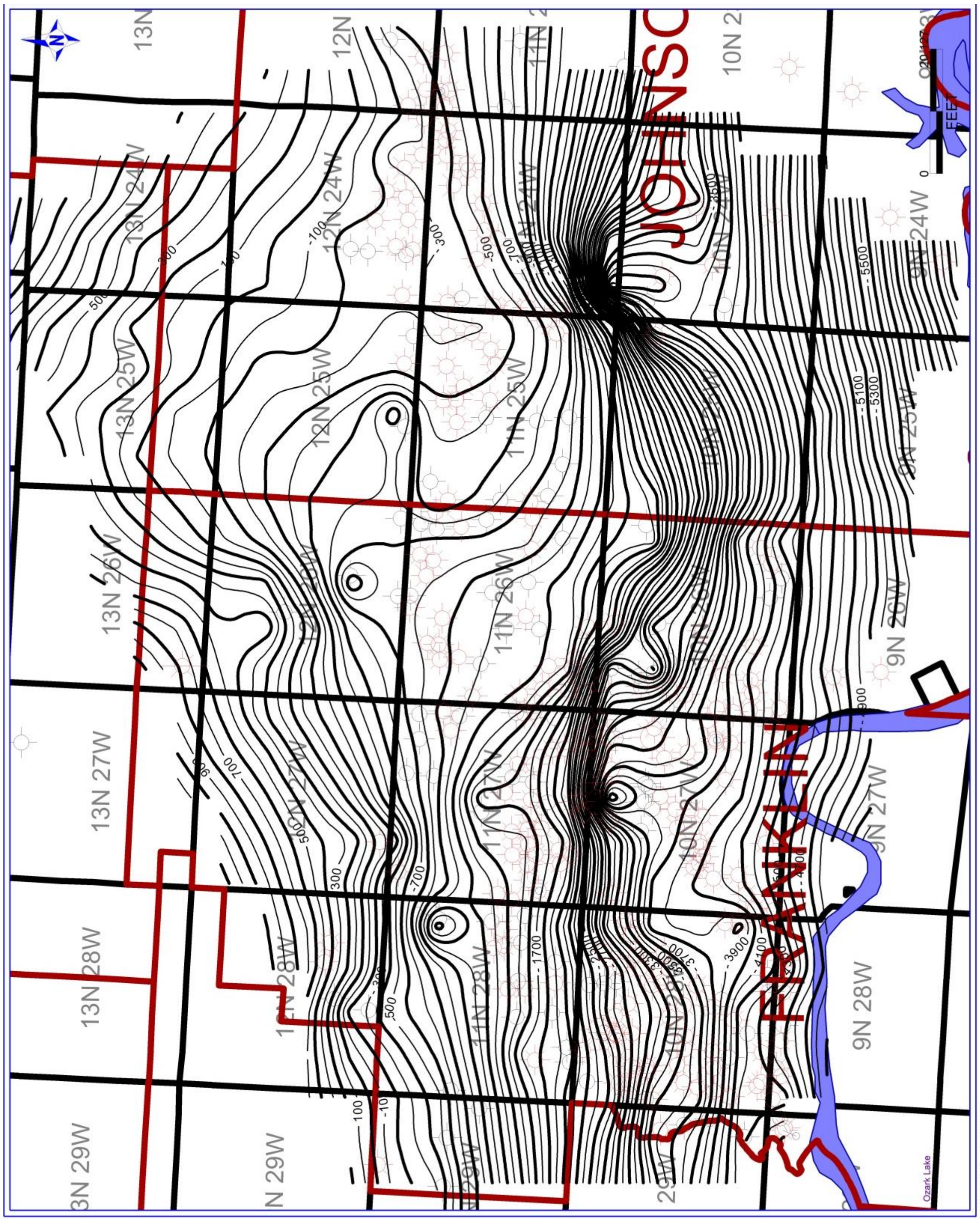

Figure 8. Structural contour map of the top of the Pitkin.

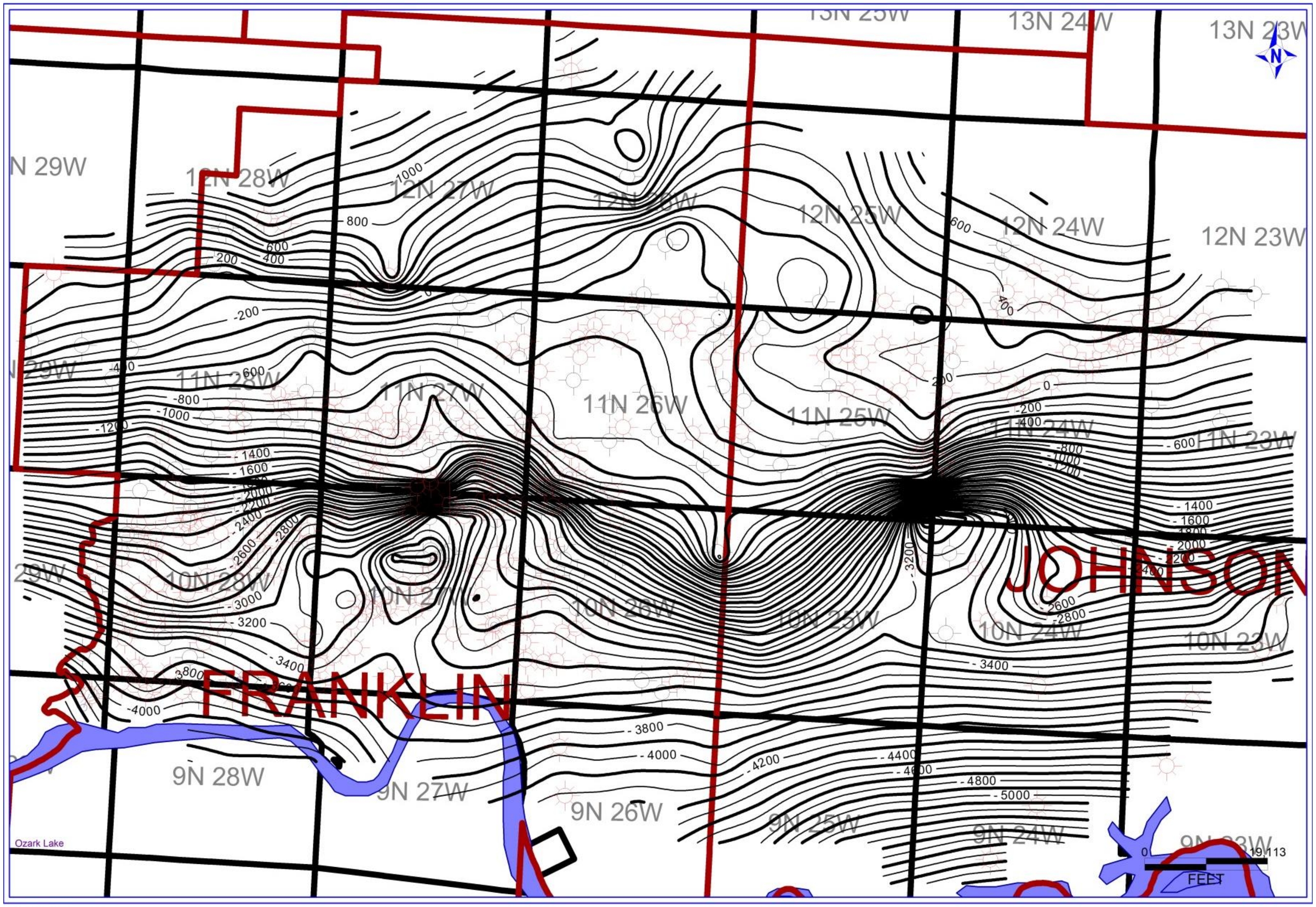

Figure 9. Structural contour map of the top of the Morrow.

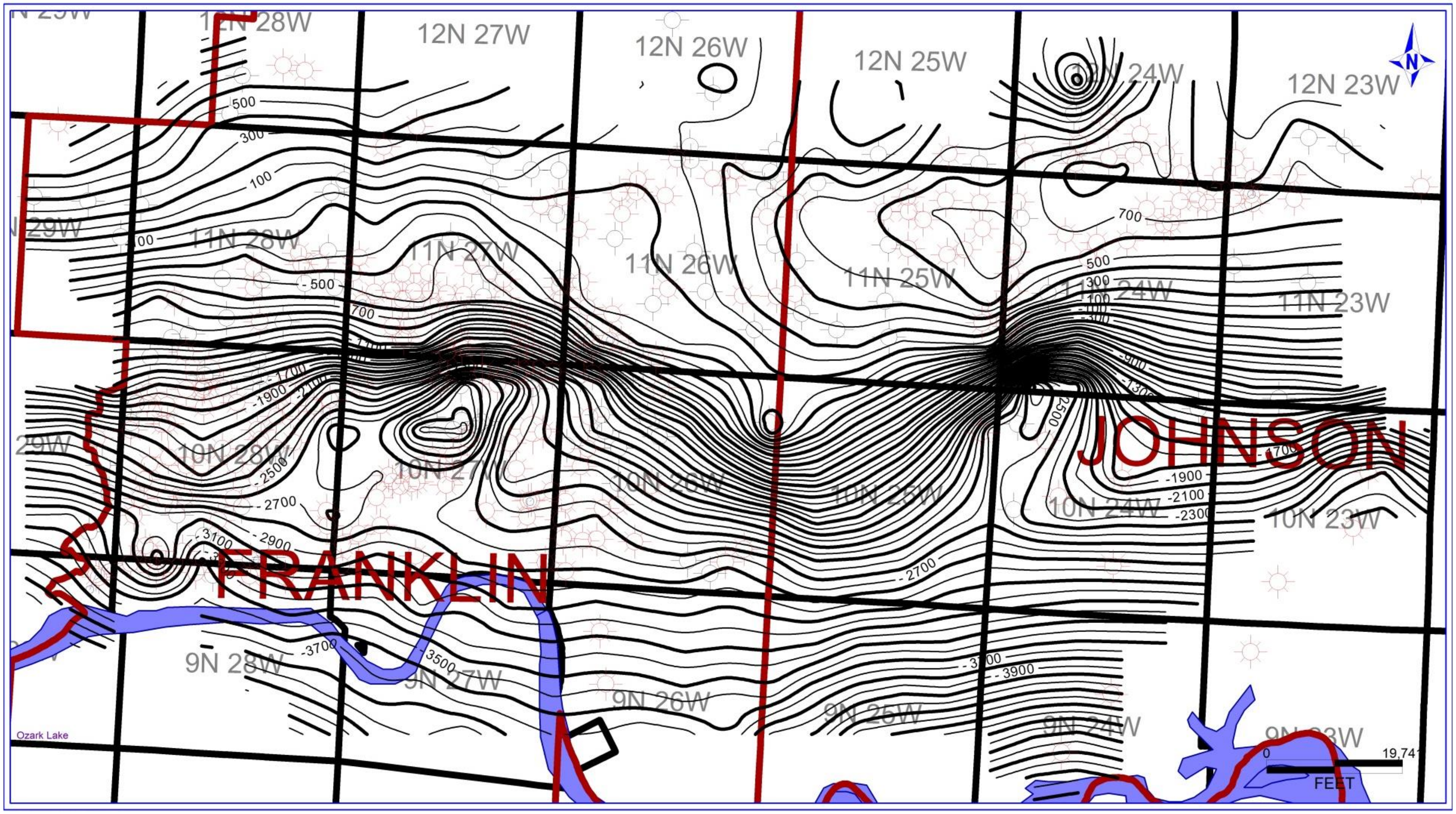

Figure 10. Structural contour map of the top of the lower Atoka.

Two isopach maps were created in Petra of the Morrow and the lower Atoka. Morrow and lower Atoka thickness increase to the east and to the south. There is a 350 foot difference in stratal thickness of the Morrow from the northwest to the southeast (Figure 11), with the greatest thickness of sediment located in the southeastern corner of the map. This is due to proximity to a northeastern sediment source coming from the Illinois Basin (Sutherland, 1988).

Within the lower Atoka, thickness steadily increases from 400 feet on the shelf in the north to 850 feet in the south (Figure 12). Initial subsidence in the northern part of the basin provided accommodation space for the additional 450 feet of sediment to accumulate. The shape of the isopach map for the lower Atoka differs from the shape of the map for the Morrowan because of the difference in well coverage areas.

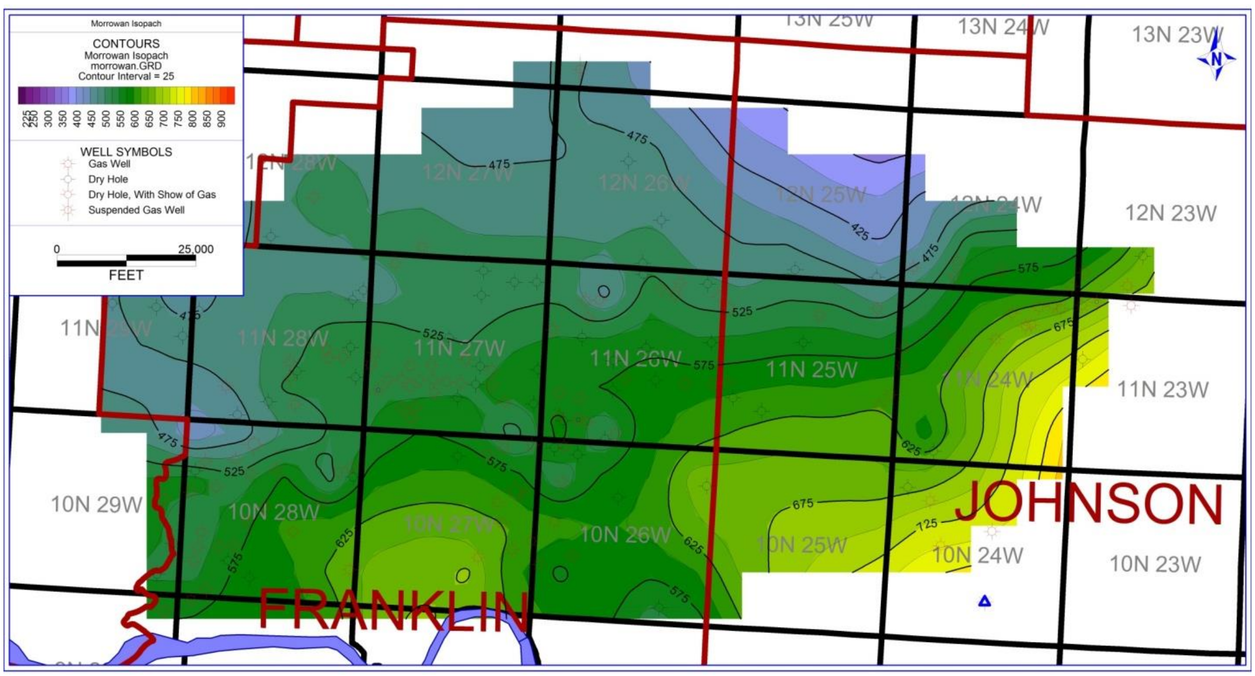

Figure 11. Morrow isopach map.

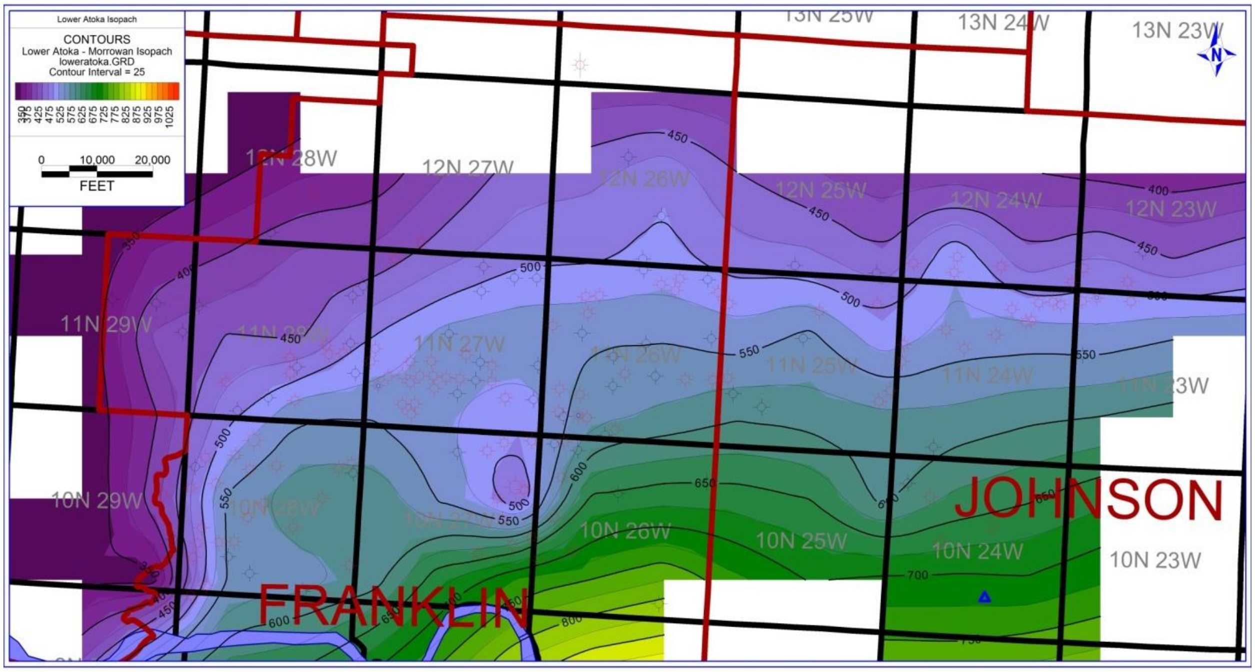

Figure 12. Lower Atoka isopach map.

Regional Cross Sections

Two west to east and three north to south cross sections were constructed. The Sells, Kessler, and Pitkin were identified in all logs selected for the cross sections. The five lines of section are illustrated on Figure 4 and labelled: A-A', B-B', C-C', D-D', and E-E'. Structural and stratigraphic cross sections were constructed for all lines of section. Stratigraphic cross sections are hung on the lower Atoka Sells. Thickening of the Morrow and the lower Atoka occurs along structural strike from west to east. The lower Atoka is characterized by shales that coarsen upward into sandstone. These shale-sandstone couplets repeat up to seven times within the logs.

Cross Section C-C'

Cross section C-C' is the northern most cross section and includes well numbers 10 through 14 (Figure 4). Wells are located in both Franklin and Johnson counties through Township 12N, Range 28W-23W. The section spans twenty-nine miles from west to east, making it the longest section in this study. The section is interrupted by two grabens in wells 11 and 14, with displacement values ranging from 100 to 120 feet (Figure 13). The horst and graben structures are likely a result of reactivation of normal faults that occurred during the last phases of Ouachita development (McGilvery and Houseknecht, 2000).

The lower Atoka and the Morrow have a very gradual and gentle increase in stratal thickness to the east due in part to the stable, shallow environment that existed on the Arkoma shelf. A 121 foot difference in Morrow thickness exists between well 10 and well 14, the eastern most well (Figure 14). Thickening occurs along the down thrown side of the grabens in wells 11 and 14 suggesting that movement along these faults began during deposition (Figure 13). The basal Morrow shale thickens on the downthrown side of the fault in well 14 (Figure 14).

However, little change is noted in the basal Morrow thickness in well 11. These faults do not appear to affect the sandstone and shale units of the lower Atoka. The lower Atoka has a very small increase in thickness of 31 feet between the western and eastern most well.

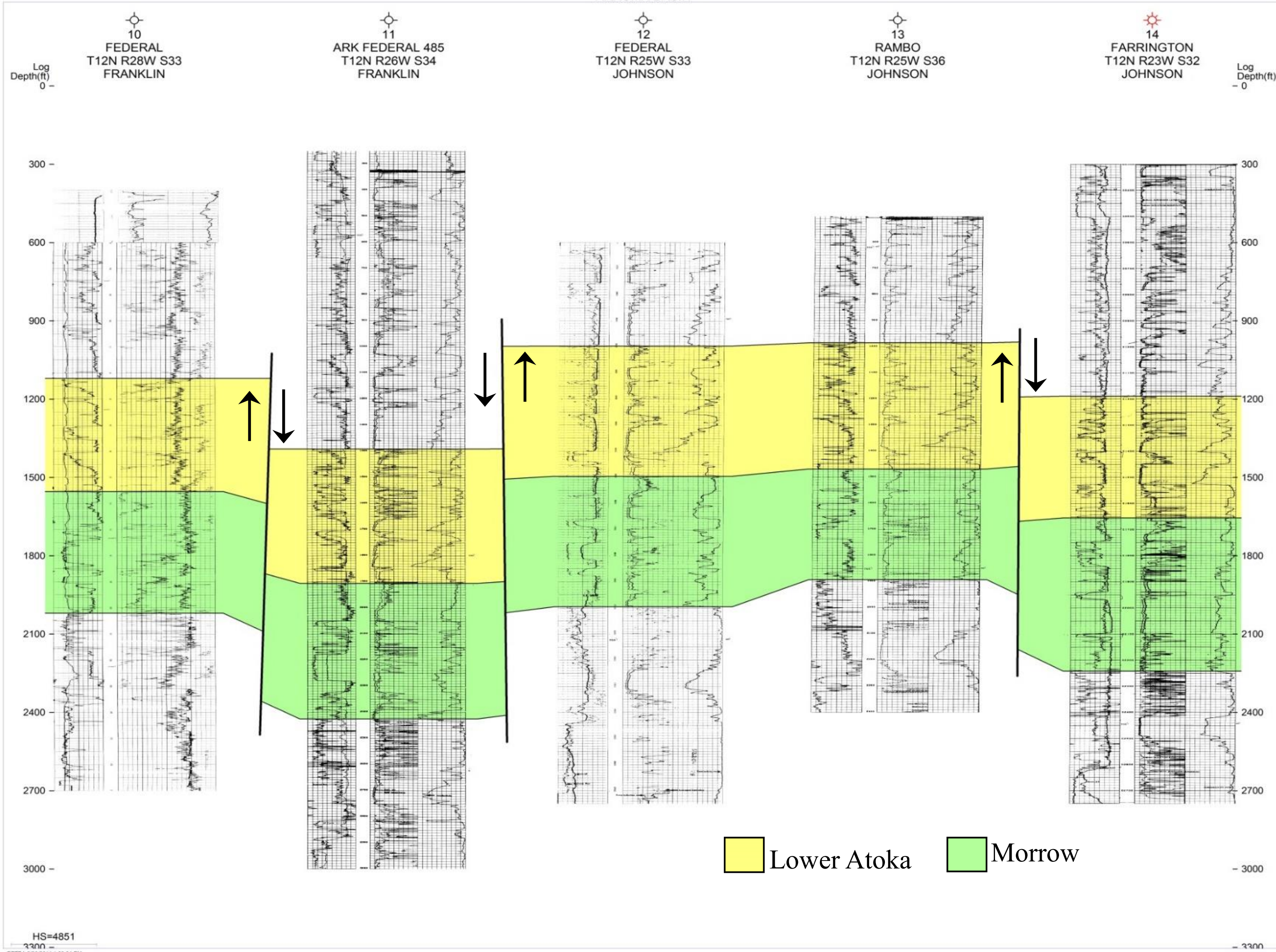

Figure 13. West to east structural cross section C – C' through Township 12N, Range 28W-23W

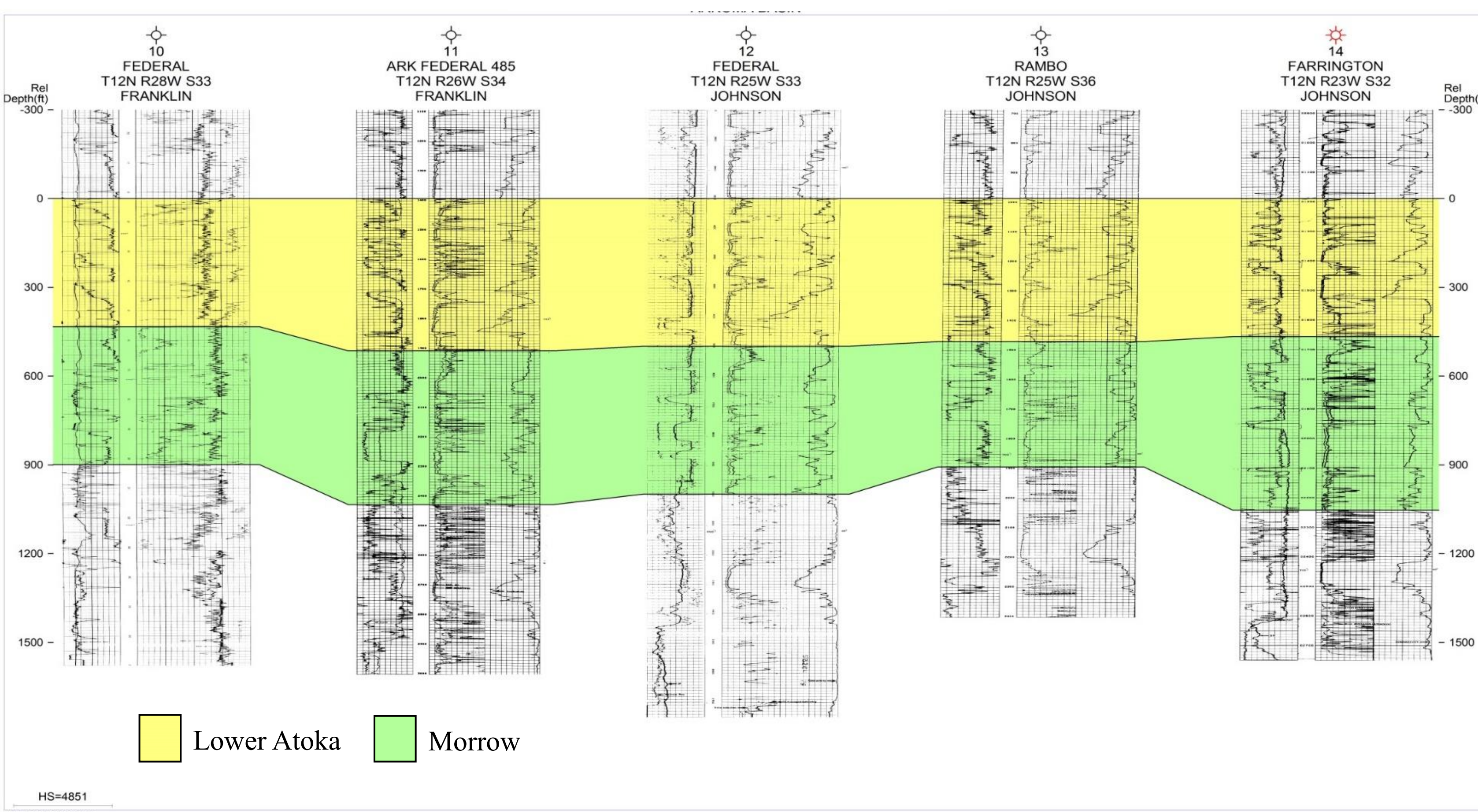

Figure 14. West to east stratigraphic cross section C-C' through Township 12N, Range 28W-23W hung on top of the lower Atoka.

Cross Section D-D'

Cross section D-D' is the southernmost west to east cross section located in the northern part of the Arkoma basin (Figure 3). Well numbers 15 through 19 are included in this 28.4 mile line that cuts through both Franklin and Johnson counties in Township 10N, Range 24W-28W. This section is disrupted by two grabens in wells 16 and 18 (Figure 15). Displacement values between wells 16 and 17 approaches 1000 feet and 700 feet between wells 18 and 19.

The Morrow thickness increases 194 feet from the west to the east. There is a dramatic increase of 349 feet in the lower Atoka from well 15 in the west and well 19 in the east. A portion of the lower Atoka is faulted out in well 15, which accounts for part of the increase in the width in wells 16 through 19 (Figure 16). In contrast to cross section C-C', the thickening pattern is a regional one not associated with faults.

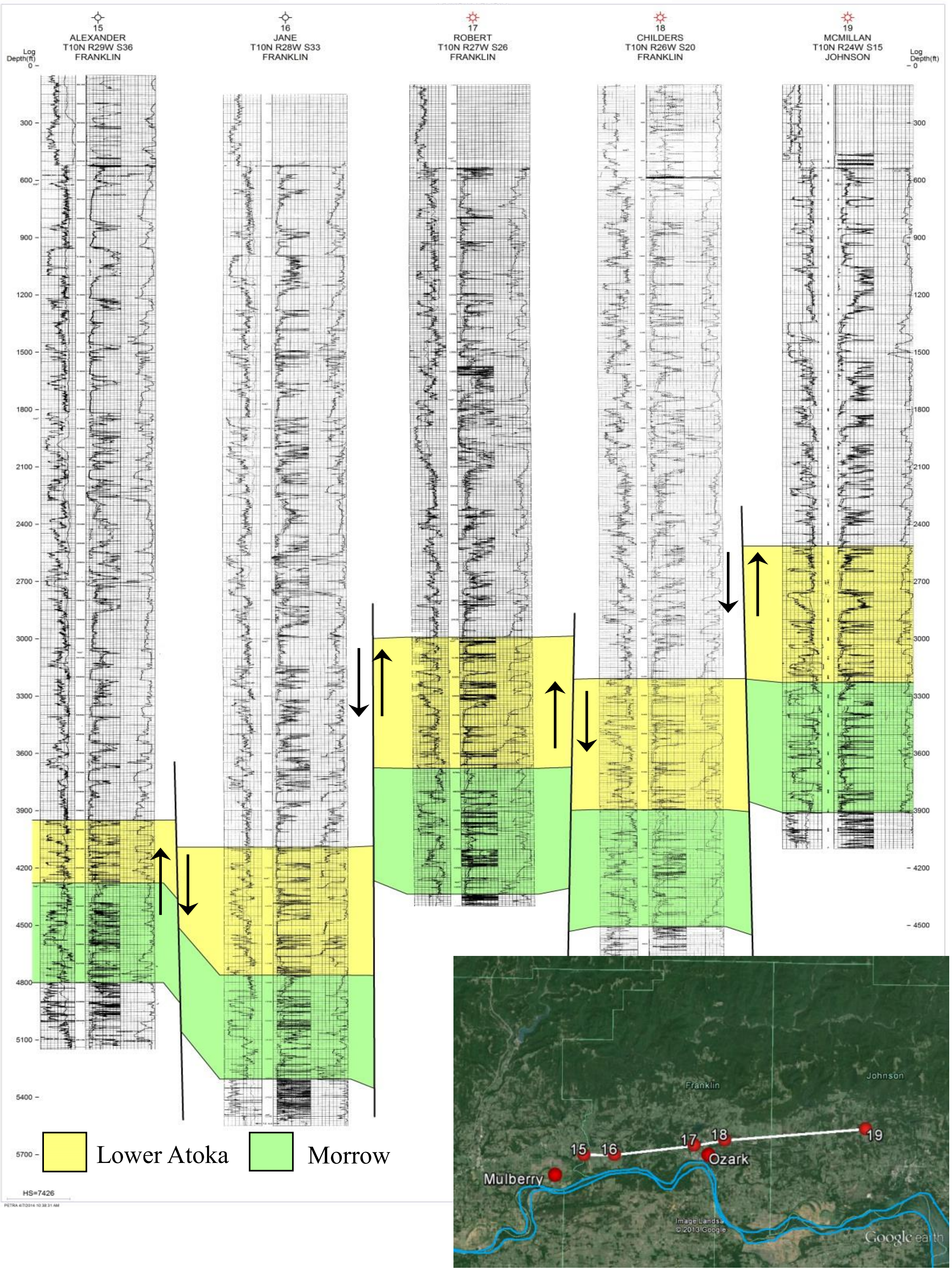

Figure 15. West to east structural cross section D-D' through Township 10N, Range 29W-24W

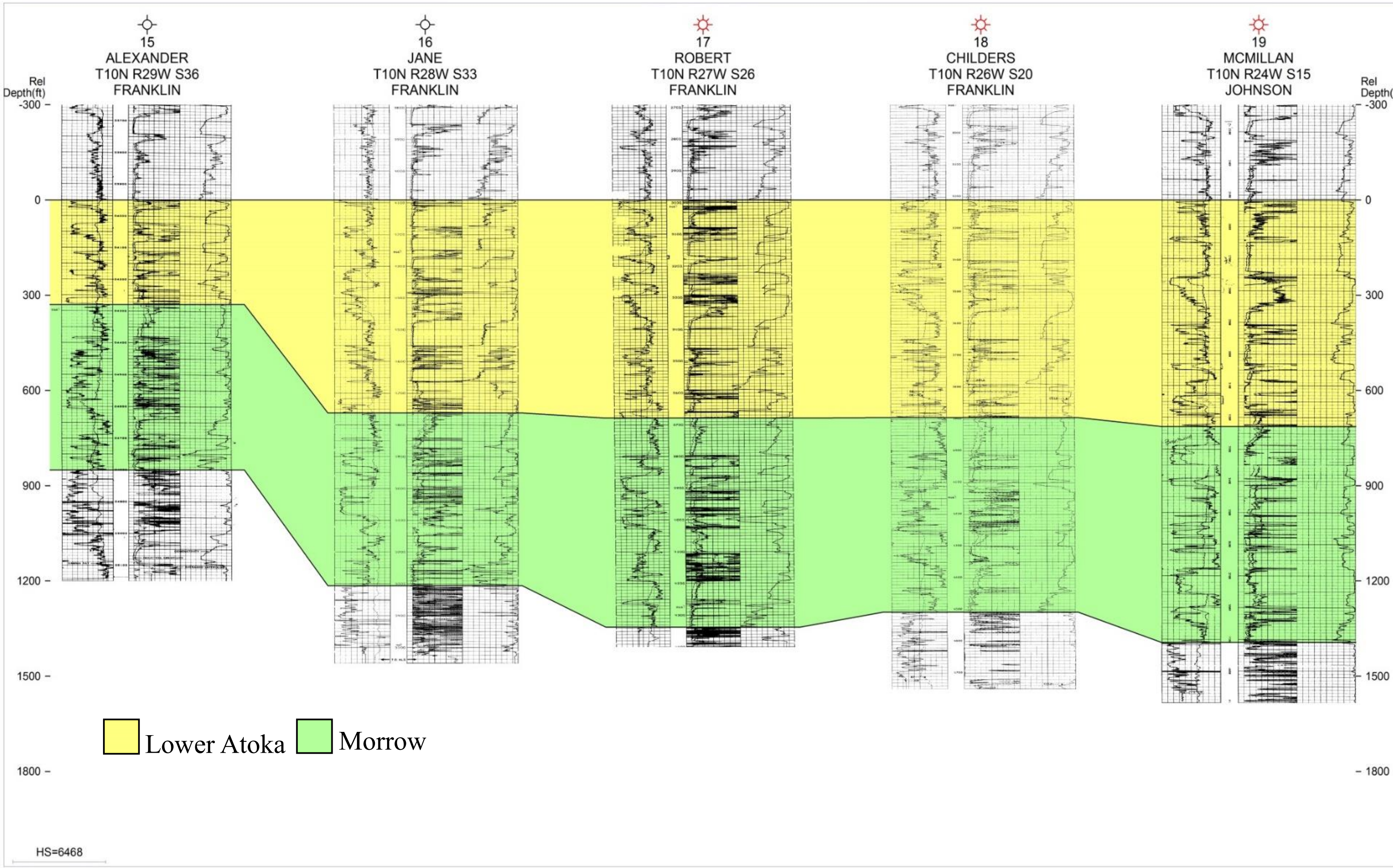

Figure 16. West to east stratigraphic cross section D – D' through Township 10N, Range 29W-24W hung on top of the lower Atoka.

Cross Section A-A'

Cross section A-A' is located in the far eastern portion of the study area in Franklin County in Townships 9N-11N, Range 28W (Figure 4). It includes well numbers 1 through 4 and covers a north to south distance of 12.7 miles (Figure 4). Morrow thickness increases 64 feet from the north to the south. Two normal faults in the southern portion of the cross section line are preserved between wells 2 and 3 and wells 3 and 4 (Figure 17). Twelve hundred feet of displacement is caused by the first fault and 1900 feet of displacement exists between well 1 and well 4.

Descending south from the shelf into the northern portion of the basin, a steady increase in the thickness of strata is observed. Lower Atokan strata increase 171 feet from north to south (Figure 18). Morrow strata increase 64 feet southward. The blocky Prairie Grove signature is thin in well 2. Thickening occurs in the shale intervals of the Morrow and the lower Atoka on the downthrown side of the faults, indicating syndepositional faulting.

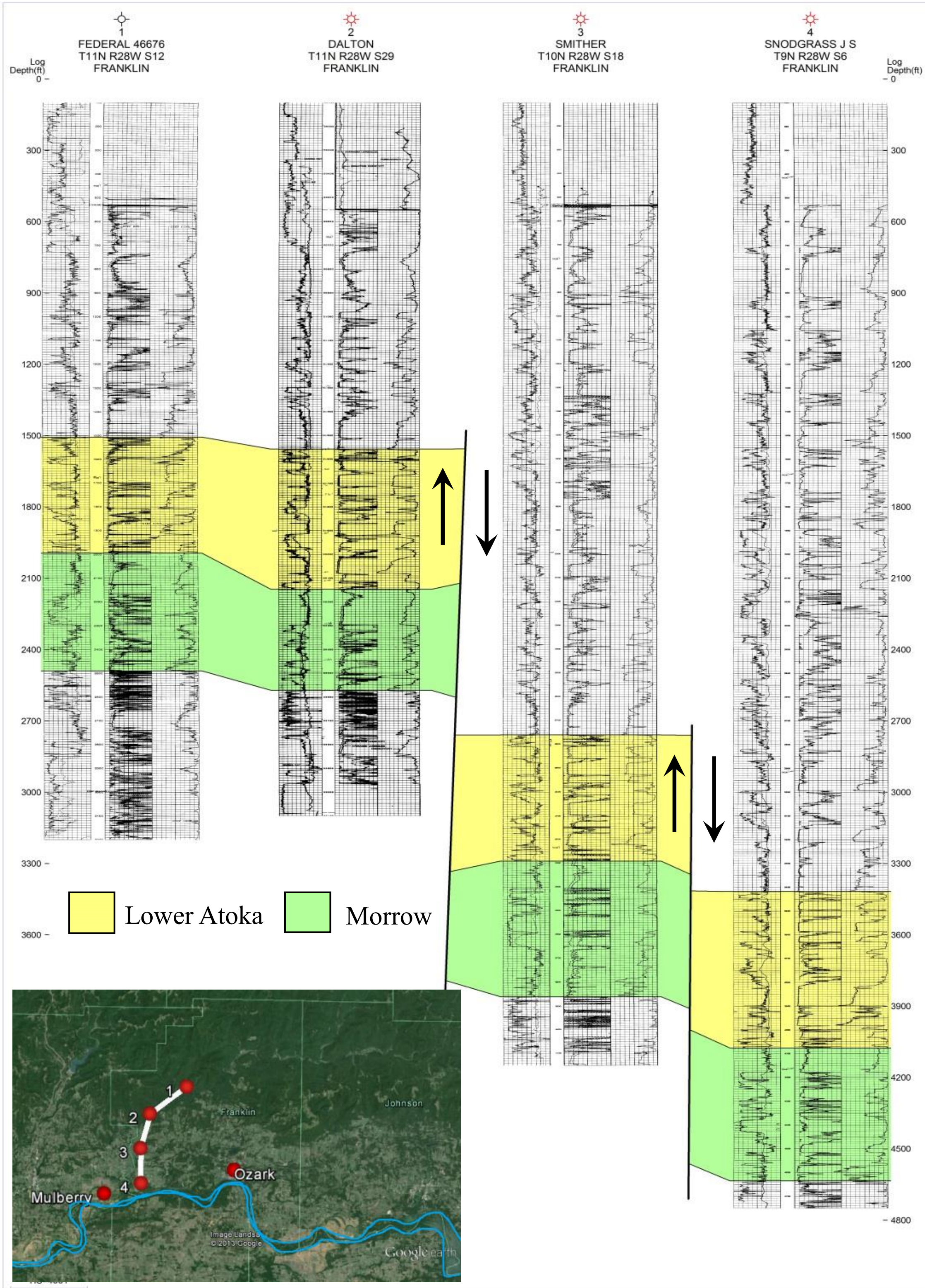

Figure 17. North to south structural cross section line A-A' through Township 11N-9N, Range 28W.

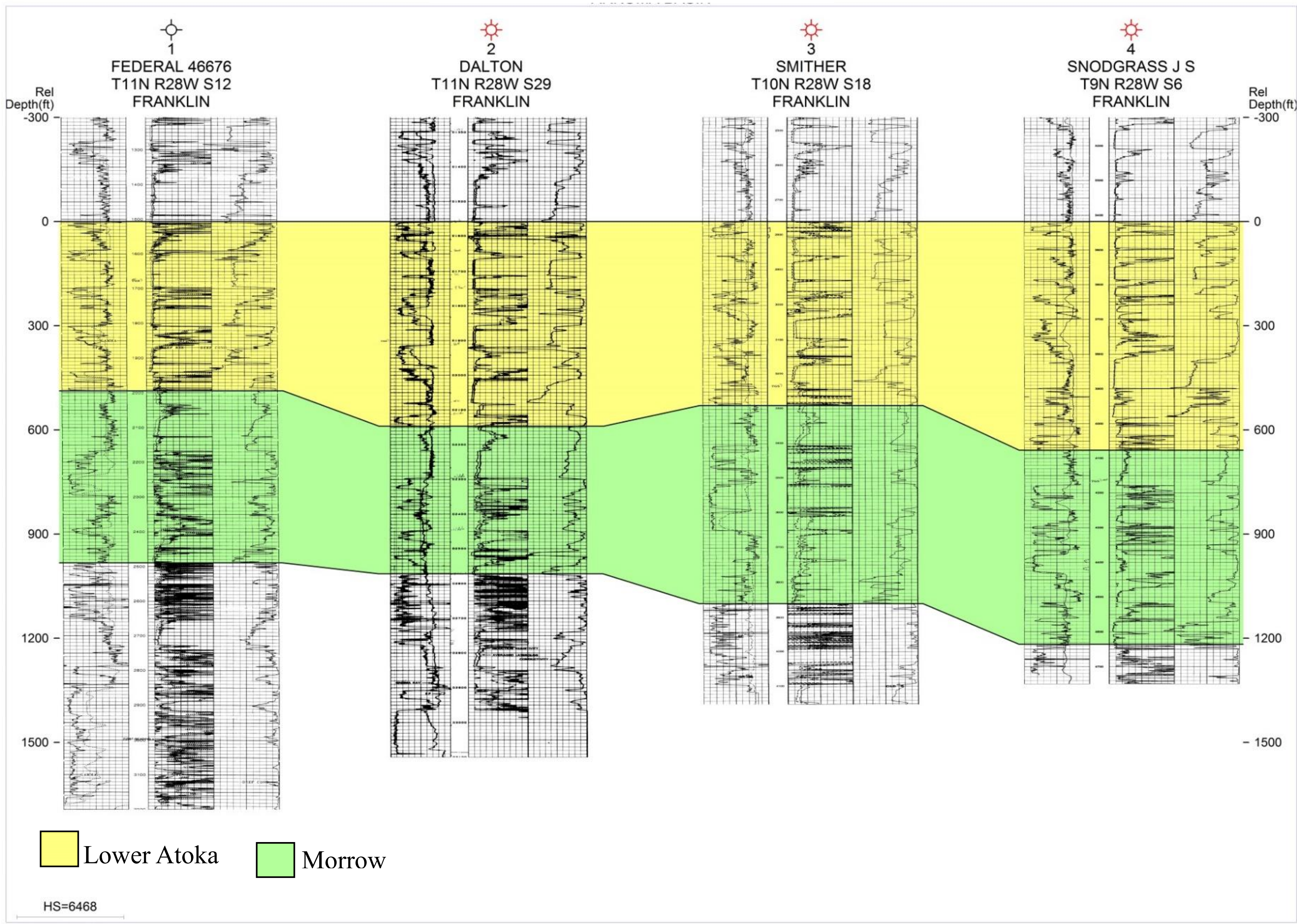

Figure 18. North to south stratigraphic cross section A-A’ through Township 11N-9N, Range 28W hung on top of the lower Atoka.

Cross Section B-B'

Cross section B-B' is located on the far western side of Franklin County in Township 10N-12N, Range 26 W (Figure 4). Well numbers 5 through 9 comprise this eleven mile north to south section. A major down to the south normal fault occurs between wells 8 and 9 with 1,430 feet of displacement on the southern side of the fault (Figure 19). This fault is visible on the structural contour maps in Township 10N where the contour lines are very tight (Figures 8, 9, 10). Wells 6 and 7 are bound by a graben with displacements of 460 feet adjacent to well 6 and 680 feet adjacent to well 7.

Stratal thickness increases in the south, with the most thickening occurring in the south in wells 8 and 9 (Figure 20). A substantial amount of thickening occurs on the downthrown side of the large normal fault in the south, with the most thickening occurring in the shale intervals in the Morrow and lower Atoka. The Morrow thickness increases 213 from north to south. Within the Morrow, the Prairie Grove is especially prominent in wells 7, 8, and 9. The Prairie Grove Sandstone is characterized by a blocky gamma ray signature. The middle Bloyd sandstone can be observed in wells 6 through 9. The lower Atoka thickness increases by 284 feet from north to south.

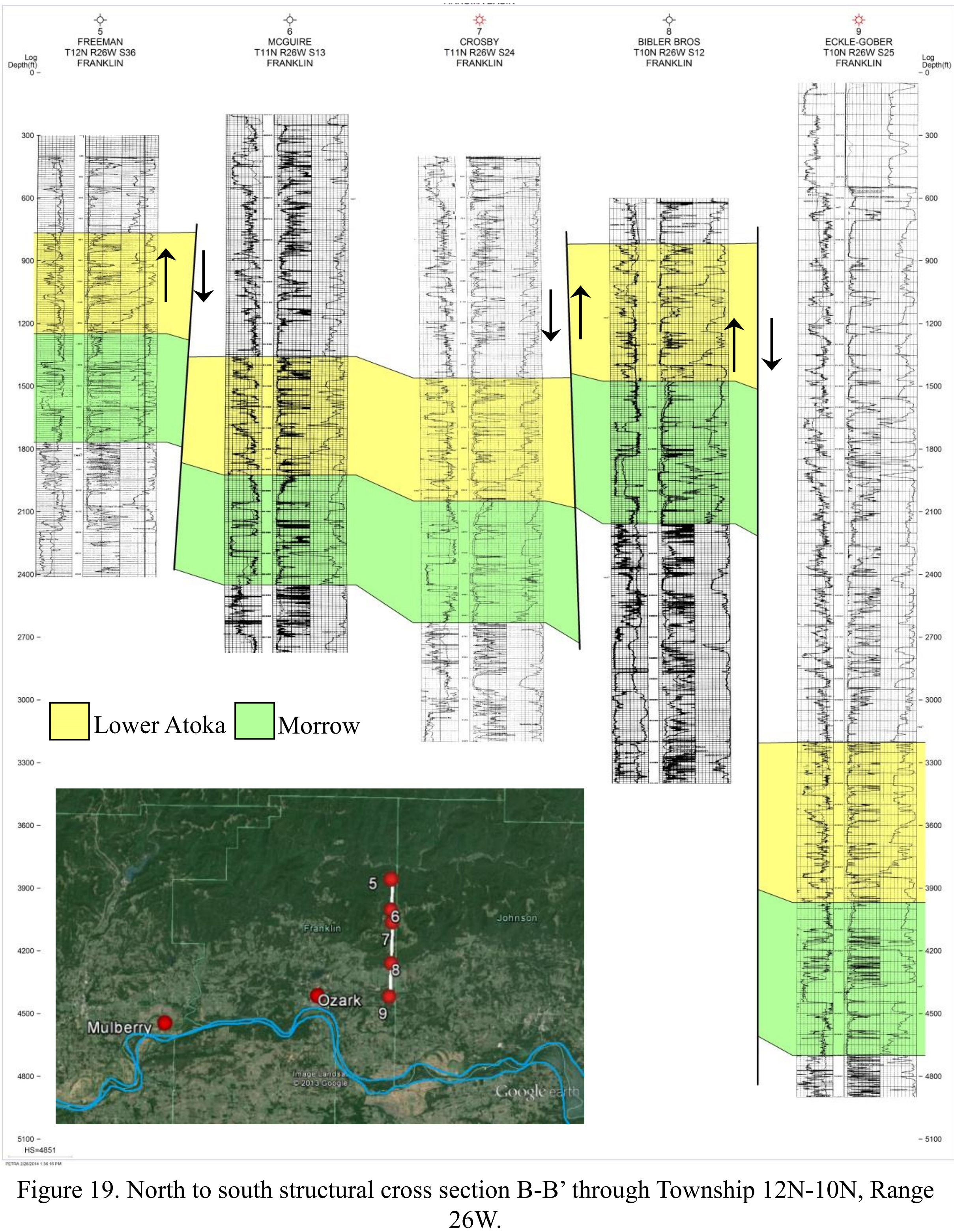

Figure 19. North to south structural cross section B-B' through Township 12N-10N, Range 26W.

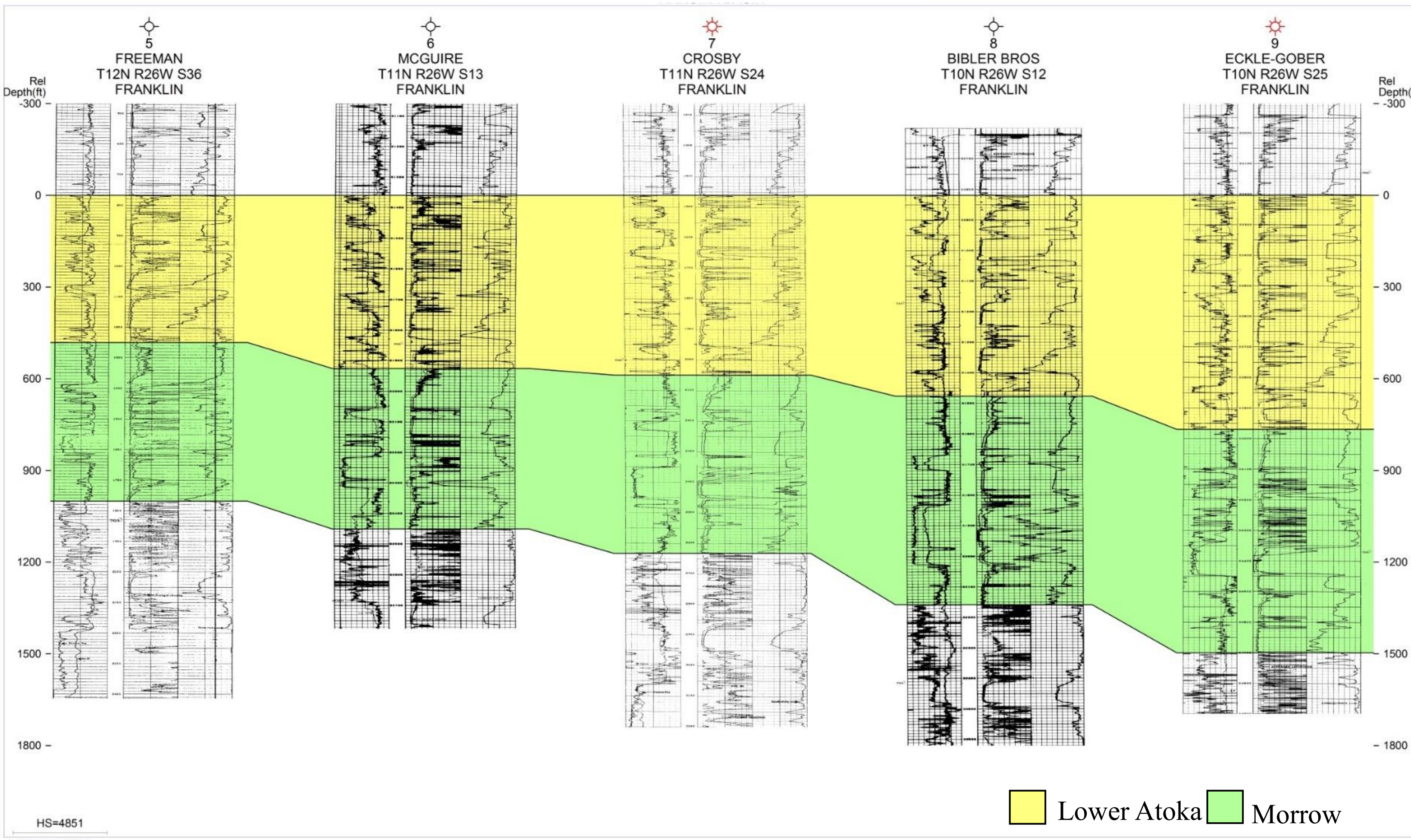

Figure 20. North to south stratigraphic cross section B – B' through Township 12N-10N, Range 26W hung on top of the lower Atoka.

Cross Section E-E'

Cross section E-E' is located on the west side of Johnson County in Townships 9N-12N, Range 24W, has the southernmost well in the study area (Figure 4). Well numbers 20 through 23 are contained within in this 16.5 mile north to south cross section. Major down to the south normal faults are located between wells 20 and 21, between 21 and 22, and between 22 and 23. Nearly 1500 feet of displacement caused by normal faulting is recorded between wells 20 and 23 (Figure 21). The fault between wells 21 and 22 can be observed on the structural contour maps as well (Figures 8, 9, 10).

This stratigraphic cross section has the most dramatic increase in thickness in the Morrow and lower Atoka combined (Figure 22). Thickening occurs in the shale intervals within the Morrow and lower Atoka section. Morrow thickness increases 287 feet to the south and the lower Atoka increases 325 feet to the south. Substantial thickening in the Morrow and lower Atoka section between wells 22 and 23 suggests synchronous sedimentation and fault movement.

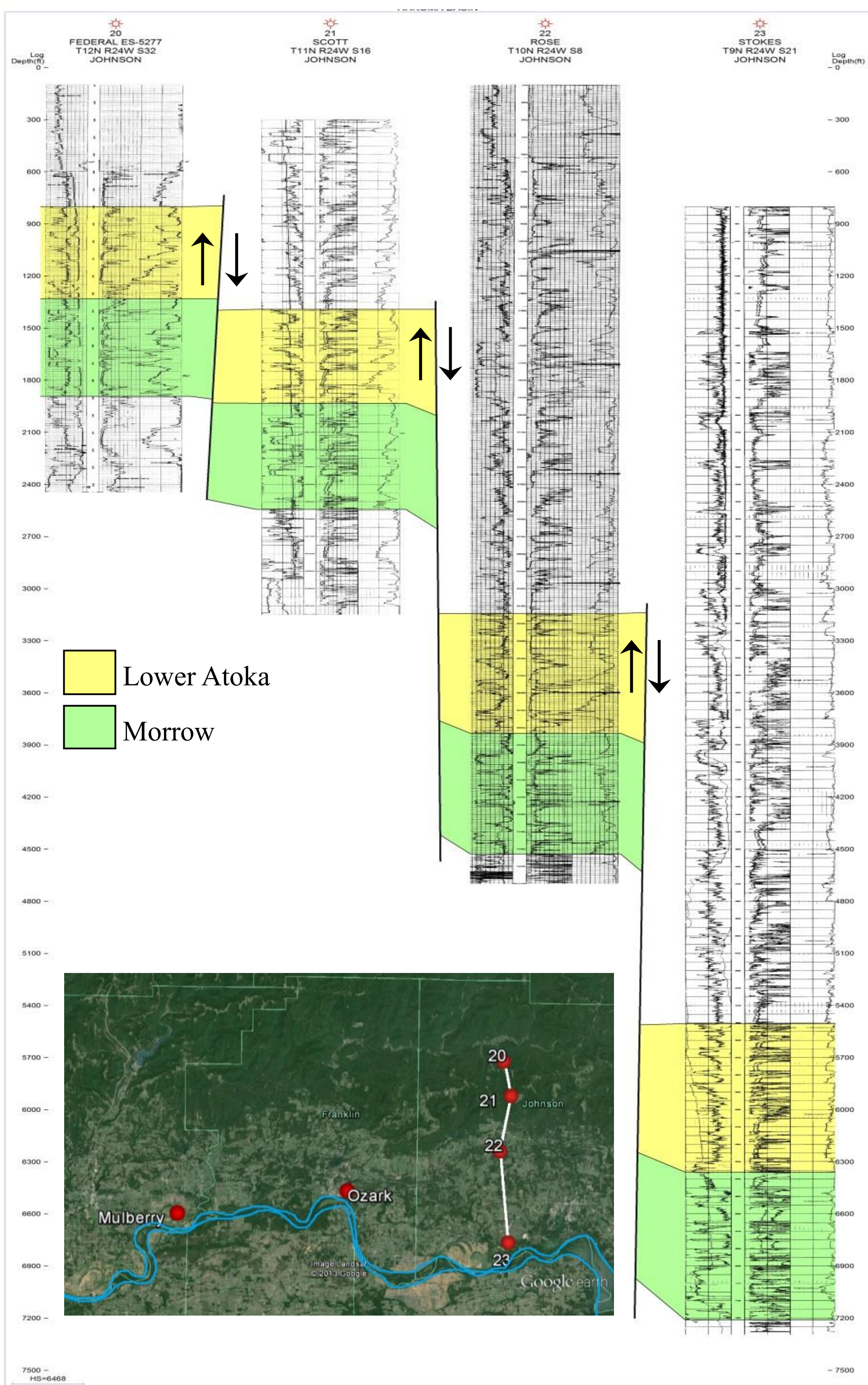

Figure 21. North to south structural cross section E – E' through Township 12N-9N, Range 24W.

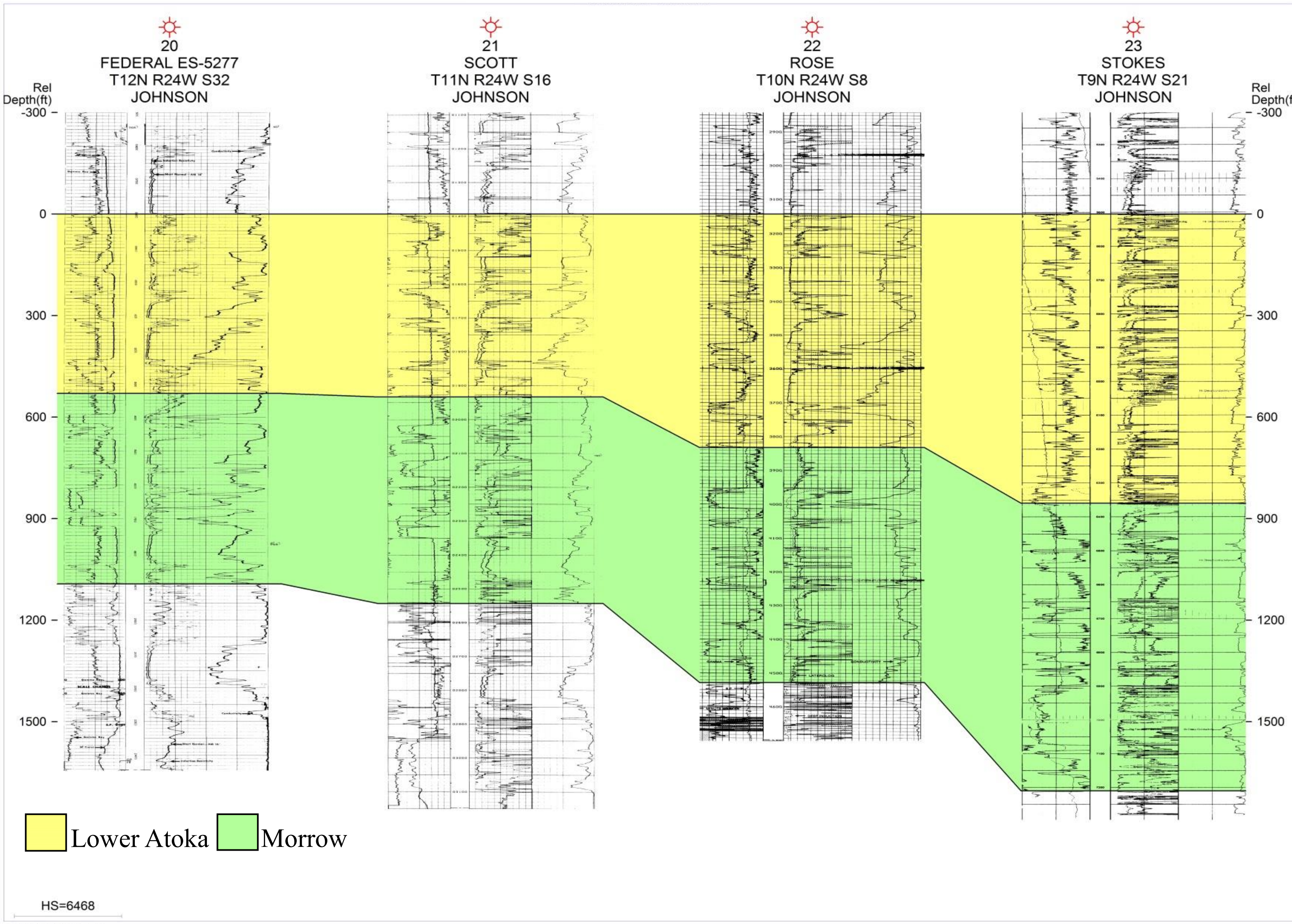

Figure 22. North to south stratigraphic cross section E – E’ through Township 9N-12N, Range 24W hung on top of the lower Atoka.

Comprehensive Stratigraphic Examination

In order to more closely examine the stratigraphic changes that occur within the Hale, Bloyd, and lower Atoka Formations, 3 west to east wells (4, 9, and 19) in the southern part of the study area and one well (11) in the north was selected. Logs were analyzed and broken down into individual color-coded packages: the Cane Hill interval, the Prairie Grove interval, the Kessler interval, and the Lower Atoka interval.

Cane Hill Interval

The Cane Hill interval unconformably overlies the Mississippian Pitkin Limestone or the Fayetteville Shale Formation, where the Pitkin is truncated. The interval is composed of alternating sandstone and shale units in surface sections (Figure 23) and in the subsurface (Figure 24). In a surface section along Highway 45 near Huntsville the interval contains two, thin bedded sandstone units and adjacent intervals of sandy shale. The interval is well expressed on wireline logs in wells 11, 4 and 9 (Figure 24). The wells are also illustrated along Regional Cross Sections A-A', B-B' and C-C'. In each of the wells, two sandstone units are prominent. The gamma ray curves are extremely serrate opposite the sandstone units indicating dispersed clay content. The shale units that separate them are also serrate indicating thin sandstone laminations. This is consistent with surface exposures along Highway 45 (Figure 23). Abundant flaser and wavy stratification as well as ripple marks and burrows suggest accumulation on a shallow tidal dominated shelf that developed as transgression across the Pitkin surface proceeded and as water depth increased on the shelf. The Cane Hill interval thickens from 145 feet in well 11 southward to 250 feet in well 9 (Figure 24).

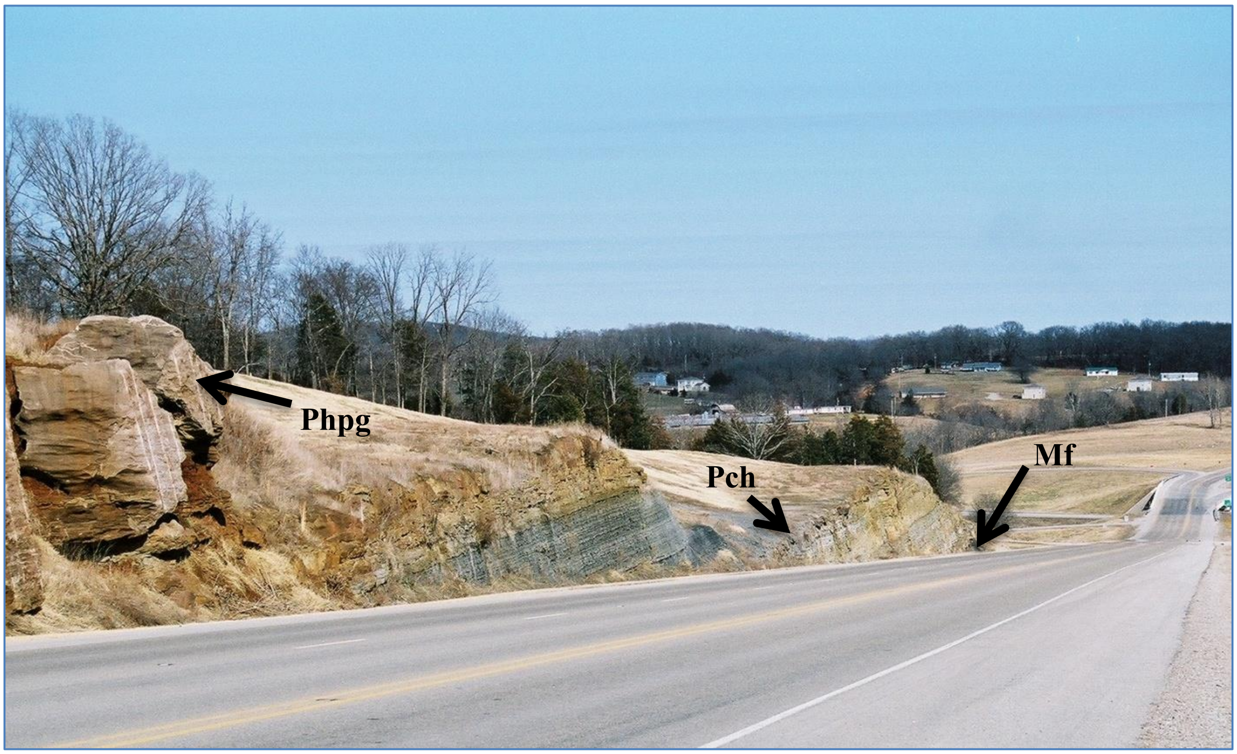

Figure 23. Mississippian and Morrowan section along Highway 45 near Huntsville. (Mf- Fayetteville Formation, Phch-Cane Hill Member, Hale Formation, Phpg- Prairie Grove Member of the Hale Formation) (Photo credit: Doy Zachry)

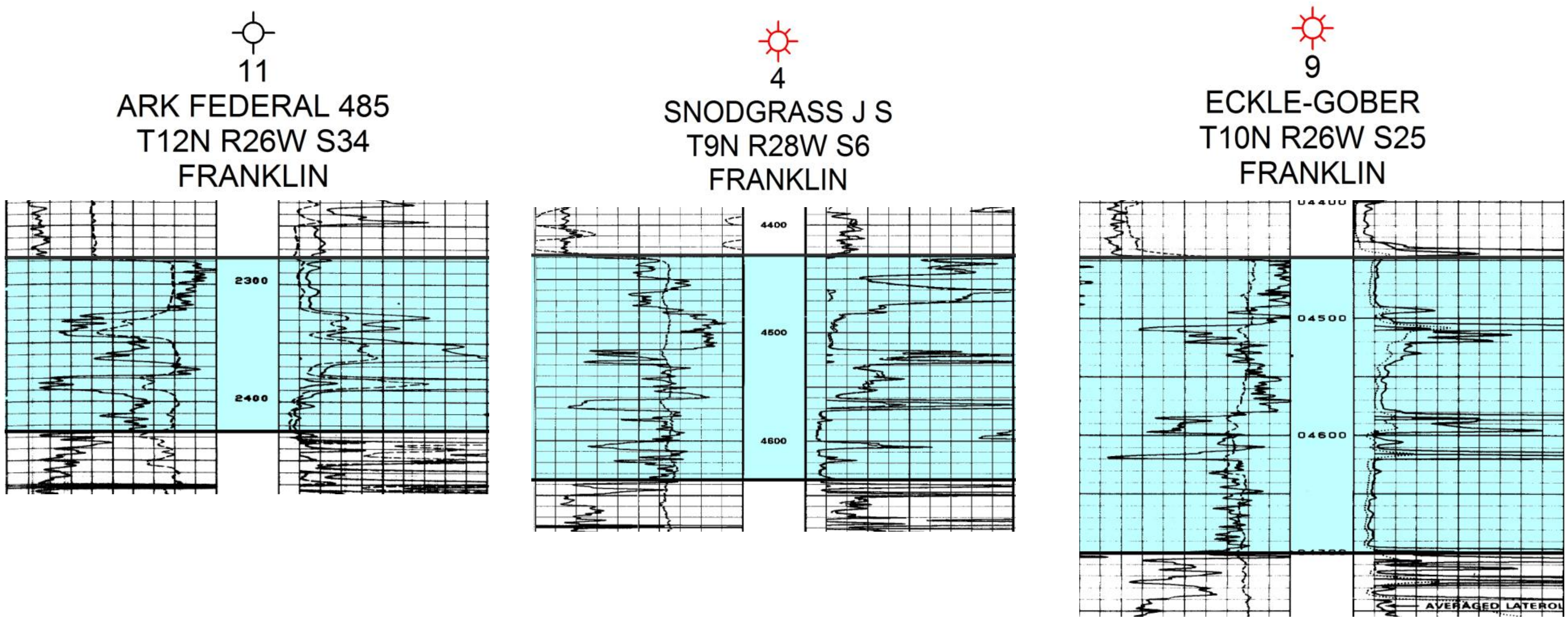

Figure 24. Cane Hill interval wireline log expression from wells 11, 4, 9.

Prairie Grove Interval

The Prairie Grove interval conformably overlies the Cane Hill interval and includes strata formally assigned to the Prairie Grove Member (Hale Formation), as well as the Brentwood and middle Bloyd sandstone members of the Bloyd Formation. The surface section along Highway 45 contains an intensely cross-bedded sandstone (Figure 25). The Prairie Grove Member typically displays dune cross-bedding, with no shale breaks or laminations. The interval passes upward into the limestone and shale interbeds of the Brentwood Member and unconformably into the middle Bloyd sandstone that forms prominent bluffs (Figure 26).

In the subsurface, the Prairie Grove interval is well expressed in wireline logs in wells 11, 4, 9, and 19 and along the regional cross sections (Figure 28). The interval thickens from 230 feet in the north in well 11 to 460 feet in the southeast in well 19. In wells 4, 9, and 19, which are in the south, thickening gradually increases west to east from 240 feet in the west to 460 feet in the east.

Gamma ray curves display multiple sandstone units characterized by blocky signatures. The absence of serrate signatures indicates little shale in the interval, which is consistent with surface outcrops. Wells 11, 9, and 19 display a prominent blocky signature at the base of the interval where the Prairie Grove directly overlies the strata of the Cane Hill interval (Figure 28). Multiple curves with low gamma readings reflect thin limestone beds separated by shale, which is likely the Brentwood Member. A substantial unit with blocky signatures occurs at the top of the interval and is the sandstone unit of the middle Bloyd sandstone (Figure 27).

Figure 25. Prairie Grove member outcrop displaying cross-bedding along Highway 412 near Huntsville, AR. (Photo credit: Doy Zachry)

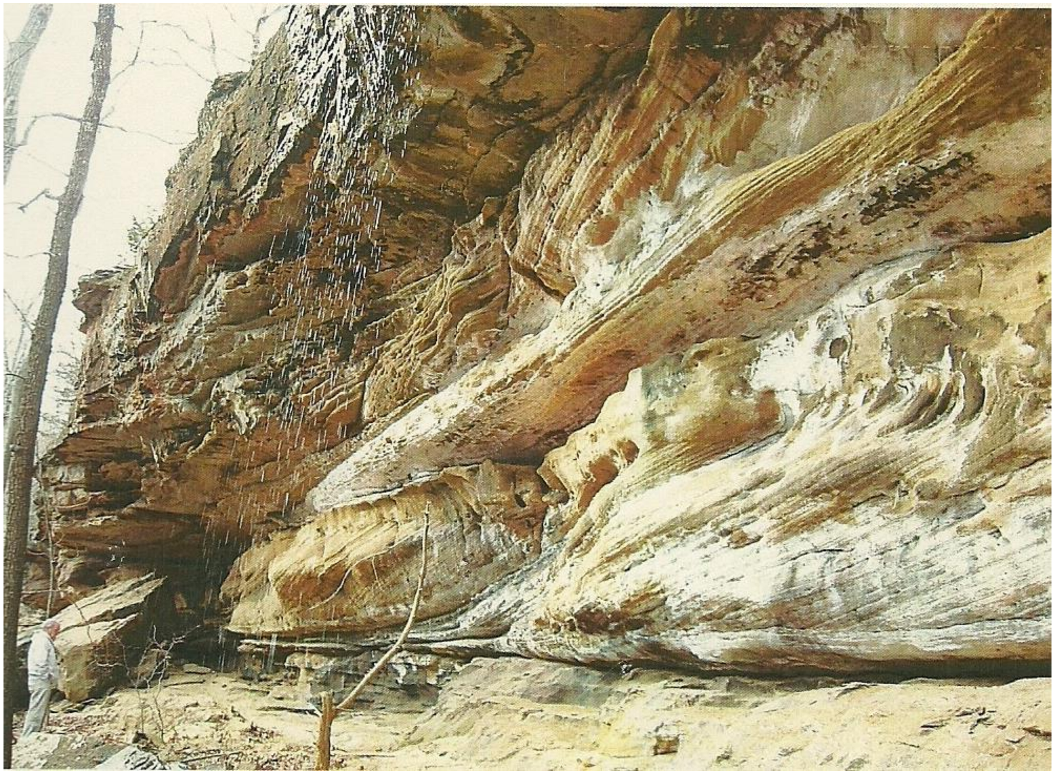

Figure 26. Middle Bloyd sandstone outcrop with Brentwood at the base, on Cannon Creek near Highway 45. (Photo credit: Angela Chandler)

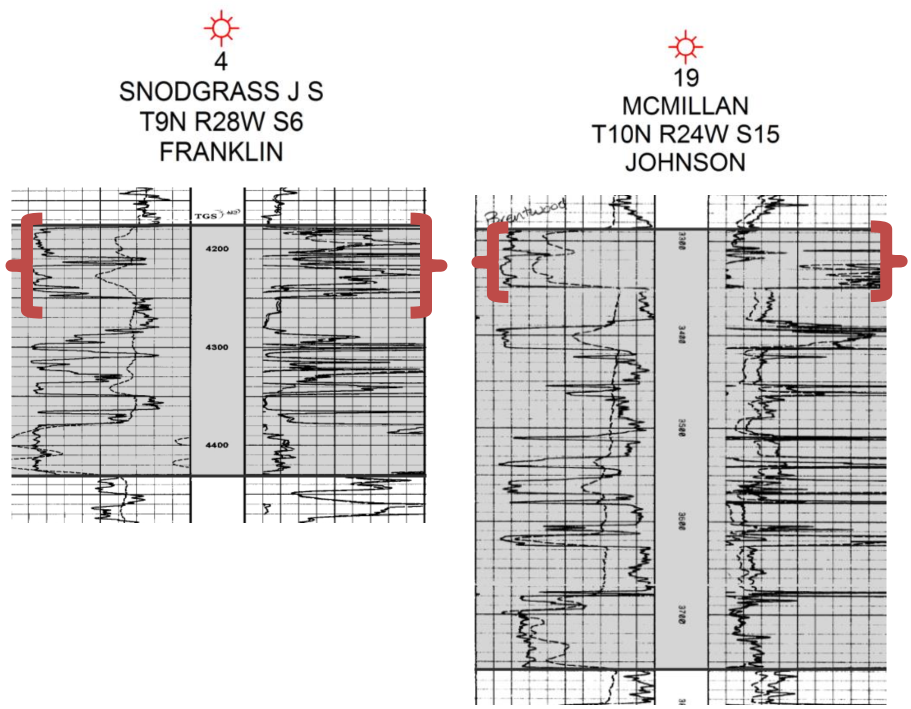

Figure 27. Logs with middle Bloyd signature highlighted.

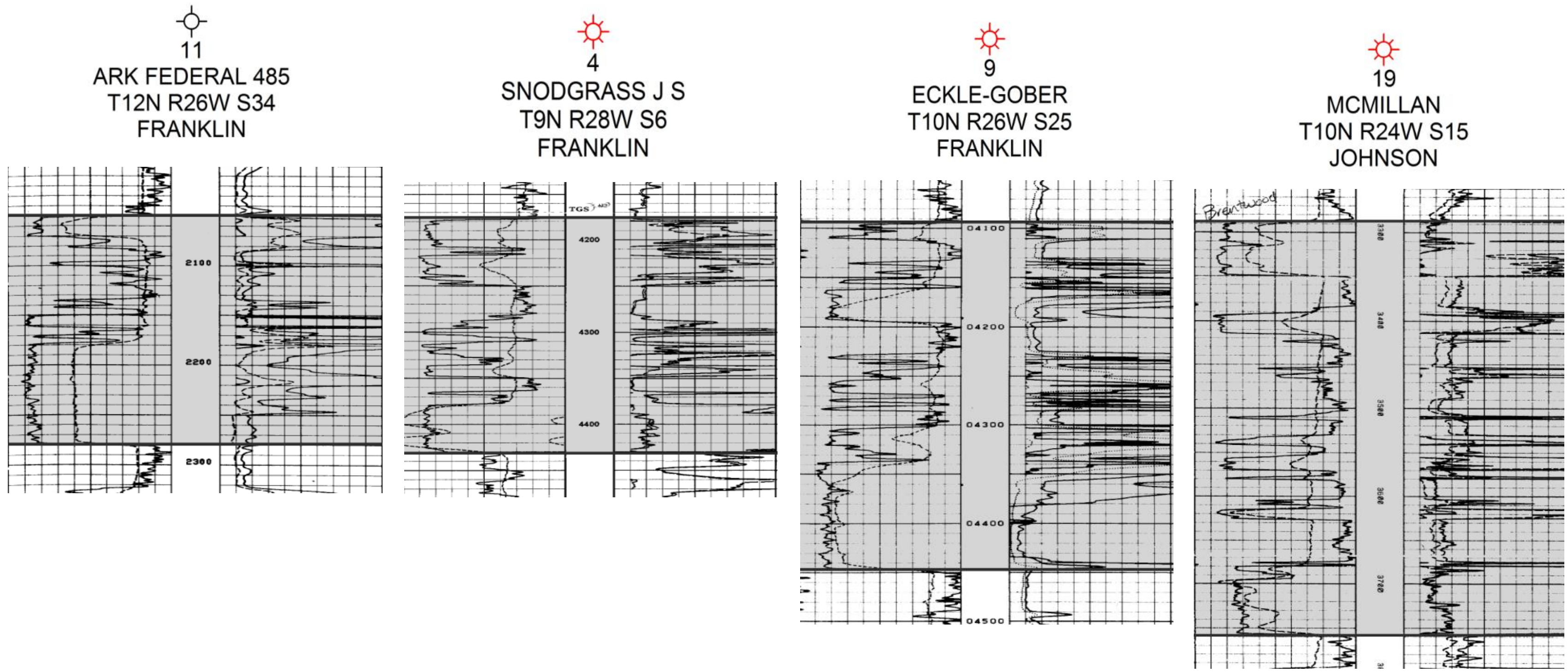

Figure 28. Prairie Grove interval wireline well log signatures.

Kessler Interval

The Kessler interval overlies the middle Bloyd sandstone and the Prairie Grove interval. It includes the Dye Shale Member and the Kessler Limestone Member, members of the Bloyd Formation. At the surface, the Kessler interval is a marine, fossil bearing dark gray shale that is overlain by a limestone unit ranging to 10 feet in thickness (Figure 29, 30). The limestone is very fossiliferous and contains occasional grains of quartz sand. In the subsurface, the gamma ray curves through this interval display a very consistent pattern, making it easily identifiable (Figure 31).

In the subsurface, the shale unit underlying the limestone is expressed as a funnel shaped, serrate signature becoming more calcareous upward (Figure 31). The limestone at the top of the Kessler interval is expressed as a low gamma radiation unit with a high resistivity signature. The interval is thinnest in the east in well 19 where it is only 60 feet thick. Thickness increases to 145 feet in the north in well 11. The Kessler behaves differently than the other intervals and diplays thinning to the east and thickens both in the north and the south.

Figure 29. Kessler interval along Interstate I-540. (Photo credit: Doy Zachry)

Figure 30. Dye Shale Member and Kessler Limestone along Interstate I-540. (Photo credit: Elizabeth Studebaker)

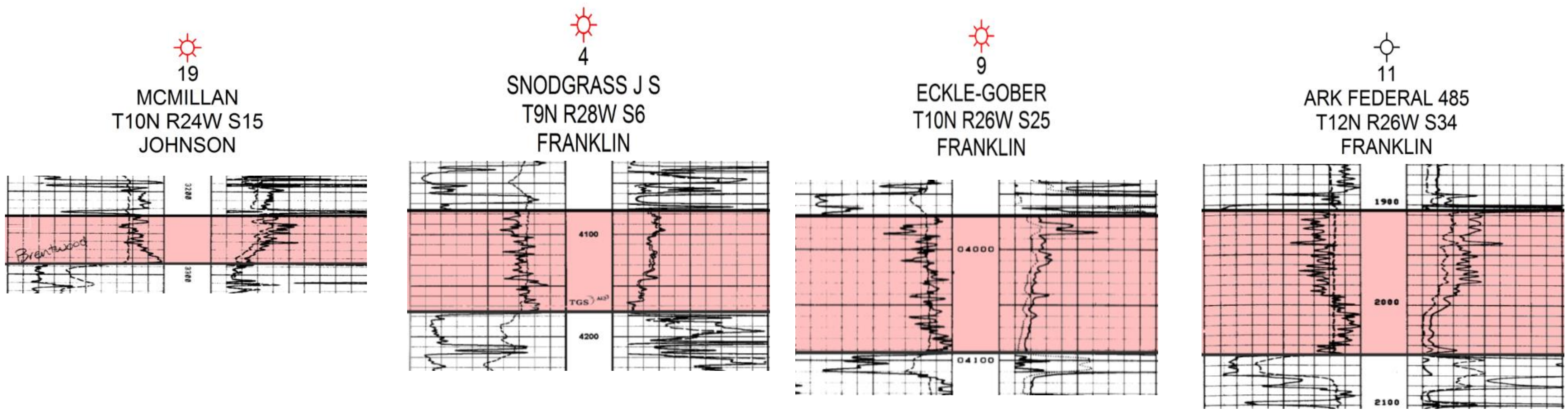

Figure 31. Kessler interval in wells 19, 4, 9, 11.

Lower Atoka Interval

The lower Atoka interval unconformably overlies the Kessler Limestone in Franklin, Johnson, and Madison counties. East of Madison County, the Kessler is absent at the surface but persists eastward across Johnson County in the subsurface of the northern Arkoma Basin. A prominent shale unit occurs about 500 feet above the top of the Kessler Limestone. The unit is regional in extent in the Arkoma basin and the base of the unit serves as the top of the lower Atoka interval. No formal names have been given in this interval and stratigraphic nomenclature follows the informal names used by petroleum geologists (Table 1). The lower Atoka is comprised of a series of seven repeating sandstone and shale intervals that can be viewed at the surface along I-540 in northwest Arkansas (Figure 32).

In the subsurface, sandstone units in the lower Atoka frequently display a funnel or coarsening upward pattern with abrupt terminations (Figure 33). This pattern is consistent with progradational systems and produced by coastal sands or deltas. Many of the sandstone units are characterized by low gamma readings (Figure 33). The lower Atoka interval thickness ranges from 500 feet in the north (well 11) to 770 feet in the south (well 9) reflecting a pattern of basinward thickening (Figure 33). Thicknesses from west to east through wells 4 and 19 remain fairly consistent at 660 feet.

Figure 32. Lower Atoka interval outcrop along Interstate I-540. Here multiple sandstone untis are separated by units of shale. Shale units are frequently covered by vegetation. (Photo credit: Doy Zachry)

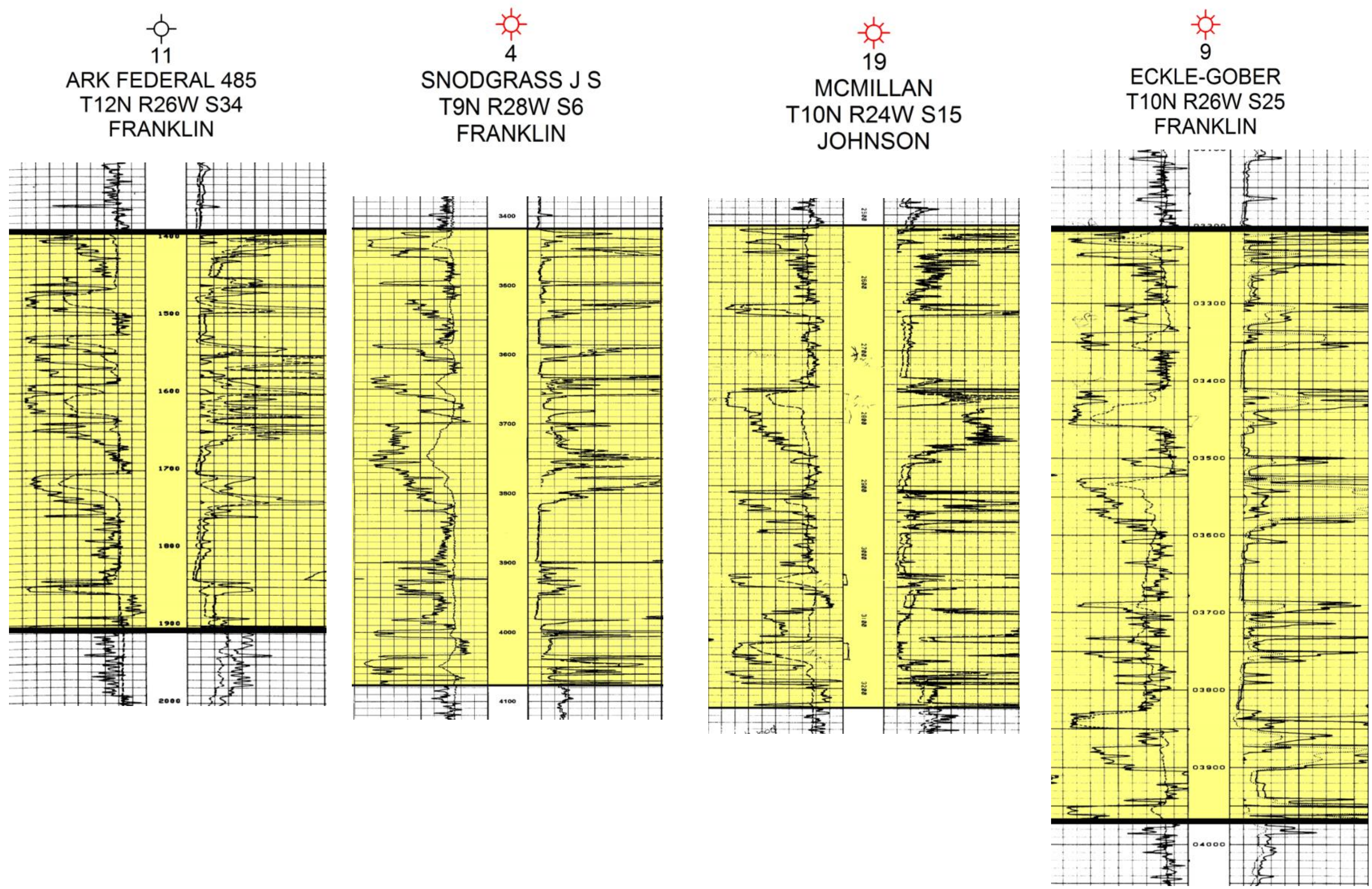

Figure 33. Lower Atoka interval wireline log signatures in wells 9, 4, 19, and 11.

SUMMARY AND CONCLUSION

Rocks of Morrow and lower Atoka age outcrop throughout the Boston Mountains in Arkansas. South into the Arkoma shelf and basin, Morrow and lower Atoka rocks are in the subsurface due to down to the south normal faults. The Morrow and lower Atoka succession were poorly defined on the shelf and in the northern portion of the basin in the subsurface in northwestern Arkansas. To help bridge this gap, regional stratigraphic and structural cross sections in Franklin and Johnson counties were constructed from 23 wireline well logs to examine the structural and stratal changes that occur in this transition zone. Tops were picked and correlated in 342 wells for the purposes of constructing two isopach maps and three structural contour maps. In addition to these, four logs from the regional cross sections were used to closely examine the stratigraphic changes within four intervals in the Morrow and the lower Atoka.

The top and base of the Morrow and the lower Atoka are easily identifiable in logs for the regional cross sections. Five structural cross sections were constructed and indicated that down to the south normal faulting is prevalent throughout the study area. Displacement values greatly increase in the south. The faults facilitated subsidence, providing accommodation space for the lower Atoka in the northern portion of the basin. A portion of the normal faults were reactivated, creating a horst and graben structure. Stratigraphic cross sections were hung on the Sells, the upper most sandstone in the lower Atoka to examine thickness changes that occur west to east and north to south. Descending south into the basin, the Morrowan and the lower Atoka thicken dramatically.

The four intervals that were created are: the Cane Hill interval, the Prairie Grove interval, the Kessler interval, and the lower Atoka interval. The Cane Hill interval includes the Cane Hill member of the Hale Formation. The Prairie Grove interval is comprised of the Prairie

Grove member of the Hale Formation and also includes the Brentwood and middle Bloyd sandstone of the Bloyd Formation. The middle Bloyd sandstone can be identified within two of the selected logs. This is significant because the middle Bloyd is difficult to identify within gamma ray logs. The Kessler Limestone and Dye Shale make up the Kessler interval. The lower Atoka interval contains the lower Atoka sandstones and shales. Within each interval, thicknesses and log signatures were compared. A terrigenous sediment source to the east facilitated eastward thickening in the Cane Hill and Prairie Grove interval of the Morrow. The Kessler interval is the only interval that thins to the east and thickens to the north. Thickening in both the Morrow and the lower Atoka occurs to the south and to the southeast due to accommodation space that was created by syndepositional faults. The Morrow and lower Atoka were deposited in a stable shelf environment.

REFERENCES

Cardot, B.J., 2012, Bibliography of the Arkoma Basin and Northeast Oklahoma Shelf, Oklahoma Geological Survey, 24p.

Cherry, S.A., 2012, Sequence Stratigraphy and Depositional Systems of the Mansfield Sand, Upper Atoka Formation, Arkoma Basin, Arkansas: [Master's Thesis, unpublished], University of Arkansas, Fayetteville, 74p.

Delavan, G., 1985, Subsurface Lithostratigraphy and Stratigraphic Framework of the Bloyd Formation (Morrowan) in Franklin, Johnson, and Pope Counties, Arkansas: [Master's Thesis, unpublished], University of Arkansas, Fayetteville, 81p.

Haley, B.R., and others, 1993, Geologic Map of Arkansas.

Hanford, C.R., and Manger, W.L., 1990, Sequence Stratigraphy and Sedimentology of the Mississippian System in Northern Arkansas, Midcontinent Section, Society of Economic Paleontologists and Mineralogists, 1990 Field Conference Guidebook, unnumbered.

Herndon Map Service Inc., 2013, Arkoma Quarterly Service, updated 10-07-13

Houseknecht, D.W., and Kacena, J.A., 1983, Tectonic and Sedimentary Evolution of the Arkoma Foreland Basin, Tectonic-Sedimentary Evolution of the Arkoma Basin and Guidebook to Deltaic Facies, Hartshorne Sandstone, v. 1, p. 3-33.

Houseknecht, D.W., 1986, Evolution from Passive Margin to Foreland Basin: the Atoka Formation of the Arkoma Basin, South-Central U.S.A., International Association of Sedimentologists, Special Publications 8, p. 327-345.

Houseknecht, D.W., 2009, Natural Gas Assessment of the Arkoma Basin, Ouachita Thrust Belt, and Reelfoot Rift: Arkoma Basin Shelf and Deep Basin Plays, Oklahoma Geological Survey Meeting Presentation.

Long, W.A., 1997, The Mulberry Fault Zone: An Analysis of Subsurface Geometry and Timing of Fault Displacement: [Master's Thesis, unpublished], University of Arkansas, Fayetteville, 121p.

Manger, W.L., and Zachry, D.L., 1998, Morrowan (Lower Pennsylvanian) Reservoir Stratigraphy, Southern Ozark Region, Northern Arkansas, Unpublished Field Guide, Fayetteville, Arkansas: University of Arkansas Department of Geosciences.

Manger, W.L., Zachry, D.L, and Garrigan, M.L., 1988, An Introduction to the Geology of Northwestern Arkansas: The Compass, Sigma Gamma Epsilon, v. 65, no. 4, p. 242-257.

McFarland, J.D., 2004, Stratigraphic Summary of Arkansas: State of Arkansas, Arkansas Geological Commission: Information Circular 36, p. 38.

McGilvery, T.A, and Houseknecht, D.W., 2000, Depositional systems and diagenesis of slope and basin facies, Atoka Formation, Arkoma Basin, Marine clastics in the southern Midcontinent, 1997 symposium: Oklahoma Geological Survey Circular 103, p. 129-140.

Pontiff, J.L., 2007, Regional Stratigraphic Framework of Morrowan Strata, Northern Arkoma Basin: [Master's Thesis, unpublished], University of Arkansas, Fayetteville, 86p.

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.

Zachry, D.L., 1979, Early Pennsylvanian Braided Stream Sedimentation, Northwest Arkansas: Tulsa Geological Society Special Publications 1, p. 269-81.

Zachry, D.L, 1983, Sedimentological Framework of the Atoka Formation, Arkoma Basin, Arkansas: In D.W. Houseknecht, (ed.), Tectonic-Sedimentary Evolution of the Arkoma Basin: Journal of Sedimentary Petrology, Mid-Continent Section Guidebook, v. 1, p. 34-52.

Zachry, D.L., and Sutherland, P.K., 1984, Stratigraphy and Depositional Framework of the Atoka Formation (Pennsylvanian) Arkoma Basin of Arkansas and Oklahoma, Oklahoma Geological Society Bulletin 136, p. 9-17.

Appendix A: Cross Section Well Data

Cross Section	UWI/API	WELL NAME	LABEL	COUNTY	OPERATOR
A-A'	3047110800000	FEDERAL 46676	1	FRANKLIN	SEECO INCORPORATED
	3047102950000	DALTON	2	FRANKLIN	SEECO INCORPORATED
	3047109520000	SMITHER	3	FRANKLIN	SEECO INCORPORATED
	3047113610000	SNODGRASS J S	4	FRANKLIN	STEPHENS PRDCTN CO
B-B'	3047101380000	FREEMAN	5	FRANKLIN	TENNECO OIL CO
	3047106350000	MCGUIRE	6	FRANKLIN	HENRY PETROLEUM INC
	3047101870000	CROSBY	7	FRANKLIN	SEECO INCORPORATED
	3047103010000	BIBLER BROS	8	FRANKLIN	CELERON O&G CO
	3047105040000	ECKLE-GOBER	9	FRANKLIN	MAXUS ENERGY CORP
C-C'	3047101150000	FEDERAL	10	FRANKLIN	C & K PETROLEUM INC
	3047102100000	ARK FEDERAL 485	11	FRANKLIN	TEXAS O&G CORP
	3071101860000	FEDERAL	12	JOHNSON	TENNECO OIL CO
	3071104530000	RAMBO	13	JOHNSON	WEISER-BROWN OPER CO
	3071102510000	FARRINGTON	14	JOHNSON	SEECO INCORPORATED
D-D'	3047104020000	ALEXANDER	15	FRANKLIN	EXOK INCORPORATED
	3047108910000	JANE	16	FRANKLIN	SEECO INCORPORATED
	3047109300000	ROBERT	17	FRANKLIN	SEECO INCORPORATED
	3047108520000	CHILDERS	18	FRANKLIN	HANNA OIL & GAS CO
	3071107190000	MCMILLAN	19	JOHNSON	SEAGULL MID-STH INC
E-E'	3071101090000	FEDERAL ES-5277	20	JOHNSON	ARKANSAS WESTERN GAS
	3071101850000	SCOTT	21	JOHNSON	SEECO INCORPORATED
	3071106070000	ROSE	22	JOHNSON	MUELLER THOMAS C
	3071108970000	STOKES	23	JOHNSON	SAGELY FLYD PROP LTD

	LABEL	DATUM (KB)	SELLS (FT)	KESSLER (FT)	PITKIN (FT)	L. Atoka Thickness	Morrow Thickness	L. Atoka Thickness Difference	Morrow Thickness Difference
A-A’	1	892	1506	1994	2490	488	495		
	2	600	1557	2146	2571	590	425		
	3	486	2759	3290	3860	530	571		
	4	456	3418	4076	4635	659	559	171	64
B-B'	5	929	766	1248	1767	482	519		
	6	1735	1358	1925	2450	567	525		
	7	1783	1460	2048	2631	588	583		
	8	982	819	1476	2158	657	682		
	9	526	3203	3969	4700	766	731	284	213
C-C'	10	1491	1121	1554	2020	433	466		
	11	1540	1391	1906	2425	515	519		
	12	929	997	1496	1996	499	500		
	13	1417	984	1468	1892	484	424		
	14	1814	1189	1655	2242	467	587	33	121
D-D'	15	398	3949	4279	4800	330	521		
	16	542	4090	4761	5305	671	544		
	17	535	2991	3678	4337	687	659		
	18	639	3209	3894	4507	686	612		
	19	755	2515	3194	3909	679	715	349	194
E-E'	20	1618	800	1330	1893	530	563		
	21	2022	1392	1933	2543	541	610		
	22	605	3143	3833	4527	690	695		
	23	465	5505	6359	7210	855	850	325	287