Stratigraphic and Structural Analysis of Middle Atoka Formation in Aetna Gas Field, Franklin, Johnson and Logan Counties, Arkansas

Ikramuddin Bahram
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Stratigraphic and Structural Analysis of Middle Atoka Formation in Aetna Gas Field, Franklin, Johnson and Logan Counties, Arkansas

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Geology

By

Ikramuddin Bahram
University of Peshawar
Bachelor of Science in Geology, 2010

December 2015
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This thesis is approved for recommendation to the Graduate Council.

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Abstract

Arkoma basin is a prolific natural gas basin. The defining feature of this basin is the Atoka Formation that was deposited in the early-middle Pennsylvanian. The Atoka is held equivalent to the tectonic and structural evolution of the basin. This study focuses on one of the many gas fields in the Arkoma Basin in Arkansas to assess the stratigraphic and structural evolution that the strata in this particular field display.

Aetna Gas Field extends from T. 8N, R. 27 W to T. 9 N, R. 27 W and T. 8 N, R. 26 W to 8N, R. 27. Geographically, Aetna field covers parts of Franklin, Johnson and Logan counties. It is one of the pioneer gas fields in the Arkoma Basin. First discovery of gas in Aetna Field was made in March 1928. The first three producing wells were completed in the upper Carpenter and middle Alma sands of the middle Atoka Formation. An analysis of structures and stratigraphy of the gas field through well log correlations reveal a combination trap for the gas.

Using IHS Petra, stratigraphic correlations were performed on 49 wells in 10 cross sections. The wells selected were sorted by several criteria. Gamma ray logs were given priority. Stratigraphic tops were determined for correlation purposes. The stratigraphic tops were picked and correlated. The middle Atoka Formation was addressed exclusively for the purpose of this study. Structural analysis indicates an arch-and-trough setting that led to gas accumulation in this field. The stratigraphic analysis confirms a thickening to the south following the general southern thickening trend of Atoka Formation in the Arkoma Basin.
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I would extend my warmest gratitude to Dr. Doy Zachry for his guidance, his support and encouragements throughout my thesis work. I would like to thank Dr. Ralph Davis and Dr. Gregory Dumond for serving on my committee and providing their insights into my thesis. I extend special thanks to Jamie Woolsey for her generous help on PETRA and mentorship throughout my lab work. Without her countless hours of assistance on PETRA, this work would have not been possible.

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A number of institutions deserve to be thanked too. In fact, without their support, I would have not been able to accomplish this work. I am eternally grateful to the Foreign Fulbright Scholarship Program for the award of a scholarship to me to pursue my masters at the University of Arkansas. I would also like to thank the IIE (Institute of International Education) for the facilitations throughout my grant period. The office of Sponsored Students and Scholars at the University of Arkansas owe me thanks for their support and encouragement throughout my program of study here.

Last but not the least, I would like to thank my father, my mother, and my brothers and sisters. Their unconditional love, prayers, and sacrifices have made it possible for me to accomplish what little I have accomplished.
Dedication

This thesis is dedicated to my Aapay Jaan (mother) and Aatay Jaan (Father). Though you could not live your dreams, you made it possible for your son to live his, Aapay Jaan and Aatay Jaan. Not only this thesis but also my life is and will remain dedicated to them.
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Chapter 1

Introduction:

The Arkoma Basin in west-central Arkansas and southeastern Oklahoma is a prolific natural gas basin in North America. It is one of several Carboniferous (Mississippian-Pennsylvanian) foreland basins that bound the craton in the southern midcontinent (Suneson, 2012). From the history of exploration in the Arkoma Basin chronicled by Suneson, it can be seen that the focus of attention of petroleum exploration geologists, academics, and companies have been reservoir quality, and regional geology with very little attention to one of the important components, the trap mechanism. Where mention has been made of a trap mechanism, it has sufficed for the authors to refer to a structural unit as a trap. An attempt is made at examining one of the many gas fields. The Aetna Gas Field is used as a model to understand the stratigraphic framework that led to the entrapment of natural gas.

The Arkoma Basin is an elongate, east-west trending sedimentary basin (Fig. 1). It encompasses an area of approximately 13,488 square miles in the south-central United States, covering the east-central part of Oklahoma and west-central part of Arkansas (Sutherland and Manger, 1982).

The basin is a peripheral foreland basin associated with the Ouachita orogenic belt, which functions as its southern boundary. The Ozark uplift and the Northeast Oklahoma platform serve as the northern boundary of the basin (Sutherland, 1988). The basin is 20 to 50 miles wide, is bounded to the east by the Gulf Coastal Plain, and extends 250 miles to the Arbuckle Mountains in Oklahoma (Zachry and Sutherland, 1984).
Arbenz (1989; 2008) divided Arkoma Basin into two regions. The shallow geology of the southern part is dominated by compressional structures, thrust-cored anticlines that are the traps for most of the major gas fields in the basin. Folds in the northern part of the basin are “drape” anticlines over mostly middle Atokan south-side-down normal faults; there is little evidence here for compression. These folds also form traps. Identification of these structures (folds, normal faults, thrust faults) has been one key to the development of Arkoma Basin gas reservoirs, and further delineation of triangle-zone structures such as duplexes will continue to be important, particularly in the very southern part of the basin adjacent to the Choctaw Fault and Ross Creek Fault.

Objectives

The objectives of this study are:

1. To carry out a study of gas trap mechanisms through the analysis of well-log data using IHS Petra software

2. To contribute to the current understanding of the local stratigraphy and structure of the basin.

Study Area:

The study area (Figures 1-2C) for this investigation is the Aetna Field, which extends from T. 8N, R. 27 W to T. 9 N, R. 27 W and T. 8 N, R. 26 W to 8N, R. 27 W. Geographically, the Aetna Field covers parts of Franklin, Johnson and Logan counties.

The study area has been delineated on the geological map of Arkansas in figure 2A, and figure 2B presents the study area on a Township and Range map, whereas, Figure 2C puts the study area in the context of regional geological setting on a GoogleEarth image.
Figure 1. Arkoma Basin is an elongate, east-west trending sedimentary basin bordered by Ouachita Fold and Thrust Belt to the south, Ozark Uplift (Boston Mountains Plateau) and Northeast Oklahoma Platform to the north and northeast, by Gulf Coastal Plain (Mississippi Embayment) to the west and by the Lawrence Uplift and Arbuckle Mountains to the southwest. The study area is indicated by the green rectangle in the Arkoma Basin. (Modified and adopted after Manger, Zachry, and Garrigan, 1988)
Figure 2A. Location of the study area on the geological map of Arkansas (Arkansas Geological Survey). Northwest Arkansas, where the study area is located, has escaped major structural deformations. However, it has accommodated extensional features chiefly represented by numerous east west trending normal faults that are down to the south.
Figure 2B. Location of Aetna Gas Field on a Township and Range map. Well locations are indicated.
Figure 2C. Aetna Gas Field in the context of local and regional geology. (Modified and adopted after Yezerski and Cemen (2014) on GoogleEarth image).
Methodology

The Aetna Gas Field was selected for the purpose of this study. It lies between 9N 27W, 9N 26W, 8N, 27W, AND 8N 26W.

Geographically it covers parts of Logan, Johnson and Franklin counties. The Middle Atoka is the focus of this study. Therefore, the nomenclature for the units are limited to the Middle Atoka units. This includes thick shale units inter-layered with lobate sandstone units namely (from bottom to top; names are based on industrial nomenclature) Casey, Bynum, Areći, Tackett, and Morris as provided in Figure 3. The tops were selected for Dunn_A through Morris for consistency. Ten cross sections were constructed using the logs from 49 wells given in figure 4.

Raster logs were acquired from IHS Energy. The data are uploaded on IHS Petra interface for analysis. The study area was delineated in the areal extent of Aetna Field and the data was loaded. Wells were identified on the map view for constructing cross sections for well-to-well correlation studies. The wells selected were sorted by several criteria. Gamma ray logs were given priority. Stratigraphic tops were determined for correlation purposes. A total of 49 wells with good quality logs (logs that contained readable gamma, resistivity and conductivity logs) were selected for correlation purposes. Ten cross sections were constructed and correlated to allow more detailed study of the intervals in the Middle Atoka (Figure. 4). These section lines were named conventionally as A-A’, B-B’, C-C’, D-D’, and E-E’ for the cross section lines trending north to south. The cross section lines trending east to west were named V-V’, W-W’, X-X’, Y-Y’ and Z-Z’. Stratigraphic tops were used to correlate the sand units in each well. Structural and subsequent stratigraphic cross sections were constructed. The subsurface lithology and structures were then described and interpreted.
Figure 3. Simplification of the Middle Atoka presenting only major units. The focus of this study was on indicated inside the blue box.

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<td>Base of Middle Atoka (Zachry, 1983)</td>
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Chapter 2

Previous Investigations:

Arkoma Basin has been the subject of extensive studies in the past owing to its significance as a ‘prolific natural gas basin’. These studies have focused on the lithology, stratigraphy, structural, and tectonic settings of the basin. Owen (1858) was the first to publish accounts of a sandstone and shale sequence overlying “Millstone grit”, which is now known as the Bloyd Formation in Washington County, Arkansas. Taff and Adams (1900) studied the Choctaw Coal fields in Oklahoma. They described the Hartshorne Formation in the area. Further studies focused on mineralogy of the basin as well. Adams and others (1904), for example, studied the relationships of the zinc and lead deposits in Northern Arkansas. Renaming of “Millstone Grit”, which was a European adoption, was undertaken in such studies as well. In cooperation with the Arkansas Geological Survey, Croneis published a special report on “The Geology of Arkansas Paleozoic Area with Special Reference to Oil and Gas Possibilities” in 1930. Croneis (1930) established and extended the use of Atoka Formation by finding that the Winslow of the Boston Mountains and Atoka Formation of the Arkansas valley are continuous with one another; both overlie Morrowan strata and are overlain by the Hartshorne Formation.

Lower Atoka and Morrow strata of the Arkoma Basin in northwestern Arkansas have been examined extensively in publications and theses. Houseknecht and Kacena (1983), Houseknecht (1986), Zachry (1983), McGilvery and Houusknecht (2000) and Cardott (2012) and others have studied the structures, stratigraphy, tectonics, and depositional environments of the basin in sufficient details. Houseknecht (1986) published on the tectonics of the basin and Zachry (1983, 1984) worked on the depositional framework of the Atoka Formation and described the stratigraphic frameworks of the basin. Arbenz (1998, 2008) described the structure
of the basin and provided a structural evolution model and Suneson (2012) has chronicled the history of oil and gas exploration in the Arkoma Basin.

Many previous graduate students have compiled Master’s theses addressing a particular point of interest associated with the Arkoma Basin. The share of upper and lower Atoka in such studies is more voluminous than the middle Atoka, the middle Atoka has nevertheless been studied to some extent. Master’s theses by Williams (1983), Thomas (1983), Stephens (1985), Gaston (1985), Melody (2002), Wenger (2002) and Studebaker (2014) address aspects, such as, stratigraphy, sequence stratigraphy and depositional systems and environments of the middle Atoka particularly associated with the sandstone units. However, the names of these sandstone units are still arbitrary. No detailed study of the thick shale units that alternate with the thin sandstone units in the middle Atoka Formation has been conducted. This provides the opportunity to study and understand the stratigraphic and structural dynamics of these units.

**History of Natural Gas Exploration in Arkoma Basin:**

Planalp (1968) records that the Ozark Natural Gas Company originally discovered natural gas in the Aetna field in March 1928. Of the eight shallow wells that were drilled, three producing wells were completed in the upper Carpenter and middle Alma sands, both are middle Atoka. The first successful wells in southeastern Oklahoma were drilled on the crest of the Poteau anticline. Much of the early drilling occurred on anticlines, thus, structure has played a key role in the development of Arkoma Basin petroleum resources. More recently, understanding fractured reservoirs has become increasingly important, as has the role of natural versus induced fractures.

Arbenz (2008) divides the Arkoma Basin into two parts based on the origin of the folds.
1. The northern part, which borders the Ozark uplift and Cherokee Shelf, is characterized by “Common Anticlinal” drape structures over deep faults that form numerous traps of gas fields.

2. The southern part that Arbenz (2008) calls the Southern Arkoma Basin Fold Belt. Folds in this part of the Arkoma Basin are the result of Ouachita compressional tectonism and north-directed thrusting.

Suneson (2012) divides the historical evolution of the Arkoma Basin as a prolific gas-producing basin into six major divisions starting with Pre-1910 through Present (2012). His six major divisions are briefly outlined as follows:

**Solids (Pre-1910):**

- Explorer John Maley first recorded the presence of asphaltite in 1812
- The Osage Coal and Mining Company opened the first commercial underground coal mine near the town of Krebs, Oklahoma (Guning, 1975).
- Prior to 1910, very little note was made of natural gas or oil as a resource in the Arkoma Basin

**Anticlines (1910-1935)**

- Gas was first discovered in the Arkoma Basin near Mansfield, Arkansas in 1902.
- Exploration focused mostly on the anticlines
- Reports and maps were published between 1937 and 1949.
Geological Maps (1935-1950)

- U.S. Geological Survey and Oklahoma Geological Survey published a number of detailed surface geologic maps of the Arkoma Basin and Ouachita Mountains that greatly improved geologists’ knowledge of the structure and stratigraphy of the area.
- Reports and maps were published between 1937-1949.


- Beginning in about 1950, three major types of gas discoveries were made in the Arkoma Basin and Ouachita Mountains.
- The identification of deeper reservoirs in the long-productive anticlines in the Arkoma Basin. Mostly in the southern part of the basin in the transition zone between the basin and the fold-and-thrust belt as well as sub-Choctaw Fault reservoirs.
- Unconventional reservoirs – in this case, fractured reservoirs.

Plate Thrusts (1980-1990)

- Drilling in the Arkoma Basin and the Ouachita Fold-Belt resulted in the discovery of gas and detailed description of the model for the tectonics of the Ouachita fold belt.
- In 1988, Sutherland (1988) published a paper on the depositional history of the Arkoma Basin. This paper clearly described the evolution and relation of the shelf sediments (to the north) to the basinal sediments (to the south), the changing source terranes of the different sedimentary units, and the relation between clastics and carbonate units.
Horizontal Wells (1990-Present)

- The first coalbed methane (CBM) well in the Arkoma Basin was drilled in 1988 and the first horizontal CBM well in 1998.
- The peak of vertical CBM drilling occurred in 2002 after which activity rapidly declined.
- The peak in both vertical and horizontal CBM drilling (353 wells) and horizontal drilling (333 wells) occurred in 2005.
- 2004 through 2011, 2005 only Woodford (Devonian) wells had been completed, with most in the Arkoma Basin.
Chapter 3

Tectonics of the Arkoma Basin

In Northwest Arkansas, Paleozoic strata are exposed in three main structural provinces. From north to south, these include the northern Arkansas structural platform (Chinn and Konig, 1973), the Arkoma Basin and the Ouachita Mountains. The area of this investigation lies within the second northernmost of these structural provinces. The northern Arkansas structural platform is generally bordered on the north by the Ozark Dome and on the south by the Arkoma Basin.

The structural platform is approximately 40 miles wide and trends in an easterly direction across northern Arkansas. Paleozoic strata of the platform are essentially horizontal between the Arkansas-Missouri state line and the general area of Gaylor Mountains, Arkansas (Chinn and Konig, 1973), with only a slight regional dip to the south.
Figure 5. An outline map of Northwest Arkansas after Chinn and Konig, 1973, showing the divisions into major structural provinces. The study area is located in the Arkoma Basin, the second northernmost structural province in this scheme.
Tectonic History:

Houseknecht and Kacena (1983) and Houseknecht (1986) constructed a widely accepted model for the tectonic development of the Arkoma Basin. According to this model, given in Figure 6, during the late Precambrian and through the early Paleozoic, major rifting occurred, opening an ocean basin. Shelf facies accumulated during this time and were dominated by carbonates with quartzose sandstone and shale. By the early Mississippian, the ocean basin began to close as southward subduction began. An accretionary prism formed in association with the subduction zone that would later become the Ouachita orogenic belt. Slow sedimentation occurred during the Mississippian and early Atokan on the southern margin of North America in shallow marine and non-marine environments. Throughout this time, flysch (deep marine facies) accumulated in the deep remnant ocean basin. Convergence during the early Atokan facilitated formation of large down to the south growth faults during sedimentation, creating accommodation space for the middle and upper Atoka. These faults strike parallel to the Ouachita orogeny, which was uplifted during this period. Uplift of the Ouachitas was complete by Late Atokan time and the structural evolution of Arkoma was completed (Houseknecht, 1986).

Regionally, the sandstone units of the middle Atoka are thicker and display greater variability in thickness and composition than those of the lower Atoka. Individual sandstone units are also more complex containing varied amounts of shale (Fritsche, 1980). Thicker intervals contain up to 70% shale with thin (30-50 feet thick) sandstone units concentrated near the top.

The concentration of sandstone maxima in lobate and elongate belts, and the development of shaley successions away from those belts suggest that the middle Atoka
sandstones accumulated in high constructive delta systems that prograded southward across the northern and central parts of the Arkoma Basin. The substantial increase in thickness of individual sandstone units and the multistoried development of delta front and distributary channel sandstones as compared to the thin, multilateral units of the lower Atoka indicate that the rate of subsidence of the central and northern part of the shelf increased in middle Atokan time (Houseknecht, 1986).

The middle Atoka succession is dominated by shale. Thin sandstone units ranging to 15 feet in thickness occur in repetitive succession forming packages several hundred feet thick. The packages are isolated by thick intervals of shale, and become more numerous toward the top of the Middle Atoka interval Houseknecht (1983).

The late Proterozoic and Paleozoic structural evolution of the Arkoma Basin may be summarized as follows:

- Late Proterozoic or Early Cambrian rifting (Houseknecht and Kacena, 1983)
- Deposition of Cambrian strata through the Mississippian Pitkin Limestone on a passive plate margin.
- Down-to-the-south normal faulting (Frezon and Glick, 1959) and formation of footwall anticlines in the latest Mississippian, probably due to Ouachita thrust loading south of the Arkoma Basin (Houseknecht, 1986).
- Truncation of the anticlines by the Pre-Morrowan (Mississippian-Pennsylvanian) unconformity.
- Deposition of the Pennsylvanian Morrowan and Atokan strata.
• Down-to-the-south listric normal faulting within the Morrowan and Atokan rocks during the Pennsylvanian, with the faults primarily soleing into the steep surfaces of the Pre-Morrowan unconformity (Van Arsdale, 1999)

• Late Pennsylvanian Ouachita orogeny thrusting and formation of the Ross Creek thrust (Arbenz, 1984; Sutherland, 1988).
Figure 6. Tectonic Model presented by Houseknecht (1986).

Figure 6A, illustrates a major episode of rifting that resulted in the opening of an ocean basin during the latest Precambrian or earliest Paleozoic time (Houseknecht, 1986). Southern North America then evolved into a passive continental margin (Figure 6B) that persisted through
the middle Paleozoic. Figure 6C illustrates the closing of the ocean basin during the Devonian or early Mississippian, accommodated by southward subduction beneath Llanoria (the ocean basin that opened up following rifting). Also during this time, the foreland style thrusting became predominant as the subduction complex pushed against strata deposited in these settings. This caused uplift along the frontal thrust belt of the Ouachitas, and the early foreland basin was formed (Figures 6C, 6D, 6E). By early Atokan (early to mid-Pennsylvanian) time, (Figure 6D) the ocean basin had been consumed by subduction and the northward advancing subduction complex was being obducted onto the rifted continental margin of North America. At this time, Arkoma basin sedimentation began as passive margin sedimentation ceased. Figure 6E represents late Atokan time. By the late Atokan, foreland-style thrusting became predominant as the subduction complex pushed forward. At that time, the gross structural configuration of the Arkoma-Ouachita system was essentially the same as the present, although relatively minor folding and thrusting continued after the Desmoninesian (Houseknecht, 1986).

**Regional Stratigraphy**

The deposition of the Atoka Formation (Mid-Atoka) is held equivalent to the tectonic and structural evolution of Arkoma Basin. The structural evolution inclusive but not restricted to listric, growth, and thrust faulting are manifested in the Atokan deposits. Therefore, the stratigraphy of the Atoka Formation merits special treatment.

The sedimentary sequence of Northwest Arkansas is approximately 5000 feet thick (Frezon and Glick, 1959) and consists dominantly of limestone, sandstone, and shale. Exposed sedimentary strata are of Ordovician, Devonian, Mississippian, and Pennsylvanian age. Rocks of Ordovician, Devonian, and Mississippian age are characterized by a dominance of limestone and
dolomite, whereas strata of Pennsylvanian age consist chiefly of sandstone and shale as illustrated in Figure 7.

The lower Pennsylvanian and older rocks of northern Arkansas generally increase in thickness south of the Ozark region from approximately 5000 feet on the northern Arkansas structural platform to more than 20,000 feet in the Arkansas Valley. The sedimentary section, depending on where the margins are placed, ranges from 3,000 feet on the shelf to a probable 30,000 feet along the forefront of the Ouachita mountain system in the south (Branan, 1968).

Morrowan age rocks underlie the Atoka Formation. Morrowan strata are composed of limestone, shale, and sandstone units that accumulated in various shallow-shelf environments. The thickness of the Morrowan succession ranges to several hundred feet thickness (Zachry and Sutherland, 1984).

The Atoka Formation within the basin is informally divided into lower, middle and upper intervals (Zachry, 1983). The lower units range in thickness from 900 feet to approximately 2,000 feet. It is composed of multiple units of sandstone separated by shale units. Individual sandstone units range from 20 feet to 200 feet in thickness. The lower Atoka of Oklahoma is characterized by widespread basal sand, the Spiro Sandstone, overlain by shale. On the informal division of the Atoka Formation into lower, middle and upper informal units based on lithology, Sutherland (1988) and Valek (1999) follow Johnson (1968) and Zachry (1983). Valek (1999) notes that the adoption of subdivisions of Zachry (1983) “clearly divides” the Formation into a sandstone – shale sequence of approximately equal development in the lower Atoka, a shale-dominated middle Atoka, and a sandstone – dominated upper Atoka. This thesis also follows the nomenclature adopted by Zachry (1983) for the Arkansas part of the Atoka Formation. This nomenclature is also supported by the Article 23 of the North American Stratigraphic Code.
Similarly, Zachry (1983) identifies the Sells/DunnA sand as the top of the lower Atoka interval. In this thesis, I use this to delineate the middle from the lower Atoka. Similarly, the top of Morris sand unit marks the upper contact of the middle Atoka.

The middle Atoka unit is composed of laterally discontinuous sandstone units, ranging in thickness to 100 feet, and is separated by thick intervals of shale. The middle Atoka interval in Arkansas is composed dominantly of shale but several sandstone units occur within the succession. The middle Atoka interval in Oklahoma is composed dominantly of shale with few major sandstone units (Zachry and Sutherland, 1984).

The upper Atoka interval in the Arkoma Basin of Arkansas is composed of sandstone units alternating with thick shale units whereas in Oklahoma it is composed of thick units of shale with thin, discontinuous sands, and conforms to the pattern of thickening displayed by the upper Atoka unit in Arkansas (Zachry and Sutherland, 1984).

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

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

Resting unconformably on top of the Morrow, the Atoka Formation, named for Atoka County Oklahoma, ranges in thickness from 500 feet at the northern edge of the basin to 20,000 feet at its southern margin. The lower Atoka consists of several sandstone units that are separated by intervals of shale. All sandstones within the lower Atoka are composed predominantly of quartzarenite (Sutherland, 1988, Zachry, 1984). The lower Atoka sands are the Spiro, Patterson, Cecil Spiro, Dunn C, Lower Jenkins, Upper Jenkins, and Sells/Dunn_A.

The middle Atoka is represented by the lower boundary marked by Dunn_A and upper boundary by Morris defined by Zachry (1983). This thesis explains the stratigraphic and structural features of the middle Atoka in Aetna Gas Field (Figure. 7).

The upper Atoka contains the sand units namely lower Carpenter, lower Alma, middle Alma, upper Alma and upper Carpenter. Upper Atoka strata were deposited after the cessation of normal faulting that produced the structural relief and thick sediment fill characteristic of the southern Arkoma Basin. Sandstone units within the Upper Atoka of Arkansas are related to the progradation of deltaic systems southward across a muddy, open shelf (Zachry, 1984). Periodic regional transgression interrupted deltation forming the shale units. Sediment supply remained high, but subsidence slowed, allowing deltaic sands to be removed laterally into strand-plain and coastal sand environments.
Figure 7. Stratigraphic Column presenting Morrowan, Atokan and Desmoinesian Series of the Pennsylvanian. The informal nomenclature has been modified after Houseknecht and Kacena, 1983). The industrial nomenclature, in red rectangle, for Middle-Atoka is used in this thesis. The boundaries of the informal units of Atoka are adopted after Zachry (1984).
Chapter 4

Depositional History of Arkoma Basin:

Atokan strata of the Arkoma basin record the transition from sedimentation on a passive margin to sedimentation in a foreland basin developed by convergent tectonic activity along the Ouachita orogenic belt (Houseknecht, 1986). The Atoka Formation of the Arkoma Basin is a complex terrigenous deposit that accumulated prior to and during the development of a peripheral foreland basin associated with the Ouachita Fold Belt. The distribution and character of the various detrital rocks was controlled by the volume of sediments supplied to the region, the geographic positions where sediment entered the area, and the tectonic activity that accompanied sedimentation (Zachry and Sutherland, 1984). During deposition, subsidence occurred in the southern and central parts of the basin causing the geometry of the Atokan fill to be asymmetrical. At its northern margin, the formation is truncated by the modern erosion surface and thickens to the south toward the frontal Ouachita Mountains (Zachry, 1983).

The structural and stratigraphic transition from the central portion of the Arkoma Basin to the northern shelf is poorly defined in Arkansas. Previous studies have suggested that the transition involves significant changes in structural style, stratal thickness, and sedimentary facies (Sutherland, 1988). Basin subsidence began in the late Mississippian and early Pennsylvanian in northwestern Arkansas (Zachry, 1983), affecting the Morrow section stratigraphically and structurally. Normal faulting facilitated south to north subsidence in the Morrow section as sedimentation occurred (Zachry and Sutherland, 1984).

The Arkoma Basin was depositionally part of the shelf that lay north of the Ouachita Trough during Cambrian to Early Pennsylvanian time. Shallow shelf conditions persisted during
Morrowan and early Atokan time, and the area did not become a depositional basin until the beginning of deposition of the middle part of the Atoka Formation (Zachry and Sutherland 1984). Lower Atoka strata in the Arkoma Basin accumulated on a shallow-shelf. Deposition was continuous from Morrowan to Atokan time on the southern part of the shelf in Oklahoma and probably in Arkansas. Widespread Atoka sedimentation was initiated by northward transgression of Atokan seas across an erosion surface cut on Morrowan strata. The basal Spiro Sandstone in Oklahoma accumulated in pre-transgression channel systems and in blanket-sand unit at the base of the Formation. Multiple sand units above the basal sand thicken eastward in Arkansas and are absent in Oklahoma, suggesting that the dominant sediment supply entered the basin from the northeast and north in Arkansas. High, destructive cratonic deltas that prograded southward across a shelf characterized by little subsidence formed widespread but thin sand units in delta and delta-related environments. Progradation was interrupted by periodic northward transgressions, bringing open-shelf environments to the Arkoma Basin area and forming shale units. Distal to the major sediment source, the shelf in Oklahoma was a site of shale accumulation (Zachry, 1983, 1984).

The lower Atoka shelf was subjected to tensional stress during the deposition of the middle Atoka, and large, east-and northeast-trending normal faults developed in a stepwise fashion from south to north. Large volumes of sediment bypassed the northern shelf areas and accumulated on the downthrown sides of active faults, forming the middle Atoka clastic wedge.

Upper Atoka strata were deposited after the cessation of normal faulting that produced the great structural relief and thick sediment fill characteristic of the southern Arkoma Basin. Sandstone units within the upper Atoka of Arkansas are related to the progradation of deltaic systems southward across a muddy, open shelf. Periodic regional transgression interrupted
deltation forming the shale units. Sediment supply remained high, but subsidence slowed, allowing deltaic sands to be moved laterally into strand-plain and coastal sand environments. This redistribution of sand allowed for the development of sandstone units with great lateral continuity during progradation (Zachry, 1984).

**Structural Framework of the Arkoma Basin**

The Arkoma region is both a structural and topographic low, having been extensively eroded by the valley of the Arkansas River (Valek, 1999). The basin originated as a structural feature during middle Atokan time in response to tectonic loading associated with the first pulses of the Ouachita Orogeny. Climax of the Ouachita orogeny elevated the region and ended deposition with the Middle Pennsylvanian through the southern Ozarks and the Arkoma Basin (Valek, 1999).

Structural deformation in Arkansas was most intense in the Ouachita Mountain fold belt and was less intense in the Arkoma Basin and mild on the northern Arkansas structural platform (Chinn and Konig, 1973). The general trend of decreasing structural complexity northward from the highly deformed strata of the Ouachita region suggests that deformation was related to the north-directed stress produced by a phase of the Ouachita orogeny. Tectonic activity responsible for many of the observed structural features of northern and central Arkansas is thought to have occurred during early to middle Pennsylvanian time (Chin and Konig, 1973).

The Ouachita mountains of southeastern Oklahoma and southwestern Arkansas are the largest outcrop area of the Paleozoic orogenic system that formed along the southern margin of the Paleozoic North American craton (Arbenz, 2008).
From north to south, the major regional structural elements of the outcrop area in the Ouachita Mountains comprise:

1. The extensionally faulted and mildly drape-folded, south-dipping part of the Arkoma Basin that abuts the compressional thrust front but still belongs to the Paleozoic North American continental platform

2. A north and northwest-facing frontal thrust-and-fold belt of varied complexity

3. The main outcrop region of Ouachita Mountains proper, which consists of a complex set of thrust sheets made up entirely of deep-water sediments of Cambrian to Pennsylvanian age (Arbenz, 2008).

Arbenz (2008) concluded that within the Ouachita allochton, the deformational styles are closely related (Figure. 8) to the folding character (wavelengths and amplitudes) of competent beds of varying thickness and rigidity as they appear in the stratigraphic section. Therefore, subdividing the area into structural provinces by mechanical behavior of major stratigraphic intervals may be more suitable.

Because of the great thickness (~10 km) of the entire stratigraphic column of the Ouachita facies, Arbenz (2008) proposes a subdivision into at least three significantly different vertical segments illustrated in Figure 8.

1. A style of alternating ductile marine shales and competent sandstones and cherts is prevalent in the pre-Carboniferous rocks. This section is essentially shale-dominated, but the competent, folded and faulted, ridge-forming sandstone and chert formations display separate fold trains that demand much flowage in the separating shales.
2. The next style interval is confined to the highly deformed and overall ductile section of the shaley flysch facies that characterizes the lower two-thirds of the Mississippian Stanely Group (~2km thick). Numerous thin clayey sandstone members show mappable chevron type fold trains, but these are usually discontinuous and often disharmonic. This whole interval acts as the main zone of disharmony and detachment that exists between the pre-Carboniferous structures and the greatly different structural style of the younger turbidites (Arbenz, 2008).

3. The third and youngest structural style is characterized by the late-to gigantic-scale flexural folds that deform the Late Mississippian and Pennsylvanian deep-water turbidite sandstones and shales and occupy a large portion of the outcrops of the Ouachita Mountains. Turbidite sandstones form an almost continuous assemblage from the upper Stanley Group (Mississippian), the Jackfork Group and Johns Valley Shale (Morrowan), and the overlying Atoka Formation (Atokan). The sandstone units are interbedded with countless shale partings and shale members as much as several hundred meters thick. These shale beds facilitate the mechanism of flexural folding. In the Oklahoma salient, the combined sandstone package is almost 4 km thick and appears to act as a single buckled plate. The resulting folds have wavelengths as large as 15 km and amplitudes >5km (Arbenz, 2008).
Inferred Structural Evolution –
Southern Arkoma Basin & Ouachitas

Early Desmoinesian

Late Atokan

Middle Atokan

Early Atokan

Late Morrowan

Mississippian - middle Morrowan

Cambrian - Devonian

Figure 8. Structural model presented by Arbenz (2008) for the evolution of Arkoma basin throughout geological history.
Chapter 5

Discussion:

Planalp (1968) shows through an isopach map that the entire stratigraphic section in the Aetna field thickens southward, in conformance with the regional thickening. The Atoka thickness ranges from 5,400 to more than 7,500 feet in the field (Planalp, 1968). Isopach maps were created to evaluate the extent of thicknesses across the gas field. These isopach maps, given in Figure 9, Figure 10 and appendix D, confirm the thickness to the south.

Figure 9. Isopach map for the interval Tackett showing a gradual thickness to the southeast corner. Hot colors indicate increasing thickness.
Figure 10. Isochoric map of interval Bynum, the thickest interval in the Middle Atoka, shows a gradual increase in thickness to the south.

**Stratigraphic Analysis:**

The stratigraphic analysis for Aetna field, in this study, is based on five north-south trending cross-sections named A-A’, B-B’, C-C’, D-D’, and E-E’ (Figure 5). For the purposes of detailed study, the stratigraphic intervals from top of Dunn_A through Morris were divided into five units based on the nomenclature used in the industry and adopted in the previous theses studies carried out at the University of Arkansas. These stratigraphic units, correlated and compared in figures 12A through 12E, from top of the middle Atoka to the bottom are Morris, Tackett, Arei, Bynum, and Casey. Gamma log signatures extracted from these cross-sections...
were specifically used for this purpose. A type log Rich Toka 1, given in figure 11, located at T9N R27W S34 was used as reference log with all the tops positive identified at accurate intervals.

Figure 5 displays a complete list of the ten cross sections that were utilized in this study covering 49 wells. The north-south trending cross sections, referred to above, were specifically utilized to understand the north-south variation in stratigraphic columns as well as the structure of the gas field.
Figure 11. Type log for the stratigraphic tops modeled by Well Rich Toka1, located in T9N, R27W in Aetna Gas Field, Franklin County, Arkansas.
Morris is the highest interval/unit in the middle Atoka. North to south in the Aetna Gas Field, it maintains a constant thickness. The thickness of this unit ranges from 135 feet to 314 feet. The sandstone in this unit is coarse grained as indicated by low gamma ray value. Dominated by sandstone, the bottom part of the unit is covered by fine-grained shale. Morris is thicker in the western part of the Aetna Gas Field than the eastern part.
Tackett is overlain by Morris and underlain by Areci units. The thickness of the unit varies from a thin of 215 feet in the eastern part of the gas field to a maximum thickness of 852 feet in the south central part of the gas field. The shaley character gets strongly pronounced in the eastern part of the basin. The unit thickens to the south following the general thickening pattern for the Arkoma basin and the gas field.
Areci ranges in thickness from 266 ft to 723 ft in the Aetna Gas Field. It constitutes blocky but thin sandstone units in the western part of the field and serrated logs representative of rapidly changing environments in the eastern part of the basin. Thickening to the south is noted. Coarsening upward sequences are recorded by gamma ray logs. Shale dominates the lower part of the unit and transitions to sandy shale and then to coarsening upward sequence of sandstone which becomes blocky in the western part of the field.
A blocky pattern is characterized by generally abrupt boundaries both above and below. Depositional environments represented by this pattern include fluvial-channel-fill sandstone, tidal-channel-fill sandstone, nearshore-marine deposits, and deep-marine deposits. When this pattern occurs in association with successive coarsening-upward sections, a deltaic to coastal-plain environment can be inferred.

Serrated patterns appear jagged and suggest sporadic sediment supply which could be related to seasonal variance in climate causing wet/dry or cold/hot cycles. However, it can also result from deposition under the influence of rapidly alternating high and low energy. When energy is high, sand is deposited, if available, and when energy is low, mud or silt is deposited. Such rapid energy variations can occur in nonmarine floodplain environments, lower-shoreface to offshore transitional environments, shallow water transgressive settings, and deep-water turbidite settings. It should be noted that any log signature can be serrated depending on sediment fluctuations.
Fig. 12D. Gamma ray logs for the Bynum unit.

Bynum is thickest unit of the middle Atoka formation in the Aetna gas field. It ranges in thickness from 440 feet to 1,046 feet. It is the thickest and most persistent interval of the middle Atoka in Aetna Field. This unit thickens to the south and to the east. It exhibits a sandy shale/shaley sand composition which at times spike toward one or the other. This is true particularly as depicted...
by the gamma ray logs (B-B’, C-C’, D-D’ and E-E’) with a little variation. Alternating blocky and serrated patterns dominate the lithology. However, a pure shale unit or a pure sandstone unit seems to be lacking or is not exhibited by the gamma logs at least.

Fig. 12E. Gamm ray logs for the lowest interval Casey, the lowermost unit of the Middle Atoka. It is separated from the lower Atoka by the top of Dunn_A.

Thick shale unit dominates this interval. Its thickness varies from 290 feet to 695 feet. The shaley character transitions to thin sandy character but abruptly goes back to being shaley in the middle part. However, the highest unit is undoubtedly a sandstone unit that continues to Byunum and forms its base. North to south, thickening is demonstrated. The shale content is comparatively stronger in the eastern wells than the western ones.
Structural Analysis:

A structural cross section depicts the configuration of many formations as usually viewed in a vertical plane. Structural cross sections are constructed in the direction of interest. The section can be oriented perpendicular, parallel or oblique to structural strike. For solving problems, it is common for the line of section to be laid out in the dip direction or over the crest of a structure (Tearpock and Bischke, 1991). A line of section perpendicular to the dip direction of a fault is best for solving fault problems. Such an approach is utilized in this study where lines of sections for structural cross section are perpendicular to the dip direction of faults.

Five dip section cross sections trending north to south (Figure. 5) were analyzed for structural features inclusive of normal faults, and smaller synthetic and antithetic faults. Structural cross sections illustrate structural features such as dips, faults, and folds (Tearpock and Bischke, 1991). Several normal faults are noted that trend down to the south (Figure 13). Planalp (1968) has noted two normal faults that he called North Aetna Fault and South Aetna Fault respectively (Figure 11). However, the well log correlations carried out for 49 wells (Appendix E) in this study confirms the presence of at least five faults. These fault are well developed in all the five cross sections used for this analysis. This is interpreted as a zone that was faulted extensively. To accommodate extension, antithetic faults did develop in the central part of the gas field as indicated by cross-section D-D’ in figure 14.

Middle Atoka formed at the time when the basin was going through closure due to the northerly push of the Ouachitas toward the North American Continent. The basin closure is punctuated by the development of normal faults and their consequential antithetic faults. Structural cross sections constructed after the correlation of well log data from Aetna Gas Field
(Figure 13), show the development of these thoroughgoing normal faults in a bookshelf faulting style.

The structural cross section A-A’ (Figure 17) provides evidence that the offset in the lower intervals of middle Atoka is more pronounced. Cross sections B-B’ and E-E’ (Appendix C) provide evidence of a consistent growth of normal faults throughout the Gas Field in the Middle Atoka beds.

The overall structure of the gas field, from north to south, is defined by parallel normal faults that probably constitute either the western limb of a major syncline or the eastern limb of an anticline. Such extensively faulted areas provide structural traps for the fluid.

The lower Atoka shelf was subjected to tensional stress during the deposition of the middle Atoka, and large, east-and northeast-trending normal faults developed in a stepwise fashion from south to north. Large volumes of sediment bypassed the northern shelf areas and accumulated on the downthrown sides of active faults, forming the middle Atoka wedge.
Figure 13. Three normal faults trend parallel from north to south.
Figure 14. Five normal faults from north to south are noted. Two of the faults trend to the north while three trend down to the south.
Planalp (1968) describes that maximum subsidence was in the early and middle Pennsylvanian in the Atoka and early Desmoinesian. During this period of accelerated subsidence, extensive block faulting occurred in the basin. Aetna field is defined by the Aetna anticline (Figure 15). The surface axis of this anticline is faulted down to the south, which causes the surface anticlinal axis to be slightly south of the subsurface anticline. The south flank of the Aetna anticline is faulted down by a second major fault, which divides the field into three separate reservoirs. The north flank of the anticline is bounded by the Smith Creek syncline while the southern flank has fault closure but overall the southern limit of the feature is defined by Paris syncline (Planalp, 1968).
Figure 15. Two major faults trending north-south across the Aetna gas field. The angle of these faults ranges from 39° to 43°, with a definite flattening at depth. Thickening of the section southward also results in increasing fault displacement at depth (Planalp, 1968)
Trapping Mechanism:

Planalp (1968) defines Aetna gas field as a “multiple trap”. The well-defined anticline defines the structural feature. However, gas has been found structurally low on the downthrown side of the faults and several permeability pinchouts are present (Planalp, 1968).

Branan (1968) notes that nearly all of the early wildcat discovery wells in the Arkoma basin were drilled on surface anticlines, however, much of the gas production is from stratigraphic traps which have little or no relation to surface structural features. Aetna field, Franklin County, may be classed as a combination of structural and stratigraphic accumulations.

As a result of the examination of logs carried out for this study using IHS Petra, it has been established that there exists a combination trap for the natural gas in the Aetna Field. The cross section A-A’ in Figure 16 trend north-south across the Aetna field 9N 27W to 8N 27W, displays a narrow arch when flattened on the Morris sandstone unit of the Middle Atoka. Here the Morris is treated to serve as the arbitrary boundary between the middle Atoka and upper Atoka following Zachry (1983). When flattened on the Morris, the logs indicate that the arch structure predates the Morris sandstone deposition. However, the subsequent subsidence depicted in the structural cross section in Figure 17, post-dates the Morris sandstone deposition. It appears that this arch structure controlled the natural gas distribution in Aetna field. This may also represent an earlier phase of compression in the tectonic history of the field.
Figure 16. Cross section A-A’ displaying a narrow arch to the western part of the field. This arch is more pronounced in the lower middle Atoka particularly by Bynum, Casey and Dunn-A units.
Figure 17. Structural cross-section A-A’. Note the strongly pronounced Arch to the left (Northwestern part of the Aetna field) of the cross-section.
The north-south cross section titled C-C’ (Figure 18) confirms a more pronounced arch structure to the western part of the Aetna field that transitions to a trough structure in the eastern part of the Aetna field. This provides further evidence supporting the interpretation that while in the western part of the field the western limb of the arch provides a closure to the natural gas trap, in the eastern part a stratigraphic trap could be speculated as the stratigraphic units continue in a structural trough.

In total, five stratigraphic cross-sections that trend north-south were constructed. All of these cross-sections indicate that there is a strongly pronounced arch in the western part of the Aetna field, that transitions into a structural trough in the eastern part. It is also worth noticing that the arch is pronounced strongly in the lower units while it diminishes in the upper units of the middle Atoka. This supports the interpretation that the lower mid-Atoka was subjected to the consequences of an extensional environment more than the upper mid-Atoka. Figure 19 represents the eastern most, north-south trending cross-section titled E-E’. In this cross-section, the trough structure is more prominent and in conformity with the cross-sections discussed earlier. Similarly, five cross-section lines running west to east in the Aetna field show a similar structure and pattern as the ones observed in cross-section lines trending north-south. Cross-section V-V’ marking the northernmost west-east cross section, given in Figure 20, shows an arch structure in the western part of the basin which is more developed in the lower units of the middle Atoka such as Areci, Bynum, and Casey. Similarly, the X-X’, given in Figure 21, cross-section marks the departure from an arch structure to a trough as we move to the southern part of the west-east cross sections. Finally, the southernmost west-east cross section titled Z-Z’, (Figure 22), presents a trough. This trough has replaced the arch in the northern part of the basin. It could be inferred that the northern and northwestern part of the Arkoma basin in the Aetna field
consists of an arch whose western limb acts as a structural limit to the gas reservoir. It is inferred based on the same parameters that the southern and southeastern part of the basin represent a trough but apparently the trap becomes more of stratigraphic one. This requires the thick shale unit to be invoked as a stratigraphic trap that limits the escape of gas from the porous sandstone units of middle Atoka.
Figure 18. Cross-section C-C’ flattened on Morris illustrates a transition from an arch structure in the western part of the Aetna field to a structural trough in the eastern part of the field.
Figure 19. Cross-section E-E’ represents the eastern limit of the Aetna field and the complete transition of an arch structure, as noted in cross-section A-A’, to a trough structure.
Figure 20. Cross-section V-V’ displays strongly pronounced arch in the western part of the section.
Figure 21. Cross-section X-X’ marks the initiation of a transition phase from an arch to structural trough in the south.
Figure 22. Cross-section Z-Z’ confirms the complete migration from an arch structure in the northern part of the basin to a structural trough in the eastern part of the basin in Aetna field (and also a shift to the eastern part of the field.)
Conclusion:

1. General increase in thicknesses from N-S in all units is noticed.

2. Thicknesses are more evident and prominent in the western part of the field compared to the eastern wells as depicted by cross sections D-D and E-E' especially in Morris and Tackett.

3. There is a noticeable transition from a shaley dominated lower-Middle Atoka (Casey) to a Sand dominated Upper-Middle Atoka (Morris)

4. The thickest unit is Bynum at a maximum thickness of 1,024 feet and the thinnest unit is Morris at an average thickness of 227.5 feet in the gas field.

5. An arch-trough structure and stratigraphic continuity beyond the structure combine to form a combination trap (Structural and Stratigraphic) for the gas in the field.

6. Deposition is in a deltaic environment. The deposition reflects a cyclic transgression and regression in which constructive delta system dominates.

7. The presence of three normal faults, and an arch (An anticline) define the structure of the gas field.
References


Appendix A. Map of Lines of cross sections.
Appendix B. Stratigraphic cross sections.
Appendix C. Structural Cross Sections.
Appendix D. Isopach Maps
### Appendix E. List of wells used.

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