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Initial Structural Subsidence as Reflected in Morrowan and Atokan (Pennsylvanian) Subsurface Stratigraphy, Northern Arkoma Basin, North-Central Arkansas

Fatimah Taher Nahi Al Asadi
University of Arkansas, Fayetteville

Initial Structural Subsidence as Reflected in Morrowan and Atokan (Pennsylvanian) Subsurface Stratigraphy, Northern Arkoma Basin, North-Central Arkansas

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by

Fatimah Taher Nahi Al_Asadi
University of Basra, Iraq
Bachelor of Science in Geology, 2011

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University of Arkansas

This thesis is approved for recommendation to the Graduate Council.

____
Dr. Doy Zachry
Thesis Director

____
Dr. Christopher Liner
Committee Member

____
Ms. Jamie Woolsey
Ex-Officio Member

____
Dr. Thomas A. (Mac) McGilvery
Committee Member

Abstract

The Arkoma Basin is a carboniferous foreland basin that is known for its prolific gas production. The objective of this research is to study the initial subsidence of the basin by analyzing the stratigraphic and structural features of the study area. This was accomplished through IHS Petra, Surfer 13, and Win-Tensor software. Field work studies comprised a large part of this study. Also, a seismic profile and Google earth elevation profiles are among the methods used to study the initial subsidence of the Arkoma Basin. The study area within the basin represents a transitional zone from the shelf into the northern portion of the basin. The defining formations in this project are of Morrowan and Atokan age.

Within the vicinity of the Arkoma Basin in north-central Arkansas, the stratigraphic analysis confirms a continuous thickening of the Middle Atoka interval south of the study area toward the Ouachita thrust belt, determined through utilizing raster well logs. Furthermore, system tracts were defined for each formation in this study, giving a general overview of the change in sea-level associated with the process of subsidence of the basin.

Structural analysis presents distinctive features that dominated the study area. Both the Mulberry and Clarksville master faults are east-west trending normal faults. These master faults are considered to be growth syn-depositional faults, which are the main evidence for tectonic subsidence of the basin. Additionally, the area shows a graben feature named Bullfrog Graben that is considered significant evidence for the local flexure loading of the Arkoma basin.

Acknowledgment

My successful academic studies have involved lots of good people whom deserved to be thanked.

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CHAPTER 1

INTRODUCTION

1.1 Problem Statement

The Arkoma Basin is one of several petroleum basins in the United States. It extends from west-central Arkansas to southeastern Oklahoma over an area about 33,800 sq. mi (Perry, 1995). Sedimentary rocks in the modern Arkoma Basin record a history of basin formation as a structural feature. The beginning of basin subsidence may be documented in the stratigraphic units of the basin. The structural characterization of the basin reflects a distinctive faulting pattern, interpreted to be caused by normal faults. The growth faulting in the Arkoma Basin developed during Pennsylvanian time. The inception of Arkoma Basin development is recorded in late Mississippian and early Pennsylvanian time.

This study focuses on the Morrowan, Lower Atoka, and Middle Atoka (Carboniferous, Paleozoic) in the Arkoma Basin of north-central Arkansas. The sequence of deposition in the Middle Atoka Formation provides valuable insight in timing of faulting in the development of the Arkoma Basin (Buchanan and Johnson, 1968). A model based on structure and stratigraphic analysis is presented in this study.

The purpose is to document the tectonic history of the Arkoma Basin in terms of sedimentation, subsidence, and growth faulting. This study provides an interpretation of the subsurface by documenting the changes in structure and stratigraphy of the basin in northcentral Arkansas. In order to achieve this objective, several methods were utilized.

1.2 Location of Study Area

The Arkoma is bordered on the north by the Ozark Uplift and on the south by the Ouachita fold belt (Figure 1.1). It is located in the northern part of the Arkoma Basin of north-central Arkansas. It is bounded to the north by Township 11N and to the south by Township 8N. The western boundary is Range 23W and the eastern boundary is Range 18W in Pope, Logan, and Johnson counties (Figure 1.2). The area for this study includes numerous gas fields that are present within the thirty township area. It encompasses approximately 1,080 square miles in the Arkoma Basin.

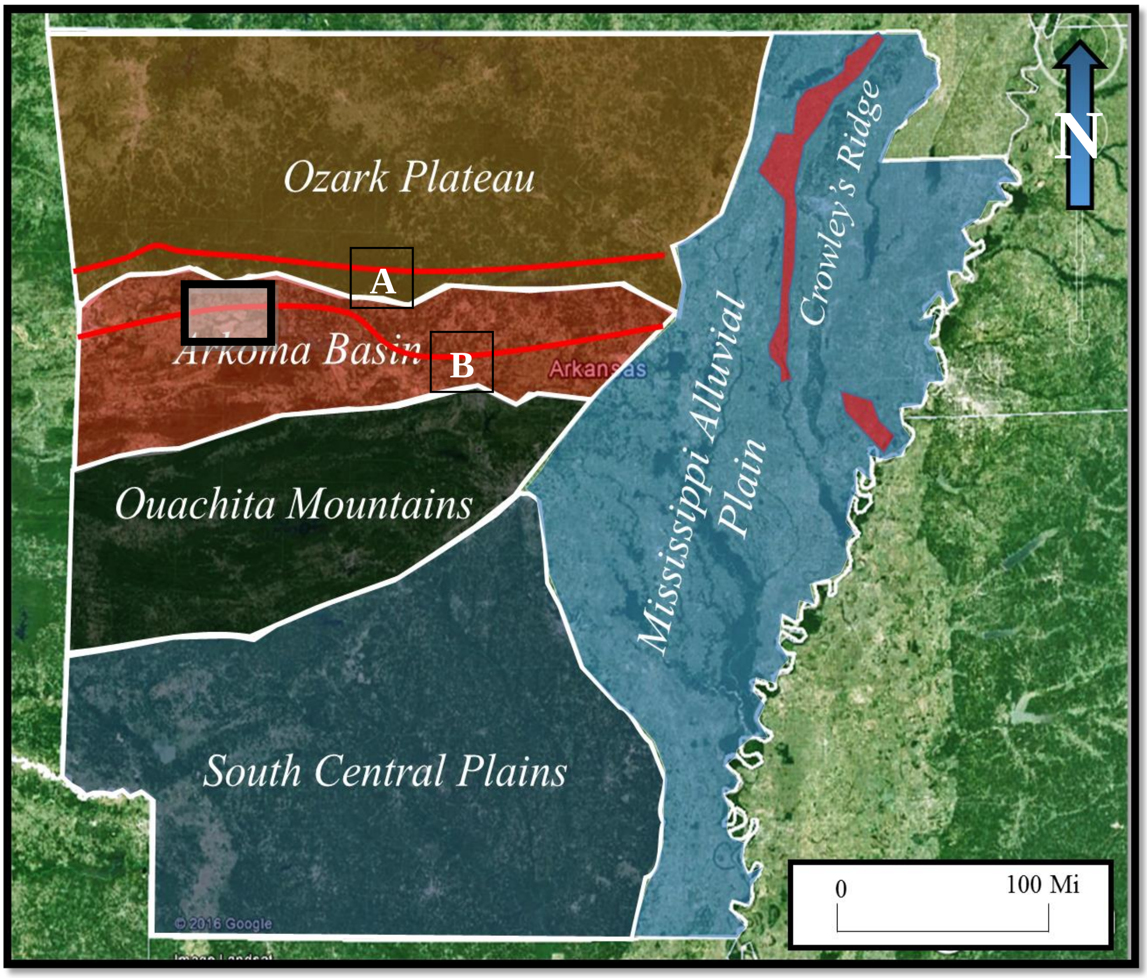

Figure 1-1: Tectonic Provinces of the Arkoma Basin in Arkansas. Study area is highlighted in the box, indicating the position for both the Cass Monocline Fault (A) and the Mulberry Fault (B).

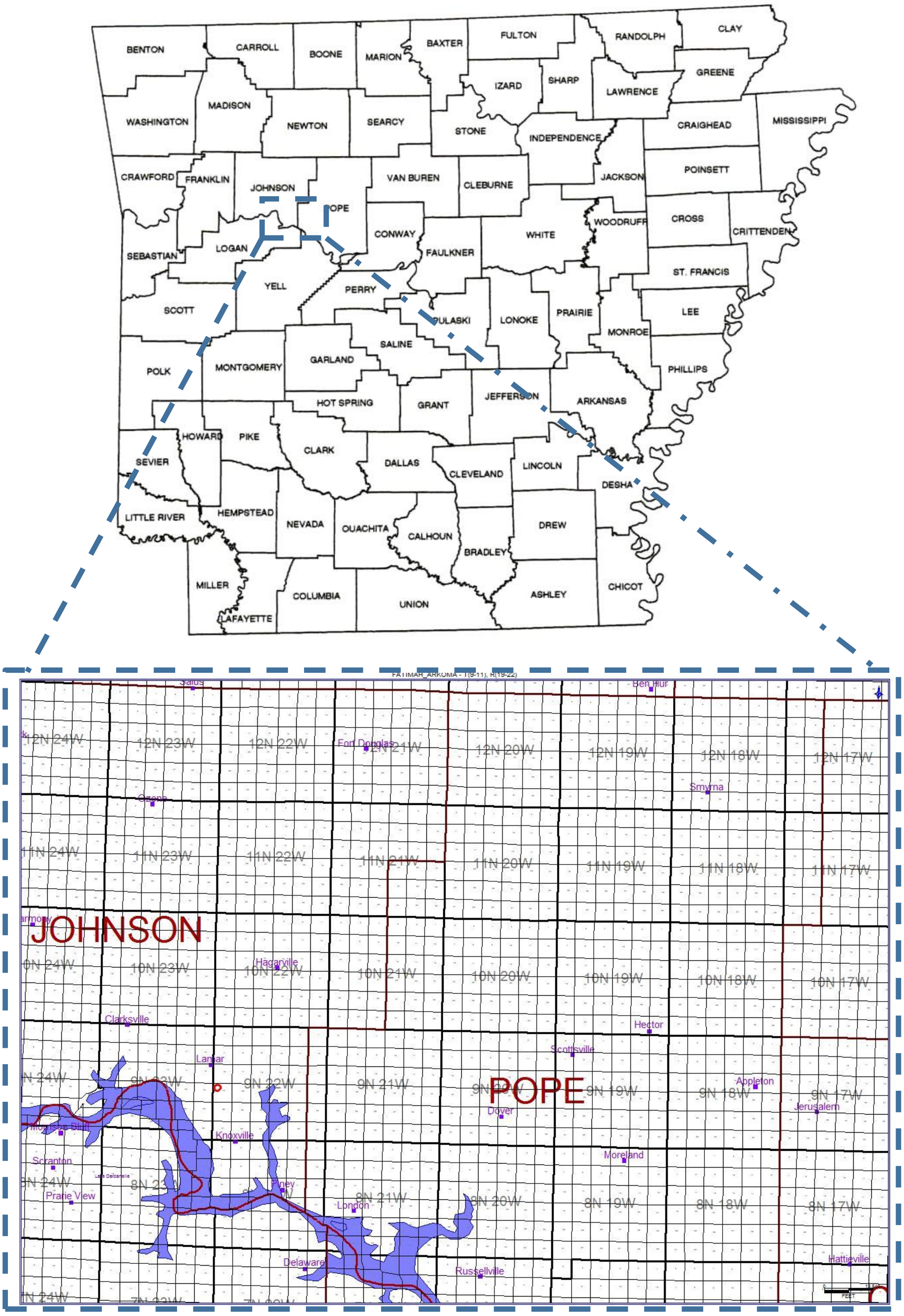

Figure 1-2: Location map of the study area in northcentral Arkansas within Johnson and Pope counties. The Arkansas River crosses the southwestern part of the area.

1.3 Previous Studies

The Arkoma Basin is one of the main gas producing basins in the United States. Numerous studies have been published on significant aspects of Morrowan and Atokan strata in northern Arkansas. Morrowan and Atokan formations of the Pennsylvanian section were studied with an emphasis on natural gas producing reservoirs. The studies have examined different aspects of the Arkoma Basin, including lithology, stratigraphy, and tectonic settings.

Most models for the Arkoma Basin have focused on tectonics as the dominant mechanism for controlling the depositional environment. A growth fault model was presented by Buchanan and Johnson (1968) to explain the development of the Middle and Lower Atoka formations. They described the model by producing structural cross sections to emphasize the role of tectonics in in shaping the basin. During the development of these tectonically driven listric growth faults, an increase in sediment supply was also occurring and has been attributed to the same tectonic activity.

Delavan (1985) completed a subsurface stratigraphic framework of the Bloyd Formation in the Arkoma Basin in Arkansas. The study focused on Morrowan strata. Depositional settings were discussed by examining and correlating mechanical well logs from petroleum exploration wells. His subsurface cross-sections and isopach maps suggested that Morrowan strata gradually thicken to the east within the basin.

Houseknecht (1986) conducted a study on the development of the Arkoma Basin in relation to tectonic activities, deducing that syn-depositional movement along normal faults was the main control for the development of depositional facies in early Atokan time. He also presented a tectonic model for the basin that emphasized the Ouachita Orogeny's role in shaping the Arkoma Basin (Figure 1-5).

Goff (1989) focused on the structural configuration of the Hunton Group in northcentral Arkansas. She described the change in depositional patterns throughout geological time utilizing isopach maps. The structural study emphasized the association of natural gas accumulations with normal faults that resulted from the extensional forces.

Jameson (1998) interpreted two 2D seismic profiles and correlated more than 70 well logs in order to document the stratigraphic and structural styles in northwestern Arkansas. He prepared cross sections from well logs that revealed a diverse subsurface structural style.

LaGrange (2002) determined the depositional characteristics and reservoir performance in the Lower Atoka Formation. He studied the potential source of sediment deposits with detailed analysis, suggesting that the main source consisted of sedimentary rocks from the Appalachians with sediments transported across the cratonic interior.

Pontiff (2007) defined the stratigraphic framework of the middle Bloyd sandstone of the Morrowan section in Franklin, Johnson and Pope counties of northcentral Arkansas. She examined the changes in lithology during the transition of the depositional regime from braided stream to marine deposits.

1.4 Tectonic History of the Arkoma Basin

In Arkansas, the regional geology consists of three tectonic provinces from north to south; the Ozark Platform, Arkoma Basin, and Ouachita Fold and Thrust Belt (Figure 1-1). The study area lies within the northcentral part of the Arkoma Basin. The development of the basin occurred during Early Pennsylvanian time. The Arkoma Basin is one of several foreland basins that formed during various phases of the Ouachita Orogeny. Geologically, the basin is bounded by tectonic boundaries as a result of subduction and a sequence of collision events between the North American continental margin and the Sabine terrain. The Arkoma is a peripheral foreland basin that is associated with the Ouachita Fold Belt of Arkansas and Oklahoma. The basin is approximately 50 miles wide and 250 miles long (Delavan. 1985).

1.4.1 Ozark Platform

The northern portion of Arkansas is composed of the Ozark Uplift or Ozark Dome, which covers about 12% of the state of Arkansas. The Ozark Platform was formed about 1.5 billion years ago as a part of the North American Continent (Cohoon, 2013). The southern margin of this stable platform was broken by series of extensional normal faults as it evolved into the Arkoma foreland basin during the early Pennsylvanian (340-320 M.A) (Jameson, 1998). The Ozark Uplift is centered in southern Missouri, northeastern Oklahoma, the northern part of Arkansas, and the very southeastern corner of Kansas. The southern boundary of the uplift extends across the northern part of both Franklin and Crawford counties in Arkansas. The sediments in the southern and western flanks of the Ozark Platform in Arkansas are dominated by clastic sediments and calcareous mudstone. The sediments that were dominantly deposited during pre-Pennsylvanian time were composed of limestone, whereas during the Pennsylvanian, the sediments were composed mostly of interbedded sandstone and shale.

The southern flank of the Ozark Plateau is bounded by the Mulberry Fault characterized as a transitional zone between the Ozark Uplift and Arkoma Foreland Basin. Moyer (1985) identified the actual location of the transitional zone, which extends from the Cass Fault System on the Ozark Plateau to the Mulberry Fault in the Arkoma Basin in Arkansas. The study area is located in the southern part of the transitional zone between the Ozark Platform and Arkoma Basin (Figure 1-1).

1.4.2 Arkoma Basin

The Arkoma is a foreland basin with an elongate shape. It extends from the east across northcentral Arkansas westward into the southeastern part of Oklahoma. In Arkansas, the basin is bordered by the Ozark Uplift to the north and by the Ouachita Fold Belt to the south (Figure 1-3). The southern part of the Arkoma Basin is characterized by a series of thrust faults. The basin is described as a synclinorium composed of Paleozoic strata (Houseknecht, 1987). The strata exhibit southerly dips which range from less than one degree on the Ozark Platform to eight degrees on the northern flank of the Arkoma Basin. The northern part of the Arkoma Basin is dominated by numerous northwest to southeast trending faults and asymmetrical folds (McGilvery, 1982). During the Pennsylvanian, clastic sediments filled the basin forming the Hale and Atokan formations, while carbonate sediments covered the upper part of the Morrowan series, specifically in the Kessler and Brentwood members of the Bloyd Formation. The sediments that filled the Arkoma were derived from the southern margin of the North American Craton (Long, 2005)

The basin contains a series of faults and folds, both at the surface and in the subsurface that resulted from extensional forces associated with the development of the Arkoma Basin. These forces were referred to as the Ouachita Orogeny (Figure 1-4). They resulted in the uplift of the Ozark Plateau, causing trends of anticlines, synclines, and both normal and reverse faults (Delavan. 1985) (Figure 1-3). The compressional tectonic effect migrated northward during the Middle Pennsylvanian (McGilvery, 1982). The Arkoma Basin development started in the Early to Middle Atokan time, approximately 320 MY ago, when most of the subsidence took place in the basin. Sediments were deposited in thicknesses up to 25,000 feet (5.5 km) simultaneously with the fault driven subsidence in the basin (Figure 1-4) (Houseknecht, 1986).

Houseknecht (1986) illustrated the tectonic events of the Arkoma Basin from late Precambrian to early Paleozoic time. Figure 1-5 represents the geological time series of Arkoma Basin development. The first tectonic series (A) of the Arkoma Basin recorded the opening of the proto-Atlantic Ocean basin during the late Precambrian to Cambrian time. The second tectonic stage (B) beginning in the Late Cambrian to Early Mississippian time, represented the onset of the ocean basin closure due to the northern encroachment of “Llanoria” (Figure

1-5). By Early Mississippian to Early Atokan time (C), as a result of southward subduction beneath Llorania, resulting in series of east-west trending normal faults. The basin started to form through the generation of growth faults and an increase in sediment supply from the east side of the basin. Houseknecht states that during the Early to Middle Atokan time (D), the ocean closure was completed. He also suggested that there was reactivation of the normal growth faults later causing the development of the foreland basin. During Middle to Late Atokan time (E), the Arkoma Basin development continued to result in complex structural deformation adjacent to the Ouachita Mountains (Houseknecht and Kacena, 1983). During the fourth and fifth tectonic stages, the Middle Atoka Formation experienced major facies thickening, which was controlled mainly by the increase of accommodation space for the re-ceived sediments.

Figure 1-3: Geological Map for the research project highlighting the study area. (A) the geological map of Arkansas (modified from Aransas Geological Survey,1993), (B) the study area selected in terms of faults and counties, and (C) the local area in terms of the structural boundaries (modified from Cohoon in 2013).

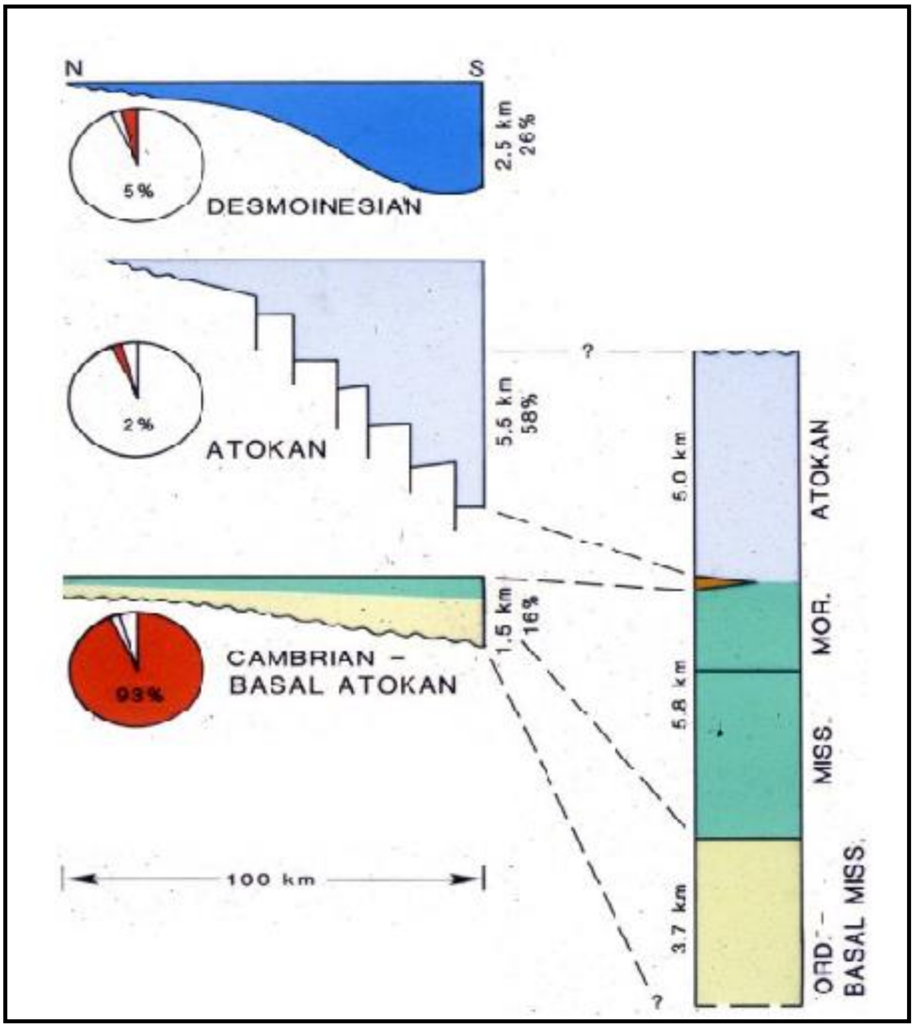

Figure 1-4: A tectonic- stratigraphic diagram representing the development of the Arkoma Basin during Mississippian and Pennsylvanian time. The diagram illustrates the thickness increase and the time of sedimentation during Middle Atokan time (modified from Houseknecht, 1986).

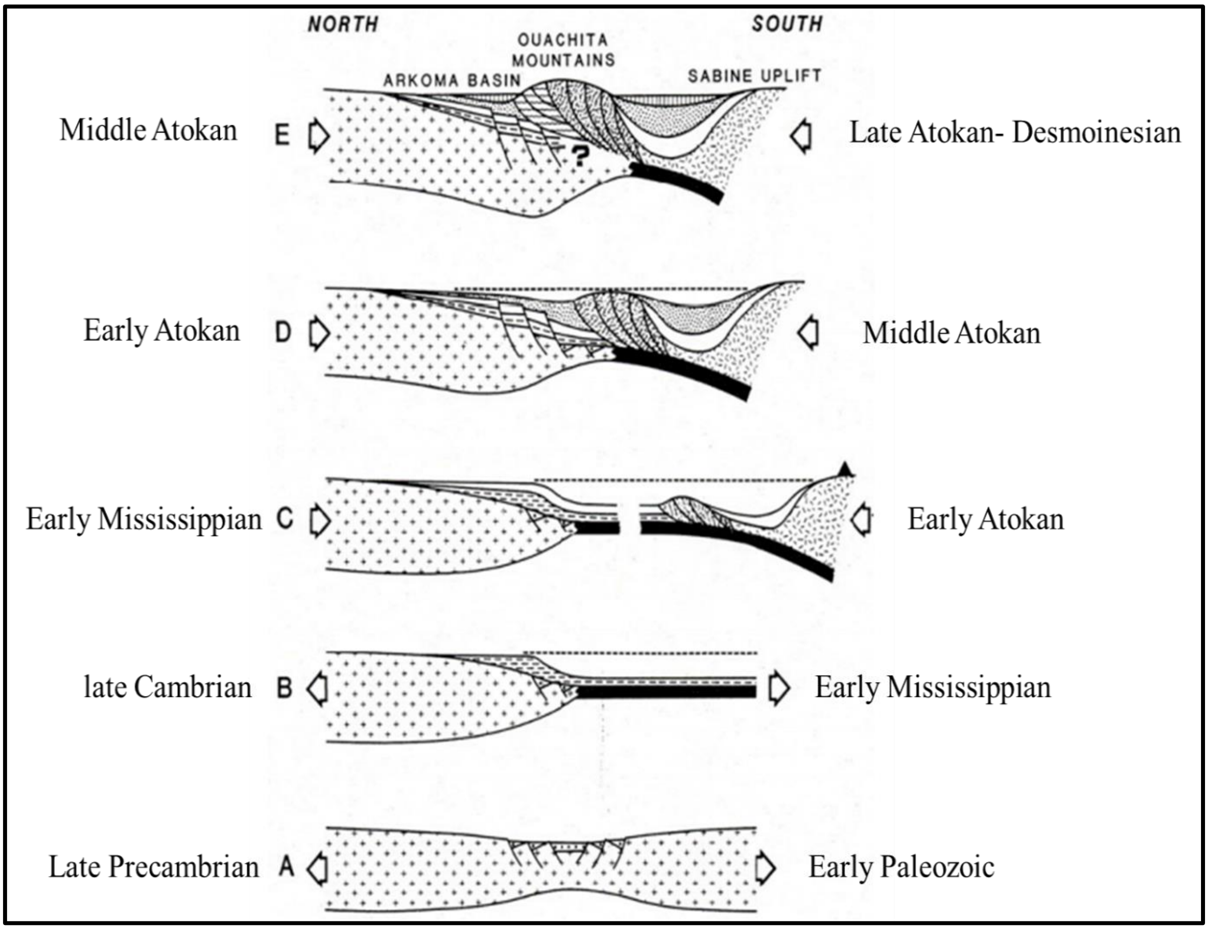

Figure 1-5: The tectonic history of the Arkoma Basin. The diagram represents the development of the basin from Precambrian through Devonian rifting in A to B, whereas stages C to E represent the development of the basin from Mississippian to Pennsylvanian time (modified from Houseknecht, 1986).

1.4.3 Ouachita Fold Belt

The Arkoma Basin is bounded on the southern margin by the Ouachita Fold and Thrust Belt Zone (Figure 1-1). The Ouachita Belt is defined to the north by the trace of the Choctaw Thrust Fault in Oklahoma and the Ross Creek Thrust Fault in Arkansas (Sutherland, 1988), while the southern boundary is defined by the Gulf Coastal Plain or the South Central Plains, which are dominated by Cretaceous deposits. This area is characterized by extreme structural deformation, resulting in numerous thrust faults, synclines, and anticlines.

1.5 Methodology

Two important methods were used in this study; well log analysis and field techniques. Using these methods provided a simple understanding of the depositional environment that existed during Arkoma Basin subsidence. The analysis of these procedures is important for generating a depositional model for the basin.

1.5.1 Log Analysis and Isopach Maps

Well log data and field studies are the primary methods to accomplish this study. The wireline log study is a preliminary approach used to provide better understanding of the geology of the study area. Within the study area, 1549 wells (Figure 1-6) were processed using IHS Petra log software. The well logs are important for constructing structural and stratigraphic cross sections, as well as building structural contour and isopach maps. Well logs were used to construct a grid of north-south and east-west cross-sections for the area of interest in order to understand the subsurface structure and stratigraphy. The raster well logs were correlated using the gamma ray and resistivity curves to pick the tops based on the identical well log signature in type logs of relatively close distance within the study area. The wells were selected based on location, drilling depth, and the quality of the log curves. Units that were identified by examining boundaries on the well logs include the Hale, Bloyd (Kessler and Brentwood members), Lower Atoka (the base of the Casey unit), and Middle Atoka (Tackett) formations.

Isopach maps for most of the Morrowan and the Atokan formations were generated by examination of the well logs from IHS Petra. Furthermore, understanding the variation in the formation thickness provided more evidence for the growth faults that were generated during the Middle Atokan Formation in relation to the facies thickness change, either thickening or thinning as sediments were deposited in the basin.

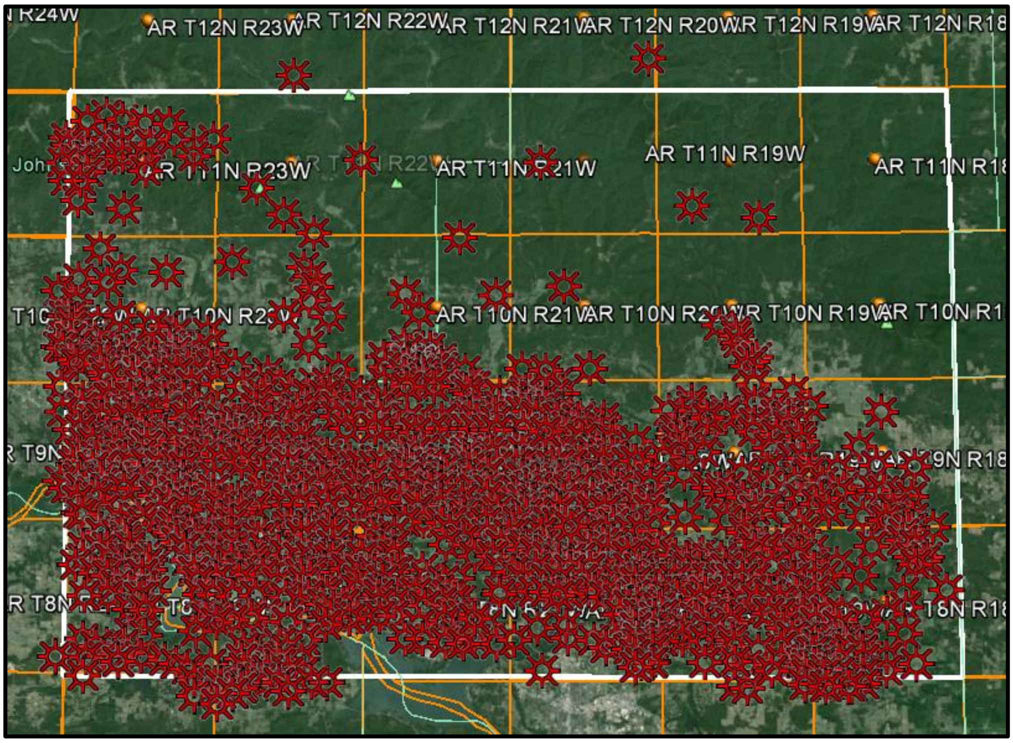

Figure 1-6: Google Earth map of the study area illustrating the well locations within the Townships and Ranges.

A dynamic 3D structural diagram was constructed through Surfer 13 in kriging key parameter in order to assist in the visualization of some of the structural features. Moreover, Google Earth software was utilized in this study to provide two topographic profiles for the mapped area. Utilizing the Google Earth profiles is significant when correlating to the sub-surface structure.

1.5.2 Field Techniques

The field technique is considered to be another important tool to aid in petrographic analysis for determining the effect of growth faulting during the Middle Atokan Formation, as well as observing the stratigraphic characterizations for the study area. Most of the examined outcrops are mapped outside the area limit. There are two reasons for choosing the locations of the outcrops. First, the study area does not have good formation exposures. Second, the interpreted outcrops have similar characteristics to ones within the study area. The outcrops include Morrowan strata (Hale and Bloyd formations) and Atokan strata (Lower and

Middle Atoka formations). Field studies are significant to present the reflection of the depositional environment through the selected facies. Also, they provide an important tool in assisting the subsurface correlation of stratigraphic cross-sections and the subsequent maps generated from the well log signatures.

CHAPTER 2

ARKOMA BASIN STRATIGRAPHIC ANALYSIS

2.1 Regional Stratigraphy

Stratigraphic analysis is significant in order to reconstruct a model for the depositional settings within a chronostratigraphic framework for the Arkoma Basin. In other words, it provides a powerful tool for understanding sedimentary basin evaluation. Also, it is important for presenting the general geological settings for gas producing areas, specifically in the northcentral part of the Arkoma Basin since the stratigraphic traps are considered to be one of the main traps for hydrocarbons.

The Arkoma Basin is characterized by several unconformities within the stratigraphic column. The study area has two main unconformities that bound the Pennsylvanian. The first unconformity separates the Chesterian and Morrowan series (about 325 Ma), and the second one separates the Morrowan and Atokan series (about 313 Ma). Unconformities in the Arkoma Basin are also important in identifying the sequence boundaries for the system tracts.

2.2 Log Signatures

In terms of subsurface stratigraphic analysis, wire-line logs are considered to be one of the most common types of geologic data used. The raster log images were used to study the subsurface stratigraphy of the Arkoma Basin. Even though wire-line logs do not provide direct information about lithologic and stratigraphic interpretations, they are helpful in providing some related information about petrophysical properties of penetrated strata. For the purpose of this study, the electric logs that are mostly depended on are gamma ray (GR), resistivity, and conductivity curves.

Well log data provide significant information for interpreting parasequence sets within the mapped formations. Figure 2-1 shows a well log, highlighting the formations examined in this study. Each formation shows some change in the strata thickness, associated with the depositional environments. The change in thickness within a selected formation reveals different parasequence types. The Hale Formation displays an upward thickening-coarsening pattern within sandstone intervals. This thickening suggests progradational parasequence sets. Whereas, the Bloyd intervals (Kessler and Brentwood) are difficult to interpret because of their different lithology (carbonate deposits), and the thinner intervals compared to other intervals in this study. Additionally, both Atokan formations (Lower and Middle) display aggradational parasequence sets due to the change in the thickness of sandstone and shale intervals.

Each interval in this study is interpreted to represent a high-stand system tract, which is due to the location of the study area along the northern margin of the basin. Generally, the slope of the Arkoma Basin represents high-stand system depositional pattern. However, within the slope location, low-stand system deposits might be present. The low-stand deposits are interpreted to represent the lowest depositional area within the same location. In order to justify the change in the system tracts, a detailed study is required for each individual formation interval.

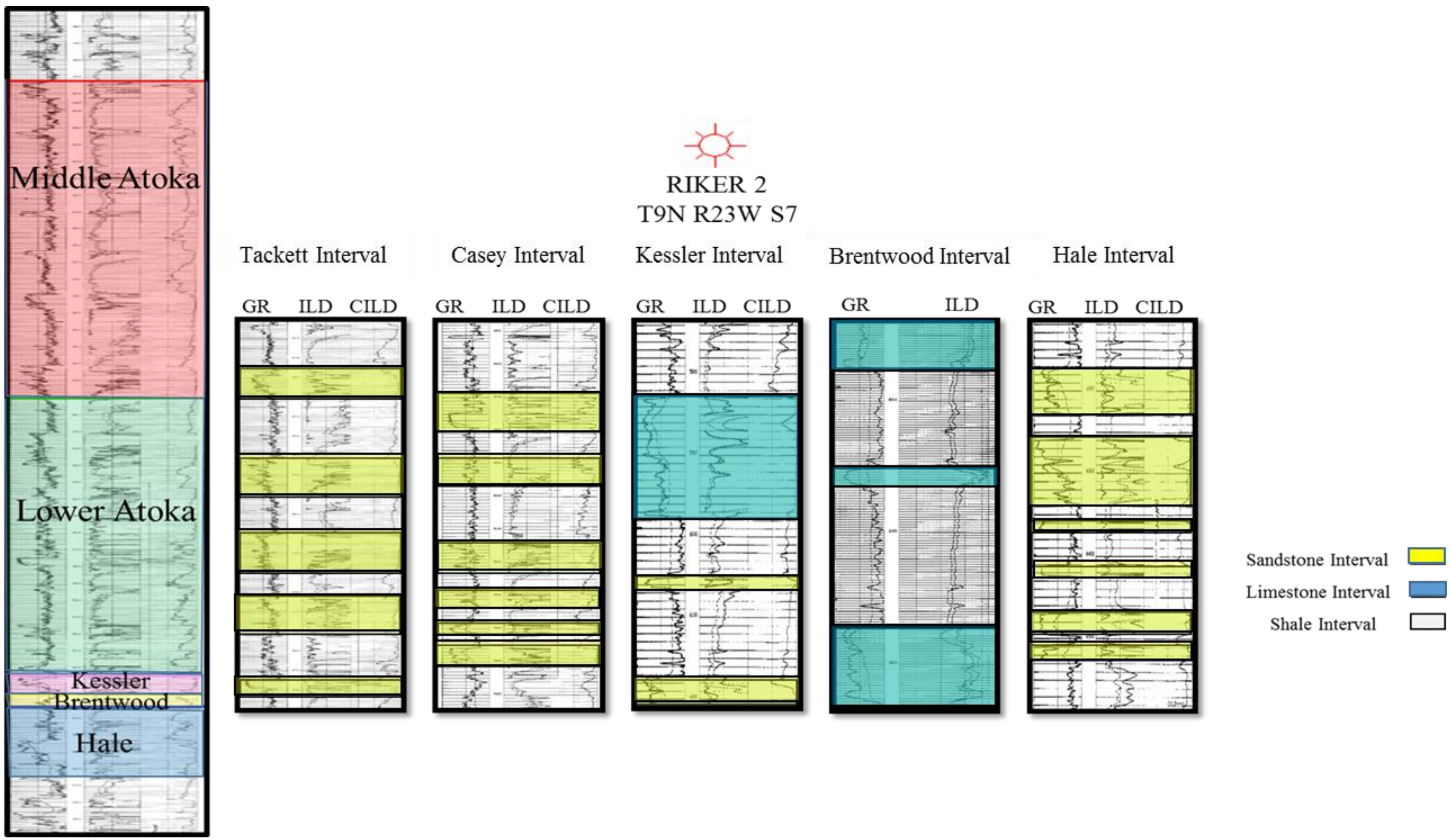

Figure 2-1: Detail well log of the Morrowan (Kessler, Brentwood, and Hale formations) and Atokan (Tackett and Casey formations) in the Riker 2 well. The figure shows gamma ray (GR), resistivity (ILD), and conductivity (CILD). Also, the well

2.3 Lithological and Stratigraphic Properties of Study Area

The stratigraphic section of the Arkoma Basin in Arkansas is composed mainly of sandstone, shale, and limestone units (Figure 2-2). During the Pennsylvanian, the stratal patterns and changes in the lithofacies distribution were controlled mainly by the relative change in sea level. The change in sea level is represented by various transgressive and regressive depositional sequences, which are reflected by the deposits of terrestrial and marine origin (Pontiff, 2007).

The stratigraphy of the study area includes the Hale and Bloyd formations of the Morrowan series and the Lower and Middle Atoka formations of the Atokan series in the Pennsylvanian. The sedimentary rocks of both the Morrowan and lower Atokan were deposited on a stable shelf in the Arkoma Basin in northwestern Arkansas. The Morrowan series of the Arkoma Basin is composed of two members; Hale and Bloyd formations (Table 2.1). The Hale Formation consists of two members; a lower, Cane Hill Member, composed of calcareous siltstone, sandstone and shale, and an upper, Prairie Grove Member, composed of calcareous sandstone with fossiliferous sandstone lenses, comprising the upper Hale Formation (Delavan, 1985). The lithologic facies of the Morrowan sections indicate a marine environment. The lower and middle members of the Atokan Formation consist primarily of thick intervals of sandstone, siltstone, and shale that represent the passive margin of the Arkoma Basin (Houseknecht, 1986). Both well logs (Figure 2-3) and field techniques are used in this study to assist in the general description of the formations.

System	Series	Formation	Unit	Commonly Used Names	Lithology
Pennsylvanian	Atokan	Middle Atoka	Glassy Morris Tackett Areci Moyer Bynum Freiburg Casey Vernon	Self, Tackett Woolsey, Morris Self Hood, Upper Bynum, Lower Bynum Henson, Pearson Hudson 1	Series of sandstone and shale intervals, thick sandstone intervals
		Lower Atoka	Sells Upper Jenkins Lower Jenkins Dunn C Paul Barton Hamm Patterson Spiro	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	Series of sandstone and shale intervals, thin sandstone intervals
	Morrowan	Bloyd	Kessler Lm.	Wapanucka	Interbedded bioclastic limestone and shale
			Dye Shale		Fissile shale with silt-stone
			Woolsey	Middle Bloyd Sandston	Fissile shale interbedded with thin siltstone
			Middle Bloyd		Cross bedded sandstone
			Brentwood Lm.		Limestone shale inter-vals
		Hale	Prairie Grove	Upper	Cross bedded sandstone
			Cane Hill	Lower	Alternating sandstone and shale intervals

Table 2-1: Stratigraphic column representing the Morrowan and Atokan Series with members and unit's names (modified from Zachry, 1983).

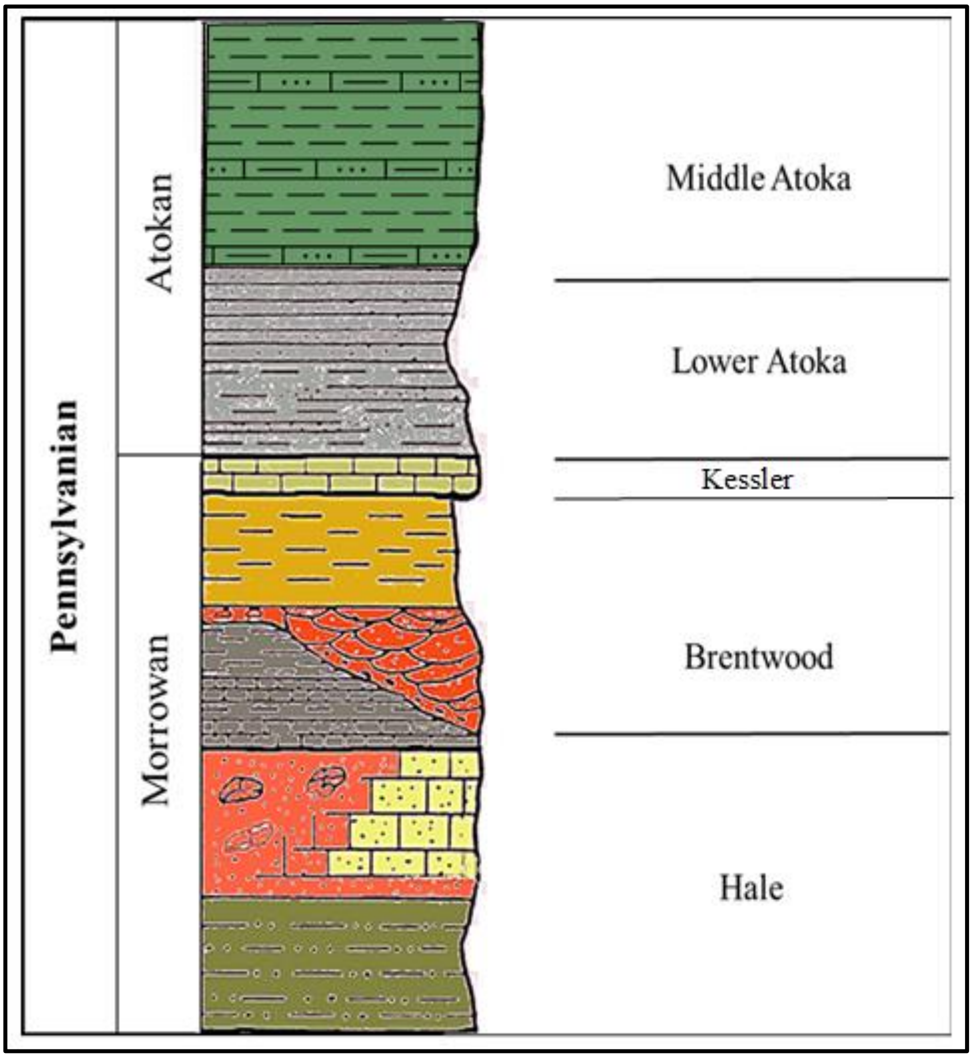

Figure 2-2: Generalized stratigraphic column of the Morrowan and Atokan series of the Pennsylvanian succession of northcentral Arkansas. (Modified from McGilvery, 1982).

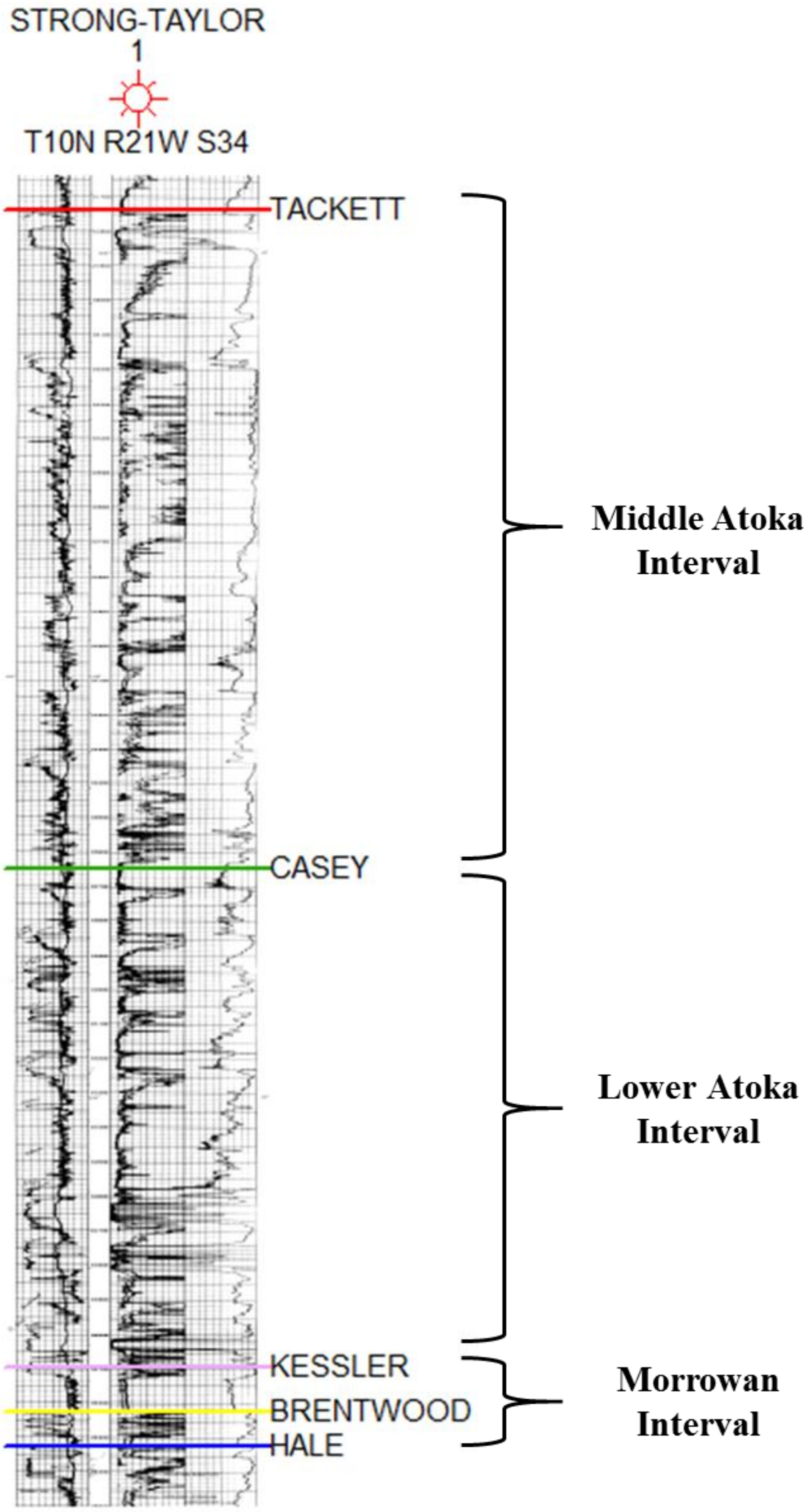

Figure 2-3: Wireline well log showing the log signature for all of the formation intervals for the study area highlighted with distinctive colors.

2.3.1 Morrowan Strata

The Morrowan Series (Early Pennsylvanian) is composed of a succession of alternating layers of sandstone, siltstone, shale, and limestone that accumulated on a passive continental margin. Several studies have been conducted to analyze the Morrowan strata. Due to the fact that the Morrowan deposits have potential for natural gas production, numerous wireline logs are available for subsurface studies. In addition, the outcrop exposures of the Morrowan succession provide more stratigraphic information to relate subsurface studies from the wireline logs to surface exposures. Morrowan strata consist of the Hale and overlying Bloyd formations (Figure 2-5).

The Hale Formation (Lower Morrowan) is separated from underlying Mississippian rocks by a regional disconformity (Delavan, 1985). The Hale interval is mainly composed of alternating sandstone and shale units in surface and subsurface observations. It consists of two members in northwest Arkansas: the lower Cane Hill and upper Prairie Grove members.

The Cane Hill Member of the Hale Formation overlies the Pennsylvanian– Mississippian contact in Arkansas. It is composed mainly of silty shale intervals interbedded with non-calcareous siltstone, shale, and thin-bedded, fine-grained sandstone intervals (Studebaker, 2014). The upper Hale interval is composed of thin bedded sandstone units, while the lower interval is composed of interbedded sandstone with shale units. The lower interval is well expressed on wireline logs (Figure 2-1). However, in this study, they are combined in one interval for ease interpretation.

The Prairie Grove Member of the Hale Formation (Figure 2-4) unconformably overlies the Cane Hill Member and underlies the Brentwood Member of the Bloyd Formation. It is mainly composed of fine to medium grained fossiliferous, cross bedded sandstone with lenses of highly fossiliferous sandy limestone as well as oolitic limestone. Honeycomb weathering is a very typical characteristic of the surface exposure of the Prairie Grove (Studebaker, 2014). The surface outcrop along Highway 412 presents highly cross-bedded sandstones (Figure 2-4 (B)). Also, it is well-expressed in wireline logs (Figure 2-1) as a thick blocky signature of sandstone, reflected by low gamma readings, with little shale in the Prairie Grove interval.

Both field studies and well log analyses indicate that the Cane Hill and Prairie Grove members are characteristic of a marine environment, indicated by wavy stratification, ripple marks, and burrows. These outcrop observations suggest that the Cane Hill Member was deposited in shore zone, tidal flat environments and the overlying Prairie Grove was deposited in near shore, shallow marine settings. This indicates an upward deepening, transgressive systems tract.

Figure 2-4: Prairie Grove Member along Arkansas 412. Photograph (A) shows thick calcareous sandstone beds and photograph (B) displays the development of cross bedding within the sandstone. Fossils in the sandstone indicate a marine environment.

The Bloyd Formation overlies the upper strata of the Prairie Grove Member and underlies Atokan strata of the Casey unit (Lower Atoka Formation). The boundary between the Bloyd and Lower Atoka Formation is characterized by a major unconformity, the Morrowan-Atokan boundary. The Bloyd interval is divided into the following four members, listed in ascending order: Brentwood Limestone, Woolsey Shale (very western part of Arkoma) and the middle Bloyd sandstone (substituting the Woolsey Shale in most parts of the Arkoma Basin), Dye Shale, and Kessler Limestone (McGilvery, 1982). These intervals are characterized by a heterogeneous sequence of predominantly marine shale, sandstone, siltstone, and limestone units in northwest Arkansas (Delavan, 1985). The Bloyd Formation accumulated over a broad ramp that was gently sloping toward the central part of Arkansas prior to the development of the Arkoma foreland basin. In general, the Bloyd Formation members were deposited in shallow marine and non-marine environments. Both field studies and wire-line well logs are used to identify the Bloyd Formation members in this study.

Lithologies must be identified to understand the sedimentary environments that control the deposition of the Bloyd member. The Brentwood Limestone Member composes the lower part of the Bloyd Formation. It overlies the Prairie Grove Member of the Hale Formation and underlies the Middle Bloyd Member of the Bloyd Formation. The boundary between the Bloyd and Hale formations is interpreted as a sharp boundary that represented by thin shale interval (Figure 2-5). The Brentwood Member is described as a succession of alternating strata of limestone and shale that were deposited in shallow marine environments. The thin bedded shales are described as dark colored, fissile, and non-calcareous (McGilvery, 1982), which was supported by field observations (Figure 2-6). The well log interpretation (Figure 2-1), shows some lateral variations in the Brentwood facies, indicated by thin limestone beds (low gamma ray readings) separated by shale facies.

Figure 2-5: Photograph of the transitional contact between the Prairie Grove and Brentwood Limestone members along Arkansas Highway 23 near Huntsville. The outcrop displays a carbonate buildup generated by storm activity.

Figure 2-6: Sandstone- shale sequence in the Brentwood Limestone interval along Arkansas 412 near Huntsville in Madison County.

The Woolsey Shale Member was deposited over the Brentwood Member. It is composed of fissile, medium to dark grey, thinly laminated, non-calcareous shale interbedded with thin, brown siltstone, representing terrestrial sediments that were deposited in a continental environment that trailed a regressing Morrowan sea. The Woolsey Shale sequences terminate at another unconformity in the Morrowan overlain by the marine "caprock" of the

Dye Shale Member. East of the Arkoma Basin, the Woolsey Shale interval passes into an equivalent interval of the Middle Bloyd sandstone deposits.

The boundary between the Brentwood and underlying Middle Bloyd members is described as a sharp boundary (Figure 2-7). The Middle Bloyd Formation (Figure 2-8) is composed of fine to medium grained sandstone, with cross-stratification. Pontiff (2007) described the middle Bloyd sandstone as composed of conglomeratic sandstones, which is interpreted to be deposited along the shelf and outer margins of the Arkoma. In addition to the record of the repetitive sections and the evidence of unidirectional current patterns, these evidences suggest that the middle Bloyd sandstone unit was deposited by a braided stream system within the overall marine deposits of the Morrowan strata.

The fossiliferous, marine deposits of the caprock at the base of the overlying Dye Shale Member suggested that these deposits were brought by transgression of late Morrowan seas (McGilvery, 1982).

Figure 2-7: Contact developed between the Brentwood Limestone and Middle Bloyd Sandstone members along Arkansas Highway 16 south of Huntsville.

Figure 2-8: Contact between the Brentwood and Middle Bloyd members of the Bloyd Formation indicating abrupt change in the lithology. Cross bedding dominates both the Brentwood and Middle Bloyd members along Arkansas Highway 16 south of Huntsville.

The Dye Shale Member was unconformably deposited above the Woolsey and middle Bloyd sandstone members. The Dye Shale Member is underlain by the caprock, which refers to thin layers that are composed of calcareous sandstone or sandy limestone. The caprock reflects a transgressive surface that marks the return of a marine environment succeeding the interval of terrestrial Woolsey deposits (Delavan, 1985). Also, the caprock represents the initial transgression and the re-building of marine deposits (McGilvery, 1982). The Dye Shale Member is composed of dark gray to black shale and siltstone. McGilvery (1982) referred to the caprock as the basal part of the Dye Shale Member that was deposited in shallow marine conditions. Although these members (Woolsey, the caprock, and Dye Shale) have been studied in detail in previous theses, they have not been utilized in the subsurface studies of the Arkoma Basin.

The Dye Shale is conformably overlain by the Kessler Limestone (Figure 2-9). The Kessler Member is overlain unconformably by the Lower Atokan Formation. It is composed dominantly of bioclastic, oolitic limestones and sometimes a sequence of interbedded shale and limestone (Studebaker, 2014). The Kessler Limestone Member is present at the surface and in the subsurface, making it easy to identify. In surface exposures (Figure 2-9), the Kessler Member was deposited in thin layers of limestone atop dark shale representing the Dye Shale Member. Also, wireline logs record low gamma ray readings in the thin interval for the Kessler Member (Figure 2-1). McGilvery (1982) described the Kessler Member deposits to represent the re-establishment of a carbonate shelf environment. Delavan (1985) described the Kessler sediments as a result of mixing processes during deposition due to an increase in siliciclastic sediments deposited within the carbonate sediments.

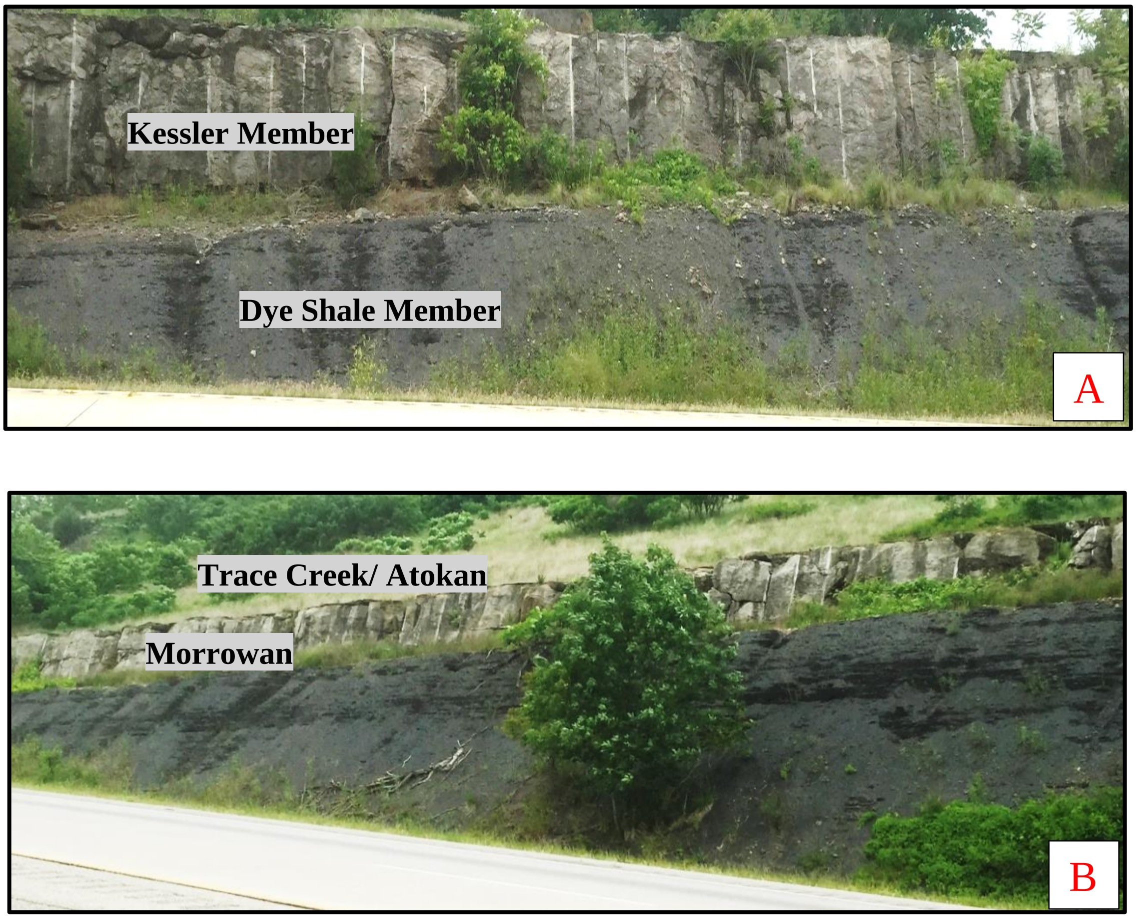

Figure 2-9: (A) Limestone-shale sequence between the Kessler and Dye Shale members. (B) The unconformable boundary between the Morrowan and Atokan series. Both photos were taken along Interstate 49, south of Fayetteville.

For the purpose of this study, the Morrowan series has been divided into the following three units based on well log interpretations: Hale, Brentwood, and Kessler intervals. They are divided to define the top of the Hale and the top and base of the Bloyd Formation.

2.3.2 Atokan Description

The Atokan is a thick succession of shallow marine deposits (Zachry, 1983). The interval is subdivided into the following three formations, the Upper, Middle, and Lower Atoka. These formations are based on the structural configuration of the Arkoma Basin. The Lower Atoka represents the last deposits on the stable Ozark Platform before its transition into the Arkoma Foreland Basin during the Middle Atokan. The focus of this study is to improve the understanding of the structure and timing of this transition. The sediments were transported to the basin from source areas to the east in the Appalachian region. Additionally, the higher rate of sediment accumulation is attributed to the closing and reduction of the basin area, which confined the transport of the sediments through the time. In early to middle Atokan time, the sedimentary facies were deposited as a result of deep water environment to the south and west of the study area, while shallow marine and fluvial-deltaic facies were deposited to the north on the Arkoma shelf.

At the surface, the contact is with the Trace Creek Shale. Because in the basin/subsurface, it is with the Spiro sandstone (Figure 2-9 (B)). The Lower Atoka is composed of about seven to eight sandstone lithostratigraphic units; Spiro, Patterson, Cecil Spiro, Dunn C, Lower Jenkins, Upper Jenkins, and Sells (Table 2-1). These units are bounded by intervals of shale. Also, the Atokan units were deposited on a stable shelf environment in highly destructive delta systems. The shale intervals of the Lower Atoka Formation show upward coarsening toward the sandstone facies (Figure 2-1). Also, the shale intervals are considered to be good indicators for an open-shelf environment during multiple cycles of transgression and regression of delta progradation (Jameson, 1998). The Lower Atoka Formation shows a gentle thickening due to stable shallow marine to shore zone environment. The Spiro Unit represents the first Atoka sandstone above the Morrowan Kessler Member in most parts of the basin. For the purpose of this study, the base of the Casey Unit represents the last sandstone unit in the Lower Atoka Formation as a boundary to the Middle Atoka Formation. In this study, the Lower Atoka Formation is mapped through wireline logs to represent one interval. This study focuses on mapping the Casey Unit as the upper contact of the Lower Atoka Formation. Additionally, the Lower Atoka Formation is studied in the field to highlight the boundary between the Morrowan and Atokan series and to provide more information about the depositional environment (Figure 2-10 to 2-12).

Figure 2-10: Lower Atoka outcrop along Highway 123 near Pelsor. Thick cross bedded sandstone interval characterizes the outcrop.

Figure 2-11: A Lower Atoka interval outcrop along Highway 23. The outcrop shows multiple sandstone and shale units. This pattern of depositional strata shows a similar pattern to well log signature.

Figure 2-12: Herringbone cross-stratification indicating the tidal environment during the Lower Atoka deposition along Highway 123.

The Middle Atoka Formation is considered to be the thickest formation in the Arkoma Basin. It averages (1500 to 3500 feet) in the study area. The increase in thickness compared to the Lower Atoka is due to the increase in sediment supply as increased subsidence (Houseknecht, 1986). The Middle Atoka Formation is subdivided into five units: Casey, Freiburg, Moyer, Areci, Tackett, and Morris (Table 2-1). These intervals are described by Woolsey

(2007) as shale-dominated units separated by sandstone intervals. Even though the shale intervals dominate the Middle Atoka interval, the sandstone units are much thicker than in the Lower Atoka Formation (Figure 2-13). These intervals of sandstone and shale were deposited in high constructive delta systems that are characterized by prograding facies south of the basin (Zachry, 1983). For this study, the base of the Middle Atoka Formation is mapped as the top of the Casey Unit as a distinctive boundary from the Lower Atoka. Also, the top of the Middle Atoka is mapped using the top of the Tackett Unit as its upper boundary. The Casey and Tackett units are mapped using wire line logs.

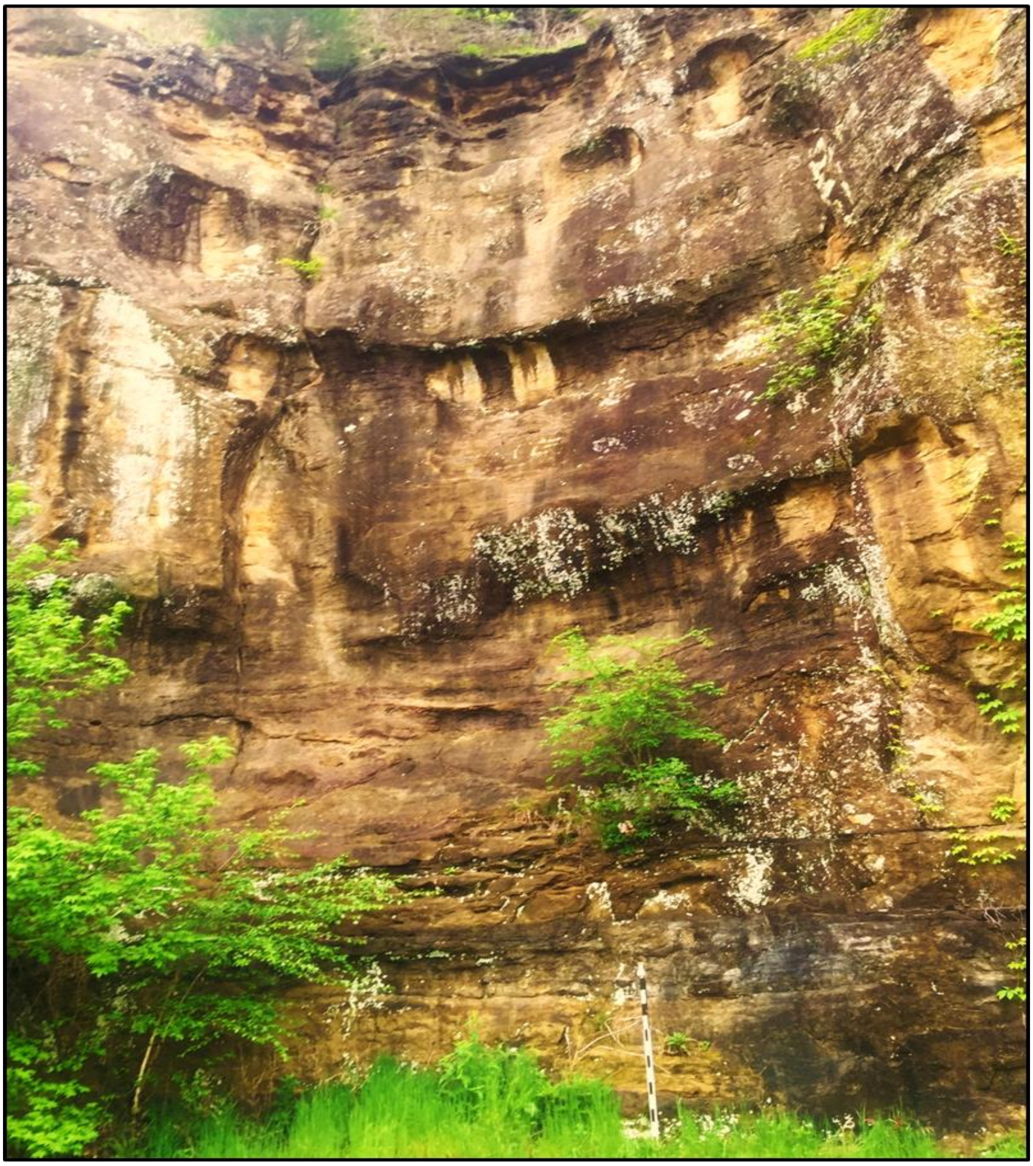

Figure 2-13: Middle Atoka interval along Arkansas 215. The outcrop is characterized by thick sandstone intervals, which represent the lowest part of the formation.

2.4 Local Cross Sections Description

For a comprehensive analysis of the stratigraphy of the study area, six cross sections were constructed; two west-east strike sections and four north-south dip sections (Figure 2-14). The regional cross sections (A -A and B-B') extend west to east from east Johnson County to central Pope County. These cross sections include the Morrowan and Atokan formations. From base to top, the identified formation intervals are the Hale, Brentwood, Kessler, Lower, and Middle Atoka intervals. The stratigraphic cross sections are flattened on the top of the Middle Atoka interval. All of the intervals are identified in the wireline logs selected for the cross sections. The Gamma ray log (GR) is the primary curve used to correlate the intervals in this study. These cross sections define the development of the lithostratigraphic-sequence of the stratigraphic framework, the depositional environment, and depositional timing.

It is essential to understand the differences in the orientation of the stratigraphic cross-sections. The stratigraphic, dip oriented cross sections reflect landward to basinward changes in stratigraphy and depositional facies. The stratigraphic, strike orient sections reflect lateral facies continuity or change along strike. For this study, both types of cross sections are used in order to provide an accurate visualization for the change in the depositional facies vertically or horizontally. Additionally, it is important to distinguish the type of stratigraphic contacts between the mapped intervals for the stratigraphic interpretation purposes. A sharp contact may represent a flooding surface or an unconformity. Since the base of the Hale Formation is not mapped, it is difficult to interpret the increase in its thickness. The base of the Bloyd Formation is represented by the Brentwood interval, and the top of the formation is represented by the Kessler interval.

In general, knowing the type of facies contacts is important in the stratigraphic interpretation. Facies contacts represent the boundaries between two facies joined through Walther's Law. The contact between the Bloyd and Hale formations shows as a sharp contact. This type of sharp contact results from a maximum flooding surface. The contact between the Lower Atoka Formation and the Kessler Member showed a sharp contact as well. This sharp contact boundary may not have displayed substantial erosional relief, but it shows some laterally varying depths of erosion between Lower Atoka and Kessler indicating an unconformity boundary. However, the boundary between the Lower and Middle Atoka formations shows a gradual change in the boundary which relates to the similarity in the depositional facies for both formations. The point is sharp contacts can result from different conditions, they are "non-unique". Therefore, it is very important to understand the contact when interpreting the contact character.

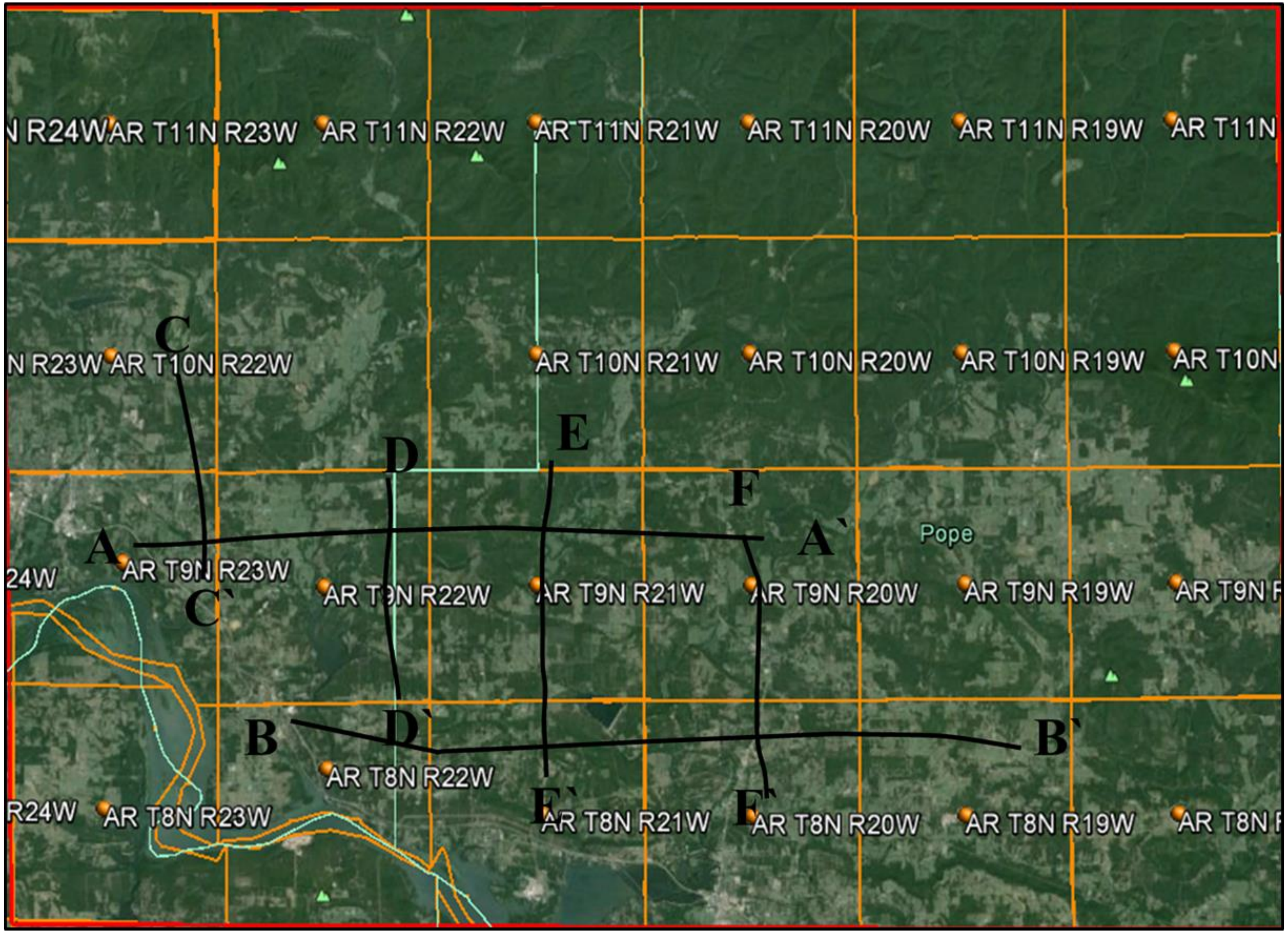

Figure 2-14: Google earth image for the regional cross sections with the location indicated by Townships and Range.

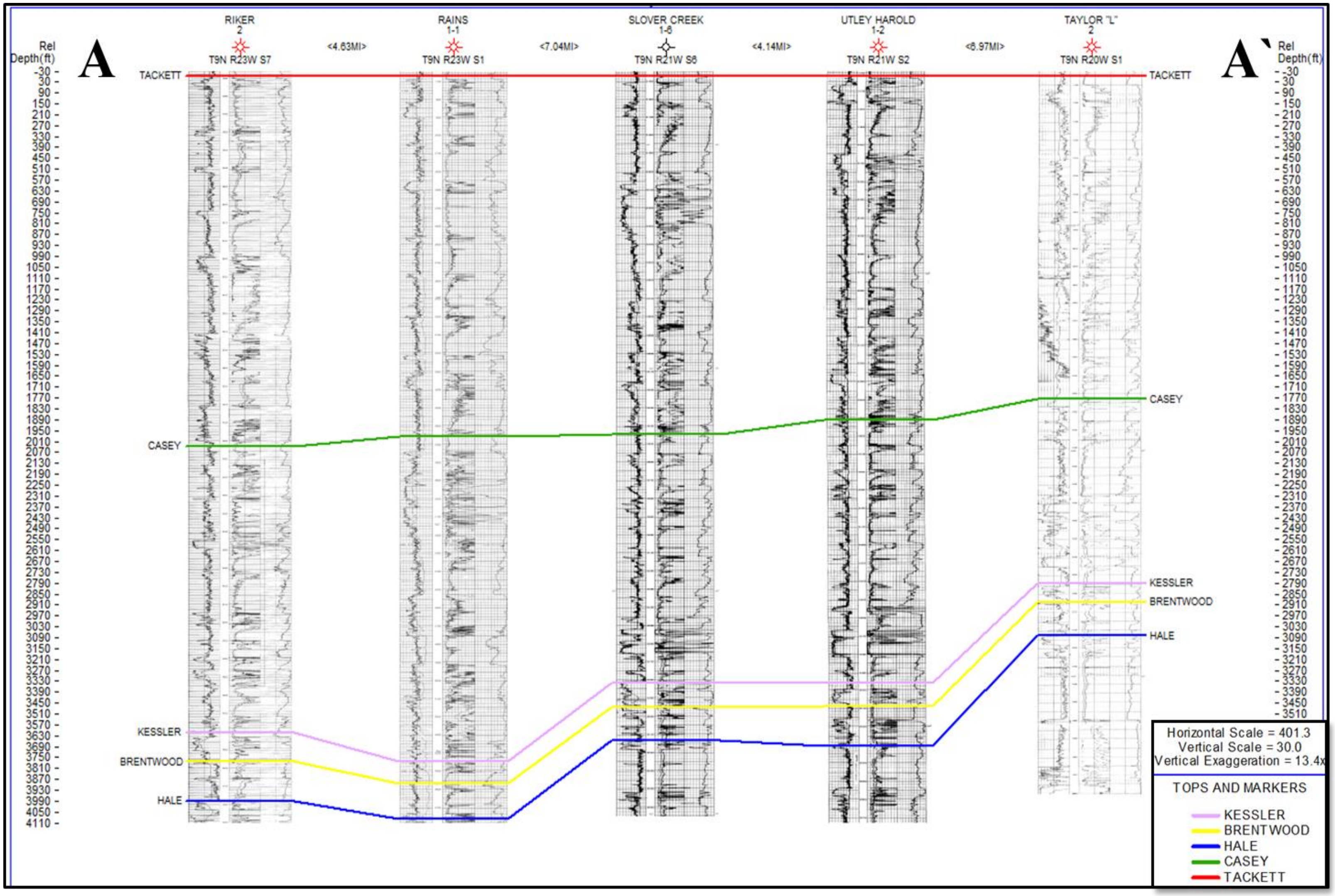

Figure 2-15: East –West regional stratigraphic cross section in northcentral part of the Arkoma Basin depicting the main intervals for this study. The cross section datum is the upper boundary for the Middle Atoka Formation.

2.4.1 Cross Section A-A’

Cross section A-A` is the northernmost west to east cross section in the study area (Figure 2-15). It extends from the west in east Johnson County to the east in central Pope County in Township 11N, Ranges 23W-20W (Figure 2-14). The coveys distance of approximately 23 miles. Five well logs were used to construct this cross section. These well logs are not equally spaced in terms of the horizontal distance.

The Bloyd Formation shows a constant lateral thickness along the northern part of the study area. The increase in depth is about 60 feet deep toward the west side of the cross section. The Lower Atoka interval shows a lateral increase in its thickness toward the west side of the cross section. This increase is gradual in thickness due in part to the shallow depositional stable environment of the stable Arkoma shelf. The lower Atoka thickness increases to 540 feet in thickness between the western and eastern most wells. The Middle Atoka interval thickness increases as well to the very western side of the study area. The increase is about 300 feet. In essence, the increase in the Bloyd strata is more likely to have been controlled stratigraphically. However, the increase in thickness in the Lower and Middle Atoka intervals is more likely to have been caused by structural control.

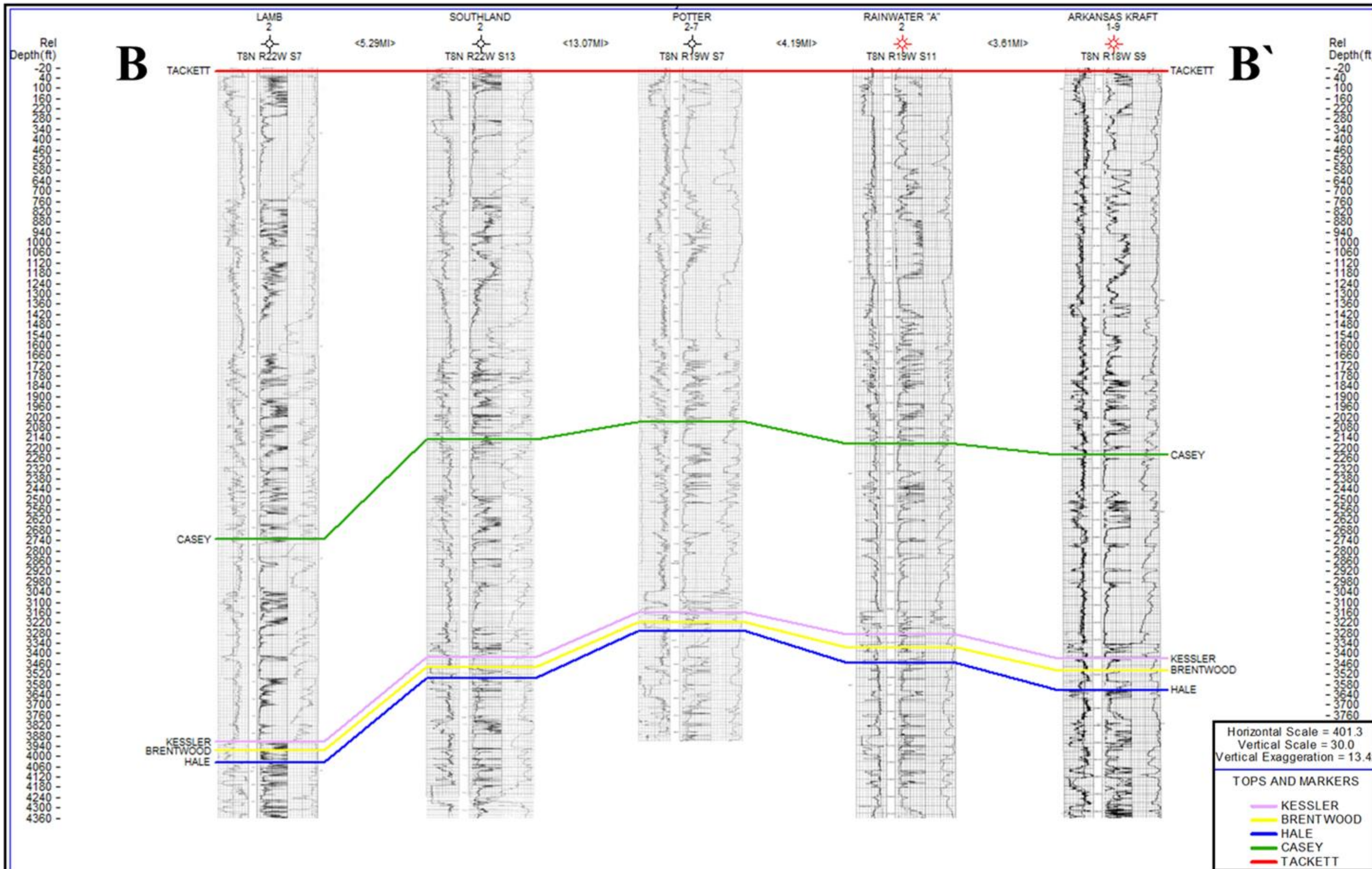

Figure 2-16: East –West regional stratigraphic cross section in the northcentral part of the Arkoma Basin depicting the main formation tops for the study.

2.4.2 Cross Section B-B`

Cross section B-B` is the southernmost west to east cross section in the study area (Figure 2-16). It extends from the west in east Johnson County to the east in central Pope County in Township 8N, Range 22W-18W (Figure 2-14). The cross section covers a distance of approximately 26 miles horizontally. The well logs are not spaced equally. Similar to the cross section A-A`, the Bloyd interval shows a constant lateral thickness along the southern part of the study area. The two west-east stratigraphic sections display similar thickness. The thickness of the Bloyd Formation displays a lateral gentle increase to the western side of the study area. This increase is minimal (about 40 feet thick) comparing to both the Lower and Middle Atoka intervals. In contrast, The Lower Atoka Formation displays a minimal decrease in the strata thickness about 60 feet to the west side of the area. It is hard to interpret the main control for the depositional strata in this cross section since the well logs are not equivalently picked over the 26 miles of the total area. However, the Middle Atoka Formation is increased by about 540 feet in thickness to the western side of the study area.

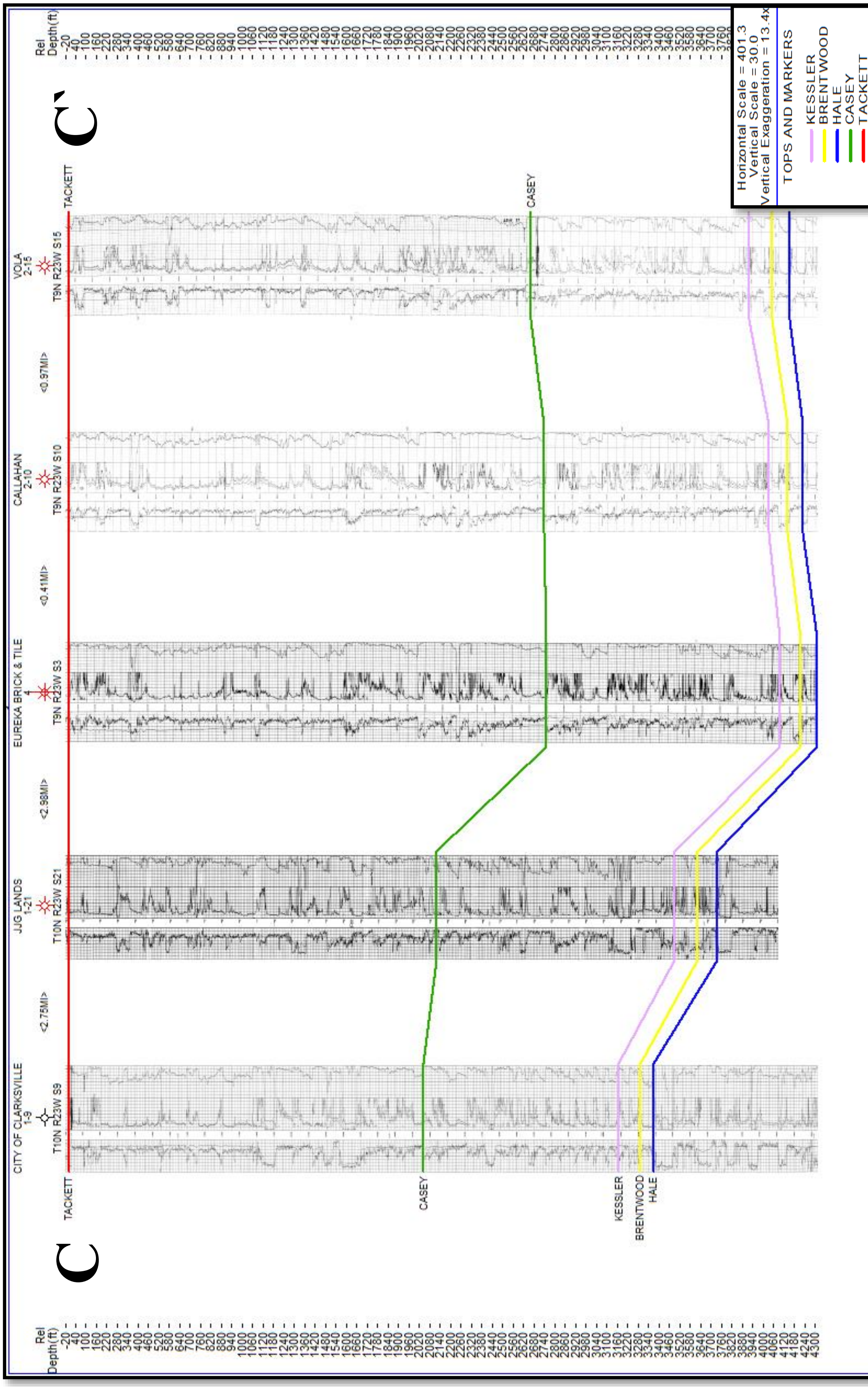

Figure 2-17: North-South regional stratigraphic cross section in the northcentral part of the Arkoma Basin depicting the main intervals for the study area.

2.4.3 Cross Section C-C`

Cross section C-C` is located at the very far western edge of Johnson County in Townships 10N-9N, Range 23W (Figure 2-17). It extends north-south in the study area (Figure 2-14). The overall distance that covered by this cross section is about seven miles. Five well logs are used in this cross section. The change in the depositional style is due to a fault. This study area is part of the Mulberry Fault zone system (see chapter 3). The fault presented between the well JJG LANDS and well EUREKA BRICK & TILE. The Bloyd interval of this cross section indicates a constant vertical depositional style for the whole cross section. Also, it displays a lateral gentle decrease in the thickness to the northern side. Also, the Bloyd Formation strata show gradual thinning of the study area. The decrease in the measured thickness of the Bloyd interval is about 120 to 80 feet. The Lower Atoka Formation follows the same depositional style. The thickness of the Lower Atoka also shows a decrease to the northern part of the area (approximately 60 feet). The thickness decrease is measure previously in the cross section B-B`. The Middle Atoka interval thickness is also reduced by about 660 feet to the north side of the area.

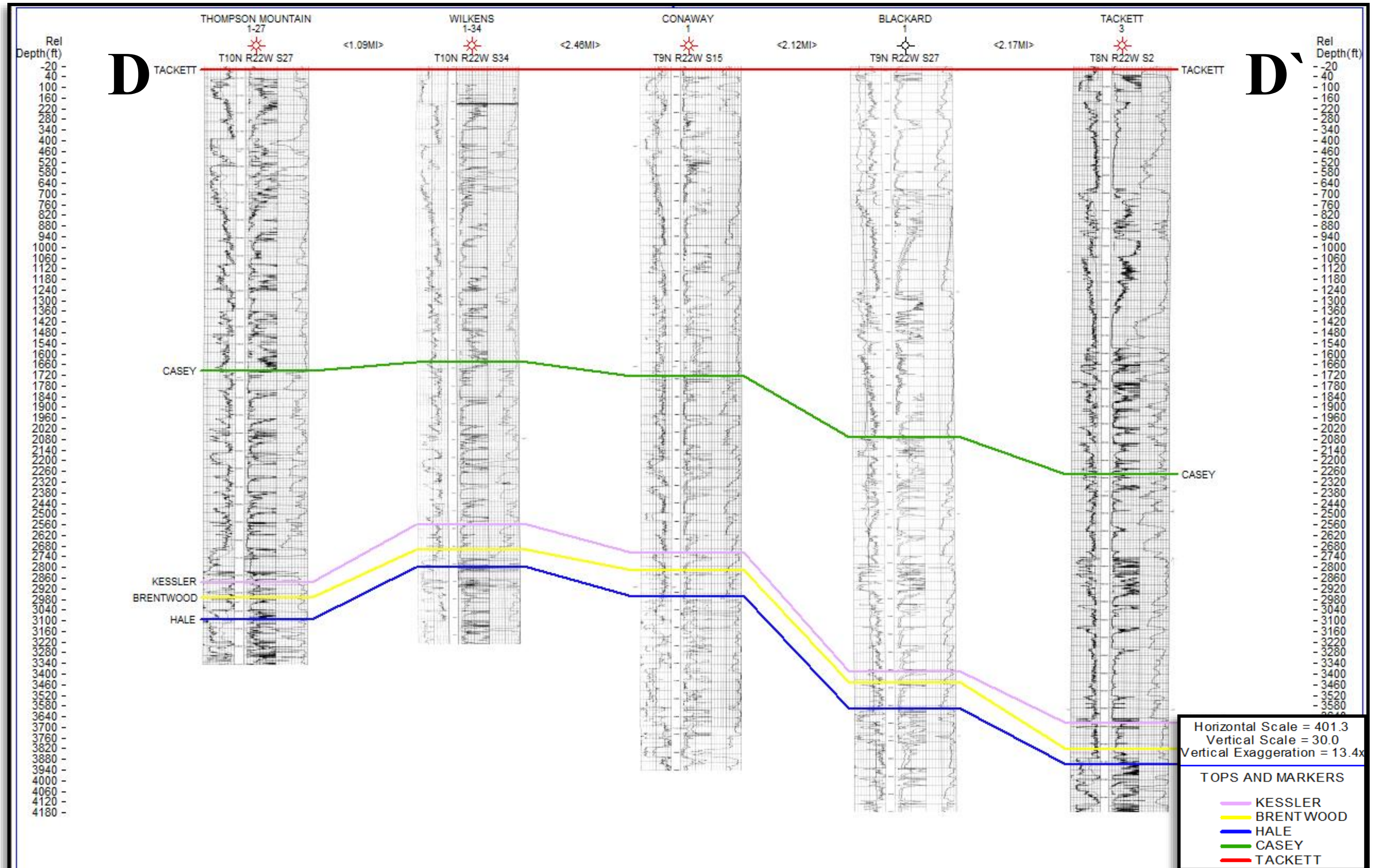

Figure 2-18: North- South regional stratigraphic cross section of the Arkoma Basin.

2.4.4 Cross Section D-D`

Cross section D-D` is located at the western side of Johnson County in Townships 10N-8N, Range 22W (Figure 2-18). This cross section covers a distance of approximately eight miles (Figure 2-14). The units in this cross section are affected by the Mulberry Fault zone as the previous cross section. The Bloyd Formation shows a nearly perfect constant thickness that extends from south to north. The Bloyd Formation shows a constant thickness extent. The Lower Atoka interval follows the same depositional style as the previous cross section (C-C`). It shows a gradually gentle decrease in its thickness to the north side of the cross section. The measured thickness of the Lower Atoka Formation reveals a value of 240 feet of differences between the southern part and the northern part of the cross section. As a result, the Lower Atoka interval is thinner to the northern side of the two north-south cross sections, specifically in Townships 10N to 8N. The Middle Atoka Formation thickness is also reduced by about 540 feet to the northern portion of the area. Comparing to the previous cross section, the decrease in thickness is dropping by 120 feet as mapping toward the eastern part of the study area.

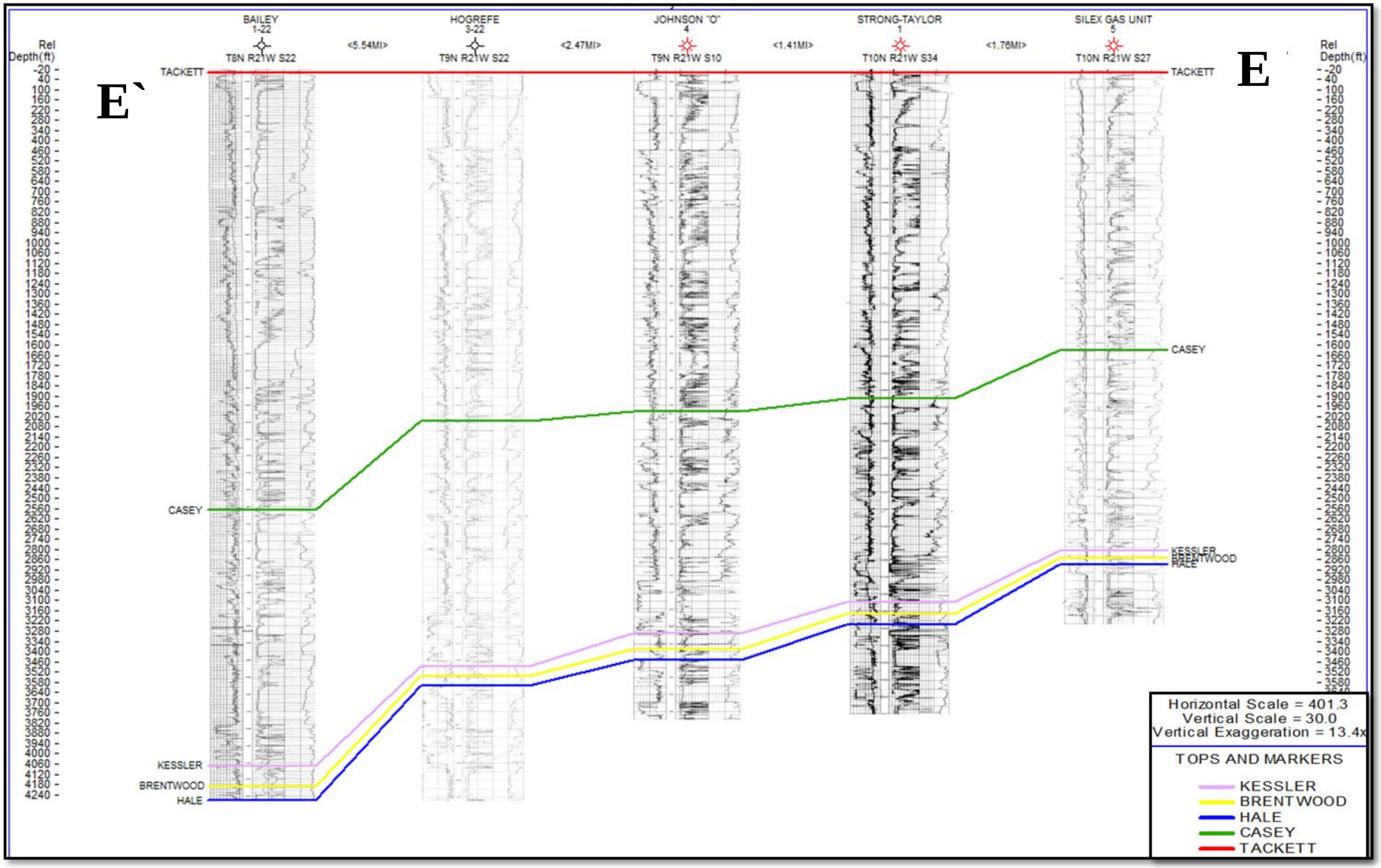

Figure 2-19: E-E` North – South regional stratigraphic cross section in the northcentral part of the Arkoma Basin.

2.4.5 Cross Section E-E`

Cross section E-E` is located at the central part of Pope County in Townships 10N-8N, Range 20W (Figure 2-19). This closely spaced cross section covers a distance of approximately 11 miles. The well logs in this cross section are spaced relatively close distance. In this cross section, the mapped units for the Morrow and Atoka intervals show a gradual change to the north of the cross section. The Bloyd Formation interval reveals upward thickening to the southern side of the study area. The observed increase in the thickness of the Bloyd interval is about 60 feet descending south from the shelf into the southern portion of the basin. The Lower Atokan interval increases about 340 feet from north to south. Thickening occurs in the shale intervals of the Lower Atoka interval, whereas, the thickening in the Middle Atoka interval occurs at the sandstone intervals. The Middle Atoka strata increase about 900 feet northward. That major increase in thickness indicates the role of syn-depositional faulting effect on controlling the depositional strata of the Middle Atoka.

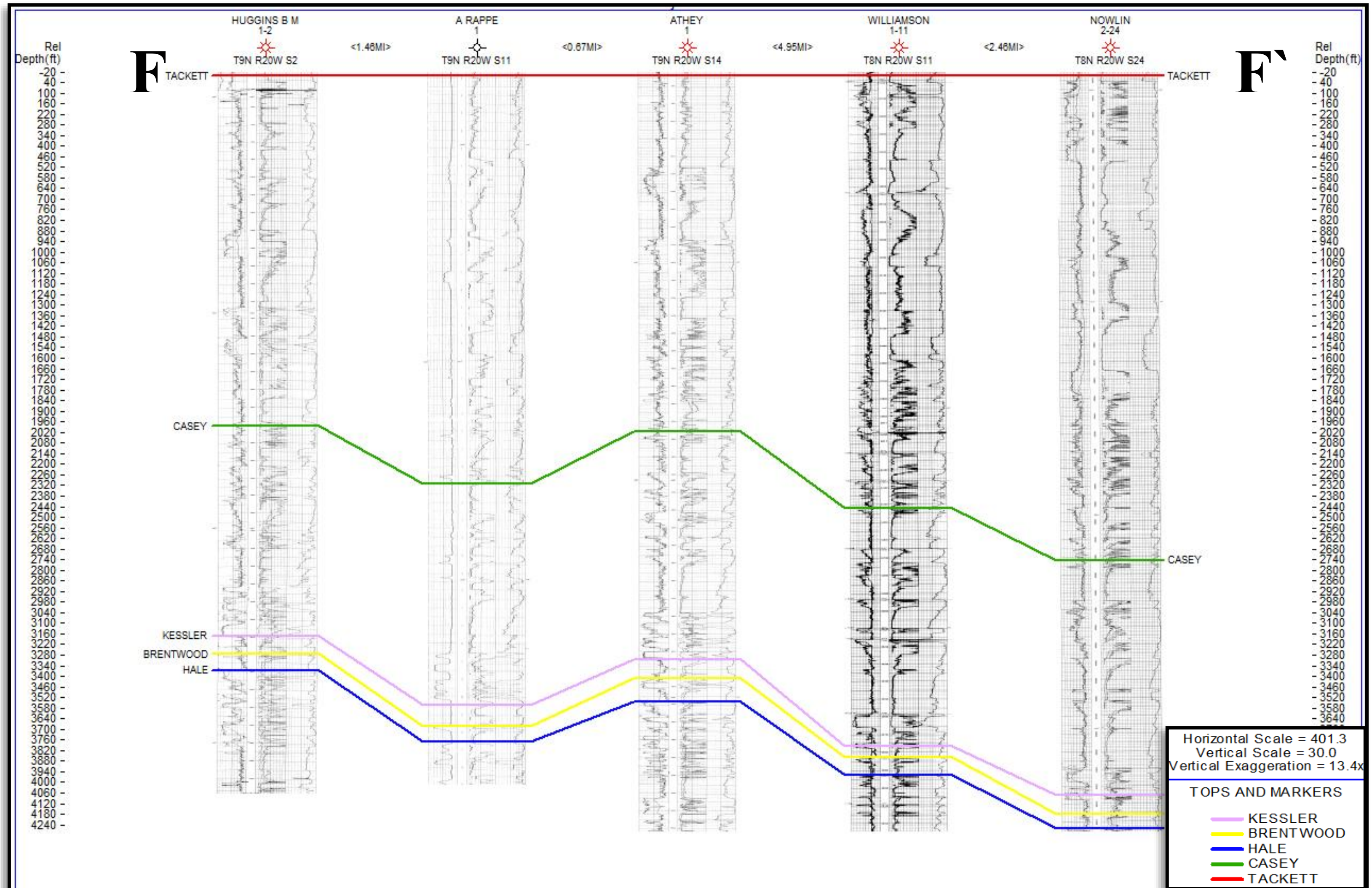

Figure 2-20: North- South regional stratigraphic cross section in the northcentral part of the Arkoma Basin

2.4.6 Cross Section F-F`

Cross section F-F` is located in the very far eastern edge of Pope County in Townships 10N-8N, Range 20W (Figure 2-20). This cross section covers a distance of approximately 10 miles. In similarity with the cross sections C-C` and D-D`, this cross section reveals a continuous increase in the thickness of the mapped intervals for the Morrowan and Atoka formations toward the southern portion of the study area. The thickness displays a gradual increase to the southern part. The Bloyd Formation interval reveals a constant thickness interval from north to south. The Bloyd Formation thickness is approximately 180 feet. The constant thickness interval of the Bloyd formation is similar to the one shown in section (D-D`). The Lower Atoka strata increase to about 120 feet from north to south. The Lower Atoka interval thickness increases gradually along with the syn-depositional faulting system, which is important in terms of the Arkoma Basin development. Additionally, the Middle Atoka strata reveals a thinning upward pattern to reveal a value of approximately 780 feet of the whole measured section.

2.6 Isopach Maps

The cross sections indicate variations in the thickness of stratigraphic units. Four isopach maps were generated using Golden Software (Surfer 13). The first isopach map shows the Brentwood interval at the base of the Bloyd Formation. The Kessler interval isopach map is constructed to include the rest of the units in the Bloyd as well as the Kessler. The two other isopach maps represent the Lower, and Middle Atoka intervals. The generation of isopach maps is helpful in interpreting the stratigraphic relationships of the geologic formations in the study area. Also, isopach maps are helpful in the structural interpretation to determine the effect of important structural features, such as faults, anticlines, synclines, grabens, and horsts. For the purpose of this chapter, the focus of isopach maps is mainly on understanding the stratigraphic relationships of the Bloyd (Kessler and Brentwood intervals) and Atoka (Lower and Middle) formations (Figure 2-3).

Isopach maps provide critical information in terms of structural and stratigraphic controls of sediment deposition. An isopach map for an interval can be a few feet thick, such as Kessler and Brentwood intervals, or it can be several thousand thick, such as the Lower and Middle Atoka formations. Both the Lower and Middle Atoka formation isopach maps show a gentle increase in the stratal thickness to the northern and northeastern part of the formation intervals. These maps will be described individually in this section.

2.6.1 Brentwood Interval Isopach Map

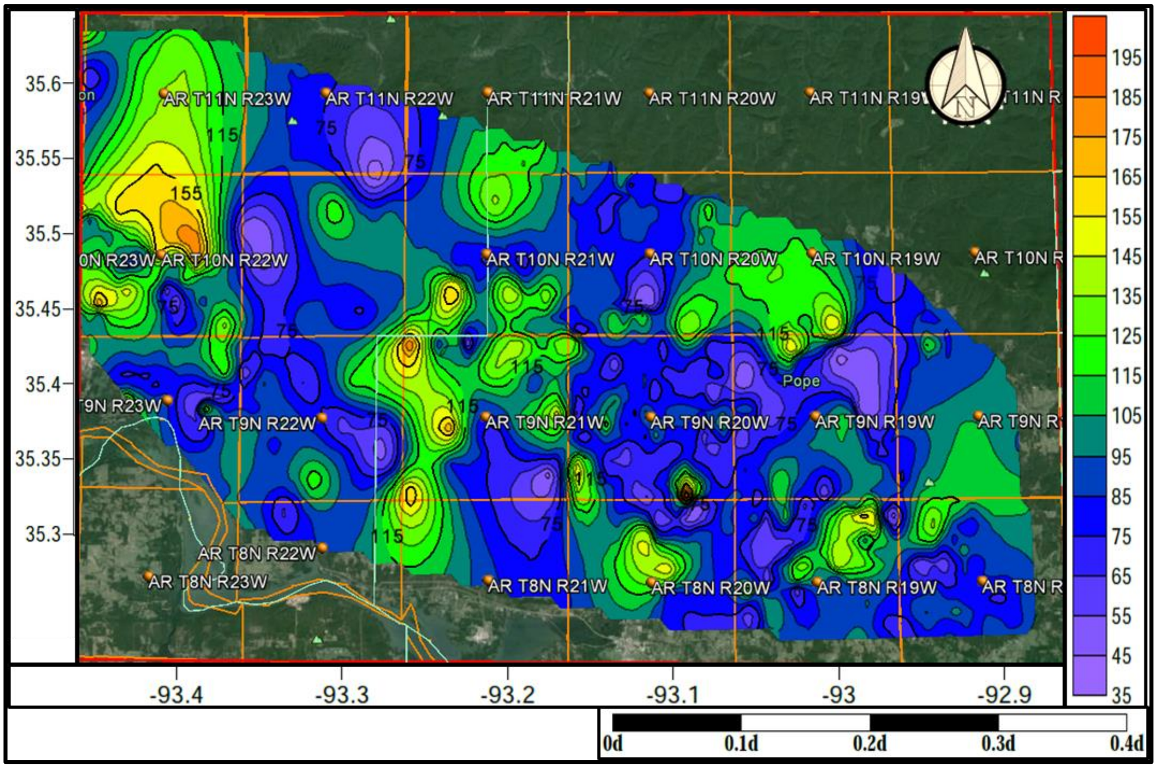

Figure 2-21: The Brentwood interval isopach map.

The Brentwood interval reaches a maximum thickness of about 200 feet in the western most side of the study area, Townships 11N-10N, Range 23W, and a minimum thickness of about 35 feet (Figure 2-21). The map shows that most of the mapped area indicates a slight decrease in average thickness compared to the Atoka intervals isopach maps. It is difficult to determine the general trend of thickening or thinning in the Brentwood isopach map. However, overall thickening appears to be on three parts of isopach maps, the northwestern part, central part, and small area to the north eastern section. The three parts of the area showing a relative thickening (around 155 feet) compared to the other parts that suggest an overall a small thickness of around 75 feet. The possible cause of these areas is either graben features or connected channels that is related to the depositional environment.

2.6.2 Kessler Interval Isopach Map

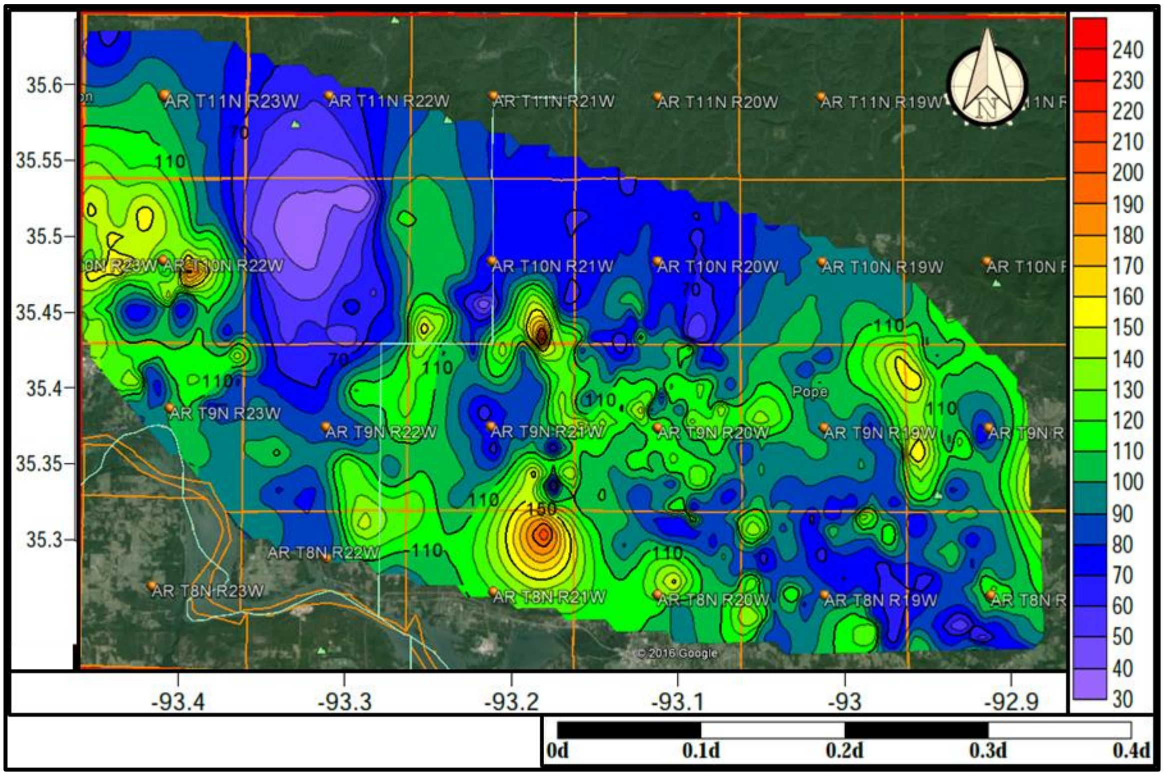

Figure 2-22: The Kessler interval isopach map.

The Kessler interval of the Bloyd Formation (Figure 2-22) follows the same thickness pattern as the Brentwood interval, with thickness ranging (30-240) feet. The isopach map of the Kessler Interval indicates a continuous thickening in most portions of the interval, except for the northeastern part of the map. In the wetren part of the isopach map, especially in Townships 11N-8N, Range 22W, there is an obvious thinning, suggesting that there might be an increase in the subsidence rate of the basin that provide more space for sediments to accommodate later in Lower Atokan time. Additionally, this thickness map shows different depositional pattern to the south-central portion of the area, especially in Township 8N, Range 21W, which suggest that there is an increase in the thickness of the area from about 35 feet of the Kessler Interval to about 200 feet.

This pattern of thinning and thickening might be related to the depositional environment of the underline Bloyd Formation of the Morrowan Series.

2.6.3 Lower Atoka Interval Isopach Map

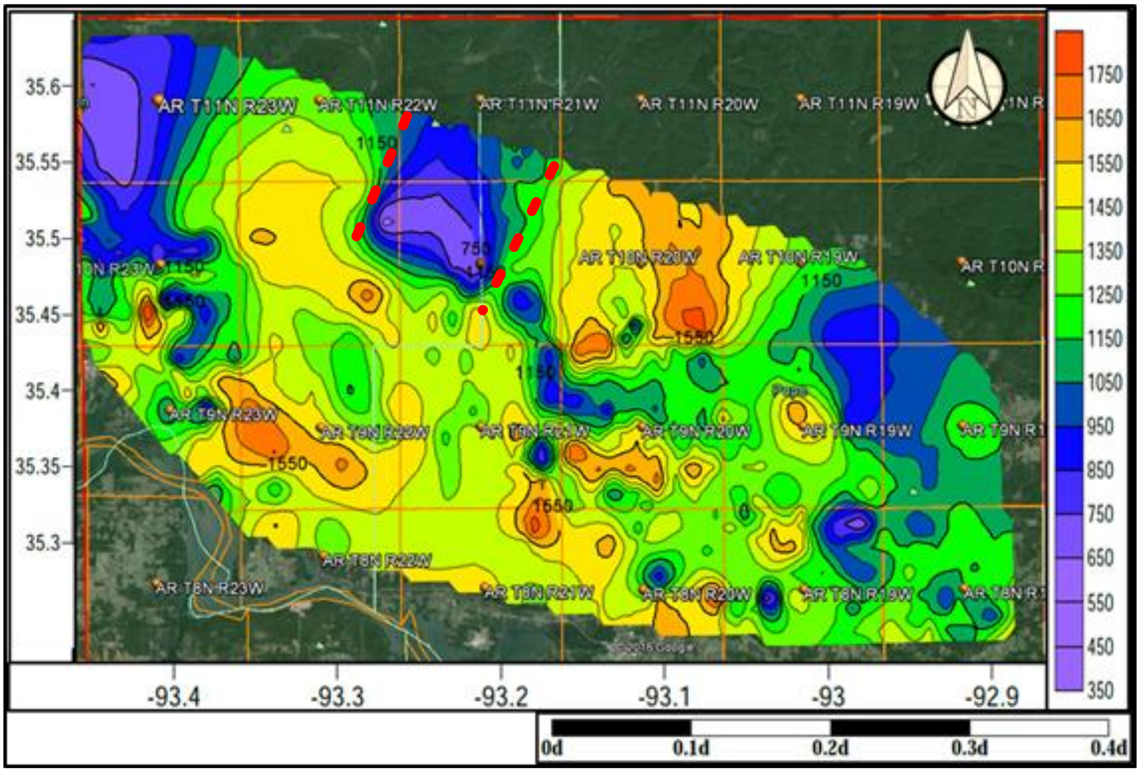

Figure 2-23: The Lower Atoka interval isopach map, with faults bounded the graben in red color.

The Lower Atoka interval lies above the Kessler interval in the stratigraphic column (Figure 2-2). This interval (Figure 2-23) represents the total thickness of the Lower Atoka Formation, which is significant to focus on because it represents deposition before the inception of the Arkoma Basin subsidence. The Lower Atoka isopach map attains a maximum thickness of approximately 1750 feet in the northeastern part of the study area, in Township 10N, Range 20W, and it attains a minimum thickness of approximately 55 feet in Township 10N, Range 19W. The decrease in thickness in this part of the area may be controlled structurally. The isopach map shows decrease in thickness in three different locations of the map, suggesting an increase in local erosion.

2.6.4 Middle Atoka Isopach Map

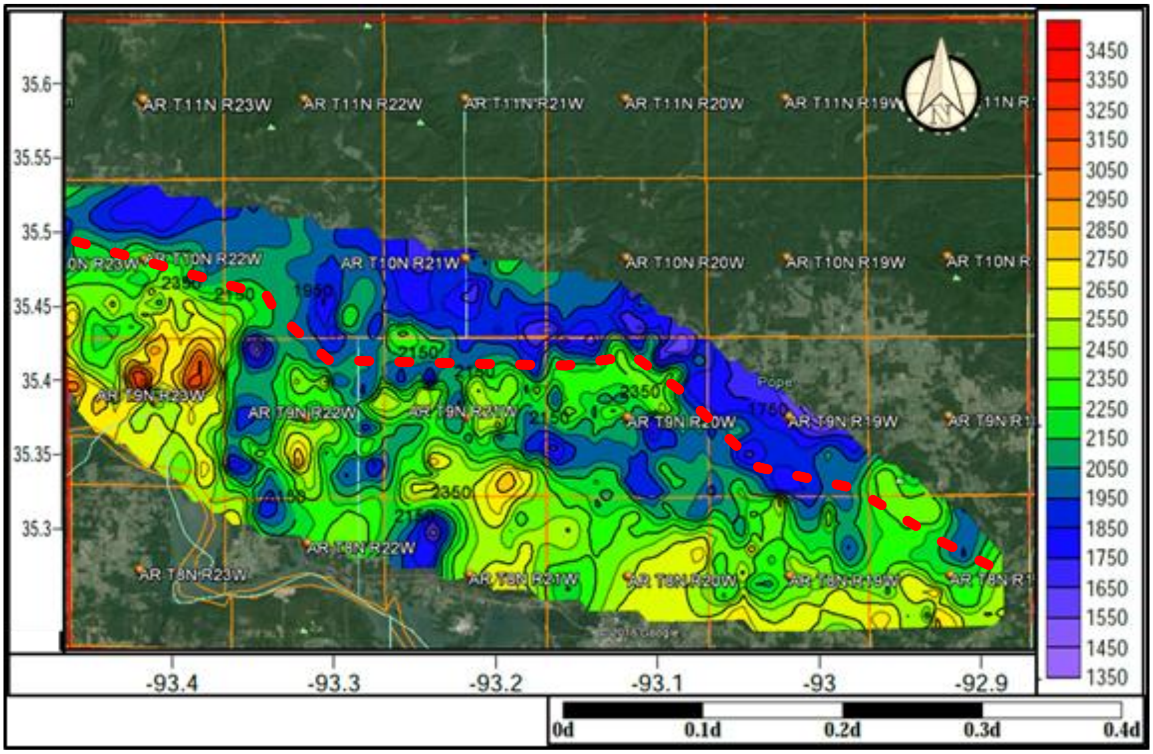

Figure 2-24: The Middle Atoka interval isopach map, highlighting the Clarksville Fault in red color.

The Middle Atoka interval isopach map (Figure 2-24) was created through Surfer 13 to represent the change in the stratal thickness. The map shows a thickness range of the Lower Atoka interval of 1950 feet to 2950 feet. The Middle Atoka interval shows different coverage of the study area comparing to the previous mapped formations, which is due to the well log control. The isopach map shows a sudden change in the northern half of the map, which is caused the Mulberry Fault. The thickness of the up-thrown side of the Mulberry Fault is less than the thickness of the down-thrown side. This map is important in terms of providing some information in relation to the initial subsidence of the Arkoma Basin.

CHAPTER 3

STRUCTURAL EVOLUTION OF THE ARKOMA BASIN

3.1 Structural Analysis

The primary objective of subsurface structural analysis is to develop an understanding of the overall structural behavior of rock deformation. This introduction aims to provide a short description for the most significant terminologies or elements of structural geometries that will be discussed in this chapter. Explaining the structural classification in relation to the role of tectonics is helpful in determining the affective stresses that caused the deformation on depositional strata. Then, it provides valuable tool in the exploration for hydrocarbons.

The method used in this chapter is mapping formation intervals of the study area as interpreted on well logs through the IHS Petra. Formation tops picked on the well logs were transferred to Surfer 13 to generate structural contour maps. Finally, cross sections were made through IHS Petra based on the generated structural maps to illustrate structural relationships in profile.

3.2 Previous Subsurface Studies

Several studies have been conducted on the structural configuration of the Arkoma Basin. Prior to explaining the regional structure, it is important to have a general understanding for some of the structural terminologies that have been used in this chapter. The Arkoma Basin is characterized by series of normal faults. Those faults resulted from tectonic activities that are associated with the Ozark Uplift and Ouachita Orogeny.

The main focus in this study is to analyze the normal faults in the study area. A complex system of faulting (Figure 3-1) within the Lower to Middle Atoka formations was described as the inception of the Aroma Basin development.

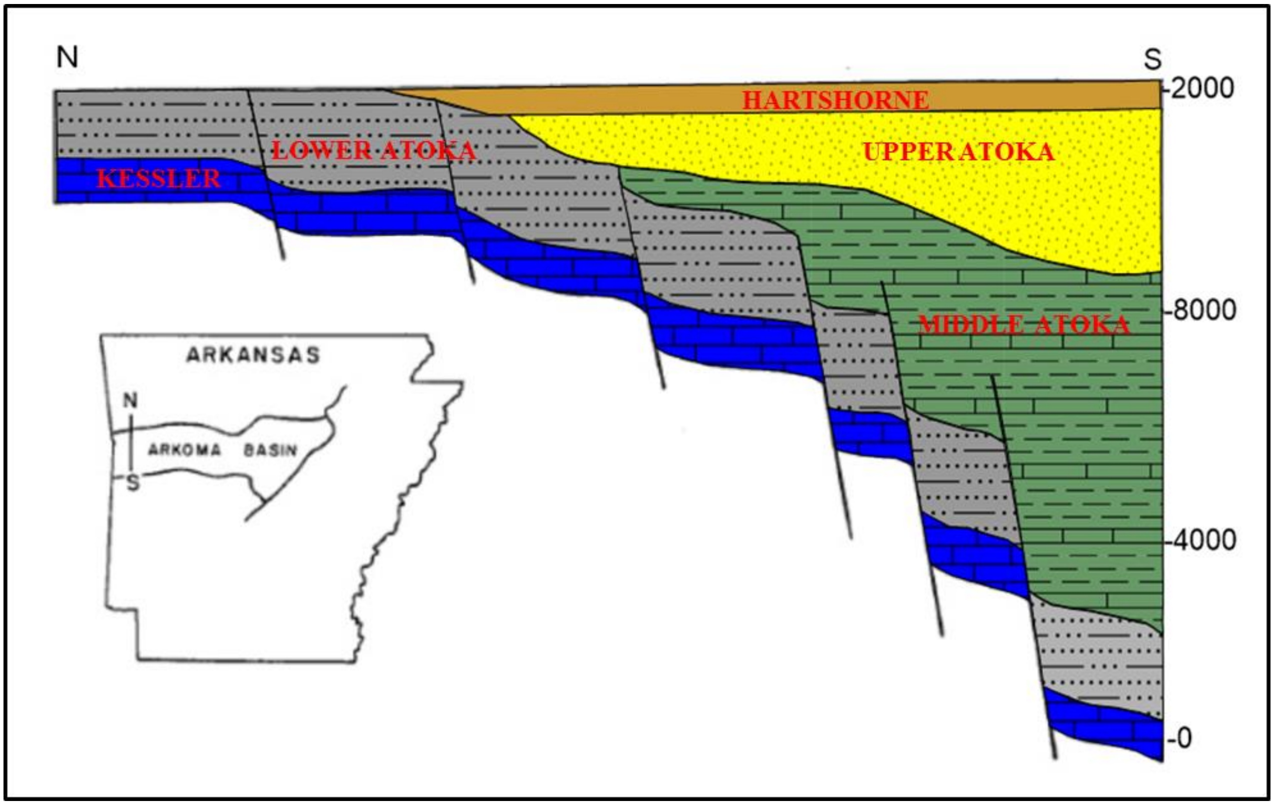

Figure 3-1: North- south cross section (modified from Zachry and Sutherland, 1984). The section shows the thickening of the Atoka section on the downthrown side of the growth normal faults.

Most of the faults in the Arkoma Basin are east-west trending down to the south normal faults. A master fault is one with major displacement. The growth faults in the Arkoma were generated during subsidence of the basin when sedimentation rates were high, Middle Atoka sediment accumulated during this time (Houseknecht, 1986).

3.3 Well logs and Seismic Profile Analysis

In order to describe the subsurface structure of the western-central Arkoma Basin, about 1550 raster logs and a migrated seismic reflection profile were utilized. Subsurface studies use different logging elevations for structural purposes (Figure 3-2). These measurements include; Kelly Bushing (KB), Measured Depth from the Kelly bushing (MD), True Vertical Depth (TVD), Sub-Sea True Vertical Depth (SSTVD), and Subsea (SS) depth. For the purpose of this study, the subsea true vertical depth (SSTVD) measurement was used. SSTVD refers to the vertical distance or depth from sea level to the mapped subsurface formation (Tearpock and Bischke, 1991).

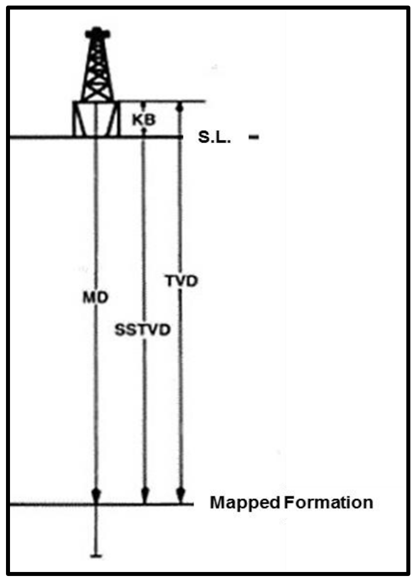

Figure 3-2: The elevation value based on subsurface location in relation to a mapped formation (modified from Tearpock and Bischke, 1991).

Wireline log correlations can document repeated or a missing section (Figure 3-3). A repeated section is defined as “a part of stratigraphic section appearing twice on a log as the result of a reverse fault, and consequently lengthen the section” (Tearpock and Bischke, 1991). In addition, missing sections represent missing parts of a known formation, which usually occur as a result of a normal fault.

The study area also includes some deviated wells, especially to the southern part of the area causing an increase in thickness for the depositional stratal.

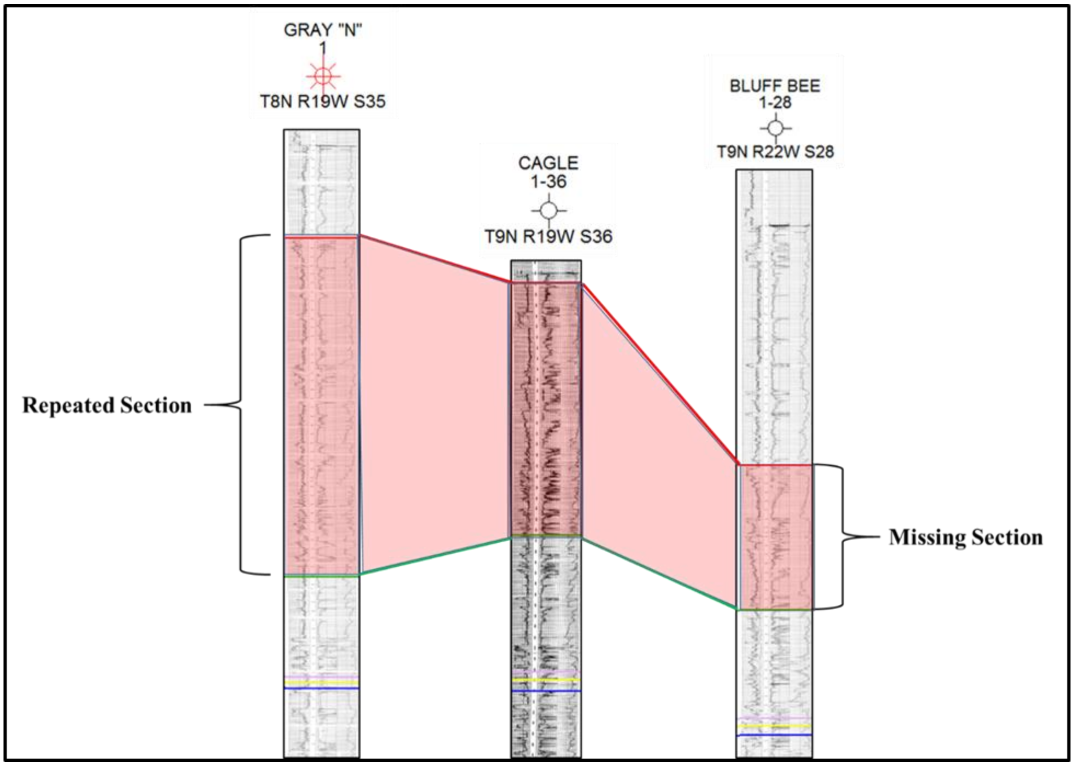

Figure 3-3: Correlation of Gray "N", Cagle, and Bluff Bee well logs, indicating the variation in the Middle Atoka Formation thickness highlighted in a red color. The section labeled missing section, in the Bluff Bee well indicate that a fault cut the well

The 2-D seismic profile (Figure 3-4) is perpendicular to the strike of east-west faults. The profile shows various small normal faults as well as the Mulberry Fault. A graben was mapped to the north of the Mulberry Fault. Most faults extend to the surface. However, it is difficult to determine if these faults transect the Middle Atoka Formation.

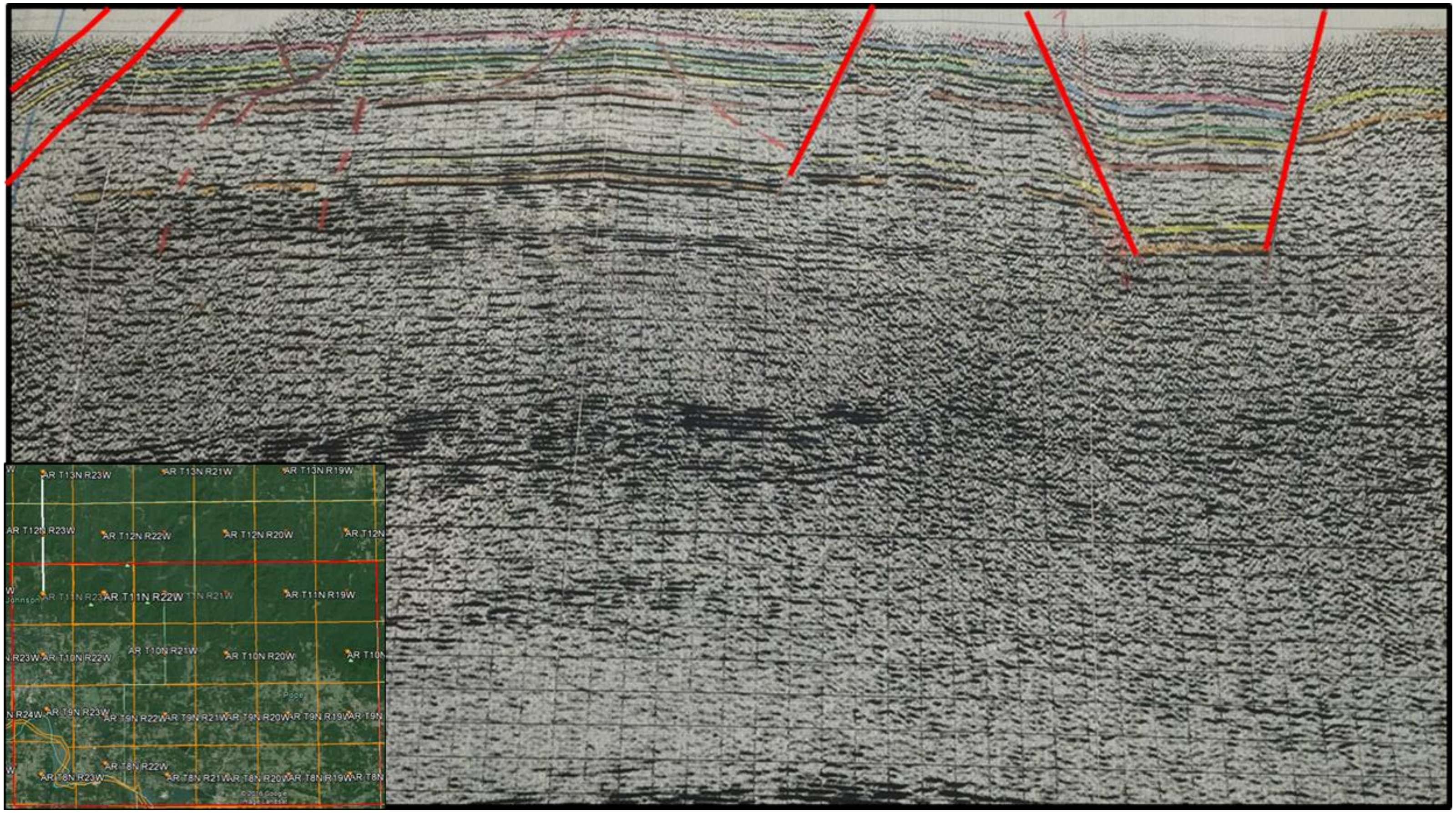

Figure 3-4: A north-south seismic profile showing the general normal faults, for location see figure (-) (Shields Company, personal communication, December 8, 2015).

3.4 Local Structure

After identifying the formation tops on the well logs, structural contour maps were constructed. In general, the geological map of Arkansas over the study area (Figure 3-5) shows numerous east- west trending faults. The mapped formations at the surface include the Hale and Bloyd formations of the Morrowan Series, and the Lower Atoka, and Middle Atoka intervals. The geological map of the study area indicates numerous east-west trending faults similar to those mapped in this study.

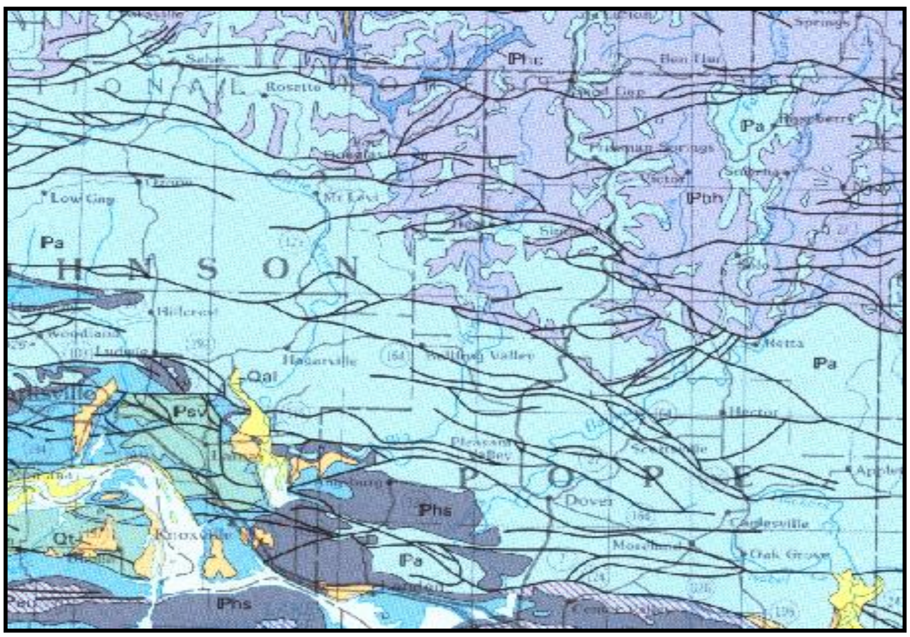

Figure 3-5: The geological map of the study area, depicting the regional east- west trending faults (modified from Arkansas Geological Survey).

This section aims to delineate the most prominent structural features in the study area. Even though the study area does not have good exposures, google earth provides valuable surface profiles to show whether or not subsurface faults have affected the topography of the study area (Figure 3-21).

3.5 Structural Contour Maps

The study area is located on the shelf and northern slope of the Arkoma Basin. Prior to constructing the structural maps, formation intervals were mapped using IHS Petra. The data for formations depths were exported to construct structural maps through Surfer 13. In order to match the IHS Petra and Surfer 13 well log coverage, the maps were transferred to Google Earth to show the actual coordinates for the structural maps in terms of townships and ranges. Generally, the maps are oriented roughly in a slight southeast to northwest orientation. The orientation is constructed based on well log control in the study area.

Structural contour maps were generated for the Hale, Bloyd, and Lower and Middle Atoka intervals (Figure 3-6 to 3-10). The maps show two major east-west trending normal faults crossing the area in the northern and southern quadrants. These two master faults are mapped as lines on the structural maps. Usually, faults have planar or smoothly curved in most of local structural contour maps (Groshong, 2006). The maps for the Morrowan and Lower Atoka Formations define an additional geological feature that is interpreted as a graben.

The northern most fault is the Mulberry Fault. Few publications mention that a second master fault in the study area is the Clarksville Fault (Collier et al., 1907). For analyzing these two master faults as well as several small faults, seven north-south and two east-west cross sections were constructed. In addition to the east-west trending faults, north-south trending faults are discussed. The north-south faults are oriented perpendicular to the Mulberry Fault. The structural contour maps revealed other structure evidence indicating the orientation of the two master faults surfaces, and a major graben feature that exists at the top of the mapped designated region.

3.5.1 Structural Contour Map of the Hale Formation Interval

A structural contour map was generated to illustrate the structural geometry at the top of the Hale interval (Figure 3-6). A few anomalies are present in the Hale structural map, specifically in the central part of the contour map. The Hale interval dips steeply into the basin, which is highlighted by the change in color from red (shallow) to blue (deep). The two east-west trending master faults can be observed on all of the structural maps, except for the Middle Atoka interval. The Mulberry Fault extends from Township 11N and Range 24W to Township 9N and Range 18W. The Clarksville master fault extends from Township 10N and Range 23W to Township 8N and Range 18W. These two master faults are recognized because of the rapid change in spacing of the contour lines. Also, the structural map shows that there is a sudden change of the Mulberry Fault at the central part. The change represents a decrease in the depth, represented by the contour lines. This decreased was bounded by two small or antithetic faults that are trending in the opposite direction of each other forming a graben.

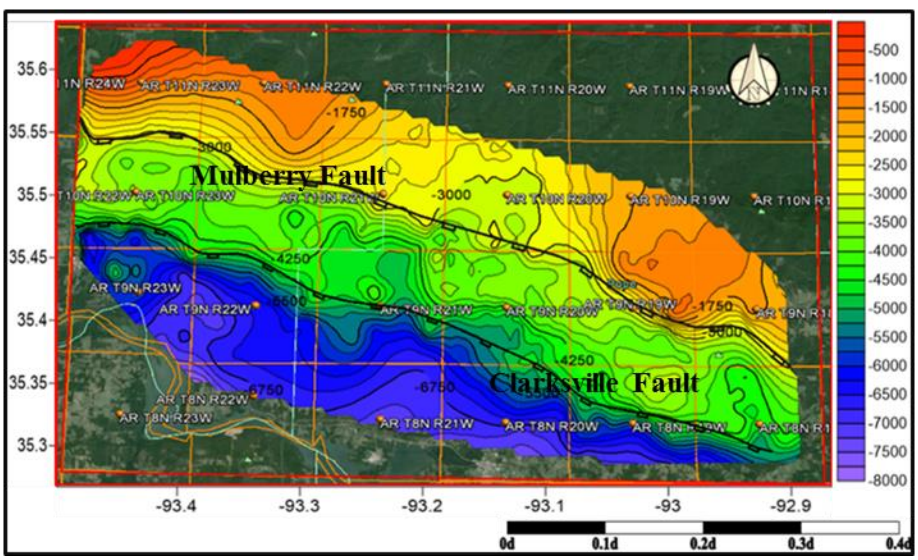

Figure 3-6: Structural contour map of the Hale Formation interval.

3.5.2 Structural Contour Maps of the Bloyd Intervals

The overall structure of the Kessler and Brentwood intervals of the Bloyd Formation are very similar to that of the Hale interval (Figure 3-7 and 3-8). The area has a good well logs coverage. The master faults cutting the Bloyd intervals are located at the same location as the faults in Hale interval. Also, the east-west trending faults cross the area in almost a straight line. The isopach maps in chapter two for the Kessler and Brentwood intervals (Figure 2-24 and Figure 2-25) do not show an obvious thickening as a result of faulting. It leads to interpreting that the movements on master faults are either not active or they were generated after the Morrowan time. Several regional small east-west trending normal faults are recognized through the cross sections.

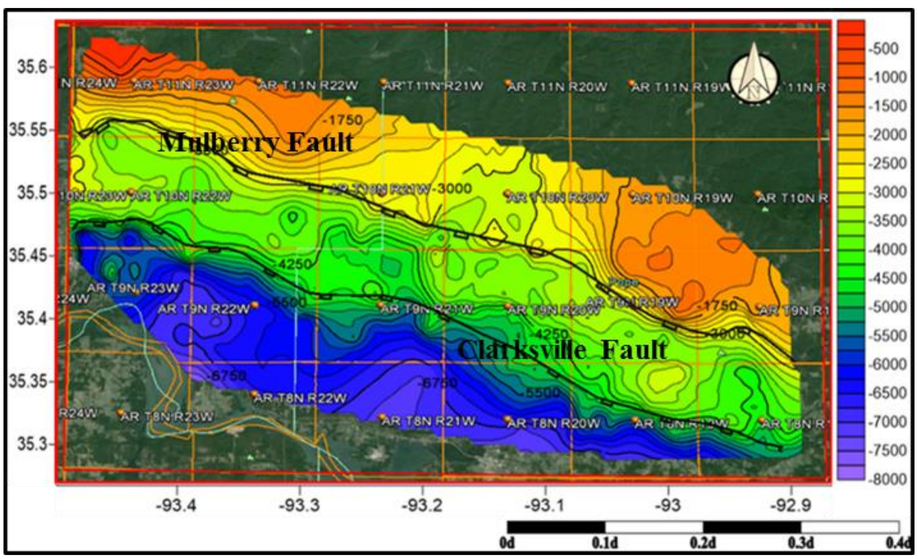

Figure 3-7: Structural contour map of the Brentwood interval.

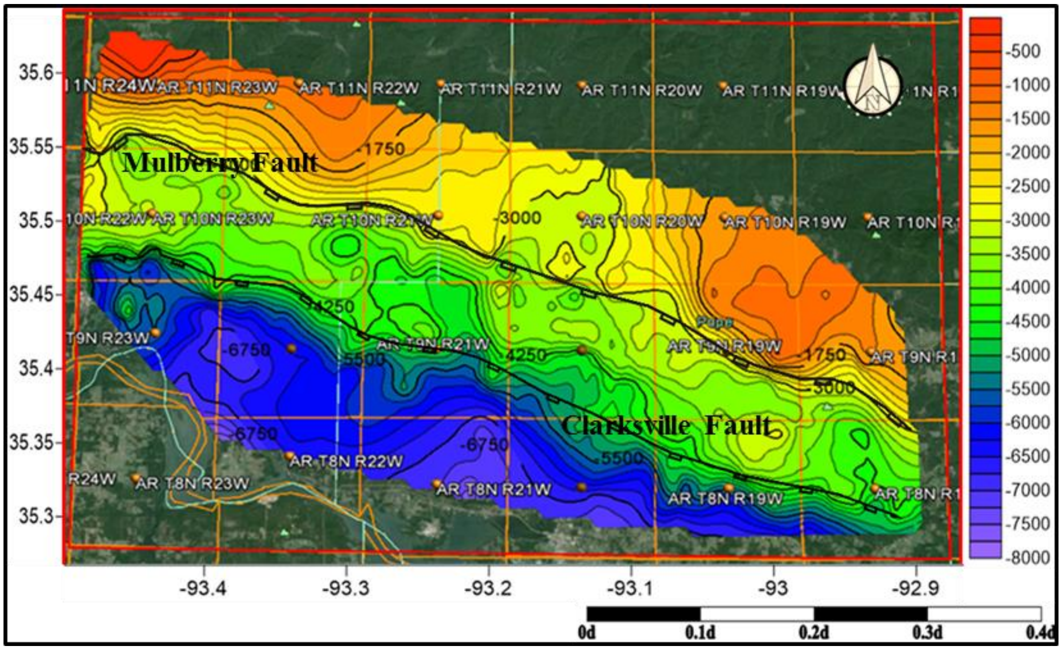

Figure 3-8: Structural contour map of the Kessler interval.

3.5.3 Structural Contour Map of the Lower Atoka Formation Interval

The Lower Atoka structure map (Figure 3-9) has similar structural pattern to the one of the Morrowan formations. The map indicates the effect of the master faults to the north and south portion of the map. In addition, the graben at the lower Atoka level is more well defined because the top Lower Atoka picks can be identified in most of the wells. The two master faults separated the formation into three parts. Strata on the up-thrown block of the Mulberry Fault are thinner than on the down-thrown block. The same is the case for the Clarksville Fault to the south. In general, the structural map for the Lower Atoka interval shows some structural changes south of the study area. The displacement between the up-thrown side of the Mulberry Fault and the down-thrown side of the Clarksville Fault is about 2500 ft.

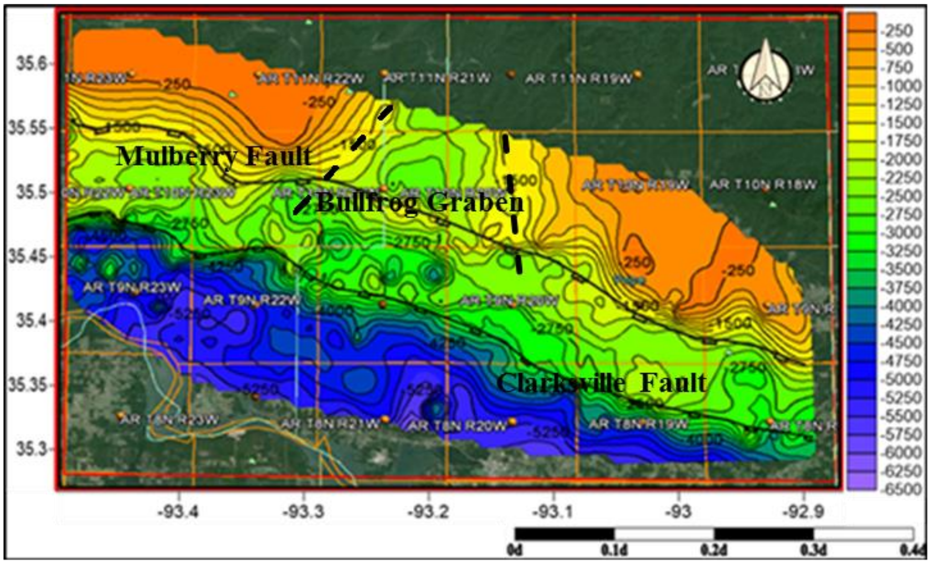

Figure 3-9: Structural contour map of the Lower Atoka interval.

3.5.4 Structural Contour Map of the Middle Atoka Formation Interval

The Middle Atoka Formation interval structure map has different structural style in comparison to the Morrowan maps (Figure 3-10). The change in the structural configuration of the Middle Atoka interval resulted in difficulty in identifying the Mulberry and Clarksville faults at this horizon. One of the master faults shows a dramatic structural change. It crosses the northern part of the study area from west in Township 10N and Range 23W to east between Township 9N and 8N and Range 19W and 18W. Initially, it is difficult to identify which one of the master faults is affecting the area just by analyzing the structural contour map alone. However, the cross sections (Figures 3-12 to 3-19) indicate that it is the Clarksville Fault because the Middle Atoka interval is eroded on the up-thrown side of the Mulberry Fault. In fact, this change of the Middle Atoka unit in relation to the extensional master fault suggests evidence for the inception point of the subsidence in the Arkoma Basin. The graben feature is hard to identify in this map, but it is easy to describe within the east-west cross sections. Also, the Google earth profile (Figure3-21) shows obvious surface depression on the topography of the graben. The hanging wall of the mapped fault blocks is interpreted to be have undergone varying amounts of local erosion after they were uplifted by the tectonic activity of the Arkoma Basin.

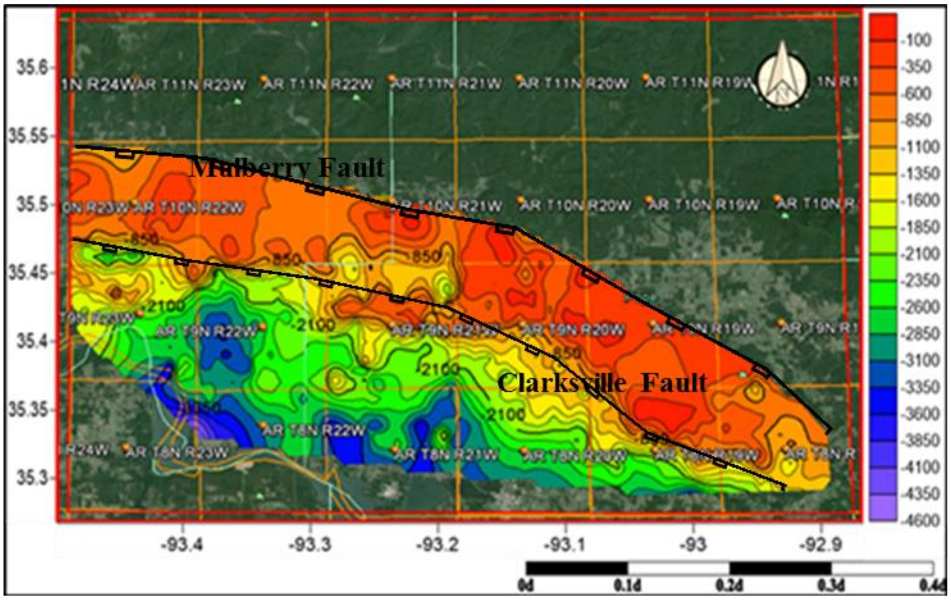

Figure 3-10: Structural contour map of the Middle Atoka interval.

3.6 Local Cross Sections Description

A structure contour map alone cannot represent a complete picture of the subsurface. A series of structural cross sections were constructed to illustrate the various structures in profile. By combining structure maps and cross sections, one can develop a better understanding of the 3-dimensional aspect of the structural configuration. In general, a cross section that is perpendicular to the strike of the structural feature, such as a normal fault is called “dip section”. A cross section that is parallel to the strike is called “strike section” (Figure 3-11). In other words, the first seven cross sections (A-A` to G-G`), drawn from the North West to the South East dip sections. The reason for picking the dip orientation is that they are perpendicular to the master faults in the structure contour maps. Since the contour maps indicate a different structural style in the area above the central part of the Mulberry Fault, the strike cross section (AA-A`A`) is constructed. Also, the strike cross section (BB-B`B`) is constructed to provide a significant indication for the graben structural style north of the Mulberry Fault that does not affect the Clarksville Fault south of the study area.

All of the cross sections are north of the Arkansas River, except for the southern part of the cross section (B-B`), as most of the well logs south of the river are deviated wells. Most of the deviated well logs were avoided due to untrue thickness representation. The orientation of the cross section is important because the local structure might result in some distortion of the subsurface geometry. The master faults on the cross sections are represented in black lines, while the small faults are represented by red solid lines in order to distinguish between them on the cross sections.

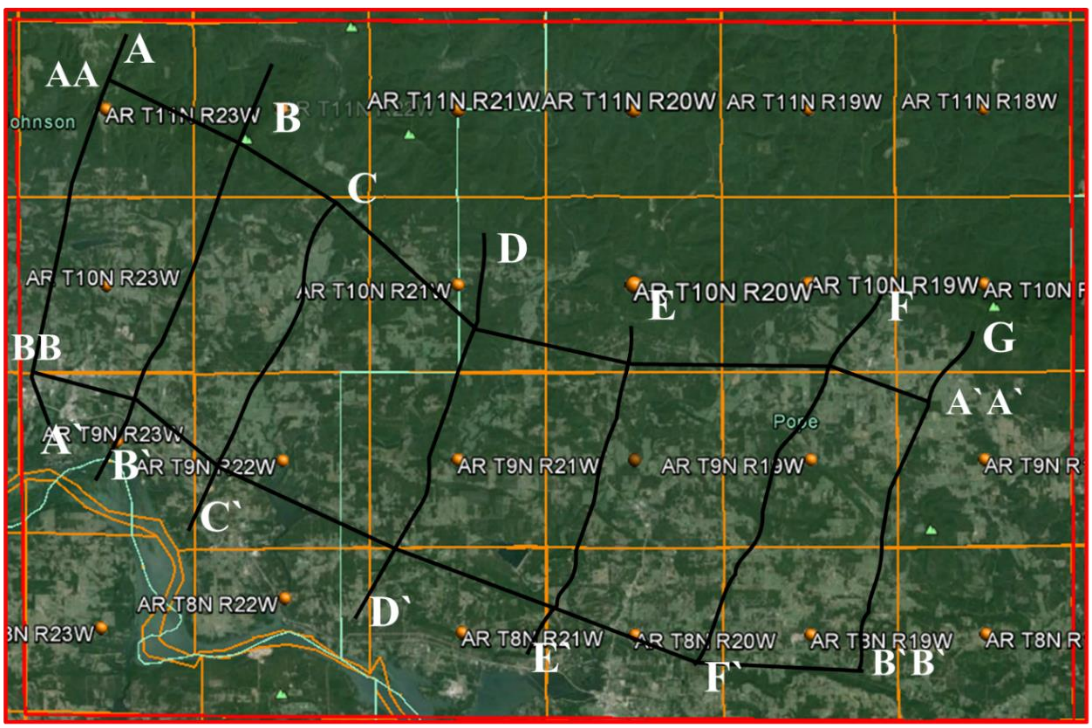

Figure 3-11: The orientation of the structural cross sections in the study area in Google earth.

3.6.1 (A-A`) Cross Section

Cross section A-A` is located at the western part of the study area (Figure 3-12). This cross section extends from the north in Townships 9N-11N, Range 23W in Johnson County (Figure 3-11). The cross section contains seven well logs (see Appendix 2). The well logs are spaced relatively close to each other. The wells are spaced at approximately 1 to 3 miles apart. This cross section covers a distance of 13.5 miles. The two master normal faults are mapped in black lines. The thickness of both the Bloyd and Lower Atoka intervals is relatively constant through the cross section. In contrast, the Middle Atoka interval thickness increases moving toward the southern part of the area. The thickening of the Middle Atoka is due to syn-depositional faulting. The Middle Atoka shows regional erosion of the up-thrown side of the Mulberry Fault, which has a displacement of about 2,170 feet, whereas the Clarksville Fault indicate a smaller displacement compared to the Mulberry Fault of about1,080 feet.

The cross section shows an additional normal fault that has a displacement of about 960 feet. It indicates a semi horst and graben structural features with the last two additional faults. For the purpose of this study, the description of the cross sections defines the structural configuration with the term highs and lows instead of horst and graben. This pattern of high and low structures was described as the result of reactivation of normal faults that occurred during the last phases of Ouachita compression (McGilvery and Houseknecht, 2000). The Mulberry Fault dips in a low angle between 45 and 50 degrees to the south east. The interpreted seismic profile (Figure 3-4) supports the measurements to define a value of 45 degrees for the Mulberry Fault. On the other side, the Clarksville Fault is dipping in a high angle of about 83 degrees.

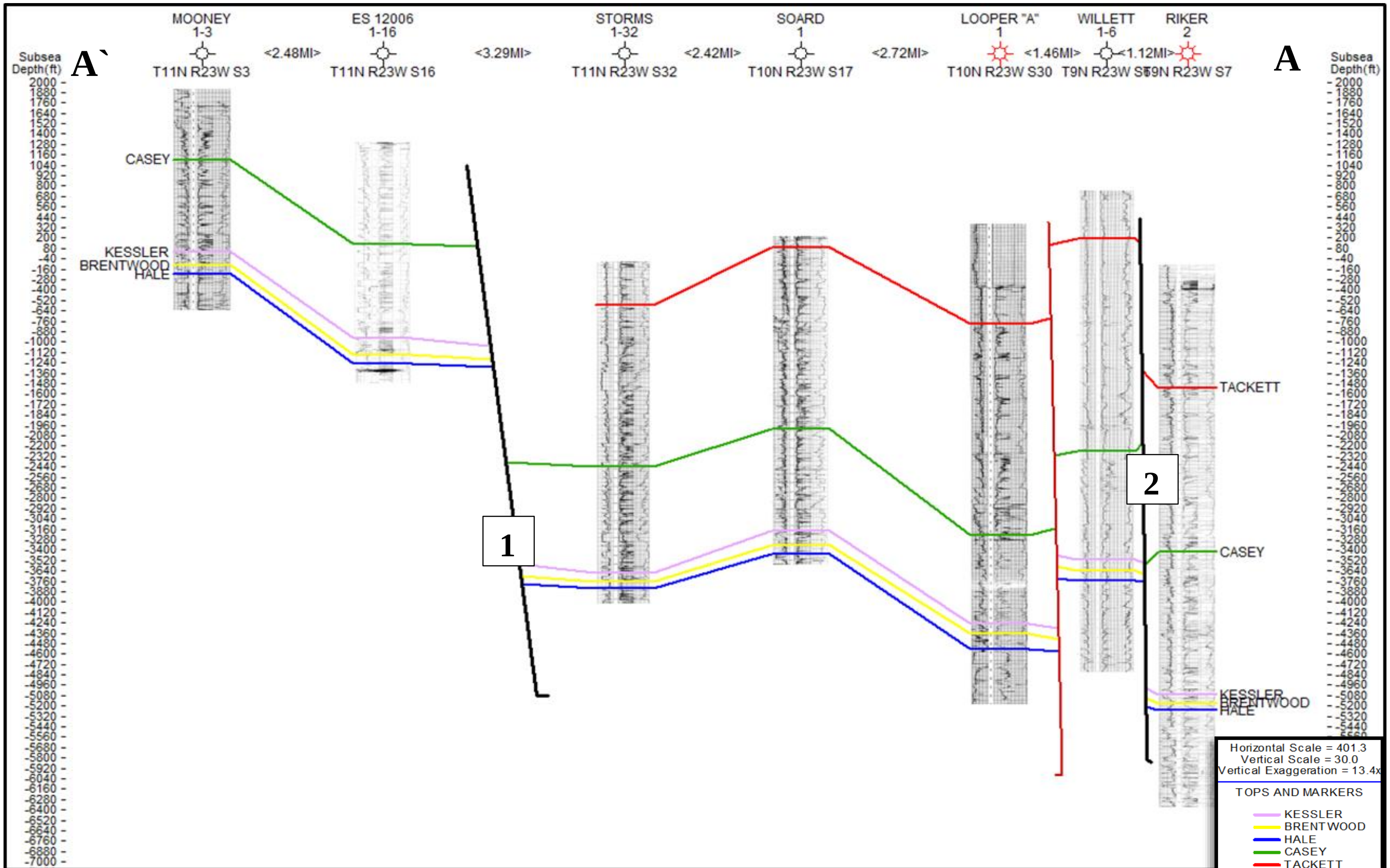

Figure 3-12: North to south structural cross section A-A`, with the Mulberry (1) and Clarksville (2) faults in the black lines.

3.6.2 (B-B`) Cross Section

Cross section B-B` is located at the western side of the study area (Figure 3-11). (B-B`) cross section extends from the north to south in Townships 9N-11N, Ranges 22W- 23W in Johnson County. The cross section contains six well logs (Figure 3-13). The well logs are picked to be closely spaced in order to provide more detailed illustration of the structure of the area. The well logs were selected to cover a total area of 14.66 miles from north to south. The wells are spaced between 2 to 3 miles of each other. The cross section (B-B`) shows similar faulting pattern to the cross section (A-A`).

Since the base of the Hale Formation is not mapped, it is hard to determine the total thickness of the Morrowan. However, the cross section shows a constant thickness of the Bloyd formation interval. Also, the Lower Atoka interval is thinner to the central part of the mapped section. The Middle Atoka interval shows a different depositional pattern compared to the other mapped formations. It is interpreted to show a decrease in its thickness to the northern part of the cross section, which is related to the previously described local erosion.

The master faults show major displacement on the Morrowan and Lower Atokan formations, while it is hard to measure the displacement on the Middle Atoka due to the local erosion on the up-thrown side of the Mulberry Fault. The Mulberry Fault in this section has a displacement of about 1,880 feet, whereas the Clarksville Fault indicates a smaller displacement comparing to the Mulberry Fault of 600 feet. Unlike the previous pattern for the master faults with the highs and lows structures, the faults show a stepped pattern, with a gradual deepening to the south.

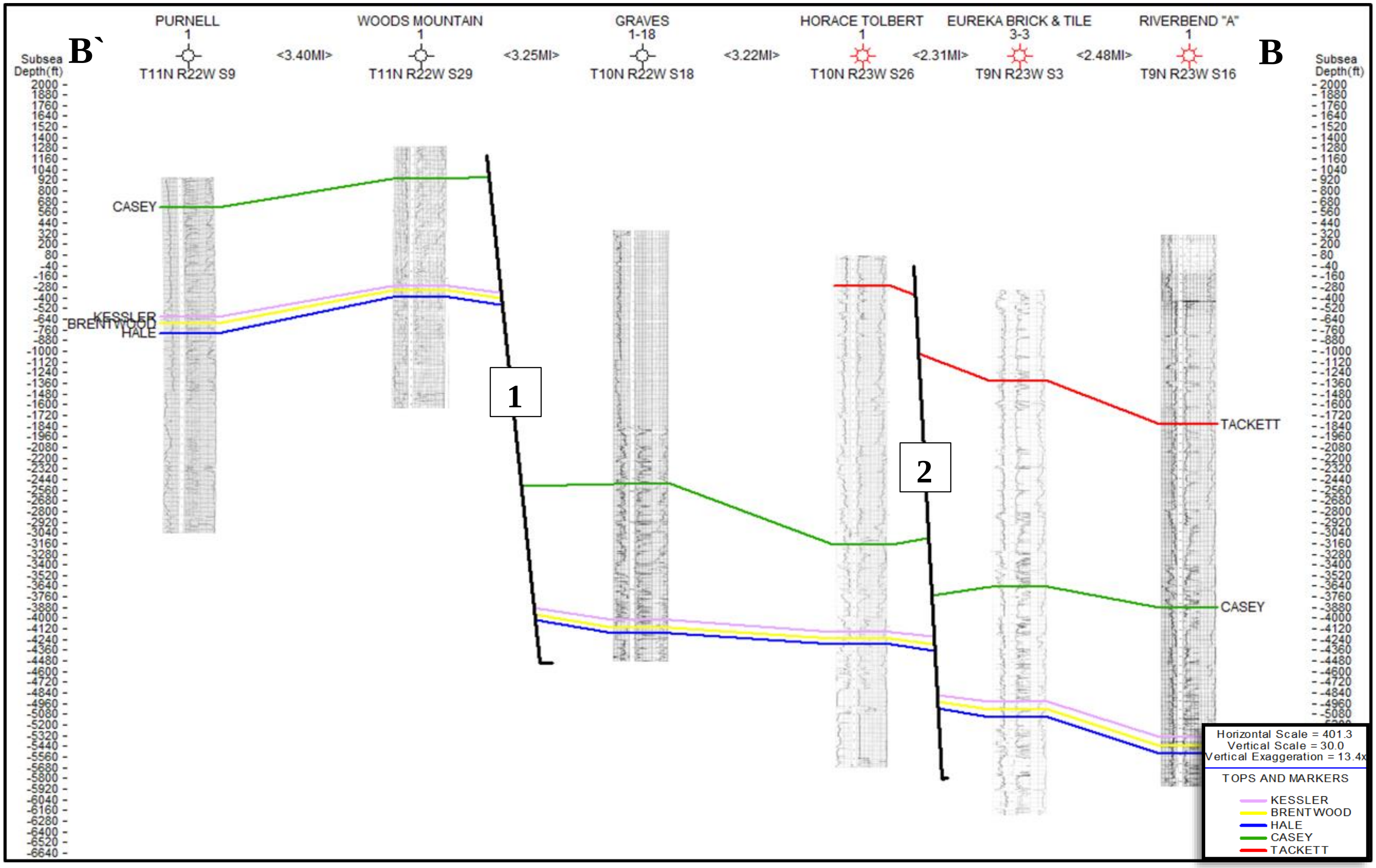

Figure 3-13: North to south structural cross section B-B`, with the Mulberry and Clarksville faults in the black lines.

3.6.3 (C-C`) Cross Section

Cross section C-C` is located at the western side of the study area (Figure 3-11). It extends from northeast to southwest in Townships 9N-10N, Ranges 22W-23W in Johnson County. Seven well logs are used in the cross section from north to south (Figure 3-14). The distance between the well logs are spaced between one to two miles. Additionally, the cross section covers a total area of 12.8 miles. Some of the well logs in this cross section penetrate deep enough to reach the Boone Formation. Furthermore, this cross section indicates similar style of down to the basin, stepped faulting to cross section (B-B`). The thickness of both Bloyd and Lower Atoka intervals is calculated. In general, thickness of the Lower Atoka and Bloyd formations remains constant as previous cross sections indicated. To the south, a continuous increase in the thickness of the Middle Atoka is recognized. The increase in Middle Atoka Formation thickness is about 1820 feet.

The master faults show major displacement on the Morrowan and Lower Atokan formations. As the Middle Atokan is not penetrated by the Mulberry Fault due to the local erosion, the displacement on fault for the Middle Atoka is not included. The displacement on the Mulberry Fault is about 1,680 feet at the top Lower Atoka, while it is calculated to be about 2,100 feet on the Clarksville Fault.

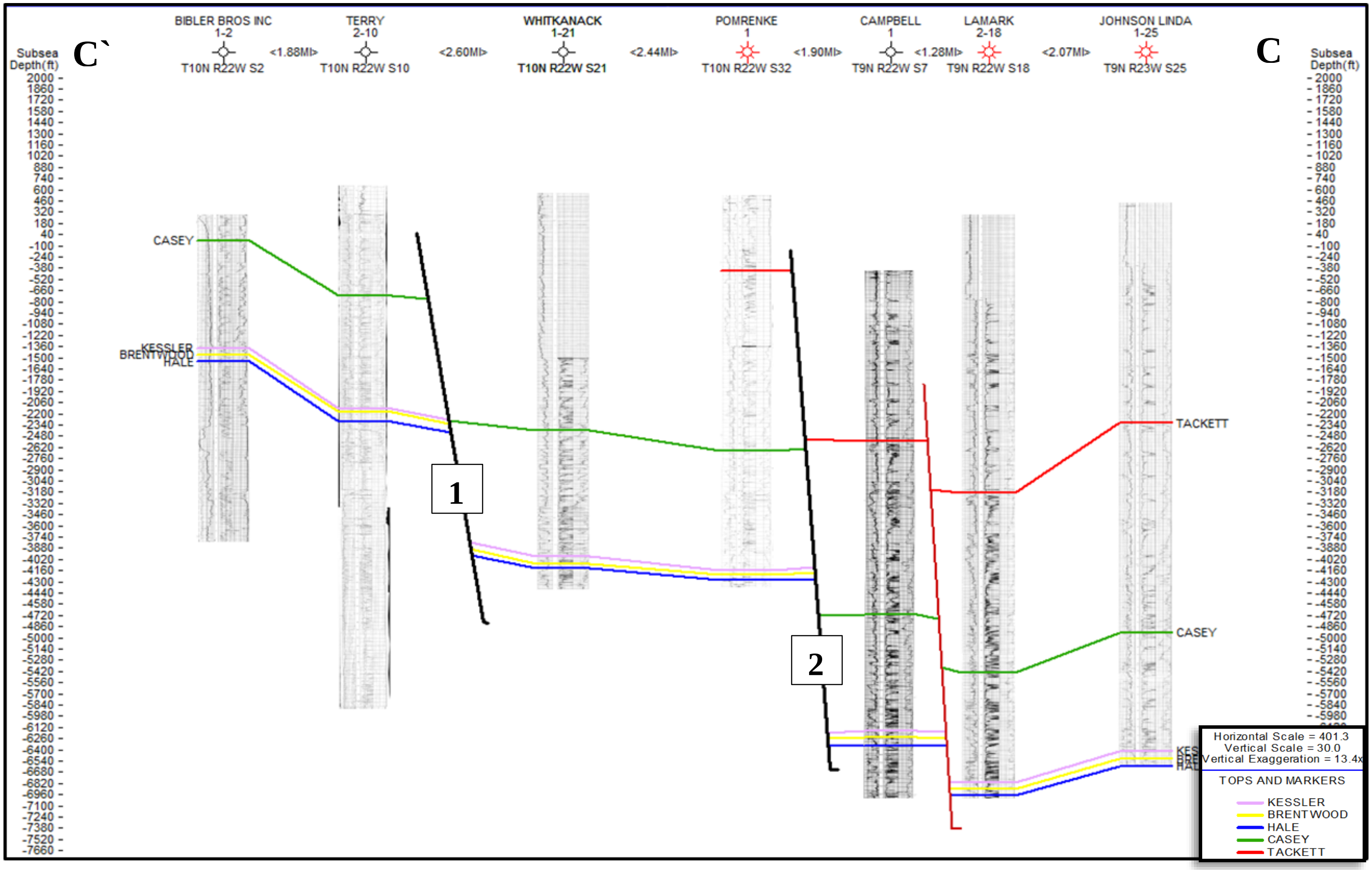

Figure 3-14: North to south structural cross section C-C`, with the Mulberry and Clarksville faults in the black lines.

3.6.4 (D-D`) Cross Section

Cross section D-D` is located in the middle part of the study area (Figure 3-11). This cross section extends from the north in Townships 10N-8N, Ranges 21W-22W in Pope County. The cross section is constructed using nine well logs (Figure 3-15). The spacing of the well logs in this cross section ranges between one and a half to two miles from north to south. The total distance covered by this cross section is about 14 miles. The well logs are not deep enough to provide a detail analysis of the Morrowan and Lower Atoka strata in the cross section. However, it appears that both Bloyd and Lower Atoka formations have relatively constant thickness over the study area. To the northeastern side of the study area, the Middle Atoka Formation contains the entire stratigraphic succession. Unlike the previous cross sections. The complete Middle Atoka is preserved on D-D`. This is defined by the consistent Top Tackett pick and correlation on all of the well logs. Note that there is only a subtle basinward thickness increase in the Middle Atoka. The complete section of the all formations is due to the structural configuration of the study area. Also, there is no strong evidence for the effect of the erosion on this part of the study area, especially on the up-thrown side of the Mulberry Fault because of the present of all formations.

The cross section shows three small faults that are distributed randomly in the area in addition to the two master faults. The Mulberry Fault displaced the strata vertically of about 1,340 feet, while the Clarksville Fault showed smaller displacement compared to the Mulberry Fault of about 620 feet. Additionally, the cross section shows series of highs and lows structural features that constructed by the small faults to the south of the cross section. The Mulberry Fault shows a dip in a high angle about 83 degrees, which is the highest dip in the area for the fault, whereas the Clarksville Fault dips in a lower angle of about 63 degrees.

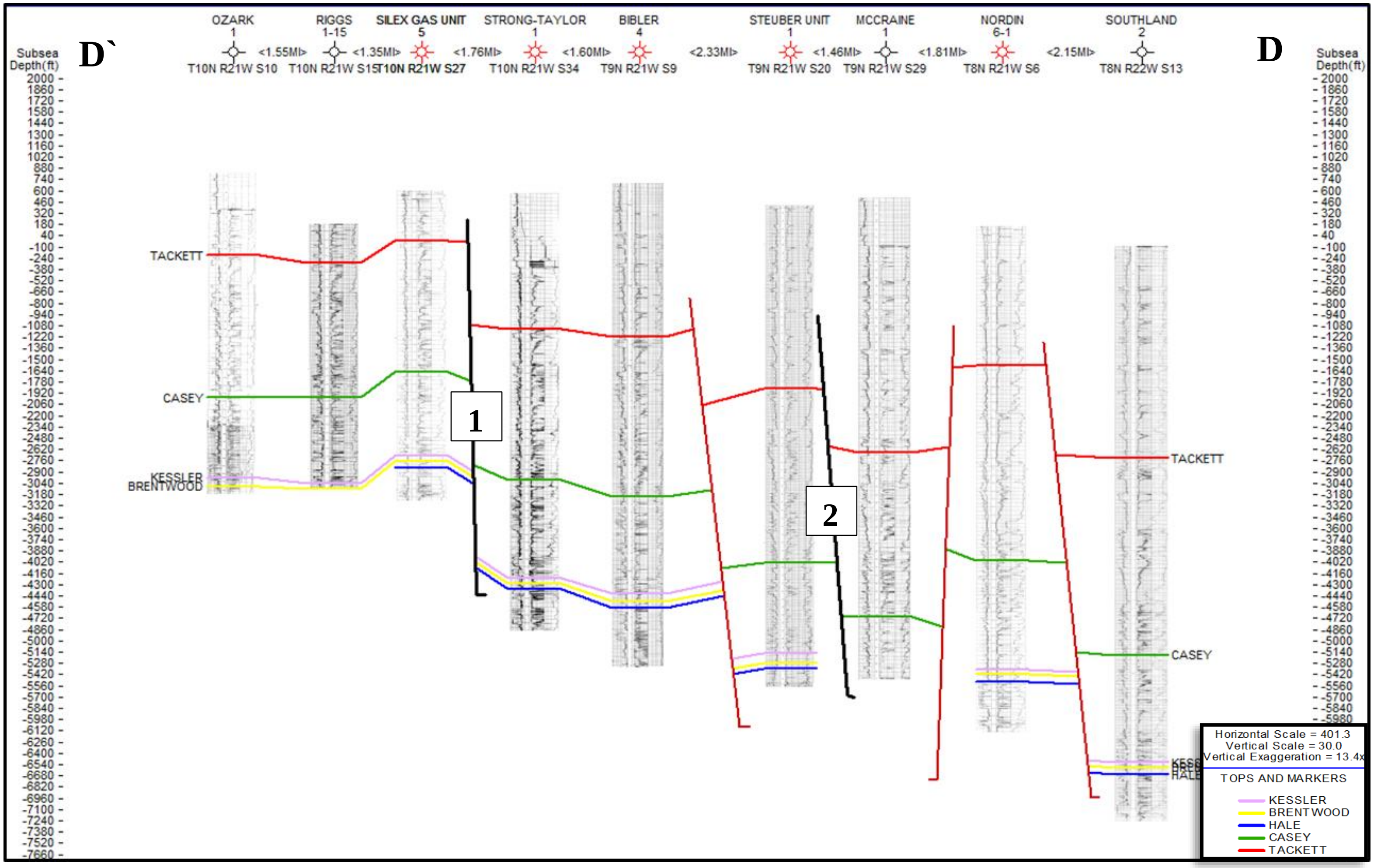

Figure 3-15: North to south structural cross section D-D`, with the Mulberry and Clarksville faults in the black lines.

3.6.5 (E-E`) Cross Section

Cross section E-E’ is located at the eastern part of the study area (Figure 3-11). This cross section extends from the north in Townships 10N-8N, Ranges 20W-21W in Pope County. The cross section is constructed using seven well closely spaced (Figure 3-16). The cross section covers an area of 11.6 miles. Similar to the cross section (D-D`), this cross section has good well log control to map all of the formation tops. As described in the previous cross sections, the thickness of the Bloyd and Lower Atoka formations is constant. However, the Middle Atoka Formation thickness shows an increase of about 1,070 feet.

This section is characterized by some individual small faults. Also, there is little evidence for the effect of erosion in this part of the area as seen along the western side. The Mulberry Fault shows minor displacement of about 560 feet in comparison to the Clarksville Fault that has a layer displacement of approximately 1,180 feet.

Additionally, the structure map shows thicker intervals to the southern portion as a result of faulting. The mapped faults show down to the basin stepped pattern as the strata are gently dipping to the south. The master Mulberry Fault dips 73 degrees, and the Clarksville Fault dips 55 degrees toward the southeastern part of the study area.

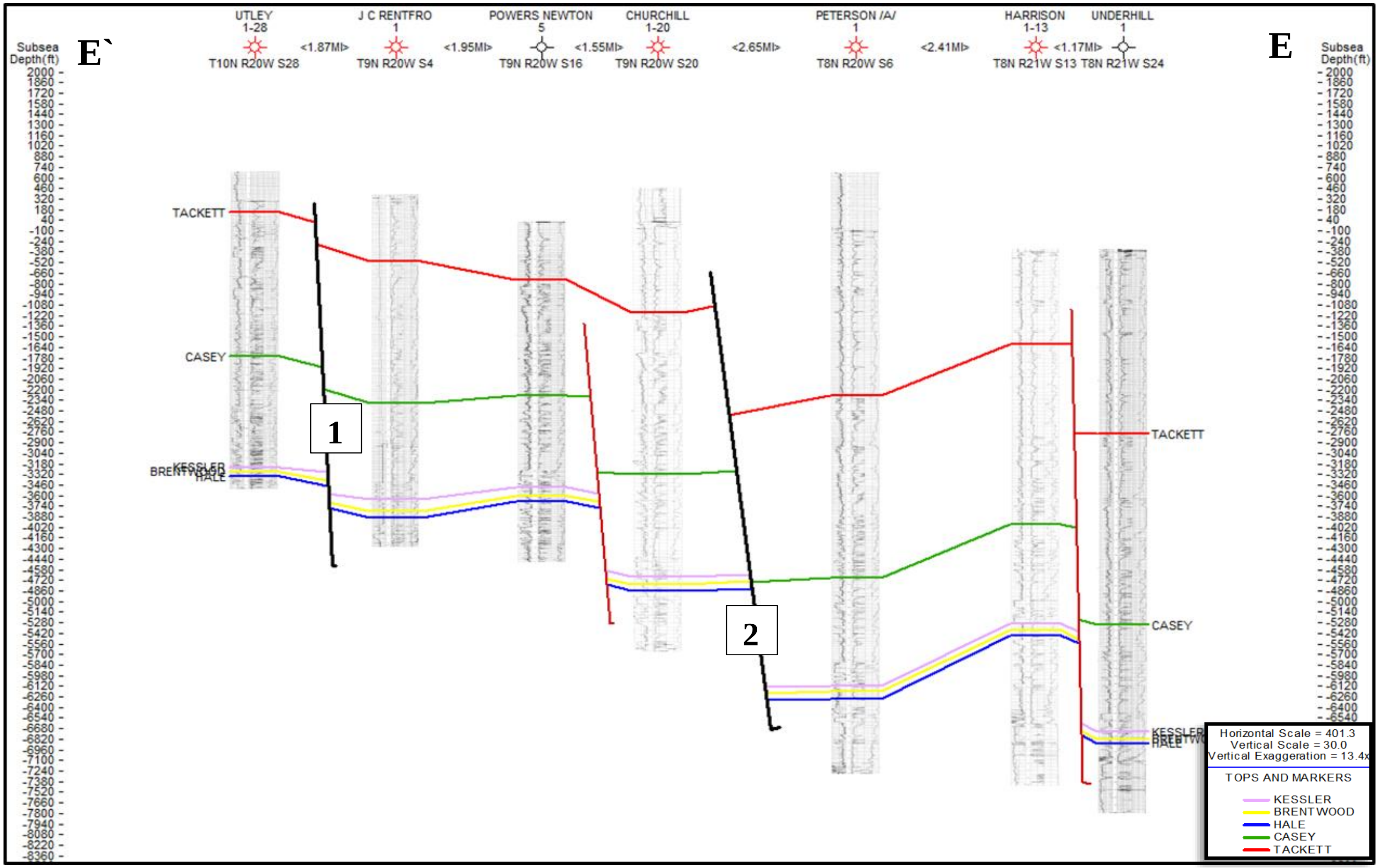

Figure 3-16: North to south structural cross section E-E`, with the Mulberry and Clarksville Faults in the black lines.

3.6.6 (F-F`) Cross Section

Cross section F-F` is located at the eastern part of the study area (Figure 3-11). This cross section is mapped from the north in Townships 10N-8N, Ranges 19W-20W in Pope County. Nine well logs were used to construct this cross section, and they are spaced in a range between one to three miles (Figure 3-17). This cross section covers a total distance of approximately 14.5 miles from north to south. Like cross section (E-E`), this cross section provides different structural and stratigraphic configurations for the Middle Atoka. At the northern part of the cross section, it is obvious that local erosion has affected the up-thrown side of the Mulberry Fault. Moreover, the depositional rate of the Middle Atoka increased simultaneously with the increase of the accommodation space, which provides additional space of sediment to be transported and deposited at the southeastern part of the study area. The syn-depositional fault movement is suggested by significant thickening of the Middle Atoka on the down thrown side of the key faults. This establishes the timing for the onset of the tectonic development of the Arkoma Foreland Basin. This section shows some evidence in relation to syn-depositional faults.

Four small faults in addition to the master faults are mapped. The small faults are mapped with uncertainty since they might result from stratigraphic controls rather than structural. The Middle Atoka Formation indicates a recognizable increase in thickness of about 1600 feet to the south of the cross section. The increase in thickness is controlled by series of normal faults. The vertical displacements along the master faults are measured to reveal a value of about 1,800 feet for the Mulberry and 360 feet of the Clarksville faults. Finally, the cross section shows series of down to the basin step faulting. It seems that the faults in this part of the region are either not reactivated or they reactivated later after the sediments deposition increased.

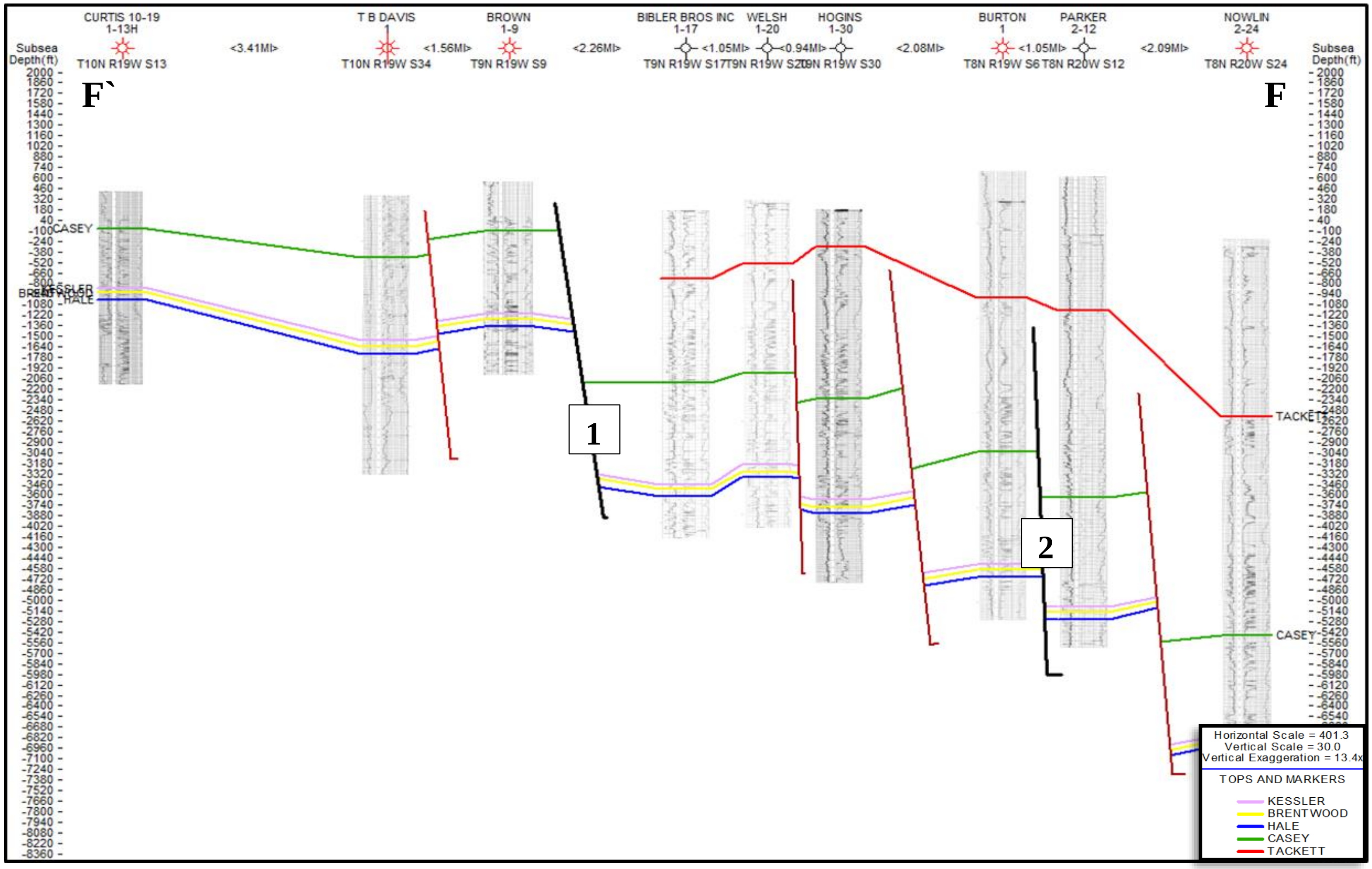

Figure 3-17: North to south structural cross section F-F`, with the Mulberry and Clarksville faults in the black lines.

3.6.7 (G-G`) Cross Section

Cross section G-G` is located at the far eastern part of the study area (Figure 3-11). This cross section extends from the north in Townships 10N-8N, Ranges 18W-19W in Pope County. Eight well logs were utilized to construct this cross section. The well logs are chosen to be in a range of between one to two miles, and to cover a total distance of approximately 13 miles from north to south (Figure 3-18). Cross section (G-G`) is interpreted to have four normal faults that originated in a step faulting style. This cross section is significant in terms of syn-depositional faulting aspect, which is important in interpreting the initial subsidence of the Arkoma Basin.

As in most of the structural cross sections, the up-thrown side of the Mulberry Fault is eroded. Therefore, it is impossible to determine if there was syn-depositional fault movement and thickening of the Middle Atoka in the down thrown side. Descending south from the shelf into basin, the stratal thickness of the Middle Atoka Formation steady increases. The overall southward increase in thickness of the stratigraphic sequence of the Middle Atoka is due to the increase in the subsidence rate of the basin. Moreover, the syn-depositional faults do not cross the whole interval of the Middle Atoka Formation. The displacement on the two master faults is measured to reveal a value of 1,530 feet of the Mulberry and 1,400 feet of the Clarksville. Similar to the previous cross section (F-F`), step faulting pattern characterized the G-G` cross section. There appears to be significant expansion and thickening of the Middle Atoka on the down thrown side of the southernmost fault. this growth fault may have pre-dated the Mulberry Fault.

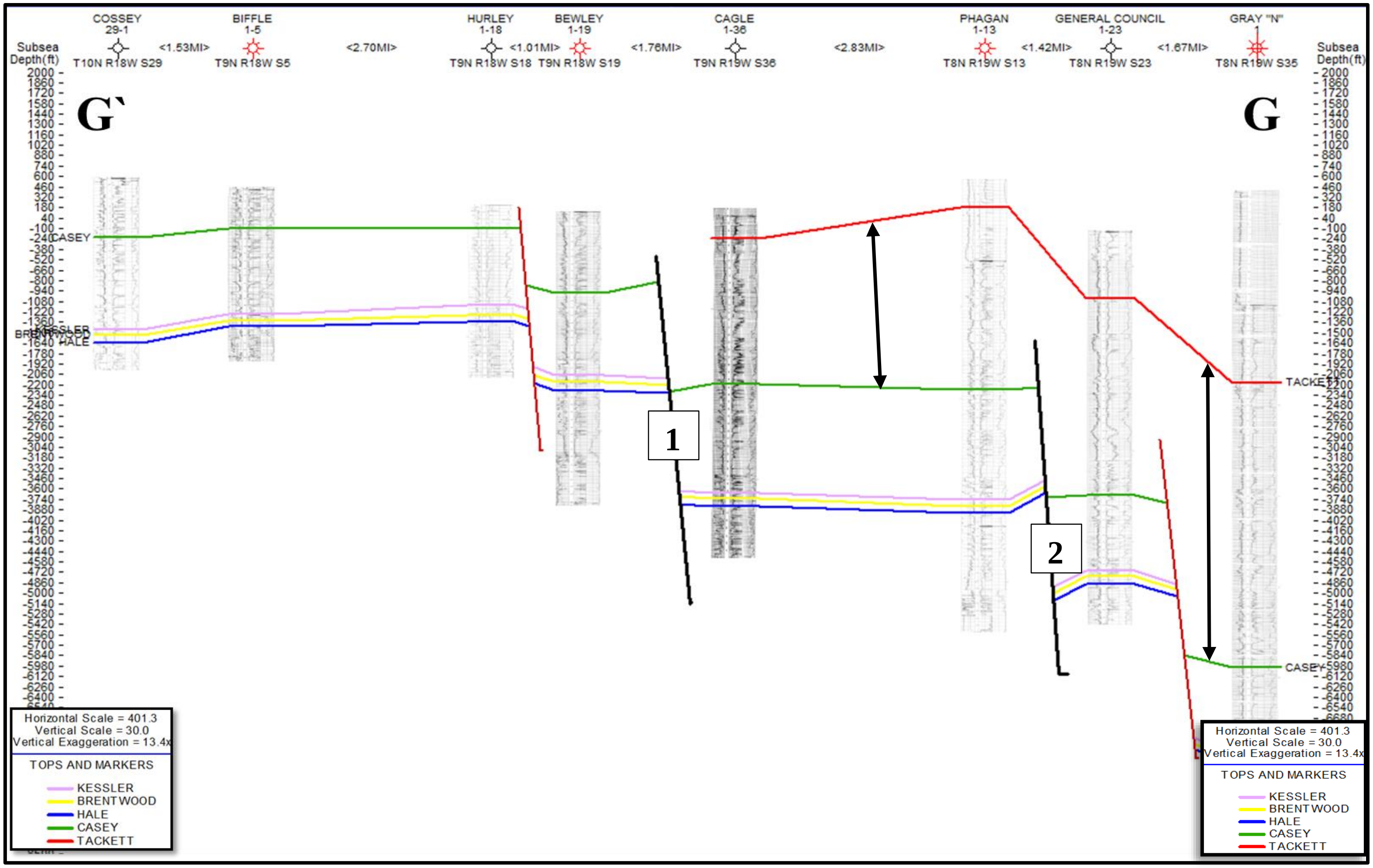

Figure 3-18: North to south structural cross section G-G`, with the Mulberry and Clarksville faults in the black lines.

3.6.8 (AA-A`A`) Cross Section

Cross section (AA-A`A`) is located in in both Johnson and Pope counties through Townships 11N-9N, Ranges 23W-18W of the study area (Figure 3-11). The section contains eleven well logs that span about thirty-two miles from west to east (Figure 3-19). The primary reason to construct this cross section is to show the orientation of a graben in the area, which is perpendicular to the Mulberry Fault. The well logs in this cross section are spaced to show the overall structural configuration of the northern part of the area.

The Bloyd and Lower Atoka Formation thickness is relatively constant, while there is a noticeable change in the Middle Atoka Formation. This cross section is interrupted by a graben between well Brown and (1-9) and well Watson (1), with a vertical displacement range from 1,800 feet to 1,650 feet to the east. This cross section is included to emphasize the faults that form the graben. Other faults were ignored. Generally, the cross section shows a pattern of step faulting. However, the area might be controlled stratigraphically. The normal faults that bounded the graben are north-south trending faults. These faults are varying in dips. The western fault dips at a low angle of 48 degrees, while the eastern fault dips at a high angle of 77 degrees. Therefore, these faults form asymmetrical graben.

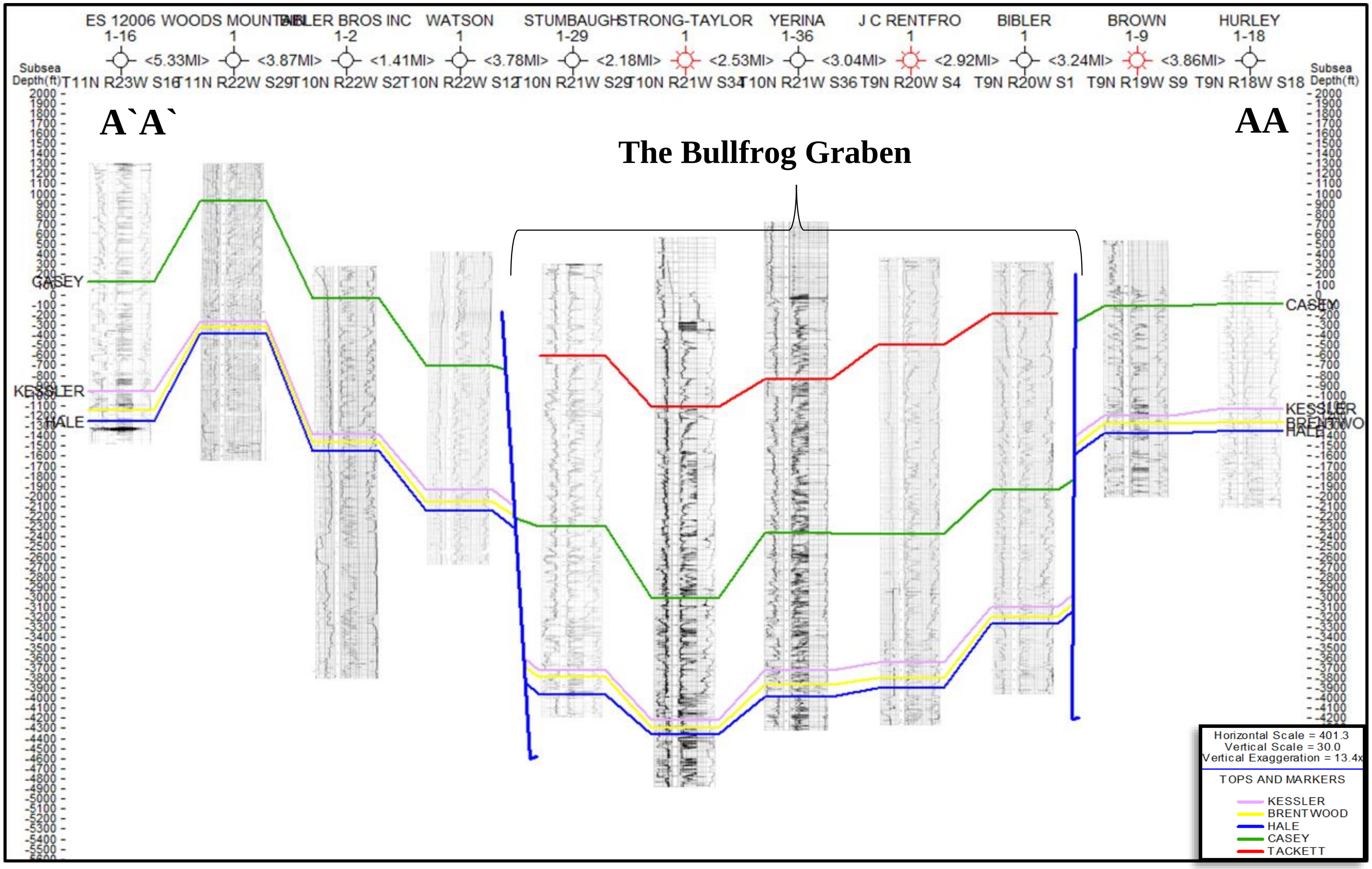

Figure 3-19: West to east structural cross section AA-A`A`, with the bounding faults of the Bullfrog graben mapped in blue lines.

3.6.9 (BB-B`B`) Cross Section

Cross section (BB-B`B`) is located in both Johnson and Pope counties through Townships 9N-8N, Ranges 22W-20W (Figure 3-11). The section is constructed by utilizing eleven well logs that span about thirty-one miles from west to east (Figure 3-20). Also, the spacing between the well logs is based on constant distance between the well logs. This cross section is important in terms of measuring the extension of the bounding faults of the graben. The cross section is constructed to be parallel to the Clarksville Fault.

It is significant to notice that the faults in this cross section are mapped in the same orientation and location to the previous graben faults, but they form a step faulting pattern instead of structural graben feature. The interpretation of the two east-west cross sections supports the idea of that the graben might be newer than both the Mulberry and Clarksville faults as they are perpendicular to the Mulberry fault and displace the Middle Atoka Formation. The western fault dips by four degrees, while the eastern fault dips by 16 degrees.

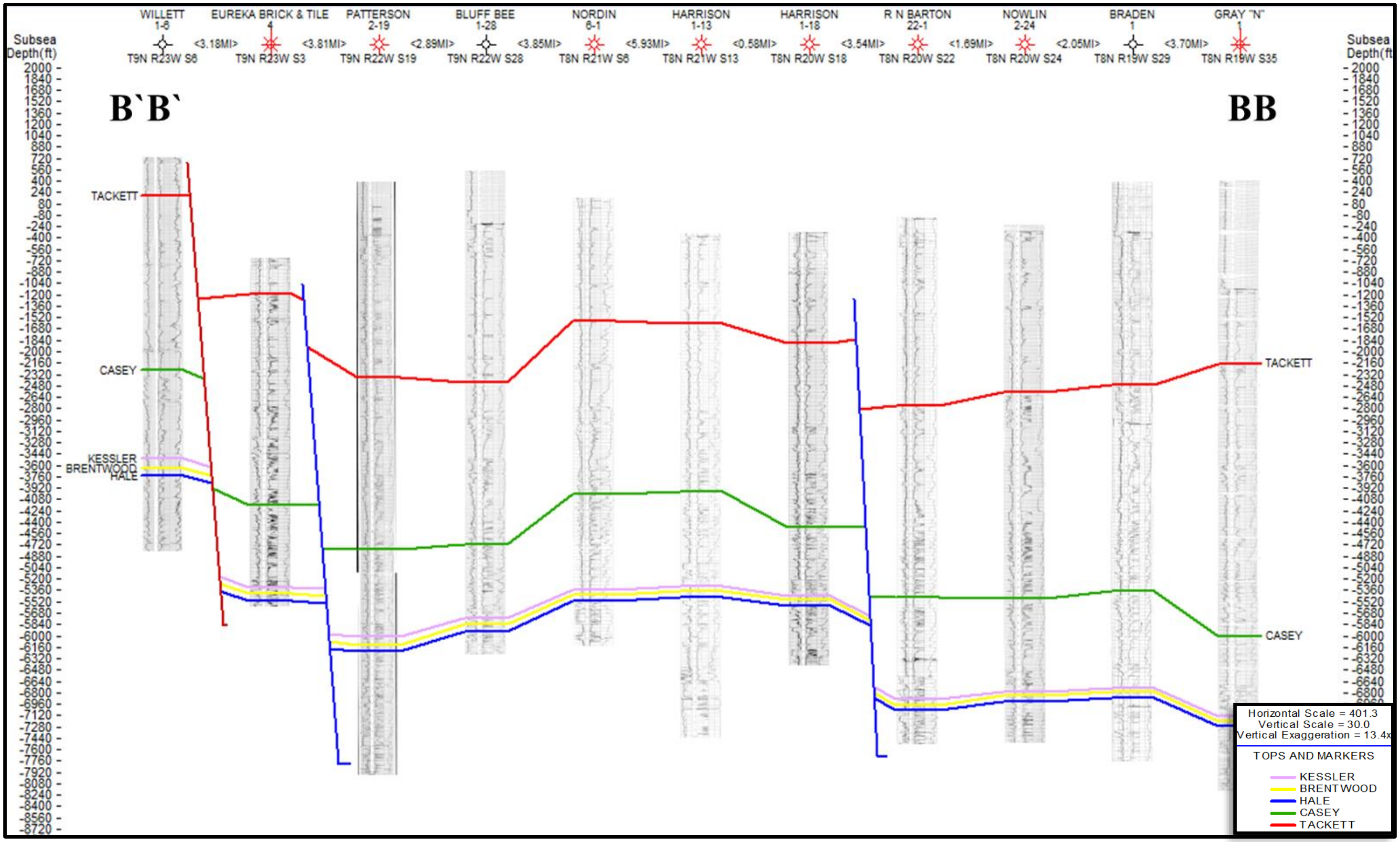

Figure 3-20: West to east structural cross section BB-B`B`, with the bounding faults of the graben mapped in blue lines.

3.7 Google Earth Profiles

In this study, Google earth is used to generate three elevation profiles to aid in providing additional information in terms of correlating the surface structure with the subsurface analysis. The elevation profiles (Figure 3-21 A and B) represent north-south sections that are perpendicular to the Mulberry Fault. The profile (Figure 3-21 A) covers a distance of 1.38, while the second profile (Figure 3-21 B) covers 3.23 miles. The profiles show major vertical displacements on the Mulberry Fault surface. Those profiles indicate that the Mulberry Fault reaches shallow depths to the surface of approximately 1104 feet elevation, allowing future field studies to measure the dip along the Mulberry Fault. Additional profiles are made in order to present further evidence for the Clarksville Fault; however, the Clarksville Fault does not present major displacement on the surface like the subsurface vertical displacement.

Additionally, an east-west elevation profile is generated to correlate the surface with subsurface structure of the mapped graben (Figure 3-21 C). The profile is mapped to cover a distance of 8.58 miles. In correlation with the subsurface cross section (AA-A`A`), the graben shows asymmetrical geometry. However, the faults that bound the graben do not present obvious evidence on the surface of the graben profiles like the Mulberry Fault profiles. See appendix 2 for a topographic map.

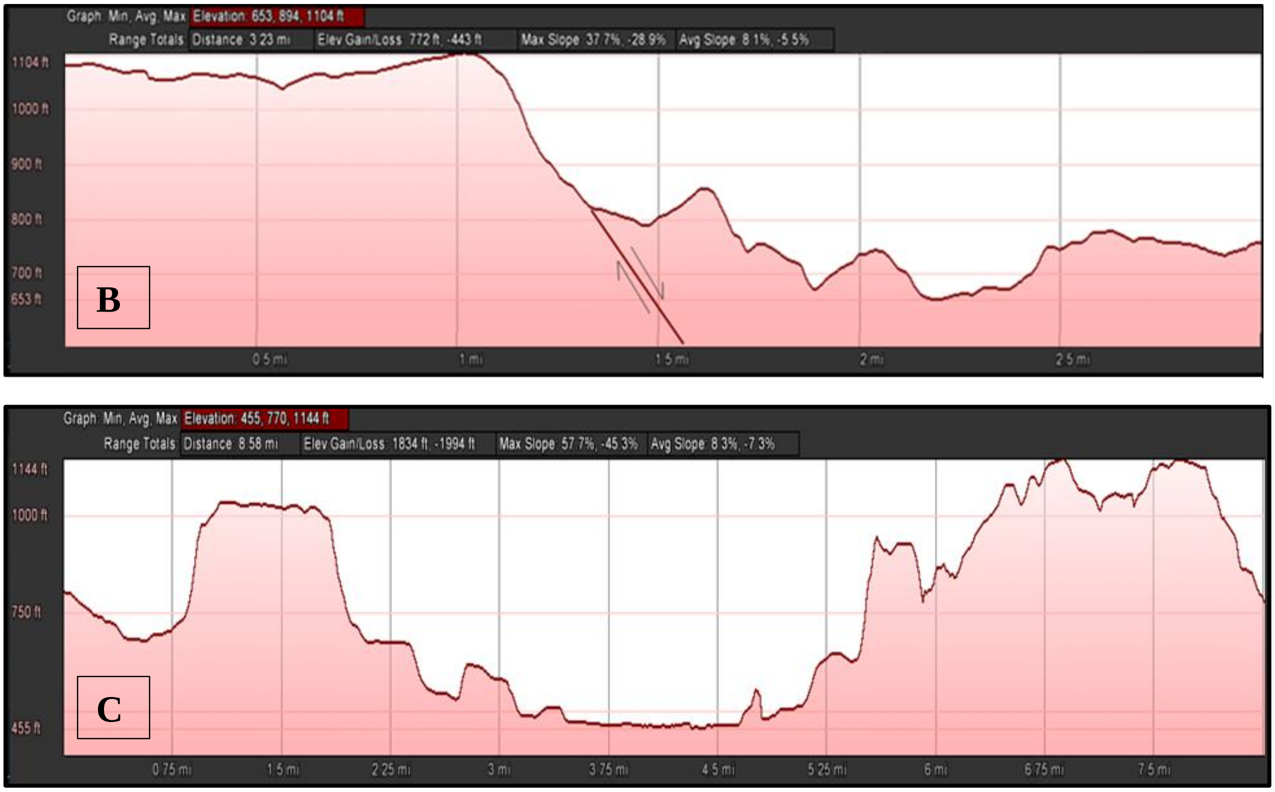

Figure 3-21: Google earth elevation profiles showing cross sectional view of the surface topography along the paths. (A) Elevational profile for northwest to southeast path of the western part of the Mulberry Fault, (B) Elevational profile for northwest to southeast path of the eastern part of the Mulberry Fault, and (C) Elevational profile for east- west path of the central part of the graben.

3.8 Faults Analysis

There have been numerous publications to describe the fault components and terminologies. This section aims to define the only components that are related to this study (Figure 3-22).

Cross-section	Strike (The Mulberry Fault) (degree)	Dip Angle	Strike (The Clarksville Fault)	Dip Angle
A-A`	200	50	198	83
B-B`	199	54	197	70
C-C`	200	47	197	67
D-D`	196	82	196	63
E-E`	195	73	197	55
F-F`	194	53	197	79
G-G`	197	61	198	72
	Graben/West Fault		**Graben/East Fault**	
AA-A`A`	115	48	290	77

Table 3-1: Measured strikes and dips for the Mulberry and Clarksville master faults, and fault bounded graben, generated based on the structural contour maps and cross sections.

The average dip of the Mulberry Fault results in a value of about 50 degrees, which is relatively close to the value observed on the seismic profile of 45 (Figure 3-4), while the Clarksville Fault dips an average of about 70 degrees. Even though the Mulberry Fault dips at a lower degree compared to the Clarksville Fault, it has a larger vertical displacement of an average of 1567 feet compared to the Clarksville Fault, which has a displacement of an average 1050 feet. Generally, the traditional dip for a normal fault is typically around 60 to 70 degrees (Tearpock and Bischke, 1991). Therefore, the Clarksville Fault is considered to be within this range. However, the Mulberry Fault dips at a lower angle.

Low-angle normal faults, such as the Mulberry Fault, tend to be widely recognized by most structural geologists, especially in foreland basins. In general, normal faults have been described as they were modified by the rotation of high angle faults. Also, several studies have described low angle faults as listric faults. A listric fault can be defined as “a curved, concave upward fault that is gradually flattened with depth” (Fossen, 2010). The explanation of listic faults has been supported by many publications conducted in relation to the Arkoma Basin structure. Eastern Arkoma Basin structure shows some evidence in terms of mapped listric normal faults (VanArsdale and Schweig, 1990).

3.9 Mulberry Fault

The Mulberry fault is the most northern master east-west trending fault that dips to the south (Figure 3-23). Numerous small faults and flexures have been recognized south of the Mulberry Fault. However, these structures are too small to be represented on the structural contour maps. The Mulberry Fault crosses the study area in Townships 11N-9N, Ranges 23W-18W.

The Mulberry Fault may have been an existing extensional normal fault that was reactivated as a result of flexural down bending during the convergent tectonic movement. Also, it has been described as a result of the reactivation of pre-existing basement faults and then overlaid by sedimentary strata (Long, 2005). The Mulberry Fault is the transitional zone between the Ozark Platform and the Arkoma Basin to the southern boundary of the Boston Mountains. In the study area, the Middle Atoka Formation strata have been eroded on the up-thrown side of the Mulberry fault.

3.10 Clarksville Fault

The Clarksville fault is the second east-west- trending master fault that dips to the south of the study area, north of the Arkansas River (Figure 3-23). It extends from Township 10N, Range 23W in the western part to Township 8N, Range 18W in the eastern part of the study area for a distance of approximately 31 miles. The Clarksville Fault zone has not been regionally described on the geological maps, and very little has been published in terms of its character. It was described in 1907 for its economic importance of coal production in Arkansas. Also, it was interpreted to have a vertical displacement of about 500 feet according to Collier et al. (1907). The interpretation of the Clarksville Fault is supported by the structural cross sections as well as the structural contour maps in this study. The average vertical displacement on the fault is measured to be about 1050 feet.

Based on the structural analysis of the Clarksville Fault, it seems that this fault was caused by the flexural tectonic movement of the Arkoma Basin. Also, the fault might be caused by the reactivation of preexisting normal faults that extended into the crystalline basement during early Mississippian, or the Clarksville fault might have formed later in early Atokan time. This interpretation is based on the analysis of the cross sections of the study area. Additionally, the fault is a syn-depositional normal fault because of the increase in the depositional thickness of the Middle Atokan Formation, as it indicated in cross sections (F-F`) and (G-G`) to the eastern part of the study area.

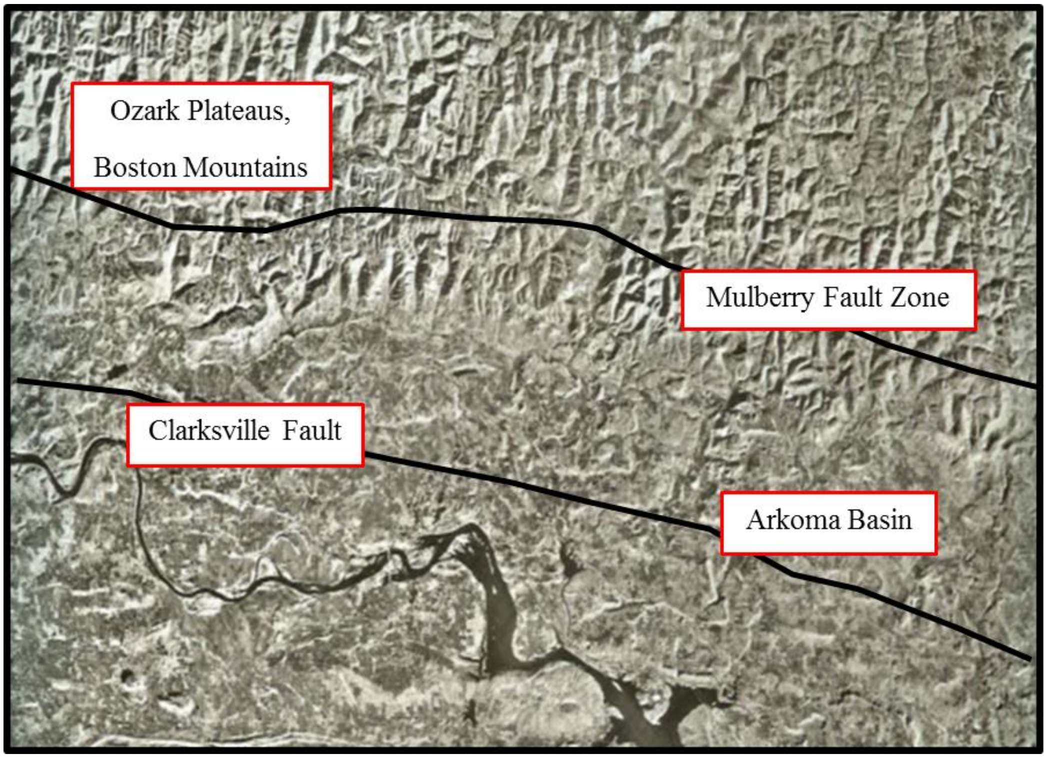

Figure 3-23: The location of the study area in regard to both the Mulberry and Clarksville fault zone with the boundary of the Ozark Plateaus and Arkoma Basin placed (modified from Cohoon, 2013).

3.11 The Bullfrog Graben

The structural contour map defines a graben, bounded by two north-south trending normal faults (Figure 3-6 to 3-10). It has not been described in the previous literature. It is named the "Bullfrog Graben" because of its association with the Bullfrog Valley. The Bullfrog Graben is located along the Highway 164 near the Johnson-Pope counties line. A 3D diagram (Figure 3-24) is design based on increasing the vertical exaggeration of the Lower Atoka Formation structural contour map. The Lower Atoka Formation map (Figure 3-19) is considered to be the base map for constructing the Bullfrog Graben because of the recognizable characterization of the graben comparing to the other formations in the study area.

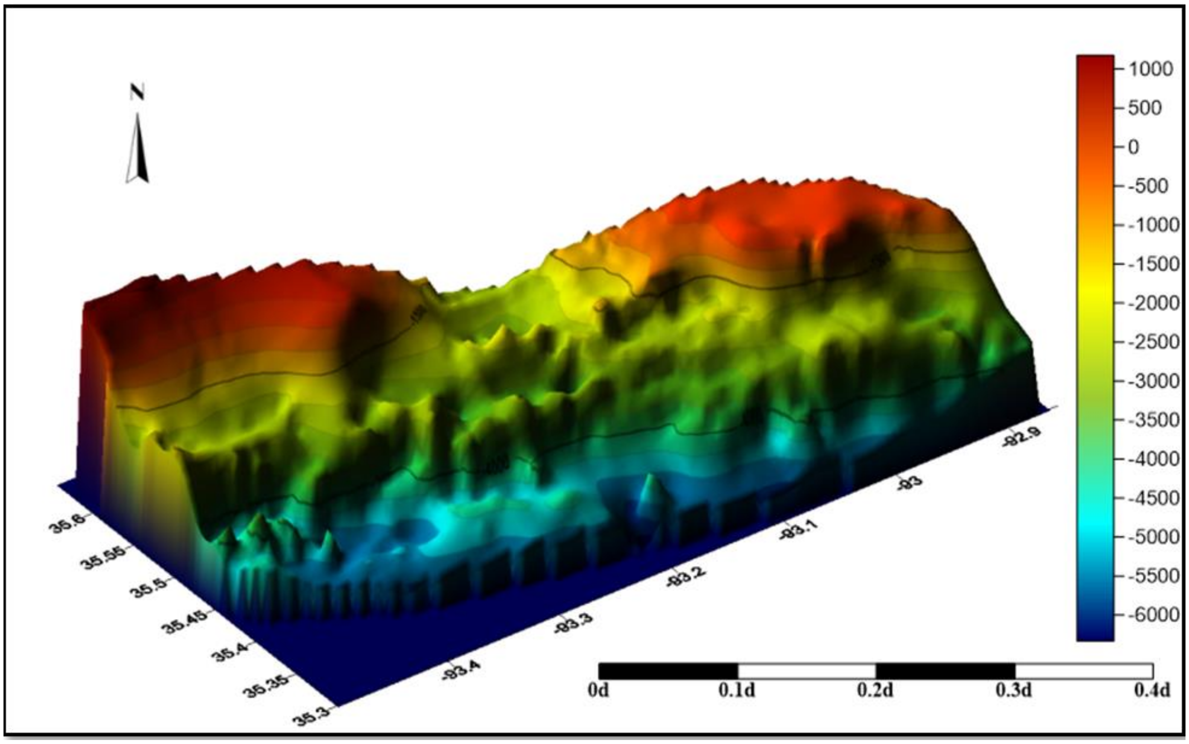

Figure 3-24: A 3D diagram of the Bullfrog Graben defined the Lower Atoka structure contour map.

The graben has a measured width of about 16.5 miles. The Bullfrog Graben displays asymmetrical geometry. Previous publications in the Arkoma Basin interpreted several grabens referred to as major synclinal features. However, most of these synclines were east-west trending instead of north-south trending like the Bullfrog Graben. As shown in the cross section (AA-A`A`), the Bullfrog Graben is bounded by two small normal faults. These faults are perpendicular to the Mulberry Fault to the south. The Bullfrog Graben might be formed as a result from the bending of a normal fault (Figure 3-25) since the faults bounded the graben do not cross the Clarksville Fault as showing in the cross section BB-B`B`.

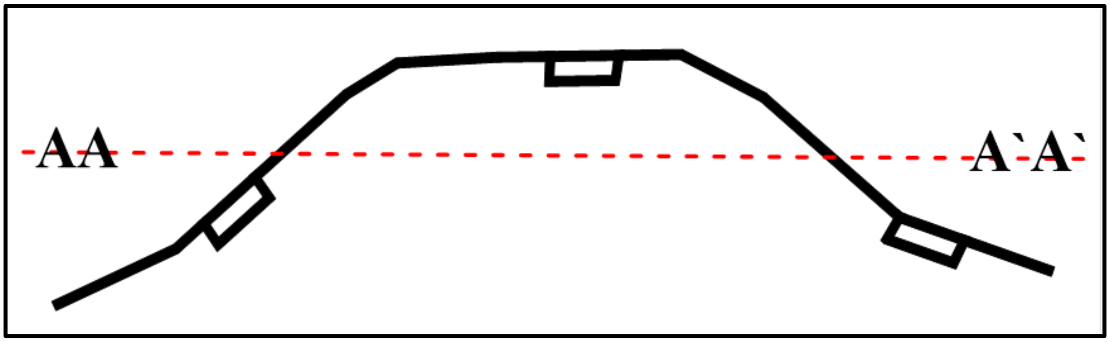

Figure 3-25: The AA-A`A` east-west cross section on a proposed bending normal fault.

The distribution of the north-south trending faults that bound the graben suggests that the stresses caused by vertical flexural loading, which were higher on the western than the eastern side because of the higher displacement that was caused by the faults. The measured slip on the faults that bound the graben is approximately (1,800-1,650) feet. The slip on the faults indicates that a comparative amount of deformation occurred as a result of flexure in responding to extensional tectonic movement. The flexural bending of the upper part of the tectonic plate induced the development of normal faults (Golf, 1989). Moreover, the flexural bending happened as a result of preexisting zones of weakness in the strata, and that weakness was caused later by the generation of the normal faults (Figure 3-26).

The second explanation includes the effect of strike-slip faults. Strike-slip faults have been inferred in some studies in northwestern part of the Arkoma Basin in Arkansas, but there are not much published. Hudson (2000) reported a movement of strike-slip faulting in the southern part of the Ozark Plateau, northern Arkoma Basin by using equal area projection.

Based on these two explanations, the Bullfrog Graben is a subsurface fault bounded incised valley. Also, the graben was supplied by sediments in relation to sea-level cycles, specifically during the falling of sea level and filling. Due to the lack of well log control and field studies on the Bullfrog Graben, it is hard to determine which explanation is more reasonable.

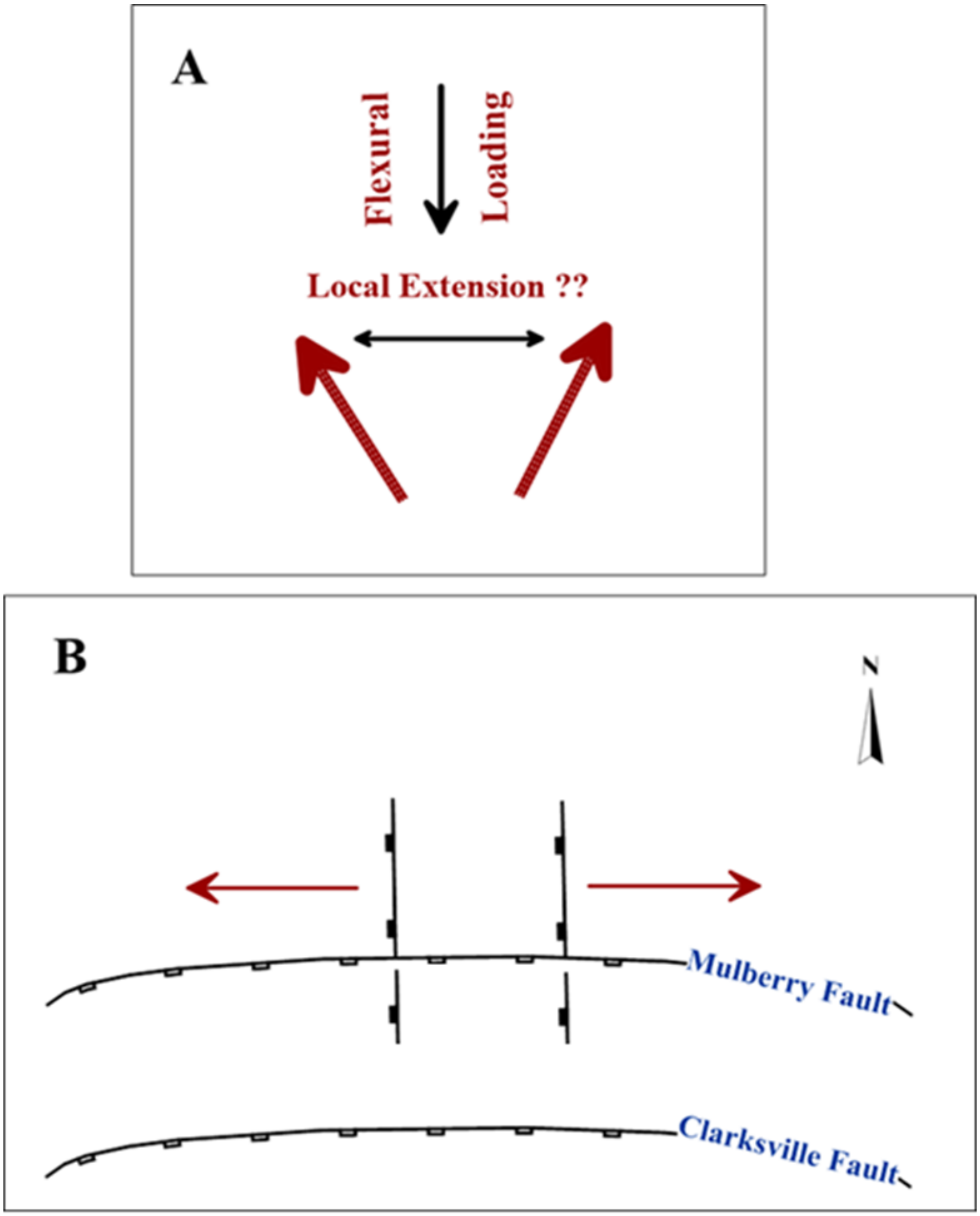

Figure 3-26: Schematic illustrations of the flexural bending for the Bullfrog Graben in the study area of the Arkoma Basin showing the two north-south trending faults perpendicular to the Mulberry master fault (Sketched by Dr. Thomas A. (Mac) McGilvery).

3.12 Stereographic Projection

The Arkoma Basin developed as a result of series of extensional tectonic movements, resulting in series of normal faults. An extensional normal fault can be developed as a result of applying vertical stress to rock bodies leading the rock materials move or flowing in the direction of least stress.

There are three kinds of stresses in which the dynamic analysis classification was based on; the maximum (σ_1), minimum (σ_3), and intermediate (σ_2), called principal stresses. The direction of the principal stresses is called the stress axes (Figure 3-27). The analysis of principal stresses is significant in terms of interpreting the orientation of the stresses along fault surfaces. Based on the orientation of principal stress axes or the slip fault and the amount of stress that have been applied to rock surface layers, faults are broadly categorized into three types: normal, reverse, and strike-slip faults. For the purpose of this study, normal fault type is the only fault type discussed. In essence, the structural kinematic classification deals with strain, while the dynamic classification deals with stress. In a normal growth fault type, the maximum principle stress (σ_1) applied vertically to the fault surface.

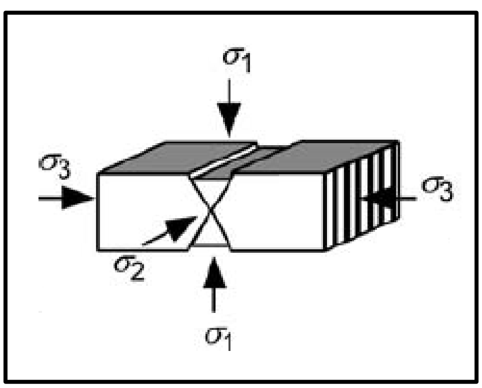

Figure 3-27: The principle stresses of a normal fault (Groshong, 2006).

In order to determine the principle stress axes of the extensional master faults and Bullfrog Graben, the Win-Tensor program was utilized. The Win-Tensor Program is free source software that was developed originally by Delvaux (1993), available at http://www.damiendelvaux.be/Tensor/tensor-index.html. Also, the Win-Tensor program is used to aid in the interpretation of stereographic displays in a lower hemisphere and equal-area projection. The generated stereonet provide some information about the general representation of both the master faults and graben (Figure 3-28 (A, B, and C)).

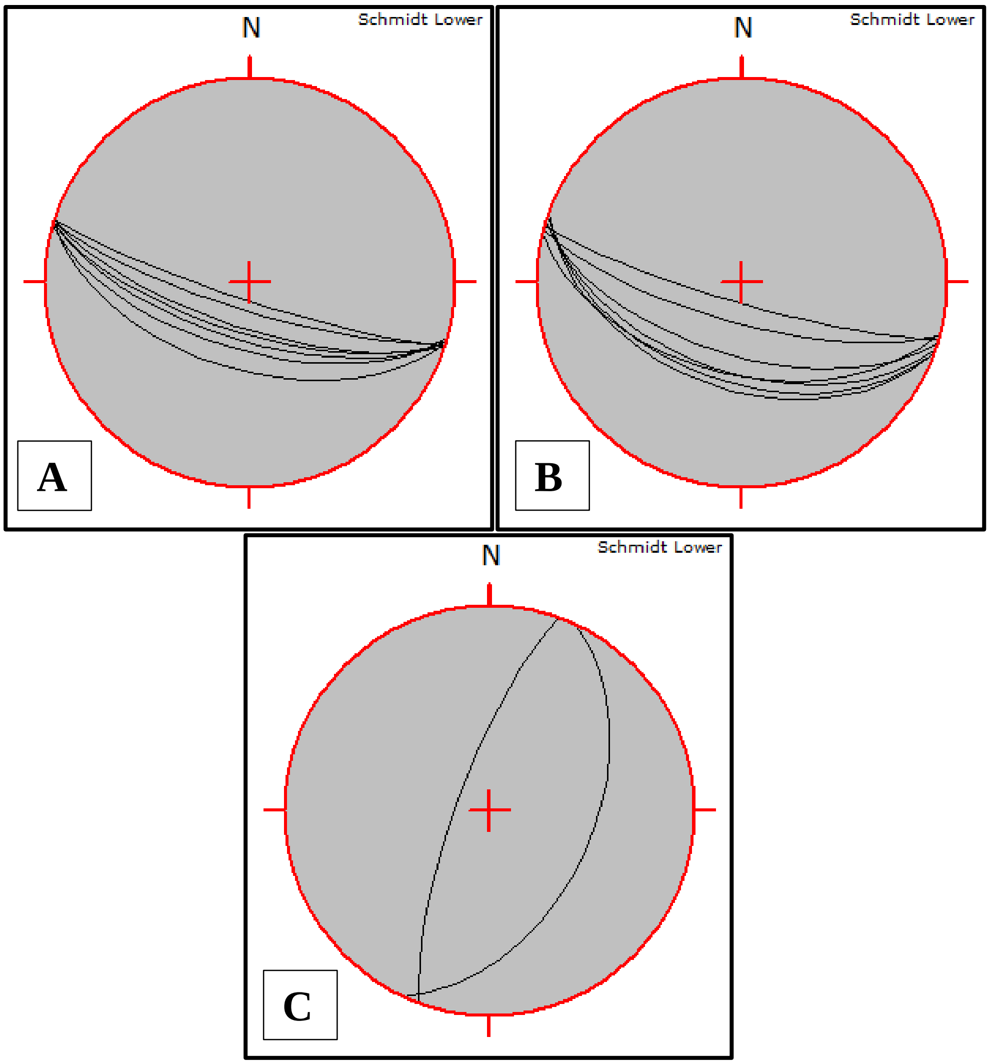

Figure 3-28: Equal -area projection of lower hemisphere of (A) the Mulberry Fault, (B) the Clarksville Fault, (C) the Bullfrog Graben.

Having applied both the master faults and graben resulted in Figure 3-29 to represent the general description of the structure of the study area.

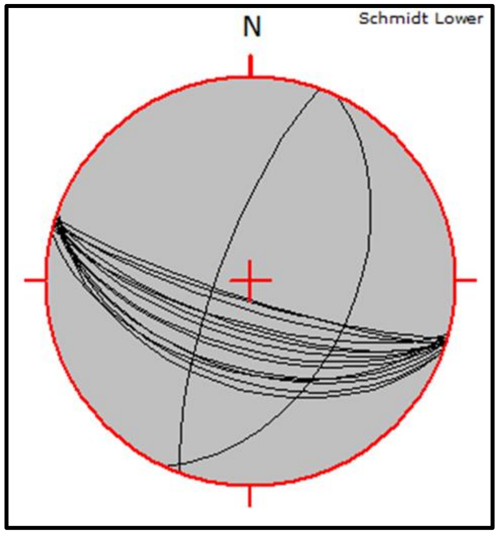

Figure 3-29: Equal-area projection that presents integrated structural features of the study area.

Also, the Win-Tensor software is helpful in terms of providing some information about the direction of greatest principle stress that is applied to the structural features (Figure 3-30 (A, B, and C)). The red arrow refers to the extensional tectonic movements. The major principle stresses of the normal faults suggest that these east-west trending faults are constructional faults based on the general strain regime, presented by Figure 3-30. Also, the north-south trending faults that bound the Bullfrog Graben are interpreted to have the same extensional regime of tectonics in the Arkoma Basin. Additionally, it is obvious that the maximum principle stress direction is 90 degrees with the fault surfaces for both the east-west and north-south faults. This interpretation leads to the conclusion that the area has not been affected by the movement of strike-slip fault system.

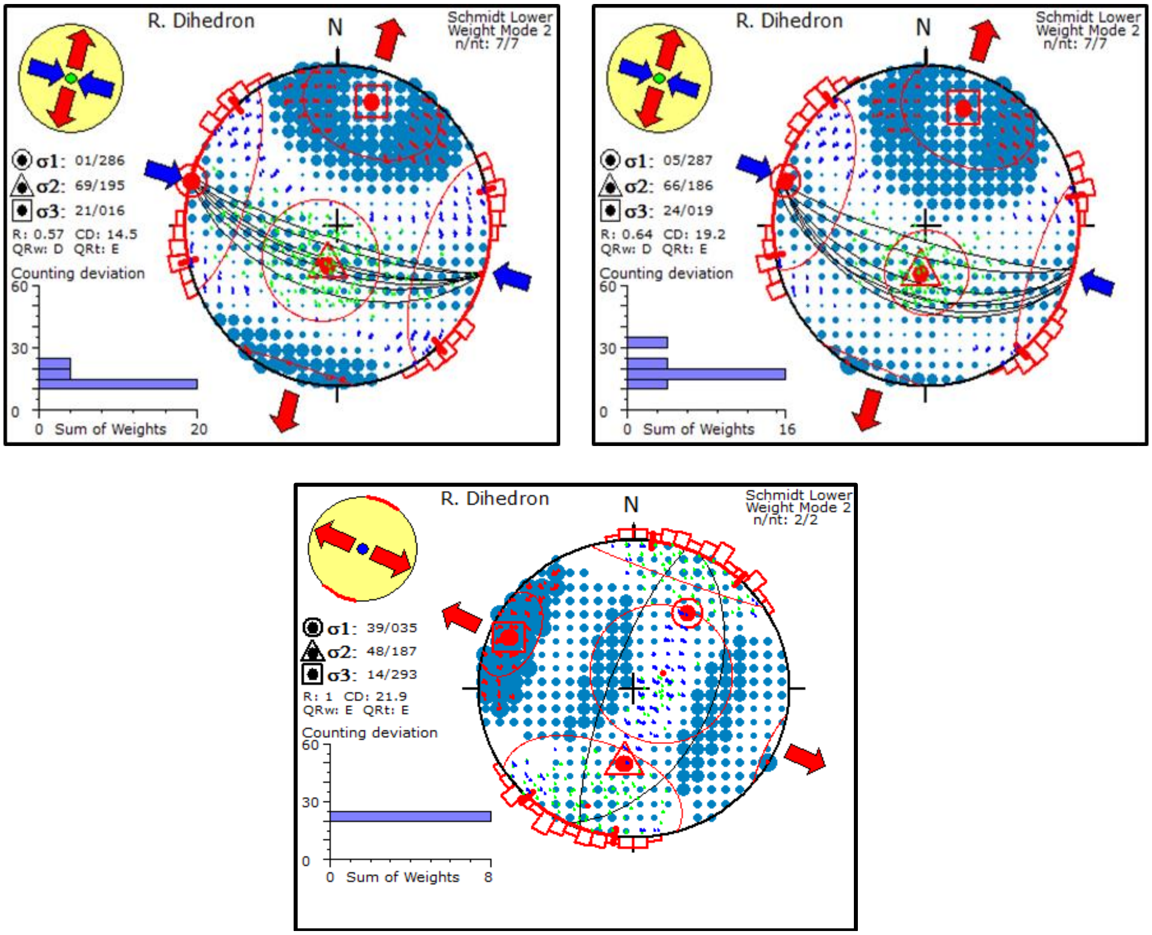

Figure 3-30: Equal-area projection in Win-Tensor software presenting the greatest stress that is perpendicular to the faults surfaces in solid read arrows. (A) represents the main directions of the three principle stresses on the Mulberry Fault, (B) represents the major stresses on the Clarksville Fault, and (C) represents the major stresses on the Bullfrog Graben.

3.13 Structural Interpretation and Discussion

The general observation of the structural maps and cross sections reveals some unique structural features. First, both cross sections and maps show two master faults and several small faults that are distributed in the study area. The small faults are not definite because they might be stratigraphically controlled rather than structurally. However, these small faults provide geometrical evidence, such as the amount of vertical displacement. Most of these faults are east-west trending. Also, north-south trending faults are observed. The north-south faults are important in terms of forming the Bullfrog Graben feature in the northern part of the study area. The cross sections as well as the isopach map show a constant thickening to the south of the study area in the Middle Atoka Formation. Most of the thickening occurs on the downthrown side of the faults, indicating syn-depositional faulting. Additionally, some of the described cross sections produced a fault stepping pattern, which probably is caused by the change in the attitude of the fault plane with respect to the movement on the fault surfaces.

Buchanan and Johnson (1968) described two types of normal fault patterns in the Arkoma Basin. The first type is faulting that originated during the middle Atokan time. This kind of faults is interpreted to be in the shallower reaches of the foreland basin. For the purpose of this study, this kind of faulting is named the Middle Atokan faults. The second type of faulting is the faults that are in the deeper part of the Arkoma Basin. This kind of faulting does not persist above the Middle Atoka Formation. In this study, the second described faulting is called pre-Middle Atokan faults. Most of the mapped faults in the area, especially the master faults, are considered to be pre-Middle Atokan faults since these faults do not persist above the Middle Atoka Formation in some cross sections. Also, there is a recognizable thickening in the same formation, which is indicated that these faults are syn-depositional faults.

CONCLUSION

Stratigraphic and structural data from an area (1,080 square miles) at the northern margin of the Arkoma Basin provide critical information about basinal development during the Carboniferous. Data were derived from field exposures and 1549 wireline logs supplemented by a seismic line. Geomorphic profiles derived from Google Earth were also utilized. Carboniferous units investigated included the Hale and Bloyd formations of Morrowan age and the Lower and Middle Atoka of Atokan age. A dramatic thickness increase during Middle Atoka time accompanied increased subsidence rates enhanced by growth faults particularly during Middle Atoka sedimentation that produced thick sections on the downthrown side. This study presented a comprehensive analysis of subsidence history in the Arkoma foreland basin.

Structural and isopach contour maps and regional stratigraphic and structural cross sections were constructed to examine the general characteristics of the basin. Thickness of analyzed intervals varied across the study area, ranging from hundreds to thousands feet thick. The variation in thickness is described in terms of the change in the depositional environments. Shallow marine environment, were the dominated facies that generated thick successions of Atokan deposits.

Two master east-west trending normal faults were analyzed; the Mulberry and Clarksville resulted from reactivation during compressional stress regimes. These faults facilitated subsidence, providing more space to accommodate Morrowan and Atokan sediments. Evidence from the Lower Atoka structure map suggested a local flexure bending in the northern-central part of the study area. The local flexure was represented by the Bullfrog Graben that took place after deposition. During Middle Atokan time, flexure and syn-depositional normal faults were accompanied by subsidence indicating the inception of the Arkoma Basin formation.

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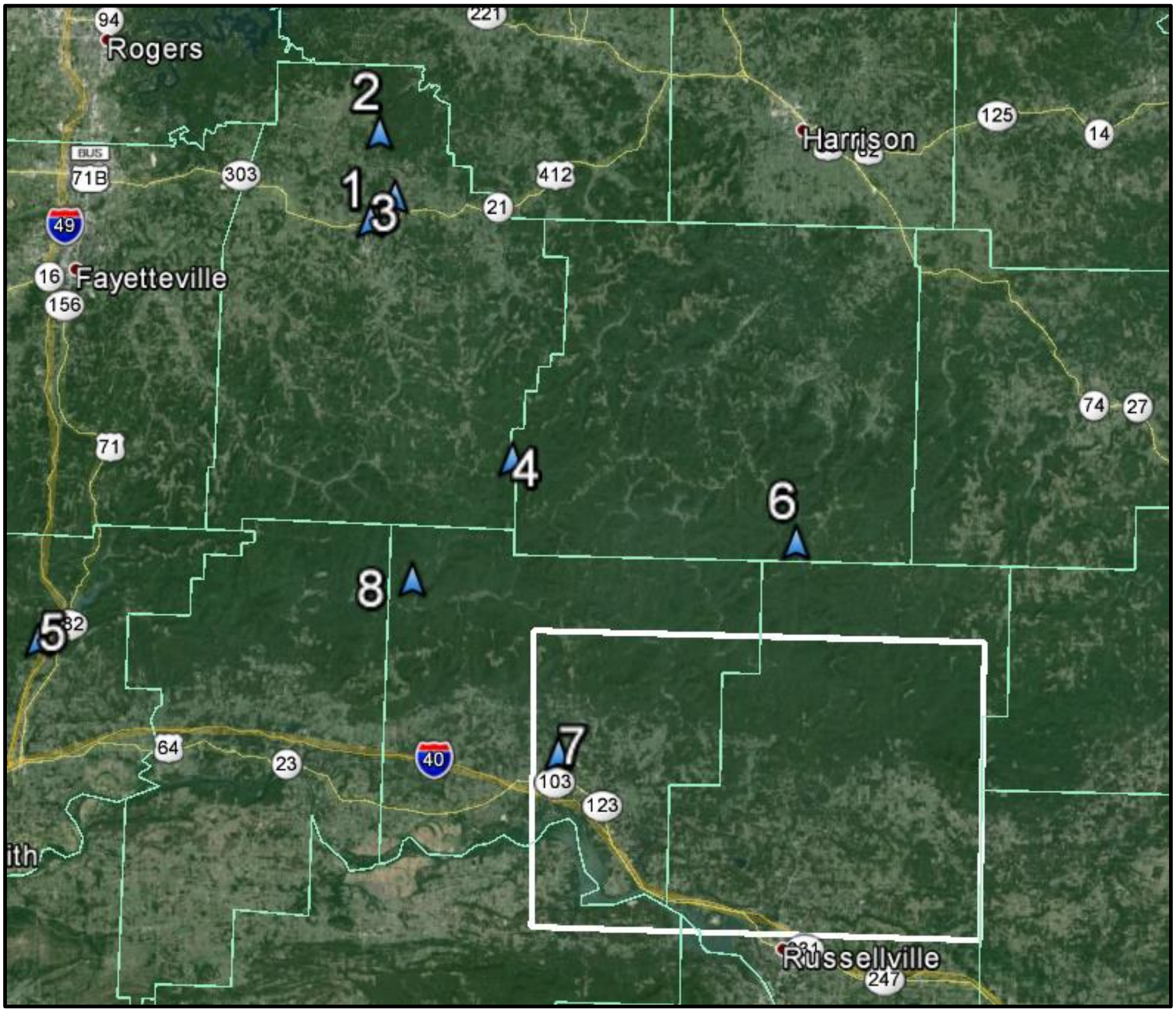
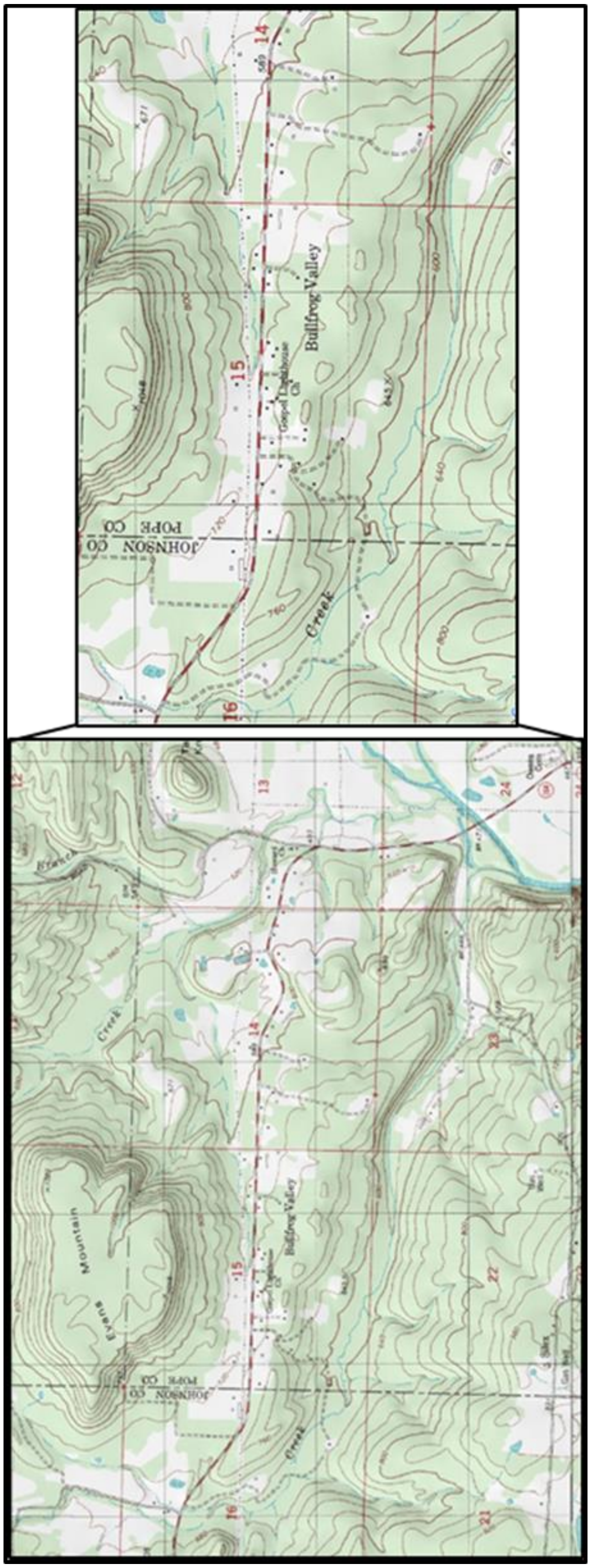
APPENDIX (1)



A map displays on the Google Earth showing the study area highlighted in white and approximate locations for the outcrops including; (1 in Figure 2-4), (2 in Figure 2-5), (3 in Figure 2-6), (4 in Figure 2-7), (5 in Figure 2-9), (6 in Figure 2-10), (7 in Figure 2-11), and (8 in Figure 2-13).

APPENDIX (2)



A topographic map for the Bullfrog Graben.

APPENDIX (3)

A-A`

Well Label	Field Name	API	County	KB	TACKETT	CASEY	KESSLER	BRENTWOOD	HALE
09N 23W 07 RIKER 2	SPADRA	10557	JOHNSON	381	2188	4223	5805	5962	6180
09N 23W 01 RAINS 1-1	SPADRA	10781	JOHNSON	512	1672	3652	5446	5568	5759
09N 21W 06 SLOVER CREEK 1-6	ROSS	10379	POPE	534	1474	3444	4816	4950	5129
09N 21W 02 UTLEY HAROLD 1-2	ROSS	10218	POPE	439	1618	3509	4955	5084	5305
09N 20W 01 TAYLOR L" 2"	DOVER	10465	POPE	585	1048	2824	3839	3942	4126

B-B`

Well Label	Field Name	API	County	KB	TACKETT	CASEY	KESSLER	BRENTWOOD	HALE
08N 22W 07 LAMB 2	KNOXVILLE	10750	JOHNSON	380	4132	6863	8049	8099	8167
08N 22W 13 SOUTHLAND 2	KNOXVILLE	10603	POPE	703	3585	5732	7004	7063	7126
08N 19W 07 POTTER 2-7	MORELAND	10579	POPE	875	1935	3985	5097	5150	5205
08N 19W 11 RAINWATER A" 2"	MORELAND	10434	POPE	707	761	2940	4052	4126	4214
08N 18W 09 ARKANSAS KRAFT 1-9	OAK GROVE	10179	POPE	496	1078	3317	4504	4578	4689

C-C`

Well Label	Field Name	API	County	KB	TACKETT	CASEY	KESSLER	BRENTWOOD	HALE
10N 23W 09 CITY OF CLARKSVILLE 1	LUDWIG	10433	JOHNSON	775	714	2756	3881	4008	4083
10N 23W 21 JJG LANDS 1-21	LUDWIG	10846	JOHNSON	686	612	2734	4101	4235	4351
09N 23W 03 EUREKA BRICK & TILE 4	SPADRA	10525	JOHNSON	555	1744	4497	5843	5961	6056
09N 23W 10 CALLAHAN 2-10	SPADRA	10526	JOHNSON	517	1593	4333	5626	5736	5819
09N 23W 15 VOLA 2-15	SPADRA	10195	JOHNSON	479	1560	4220	5478	5610	5714

D-D`

Well Label	Field Name	API	County	KB	TACKETT	CASEY	KESSLER	BRENTWOOD	HALE
10N 22W 27 THOMPSON MOUNTAIN 1-2	ROSS	10594	JOHNSON	702	1351	3044	4236	4324	4443
10N 22W 34 WILKENS 1-34	ROSS	10772	JOHNSON	735	1215	2857	3774	3918	4012
09N 22W 15 CONAWAY 1	ROSS	10474	JOHNSON	369	2655	4378	5371	5471	5621
09N 22W 27 BLACKARD 1	ROSS	10501	JOHNSON	379	2618	4688	6005	6068	6212
08N 22W 02 TACKETT 3	KNOXVILLE	10521	JOHNSON	674	3202	5477	6876	7025	7109

E-E`

Well Label	Field Name	API	County	KB	TACKETT	CASEY	KESSLER	BRENTWOOD	HALE
08N 21W 22 BAILEY 1-22	KNOXVILLE	10245	POPE	389	3343	5913	7417	7534	7620
09N 21W 22 HOGREFE 3-22	ROSS	10354	POPE	457	2342	4386	5828	5884	5944
09N 21W 10 JOHNSON O" 4"	ROSS	10644	POPE	737	2047	4036	5339	5436	5500
10N 21W 34 STRONG-TAYLOR 1	SILEX	10185	POPE	617	1733	3647	4845	4909	4973
10N 21W 27 SILEX GAS UNIT 5	SILEX	10092	POPE	888	909	2540	3714	3758	3797

F-F`

Well Label	Field Name	API	County	KB	TACKETT	CASEY	KESSLER	BRENTWOOD	HALE
09N 20W 02 HUGGINS B M 1-2	DOVER	10261	POPE	886	417	2401	3588	3690	3786
09N 20W 11 A RAPPE 1	WILDCAT	21	POPE	700	582	2895	4143	4265	4355
09N 20W 14 ATHEY 1	DOVER	10274	POPE	710	736	2752	4041	4150	4278
08N 20W 11 WILLIAMSON 1-11	FURGERSON	10219	POPE	675	1966	4419	5763	5828	5925
08N 20W 24 NOWLIN 2-24	MORELAND	10352	POPE	486	3075	5823	7147	7255	7335

APPENDIX (4)

A-A`

Well Label	Field Name	API	County	KB	TACKETT	CASEY	BRENTWOOD	KESSLER	HALE
11N 23W 03 MOONEY 1-3	OZONE	10319	JOHNSON	1964		868	2074	1923	2183
11N 23W 16 ES 12006 1-16	WILDCAT	10347	JOHNSON	1805		1674	2947	2764	3059
11N 23W 32 STORMS 1-32	WILDCAT	10351	JOHNSON	430	1002	2874	4190	4092	4269
10N 23W 17 SOARD 1	LUDWIG	10242	JOHNSON	672	577	2682	4017	3855	4114
10N 23W 30 LOOPER A" 1"	SPADRA	10376	JOHNSON	414	1205	3643	4779	4668	4955
09N 23W 06 WILLETT 1-6	SPADRA	10197	JOHNSON	1187	995	3444	4825	4694	4939
09N 23W 07 RIKER 2	SPADRA	10557	JOHNSON	381	1918	3805	5556	5449	5633

B-B`

Well Label	Field Name	API	County	KB	TACKETT	CASEY	KESSLER	BRENTWOOD	HALE
11N 22W 09 PURNELL 1	WILDCAT	10169	JOHNSON	1250		631	1870	1946	2047
11N 22W 29 WOODS MOUNTAIN 1	WILDCAT	10151	JOHNSON	1900		966	2162	2221	2287
10N 22W 18 GRAVES 1-18	LUDWIG	10899	JOHNSON	553		3039	4577	4660	4717
10N 23W 26 HORACE TOLBERT 1	LUDWIG	10043	JOHNSON	716	2326	3894	4869	4943	5009
09N 23W 03 EUREKA BRICK & TILE 3	SPADRA	10503	JOHNSON	535	2539	4635	5473	5559	5648
09N 23W 16 RIVERBEND A" 1"	SPADRA	10480	JOHNSON	357	2174	4242	5692	5788	5878

C-C`

Well Label	Field Name	API	County	KB	TACKETT	CASEY	KESSLER	BRENTWOOD	HALE
BIBLER BROS INC 2-Jan	WILDCAT	10236	JOHNSON	736		771	2127	2205	2286
TERRY 10-Feb	WILDCAT	10237	JOHNSON	685		1405	2818	2860	2987
WHITKANACK 21-Jan	AGARVILL	10738	JOHNSON	655		3068	4643	4731	4783
WHITKANACK 21-Jan	AGARVILL	10738	JOHNSON	655		3068	4643	4731	4783
POMRENKE 1	ROSS	10278	JOHNSON	626	1042	3289	4786	4843	4907
CAMPBELL 1	ROSS	10616	JOHNSON	437	2980	5141	6604	6689	6788
LAMARK 18-Feb	ROSS	10792	JOHNSON	432	3622	5874	7239	7324	7402
JOHNSON LINDA 25-Jan	SPADRA	10782	JOHNSON	477	2793	5421	6891	6987	7087

D-D`

Well Label	Field Name	API	County	KB	TACKETT	CASEY	KESSLER	BRENTWOOD	HALE
10N 21W 10 OZARK 1	WILDCAT	10259	POPE	867	1064	2832	3845	3946	
10N 21W 15 RIGGS 1-15	SILEX	10319	POPE	686	987	2651	3725	3791	
10N 21W 27 SILEX GAS UNIT 5	SILEX	10092	POPE	888	909	2466	3591	3661	3740
10N 21W 27 SILEX GAS UNIT 5	SILEX	10092	POPE	888	909	2466	3591	3661	3740
10N 21W 34 STRONG-TAYLOR 1	SILEX	10185	POPE	617	1733	3624	4833	4909	4973
09N 21W 09 BIBLER 4	ROSS	10637	POPE	885	2099	4086	5304	5392	5479
09N 21W 20 STEUBER UNIT 1	ROSS	10050	POPE	819	2686	4850	5975	6090	6171
09N 21W 29 MCCRAINE 1	ROSS	10680	POPE	611	3271	5306			
08N 21W 06 NORDIN 6-1	KNOXVILLE	10098	POPE	860	2428	4860	6214	6279	6367
08N 22W 13 SOUTHLAND 2	KNOXVILLE	10603	POPE	703	3428	5891	7214	7280	7359

E-E`

Well Label	Field Name	API	County	KB	TACKETT	CASEY	KESSLER	BRENTWOOD	HALE
10N 20W 28 UTLEY 1-28	DOVER	10570	POPE	786	644	2537	4014	4077	4127
09N 20W 04 J C RENTFRO 1	DOVER	10013	POPE	773	1270	3148	4422	4575	4670
09N 20W 16 POWERS NEWTON 5	DOVER	10502	POPE	512	1264	2791	3994	4120	4195
09N 20W 20 CHURCHILL 1-20	NEW HOPE	10260	POPE	516	1700	3829	5182	5284	5372
08N 20W 06 PETERSON /A/ 1	FURGERSON	10223	POPE	714	2986	5399	6828	6907	7008
08N 21W 13 HARRISON 1-13	KNOXVILLE	10293	POPE	461	2059	4434	5755	5838	5918
08N 21W 24 UNDERHILL 1	KNOXVILLE	10308	POPE	403	3187	5714	7124	7220	7279

F-F`

Well Label	Field Name	API	County	KB	TACKETT	CASEY	KESSLER	BRENTWOOD	HALE
10N 19W 13 CURTIS 10-19 1-13H	YETTEVLLE SHA	10682	POPE	604		673	1465	1527	1623
10N 19W 34 T B DAVIS 1	SCOTTSVILLE	63	POPE	754		1210	2310	2399	2493
09N 19W 09 BROWN 1-9	SCOTTSVILLE	10593	POPE	588		696	1792	1861	1960
09N 19W 17 BIBLER BROS INC 1-17	DOVER	10236	POPE	719	1461	2834	4181	4247	4335
09N 19W 20 WELSH 1-20	DOVER	10250	POPE	759	1303	2747	3960	4053	4132
09N 19W 30 HOGINS 1-30	DOVER	10529	POPE	623	936	2948	4288	4385	4464
08N 19W 06 BURTON 1	MORELAND	10581	POPE	788	1773	3824	5313	5384	5475
08N 20W 12 PARKER 2-12	MORELAND	10414	POPE	660	1816	4294	5751	5821	5909
08N 20W 24 NOWLIN 2-24	MORELAND	10352	POPE	486	3059	5955	7280	7324	7405

G-G`

Well Label	Field Name	API	County	KB	TACKETT	CASEY	BRENTWOOD	KESSLER	HALE
10N 18W 29 COSSEY 29-1	HECTOR	10411	POPE	791		1015	2328	2243	2429
09N 18W 05 BIFFLE 1-5	HECTOR	10294	POPE	752		857	2084	1996	2166
09N 18W 18 HURLEY 1-18	WILDCAT	10093	POPE	722		817	1986	1851	2078
09N 18W 19 BEWLEY 1-19	MORELAND	10453	POPE	720		1683	2879	2797	3002
09N 19W 36 CAGLE 1-36	MORELAND	10272	POPE	672	903	2863	4402	4328	4504
08N 19W 13 PHAGAN 1-13	MORELAND	10263	POPE	653	471	2921	4484	4399	4575
19W 23 GENERAL COUNCIL	MORELAND	10482	POPE	571	1607	4250	5344	5270	5441
08N 19W 35 GRAY N" 1"	MORELAND	10473	POPE	508	2686	6512	7708	7638	7773

AA-A`A`

Well Label	Field Name	API	County	KB	TACKETT	CASEY	KESSLER	BRENTWOOD	HALE
11N 23W 16 ES 12006 1-16	WILDCAT	10347	JOHNSON	1805		1674	2764	2947	3059
11N 22W 29 WOODS MOUNTAIN 1	WILDCAT	10151	JOHNSON	1900		966	2162	2221	2287
10N 22W 12 BIBLER BROS INC 1-2	WILDCAT	10236	JOHNSON	736		771	2127	2205	2286
10N 22W 12 WATSON 1	WILDCAT	63	JOHNSON	771		1479	2711	2823	2920
10N 21W 29 STUMBAUGH 1-29	SILEX	10359	JOHNSON	805	1408	3107	4527	4591	4775
10N 21W 34 STRONG-TAYLOR 1	SILEX	10185	POPE	617	1733	3624	4833	4909	4973
10N 21W 36 YERINA 1-36	DOVER	10671	POPE	767	1600	3126	4496	4631	4751
09N 20W 04 J C RENTFRO 1	DOVER	10013	POPE	773	1270	3148	4422	4575	4670
09N 20W 01 BIBLER 1	DOVER	10018	POPE	680	869	2620	3775	3875	3944
09N 19W 09 BROWN 1-9	SCOTTSVILLE	10593	POPE	588		696	1792	1861	1960
09N 18W 18 HURLEY 1-18	WILDCAT	10093	POPE	722		817	1851	1986	2078

BB-B`B`

Well Label	Field Name	API	County	KB	TACKETT	CASEY	KESSLER	BRENTWOOD	HALE
09N 23W 06 WILLETT 1-6	SPADRA	10197	JOHNSON	1187	995	3444	4694	4825	4939
09N 23W 03 EUREKA BRICK & TILE 4	SPADRA	10525	JOHNSON	555	1740	4723	5879	5961	6056
09N 22W 19 PATTERSON 2-19	KNOXVILLE	10304	JOHNSON	445	2250	5221	6459	6568	6655
09N 22W 28 BLUFF BEE 1-28	KNOXVILLE	10396	JOHNSON	582	3489	5118	6337	6424	6527
08N 21W 06 NORDIN 6-1	KNOXVILLE	10098	POPE	860	2428	4860	6214	6279	6367
08N 21W 13 HARRISON 1-13	KNOXVILLE	10293	POPE	461	2059	4434	5755	5838	5918
08N 20W 18 HARRISON 1-18	FURGERSON	10303	POPE	477	2363	4944	5913	5962	6054
08N 20W 22 R N BARTON 22-1	FURGERSON	10138	POPE	427	3184	5890	7308	7401	7477
08N 20W 24 NOWLIN 2-24	MORELAND	10352	POPE	486	3059	5955	7280	7324	7405
08N 19W 29 BRADEN 1	MORELAND	10333	POPE	476	2946	5847	7206	7265	7346
08N 19W 35 GRAY N" 1"	MORELAND	10473	POPE	508	2686	6512	7638	7708	7773