Stratigraphic Characterization and Depositional History of the Barnett Shale within the Fort Worth Basin in Denton County, Texas

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Stratigraphic Characterization and Depositional History of the Barnett Shale within the Fort Worth Basin in Denton County, Texas
Stratigraphic Characterization and Depositional History of the Barnett Shale within the Fort Worth Basin in Denton County, Texas

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

By

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University of Arkansas
Bachelor of Science in Geology, 2012

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This thesis is approved for recommendation to the Graduate Council.

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ABSTRACT

The Barnett shale, located in the Fort Worth Basin, is a geologic unit that has undergone extensive study and currently holds great economic importance. It contains well-known stratigraphy, but still holds questions with regard to the specific stratigraphic variation over much of its area. Denton County contains a large geographic area of the Barnett shale, and holds many answers to the varying stratigraphy of the Barnett shale, as well as an explanation into its depositional history. The investigation involved the use of two cross sections utilizing 32 and 26 wells respectively in the western region of Denton County, Texas. From the cross sections produced, the variation in stratigraphy and structure with the Barnett and related lithologies across a large area was compared with known stratigraphy of the Barnett shale. The variation in structure and stratigraphy agrees with the previous work examined in this study. All of the gamma ray signatures observed within the Barnett shale and related lithologies matched well with the type log used for comparison with all the wells included in the study. The cross sections confirmed the variation expected for the stratigraphy and structure in the region of Denton County along with the location of the area in relation to the Fort Worth basin as well. The Barnett shale shows two individual members, upper and lower, as expected. The presence of the Forestburg limestone dividing the Barnett shale into upper and lower members is also confirmed with the cross sections.

Multiple stratigraphic cross sections were produced along the same south to north and southwest to northeast directions as the in situ cross sections covering the entire study area in Denton County, Texas. This allowed definitive variations of both the individual stratigraphic thickness and change in structural depth to be observed. The overall trends from the stratigraphic cross sections indicate a general deepening to the north and northeast from the south and
southwest seen in every section. An increase in stratigraphic thickness is also seen with all of the lithologic units, with the general increase found toward the northeast from the south and southwest. The Marble Falls limestone showed increase from the north to the south, while the Forestburg limestone showing an increase from the south to the northwest.

Isopach and structure maps produced from each lithologic unit confirmed and defined structural and stratigraphic trends seen across the study area. The structural trend includes a deepening from the southwest toward the northeast seen with each of the lithologic units on each of the structural maps. The stratigraphic trend with regard to stratigraphic thickness increase seen was varied with each of the lithologic units. The Marble Falls limestone’s increase in stratigraphic thickness occurs from the north to the south edge of the study area. The Upper Barnett shale’s increase in stratigraphic thickness occurs along a zone around the center of the study area from the western edge of the area to the northeast. The Upper Barnett shale’s stratigraphic thickness increases from the south to the center zone and from the northwest to the center zone as well. The Forestburg limestone’s increase in stratigraphic thickness occurs from the south edge of the study area toward the northwest edge of the area. The Lower Barnett shale’s increase in stratigraphic thickness occurs from the south edge of the study area toward the northeast edge of the study area.
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DEDICATION

This thesis is dedicated to my wife, Casey Cope, for all her kindness, support, and patience during the process and completion of this thesis. Without her support throughout the process, this thesis would not be possible.
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**Introduction**

The Barnett Shale (Mississippian) is the source, seal, and reservoir for to a world-class natural gas accumulation in the Fort Worth basin (Montgomery *et al.*, 2005). The Barnett shale was initially recognized by Girty (1912) as a shale interval found at the base of the Bend Series between the Marble Falls Limestone (Pennsylvanian) and the Ellenburger Group (Ordovician). The Barnett shale was initially called the Lower Bend Shale by Udden *et al.*, (1916), but was subsequently named the Barnett Shale by Plummer and Moore (1922). The type section of the Barnett Shale is found near Barnett Springs, San Saba County, Texas (Sellards, *et al.*, 1932).

The purpose of this study is to determine the stratigraphic variation and depositional history of the Barnett Shale. Correlation of well log data and synthesis of existing data were used to document the stratigraphic variation of the Barnett shale.

**Location**

The location of this study is in the western section of Denton County, Texas. An aerial view from GoogleEarth™ of the county is shown in Figure 1, including the locations of the cross-sections created in this study. The geography, which underlies the location of both cross-sections involved in this study, consists of flat prairie plains with minor variation in topography. The mean surface elevation varies across the county from 500 to 900 feet (150 to 270 meters), with an average elevation of 642 feet (195 meters). The major land use across the county is a mix between agricultural and industrial uses, along with an increasing amount of large-scale housing development taking place throughout the county over the last decade. Most of the county contains large acres that are open and undeveloped, allowing many
drilling rigs to come and go across the western portion of the county with ease. The drilling activity by major producers such as Devon Energy and Chesapeake is also very active throughout the western section of the county near the city limits of Denton, Argyle, Justin, and Krum along Interstate Highway 35-East. Flat-lying topography makes the drilling much simpler and allows a much larger area of production to be possible with the absence of steep topography for all companies with lease holdings across the region.

A study on the Barnett shale conducted by the Bureau of Economic Geology (BEG) at the University of Texas at Austin in 2011 indicates that production from the Barnett will decline through 2030, but until then there’s still an enormous resource and huge potential, even with the current low prices (Durham 1). The study integrates engineering, geology and economics in a numerical based model that enables scenario testing based on a multiple of input parameters (Durham 2). In the base case using $4 gas, the assessment forecasts a cumulative 44 TCF of recoverable reserves from the Barnett shale through 2050 based on already-drilled wells and the wells to be drilled through 2030 (Durham 2). The base case also shows annual production declining in a predictable curve from the current peak of 2 TCF per year to about 900 BCF per year by 2030 (Durham 2). The BEG effort is unique in its approach in that it takes a ‘bottoms-up’ approach, beginning with the production data from every well and then determining what areas remain to be drilled; rather than a ‘top-down’ view of production that relies on aggregate views of average production (Durham 2). The “bottoms-up” approach provides a more accurate and comprehensive picture of the basin (Durham 2). Production data from than 16,000 wells drilled in the Barnett play up to mid-2011 were examined and divided into 10 productive tiers (Durham 3). They were then further divided by high and low Btu liquids and dry gas (Durham 3). At $3.50 to $4 gas, operators
have retreated slightly from the poorer quality rock, tiers 5 to 10, back to tiers 1 to 4 and are
drilling fewer wells but still making money because of better rock quality and higher
Estimated ultimate recoveries (EURs) (Durham 3). The BEG assessment is optimistic in their
forecast that there are a number of locations in what is included in the top half of the tiers in
the $4 base case (Durham 3). The 16,000 wells were all individually examined with regard to
their decline curves and per-well economics, allowing the locations still open to drill to be
considered (Durham 3). Even if existing wells already drilled in the play are left to decline
and not another well is drilled (as stated in 2011) 20 TCF total gas would still be approached
(Durham 3). It has produced 13 TCF to date (2011), and another seven to eight TCF would
be expected from wells already drilled (Durham 3). Another 10,000 wells are expected to be
drilled with most being in the better areas because those have been tested (Durham 3).
Figure 1. Aerial view of study area in Denton County, Texas. Cross section lines shown in black. (Google Earth™, 03/15/2014).
Geologic Background

The Barnett Shale in Denton County is located in a primarily Dry Gas window in terms of thermal maturity, and lies adjacent to the Muenster Arch within the Fort Worth basin. Figure 3 shows the features in Denton and the surrounding counties. The Barnett Shale was deposited in a deep-water environment over a period of 25 million years, from 345 to 320 million years ago (Montgomery et al., 2005; Loucks and Ruppel, 2007). Deposition of the Barnett Shale took place during a prolonged second-order highstand of global sea level, and at least ten third-order cycles of change in global sea level took place during this second-order highstand (Ross and Ross, 1988). Figure 4 shows the eustatic curves described (Loucks and Ruppel, 2007; Ross and Ross, 1987). The Barnett Shale is unique in multiple ways as a shale play. It produces from greater depths and pressures than other shale-gas plays (Bunting, 2007). The Barnett Shale is also entirely thermogenic in origin and occurs with liquid petroleum. One poorly understood aspect of the Barnett is how natural fractures do not seem to be essential for the production and can even reduce performance (Montgomery et al., 2005).

The Fort Worth basin is a northward deepening depression – a late Paleozoic foreland basin associated with the advancing Ouachita fold belt (Walper, 1982). It covers approximately 15,000 square miles in north-central Texas (Bunting, 2007). The basin is bound to the north by the Red River and Muenster arches, to the east and south by the Llano uplift and Ouachita structural front and to the west, the basin thins against the Bend arch (Figure 3) (Bunting, 2007). The Bend arch forms the western margin of the basin and the Ouachita thrust front forms the eastern margin (Steed 2006). The basin covers approximately 15,000 square miles and is one of a series of foreland basins formed along the southern
margin of the North American craton during the late Paleozoic Ouachita orogeny (Steed 2006).

The Ouachita fold-thrust belt and the associated Ouachita Basin formed as a result of the oblique collision of North America with a northward moving southern plate (Arbenz, 1989) (Figure 2) The exact identity of this southern plate is unknown, but is generally believed to have been a subductional accretionary thrust front with one of the following four bodies as the colliding object: 1) Gondwana, 2) a mid-oceanic volcanic arc, 3) an unknown foreign terrane, or 4) a former piece of North America which had been removed from the craton during Cambrian rifting (Arbenz, 1989). Graham et al. (1975) combine the Appalachian and Ouachita orogenies into one system which significantly complicates the orogenic event by introducing several crustal bodies (e.g., North America, Eurasia, Gondwana) into the collision.

The Muenster arch is a fault block bound by basement faults reactivated during the late Paleozoic (Steed 2006). The Barnett shale is thickest (700 to 1,000 feet) to the northeast against the Muenster arch and thins to a feather edge (<30 feet) over the Llano uplift to the southwest (Steed 2006). The preserved fill of the Fort Worth basin reaches a maximum thickness of about 12,000 feet. The deposits consist of 4,000-5,000 feet of Ordovician-Mississippian carbonates and shales; 6,000-7,000 feet of Pennsylvanian clastics and carbonates; and a thin cover of Cretaceous rocks in some parts of the basin (Montgomery et al., 2005). The structural history of the basin includes periods of both major and minor faulting, local folding, fracturing, and karst related collapse features (Montgomery et al., 2005). A general stratigraphic section of the Fort Worth basin from the southwest to the northeast is shown in Figure 5.
Figure 2: Paleoreconstruction of plate tectonic movement during the A) early Carboniferous, B) late Carboniferous and C) late Permian. Note the progressive closing of the ocean basin between North America and Africa as you move forward in time from the early Carboniferous to late Permian time. From the Paleomap Project website (www.Scotese.com) (2002). From (Wright, 2002).
Figure 3. Map of Fort Worth basin modified from Montgomery et al. (2005).
Figure 4. Coastal onlap and eustatic curves for the Mississippian. Modified slightly from Loucks and Ruppel (2007). Curves modified from Ross and Ross (1987).
Figure 5. Stratigraphic section of Fort Worth basin. Note the division of the Barnett into two distinct members that takes place from SW to NE, along with the introduction of the Forestburg limestone between the Upper and Lower Barnett shale members. The Ellenburger carbonate also gives way to the Viola-Simpson carbonate towards the NE of the section. Modified from Montgomery et al. (2005).
Following an extensive early Paleozoic transgression, erosion removed all of the Silurian and Devonian strata from the Fort Worth basin (Henry, 1982). The Barnett was the first unit to be deposited when the seas returned and was deposited on a karsted surface (Steed 2006). It developed on the top of the Ellenburger Group over a wide area (Kier et al., 1980). A subtle angular unconformity (<1°) is present between the Barnett Shale and the the underlying limestones of the Ellenburger Group (Henry, 1982). An unconformity also separates the Barnett from the overlying Pennsylvanian strata (Cheney, 1940). Loucks and Ruppel (2007) estimated water depths from 400 feet to 700 feet during the deposition of the Barnett. Bottom waters were dysaerobic to anaerobic allowing organic matter in the shale to be preserved (Steed 2006).

Plate and paleogeographic reconstructions by Blakey (2005) show the area of the Fort Worth basin covered by relatively deep waters during the Late Mississippian. Water depths become shallower to the west (present day directions) toward the Chappel shelf and Llano uplift where exposed areas served as sources of terrigenous sediment (Steed 2006). To the south and east was an arc-trench system formed by the subduction of the North American plate beneath the South American plate (Steed 2006). Laurussia to the north and Gondwana to the south were being brought together as the ocean between them closed (Steed 2006).

**Literature Review**

The Mississippian Barnett Shale is one of the largest known unconventional shale plays in the world, producing more than 158 mcm (5.6 tcf) of gas (Berman, 2009) since the play’s discovery in 1981 by Mitchell Energy Company (Martineau, 2007). The initial discovery for the Barnett Shale by Mitchell Energy Company in 1981 occurred with the drilling of the C. W. Slay No. 1 in southeast Wise County. This well was proposed in early 1981 as a Rhome
area Caddo/Atoka development well on an expiring lease (Steward 2007). The initial production rates from the Clay well were initially 120 MCFG/D after cleanup in June 1982 (Steward 2007). The production rate was improved to 274 MCFG/D after cleanup, or more than twice that of the previous stimulation in April 1983, through re-perforation over a longer interval and refracing in the lower Barnett with a carbon dioxide foam frac having a theoretical frac half length (TFHL) of 500 feet (Steward 2007). But, with the completion cost it was made apparent that it would be prohibitive to get the rate to something acceptable, and the well was put back on production and monitored (Steward 2007). After continued use of the carbon dioxide foam fracs, it proved to be problematic due to the producing gas stream being contaminated with carbon dioxide for an extended length of time (Steward 2007). Over the course of the next two years, based on the results of sensitivity analyses from core work, Mitchell engineers experimented with a nitrogen foam frac and finally went to a nitrogen-assist, gelled water frac (Steward 2007). Mitchell Energy presented the Barnett Shale in a case in July 1983 before the Texas Railroad Commission to be classified as a tight gas formation under Section 107(b) of the Natural Gas Policy Act of 1978 (Steward 2007). As applicant, Mitchell’s technical witnesses had to prove the formation had an average in situ permeability of 0.1 millidarcies (md) or less, and that a pre-stimulated flow rate would not exceed 251 MCFG/D (Steward 2007). To the best of their ability Mitchell had to demonstrate that the formation would be continuous over the requested designated area, and fall within the same permeability and rate restrictions above (Steward 2007). Loren Vogel and his engineer (of Mitchell Energy) were able to demonstrate the low-permeability using core data from the W. T. Smith No. 2, and pressure buildup data from the C. W. Slay No. 1 (Steward 2007). These sources indicated ~ .008 to .0009 md and ~ .002 to .003 md respectively, with
both wells below the 0.1 md cutoff, and in addition, post-acid treatment and pre-frac stimulation in the J. D. Karnes No. 7 failed to establish and more than a weak blow of gas from the well (Steward 2007). Christopher Veeder (of Mitchell Energy) presented geological testimony consisting of an area map showing the proposed designated areas of Wise, Montague, Clay, Jack, Palo Pinto, Parker, Denton, and Tarrant counties; and two stratigraphic cross sections demonstrating the formation continuity across the area (Steward 2007). This request was approved by the Texas Railroad Commission in September 1983, and forwarded to the Federal Energy Regulatory Commission (FERC) for approval (Steward 2007). But, due to concerns on the part of their staff to dedicate such a large area on the basis of data from two or three wells, Mitchell was asked to reduce the area, and in May 1985, a new area was submitted including all of Wise County, the west half of Denton, and the northwest quarter of Tarrant County, and on December 31, 1985 the designation was approved by FERC (Steward 2007).

By 1998, industry perseverance along with technological advances like hydraulic and horizontal drilling developed the Barnett Shale into an economically successful play (Martineau, 2007) (Figure 6). These drilling and completion techniques were quickly applied various shale plays across the United States, rendering them economic successes and making the Barnett Shale the key play that initiated the search for additional unconventional oil and gas plays throughout the United States that now are numerous in number, and worldwide as well (Kuhn, 2011).
Figure 6. Representation of the increased Barnett Shale production since the play’s discovery in the early 1980s from Powell et al. (2011).

Stratigraphy and Lithology of the Barnett Shale

The Barnett Formation is composed predominantly of dark brown to black, thinly laminated, petroliferous shale (Liner et al., 1979). Large ellipsoidal, microsparite concretions up to 6 ft. in longest dimension characterize the lower 1/3 of the formation (Liner et al., 1979). The concretions form laterally persistent horizons connected by thin concretionary limestone beds, and the individual concretions may develop septarian structure and occasionally contain ammonoids and other fossils (Liner et al., 1979). Thin beds of phosphatic limestone and shale form the upper 2-5 ft. of the Barnett Formation in the
northeastern Llano region (central Texas) (Liner et al., 1979). The limestone beds are composed of dark yellow–brown, fine to course grained, poorly sorted, ammonoid–bearing oomicrite and biomicrite (Liner et al., 1979). The fossil constituents are usually replaced by phosphorite, and exposures of the Barnett typically weather to a light to medium yellow–brown, calichified shale (Liner et al., 1979). This shale commonly forms slopes and complete exposures are rare (Liner et al., 1979). The phosphatic limestones in the upper Barnett are more resistant to weathering, but may become slumped or otherwise covered (Liner et al., 1979). In the northeastern Llano region, the Barnett Formation averages 44 feet with no thickening or thinning patterns evident (Zachry, 1969; Kier, 1972). It conformably overlies the Chappel Limestone (Lower Mississippian), but may rest unconformably on the Ordovician Ellenburger Group where the Chappel is absent (Liner et al., 1979). The Barnett Formation is overlain by the Marble Falls Formation throughout the northeastern Llano region, as well as throughout other regions of the Barnett (Liner et al., 1979). But, the Mississippian–Pennsylvanian boundary, which generally coincides with the Barnett–Marble Falls lithostratigraphic contact, cannot be taken as being the Mississippian–Pennsylvanian boundary without detailed faunal analysis being done.

The nature of this Barnett–Marble Falls contact in the Llano region, central Texas, is one that remains an unsettled controversy (seen also through comparison of Liner et al., 1979 with Kier et al., 1979 and Merrill, 1980) (Manger et al., 1980). Lithostratigraphic evidence has been used to support its interpretation as a conformable, intertonguing relationship, while biostratigraphic evidence, particularly conodont occurrences, suggests that the boundary is a major regional unconformity (Manger et al., 1980). Studies conducted by Manger et al. (1980) regarding the biostratigraphy at this boundary, came to conclude that the continuous
deposition across the Mississippian – Pennsylvanian boundary would be difficult to reconcile with the cratonic setting and shallow shelf environments of the Llano region at that time (Manger et al., 1980). The apparently conformable contact between the Barnett and Marble Falls can be explained by Pennsylvanian seas slowly transgressing the weathered Mississippian shale surface (Manger et al., 1980). Redeposition of thin shales resembling those of the Barnett would be expected and in fact, absence of a basal Pennsylvanian shale under those circumstances would seem to be more unusual than its presence (Manger et al., 1980). Similarity of upper Mississippian and lower Pennsylvanian carbonates associated with the shales reflects reestablishment of similar environments during the regressive – transgressive cycle and certainly is not unknown in the record (Manger et al., 1980).

Manger et al. (1980) concluded that a major middle Carboniferous hiatus could be identified in numerous sections around the Llano uplift using conodonts and fusulinids (Manger et al., 1980). The most diminished duration of this unconformity still involves a gap of seven conodont zones, and in the western portion of the uplift, the missing interval includes the entire upper Chesterian, Morrowan, and the pre-Profusulinella part of the Lower Atokan Series (Manger et al., 1980). To argue that faunal differences at the boundary are only ecologic ignores both the biostratigraphic and lithostratigraphic evidence in favor of solely conjecture (Manger et al, 1980). The arbitrary placement of the Barnett – Marble Falls contact at either the highest shale, or the lowest limestone, or at some point in between, obscures, but does not eliminate, the unconformity, and unnecessarily complicates the middle Carboniferous geologic history (Manger et al., 1980).
Depositional History

The deposition of the Barnett Formation occurred during the Mississippian, during which tectonic loading of Gondwana on the North American carbonate platform resulted in the formation of a foreland basin on the southern edge of North America (Gutschick and Sandberg, 1983). Global plate reconstructions by Blakey (2005) suggest that the Fort Worth basin was the site of a narrow, inland seaway bound to the west by a carbonate shelf and to the south and east by the Caballos-Arkansas island chain (Montgomery et al., 2005) (Figure 7). Poor circulation within the restricted seaway produced an anoxic environment (Montgomery et al., 2005). The foreland basin, flooded by the seaway, created new accommodation space where deep-water clastics were deposited in a sediment-starved, anoxic environment over a 25 million year period (Loucks and Ruppel, 2007). The sediment deposited in the Fort Worth basin would eventually comprise the black, organic-rich Barnett Shale overlying the pre-Barnett erosional unconformity (Kuhn, 2011). Carbonates were also deposited along the western margin of the Fort Worth basin during the early Mississippian and constitute the Chappel limestone, which consists of crinoidal limestone and local pinnacle reefs up to 91 m (~300 ft.) in height (Browning, 1982; Ehlmann, 1982).
Figure 7. Paleogeographic reconstruction during the Early Carboniferous (Mississippian) after Blakey (2005). During this time, the Rheic Ocean was closing as a result of converging plate margins, and sediment that comprised the Barnett shale was deposited. The Fort Worth basin is outlined in red.

An adjusted sea-level curve constructed for the Mississippian by Ross and Ross (1987) allowed Loucks and Ruppel (2007) to suggest a water depth of 120 – 210 meters (~400 – 700 ft.) for deposition to be below lowstand storm-wave base (Kuhn, 2011). This estimate concurs with Byers (1977), who concluded that water depths must exceed 140 meters (~450 ft.) in basinal, anoxic environments where evidence of shelly fauna and bioturbation is minimal and sediment is laminated (Kuhn, 2011).

The Forestburg limestone (Mississippian) is an argillaceous lime mudstone (Loucks and Ruppel, 2007) that divides the Barnett Shale into informal upper and lower shale members in the northern region of the Fort Worth Basin (Kuhn, 2011). The Forestburg pinches out southward and westward, and where absent the upper and lower Barnett Shale members can no longer be
readily differentiated (Kuhn, 2011). Compositionally, the Forestburg limestone contains much less silica and TOC than the Barnett Shale, and its origin is still yet to be fully understood (Kuhn, 2011). Loucks and Ruppel (2007) suggest that the abundance of carbonate influx into the Fort Worth basin during Forestburg depositional time may reflect a change in: 1) source area, 2) eustatic sea level, or 3) seawater chemistry (Kuhn, 2011).

Following the deposition of the Barnett Formation the first formation deposited over the Barnett Shale was the Marble Falls Limestone (shown in a stratigraphic view in Figure 8 on the following page), which includes a lower interval of interbedded limestone and gray-black shale and an upper limestone interval (Montgomery et al., 2005). Sea level regression during the Early Pennsylvanian resulted in subaerial exposure of the Marble Falls Formation (Namy, 1974), creating a low-relief erosional unconformity (Kuhn, 2011). Throughout the rest of the Pennsylvanian the Fort Worth basin continued to subside (Pollastro et al., 2003), and clastic sediments shed from the surrounding, rapidly eroding thrusted highlands, filled the basin (Kuhn, 2011). The clastics, consisting of mostly sand and pebbles derived from the east, comprise the Bend, Strawn, Canyon, and Cisco Groups in the Fort Worth basin (Walper, 1982) and mark the culmination of the Ouachita orogeny (Kuhn, 2011). Along with contributing sediment to the Fort Worth basin, the Ouachita orogeny also produced the Muenster and Red River arches (Kuhn, 2011). These structures are faulted basement uplifts generated during the Ouachita orogeny from reactivation of faults related to the Southern Oklahoma aulacogen (Walper, 1977; 1982).
Figure 8. Stratigraphic changes from the southwest towards the northeast regions of the basin after Monroe and Breyer (2011).

The Pennsylvanian strata are truncated by another erosional unconformity that rests below a thin layer of Cretaceous rocks on the eastern side of the Fort Worth basin (Flawn et al., 1961; Henry 1982; Lahti and Huber, 1982). Whether Permian, Triassic, and/or Jurassic strata were present in the Fort Worth basin is not known, but Henry (1982) and Walper (1982) suggest that much of the Pennsylvanian and possibly Permian rocks were eroded prior to the Cretaceous (Kuhn, 2011). Cretaceous rocks comprise the last stratigraphic units deposited in the Fort Worth basin (Kuhn, 2011).

**Barnett Shale Reservoir Characteristics**

The Barnett Shale is dominated by type II oil-prone marine-algal kerogens (Pollastro et al., 2003) sourced from autochthonous organic material deposited within an anoxic, reducing
environment (Tissot and Welte, 1984). Organic matter decomposition constitutes the majority of the known porosity in the Barnett Shale (Jarvie et al., 2007). The organic material comprising the complex pore network is pyrobilumen, carbon-rich residue resulting from organic degradation and conversion to hydrocarbons through thermal exposure (Loucks et al., 2010) (Kuhn, 2011). Low permeability and porosity in the matrix surrounding the organic material minimize hydrocarbon expulsion from the shale (Jarvie et al., 2003). These circumstances present a closed system during hydrocarbon generation, which helps explain why this shale reservoir is over-pressured (Jarvie et al., 2007).

The Barnett Shale is very rich in original organic matter content (Jarvie et al., 2007) and serves as the primary source of petroleum for both conventional and unconventional reservoirs in the Fort Worth basin (Jarvie et al., 2003; Montgomery et al., 2005). TOC measurements from a less thermally mature region of the Barnett Shale typically yield a higher TOC (wt. %) than those taken from thermally mature, hydrocarbon bearing regions because less of the organic carbon has been converted to hydrocarbons (Jarvie et al., 2004). The minimum amount of organic material considered a “good risk” baseline for a potential shale reservoir is 2 wt. % TOC (or ~ 4 vol. % TOC) (Jarvie et al., 2004).

Most of the high radioactivity measured from gamma ray logs run through the organic-rich Barnett Shale is due to high uranium content (Breyer et al., 2011). The remainder of the gamma ray response is due to the presence of thorium and potassium (Breyer et al., 2011). Organic material deposited in an anoxic environment is reducing due to absence of oxygen and acts as a sorbent for uranium (Lüning and Kolonic, 2003). The amount of uranium precipitated is largely influenced by sedimentation rate (Lüning and Kolonic, 2003). During Barnett Shale deposition, preservation of organic matter and slow sedimentation rates permitted substantial
uranium precipitation, and, consequently, high gamma ray responses (Lewis et al., 2004). Montgomery et al. (2005) estimate the Barnett Shale to contain 742 bcm (~26.2 tcf) of technically recoverable gas in the Fort Worth basin. Effective recovery of hydrocarbons is directly dependent on significant gas storage in the reservoir and the absence of faults and/or karst features penetrating the Barnett Shale (Jarvie et al., 2007). Barnett wells drilled into structurally complex areas are typically found to be poor producers (Bowker, 2007).

**Methodology**

For the generation of the cross-section used to determine the stratigraphic variation of the Barnett Shale across a section of the county in focus, Denton, vertical wells taken from DrillingInfo.com™ were used, and were all in the LAS file format. A total of 58 wells were chosen along two directions: 1) N-S and 2) SW-NE, in the western section of Denton County. All of the wells were uploaded into Petra™ for correlation using the gamma ray curve tracks from the log files (present for all the logs) to form two digital cross sections of the Barnett and surrounding units above and below it where present. Figure 9 below shows the spatial distribution for all of the 58 wells through the map and inset generated through Petra (See Table 1).
The faunal differences seen between the Barnett shale and Marble Falls limestone are an important topic of further research that will continue to help in determining the regional nature
throughout the exposure of the Barnett shale of the ever–controversial boundary between the Barnett shale and Marble Falls limestone. Through petrographic analysis using the procedure suggested by Manger et al. of using the major chronostratigraphic and biostratigraphic hiatus as the lithostratigraphic boundary that would also mark a major depositonal history that will be present at all localities, the understanding of this boundary’s placement will be better understood.
Figure 10. Type log of the gross reservoir illustrating shoaling-upward sequence in the northern Fort Worth basin from Kuhn (2011).
Using the Petra™ software, two structural cross sections of the Barnett Shale with multiple variations on each lithology surface related to the Barnett Shale in western Denton County, Texas, were generated from the respective gamma ray curves of the 58 total wells that were downloaded (Figures 12 and 13).

Figure 11. Map generated in Petra™ showing the lines for the first and second cross-section. (*32° 59’ 51.70” N; **97° 23’ )
Figure 12. First of two in situ cross-sections generated from Petra™ with *31 of the 58 wells selected for the analysis, and following the well-to-well path from S to N along the western section of Denton County. Well numbers (corresponding to Appendix 1 on pages 55 - 60) are listed above each GR track. Formation names are shown along the top of each formation, respectively.
Figure 13. Second in situ cross-section taken along a line running from the SW to the NE shown on Figure 10. Well numbers are listed above each gamma ray track. Formation names are shown along the top of each formation, respectively.
Figure 14. Stratigraphic cross section hung on the top of the Marble Falls limestone lithologic unit from the south to the north across the study area in Denton County, Texas.
Figure 15. Stratigraphic cross section hung on the top of the Marble Falls limestone lithologic unit from the southwest to the northwest of the study area in Denton County, Texas.
Figure 16. Structure map with depth contours of the Marble Falls limestone across the study area in Denton County, Texas. Contour interval is 50 feet. Depths are (-) and subsea. (*32° 59’ 51.70” N; **97° 23’ 08.44” W)
Figure 17. Isopach map of the Marble Falls limestone across the study area in Denton County, Texas. Contour interval is 5 feet. (*32° 59' 51.70" N; **97° 23’ 08.44” W)
Figure 18. Stratigraphic cross section hung on the top of the Upper Barnett Shale lithologic unit from the south to the north across the study area in Denton County, Texas.
Figure 19. Stratigraphic cross section hung on the top of the Upper Barnett Shale lithologic unit from the southwest to the northwest of the study area in Denton County, Texas.
Figure 20. Structure map with depth contours of the Upper Barnett Shale across the study area in Denton County, Texas. Contour interval is 50 feet. Depths are (-) and subsea. (*32° 59’ 51.70” N; **97° 23’ 08.44” W)
Figure 21. Isopach map of the Upper Barnett Shale across the study area in Denton County, Texas. Contour interval is 5 feet. (*32° 59' 51.70" N; **97° 23' 08.44" W)
**Figure 22.** Stratigraphic cross section hung on the top of the Forestburg limestone lithologic unit from the south to the north across the study area in Denton County, Texas.
Figure 23. Stratigraphic cross section hung on the top of the Forestburg limestone lithologic unit from the southwest to the northeast of the study area in Denton County, Texas.
Figure 24. Structure map with depth contours of the Forestburg limestone across the study area in Denton County, Texas. (*32° 59’ 51.70” N; **97° 23’ 08.44” W)
Figure 25. Isopach map of the Forestburg limestone across the study area in Denton County, Texas. Contour interval is 5 feet. (*32° 59’ 51.70” N; **97° 23’ 08.44” W)
Figure 26. Stratigraphic cross section hung on the top of the Lower Barnett Shale lithologic unit from the south to the north of the study area, in Denton County, Texas.
Figure 27. Stratigraphic cross section hung on the top of the Lower Barnett lithologic unit from the southwest to the northeast of the study area in Denton County, Texas.
Figure 28. Structure map with depth contours of the Lower Barnett Shale across the study area in Denton County, Texas. Contour interval is 50 feet. Depths are (-) and subsea. (*32° 59’ 51.70” N; **97° 23’ 08.44” W)
Figure 29. Isopach map of the Lower Barnett shale across the study area in Denton County, Texas. Contour interval is 25 feet. (*32° 59’ 51.70” N; **97° 23’ 08.44” W)
Figure 30. Structure map with depth contours of the Viola-Simpson limestone across the study area in Denton County, Texas. Contour interval is 50 feet. Depths are (-) and subsea. (*32° 59’ 51.70” N; **97° 23’ 08.44” W)
Results

From the first cross-section shown in Figure 12, the following results on the Barnett and its surrounding lithology are summarized, beginning with the uppermost lithology, the Marble Falls Limestone (Pennsylvanian). Across the section from S to N, the Marble Falls unit kept its general thickness across the entire section, and did show structural variation, especially in the northern portion of the section. This structural variation seen here is a result of increased proximity to the axis of the Fort Worth basin where deepening of the section would be expected, along with subsidence seen across the section which occurred during deposition. This subsidence seen across the Marble Falls is suggested through observation of the increase in thickness of the Upper and Lower Barnett Shale sections beneath the Marble Falls. The Gamma character of the Marble Falls was easily identifiable on the logs and corresponded well with the Type log used for the correlation. The next unit below the Marble Falls Limestone (Pennsylvanian) is the Upper Barnett Shale (Mississippian). The Upper Barnett, from S to N, like the Marble Falls, shows structural variation across the section, and was again most notable in the northern end of the section. Structural variation seen is due to increased proximity to the axis of the Fort Worth basin, along with an increase in the vertical depth, a result of subsidence that occurred during deposition. This subsidence is suggested by an increase in thickness across section of the underlying Lower Barnett Shale. The thickness of the Upper Barnett did show variation across the section, and showed a fair increase in thickness as you travel across the section. This increase in thickness is a result of increased accommodation space with increased proximity to the axis of the Fort Worth basin. The Upper Barnett also flattens out structurally at the northern end of the section ending much deeper vertically than where it began in the section. For the Upper Barnett the Gamma character was also easily identifiable across the section with each of the log tracks,
and corresponded well with the Gamma character shown in the type log used in this correlation. The Forestburg Limestone (Mississippian), which is found generally only in the northern region of the Barnett Shale, and divides it into Upper and Lower sections. The Forestburg Limestone, from S to N, along with the other units above also shows structural variation with regard to depth across the section, and again for the Forestburg was most notable in the northern end of the section. Structural variation resulted from increased proximity to the axis of the Fort Worth basin and subsidence that occurred during deposition. This subsidence is suggested by an increase in thickness across section seen with the Lower Barnett Shale. The thickness of the Forestburg Limestone did show variation across the section, and in this case, shows a fairly large increase from the S to the N across the section. This increase in thickness is a result of increased accommodation space created by proximity to the axis of the Fort Worth basin. The Forestburg Limestone also flattens structurally at the northernmost end of the section, and ended deeper vertically than where it began in the section, a result of the subsidence noted above. The unit next below the Forestburg Limestone (Mississippian) is the Lower Barnett (Mississippian), generally much greater in thickness than the Upper Barnett in this region. The Lower Barnett, from S to N across the section shows variation structurally across the section from the south to the north. This variation is a result of the increased proximity to the axis of the Fort Worth basin, and subsidence that occurred during deposition. This subsidence is suggested from the increase in unit thickness seen across the section, and also confirmed from the Lower Barnett isopach map, seen in Figure 29 on page 44. The thickness of the Lower Barnett shows an increase to a small extent across the section, and is thickest near the middle of the section (well 5 and 10) and continues to the north end of the section. This increase in thickness is a result of an increase in accommodation space from proximity to the axis of the Fort Worth basin allowing for a greater
The Lower Barnett deepens vertically from the S to the N across section, and structurally flattens at the northern end of the section due to the subsidence occurring during deposition previously noted. The last unit of the section is the top of the Viola-Simpson Carbonate (Ordovician), a crystalline, carbonate, that occurs beneath the Barnett in this region of its extent. For this unit, only the top was identified for the purposes of this study, and the wells across the section only had minor penetration into the unit, as seen from the Gamma log signatures. The top of the section was the only portion able to be noted. Any variations in the thickness, vertical changes, or absence, of course are not able to be included.

For the second cross-section shown in Figure 13 the direction is from the Southeast to Southwest and then up towards the Northeast. The Marble Falls Limestone (Pennsylvanian) maintains its stratigraphic thickness across the section with some minor thinning that is visible at the Northeastern end of the section, where it also begins to deepen structurally. The structural variation across the entire section for the Marble Falls is minor with deformation seen in the southwestern end of the section and slight deformation also towards the northeastern end of section also. This variation in structure resulting in deepening of the section is a result of the increase in proximity to the axis of the Fort Worth basin that is more pronounced than the previous section, and subsidence, which occurred during deposition. This subsidence is suggested by an increase in thickness seen across the Upper and Lower Barnett Shale lithologies across the section. The minor decrease in thickness at the northeastern end of the section is a result of the decrease in accommodation space resulting from a greater amount of sediment being deposited beneath that created subsequently thicker sections from greater accommodation space that existed during the time of those lithologies deposition. These thicker lithologies deposited beneath together resulted in the minor thinning seen here with the Marble Falls from a minor
decrease in accommodation space close to the axis of the Fort Worth basin. The Upper Barnett Shale (Mississippian) actually shows a slight increase in stratigraphic thickness towards the northeast across the section. The structural variation of the unit is minor and seen in the southwestern area of the section and towards the northeastern end of section, with the stratigraphic thickness staying consistent across the section towards the northeastern end of the section, where the unit begins to deepen structurally. This vertical deepening of the Upper Barnett Shale is a result of subsidence that occurred during deposition and increased proximity to the axis of the Fort Worth basin. This subsidence is suggested by an increase in thickness seen across section with the Lower Barnett Shale. The increase in thickness towards the northeast is a result of an increase in accommodation space as a result of proximity to the axis of the Fort Worth basin. The Forestburg Limestone (Mississippian) also shows an increase in thickness across the section towards the northeastern end of the section and maintains its thickness to the end of the section. The Forestburg begins to deepen structurally at the northeastern end of the section. This increase in thickness is a result of the greater accommodation space as a result of increased proximity to the axis of the Fort Worth basin. The deepening structurally of the Forestburg Limestone occurs as a result of subsidence, which occurred during deposition, and increased proximity to the axis of the Fort Worth basin. This subsidence is suggested by an increase in thickness seen across the section with the Lower Barnett Shale. The Lower Barnett Shale (Mississippian) shows an increase in stratigraphic thickness across section from the southwestern end of the section, maintains thickness across section, and at the northeastern end of section shows a stark increase in thickness. As the Lower Barnett nears the northeastern end of the section it begins to deepen structurally. The increase in depth structurally is a result of subsidence, which occurred during the time of deposition. This subsidence is suggested by the
increase in unit thickness seen across the section, and also confirmed with the Lower Barnett isopach map, seen in Figure 29 on page 44. The great increase in thickness seen across the Lower Barnett Shale is a result of the increase in accommodation space that occurred with increased proximity to the axis of the Fort Worth basin that allowed an increased volume of sediment to be deposited. The Viola-Simpson (Ordovician) Limestone formation top is visible across the section, with only a very minor portion of the unit able to be seen on each of the gamma curve across each section. The lack of this unit being included is due to the fact of the unit only having importance in terms of the completion and production success, where it acts a crucial hydraulic fracturing barrier with it being a dense, crystalline limestone. Where this unit is absent and the Ellenburger Limestone is found instead, the use of hydraulic fracturing is practically not possible due to the karstic, solution-collapse features found throughout the Ellenburger.

For both the first and second in-situ sections, any apparent faulting or folding features can be attributed as a product of abrupt change in direction among the wells on the section path, proximity between wells, and also through comparison with the overall structure maps of the individual lithologies, which indicate the dip and clear up any misrepresentations also.

**Discussion**

Examining cross sections 1A and 2A reveals the structural and stratigraphic variation that occurs with the Marble Falls limestone from the south to the north, and from the southwest to the northeast, along each line of section. In section 1A, the Marble Falls shows very minor variation structurally, with only a slight decrease in stratigraphic thickness at the northernmost well in the cross section. In section 2A, only minor variation is seen structurally and a slight decrease in
thickness also at the northeast end of the cross section. The Marble Falls limestone deepens from -4950 feet subsea in the southwest to -6900 feet subsea in the northwest at the edge of the study area. The thickness of the Marble Falls limestone over the study area is thickest at a maximum of 370 feet in the southern half of the study area, and increases in thickness from the northern end of the study area to the south. The Marble Falls limestone thins toward the northern edge of the study area to a minimum thickness of 270 feet. The decrease in stratigraphic thickness seen in the Marble Falls across the section is a result of a decrease in accommodation space that is due to the underlying lithologic units thickening across the sections from the south and the southwest toward the north and northeast. The deepening of the Marble Falls seen in both sections, along with the structure map, are a result of subsidence during the time of deposition, and trends toward the north and northeast in the direction toward the axis of the Fort Worth basin. This subsidence is suggested from the increase in thickness observed across the Upper and Lower Barnett Shale sections below the Marble Falls limestone. Sections 1B and 2B show the structural and stratigraphic variation occurring with the Upper Barnett shale across both sections south to the north and southwest to the northeast. In both sections 1B and 2B the Upper Barnett shale shows minor variation structurally, and both show an increase in the stratigraphic thickness of the Upper Barnett shale with a greater increase overall seen in section 2B. The Upper Barnett shale’s structure varies from -6300 feet subsea in the southwest edge of the study area to -7150 feet subsea in the northeast edge of the study area, deepening toward the northeast. The Upper Barnett Shale is thickest toward the northern section of the study area in a zone that extends toward the northeast edge from the west edge of the study area. It achieves a maximum thickness of 200 feet toward the west edge of the study area. The Upper Barnett shale thins toward the north and south edges of the study area with a minimum thickness of 90 feet at the southern edge.
of the study area and 110 feet in the northwest edge of the study area. Deepening of the Upper Barnett shale toward the northeast of the section is a result of subsidence that occurred during deposition, as seen by the thickening of the underlying Lower Barnett shale seen across the section toward the northeast. The increase in thickness occurring toward the north and northeast of the section is a result of subsidence occurring during deposition and the increased accommodation space resulting from this subsidence occurring toward the north and northeast of the section. In sections 1C and 2C the stratigraphic and structural variation of the Forestburg limestone is seen across both cross sections, with the greater increase in stratigraphic thickness seen in cross section 1C. Section 1C shows very minor variation in structure from the south to the north of the section. The Forestburg limestone deepens structurally from -6400 feet subsea in the southwest edge of the study area to -7400 feet subsea in the northeast edge of the study area. The Forestburg limestone thins toward the south edge of the study area where it reaches a minimum thickness of 60 feet and also thins toward the northeast of the study area where it thins to 95 feet at the northeast edge of the study area. The Forestburg limestone thickens to a maximum thickness of 200 feet toward the northwest edge of the study area, and also toward the east-central region of the study area and the east-central edge of the study area where it reaches a thickness of 130 feet. The deepening of the Forestburg limestone occurring from the southwest to the northeast is a result of subsidence that occurred during deposition that is suggested from the increase in thickness toward the northeast of the section seen with the underlying interval, the Lower Barnett shale. The increase in thickness of the Forestburg limestone seen toward the northwest edge of the study area is a result of the subsidence that occurred during deposition, creating additional accommodation space toward the northeast of the section. The increase in thickness is also due in part to thinning of the Lower Barnett shale toward the northwest of the
section, where the Forestburg thickens to its maximum. In sections 1D and 2D the structural and stratigraphic variations of the Lower Barnett shale is seen with some major structural variation seen in both sections and segmented increases in stratigraphic thickness seen in both sections as well. The Lower Barnett shale changes structurally from the southwest edge of the study area to the northeast edge of the study area where it deepens from -6450 feet subsea to -7400 feet subsea. The Lower Barnett shale thickens from the southwest edge of the study area to the northeast of the study area, where it attains a maximum thickness of 750 feet. The Lower Barnett shale thins towards the southwest edge of the study area where it reaches a minimum thickness of 300 feet. The deepening of the Lower Barnett shale from the southwest to the northeast occurs as a result of subsidence during deposition, along with increased proximity to the axis of the Fort Worth basin. The increase in thickness of the Lower Barnett shale from the southwest to the northeast is due to subsidence occurring during deposition, creating additional accommodation space for deposition across the section toward the northeast of the section. This increase in thickness from the southwest to the northeast is also due in part to increased proximity to the axis of the Fort Worth basin, where a greater amount of deposition would be possible.

The Viola-Simpson limestone changes structurally from the southwest edge of the study area to the northeast edge of the study area. This change involves the Viola-Simpson limestone deepening from -6750 feet subsea at the southwest edge of the study area to -8150 feet subsea at the northeast edge of the study area.

**Conclusions**

With further exploration and development into the Barnett shale play in Denton County, most notably into the northernmost area of the county, and to the east and south, (outside of the
Newark East Field), will provide much greater log data to allow for a deeper and more detailed understanding of the changes in stratigraphy and structure of the Barnett shale and related units across a much greater area of the county. As this increase in drilling activity into areas not yet explored may occur with the coming years ahead, continued analysis regarding stratigraphy and structure variation will add to a greater understanding of the Barnett shale in Denton and improve drilling and production efforts in Denton and the neighboring counties. The inclusion of detailed core analysis for lithology character, petrologic study, and geochemical analysis for gas and oil typing and maturity variation across the play are of great importance in the continued study of the Barnett shale play. The faunal analysis with regard to foraminifera found at the boundary between the Pennsylvanian Marble Falls limestone and Mississippian Barnett shale to address an area that is still in controversy are also of great importance in the continued study of the Barnett shale-gas play. The analysis with the above methods in Denton and other neighboring counties, would also lend greatly to the further overall understanding of the nature of the Barnett Shale across its known geographic extent, and be quite interesting to find how the Pennsylvanian - Mississippian boundary appears in the northern region of the Barnett.
# Appendix 1

## Well List

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*Well not included in cross-section and analysis due to location.

**Well had gamma ray log curve missing from LAS file. Not included in cross-section analysis or isopach/structure maps.
References


Kier, R. S., 1972 – Carboniferous stratigraphy of Eastern San Saba County and Western Lampasas County, Texas. Ph. D. dissertation, University of Texas at Austin, 437 pp.


Steed, Michael Bailey, 2009, Sequence Stratigraphy Of The Barnett Shale (Mississippian), Northern Fort Worth Basin, Texas, Texas Christian University, p. 1 – 66.


