# REGIONAL STRATIGRAPHY OF THE MARBLE FALLS FORMATION AND UNDERLYING LATE MISSISSIPPIAN TO EARLY PENNSYLVANIAN DEPOSITS, FORT WORTH BASIN, NORTH-CENTRAL TEXAS, USA

by

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November 16, 2015

Abstract

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The University of Texas at Arlington, 2015

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The Early Pennsylvanian Marble Falls Formation in the Fort Worth Basin (FWB) of North-Central Texas was deposited in a broad carbonate ramp system during the initial stages of Ouachita orogenesis. It extends across an area of more than 15,000 square miles and comprises an assortment of facies that vary considerably across the region due to high-frequency sea-level fluctuations. The Marble Falls has been studied extensively in outcrop around the periphery of the Llano Uplift where it was informally divided into lower and upper members separated by a regional unconformity representing the Morrowan-Atokan boundary. A sequence of the Marble Falls Formation was recently discovered in the northern part of the FWB where it reaches stratigraphic thicknesses of more than 450 feet and has become a fractured-driven, tight-oil resource play. The distribution of this unusually thick section was controlled by stratigraphic variations of several underlying units and extensive well log correlations across the FWB has presented new evidence that confirms this sequence is part of the lower Morrowan-age member of the Marble Falls Formation that covers a much larger geographic area than has been previously estimated. The examination of photomicrographs from whole cores and side-wall cores have also revealed that the lower Marble Falls is composed almost entirely of siliceous to partly calcareous sponge spicules similar to that observed in outcrop and this spiculite facies comprises most of the Marble Falls Formation across the entire FWB.

This study integrates >20,000 open-hole well logs, micro-resistivity image logs, petrophysical data, and core data to better understand the regional stratigraphy of the lower Marble Falls and evaluate its reservoir potential throughout the FWB. It gradually thickens from its subcrop along the Bend Arch towards the axis of the FWB to the east and northeast and is characterized by an inner ramp to basin depositional profile. The influence of foreland basin tectonics and glacio-eustatic sea-level fluctuations are evident from stratigraphic trends and shallowing-upward parasequences that were identified within the lower Marble Falls. The complicated lateral variations in these high-frequency cycles have historically created high-porosity stratigraphic traps along the Bend Arch, but the present play is concentrated in an area where the lower Marble Falls has little primary porosity or permeability and the reservoir consists of a network of naturally occurring, lithology-bound fractures (LBF) that are concentrated in the more siliceous spiculitic lithofacies. Thorough evaluation of these high-frequency cycles and stratigraphic variations in the lower Marble Falls is critical in understanding the controls on reservoir quality and the distribution of reservoir lithofacies.

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# Chapter 1

## Introduction

### Purpose

The complexity of carbonate depositional systems makes sequence stratigraphy and evaluation of carbonate reservoirs extremely difficult. However, scientific understanding of these complex systems has continuously evolved over the last century and made it easier to evaluate and exploit these highly variable reservoirs. The Early Pennsylvanian Marble Falls Formation in the Fort Worth Basin (FWB) has been recognized to record one of these highly variable and complex depositional systems. It has been documented by several workers studying the Marble Falls Formation in outcrop to contain an assortment of facies that reveal complex lateral variations over short distances and make this vertical succession of largely carbonate rock extremely difficult to map (Kier, 1980; Kier *et al*., 1979; Ruppel *et al.* 2007). The profusion of sponge spicules in the Marble Falls Formation has been recognized by most workers studying outcrop exposures and cores in the shallow subsurface around the Llano Uplift, but Farrar (2010) has been the only work to discuss this spiculitic facies in the deep subsurface in the northern part of the basin. There have been no published data tying the observations made by Farrar (2010) to the work that has been done in outcrop. Therefore, this study will be the first to present evidence that this spiculite sequence identified in the northern part of the FWB and along the eastern edge of the basin is part of the lower member (Morrowan) of the Marble Falls Formation identified in outcrop around the Llano Uplift and is hereafter referred to as the lower Marble Falls or the lower Marble Falls spiculite sequence. The lower Marble Falls was correlated and mapped across the entire FWB and was discovered to cover an area of more than 15,000 square miles (38,850$km^2$).

Significant advancements in drilling, completion, and reservoir characterization technologies over the last decade have allowed operators to revisit mature fields and re-evaluate tight reservoirs that were previously uneconomic. The Marble Falls field in North-Central Texas is a type example of a large, unconventional, oil and natural gas liquids - rich resource play emerging in a mature basin from a historically exploited reservoir. The Marble Falls field has yielded large amounts of hydrocarbons over the last century from conventional structural and stratigraphic traps scattered across the FWB. However, the current play is concentrated in Jack and Palo Pinto counties where a substantially thicker, highly fractured spiculite sequence of the lower member of the Marble Falls Formation started to be exploited with new technologies in 2009. This formation is poorly understood in the northern part of the basin because prior to the modern play there was poor deep well control and limited access to modern well logs. Fortunately, a resurgence in drilling over the last few years has provided better well control and the data to further evaluate the stratigraphy of the Marble Falls Formation and gain a better understanding of the distribution of reservoir lithofacies across the study area. The work done here should allow for more detailed sequence stratigraphic studies as well as structural and reservoir characterization studies to be prepared on the Marble Falls Formation in the future.

## Study Area

The Early Pennsylvanian Marble Falls Formation covers a much larger geographic area across the FWB than has been previously recognized, and there were several underlying Late Mississippian to Early Pennsylvanian deposits identified in the northern part of the basin that were also discovered to extend over a much greater area than has been previously documented. Therefore, the study area for this work includes most of the FWB where the Carboniferous stratigraphy has been correlated and consist of 32 counties across Central Texas and North-Central Texas that covers an area of more than 19,000 square miles (49,200 $km^2$) (Figure 1-1).

There has been little work done on evaluating and mapping the stratigraphy of the Marble Falls Formation on a regional scale or tying the Marble Falls in outcrop to the Marble Falls being exploited in the northern part of the basin. This study has utilized all of the publicly available well log data across the entire FWB to correlate and map the stratigraphy of the Marble Falls Formation and several underlying Late Mississippian to Early Pennsylvanian units (Figure 1-1). The area highlighted in light grey on the study area map in Figure 1-1 represents all of the counties in the FWB where the Carboniferous stratigraphy was correlated and mapped using the available well log data. There was also whole core data, side-wall core data, petrophysical data, micro-resistivity image logs, and a suite of modern digital vector logs that were used for this work. Most of this data was obtained from Jack and Palo Pinto counties that are highlighted in light green on the map and represent the core study area and location of the current Marble Falls play (Figure 1-1).

The lower Marble Falls sequence extends north from the Llano Uplift in Central Texas into southern Clay and Montague counties in North Texas where it is bounded to the north by the Red River Arch and the northeast by the Muenster Arch. The western limit of the lower Marble Falls is marked by the erosional north-trending subcrop that extends along the western edge of the Bend Arch from Coleman County to Throckmorton County (Figure 1-1). The eastern limit of the lower Marble Falls is more difficult to determine because it gradually grades into a mudstone-rich sequence and is therefore marked by a dashed red line to denote that the subcrop is estimated (Figure 1-1).

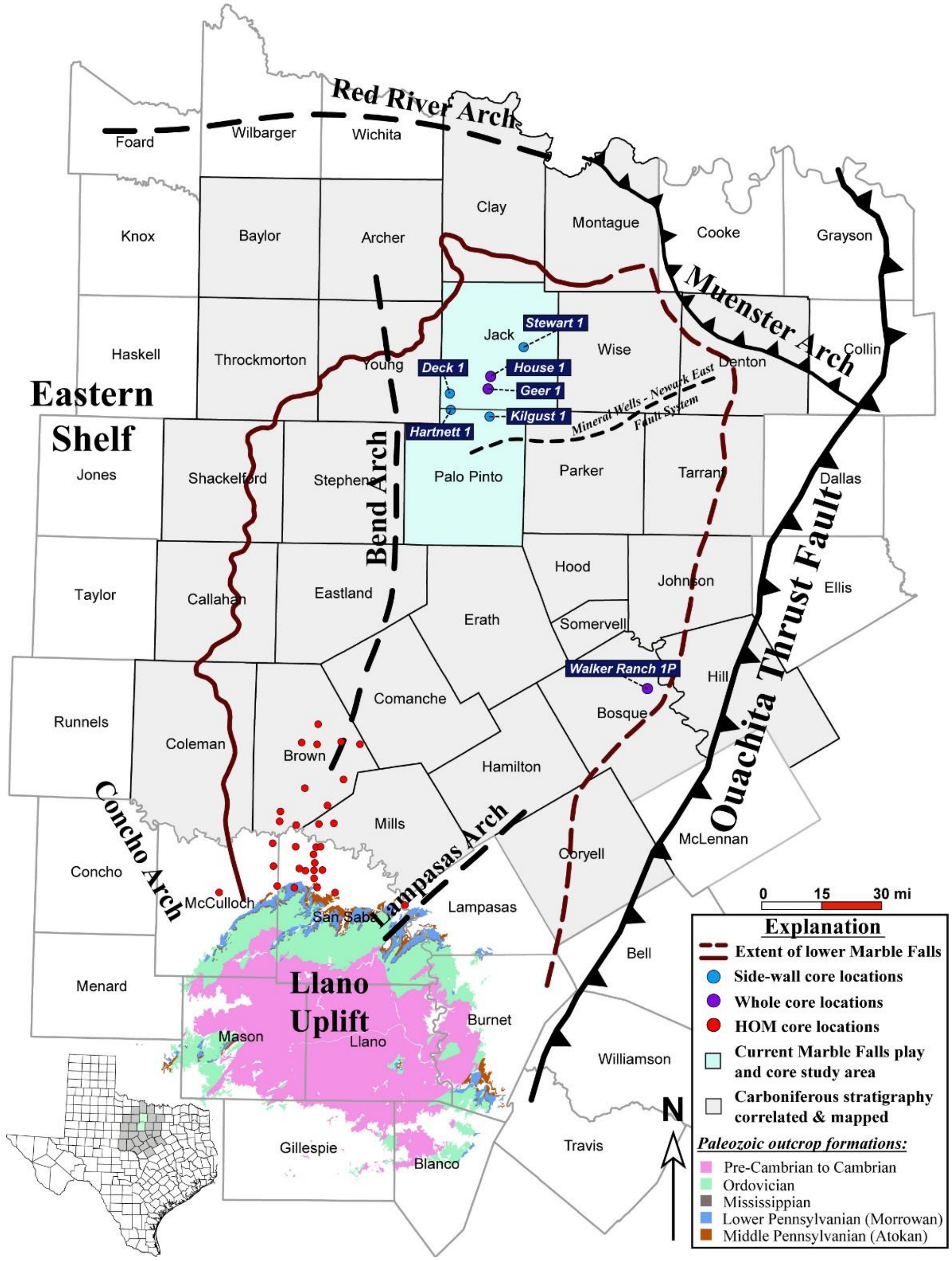



Figure 1-1. Study location map showing major structural elements from Pollastro *et al.* (2007) and extent of lower Marble Falls across the Fort Worth Basin. Location of wells with side-wall cores shown in blue and whole cores through the lower Marble Falls shown in purple. The location of 31 Houston Oil and Minerals Company cores that were used in subsurface studies by Brown (1983), Luker (1985), and Wood (2013) are shown in red.

## Overview of Marble Falls Play

### *Discovery*

The Marble Falls Formation in the northern part of the FWB around the Newark East field is largely known as a thick impermeable limestone lying stratigraphically above the Barnett Formation that acts as an upper barrier to vertical fracture growth during hydraulic fracturing of horizontal Barnett wells (Pollastro *et al*., 2007). The decline in natural gas prices in 2008 significantly impacted the exploitation of the Barnett Formation and forced operators with lease acreage in the area to explore for hydrocarbons in other formations. This eventually led to the discovery of a new field in a highly fractured, siliceous spiculite sequence in the overlying Marble Falls Formation in Jack and Palo Pinto counties. The discovery well in this new play was the Richards Ranch 9 that was drilled by EOG Resources in 2007 but discretely completed in the Marble Falls interval in 2009 (Figure 1-3). This well has subsequently produced 89,253 barrels of oil and 648,637 million cubic feet of gas as of January 2014 (DrillingInfo).

In 2010, Halek Energy drilled the Johnson 8H in the Marble Falls Formation that was located approximately 4 ½ miles to the southwest of the Richards Ranch 9 (Figure 1-3), and had initial production rates of 481 barrels of oil per day and 1,814 million cubic feet of gas per day (Henry, 2012b). This well was the key driver in attracting the attention of local operators who initiated the new highly economic, oil-rich Marble Falls play that is being developed along the western margin of the FWB. From 2009 to 2015, there was an exponential increase in the number of drilling permits issued by the Texas Railroad Commission for wells targeting the Marble Falls Formation (Figure 1-2). The majority of these permitted wells are located in central Jack County around the town of Jacksboro and in northern Palo Pinto County around the town of Graford. Approximately 900 of these wells have been drilled and completed, and another ~300 are either in the process of being drilled or completed or have yet to be drilled. Although a relatively small number of horizontal wells have been drilled in the Marble Falls play, most of the wells are vertical due to more favorable returns on investment. However, the Marble Falls could eventually be exploited utilizing horizontal wells with higher oil prices or advancement in technologies, but at the time this paper was written, horizontal wells were less economically favorable.

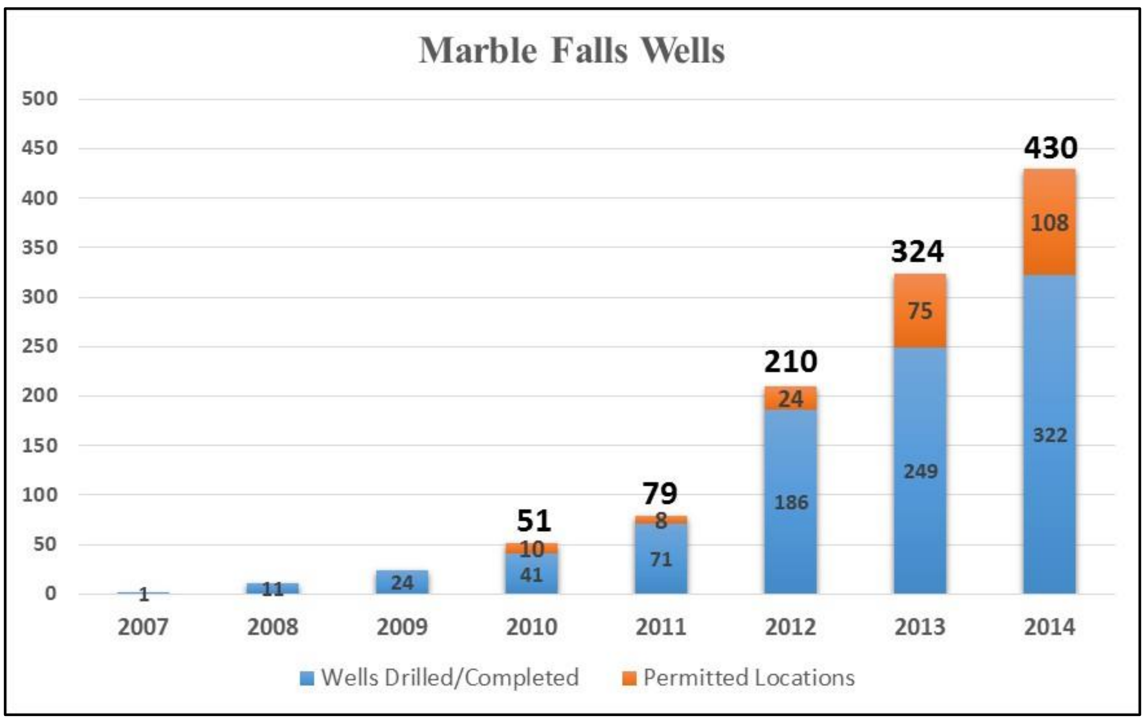



Figure 1-2. Histogram of Marble Falls wells that have been drilled and completed (blue) or permitted (orange) in Jack and Palo Pinto counties over the last 8 years. Data taken from Trey *et al.* (2014) and Craig *et al.* (2014).

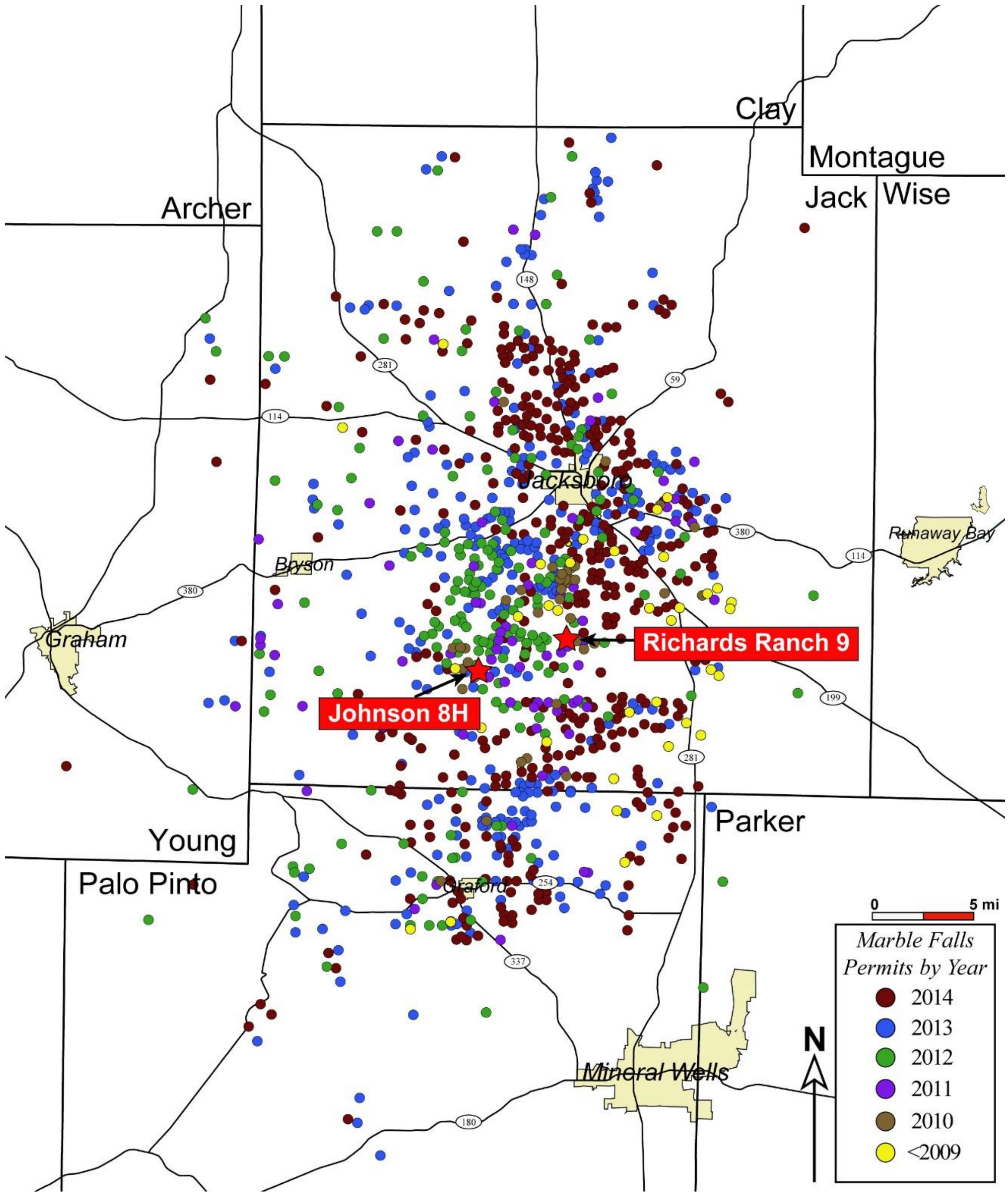



Figure 1-3. Map of northern Palo Pinto and Jack counties displaying permitted locations for the Marble Falls Formation over the last 5 to 7 years and the location of key discovery wells shown in red.

*Drilling and Completion*

The Marble Falls Formation in Jack and Palo Pinto counties is a dense, spiculitic limestone that contains an abundance of diagenetic silica and minor amounts of pyrite and glauconite that was observed in whole cores, photomicrographs, and in drill cuttings. The top of the Marble Falls Formation in this area is easily recognized by drillers and mud loggers from the sudden drop in the rate of penetration (ROP) because it is a much denser rock compared to the softer and less consolidated shales and conglomerates lying above. The slower drilling rate is generally consistent throughout the Marble Falls section and the highly siliceous nature of the Marble Falls Formation can lead to premature wear of the drill bit. It is also common to lose mud circulation while drilling through the Marble Falls and this can generally be anticipated directly after an increase in ROP. The increase in ROP is typically a warning sign that indicates a highly permeable fractured zone was encountered and will begin taking on large amounts of mud (Stearns & Friedman, 1972). Such loss of circulation through the Marble Falls Formation has been documented by industry geologists (Flippin, 1982), and the highly fractured nature of the reservoir has also been reported by a number of previous workers (Martin, 1982; Turney, 1982; Jackson, 1980). The advanced technology of using micro-resistivity to record a high-resolution electrical “image” of the wellbore has become a critical part of evaluating this reservoir. These image logs are used to identify highly fractured intervals within the Marble Falls Formation that are the primary targets for completion.

Mud logging has proven to be less valuable for evaluating this sequence of the Marble Falls Formation because there are typically no gas shows or any type of fluorescence indicating a show of oil. However, the current Marble Falls play is positioned in a prolific part of the FWB with multiple areas of potentially stacked pay, and it is useful to have a mud logger on-site to monitor gas and examine drill cuttings to better evaluate these potential hydrocarbon-bearing zones. The dense drilling in Jack and Palo Pinto counties over the last few years has allowed operators to better understand these reservoirs lying stratigraphically above and below the Marble Falls and potentially discover new or by-passed fields. The formations that are historically known to yield hydrocarbons in the study area include the Strawn sands, Caddo limestone, Davis sands, Bend conglomerate, an erosional “Marble Falls” conglomerate, Barnett Formation, Chappel limestone, and carbonates of the Ellenburger Group. Conventional high porosity stratigraphic traps have also been exploited in the spiculite sequence of the Marble Falls Formation, but the reservoir across most of the study area is characterized by tight, low-porosity rock that requires the use of a high-rate, slick-water hydraulic fracture treatment to produce commercial quantities of hydrocarbons. The hydraulic fractures create a flow path to the wellbore by connecting the network of naturally occurring macro- to micro-scale lithology-bound fractures identified in conventional whole cores, image logs, and photomicrographs. Hydraulic fracture treatments constitute a significant portion of the overall well cost (> 2/3) and developing a better understanding of the distribution of reservoir lithofacies and stratigraphic compartmentalization is critical in terms of economics because this knowledge can be used to identify the number of completion stages necessary to adequately stimulate the reservoir.

## Previous Work

The erosional remnants of exposed Carboniferous strata along the outer edges of the Llano Uplift have been studied in great detail over the last century, and due to the complexity of the Marble Falls Formation in outcrop and the subsurface it has been the focal point of these studies. The Marble Falls was first named by Hill (1889) for the lowermost limestone unit of the exposed Carboniferous rocks near the town of Marble Falls, Texas (Figure 1-4). In 1890, the first annual report of the Geological Survey of Texas was published with descriptions of the Carboniferous strata and "Bend Series" in central Texas by Dumble (1890), Cummins (1890), Tarr (1890), and Comstock (1890). A number of studies by Udden (1921; see also Udden *et al*., 1916; Waite & Udden, 1919) included some of the first descriptions of the "Bend Series" in the subsurface as it relates to the development of oil and gas. Udden and Waite (1927) were also among the first to note the abundance of sponge spicules in the Marble Falls Formation in thin sections from outcrop and drill cuttings where they occasionally called it "Spicule Rock". Some of the most comprehensive work on the Lower Pennsylvanian stratigraphy and nomenclature in North-Central Texas were presented by Plummer (1919, 1945, 1947a, 1947b, 1950; see also Plummer & Moore, 1921; Moore & Plummer, 1922; Plummer & Scott, 1937), and included further subdivisions of the upper member of the Marble Falls Formation that were never mapped (in publication) and therefore never widely accepted. Cheney (1929a, 1929b, 1936, 1940, 1943, 1947; see also Cheney *et al.* 1945) presented a detailed synthesis of the regional correlations and stratigraphic classifications of the Pennsylvanian rocks across central Texas and also contributed observations on the major structural features and tectonic history of the Fort Worth Basin (Cheney, 1934; Cheney, 1938; Cheney & Goss, 1952).

In 1957, W.C. Bell led a joint field trip by the Abilene and Fort Worth Geological Societies to study the Lower Pennsylvanian rocks in outcrop along the northeast and eastern sides of the Llano Uplift, and in proceedings of the field trip he notes that the Marble Falls should informally be separated into a lower, middle, and upper member based on lithological and petrographic properties. During the same year, a group of graduate students working on their research at the University of Texas at Austin under the supervision of W.C. Bell began an extensive investigation of the Carboniferous strata around the Llano Uplift to better understand the contributions made by earlier workers (Table 1.1). This collection of work provided more detailed insights into the stratigraphy of the Carboniferous strata, but most of these studies were confined to localized areas and no attempt was made to connect the works into a regional study.

A number of these students went on to publish some of their work on the Marble Falls Formation including Freeman, Namy, Kier, and Wiggins. Freeman (1964) discusses algal limestones within the Marble Falls Formation specifically the *Donezella* and *Komia* limestone. Namy (1969, 1974a, b) discussed the depositional cycle of the Marble Falls Formation and presented evidence of diagenetic chert development at the top of the lower member following an extensive period of subaerial exposure. Kier (1972, 1980; see also Kier *et al*., 1979) also studied the depositional environment and facies patterns of the Marble Falls Formation, and compared it to a “Bahamian-like carbonate platform”. A geochemical study relating isotopic signatures to deposition and diagenesis was prepared by Wiggins (1986) after working on his dissertation over the depositional environment and microspar development of the Marble Falls limestone (Wiggins, 1982). Other publications by students working on the Marble Falls Formation include a fusulinid study by King (1959) on the type Marble Falls limestone section, a study of carbonate petrography and depositional history by Johnson (1983), and a biostratigraphic study by Dihrberg (1988a, b). McCrary (2003) is one of the only studies concentrating on sequence stratigraphy of the Marble Falls Formation and his work was based on outcrops along the southeast edge of the Llano Uplift near Pedernales Falls State Park (Figure 1-4).

The Marble Falls Formation contains an assortment of fossils used in biostratigraphic studies but foraminifera are the most abundant and commonly used index fossils for dating the boundaries within the Marble Falls Formation. Some of the first comprehensive work on fusulinids within the Marble Falls were presented by Thompson (1942, 1944, and 1947), and due to the abundance of the genus *Millerella* in Morrowan age rocks and lack of other genera in formations from Texas, Kansas, Arkansas, Oklahoma, and New Mexico, he designated the Morrowan series as the "Zone of *Millerella*." Spivey and Roberts (1947) used fusulinid zonation to define the Marble Falls Formation as a correlative unit to the Atoka Formation in Oklahoma and proposed raising the Atoka to series status to include the Marble Falls. More recently, extensive biostratigraphic work was conducted by Manger and Sutherland (1984; see also Sutherland, 1984; Sutherland & Manger, 1983) using conodonts and fusulinids to better evaluate the complicated boundary between the Morrowan and Atokan Series. Groves

(1986, 1991, and 1992) also used fusulinid zonation within the Marble Falls Formation around the Llano Uplift to establish a more definitive boundary between the Morrowan and Atokan Series. Groves recognized the first occurrence of *Profusulinella* was adequate in distinguishing Atokan from Morrowan rocks, but he also proposes the appearance of *Eoschubertella* and/or *Pseudostaffell*a could be used to determine the base of the Atokan Series. These biostratigraphic studies along with various other works have established a Morrowan (lower member) to Atokan (upper member) age for the Marble Falls Formation.

There has been little published on the stratigraphy of the Marble Falls Formation in the subsurface, and most of the available regional studies were compiled at a time when the only available data were from drill cuttings and low-quality electric logs (Cheney, 1940; Turner, 1957; Peppard-Sounders & Associates, 1975). A few recent studies discussed the depositional history and lithofacies distribution of the Marble Falls Formation in the southern part of the Fort Worth Basin. These include the work done by Brown (1983) and Luker (1985) that were based on the examination of the Marble Falls Formation in a set of 31 cores taken by the Houston Oil and Minerals Company (HOM) just north of the Llano Uplift (Figure 1-4). Brown (1983) concentrated on 17 of the cores located in San Saba and McCulloch counties and presented 12 facies deposited across a range of environments. Luker (1985) extended the investigation of the Marble Falls Formation farther north where he examined the remaining 13 cores in Brown and Mills counties and proposed 10 different depositional facies. Erlich and Coleman (2005) compiled data from outcrop and nearby wells that allowed them to establish a back-stepping/platform drowning profile of the upper Marble Falls limestone member. The most recent work was a master's thesis completed by Wood (2013) from the University of Texas at Austin that presented a regional sequence stratigraphic framework and depositional history of the Marble Falls Formation using 21 of the same HOM cores used by Brown (1983) and Luker (1985) (Figure 1-4). Wood (2013) noted the influence of glacio-eustatic sea-level fluctuations and foreland basin tectonics on the deposition of the Marble Falls Formation, and identified 14 inner ramp to basin depositional facies.

In the northern part of the basin, there have been a number of localized subsurface studies on the Marble Falls Formation (Flippin, 1982; Hendricks, 1957; Herkommer & Denke, 1982; Martin, 1982; Plummer & Hornberger, 1935), but most of these were based on individual fields or counties and none of them presented work on a regional scale or made an attempt to correlate beyond the study areas. Farrar (2010) has been the only detailed study on the thick spiculite sequence of the lower Marble Falls present in Jack and Palo Pinto counties, and he used thin section analysis from core data and well log characteristics to provide an overview of the stratigraphy in eastern Jack and western Wise counties (Figure 1-4). He distinguished 6 facies within the Marble Falls from the EOG Resources House No. 1 core in south-central Jack County, and notes that nearly 70% of the lithology in this core is a spiculitic siltstone and the other ~30% is composed dominantly of a mudstone lithology. Ambrose *et al.* (2013) presented preliminary results of facies variability, fracture heterogeneity, and reservoir properties of the Marble Falls "limestone" based on whole-core from the Cobra Oil and Gas Geer No. 1 in south-central Jack County.

Table 1.1. University of Texas Ph.D. dissertations and master's theses on the Marble Falls Formation

| | Author | Year | Title |
|---|---|---|---|
| Masters Theses | Bogardus, E. H. | 1957 | Lower Pennsylvanian of the Richland Springs area, San Saba County, Texas |
| | Defandorf, M. | 1960 | Paleontology and petrography of Carboniferous strata in the Sloan area, San Saba County, Texas |
| | Gries, R. R. | 1970 | Carboniferous biostratigraphy, western San Saba County, Texas |
| | Kuich, N. F. | 1964 | Carboniferous stratigraphy of the Sloan area, San Saba County, Texas |
| | McKinney, W. N. | 1963 | Carboniferous stratigraphy of the San Saba area, San Saba County, Texas |
| | Oden, J. W. | 1958 | Carboniferous stratigraphy of the Leonard Ranch Area, San Saba County, Texas |
| | Pickens, W. R. | 1959 | Carboniferous stratigraphy of the Jackson Ranch Area, Lampasas County, Texas |
| | Rose, P. R. | 1959 | Carboniferous stratigraphy of the Hall Area, San Saba County, Texas |
| | Schake, W. E. | 1961 | Carboniferous stratigraphy of the Wallace Creek area, San Saba County, Texas |
| | Stitt, J. H. | 1964 | Carboniferous stratigraphy of the Bend Area, San Saba County, Texas |
| Ph. D. Dissertations | Freeman, T. | 1962 | Carboniferous stratigraphy of the Brady area, McCulloch and San Saba Counties, Texas |
| | Kier, R. S. | 1972 | Carboniferous stratigraphy of Eastern San Saba County and Western Lampasas County, Texas |
| | Namy, J. N. | 1969 | Stratigraphy of the Marble Falls group, southeast Burnet County, Texas |
| | Turner, G. L. | 1970 | Carboniferous stratigraphy of western San Saba County, Texas |
| | Winston, D. | 1963 | Stratigraphy and carbonate petrology of the Marble Falls Formation, Mason and Kimble Counties, Texas |
| | Zachry, D. L. | 1969 | Carboniferous stratigraphy of the Chappel area, San Saba County, Texas |

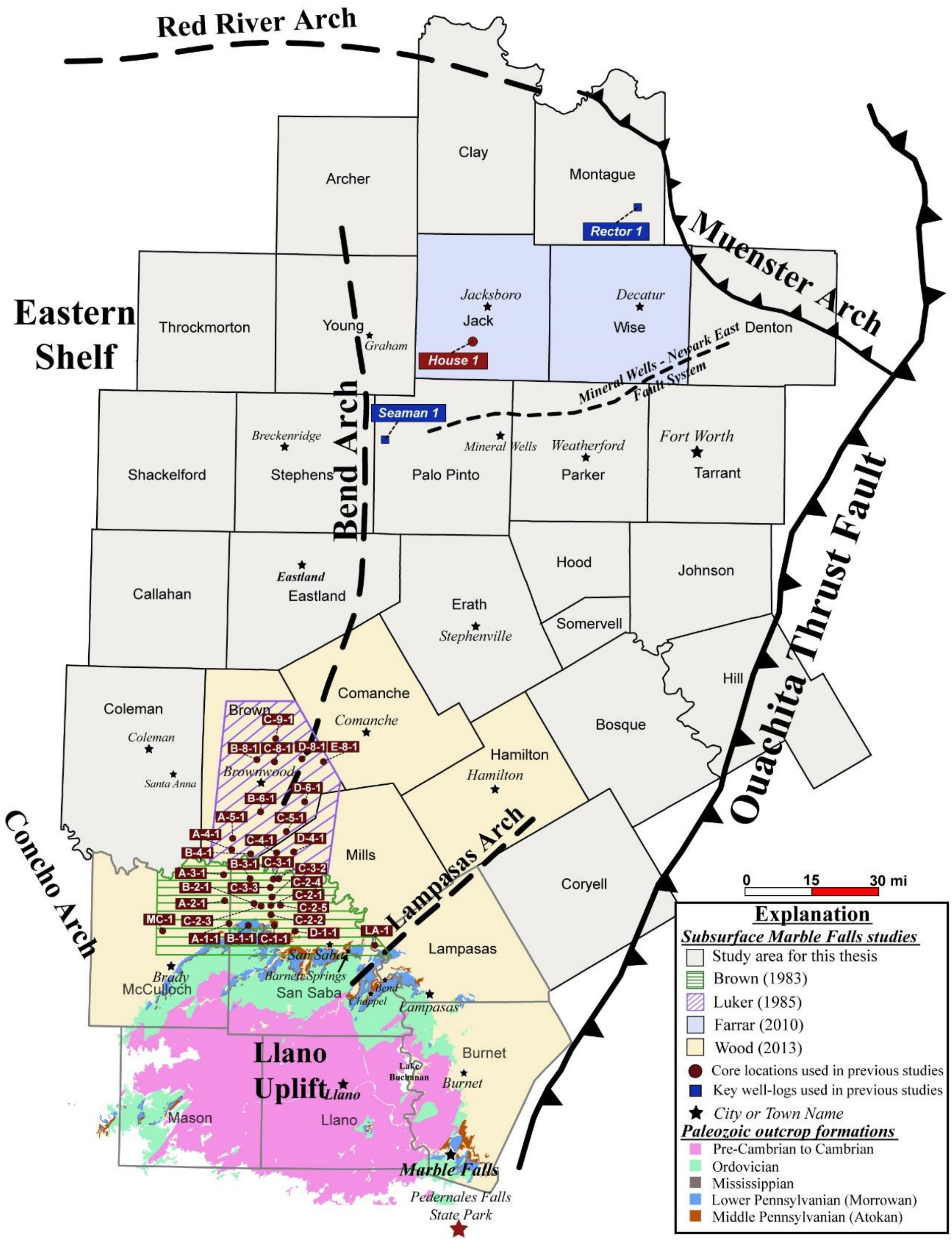



Figure 1-4. Map of previous subsurface studies with core locations and key wells used in studies.

Chapter 2

# Methodology

## Whole Cores

There have been three conventional whole cores taken through the lower Marble Falls in Jack County, but the Kaler Energy Hoefle No. 1H core was unavailable and the EOG Resources House No. 1 core was available for viewing only. However, data from a core taken by Cobra Oil and Gas in the Geer No. 1 well located in south-central Jack County and a core taken through the lower section of the lower Marble Falls in the DTE Gas Resources Walker Ranch No. 1 in Bosque County were both available for this study.

The House No. 1 core was taken from a measured depth of 4,932 to 5,339 feet and consists of 279 feet of core through the lower portion of the Bend Group, the entire lower Marble Falls, and the top section of the Comyn limestone (Farrar, 2010). The Geer No. 1 core was taken from a measured depth of 4,825 to 4,962 feet and includes the Marble Falls "erosional conglomerate" and only the upper half of the lower Marble Falls. Access was granted by Cobra Oil and Gas to view the Geer No. 1 core stored at the Bureau of Economic Geology Core Research Center in Austin, Texas, and EOG Resources granted permission to view the House No. 1 core stored at the Texas Christian University Core Storage Facility in Fort Worth, Texas. Both of these cores were examined with a 10x magnification hand lens, a standard binocular microscope, and an ultraviolet (UV) light box to observe any type of oil fluorescence. The objective of viewing these cores was to compare the different lithofacies, parasequences, and parasequence boundaries within the lower Marble Falls to that previously determined by wireline log responses. For a more detailed evaluation of these cores the reader is referred to Farrar (2010) for the House No. 1, and Ambrose *et al*. (2013) for the Geer No. 1. Data from the Geer No. 1 core analysis by Ambrose *et al.* (2013) was made available to the author because the well was acquired from Cobra Oil and Gas by Newark E&P Operating, the author's current employer. The dataset includes 101 plugs taken at one foot intervals throughout the core, XRD analyses, thin sections, and an unpublished fracture study done by W. Ambrose and R. Loucks at the Bureau of Economic Geology. Thin sections were not provided to Newark and therefore were not examined by the author, but the plug data provided valuable insights into the lithological characteristics of the lower Marble Falls and were used in this work.

The Walker Ranch No.1 well in Bosque County was cored from a measured depth of 6,526 to 6,729.80 feet and includes the lower section of the lower Marble Falls and the entire Barnett Formation. A comprehensive tight-rock analysis (TRA) and petrologic evaluation of the core was conducted by TerraTek (now Schlumberger) and included five thin sections from the Marble Falls Formation. Each thin section was examined under plane- and cross-polarized light, and the results from the petrologic evaluation of these samples are used in this work. The open-hole wireline logs were also used to compare log response patterns and lithological characteristics of the lower Marble Falls in this core along the eastern edge of the basin to the well cored in Jack County and the Houston Oil and Minerals Company cores north of the Llano Uplift.

## Rotary Side-Wall Cores and Petrography

Obtaining a conventional whole core is time and labor intensive and cost a significant amount of money, so rotary side-wall cores offer a quicker, easier, and less expensive alternative to retrieve core for analyses. It is important to note that side-wall cores are only a small piece of the rock and offer significantly less resolution compared to a conventional whole core. A rotary side-wall coring tool is capable of collecting multiple samples in a single logging run and consists of a small core bit that drills sideways into the formation, removes a sample approximately 1 inch in diameter and 2 inches in length, and stores it in a tube or barrel on the main tool string to be retrieved at the surface. The tool was designed for taking samples after a well has been drilled and an open-hole wire-line log has been run so the logs can be thoroughly reviewed before selecting the exact depths at which each core sample is to be taken. Newark E&P Operating obtained numerous side-wall cores (Table 2.1) from various formations in four wells scattered across northern Palo Pinto and Jack counties. Fortunately for this study, these four well locations were placed in areas that represent a range of depositional environments within the Marble Falls Formation and the depth of each core sample was selected to represent a range of lithologies within the Marble Falls and other formations.

Weatherford Laboratories performed porosity and permeability (P&P) measurements on the cores and prepared and examined 82 thin sections. Porosity was measured under a net confining stress (NCS) of ~1400 psi and permeability was measured using air with a Klinkenberg-corrected measurement also provided. The porosity and permeability (P&P) measurements were less useful for this study because the lower Marble Falls is such a dense rock and contains extremely low primary porosity and permeability. Thin sections were cut and prepared on standard size 27 mm x 46 mm slides and were impregnated with fluorescent-spiked, blue-dyed epoxy and dual carbonate staining. Each thin section was examined with a high-resolution digital petrographic microscope by Weatherford Laboratories, and they provided thorough descriptions on lithology, texture, grains/allochems, matrix, cements/replacement minerals, and pore system. Raw images and plates of each thin section were also provided in 50x and 200x magnification under plane-polarized light. Of the 82 thin sections prepared and examined by Weatherford Laboratories, 55 were thoroughly examined by the author with a high-resolution petrographic microscope under plain- and cross-polarized light to confirm and build upon the previous analyses, including 29 from the lower Marble Falls, 2 from the Forestburg limestone, 8 from the Comyn limestone, 2 from the upper Barnett Shale, 10 from the lower Barnett Shale, and 4 from the Chappel limestone (Table 2.1).

Table 2.1 Side-wall core sample inventory

| Well | Sample Number | Depth (ft) | Formation | Core Retrieval | P & P | Thin Section |
|---|---|---|---|---|---|---|
| Deck No. 1 | D-1 | 4407 | Marble Falls | Good | X | X |
| | D-2 | 4415 | Marble Falls | Fragmented | X | X |
| | D-3 | 4435 | Marble Falls | Good | X | X |
| | D-4 | 4465 | Marble Falls | Good | X | X |
| | D-5 | 4482 | Marble Falls | Good | X | X |
| | D-6 | 4496 | Marble Falls | Good | X | X |
| | D-7 | 4514 | Comyn | Good | X | X |
| | D-8 | 4546 | Comyn | Good | X | X |
| | D-9 | 4620 | Comyn | Good | X | X |
| | D-10 | 4655 | Lower Barnett | Good | | X |
| | D-11 | 4671 | Lower Barnett | Good | | X |
| | D-12 | 4703 | Chappel | Good | X | X |
| | D-13 | 4731 | Chappel | Good | X | X |
| Harnett No. 1 | H-1 | 4394 | Marble Falls | Good | X | X |
| | H-2 | 4412 | Marble Falls | Good | X | X |
| | H-3 | 4428 | Marble Falls | Good | X | X |
| | H-4 | 4458 | Marble Falls | Good | X | X |
| | H-5 | 4474 | Marble Falls | Good | X | X |
| | H-6 | 4506 | Marble Falls | Good | X | X |
| | H-7 | 4538 | Marble Falls | Good | X | X |
| | H-8 | 4568 | Marble Falls | Good | X | X |
| | H-9 | 4604 | Comyn | Good | X | X |
| | H-10 | 4626 | Comyn | Good | X | X |
| | H-11 | 4645 | Comyn | Good | X | X |
| | H-12 | 4720 | Comyn | Good | X | X |
| | H-13 | 4769 | Lower Barnett | Good | | X |
| | H-14 | 4799 | Lower Barnett | Good | | X |
| | H-15 | 4848 | Chappel | Good | X | X |
| | H-16 | 4878 | Chappel | Good | X | X |

Table 2.1 - *Continued*

| Well | Sample Number | Depth (ft) | Formation | Core Retrieval | P & P | Thin Section |
|---|---|---|---|---|---|---|
| Kilgust No. 1 | K-1 | 4669 | Marble Falls | Good | X | X |
| | K-2 | 4702 | Marble Falls | Good | X | X |
| | K-3 | 4742 | Marble Falls | Good | X | X |
| | K-4 | 4765 | Marble Falls | Good | X | X |
| | K-5 | 4785 | Marble Falls | Good | X | X |
| | K-6 | 4814 | Marble Falls | Good | X | X |
| | K-7 | 4834 | Marble Falls | Good | X | X |
| | K-8 | 4854 | Marble Falls | Good | X | X |
| | K-9 | 4895 | Comyn | Good | X | X |
| | K-10 | 4922 | Lower Barnett | Good | | X |
| | K-11 | 4949 | Lower Barnett | Good | | X |
| | K-12 | 4972 | Lower Barnett | Good | | X |
| Stewart No. 1 | S-1 | 5606 | Marble Falls | Good | X | X |
| | S-2 | 5646 | Marble Falls | Good | X | X |
| | S-3 | 5686 | Marble Falls | Good | X | X |
| | S-4 | 5740 | Marble Falls | Good | X | X |
| | S-5 | 5754 | Marble Falls | Good | X | X |
| | S-6 | 5777 | Marble Falls | Good | X | X |
| | S-7 | 5796 | Marble Falls | Good | X | X |
| | S-8 | 5815 | Upper Barnett | Good | | X |
| | S-9 | 5836 | Upper Barnett | Good | | X |
| | S-10 | 5960 | Forestburg | Good | X | X |
| | S-11 | 6000 | Forestburg | Good | X | X |
| | S-12 | 6038 | Lower Barnett | Good | | X |
| | S-13 | 6060 | Lower Barnett | Good | | X |
| | S-14 | 6132 | Lower Barnett | Good | | X |

Petrophysical Analysis and Open-Hole Well Log Properties

Stimulation Petrophysics Consulting, LLC used more than 800 digital vector well logs from Jack, Palo Pinto, and surrounding counties to calculate petrophyiscal properties for the Marble Falls Formation, and to create a resource evaluation petrophysical log for estimating rock properties, including brittleness/fracability, mineralogy/lithology, volume of shale, porosity, permeability, volumetrics, oil-, gas-, and water-saturation, etc. The calculations and methods used to create this petrophyiscal model of the lower Marble Falls are complex and beyond the scope of this study. The petrophysical logs were used in conjunction with the available core data to determine log curve values for each lithofacies and to determine the lithofacies that contain the best reservoir quality. This produced an accurate calibration of the open-hole logs with the core data and provided a more accurate estimate of mineralogical and lithological characteristics of the Marble Falls Formation using thousands of publicly available raster logs and hundreds of digital vector logs.

Where available, a standard logging suite was most commonly used for correlating the formations tops, defining parasequences, and identifying the various lithofacies throughout the study area. This log suite consisted of a natural gamma ray (GR), spontaneous potential (SP), resistivity (ILD), neutron-porosity (NPHI), density-porosity (DPHI), and occasionally the photoelectric effect (PE) was available. The lithological/mineralogical determinations were based on accepted log values for limestones, sands, and shales from literature (Asquith and Krygowski, 2004).

The GR log measures the natural radioactivity of a formation in API units, and because shale/mudstone typically contain abundant radioactive elements, this curve was used to distinguish the higher GR readings of the mudstone lithofacies from the lower GR readings of the limestone lithofacies and intermediate readings of the spiculite lithofacies. The limestone lithofacies has consistent GR readings around 30 API, the spiculite lithofacies typically has sporadic GR readings that are less than 90 API, and anything greater than 90 API usually contains a higher percentage of radioactive organic material and/or detrital clays and is considered a mudstone. The GR curve was also used to distinguish the bounding flooding surfaces of parasequences and the maximum flooding surfaces (MFS) of several sequences that were identified.

SP records the potential difference between a moving electrode on the logging tool and a fixed electrode at the surface. This measurement is unreliable for detailed correlation of well logs because of the highly variable signal to noise ratio and subjectivity in defining operational parameters like shifeeting of the shale baseline. However, SP can be beneficial when evaluating the Marble Falls Formation because of its ability to distinguish permeable from impermeable zones and the more highly fractured intervals have higher permeabilities that can be distinguished by a negative SP deflection away from the shale baseline.

Resistivity, measured in ohm-m, is typically used to differentiate hydrocarbon-bearing and water-bearing zones in porous rock (Asquith and Krygowski, 2004). However, with unconventional reservoirs that are composed of a tight rock with low porosity and permeability like the Marble Falls, these distinctions are not easily determined and resistivity is not as valuable for reservoir evaluation. In this study, resistivity was most commonly used in conjunction with GR to differentiate the mudstone lithofacies from the limestone and spiculite lithofacies. The mudstone lithofacies have true formation resistivity readings less than 20 ohm-m, the spiculite lithofacies have a wide range of readings from 20 to 200 ohm-m, and the limestone lithofacies have readings of 30 to 50 ohm-m.

The porosity logs (DPHI, NPHI, and PE) are used for distinguishing lithologies and evaluating reservoir potential within the Marble Falls Formation. NPHI measures hydrogen concentrations in the formation to infer pore volume of the rock, and RHOB measures the density of the formation and fluid. The RHOB is also used to derive the DPHI curve and PE curve that are both sensitive to changes in bulk mineralogy and are used to determine lithology (Asquith and Krygowski, 2004). The limestone lithofacies is characterized by nearly equal values of NPHI and DPHI, RHOB values of 2.66 to 2.72 g/cm$^3$, and a PE values of 4 to 5 b/e. The spiculite lithofacies is typically characterized by a separation of the porosity curves with DPHI reading slightly higher than NPHI. This type of separation in porosity curves is known as cross-over or the gas-effect as it can represent gas-filled pore space in the rock (Asquith and Krygowski, 2004). The magnitude of cross-over is dependent upon the tools being used and the amount of gas saturation present in the formation. The spiculite lithofacies typically displays 2 to 8 percent porosity on logs, RHOB of 2.5 to 2.65 g/cm$^3$, and a sporadic PE curve of 2.5 to 4 b/e. The mudstone lithofacies is characterized by a large separation between DPHI and NPHI curves and PE values of 3 to 3.5 b/e.

## Micro-Resistivity Image Log Analysis

The most effective way to identify and evaluate small-scale sedimentary features and lithology-bound fractures (LBF) within the Marble Falls Formation in the subsurface is with high-resolution micro-resistivity image logs. These logs are expensive to acquire and there is generally a greater risk of logging problems associated with running these tools. The tool consists of 4 to 8 pads that are designed to cover as much as the wellbore as possible and each pad contains an array of electrodes that have a depth of investigation of approximately one inch. The micro-resistivity readings are processed into a 360-degree pseudo-image of the wellbore that is split along true north and flattened into a two-dimensional view with darker colors representing more conductive rock (mudstone/shales) and lighter colors representing more resistive rock (limestone/sandstones) (Figure 2-1). There are normally two separate images presented: a static view on the right showing one contrast throughout the wellbore; and a dynamic view on the left showing variable contrast (Figure 2-1). The dynamic image was used most often by the author to identify fractures, faults, bed boundaries, unconformities, and small-scale sedimentary features because of its enhanced quality and resolution (Figure 2-1). Most service companies report spatial and vertical resolution up to 0.2 inches, caliper accuracy of +/- 0.2 inches, deviation accuracy of +/- 0.1 degrees and azimuth accuracy of +/- 2 degrees. However, the quality of the image is dependent upon a number of operational parameters and borehole conditions.

Eighty-one vertical and seven horizontal micro-resistivity image logs from various wells scattered across Jack and Palo counties were available for this study. Each well was specifically chosen to provide enough coverage across the study area to adequately characterize the fracture network of the lower Marble Falls and the *in situ* stress field in this part of the basin. The high-resolution micro-resistivity image logs were used in combination with conventional open-hole wireline logs and petrophysical data to identify small-scale lithology-bound fractures (LBF), unconformities, flooding surfaces, rock fabrics, carbonate shoaling, thin bedding, concretions, pyrite, brecciated intervals, debris flows, and lithofacies within the lower Marble Falls.

Interpretation of micro-resistivity image logs is highly subjective and requires extensive experience in geology and understanding the functionality of the tool. Therefore, most of the interpretations for this study were conducted by an expert analyst, Mike Grace (Grace, 2015) and included complete structural, stratigraphic, and fracture analyses of the Marble Falls and Barnett formations throughout the study area. Valuable information on the depositional environments, structural influences (local and regional tectonics), and characteristics of fractures were provided and used to further evaluate the Marble Falls Formation.

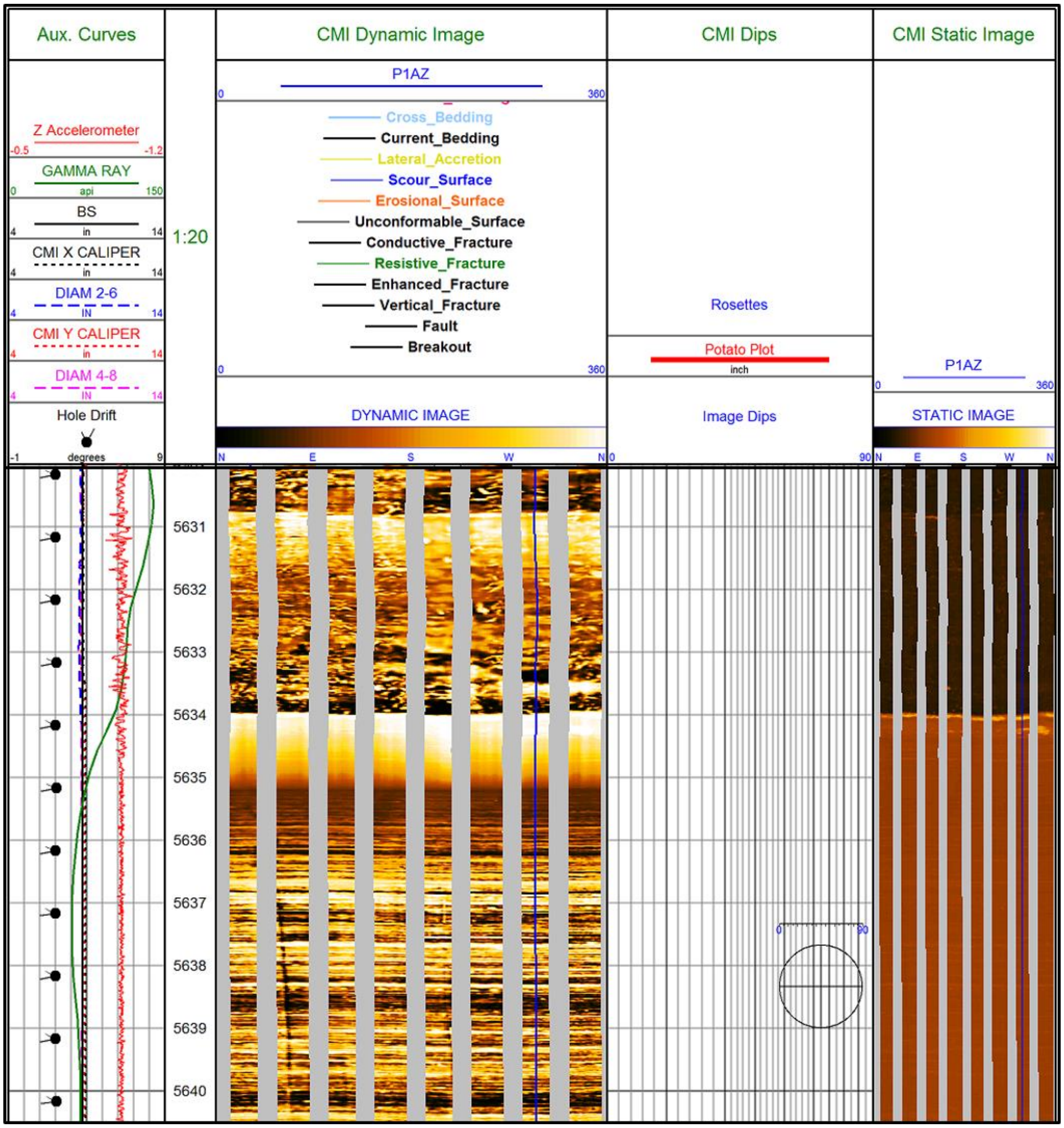



Figure 2-1. Typical image log data displayed with the dynamic view on the left and the static image on the right. A 360-degree flattened 2-D view of the wellbore is presented with north (N), south (S), east (E) and west (W) labeled at the top. The dark blue line is tracking the orientation of pad 1 and the far left track is tracking hole caliper size and hole drifeet; the GR is also displayed for the use of correlating. The track between the two images is displaying interpreted dips and a potato plot showing borehole washout or under-caliper hole size.

## Well Log Correlation and Mapping

Over the course of the last three years, an extensive regional correlation project was undertaken to better understand the stratigraphy of the Marble Falls Formation and the entire Carboniferous section throughout the FWB. All of the well and production data was downloaded from IHS and the majority of the raster well logs came from TGS. More than 250 modern raster logs with a typical triple combo suite of curves clearly displayed through the entire Marble Falls section were selected for digitizing to provide better coverage of digital vector logs over the study area for the purpose of calculating and mapping petrophysical parameters. Numerous map layers were generated from publicly available well log data, completion data, and well production data to symbolize specified well criteria including picked formation tops, cumulative oil and gas production from defined zones, specific curves or logs available, or other manually defined attributes.

Through extensive correlation of 30,000+ wireline logs across the FWB a group of approximately 5,500 well logs were selected that contained a modern vintage of log curves including a GR, bulk density, porosity, and/or resistivity curves through at least part of the Marble Falls Formation. Of these ~5,500 modern well logs, approximately 400 were selected as key wells that were included in regional cross-sections, or represent "type logs" that best represent the stratigraphy in that specific area of the basin and served as key data points for the regional correlation of the Carboniferous strata (Figure 2-2). Due to sparse drilling in the southern part of the FWB, availability of well logs was limited throughout parts of Brown, Comanche, Erath, Hood, Somervell, Bosque, Hill, Hamilton, Mills, Coryell, Lampasas, Burnet, San Saba, and McCulloch counties.

However, Brown (1983), Luker (1985), and Wood (2013) analyzed thirty cores taken through part of the Smithwick Formation, upper and lower members of the Marble Falls Formation, and Barnett Formation by Houston Oil and Minerals Company (HOM) in San Saba, Mills, and Brown counties. The formation tops those authors determined from the cores were incorporated into this study to help correlate the Marble Falls and Barnett formations with the limited offset wells that had publicly available wireline logs (Table 2.2). The cores from a number of these wells only cover a portion of the Marble Falls Formation and therefore a complete section was not available for examination by Brown (1985), Luker (1983), and Wood (2013). The intervals only partially covered by a core are represented with an asterisk in Table 2.2 and could not be used in the regional correlation because the top of the formation was not defined. The majority of the cores only penetrated the top few feet of the Barnett Formation and, although there are asterisks representing an incomplete cored interval, the formation tops were defined and could be used in the regional correlation of the Barnett Formation. Where the complete section of the Marble Falls Formation was cored and either the upper or lower member was absent due to erosion or non-deposition, an “A” represents the absence of this member in that particular area.

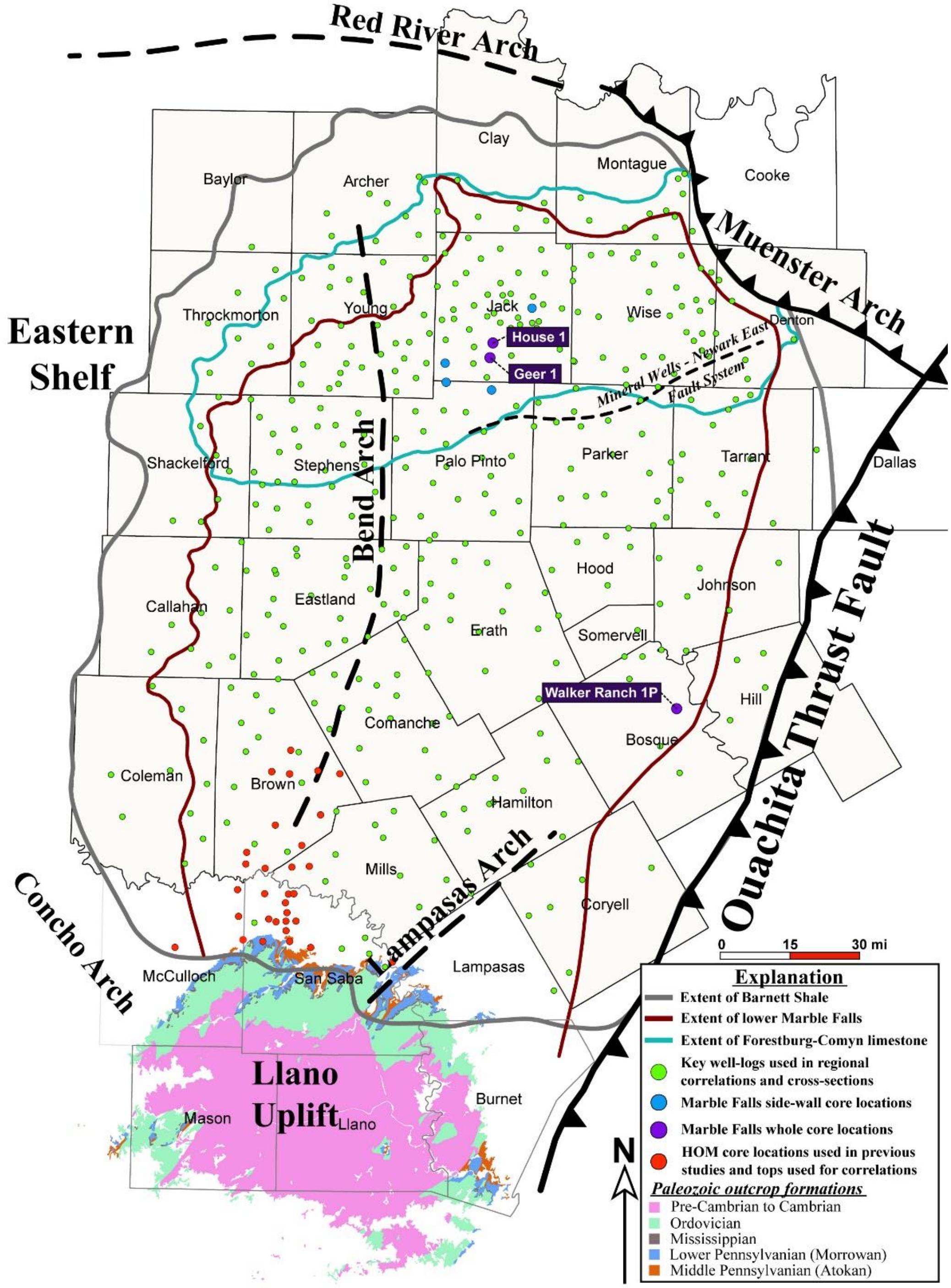



Figure 2-2. Regional correlation map with key wells used in cross-sections shown in light green, lower Marble Falls whole cores shown in purple, side-wall core locations shown in blue, and Houston Oil and Minerals Company core locations used in previous studies shown in red. The Barnett Shale subcrop is shown in grey, the lower Marble Falls subcrop is in red, and the Forestburg-Comyn limestone subcrop is in turquoise.

Table 2.2. Formation tops determined through various studies on the Houston Oil and Minerals Company whole cores

| **API #** | **Well Name & #** | **County** | **Upper Marble Falls Tops (ft-MD)** | | | **Lower Marble Falls Tops (ft-MD)** | | | **Barnett Formation Tops (ft-MD)** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | *Brown (1983)* | *Luker (1985)* | *Wood (2013)* | *Brown (1983)* | *Luker (1985)* | *Wood (2013)* | *Brown (1983)* | *Luker (1985)* | *Wood (2013)* |
| 049-31646 | Stevens, M.G. # **B-8-1** | Brown | | 1798.3 | 1798 | | 1941 | 1982 | | 2043.1* | 2042* |
| 049-31716 | Lee Sam # **C-5-1** | Brown | | 1146.1* | | | 1161.2 | | | 1233.4* | |
| 049-31744 | Carruth R. # **D-8-1** | Brown | | 2172* | | | 2204* | | | | |
| 049-31745 | Wiley Murray # **A-5-1** | Brown | | 1189.2* | | | 1240 | | | 1273.9* | |
| 049-31746 | Cope, T.M. # **B-6-1** | Brown | | 1518.7* | | | 1526.7 | 1518* | | 1578.6* | 1579* |
| 049-31769 | Potter, J.A. # **C-9-1** | Brown | | 2072.6 | 2073 | | 2278.8 | 2282 | | 2344.5* | 2350* |
| 049-31785 | Petty, N. # **D-6-1** | Brown | | 1602.7 | | | 1647.5 | 1595* | | 1672.3* | 1674* |
| 049-31786 | Posey, E. # **B-4-1** | Brown | | 975 | 960 | | 1002.4 | 1008 | | 1077.2* | 1075* |
| 049-31787 | Old Levi # **C-8-1** | Brown | | 1743.6* | 1745* | | 1811.2 | 1813 | | 1881* | 1920* |
| 049-31813 | Mullis, J.D. # **A-4-1** | Brown | | 1039.8 | 1040 | | 1075.2 | 1081 | | 1131.6* | 1132* |
| 049-31815 | Godfrey, J.D. # **E-8-1** | Brown | | 2181.4 | 2182 | | 2199.9 | ~2215 | | 2354.1* | 2355* |
| 281-30192 | Hardy, I. # **LA-1** | Lampasas | 410* | | 410* | 486 | | 523 | 617* | | 617* |
| 307-30421 | Eckert, E. # **A-3-1** | McCulloch | 824 | | | 910 | | | 977.5* | | |
| 307-30429 | Neal, R.V. # **A-1-1** | McCulloch | | | 290 | | | | | | 385* |
| 307-30447 | Scoggins, C.D. # **A-2-1** | McCulloch | 634 | | 632 | 689.8 | | 707 | 749.3* | | 753* |
| 307-30487 | Johanson, H. # **MC-1** | McCulloch | 963.5 | | 963 | A | | A | 1076 | | 1070* |

*Only part of the interval was cored and the top represents where the core ends

A - interval was absent and not described

Table 2.2 - *Continued*

| **API #** | **Well Name & #** | **County** | **Upper Marble Falls Tops (ft-MD)** | | | **Lower Marble Falls Tops (ft-MD)** | | | **Barnett Formation Tops (ft-MD)** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | *Brown (1983)* | *Luker (1985)* | *Wood (2013)* | *Brown (1983)* | *Luker (1985)* | *Wood (2013)* | *Brown (1983)* | *Luker (1985)* | *Wood (2013)* |
| 333-30194 | Beck, A.J. # **C-4-1** | Mills | | 1066* | | | 1103.5 | 1068* | | 1182.2* | 1182* |
| 333-30195 | John Rasco # **D-4-1** | Mills | | 1253* | | | 1257.5 | | | 1376.2* | |
| 411-30094 | Jordan O.C. # **C-3-1** | San Saba | 633 | | | 646 | | | 730* | | |
| 411-30095 | Roberds Paul # **C-3-2** | San Saba | 602* | | | 610.5 | | | 709* | | |
| 411-30096 | Moore, V.C. # **C-1-1** | San Saba | | | | 83* | | 83* | 173.5* | | 174* |
| 411-30097 | Powell, W. # **B-3-1** | San Saba | | | 698* | 699* | | 710 | 764.8* | | 768* |
| 411-30098 | Bradford Erna # **C-2-1** | San Saba | 568 | | | 605 | | | 695.3* | | |
| 411-30099 | Adams, O.R. # **B-1-1** | San Saba | | | | 49* | | 52* | 90.5* | | 90* |
| 411-30100 | Walker, G.B. # **D-1-1** | San Saba | 1080 | | 1083 | 1138 | | 1165 | 1255.5* | | 1255* |
| 411-30101 | Locker, W.G. # **B-2-1** | San Saba | 443 | | 443 | 491 | | 491 | 556.5* | | 555* |
| 411-30102 | Harlow, W.L. # **C-3-3** | San Saba | 650* | | 650* | 666.5 | | 670 | 749* | | 750* |
| 411-30103 | Edwards, T.B. **C-2-5** | San Saba | | | | 428* | | | 542* | | |
| 411-30104 | Glaze, F.M. # **C-2-3** | San Saba | | | | 270* | | | 309* | | |
| 411-30106 | Smith,W.H. # **C-2-4** | San Saba | | | | 453* | | | 512.5* | | |
| 411-30107 | Adams, G.P # **C-2-2** | San Saba | 455* | | | 465 | | 505* | 532* | | 540* |

*Only part of the interval was cored and the top represents where the core ends

A - interval was absent and not described

Thousands of cross-sections were used to correlate the Paleozoic strata across the FWB to better understand the regional stratigraphy and distribution of lithofacies within the Mississippian and Lower Pennsylvanian section. Unfortunately, only a small number of these cross-sections could be included in this study to effectively represent the variations in regional stratigraphy. The well logs used in each cross-section came from the key wells identified in Figure 2-2. Various cross-section templates were used for identifying and correlating formations, members, sequences, sequence boundaries, parasequences, parasequence boundaries, and lithofacies. The combination of GR, resistivity, and porosity curves were used for the majority of cross-sections presented in this study because they are the most commonly available logs and adequately display lateral and vertical variations of stratigraphic intervals. A number of stratigraphic datums were used in these templates, including the unconformable surface at the top of the lower Marble Falls (Morrowan-Atokan unconformity), the top of the lower Barnett Shale, and the Forestburg-Comyn limestone composite top.

Most of the formations within the FWB, ranging from Ordovician to Middle Pennsylvanian, were identified and correlated throughout the basin and include the following from the deepest stratigraphic interval to the shallowest: Ellenburger Group, Simpson Group, and Viola limestone (Ordovician); Chappel limestone, Chester limestone, lower Barnett Shale, lower Barnett calcareous unit, Forestburg limestone (lower, middle, and upper), Comyn limestone (lower, middle, and upper), and upper Barnett Shale (Mississippian); Marble Falls lower shale, Marble Falls lower limestone, Marble Falls upper shale, Marble Falls upper limestone, Marble Falls calcareous shale, lower Marble Falls (spiculite sequence), upper Marble Falls, lower Smithwick shale, Bend conglomerate, Davis sands/pregnant shale, Caddo limestone, upper Smithwick shale, Strawn Group, and the Palo Pinto limestone (Lower to Middle Pennsylvanian). Various composite tops were generated to simplify mapping efforts and include the Ordovician unconformity surface, top of the lower Barnett Shale, top of the Mississippian limestone, top of the Forestburg-Comyn limestone, and the Morrowan-Atokan unconformity surface separating the lower Marble Falls from the upper Marble Falls and Atoka Group. The log response patterns associated with each formation were obtained from fellow industry colleagues, detailed literature review, and experience with the stratigraphy of the FWB.

A number of regional isopach (thickness) and subsea structure maps were created for each formation and the more relevant intervals to this study were mapped in greater detail with each of the subcrops defined. LMKR's Geographix software was used for all the geological mapping in this study and a minimum curvature gridding algorithm with a convergence of 5% was used for contouring. Various values for smallest feature radius and radius of influence were used depending on the distribution of data available and the final values most applicable for each map were determined through an iterative process. A number of problems were encountered when creating these maps due to such a large data set being used. These included erroneous ground level (GL) elevations that prompted errors in the subsea structure maps and discrepancies in API numbers between the well data and well logs.

# Chapter 3

## Geological Setting

### Tectonic Elements and Structural Evolution

The Fort Worth Basin (FWB) in North-Central Texas is one of several Paleozoic peripheral foreland basins formed by the advancing Ouachita thrust belt (Figure 3-1) (Walper, 1982). It is an asymmetric synclinal feature that extends for over 200 miles from its narrowest width in Burnet County, adjacent to the Llano Uplift, toward the north where it is more than a hundred miles wide in Tarrant County (Turner, 1957). The Llano Uplift is a structural dome of Precambrian crystalline rocks exposed at the surface and acts as the southernmost boundary of the FWB (Pollastro *et al*., 2007; Walker, 1992). This uplifted area has exposed Paleozoic strata along its edges that have provided excellent exposures for studies of the Ellenburger Group, Barnett Formation, Marble Falls Formation, and Smithwick shale. The easternmost limit of the basin is defined by the structurally complex Ouachita orogenic belt with intensely folded and faulted Paleozoic rocks along its front (Flawn *et al*. 1961). The north and northeast boundaries of the FWB are defined by the buried structural highs of the Red River and Muenster Arches, respectively (Turner, 1957). Two of the more significant tectonic features along the western margin of the FWB include the Bend Arch and Concho platform, both of which had significant influence on depositional patterns of carbonate rocks within the Marble Falls Formation and Caddo limestone. The Bend Arch is a broad north-plunging structural forebulge that extends north from the Llano Uplift and formed from stresses caused by the overriding Ouachita fold belt and contemporaneous subsidence of the FWB

(Pollastro *et al*., 2007; Thompson, 1988; Walper, 1982). The Concho platform (i.e. Texas craton, Kier *et al*., 1979; Concho arch, Cheney and Goss, 1952 and Pollastro *et al*., 2007; Texas arch, Flawn *et al.*, 1961; Texas peninsula, Adams, 1954) was at one time a structural high that trend northwest from the Llano Uplift and has been recognized as a remnant of the southern peninsula of the North American Craton that was fairly stable across most of the Paleozoic (Thompson, 1988).

Other notable tectonic features include a series of horsts and grabens near the Llano Uplift that strike parallel to the Ouachita thrust belt (Thompson, 1988) and a number of faulted anticlines trending northeast known as the Lampasas, San Saba, and Cavern arches (Walper, 1982) (Figure 3-1). Thompson (1988) has noted Atokan-age intrabasinal faults that developed in various parts of the basin in response to stresses caused by subsidence of the FWB. Throughout the central part of the basin, these faults strike north-northeast with the downthrown blocks to the southeast and trend parallel to the Ouachita thrust front similar to faults near the Llano Uplift (Thompson, 1988). Most of these faults have been identified using subsea structure maps at the top of the Marble Falls, Barnett, and Ellenburger formations, and were found to extend down into the Ordovician section (Figure 3-2). A prominent structural feature in the northern part of the basin that played a significant role in exploitation of the Barnett Shale is the Mineral Wells-Newark East fault system, which trends northeast-southwest through Denton, Wise, Parker, and Palo Pinto counties (Figure 3-1; Figure 3-2) (Pollastro *et al*., 2003). The origin of this fault system is poorly understood but seismic data indicate it is a basement fault that was reactivated during the Late Paleozoic and has influenced depositional patterns of the Barnett Formation, Marble Falls Formation, and Bend Group (Montgomery *et al*., 2005; Pollastro *et al.*, 2003; Thompson, 1982). Other smaller-scale faults have been identified throughout the southern part of Wise, Jack, and Young counties that trend subparallel to the Mineral Wells-Newark East fault system (Figure 3-2). Most of these faults were defined with a subsea structure map at the top of the lower Marble Falls using high-density well control (Figure 3-2), but a number them have also been confirmed with proprietary seismic data. Other structures include thrusted fault blocks of Ouachita facies over uplifted Atoka deposits along the eastern margin of the basin, and northwest- to west-trending faults near the Muenster Arch that uplifted as much as 5,000 feet of basement rock that was the source for some of the lower Atoka beds (Flawn *et al*., 1961). Other minor faults, folds, fractures, and karst-related features have been documented across the FWB (Montgomery *et al*., 2005).

Prior to the onset of the Ouachita orogeny, most of Texas, including the area now called the Fort Worth Basin, was covered by warm shallow seas in which over 3,000 feet of carbonates accumulated along the Early Paleozoic shelf edge (Walper, 1982). The development of the FWB began during the Late Mississippian as Gondwana collided with Laurentia and formed a convergent plate boundary along the southern margin of North America (Walper, 1982). The orogenic activity continued advancing westward throughout the Late Mississippian and Early Pennsylvanian as the overriding plate formed a subduction complex that was continuously folded and uplifted (Flawn *et al*., 1961). This thrust belt became the driving tectonic force that created the FWB, caused the reactivation and uplift of the bounding Red River and Muenster Arches, and formed a forebulge that become known as the Bend Arch (Walper, 1982). This forebulge became a shelf hinge line dominated by shallow water carbonates of the Marble Falls and Caddo formations, and migrated progressively westward through time until it reached its present-day westernmost limit against the Concho platform (Kier *et al.*, 1979; Walper, 1982).

Thickness trends and variations in facies indicate that the Llano Uplift and Concho arch were a stable southern lobe of the North American Craton that greatly influenced the deposition of the Marble Falls Formation and Caddo limestone throughout the Early Pennsylvanian. The "Texas Craton" or "Texas Arch" (i.e. Concho platform and Llano Uplift) also acted as a firm buttress to the forces of the Ouachita orogeny and greatly influence the shape and geological history of the FWB over time (Flawn *et al.*, 1961). The Llano Uplift has been recognized as an area of uplift and subsidence throughout much of its geological history beginning in the Precambrian, but during the Early Pennsylvanian it was speculated to have been significantly higher than the adjacent FWB (Cheney and Goss, 1952; Thompson, 1988). This uplifted area and the continued westward movement of the Ouachita thrust front caused the basinal axis to shift northwestward adjacent to the Muenster Arch, eventually becoming the deepest part of the basin (Walper, 1982). During the Late Atokan to Early Strawn, subsidence of the FWB ceased but the Ouachita thrust front and Muenster Arch continued to be major sediment sources for prograding Strawn deltas (Walper, 1982). The final tectonic activity in the region during the Paleozoic was a slow regional tilting of the Texas Craton to the west that was the final deformation of the present-day Bend Arch (Walper, 1982).

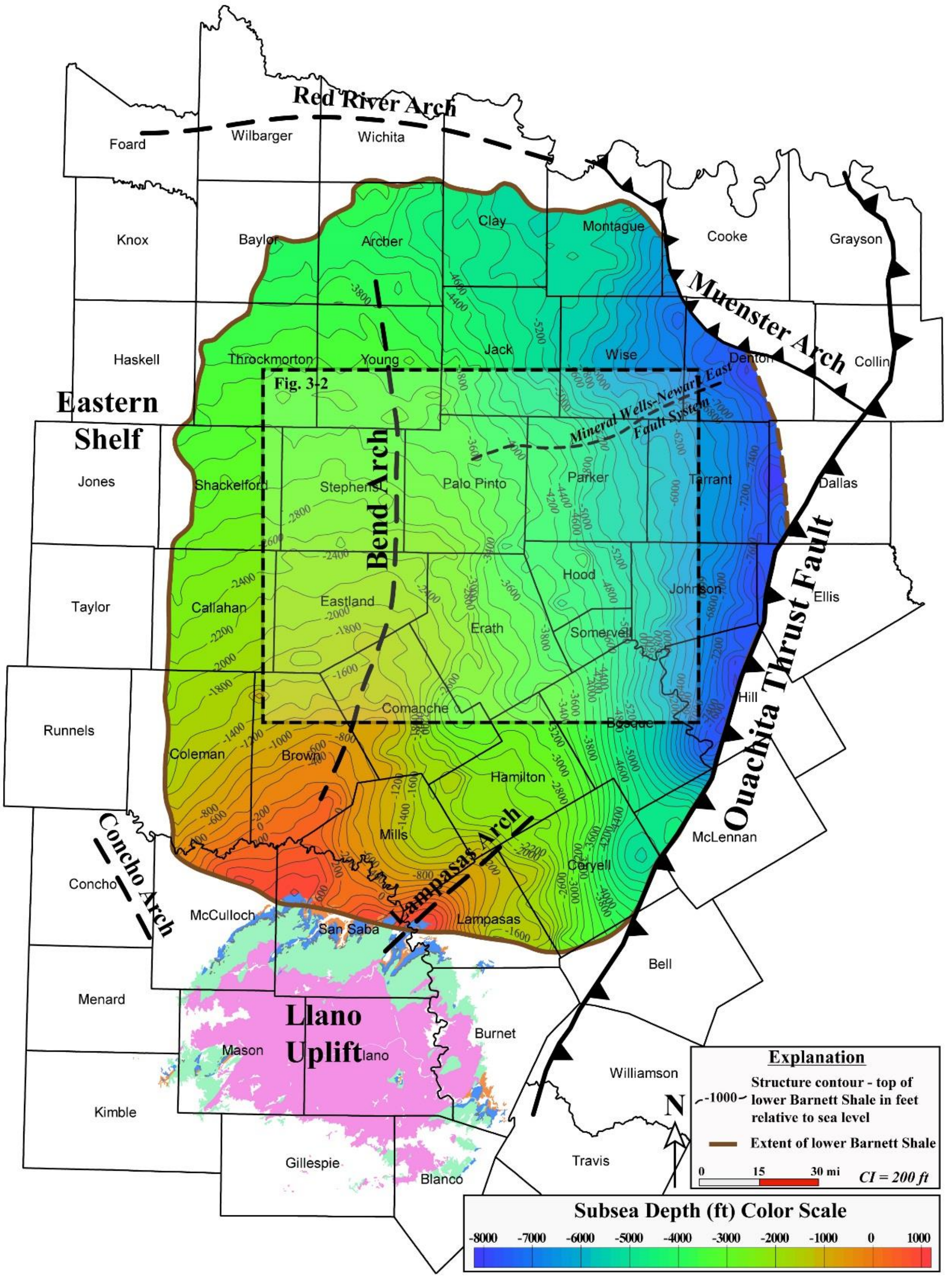



Figure 3-1. Subsea structure map at the top of the lower Barnett Shale with approximately 19,000 data points used to illustrate the structural architecture and tectonic elements of the Fort Worth Basin.

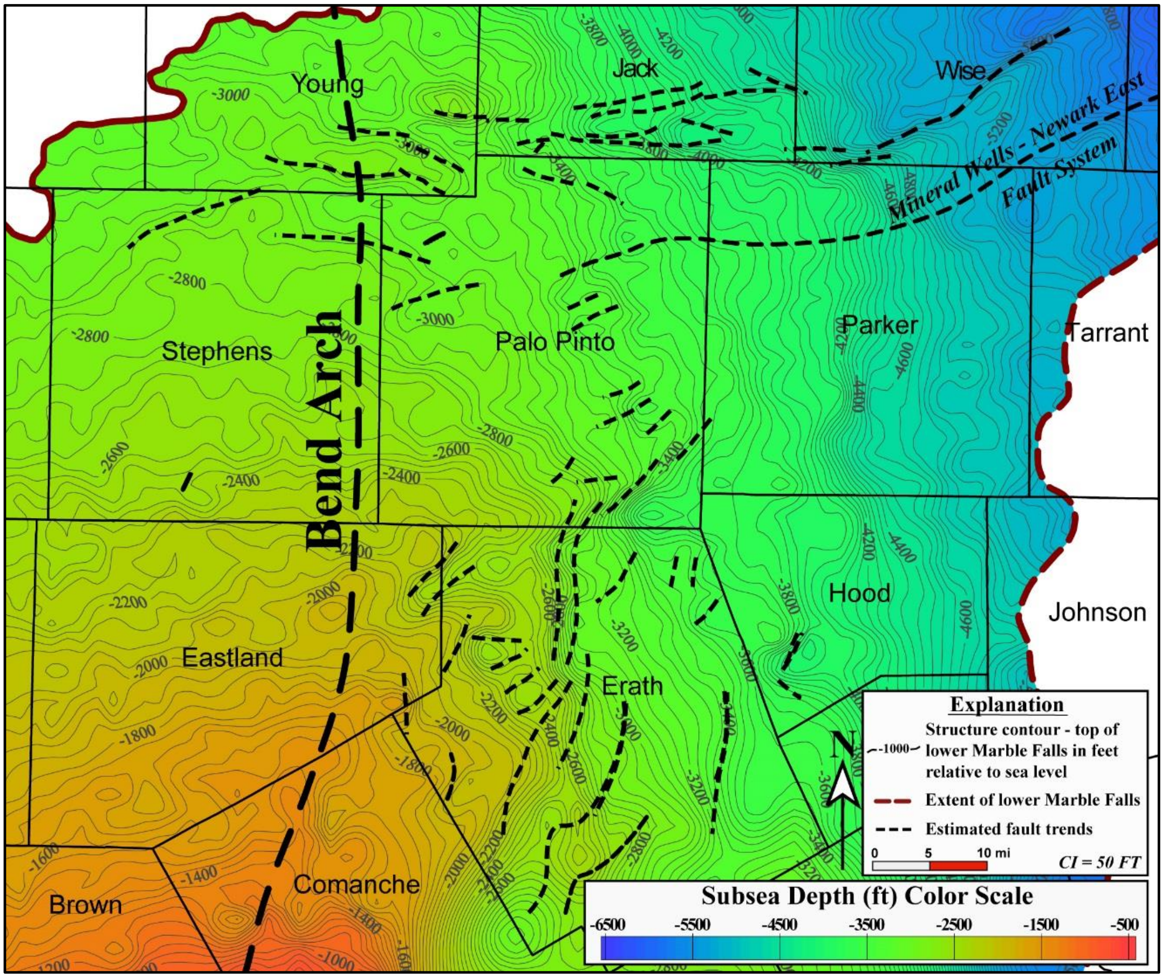



Figure 3-2. Subsea structure map at the top of the lower Marble Falls with proposed trends of minor faults subparallel to the Mineral Wells – Newark East fault system in northern Palo Pinto and southern Jack counties and parallel to subparallel to the Ouachita thrust front in northern Erath County.

## Paleozoic Stratigraphy of the Fort Worth Basin

The FWB contains sediments that were deposited from the Late Cambrian until the Permian, and most of the oil and gas discovered in North-Central Texas has been produced from siliciclastic and carbonate rocks of the Ordovician and Carboniferous systems (Figure 3-3) (Pollastro *et al*., 2003; Pollastro, 2007). Cretaceous-age sediments at the surface unconformably overlay the tilted Paleozoic section and Ouachita thrust front and were deposited in the Cretaceous Interior Seaway (Walper, 1982). Most of the strata preserved within the FWB were deposited during the Paleozoic with maximum thicknesses reaching 12,000 feet along the deepest part of the basin adjacent to the Muenster Arch (Pollastro *et al*., 2007). Montgomery and others (2005) have grouped this entire Paleozoic stratigraphic section into three intervals based on tectonic history: (1) Cambrian to Upper Ordovician carbonate rocks (Wilberns - Riley - Hickory Formations, Ellenburger Group, Simpson Group, Viola limestone) deposited on a passive continental margin; (2) Mississippian strata (Chappel limestone, Barnett Formation, Forestburg-Comyn limestone) deposited during the early stages of subsidence with a deeper-water setting to the east and shallow shelf to the west; (3) Pennsylvanian strata (lower and upper members of the Marble Falls Formation, Smithwick shale, Caddo limestone, Atoka Group, Strawn Group, Canyon Group, etc.) deposited during the main phase of basin infilling and subsidence in response to the advancing Ouachita structural belt.

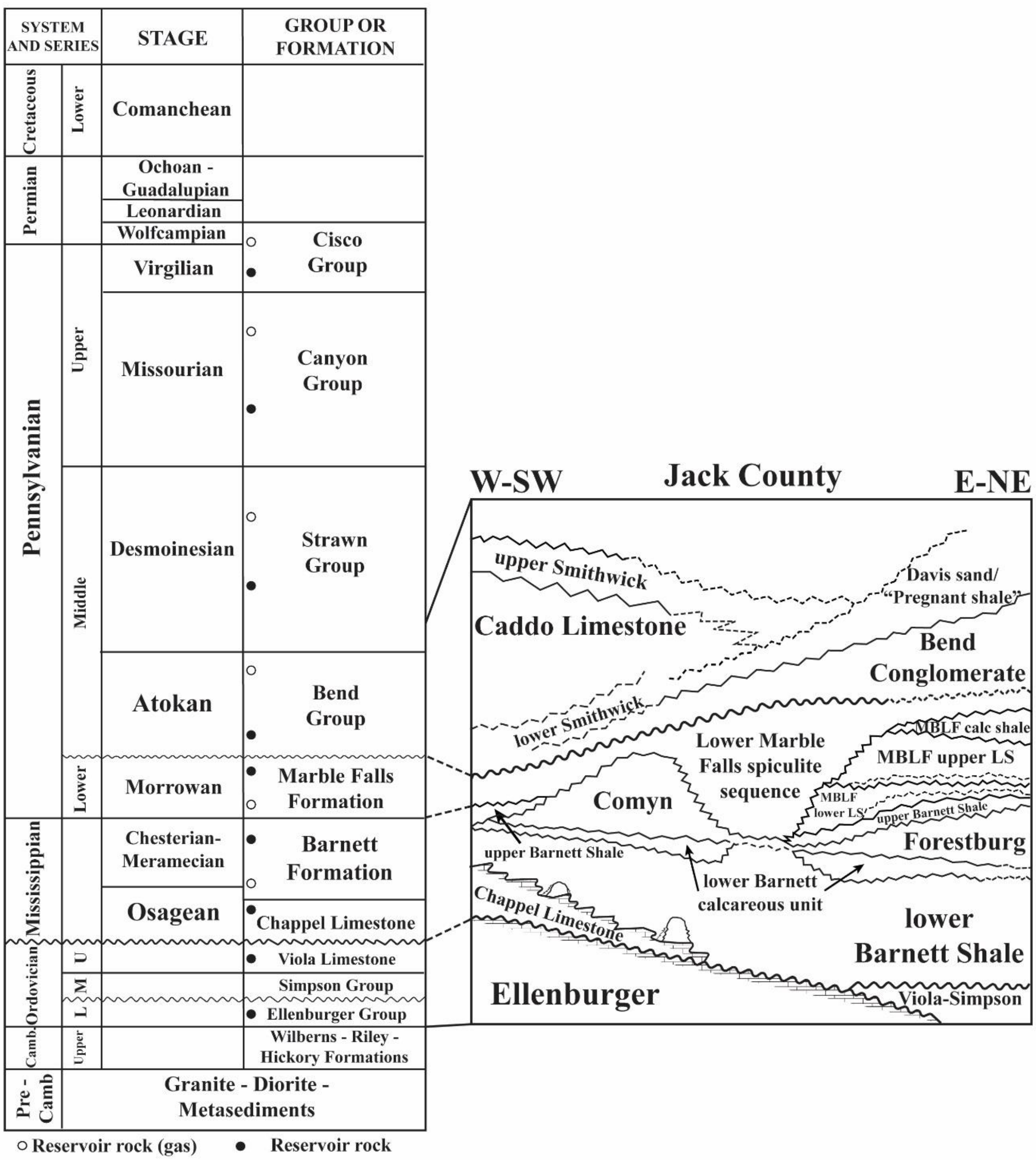



Figure 3-3. Generalized subsurface stratigraphic column of the Fort Worth Basin modified from Pollastro *et al.* (2007). The expanded section shows the detailed stratigraphy of the Mississippian, Ordovician, and Lower to Middle Pennsylvanian sections in the northern part of the Fort Worth Basin.

*Cambrian - Ordovician*

The oldest Paleozoic rocks in the FWB lie directly on top of Precambrian granite and diorite basement and include the Upper Cambrian Wilberns – Riley - Hickory Formations (Watson, 1980; Turner, 1957). It is difficult to distinguish these subdivisions of the Cambrian in the subsurface with only a few wells that have penetrated this system of rocks, but the Cambrian can be distinguished from the Ordovician by a porous sandstone at the base of the Ellenburger that is assumed to be part of the Hickory Formation.

During the Ordovician, the southern part of North America formed a stable cratonic shelf that was dominated by thick accumulations of carbonate rocks (Walper, 1982; Pollastro *et al*., 2007). In the subsurface of the FWB this system is represented by the Ellenburger Group, Simpson Group, and Viola limestone (Figure 3-3) (Flippin, 1982; Peppards-Souders and Associates, 1975). The Simpson Group and Viola limestone are only present in the east and northeast part of the FWB and the erosional subcrops of each of these formations extend from Johnson County northwest to northern Clay County (Peppards-Souders and Associates, 1975; this study). The Ellenburger Group constitutes the thickest part of the Ordovician carbonate sequence that originated from a broad epeiric carbonate platform that covered most of Texas (Keran, 1989; Pollastro *et al.*, 2007). This formation is dominated by limestone and dolomite and ranges in thickness from approximately 1,500 feet along the Bend Arch to 2,300 feet in Jack and Palo counties and up to 3,200 feet along the eastern flank of the basin. Deposition of the

Ellenburger Group was followed by a distinct drop in sea level that resulted in prolonged subaerial exposure of the carbonate platform and created numerous karst-related features at the top of the Ellenburger Group (Kerans, 1989). These karst features are present throughout the basin and can be identified using seismic data, but in areas where seismic data is not available, they can be recognized by either a pronounced thickening of the overlying Barnett Formation or significant changes in subsea depth of the Barnett Formation. A subsequent erosional event between the Ordovician and Mississippian removed all Silurian and Devonian rocks that may have been present in the basin (Henry, 1982; Pollastro *et al.,* 2007), and formed a major regional unconformable surface at the top of the Ordovician sequence that is recognized in image logs by a thick zone of karst-collapse breccia.

*Mississippian*

Mississippian strata were deposited on top of the Ordovician unconformable surface during the early stages of Ouachita orogenesis and subsidence of the FWB, and consist of the Chappel limestone, Barnett Formation, and related lower Barnett calcareous unit and Forestburg/Comyn limestone units (Figure 3-3). During this time period, the western part of the basin was dominated by deposition of shallow-water carbonates along the Chappel shelf, and a deeper-water setting prevailed to the east with accumulation of black, organic-rich mudstones and related terrigenous and carbonate material derived from either the Muenster Arch or Red River Arch (Loucks and Ruppel, 2007; Pollastro *et al*., 2007).

Chappel Limestone

The Chappel limestone has been described in outcrop as a discontinuous bed of gray to pinkish crinoidal limestone that ranges in thickness from just a few feet to approximately 45 feet (Turner, 1957). In Jack County it is recognized in drill cuttings by its white to off white color and very fine crystalline to chalky texture. In thin section it is a fossiliferous grainstone to crystalline limestone with variable amounts of visible fossil fragments. However, it is unclear if the Chappel limestone in outcrop correlates with the "Chappel" in the subsurface in north Texas because of their distinct differences in depositional environment and lithological appearances (Henry, 1982). In the northern and western part of the basin the Chappel limestone formed large isolated bioherms that grew directly on top of the erosional Ellenburger surface, and in western Jack County these organic reefs are situated along the eastern-most edge of the shelf where they reached a maximum vertical development of nearly 300 feet (Henry, 1982; this work). A typical "Chappel" reef complex in Jack County is composed of three constituents including the reef core, reef flank, and the more widespread inter-reef areas (Henry, 1982). The carbonates of the Chappel shelf were probably deposited contemporaneously with the lower part of the Barnett Formation that was a stratigraphically equivalent deeper-water deposit (Henry, 1982). The upper part of the Barnett was deposited later in the Mississippian and is typically draped over the top of the Chappel reefs where it thins to less than 30 feet in some areas (Henry, 1982).

Barnett Formation

The Barnett Formation has been studied extensively in outcrop and the subsurface of the FWB since its discovery as a major shale-gas resource play at the beginning of the 21st century. More recently, it has become known as the Barnett "Shale", but because of various lithofacies within the Barnett succession that are not actually shale and because the "shale" lithofacies is not characterized as a typical shale (Loucks and Ruppel, 2007), the original term 'Barnett Formation' used by earlier investigators (Barnes, 1948; Hass, 1953; Kier et al., 1979; Sellards, 1932; Turner, 1957) is more appropriate and will also be used herein. Nearly all of the Paleozoic reservoirs within the FWB are sourced by the petroliferous, organic-rich Barnett Formation and are part of the Barnett Total Petroleum System (TPS) (Pollastro *et al*., 2007; Jarvie *et al*., 2007)**.** In outcrop around the Llano Uplift, the thickness of the Barnett Formation ranges from just a few feet up to 150 feet and has been described by most workers as a black to gray petroliferous shale that weathers to a brownish color and contains interbeds of dark gray limestone and calcareous concretions (Kier *et al*., 1979; Plummer, 1950; Ruppel *et al*., 2007).

In the subsurface in the northern part of the basin, the Barnett Formation is described by Loucks and Ruppel (2007) as containing three dominate lithofacies including nonlaminated to laminated siliceous mudstone, laminated argillaceous lime mudstone (Forestburg-Comyn limestone and lower Barnett calcareous unit), and skeletal argillaceous lime packstone. It is considered by most workers to be a siliceous mudstone that is dominated by quartz constituents with localized areas of increased carbonate content and modest amounts of pyrite and phosphate (Loucks and Ruppel, 2007). In drill cuttings the typical Barnett sample can be identified by the following characteristics: 1) firm, blocky (non-fissile), carbonaceous texture that leaves black residue on your hands when rubbed together; 2) dark chocolate brown to black color; 3) petroliferous odor; 4) moderate amounts of silt- to sand- size quartz; 5) presence of pyrite; 6) and is typically calcareous with evidence of calcite-filled fractures present in some areas of the basin.

The Barnett Formation is generally interpreted to have been deposited in a deep-water basinal setting under anaerobic conditions and in water depths ranging from 400 to 700 feet (Loucks and Ruppel, 2007). The sediments within the Barnett section were sourced from either the Chappel shelf to the west or the Caballos Arkansas Island chain to the south and were transported into the basin and deposited by suspension settling and/or density currents (Loucks and Ruppel, 2007). The Barnett Formation is present over a large geographic area, and has been recognized in the Fort Worth, Hardeman, Midland, Delaware, and Palo Duro basins (Pollastro *et al.,* 2007). It is underlain by the Lower Ordovician Ellenburger Group across most of the FWB except where the Middle to Upper Ordovician Simpson Group and Viola limestone are present to the northeast, and where the Mississippian shallow-water carbonate rocks (e.g., Chappel Limestone and "Chester" limestone) separate the Barnett Formation from the Ellenburger Group along the western edge of the basin (Loucks and Ruppel, 2007) (Figure 3-3). In well logs, the main organic-rich mudstone lithofacies of the lower Barnett Shale interval is easily distinguished from the intervals lying above and below because of its particularly high-GR log response and corresponding high resistivity. It is commonly used as a stratigraphic datum in cross-sections because of its distinct log character and uniform deposition throughout the study area with only gradual changes in thickness. The Barnett Formation is only absent in the FWB where it has been eroded along the Red River and Muenster Arches, over the top of the Llano Uplift to the south, and where it thins to an erosional subcrop over the Chappel Shelf to the west (Pollastro *et al.*, 2007).

The Barnett Formation reaches its maximum thickness directly adjacent to the Muenster Arch where it is dominated by interbedded carbonates of the Forestburg limestone and an interval informally referred to as the “lime wash” by Pollastro and others (2007), the “calcareous shale interruption” by Henry (1982), and the lower Barnett calcareous unit in this study. Adjacent to the Muenster Arch this carbonate-rich facies of the Barnett Formation grades upward into the Forestburg limestone and the two cannot be differentiated because of their similarities in log response patterns. The calcite content of the “lime wash” gradually decreases away from the Muenster Arch to the west and southwest and it eventually grades into a low-resistivity shale in the central part of southern Clay and northern Jack counties where it was informally recognized by Henry (1982) as the “foreign shale”. This low-resistivity shale facies forms a wedged-shaped feature as it narrows to the south and grades westward into another calcite-rich lithofacies that is stratigraphically and depositionally equivalent to the calcareous unit in southern Montague County.

In the Newark East field area the Barnett Formation is subdivided into lower and upper members that are separated by a thick carbonate member informally named the “Forestburg limestone” (Henry, 1982). The upper and lower intervals of the Barnett Formation have been informally named the “upper Barnett Shale” and “lower Barnett

Shale" and where the Forestburg limestone is absent, they are typically undifferentiated on well logs (Loucks and Ruppel, 2007; Pollastro *et al*., 2007). A calcareous sequence in the upper part of the lower Barnett Shale was also identified in this work and will informally be called the lower Barnett calcareous unit. The upper Barnett Shale interval was also found to extend much farther west than previously estimated and was deposited over the Comyn limestone similar to its depositional extent of the Forestburg limestone to the east. The paleogeographic extent and thickness variations of the upper Barnett Shale was mapped using high density well log correlations and was establish to be significantly thinner to the west with thicknesses of <10 feet across most of the area, but increasing to >75 feet thick in western Stephens and eastern Shackelford counties.

Forestburg-Comyn Limestone

The depositional environment, geographic extent, and exact age of the Forestburg limestone are poorly understood because no comprehensive studies on this member of the Barnett succession have been published. Loucks and Ruppel (2007) briefly described the lithological properties, Bowker (2007) discussed the origin and depositional environment, and Pollastro *et al.* (2007) discussed the paleogeographic extent. It is a laminated argillaceous lime mudstone ("marl") dominated by calcite and contains localized areas of up to 21% dolomite (Loucks and Ruppel, 2007). Bowker (2007) presented evidence from core analysis that the Forestburg limestone was deposited by submarine debris flows with the source area most likely in southern Oklahoma. Loucks and Ruppel (2007) proposed that the Forestburg limestone was deposited as fine-grained carbonate shelf debris through dilute turbidity currents in an environment similar to the typical Barnett strata, but with a likely shift in source area, sea level, or seawater chemistry.

The extent of the Foresetburg limestone was briefly discussed by Pollastro *et al*. (2007), who provided an incomplete thickness map that was extracted from a hearing at the Texas Railroad Commission (2003). This is one of the only published maps of the Forestburg limestone and the availability of more well logs since that time has provided significantly better well control and geographic constraints on this member of the Barnett Formation.

The Comyn limestone is similar in lithologic composition to the Forestburg limestone described by Loucks and Ruppel (2007) and contains laminated beds of dolomitic claystone and micritic limestone (Farrar, 2010). The Comyn limestone splits the Barnett Formation into upper and lower members similar to the Forestburg limestone to the east, but the upper Barnett Shale is typically absent or significantly thinner above the Comyn limestone in the western part of the basin. The Comyn limestone lies directly beneath the Marble Falls Formation across most of the study area except where the Marble Falls is absent or in areas where the upper Barnett Shale is present. It generally thickens from a feathers edge in northeast Shackelford and central Stephens counties toward the northeast where it reaches a maximum thickness of more than 400 feet in eastern Young and western Jack counties. The thickness of the Comyn limestone decreases abruptly in west-central Jack County where it is replaced by the lower Marble Falls spiculite sequence.

There has been some confusion among previous workers on whether the Comyn limestone is Mississippian or Pennsylvanian in age (Cheney, 1947; Turner, 1957; Peppards-Souders and Associates, 1975; Flippin, 1982), but a thorough literature review and extensive well log correlation conducted during this study indicate that it is stratigraphically equivalent to the Forestburg limestone and most likely Mississippian in age. Due to its complex stratigraphic relationship with the overlying lower Marble Falls and the fact there have been few publications, the composite Forestburg-Comyn limestone will be discussed in greater detail in the next chapter.

*Pennsylvanian*

The majority of sediments preserved within the FWB were deposited during the Pennsylvanian period and represent a significant episode of subsidence and basin infilling related to Ouachita orogenesis (Mongomery *et al*., 2005). The Marble Falls Formation contains the oldest strata of the Pennsylvanian system and was deposited over the Mississippian Barnett Formation or, where present, the Forestburg-Comyn limestone. The boundary between the Marble Falls and Barnett formations in outcrop and the subsurface has been greatly debated with some workers having interpreted it as an unconformable contact that represents the Mississippian-Pennsylvanian boundary (Brown, 1983; Luker, 1985; Manger and Sutherland, 1984; Namy, 1969; Plummer 1950; Sellards, 1932; Turner, 1957); whereas others noted it was gradational and therefore conformable (Henry, 1982; Kier, 1972, 1980; Turner, 1970; Zachry, 1969). In the northern part of the basin, several lines of evidence from image logs and conventional whole core that will be discussed in a later section, clearly show this contact to be an erosional surface that represents an unconformity between Mississippian strata and the overlying Pennsylvanian sequence. No biostratigraphic studies have been published from this part of the basin which definitively determine a conformable or unconformable relationship between the Marble Falls Formation and underlying Forestburg-Comyn limestone and/or Barnett Formation.

Lower Marble Falls (Morrowan)

In outcrop and the immediate subsurface north of the Llano Uplift, the Marble Falls Formation has been divided into upper and lower members separated by a regional unconformity representing the Morrowan–Atokan boundary (Brown, 1983; Dihrberg, 1988; Erlich & Coleman, 2005; Groves, 1991; Kier *et al.*, 1979; Luker, 1985; Manger & Sutherland, 1984). This unconformity can be traced across most of the FWB and extends into the northernmost part of the basin where the erosional surface can be clearly identified at the top of the lower Marble Falls sequence. The upper Marble Falls member is absent north of the Mineral Wells – Newark East Fault system and the overlying Atoka strata are represented by the Bend Group (Bend conglomerate). The unconformable boundary between the Atokan and Morrowan strata is an abrupt and irregular surface across most of the basin and is typically characterized by minor karst-related features that formed due to an extended period of subaerial exposure from a drop in sea-level during the Early Pennsylvanian. No biostratigraphic studies have been published on the Marble Falls Formation in the subsurface around the study area, but evidence from this work reveal the spiculite sequence deposited in Jack and Palo Pinto counties is probably Morrowan in age. However, diachronous deposition could play a role in variations in the age of the lower Marble Falls across the basin.

The initial subsidence of the FWB caused a flexure to develop along the eastern edge of the North American plate that formed a series of shelf hinge lines which migrated westward through time (Walper, 1982). The lower Marble Falls was the first of a series of carbonates deposited along the eastern edge of this hinge line and is therefore present in the subsurface farther east than any other carbonate rocks in the Pennsylvanian section (Jackson, 1980; Walper, 1982). This Morrowan-age member of the Marble Falls Formation was deposited over a broad area and directly overlies the lower Barnett Shale across most of the basin, but along the northern and northeastern part of the FWB it lies stratigraphically above either the Forestburg-Comyn limestone, upper Barnett Shale, or a series of carbonate-rich limestone and calcareous shale units that have also been included as part of the Marble Falls Formation (Figure 3-3). It was deposited as a distally steepened ramp and contains a wide range of depositional facies across the basin (Ruppel *et al.*, 2007; Wood, 2013). It ranges in thickness from a few feet along the Bend Arch and the northwest edge of the Llano Uplift to more than 500 feet in the eastern part of the FWB where it grades into a more mudstone-rich lithofacies. In parts of Jack and Palo Pinto counties where the formation is currently being exploited for hydrocarbons, it ranges in thickness from 250 to over 450 feet.

The lower Marble Falls has been identified in outcrop as a series of dark gray to black, partly siliceous, fossiliferous limestone and interbedded black shale (Plummer, 1950). The facies distribution of the lower Marble Falls around the Llano Uplift has proven to be exceptionally difficult to map because of significant lateral and vertical variations associated with glacio-eustatic fluctuations (Kier, 1980; Plummer, 1950; Ruppel *et al.*, 2007; Wood, 2013), and this difficulty in mapping highly variable facies patterns in the lower Marble Falls was found to persist throughout the basin. A number of studies have concentrated on the complex facies assemblage within the lower Marble Falls around the Llano region and a wide range of carbonate and mudstone facies have been proposed from these investigations (Brown, 1983; Kier, 1972, 1980; Luker, 1985; Woods, 2013; Zachry, 1969). The facies patterns are generally represented from west to east by the following: carbonate lithofacies of the inner ramp, spiculite facies of the middle to outer ramp, and basinal mudstone lithofacies (Wood, 2013). The spiculite facies was deposited across most of the FWB and is the dominate lithofacies within the lower Marble Falls in Jack and Palo Pinto counties where it is interbedded with fossiliferous limestones to the west along the Bend Arch and calcareous mudstones in the deeper part of the basin to the east.

Upper Marble Falls / Smithwick Shale (Atokan)

The lower Marble Falls is unconformably overlain by the Atoka strata represented by either the carbonate rocks of the upper Marble Falls, the Smithwick Shale, or the siliciclastic deposits of the Bend Conglomerate. The shelf-edge carbonate rocks of the upper Marble Falls dominate the Atoka section across most of the southwestern counties of the study area (i.e. Brown, Comanche, Eastland, Erath, Hamilton, Mills and Lampasas) and intertongues with the diachronous deeper-water deposits of the black, organic-rich Smithwick Shale (Namy, 1982). The upper member is distinguished from the lower member by an unconformable boundary and maximum flooding surface at the top of the lower Marble Falls sequence that is recognized on well logs by a high-GR log response and occasionally the development of an erosional conglomerate deposit. The upper Marble Falls has previously been referred to as the “Big Saline Limestone” or “Big Saline Formation” until the late 1950s when a group of graduate students under the supervision of W.C. Bell from the University of Texas at Austin investigated the Carboniferous strata around the Llano Uplift and established a lower, middle, and upper member of the Marble Falls Formation.

The middle member, occasionally referred to as the middle shale, is dominantly composed of basinal calcareous shale with a lesser concentration of interbedded spiculitic biomicrite (Kier, 1980; Wood, 2013). The middle member was deposited over the lower Marble Falls erosional surface and grades upward into the carbonate section of the upper Marble Falls to the west (Kier, 1980, Namy, 1982). Kier (1980) notes that there was continuous deposition of shale and spiculitic biomicrite of the middle member in off-platform environments around the same time that the lower Marble Falls platform was being eroded. This suggests that the drop in sea level along the southern margin of the basin was just enough to expose the carbonate platform (lower member), but not enough to affect off-platform deposition of the middle member (Kier, 1980). Evidence of an unconformity was not found in well logs along the eastern edge of the FWB, and the work done by Namy (1969) confirms the unconformity is lost through continuous deposition of the spiculitic biomicrite and shale along the eastern side of the Llano Uplift. There is no distinct boundary between the middle shale and upper limestone and because these deposits appear gradational, the “middle shale” is herein incorporated with the “upper carbonates” as the upper Marble Falls member similar to several previous studies (Brown, 1983; Dihrberg, 1988; Erlich & Coleman, 2005; Groves, 1991; Kier, 1980; Kier *et al*., 1979; Luker, 1985; Manger & Sutherland, 1984).

Limestone units of the upper Marble Falls were deposited in a high-energy environment that produced algal build-ups, calcarenite shoal deposits, and other skeletal grain-rich carbonate facies (Kier, 1980; Wood, 2013). The thick accumulation of these carbonate units formed a series of northeast-southwest trending carbonate bank complexes that grade laterally into shale along the flanks and have produced a number of large stratigraphic and structural hydrocarbon traps that have been exploited since the early- to mid-1900s (Namy, 1982) (Figure 3-4). Erlich and Coleman (2005) discuss the westward back-stepping profile and subsequent drowning of the carbonate platform from the influx of prograding Smithwick-Strawn terrigenous material derived from the Ouachita thrust front. Biostratigraphic interpretations by Groves (1991) also support the westward transgression of the upper Marble Falls and he determined that it ranges from early Atokan to latest upper Atokan as it becomes progressively younger from east to west.

The Smithwick Shale was originally described in outcrop as a black carbonaceous shale with lenticular sandstone beds that directly overlie the Marble Falls limestone (Paige, 1911). McBride and Kimberly (1963) later identified the Smithwick as having

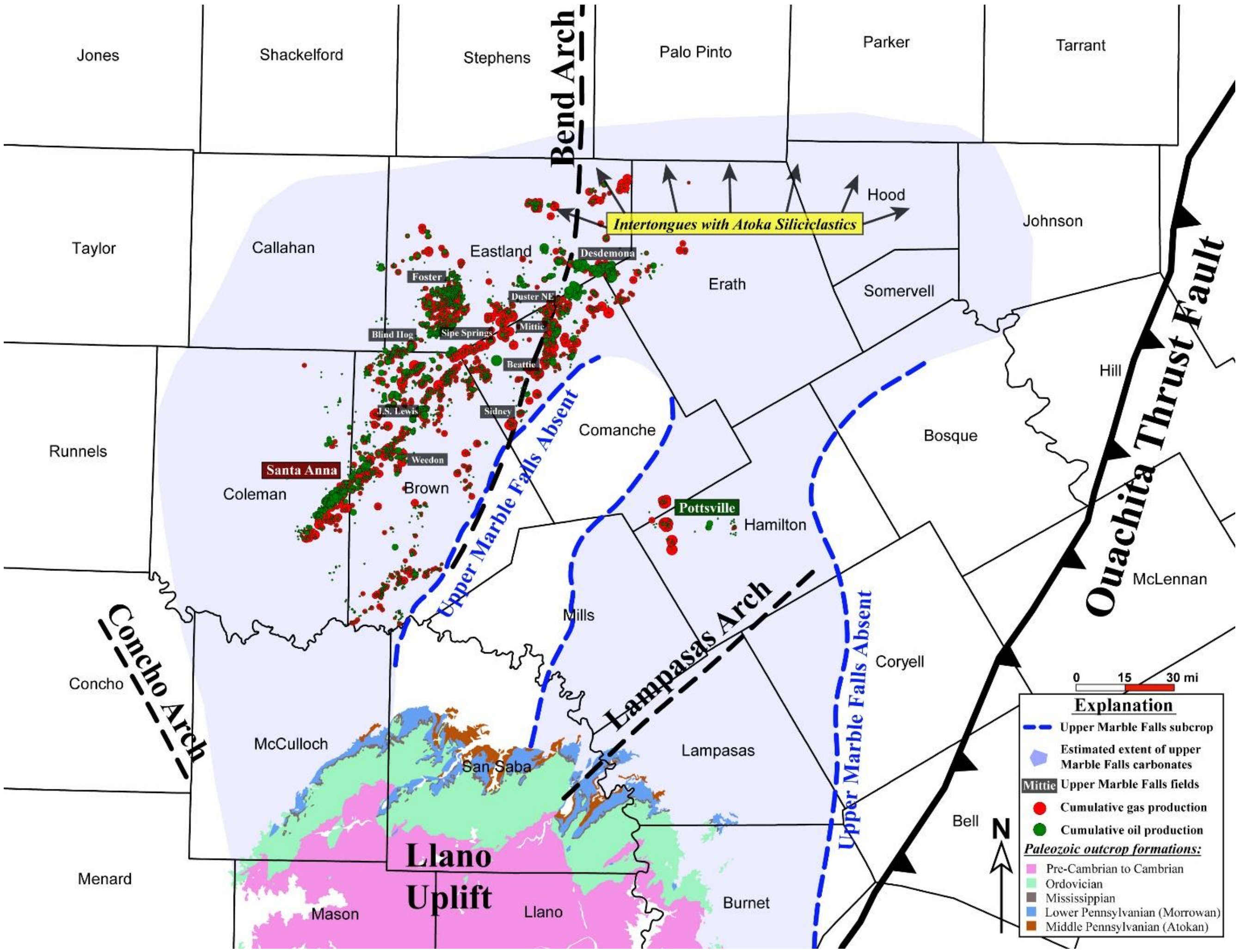



Figure 3-4. Paleogeography of upper Marble Falls carbonates with cumulative oil (green) and gas (red) production bubbles displaying northeast trending fields.

"flysch-like" characteristics that grade upward from a dark gray claystone into interbedded sandstone and claystone and suggested that deposition occurred from turbidity currents. It is more likely that the Smithwick Shale was deposited as part of a fluvial-deltaic system that filled the FWB as a series of westward prograding wedges sourced by the Ouachita orogen (Kier, 1972; Kier *et al.*, 1979; Turner, 1970). The Smithwick Shale intertongues with and overlaps the shelf-edge carbonate units of the Caddo limestone and upper Marble Falls along the Concho platform to the west (Kier *et al.*, 1979). For this study the Smithwick Shale has been separated into lower and upper members that range in age from late Atokan to early Desmoinesian and are regarded as the laterally equivalent, deeper-water mudstone facies of both the upper Marble Falls and Caddo limestone, respectively (Grayson *et al.*, 1990).

The lower member of the Smithwick Shale lies above the upper Marble Falls limestone and below the Caddo limestone and gradually thickens from a few feet along the Bend Arch to more than 200 feet in the central part of the basin where it grades into the "pregnant shale" and intertongues with the Bend Conglomerate in eastern Eastland, northern Erath, and southern Palo Pinto counties (Figure 3-3). Throughout the central part of the FWB the Caddo limestone is absent and the lower and upper members of the Smithwick Shale coalesce to form one continuous, indistinguishable unit. Along the Bend Arch to the west the upper member intertongues and overlaps the Caddo limestone. The Smithwick is a dark gray to black organic-rich shale that is identified on well logs by its high-GR/high-resistivity values and typically produces noticeable gas shows in mud logs, which have sparked interest among operators as a possible resource play. The Smithwick

Shale is also lithologically and depositionally similar in part to the terrigenous sediments of the Strawn Group and most workers have concluded that they are gradational and stratigraphically time-transgressive equivalents (Grayson *et al.*, 1990; Kier *et al.*, 1979). Extensive well log correlation throughout the FWB supports this interpretation with image logs and open-hole logs displaying a gradational contact between the Smithwick Shale and overlying Strawn Group.

Atoka Group - Bend Conglomerate / Davis Sands / Pregnant Shale

As mentioned previously, the shelf-edge carbonates of the upper Marble Falls were deposited contemporaneously with the silciclastic deposits of the Atoka Group and these two distinctly different depositional systems intertongue near the central part of the basin. This complex interfingering of shelf-edge carbonates along the Concho platform to the west and prograding delta sands from the Ouachita orogen to the east has formed large prolific stratigraphic traps that were some of the first major oil fields discovered in the FWB during the early 1900s. The upper Marble Falls limestone is completely absent to the north of the Mineral Wells – Newark East fault system and the lower Marble Falls is directly overlain by the Bend Conglomerate (lower Atoka) which is in turn overlain by the “pregnant shale” and Davis “sands” (upper Atoka) (Thompson, 1982) (Figure 3-3). These siliciclastics units were deposited as interfingering shale, sand, and conglomerate that have produced a number of large gas fields in western Wise and eastern Jack counties that are collectively known as the Boonsville field (Gardner, 1960; Hentz *et al.*, 2012).

The Atoka Group is easily distinguished from the underlying lower Marble Falls (Morrowan) by a distinct increase in GR on well logs representing the maximum flooding surface (MFS) of the lower Marble Falls sequence and the Morrowan-Atokan unconformity. This contact between the Atoka Group and lower Marble Falls is typically abrupt and represents a regional unconformity that is clearly defined on image logs by an erosional surface containing karst-related features (i.e. collapse breccia) in the underlying Marble Falls Formation. The extent of this unconformable boundary is related to the amount of time, if any, the area was affected by a relative fall in sea-level during the late Morrowan to early Atokan time-period. This drop in sea-level exposed most of the lower Marble Falls ramp to the west but was not significant enough to disrupt the continuous deposition of mudstone and coarser siliciclastic sediments farther out in the basin to the east (Kier *et al*., 1979). Therefore, it was difficult to identify and correlate a distinct boundary between the Atoka Group and lower Marble Falls in the eastern part of the where they appear to be gradational with continuous deposition from the Morrowan into the Atokan. There are also numerous areas across the FWB where a conglomerate interval was deposited just above or directly on top of the lower Marble Falls and locally replaces up to 10 or 20 feet of the upper part of the lower Marble Falls. This conglomerate is somewhat related to the lower Marble Falls and the Morrowan-Atokan unconformity, but its lithological and depositional characteristics are similar to the overlying Atoka Group. This conglomerate has been referred to as the "Marble Falls conglomerate" by local operators and has been a prolific reservoir with numerous fields scattered across the FWB (Thompson, 1982).

The clastic deposits of the Atoka Group do not crop out anywhere in the FWB, so most subsurface studies have been based on well log response patterns and core analyses which were used to separate the Atoka Group into two lithogenetic units based on stratigraphic relationships that have formed distinct packages of terrigenous clastic sedimentary rocks (Thompson, 1982). The Atoka Group is defined from the top of the lower Marble Falls (Morrowan) to the base of the Caddo limestone or its laterally equivalent deposit (Strawn Group) and is subdivided into two members informally referred to as the upper Atoka and lower Atoka (Gardner, 1960; Lahti and Huber, 1982; Thompson, 1982). The lower Atoka comprises the Bend Conglomerate and the upper Atoka consists of the “pregnant shale”, “Davis sands”, and other “post-Davis” deposits (Thompson, 1982). Lahti and Huber (1982) note an unconformity between the lower and upper members along the northern edge of the basin extending through north-central Jack, Wise, and Denton counties where the “pregnant shale” and Davis sands thin rapidly to the north and pinch-out onto this unconformable surface.

The lower Atoka, also referred to as the Bend Conglomerate throughout this study, is defined as the strata between the top of the Marble Falls Formation and the base of the “pregnant shale” (Lahti and Huber, 1982; Thompson, 1982) (Figure 3-3). Most previous investigations of the lower Atoka have defined the limits of their respective study areas as the southern boundaries of Palo Pinto, Parker, and Tarrant counties (Lahti and Huber, 1982; Thompson, 1982), but these siliciclastic deposits extend farther south and southwest into Erath and Eastland counties where they intertongue with the carbonate deposits of the upper Marble Falls and mudstone deposits of the Smithwick Shale. The complex interfingering of these formations make them extremely difficult to define and correlate across much of the central part of the FWB, and a number of workers have previously referred to this succession of carbonates and siliciclastics as the “Big Saline Formation” (Flippin, 1982), but this term is no longer used. The Bend Conglomerate is dominated by shale, sandstone, and conglomerate deposited as a prograding fluvial-deltaic system that displays an overall coarsening-upward sequence and reflects the transition from a carbonate-dominated environment to a terrigenous-dominated environment (Hentz *et al*., 2012; Thompson, 1982). The Ouachita orogen to the east and southeast has been recognized as the primary source area for the lower Atoka siliciclastic deposits (Hentz *et al*., 2012), but Thompson (1982) suggests the Muenster Arch as a secondary source and Lahti and Huber (1982) suggests the Red River Arch as a possible source. The lower Atoka succession shows a general thickening trend to the southeast from just a few feet along the northwestern edge of the basin to around a 1,000 feet in southern Parker County (Thompson, 1982), and more than 2,600 feet along the eastern edge of Tarrant and Johnson counties (Hentz *et al*., 2012).

The upper Atoka comprises all strata from the base of the “pregnant shale” up to the lowermost Strawn Group (Desmoinesian), typically represented by the base of the Caddo limestone (Hentz *et al*., 2012; Lahti and Huber, 1982) (Figure 3-3). However, over large parts of Palo Pinto and Parker counties the Caddo limestone is completely absent and the upper Atoka-lower Strawn boundary appears to be gradational and is not easily defined. The boundary between the Bend Conglomerate and “pregnant shale is recognized by a distinctive resistivity log-curve response pattern across most of the study area. However, the “pregnant shale” becomes more clay-rich as it thickens to the southeast and grades down into the Bend Conglomerate sequence making the boundary between the lower Atoka and upper Atoka difficult to define. The “pregnant shale” is one of the most easily identifiable units in the study area because of its distinct log-curve profile which characterized by a gradual upward-increasing resistivity curve giving it a bow-shaped pattern (Hentz *et al*., 2012; Lahti and Huber, 1982).

This shale unit gradually coarsens upward into a siltstone and fine-grained sandstone that is gradational with a coarser-grained and more porous “Davis sands” above. These porous sands have developed into gas-rich reservoirs which have been exploited in western Wise, northeast Palo Pinto, and northwest Parker counties, and more oil-rich reservoirs concentrated in east-central Jack County. The fields in this area were formed from stratigraphic traps where these sands pinch out onto what Lahti and Huber (1982) considered the lower Atoka - upper Atoka unconformity. The “Davis sands” were deposited as wave-dominated deltas and are composed of interfingering sands that are recognized as coastal barrier facies (Thompson, 1982). This unit thickens from only a few feet in central Jack and Wise counties to more than 600 feet to the south and southeast where the depositional axis trends from southwest to northeast through southeastern Palo Pinto, northwest Parker, and southern Wise counties (Lahti and Huber, 1982; Thompson, 1982). There is also a “post-Davis” interval that lies above the “Davis sands” that Thompson (1982) interpreted as a fluvial dominated fan-delta system with a progradational facies sequence that consist of interfingering shale and sand similar to the lower Atoka.

Strawn Group (Desmoinesian)

The upper Atoka is conformably overlain by the Strawn Group that is Desmoinesian in age and consist of a sequence more than 3,000 feet of sand and shale with lesser amounts of carbonate and coal (Brown *et al.*, 1973; Cleaves, 1982). The boundary between the Atoka and Strawn sections is gradational and has typically been placed at the base of the lowermost Caddo limestone interval or its lateral equivalents (Lahti and Huber, 1982). The Strawn was deposited as a series of westward-prograding fluvial-deltaic systems that overlapped the shelf-edge carbonates of the Caddo limestone which were deposited contemporaneously along the Concho platform to the west (Brown, 1973, Kier *et al.*, 1979). These siliciclastic deposits form thick packages of sands hundreds of feet thick that are typically water-wet, but a number of them are prolific reservoirs that were some of the first oil field discoveries in Palo Pinto County.

There has been some debate on whether the Caddo limestone is part of the Atoka Group or Strawn Group and it was difficult to resolve this issue using strictly well log correlations because the carbonate facies was found to intertongue with both the basinal Smithwick Shale deposits and siliciclastic deposits of the Strawn Group. The Caddo limestone is a prolific reservoir that has historically been exploited for hydrocarbons from conventional high porosity and permeability zones, but it is still being explored today using advanced technologies like horizontal drilling and hydraulic fracturing to extract hydrocarbons from low porosity and low permeability rock. Most of the hydrocarbons have accumulated in large carbonate build-ups or shelf-edge deposits that back-stepped westward through time due to the advancement of Strawn and Smithwick siliciclastics shed from the Ouachita orogen (Kier *et al*., 1979). The Caddo limestone contains accumulations of largely carbonate rock nearly a 1,000 feet thick along the western edge of the basin and this section thins toward the east where it eventually grades entirely into the Smithwick Shale along a distinct north-south trend that is parallel to the eastern edge of the Bend Arch.

The Strawn Group is overlain by the Missourian-age Canyon Group that consist of thick limestone and shale deposits with a total of seven formations defined in outcrop along the Colorado and Brazos River valley (Kier *et al*., 1979). The Cisco Group is Virigilian in age and lies directly above the Canyon Group and it consist of six formations that were defined in outcrop along the Brazos River valley and four formations that were identified along the Colorado River valley (Kier *et al*., 1979). The Pennsylvanian-Permian boundary has been acknowledged as conformable with the contact lying within the Cisco Group and representing continuous deltaic sedimentation (Kier *et al*., 1979).

# Chapter 4

# Results

## Nomenclature Evolution

There has been a complicated evolution in nomenclature of the Lower Pennsylvanian strata across the FWB, and at the center of this century-long discussion is the complex stratigraphy of the Marble Falls Formation. Important aspects of this work are to clarify the classification changes of the Lower Pennsylvanian section and resolve some of the confusion associated with various names that have been applied to these members and formations. This background work was conducted over a three-year period in conjunction with a detailed regional correlation and mapping project that was undertaken to better define the stratigraphy and regional distribution of the Marble Falls Formation in the subsurface of the FWB. The deciphering of stratigraphic problems associated with the Lower Pennsylvanian strata was based solely on detailed literature review and the ability to correlate these formations across the basin using more than 30,000 well logs. With the extensive resources and time devoted to this project, it was possible to achieve exceptional control on the stratigraphy of the Ordovician, Mississippian, and Lower Pennsylvanian (Morrowan and Atokan) strata across the Fort Worth Basin and gain a better understanding of the nomenclature issues. The results of these efforts are presented in Table 4.1.

The name “Marble Falls” was first proposed by Hill (1889) for the “encrinital” limestone forming “a peculiar topographic feature known as Shinbone ridge…” just east of Marble Falls, Texas. Dumble (1890) later proposed the name “Bend Series” for the beds that were exposed at McAnnelly's Bend along the Colorado River nearby. The classification of the "Bend Series" and "Marble Falls limestone" would repeatedly change over the next century as new research was presented. There was very little work conducted on the "Bend Series" after the first annual report of the Geological Survey of Texas was published in 1890 until Paige (1911,1912) proposed the name Smithwick shale for the upper black shales overlying the "Marble Falls limestone" described by Hill (1889)(Table 4.1). Udden *et al.* (1916) later noted a "Lower Bend shale" that overlies the Ordovician in eastern San Saba County and described the lithology as "black fissile shale of uniform texture, evenly bedded and highly bituminous". A few years later, Girty (1919) proposed a major unconformity between the "Marble Falls limestone" and "Lower Bend shale", and suggested that this regional unconformity represented the Mississippian-Pennsylvanian boundary. Contrary to the assertion by Moore (1919) that the "Lower Bend shale" was Pennsylvanian in age, Girty (1919) claimed it was Mississippian in age, and the two were still in disagreement in a paper they later co-authored (Girty and Moore, 1919). However, a few years later, Moore (1922) offered a brief statement recognizing a Mississippian age for the "Lower Bend shale" and wrote there was "a line of demarcation between the Barnett and the Marble Falls which is indicated by a zone of glauconite and phosphatic pebbles, and this line separates two distinct faunas." Plummer and Moore (1921) were the first to propose the name Barnett Formation for the "basal black, fissile, carbonaceous shale of the Bend Series" from an exposure near Barnett Springs five miles east of San Saba (Table 4.1).

A thinly bedded crinoidal limestone below the Barnett formation and above the Ellenburger Group was first described by Roundy *et al.* (1926) along Chappel Road 3 miles southeast of San Saba, Texas. In their detailed biostratigraphic study of the Mississippian formations, those authors simply called this the “limestone of Boone age”, and Sellards (1932) later proposed the name “Chappel formation” in his overview of the Paleozoic system in Texas (Table 4.1). The terms Barnett Formation and Chappel limestone are still widely accepted among geologists working in the Fort Worth Basin, and aside from some minor differences in the exact age of these formations their classification has changed little since they were first described.

The Marble Falls Formation, however, has had a more complex evolution in its nomenclature and has changed names and ranks numerous times over the last century (Table 4.1). The classification of the “Marble Falls limestone” did not change after it was first described by Hill (1889), until Cheney (1940) proposed that it should be elevated to group status and be classified as part of the Morrow Series. In the same work, he elevated the Smithwick Shale to group status and for the first time, proposed the term “Big Saline Group” (upper Marble Falls) for the limestone and shales that unconformably overlay the type “Marble Falls limestone” along the western and southwestern edges of the Llano Uplift. Cheney (1940) proposed that these two groups make up the “Lampasas Series”, but this term was not widely accepted and is no longer in use. Cheney (1940) was also the first to propose that the “Comyn formation” is the subsurface portion of the Marble Falls Group occurring near Ranger in Eastland County, but uses the Roxana Petroleum Company Seaman No. 1 well in northwest Palo Pinto County as the type subsurface section for the Marble Falls and Big Saline groups. The interval (4,132 to 4,320 feet) he proposes as the "Comyn formation" was based on a detailed lithologic study of drill cuttings conducted by Goldman (1922), and were never examined by Cheney himself. Based on detailed mapping presented herein, the interval from 4,132 to 4,320 feet in the Roxana Seaman No. 1 well is actually part of the lower Marble Falls that is the subject of this study. Unfortunately, the "Comyn formation" as it was identified by Cheney (1940, 1947), has been used inaccurately by operators for decades without regard to the origin of the name, its type section, or how it was defined. It is herein suggested that the name "Comyn" be discarded completely to avoid further confusion, but because of the common use of this name, the author thought it would be more appropriate to redefine the "Comyn formation," which will be discussed in a later section.

The Bend Series was re-introduced by Plummer (1945) to contain the newly proposed "upper Marble Falls Formation" (Big Saline) and the more formal "Smithwick Formation." Plummer (1945) defined the type section as the lower Marble Falls and agreed it was part of the Morrow Series, but also proposed the name "Sloan" for the equivalent member of this formation. A few years later, Plummer (1947a, b) redefined the Marble Falls Formation again by elevating the "Sloan member" (lower Marble Falls) and "Big Saline member" (upper Marble Falls) to formation status and proposing new members for the "Big Saline Formation" (upper Marble Falls). Spivey and Roberts (1946) were the first to propose that the Atoka formation, defined in Oklahoma, should be elevated to series status and that all of the Marble Falls Formation should be included in this series despite clear evidence from Cheney (1940) and Thompson (1942a, 1944) designating the type section as part of the Morrow series (Table 4.1). The Atoka series became widely accepted for the age of the upper Marble Falls member, but the type "Marble Falls limestone" section in southeast Burnet County continued to be recognized as Morrowan in age. A number of subsequent studies slightly modified the Marble Falls Formation including Thompson (1947), Cheney (1947), Cheney & Goss (1952), Bell (1957), Stewart (1957), and Turner (1957) (Table 4.1).

In 1957 a group of 16 students from The University of Texas at Austin started an extensive study on the Marble Falls under the supervision of W.C. Bell and there was general agreement among them and their advisors that the Marble Falls Formation should be informally divided into a lower member representing the Morrow Series and an upper/middle member representing the Atoka Series. The "Big Saline Formation," "Sloan Formation," and "Lampasas Series" were no longer used after the detailed work of Dr. Bell and his students, and the majority of work that followed accepted their classification of the Marble Falls Formation with lower (Morrowan) and upper (Atokan) members separated by a regional unconformity (Kier *et al*., 1979; Kier, 1980; Brown, 1983; Manger & Sutherland, 1984; Luker, 1985; Groves, 1991; Dihrberg, 1988; Erlich & Coleman, 2005) (Table 4.1).

The classification scheme mentioned above has been generally accepted among geologist working around the Llano Uplift, but there is still much confusion regarding the classification of the Marble Falls Formation in the subsurface to the north. The upper Marble Falls (Atokan) was deposited across Coleman, Brown, Comanche, Eastland, and Erath counties, and is composed of carbonate build-ups and shelf-edge deposits that accumulated along a southwest to northeast trend (Namy, 1982). The carbonate section of the upper Marble Falls are still mistakenly referred to as the “Big Saline limestone,” and Jackson (1980) erroneously referred to the upper Marble Falls in southwest Eastland County as the “Ranger limestone.” A number of operators have also reported production from the “Ranger” interval that is in fact part of the upper Marble Falls. The Bend Conglomerate was deposited during Atokan time in a more siliciclastic-rich environment and intertongues with the upper Marble Falls carbonate rock in the eastern half of Eastland County and northern Erath County. The Bend Conglomerate is also commonly referred to as the “Big Saline Formation,” but it is important to note that the name “Big Saline” was originally defined by Cheney (1940) for the limestone and shale in outcrop along the western edge of the Llano Uplift. Not only has “Big Saline” been discarded in more recent publications, but the siliciclastic deposits of the Bend Group do not crop out anywhere and, therefore, it would be inappropriate to apply the name “Big Saline” to these subsurface deposits in the northern part of the basin. The Bend Group, also commonly known as the Atoka Group, can be divided into upper and lower units based on lithological characteristics. The lower Atoka Group is represented by the Bend Conglomerate and the upper Atoka Group by the “Davis sands” and “pregnant shale” (Lahti & Huber, 1982; Thompson, 1982; Hentz *et al*., 2012).

The lower member of the Marble Falls Formation has an even more complicated nomenclature history because the lack of any detailed regional correlation studies has lead geologists to apply various names across the basin to the same stratigraphic interval. The most common names that have been assigned to the lower Marble Falls along the western edge of the basin are the Duffer, Duffer lime, lower Duffer, upper Duffer, and the “rotten chert” for more cherty intervals deposited in the upper part of the lower member. The names Comyn and Chester have also been incorrectly applied to the lower Marble Falls member, and in some cases the term “Marble Falls limestone” is used to describe all strata between the Barnett Formation (Mississippian) and Smithwick Shale (Atokan). The term Chester is generally applied to the Mississippian limestone unit between the Chappel limestone and Barnett Formation, and the term Comyn is applied to a massive limestone unit between the Barnett and Marble Falls formations.

Over the last century, there have been various names and ranks applied to the Marble Falls Formation and several modifications have been made to the “Bend Series” from how it was originally defined. The majority of these classifications were based on detailed observations from outcrops along the edge of the Llano Uplift, and it is clear that the same stratigraphic relationships are not persistent throughout the basin. Therefore, this study will use a combination of formation names and groups that have been generally accepted in published work and the more relevant nomenclature used among petroleum geologists in the subsurface. The same classification scheme of the Marble Falls Formation used in more recent studies will also be used here, with informal lower and upper members separated by a regional unconformity representing the Morrowan-Atokan boundary (Table 4.1). The lower Morrowan-age member of the Marble Falls Formation is the main focus of this work and further subdivisions of this member based on lithological characteristics will be proposed.

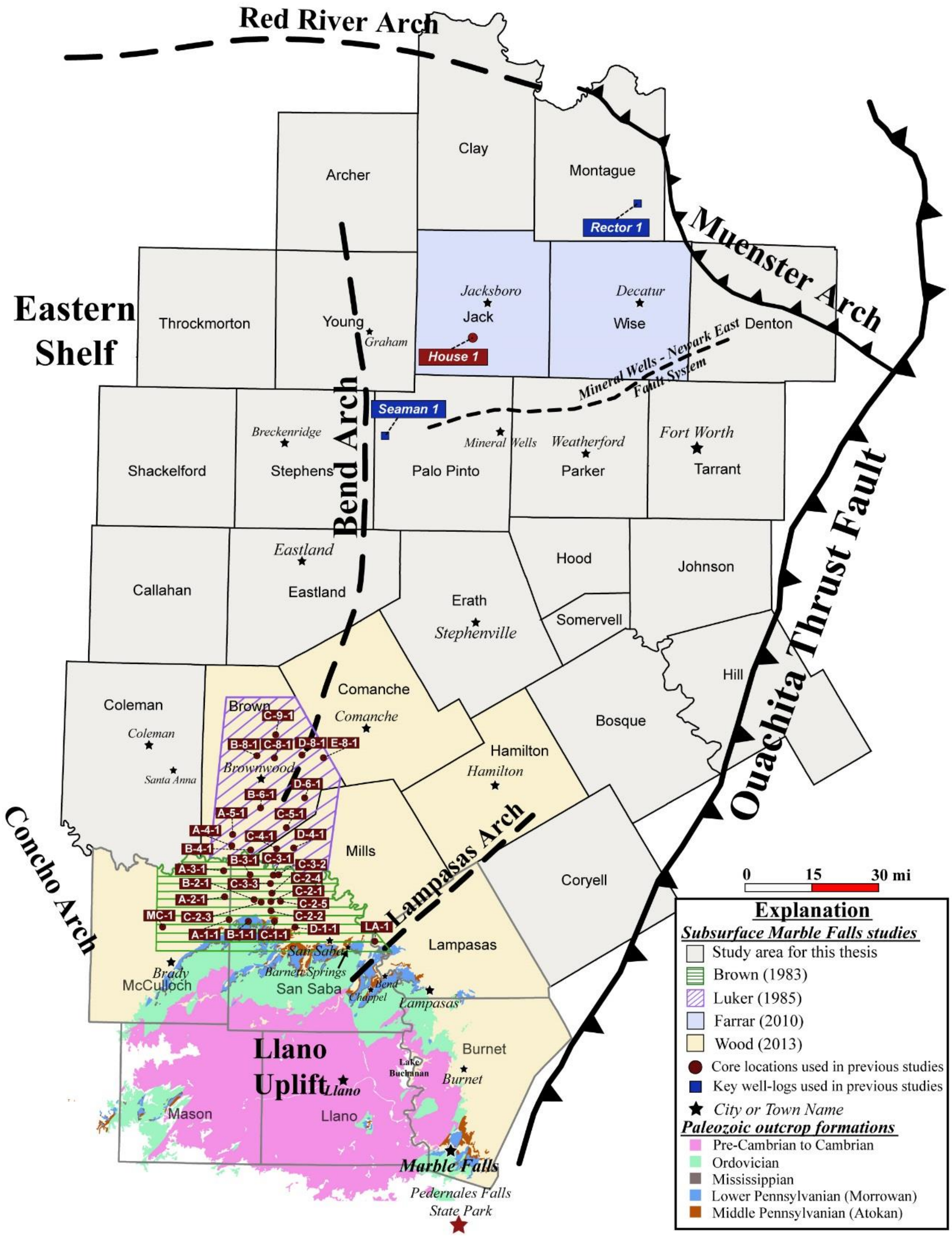



Figure 4-1. Map of previous subsurface studies with locations of cores shown in dark red and key wells used in previous subsurface studies shown in blue.

Table 4.1 Nomenclature Evolution Chart of the "Bend Series" and Marble Falls Formation

| Chappel Limestone | Barnett Shale | Comyn (subsurface only) | Marble Falls Formation: Lower Member | Marble Falls Formation: Upper Member | Smithwick Shale | Author |
|---|---|---|---|---|---|---|
| **Bend Series*** | | | | | | Dumble, 1889 |
| | | | **Marble Falls*** - "Encrinoidal" limestone | | | Hill, 1889 |
| Bend Division | | | | | | Paige, 1911 |
| | | | Marble Falls limestone | | **Smithwick shale*** | |
| Bend Series/Formation | | | | | | Udden *et al.*, 1916; Girty, 1919; Moore, 1919 |
| **Lower Bend shale*** | | | Marble Falls limestone | | Smithwick shale | |
| Bend Series/Group | | | | | | Plummer and Moore, 1921; Moore & Plummer, 1922 |
| **Barnett shale*** | | | Marble Falls limestone | | Smithwick shale | |
| Bend Series | | | | | | Roundy, Girty & Goldman, 1926 |
| **"limestone of Boone age"*** | Barnett shale | | Marble Falls limestone | | Smithwick shale | |
| Osage Group | Chester Group | | Bend Group | | | Sellards, 1932 |
| **Chappel formation*** | Barnett formation | | Marble Falls formation | | Smithwick formation | |
| | | **Morrow Series*** | | **Lampasas Series*** | | Cheney, 1940 |
| Osage Group | Meramec Group | **Marble Falls Group*** | | **Big Saline Group*** | **Smithwick Group*** | |
| Chappel limestone | Barnett formation | **Comyn formation*** | | **De Leon/ Sipe Springs formations*** | **Eastland Lake/Caddo Pool/ Parks* formations** | |

*Represents the proposal of a new name or rank

Table 4.1 - *Continued*

| **Chappel Limestone** | **Barnett Shale** | **Comyn (subsurface only)** | **Marble Falls Formation** | | **Smithwick Shale** | **Author** |
|---|---|---|---|---|---|---|
| | | | **Lower Member** | **Upper Member** | | |
| | | | Morrow Series | Bend Series | | Plummer, 1945 |
| | | | **Lower Marble Falls formation*** | **Upper Marble Falls formation*** | Smithwick formation | |
| | | | Sloan | Big Saline/Lemons Bluff | | |
| | | | Morrowan Series | **Atoka Series*** | | Spivey and Roberts, 1946 |
| | | | Absent or unnamed | Marble Falls limestone | Smithwick shale | |
| | | | Morrowan Series | Atoka Series | | Thompson, 1947 |
| | | | Marble Falls limestone (east of Cavern Ridge) | Big Saline limestone (west of Cavern Ridge) | Smithwick shale | |
| | | Morrow Series | | Lampasas Series | | Cheney, 1947 |
| Osage | Chester-Meramec | Bend Group | | | | |
| Chappel formation | Barnett formation | Comyn (subsurface) = Sloan formation (outcrop) | | Big Saline formation | Smithwick formation | |
| | | | Morrow Series | Bend/Atoka Series | | Plummer, 1950 |
| Kinderhook-Burlington | Chester | | Marble Falls Group | | | |
| Chappel formation | Barnett formation | | Sloan formation | Big Saline formation | Smithwick formation | |
| | | Morrow Series | | Atoka Series | | Turner, 1957 |
| Chappel limestone | Barnett formation | Comyn formation | Marble Falls limestone (east of Cavern Ridge) | Big Saline limestone (west of Cavern Ridge) | Smithwick shale | |

*Represents the proposal of a new name or rank

Table 4.1 - *Continued*

| **Chappel Limestone** | **Barnett Shale** | | **Comyn (subsurface only)** | **Marble Falls Formation** | | **Smithwick Shale** | | **Author** |
|---|---|---|---|---|---|---|---|---|
| | | | | **Lower Member** | **Upper Member** | | | |
| | | | | Morrowan | Atokan | | | UT students under supervision of W.C. Bell from 1957 to 1973 |
| | | | | Marble Falls Formation | | Smithwick Formation | | |
| Chappel Limestone | Barnett Formation | | | Lower Member | Upper/Middle Member | | | |
| Osage-Kinderhook Series | Meramec-Chester Series | | | Morrowan Series | Atokan Series | | | Kier *et al.* , 1980; Brown, 1983; Manger & Sutherland, 1984; Luker, 1985; Groves, 1991; Dihrberg, 1988; Erlich & Coleman, 2005 |
| Chappel Limestone | Barnett Formation/Shale | | | Marble Falls Formation/Limestone | | Smithwick Formation | | |
| | | | | Lower Marble Falls | Upper Marble Falls | | | |
| Osagean Stage | Chesterian-Meramecian Stage | | | Morrowan Stage | Atokan Stage | | | This paper |
| Chappel limestone | Barnett Formation | | | Marble Falls Formation | | Smithwick Shale | | |
| | lower Barnett Shale | Forestburg-Comyn limestone | upper Barnett Shale | lower Marble Falls | upper Marble Falls (SW) = Atoka Group (NE) | lower Smithwick Shale | upper Smithwick Shale | |

*Represents the proposal of a new name or rank

## Stratigraphy

The Carboniferous stratigraphy of the Fort Worth Basin is poorly understood on a regional scale because of the limited availability of high-quality well logs that have penetrated the Lower Pennsylvanian, Mississippian, and Ordovician systems. Additionally, most local operators are only concerned with the stratigraphy confined to the specific area they are drilling and, therefore, various names have been applied to the same stratigraphic unit in different areas of the basin. However, over the last decade a modern vintage of high-quality logs from deeper wells have become available and with advancements in geological mapping software, it is easier to conduct a regional subsurface study on the Carboniferous stratigraphy across the FWB.

The Early Pennsylvanian Marble Falls Formation was subdivided into upper and lower members separated by the Morrowan-Atokan unconformity (Brown, 1983; Dihrberg, 1988; Erlich & Coleman, 2005; Groves, 1991; Kier, 1980; Kuich, 1964; Luker, 1985; Manger & Sutherland, 1984; Turner, 1970). This unconformity is distinctly marked by a high-GR log response representing the upper maximum flooding surface (MFS) of the lower Marble Falls sequence. It can be traced regionally across the FWB from outcrop to the northernmost edge of the basin and is therefore used herein as a marker horizon and stratigraphic datum for cross-sections. This regional unconformity is also used to divide the lower member (Morrowan) from the upper member (Atokan), similarly to previous works. The upper member intertongues with the Atoka siliciclastic units (Bend Conglomerate) and Smithwick Shale in the central part of the basin and is not present north of the Mineral Wells – Newark East fault system. The lower Marble Falls was deposited across most of the FWB and is dominantly composed of a sequence that contains an unusually high concentration of sponge spicules. This sequence is referred to hereafter as the lower Marble Falls spiculite sequence and it records the influence of glacio-eustatic sea-level fluctuations with the high-frequency cycles that are present throughout this interval. Underlying the lower Marble Falls spiculite sequence east of Jack and Palo Pinto counties are five lithostratigraphic units of the Marble Falls Formation that were correlated and mapped across the study area and consist of a calcareous shale, upper limestone, upper shale, lower limestone, and lower shale.

The Barnett Formation in the northern part of the FWB is informally divided into three members that consist of four separate intervals referred to herein as the lower Barnett Shale (lower member), lower Barnett calcareous unit (lower member), Forestburg-Comyn limestone (middle member), and upper Barnett Shale (upper member). The upper Barnett Shale lies stratigraphically below the Marble Falls Formation and above the Forestburg-Comyn limestone, and in eastern Jack County it intertongues with the spiculite sequence of the lower Marble Falls. The Forestburg-Comyn limestone is present across the northern edge of the FWB and is marked by the first limestone unit that lies stratigraphically below the upper Barnett Shale or Marble Falls Formation. The lower Barnett calcareous unit lies directly beneath the Forestburg-Comyn limestone and grades downward into the typical lower Barnett mudstone facies. The lower Barnett Shale is characterized by the first high-GR/high-resistivity log response below either the calcareous unit, Forestburg-Comyn limestone, or Marble Falls Formation. This distinctive horizon can be continuously traced across the entire basin and is used herein as a marker bed and stratigraphic datum for cross-sections. The lower Barnett Shale is underlain by the Mississippian Chappel limestone along the Bend Arch to the west or unconformably by Ordovician carbonate rocks across most of the FWB.

The Late Mississippian to Early Pennsylvanian carbonate-rich sediments that lie above the lower Barnett Shale have greatly influenced the thickness and distribution of depositional facies within the overlying lower Marble Falls spiculite sequence, and the extensive correlation and mapping efforts from this study should enhance the general understanding of the stratigraphic relationship between these units. This data set reveals new thickness distributions and depositional characteristics of the following formations, members, or units that will be described and mapped from the lowermost stratigraphic interval (Chesterian-Mermacian) to the uppermost interval (Morrowan-Atokan): lower Barnett calcareous unit, Forestburg-Comyn limestone, Marble Falls lower shale, Marble Falls lower limestone, Marble Falls upper shale, Marble Falls upper limestone, Marble Falls calcareous shale, and the lower Marble Falls spiculite sequence. The lowermost stratigraphic interval will be discussed first working up through the stratigraphic section, and type-logs, cross-sections, and isopach maps will be provided for each interval.

## Lower Barnett Calcareous Unit

### *Introduction*

The Barnett Formation has been studied extensively since the start of the century with dozens of papers published on the depositional environment, lithofacies, reservoir properties, geochemistry, etc. There has been little published on the carbonate-rich facies within the Barnett Formation with most of the previous work only including the

Forestburg limestone interval (Bowker, 2007; Loucks and Ruppel, 2007; Pollastro *et al.*, 2007). However, observations from this work also reveal a newly defined calcareous unit at the top of the lower member of the Barnett Formation that is bounded at the top and base by maximum flooding surfaces and can be correlated and mapped across the basin as an individual sequence. This calcareous sequence is more closely related to the overlying Foresburg-Comyn limestone than the underlying lower Barnett Shale interval and appears to represent only slight changes in the depositional environment and source area compared to the Forestburg-Comyn limestone. This interval, referred to herein as the lower Barnett calcareous unit, is a sequence of interbedded limestone and calcareous mudstone that lies above the typical lower Barnett Shale interval and below the Forestburg-Comyn limestone.

Henry (1982) was the first to recognize a “calcareous shale interruption” in the Barnett Formation in southeastern Montague County. Although he mentioned the well in which this interval occurs, he does not provide the exact depths of the “calcareous shale interruption.” At the time of his publication there was a limited number of deep wells that penetrated the Mississippian or Ordovician systems in this area and the quality of well log data was poor. Therefore, Henry (1982) was not able to map the regional distribution of the calcareous shale and only identified the “calcareous shale interruption” in a number of wells in a north-south cross-section along the western edge of Montague County. Pollastro and others (2007) also discuss a highly calcareous section of the Barnett Formation and use the informal term “lime wash” which originated in a document supplied to the Texas Railroad Commission (2003) that referred to a thick limestone unit adjacent to the Muenster Arch. It is unclear exactly where the top and bottom of the “lime wash” occurs within the stratigraphic section, but a thickness map was provided over a small area confined to central Denton County adjacent to the Muenster Arch (Pollastro *et al*., 2007). Farrar (2010) is the only other available work that mentions a carbonate-rich unit within the lower member of the Barnett Formation and he followed Henry’s (1982) classification of the “calcareous interruption,” but only refers to this unit in cross-sections and does not provide an isopach or structure map defining its geographic extent. It is unclear if any of the previous work is referring to the same interval that has been identified and mapped in this study because no type logs were provided and it is difficult to determine the depths of this interval on the wells used in their cross-sections. Therefore, this will be the first study to define, correlate, and map this calcareous sequence lying stratigraphically below the Forestburg-Comyn limestone and above the typical lower Barnett Shale.

*Type Log and Well Log Characteristics*

The lower Barnett calcareous unit was deposited across the northern edge of the FWB and grades into a low-resistivity shale facies in south-central Clay County and north-central Jack County. This low-resistivity shale facies separates the calcareous unit into two geographically separate intervals which were deposited in similar depositional environments with slightly different well log characteristics. Therefore, there are two type logs provided for this unit that represent well log patterns of the western calcareous unit and eastern calcareous unit. The CA-TEX Drilling Prideaux ‘A’ No. 5 (42-009-43501) well in southeastern Archer County serves as the type log for the calcareous unit along the western edge of the FWB, and is defined as the interval from a measured depth of 5,170 to 5,272 feet (Figure 4-2). The Fuse Energy Duck No. 1P (42-497-36408) well in northwestern Wise County serves as the type log for the calcareous unit in the northeastern part of the FWB, and is defined as the interval from a measured depth of 6,489 to 6,685 feet (Figure 4-3). The lower Barnett calcareous unit and overlying Forestburg-Comyn limestone are separated by a maximum flooding surface that is typically identified on well logs by an increase in GR of >150 API units (Figure 4-2; Figure 4-3). In various areas within the basin the calcareous unit is gradational with the overlying Forestburg limestone and the maximum flooding surface that separates the two intervals is not well-developed. Therefore, a 10 to 20 feet shale interval present at the base of the Forestburg limestone is used to separate these two units and the top of the calcareous unit is picked at the base of this shale interval where the resistivity and PE values increase and the NPHI, DPHI, and GR values decrease. The base of the calcareous unit is clearly marked by the first high-GR/high-resistivity zone of the lower Barnett mudstone facies, but is not as easily defined near the Muenster Arch were it grades downward into a more calcareous facies of the lower Barnett Shale (Figure 4-2; Figure 4-3).

The log-curve patterns of the lower Barnett calcareous unit are similar to the overlying Forestburg-Comyn limestone but generally have lower PE and resistivity values and slightly higher GR values that signify less calcium carbonate and higher concentrations of clays (Figure 4-2; Figure 4-3). The neutron and density porosity curves display wide separation that is characteristic of most shales, but the slightly higher resistivity and PE values indicate this interval contains a higher concentration of calcite compared to a typical shale. This higher-than-normal calcite content is attributed to thin laminations of carbonate-rich sediment and well bedded shell fragments within a dominantly mudstone lithofacies that can only be recognized on micro-resistivity image logs or in core, the latter of which was not available for this work. The lower Barnett calcareous unit also displays distinct differences in well log patterns compared to the typical underlying lower Barnett mudstone facies because it is not as organic-rich and contains higher concentration of calcite that cause lower GR responses in well logs.

The lower Barnett calcareous unit can be classified as an argillaceous limestone or calcareous shale based on log-curve values which indicate both clay and calcite are present is varying amounts. It contains interbedded clay-rich sediments and carbonate-rich sediments that were deposited in shallowing-upward parasequences identified on the type logs shown in Figure 4-2 and Figure 4-3. These parasequences are distinct on well logs and can be correlated laterally across the northern FWB. They represent high-frequency depositional cycles that typically become more carbonate-rich near their tops, and are characterized on well logs by upwardly decreasing GR values, increasing resistivity values, increasing PE values, and decreasing NPHI and DPHI values. This highly cyclical sequence exhibit a wide range of well log values, with the mudstone lithofacies represented by GR values that range from 85 to 115 API, deep-resistivity values of 5 to 10 ohm-m, RHOB values of 2.5 to 2.6 g/cm$^3$ , DPHI values of 0.06 to 0.08 V/V, NPHI values of 0.24 to 0.30 V/V, and PE values from 3 to 4.1 b/e. The more carbonate-rich lithofacies have GR values that range from 62 to 90 API, deep-resistivity values from 12 to 25 ohm-m, RHOB values of 2.6 to 2.67 g/cm3, DPHI values of 0.025 to 0.065 V/V, NPHI values of 0.17 to 0.22 V/V, and PE values of 3.6 to 4.3 b/e. The low-resistivity shale facies that will be discussed below has GR readings averaging around 110 API, deep-resistivity values from 2 to 4 ohm-m, RHOB values around 2.44, DPHI values around 0.15 V/V, NPHI values around 0.35 V/V, and PE values of 2.64 b/e.

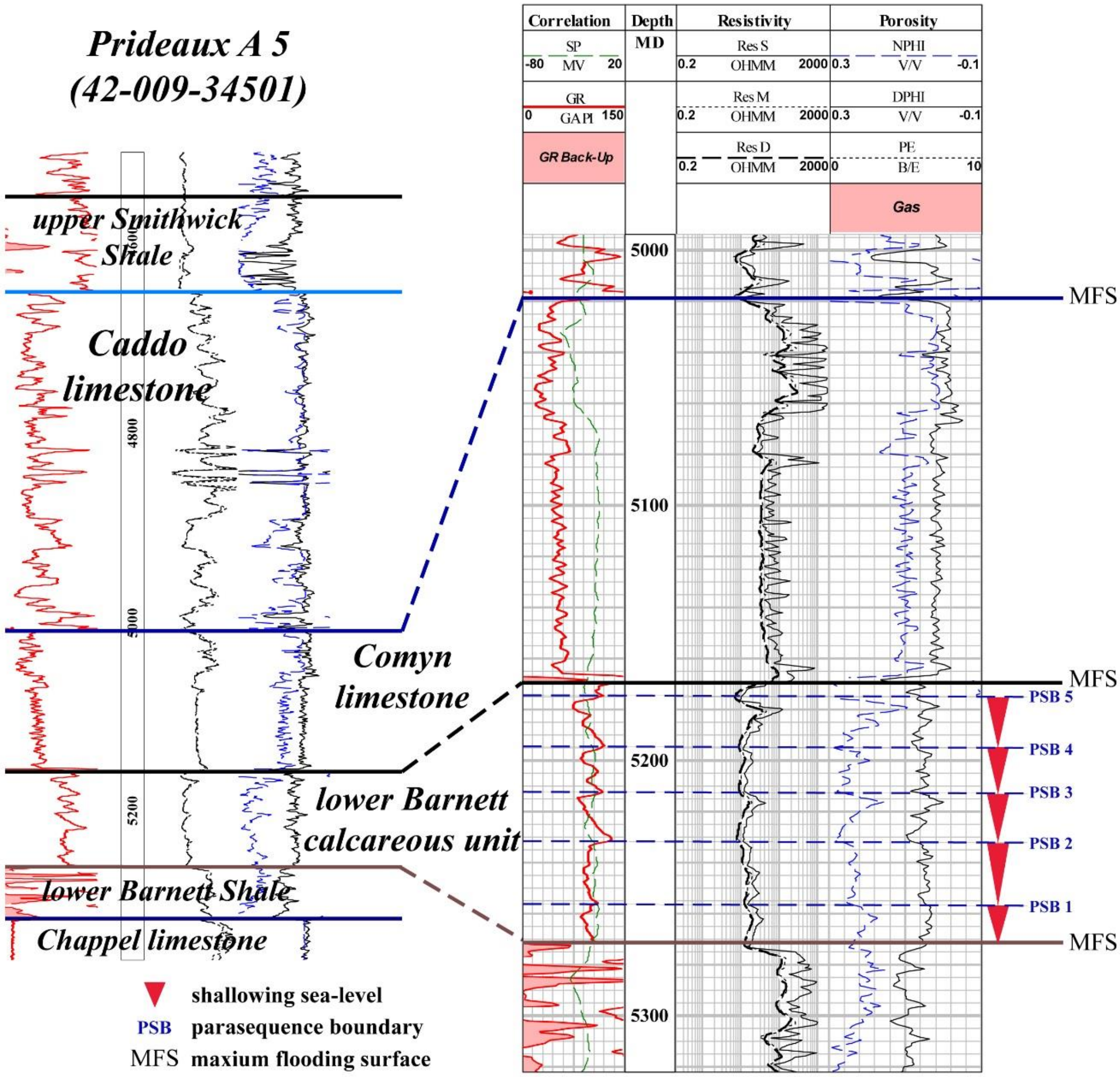



Figure 4-2. Type log of the lower Barnett calcareous unit from southeastern Archer County displaying typical well log characteristics and high-frequency shallowing-upward cycles.

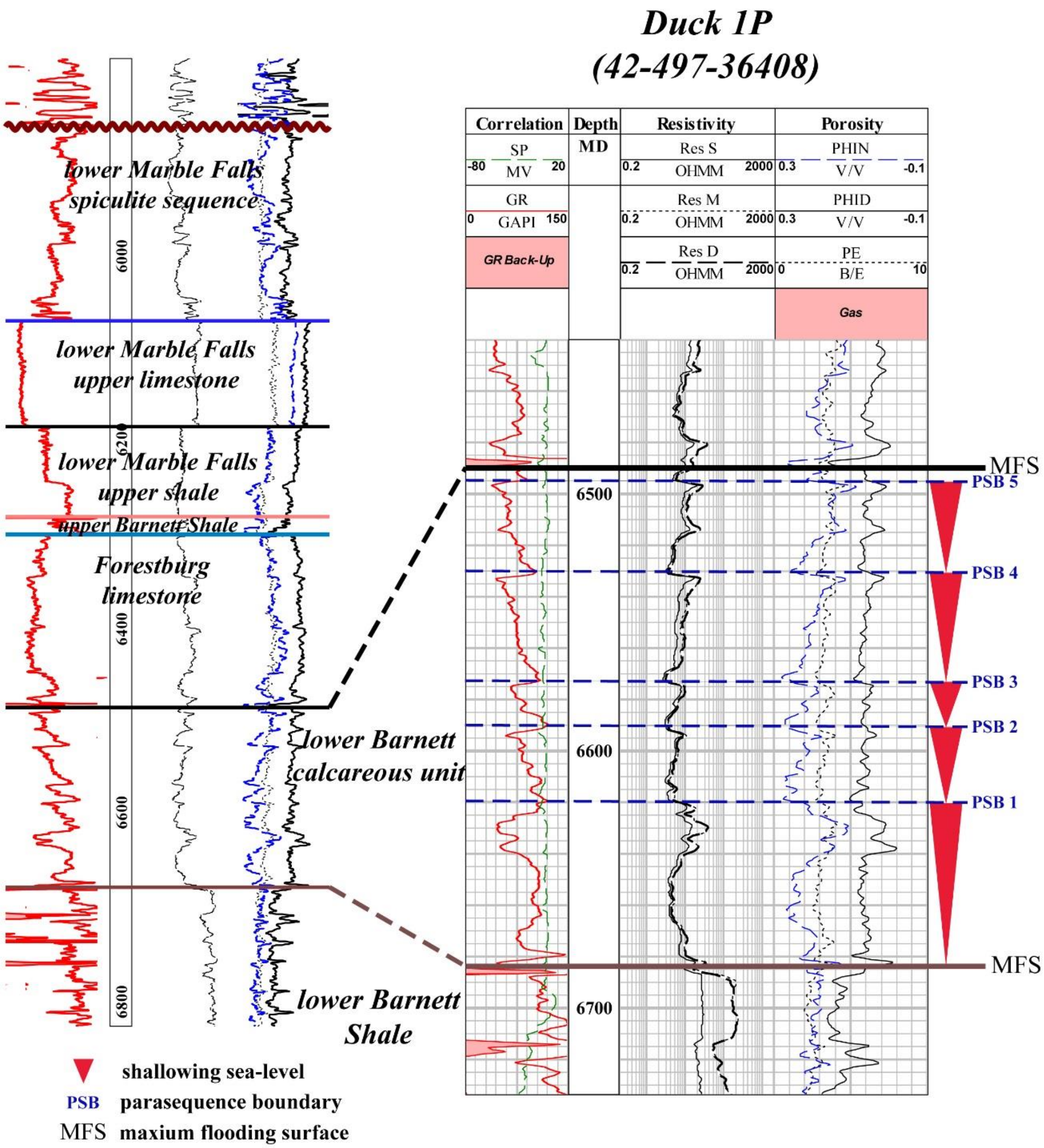



Figure 4-3. Type log of the lower Barnett calcareous unit from northwestern Wise County displaying typical well log characteristics and high-frequency shallowing-upward cycles.

*Depositional Environment*

Stratigraphic variations of the lower Barnett calcareous unit across the northern FWB was used in conjunction with image log data to help determine a likely depositional environment for this calcareous unit. An interesting characteristic of this unit compared to the overlying limestone and underlying lower Barnett mudstone facies is the evidence of more intense cyclicity across the FWB at the time the calcareous unit was deposited. There are up to 8 high-frequency cycles (HFC) identified within the calcareous unit that display the influence of Late Mississippian sea-level fluctuations (Figure 4-2; Figure 4-3). These parasequences range from over a 100 feet thick to less than 10 feet thick and reveal that this sequence was deposited at a time when the basin was experiencing sea-level fluctuations due to the waxing and waning of ice sheets or perhaps tectonically driven fluctuations from subsidence of the FWB (Figure 4-2; Figure 4-3). Compared to parasequences to the east, the parasequences in the northwestern part of the FWB are significantly thinner and most of them pinch-out toward to the south with only one shallowing-upward cycle present in the lower Barnett calcareous unit across most of western Jack, Young, and Throckmorton counties (Figure 4-4; Plate 2). The parasequences are much thicker in the calcareous unit to the east and reach maximum stratigraphic thicknesses of >120 feet along the southeastern edge of Clay County, northeastern edge of Jack County, and the southwestern edge of Montague County where there was an increase in accommodation space from the subsiding FWB to the east (Figure 4-3; Plate 1). The parasequences typically shallow upward from a mudstone lithofacies to a more carbonate-rich lithofacies, but the entire lower Barnett calcareous sequence represents an overall deepening-upward cycle with thicker and more carbonate-rich cyles lower in the section.

The lower Barnett calcareous unit was deposited in a similar environment to the Foresburg-Comyn limestone but contains a slightly higher concentration of clay and lower concentration of calcite. This could possibly reflect a gradual shift in source area from a silica-rich sediment source for the lower Barnett siliceous mudstone facies to a more carbonate-dominated sediment source for the Foresburg-Comyn limestone, or may represent a slight change in sea level, sea water chemistry, or sea water circulation compared to the overlying limestone (Loucks and Ruppel, 2007). The carbonate sediments within the calcareous unit were most likely sourced from the same area as the Forestburg-Comyn limestone, and Bowker (2007) proposes a provenance to the north in southern Oklahoma whereas Loucks and Ruppel (2007) propose the western margin of the FWB as a possible source area. It is not entirely clear where the carbonate sediments within this calcareous sequence were sourced, but the thickness distribution of the calcareous unit (and Forestburg-Comyn limestone), and the fact that both of these carbonate units are only present in the northern part of the basin suggest a more probable source area to the north, with the subsiding FWB and positive relief of the Muenster Arch to the northeast controlling sediment distribution.

The author had no access to core through this calcareous unit so it was difficult to determine the depositional environment, and the only other data that was available besides open-hole wireline logs were two high-resolution micro-resistivity image logs that displayed small-scale sedimentary features used to better understand the various depositional processes affecting distribution of sediments. Figure 4-4 shows the calcareous unit on the open-hole wireline log (left) and image log (right) in the Newark E&P Buckner No. 1 located in northwest Jack County. The ~15 feet of section shown in the image log displays the abundance of well bedded shell fragments (white specks) that are interbedded with thin laminations of carbonate-rich sediments and clay-rich sediments (Figure 4-4). The availability of more image logs or cores through this unit, especially where it is well developed along the southwestern edge of Montague County and eastern edge of Clay County, would help determine a more accurate depositional model for the lower Barnett calcareous sequence. However, based on the image logs that were available it is speculated that this unit may have been deposited in a carbonate tidal flat environment in the form of thin laminations of interbedded clay-rich sediments and carbonate-rich sediments containing abundant shell fragments. The low-resistivity shale facies in south-central Clay and northern Jack counties may represent some type of tidal channel that cut through the accumulation of carbonate-rich sediments to the east and west (Figure 4-5; Figure 4-6). It is not entirely clear what this depositional feature is but there is evidence presented in subsequent sections that reveal this feature persisted through time.

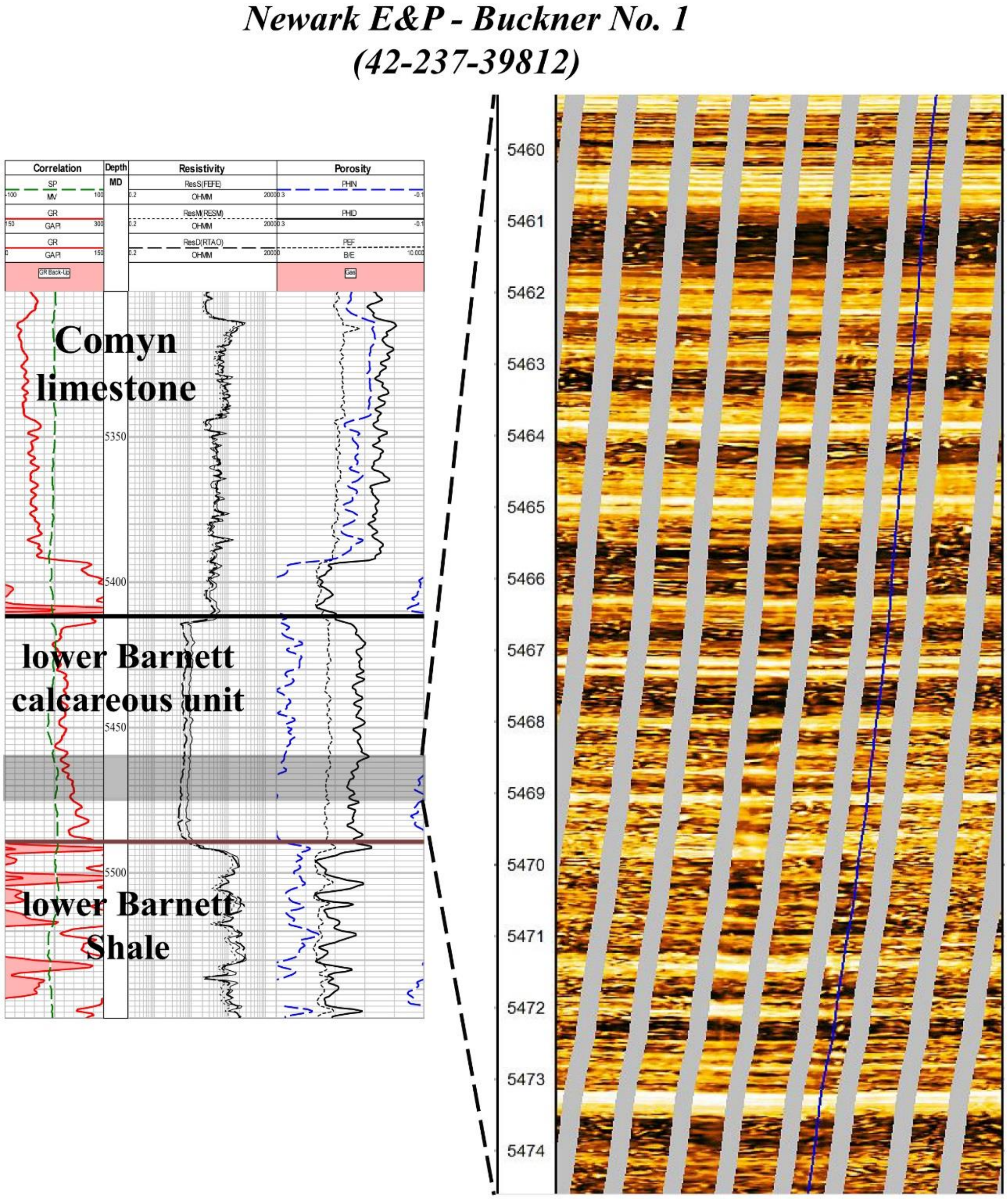



Figure 4-4. Newark E&P Buckner No. 1 open-hole well log on the left showing typical characteristics of the lower Barnett calcareous unit and a portion of the image log on the right displaying well bedded shell fragments (small light yellow to white features) and thinly laminated carbonate-rich beds that give it a high PE well log signature.

*Paleogeography and Lithofacies Distribution*

This sequence of interbedded limestone and calcareous mudstone of the lower Barnett calcareous unit starts to develop in the uppermost section of the lower member of the Barnett Formation along a northwest-trend from northeast Jack County to central Wise County (Figure 4-5). It becomes progressively more calcareous to the east and northeast and eventually becomes indistinguishable from the lower Barnett Shale near Muenster Arch where the entire Barnett succession is composed almost entirely of a limestone facies. The thickest part of this calcareous unit was deposited along a northwest-trend through eastern Clay County, southwest Montague County, and northwest Wise County. It reaches its maximum stratigraphic thickness of around 250 feet in southeast Clay County just north of the small town of Newport, Texas (Figure 4-5). This thick section of the lower Barnett calcareous unit trends parallel to the Muenster arch and extends down into northern Wise County near the town of Alvord (Figure 4-5; Plate 1). It starts to thin toward the east and northeast as it grades into another limestone facies of the Barnett Formation and thins toward the south and southwest as it pinches out and grades down into the typical organic-rich mudstone facies of the lower Barnett Shale (Figure 4-5).

The area adjacent to the Muenster Arch where the Barnett Formation is composed almost entirely of carbonate-rich sediments was not included in the thickness map in Figure 4-5 because of the difficulty distinguishing the calcareous unit from the lower Barnett Shale below and the Forestburg limestone above. Therefore, the eastern edge of the isopach denoted by the dashed blue line represents an arbitrary line where the lower

Barnett calcareous unit grades into a dominantly limestone facies and can no longer be distinguished from the lower Barnett Shale. The dark gray dashed line that surrounds the isopach map denotes the estimated subcrop of the lower Barnett calcareous unit where it pinches out or grades into another facies and could no longer be identified. The northeast dashed line trending from the Muenster Arch to the west through central Montague County represents the transition from the carbonate-rich lower Barnett calcareous unit into another facies of the lower Barnett Shale that could not be distinguished on well logs.

The lower Barnett calcareous unit thins to the west and southwest from its thickest section in southeastern Clay County and begins to lose most of its calcite content as it gradually grades into a low-resistivity shale facies designated by the dashed gray line in Figure 4-5 and identified by the lime-green color fill in the cross-section shown in Plate 1. This low-resistivity shale facies is only present in south-central Clay County and north-central Jack County and reaches maximum stratigraphic thickness of around 125 feet along the western edge of Clay County just northeast of the town of Windthorst (Figure 4-6; Plate 2). It thins rapidly to the northeast and pinches-out along the same east-west trending subcrop of the lower Barnett calcareous unit. The low-resistivity shale also becomes laterally gradational with the Forestburg-Comyn limestone toward the south as its geographic extent begins to narrow into a wedge-shaped feature in central Jack County (Figure 4-5; Figure 4-6).

The low-resistivity shale grades into another calcareous unit to the west along a northwest trend from central Jack County to the town of Windthorst in southeastern

Archer County (Figure 4-5; Figure 4-6; Plate 1). Maps or descriptions of the calcareous unit that has developed along the western edge of the FWB have never been published and it was observed to have been deposited over a large area across the northwestern part of the FWB (Figure 4-5). The calcareous unit to the west has similar well log response patterns to the calcareous unit to the east and the two units were determined to be stratigraphically equivalent with the low-resistivity shale facies separating the two (Figure 4-5; Plate 1). The calcareous unit to the west lies above the typical lower Barnett mudstone facies and below the Comyn limestone but is considerably thinner compared to the overall thickness of the calcareous unit to the east. The thickest part of the calcareous unit to the west is present in southeast Archer County where it reaches its maximum stratigraphic thickness of over 150 feet and slowly thins to the west where it has a uniform thickness of around 40 to 80 feet across southern Archer County, northern Young County, and most of Throckmorton County (Figure 4-5; Plate 2). The northwestern subcrop limit of the calcareous unit is estimated because complex stratigraphic variations of this sequence were controlled by the underlying Chappel shelf. The calcareous unit thins to the south and southeast as it pinches out along a distinct northeast-trend from central Shackelford County through northern Stephens County, southeastern Young County, and into west-central Jack County (Figure 4-5; Plate 2)

As previously discussed, the thickness map in Figure 4-5 displays two areas where the lower Barnett calcareous unit is notably thicker, with the depositional axis trending parallel to the Muenster Arch through eastern Archer and southwestern Clay counties, and through southeastern Clay, southwestern Montague, and northwestern Wise counties. The thickness trends of the calcareous unit is similar to the Forestburg-Comyn limestone lying above and the paleogeography of these units indicates that the calcareous unit was deposited slightly north to northwest of the overlying Forestburg-Comyn limestone. This further supports the hypothesis that the lower Barnett calcareous unit and Forestburg-Comyn limestone are two separate carbonate-rich sequences that were deposited in similar depositional environments with a slight shift in source area or distance away from the source area. This shift in the depositional axis to the southeast occurred due to the continuous subsidence of the FWB and the influence of the Muenster Arch as it was beginning to show prominent relief during the Late Mississippian (Walper, 1982).

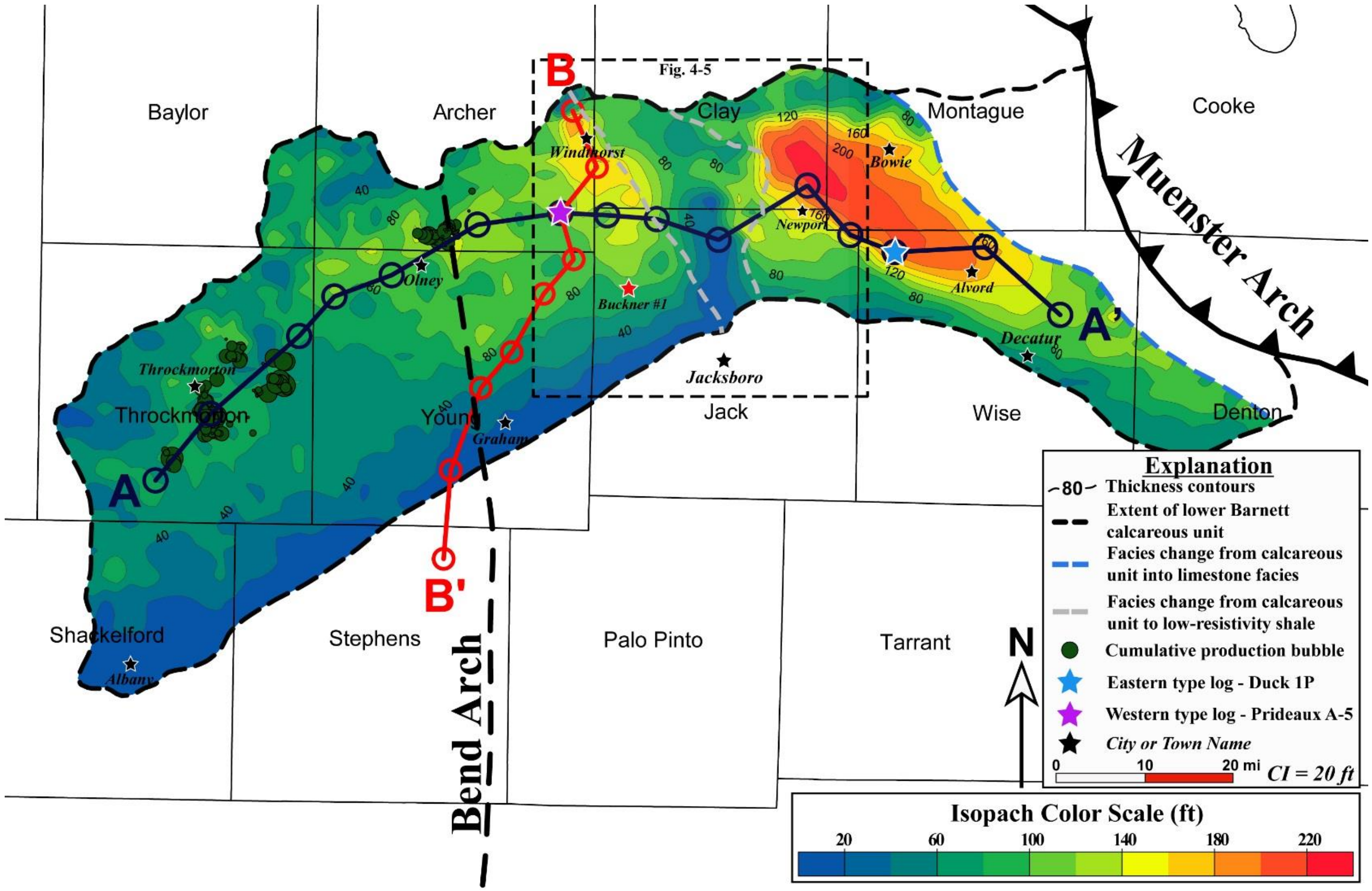



Figure 4-5. Isopach map of lower Barnett calcareous unit displaying thickness trends and its paleogeographic extent across the Fort Worth Basin. Locations of key wells are noted by the stars and referenced in the legend. An east-west cross-section line is shown in black with each circle representing the location of well logs used in cross-section A – A' in Plate 1. A north-south cross-section line is shown in red with each circle representing the location of well logs used in cross-section B - B' in Plate 2.

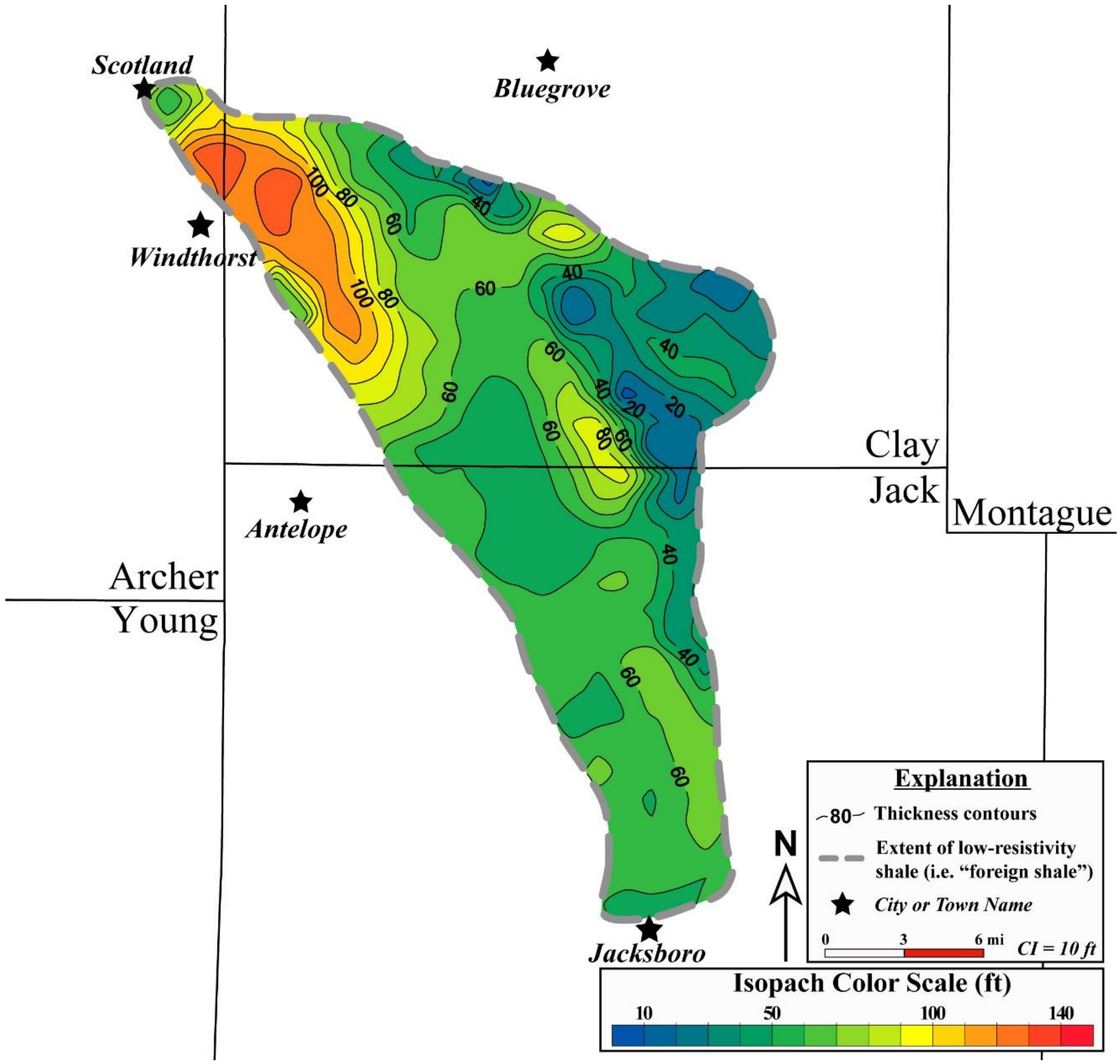



Figure 4-6. Isopach map of the low-resistivity shale facies that is interbedded and laterally equivalent to the lower Barnett calcareous unit.

*Reservoir Properties*

The lower Barnett calcareous unit is typically not productive because of its poor reservoir quality, but there are a few areas along the western and northwestern edges of the basin near the Comyn limestone subcrop where the calcareous unit develops into a porous limestone that is highly productive. The porosity development typically occurs in chert deposits that formed at the top of the calcareous unit during a period of subaerial exposure. The prospective zones were historically evaluated using electric logs and the target intervals for completion were identified by negative SP development representing higher permeability zones. There were 5 large fields discovered in eastern Throckmorton County and south-central Archer County with over 150 wells producing on average around 30,000 to 50,000 bbls of oil per well; a few produced over 100,000 bbls of oil in the lifetime of the well (Figure 4-5). The cumulative production for all 150+ wells is estimated at around 5 million barrels of oil and 6 billion cubic feet of gas. Although this porosity zone in the lower Barnett calcareous unit is typically <30 ft thick along the western edge of the FWB, there are a number of areas identified by the author where this zone could have potential for future development. In the northeast part of the basin adjacent to the Muenster Arch the lower Barnett calcareous unit becomes significantly more calcareous and occasionally develops into a porous limestone that was targeted in a number of wells but was not very productive.

## Forestburg-Comyn Limestone

### *Forestburg Limestone*

The Forestburg limestone was first defined by Henry (1982) as the carbonate formation that lies above the Barnett Formation from a measured depth of 7,190 to 7,414 feet in the Resources Investment Corporation Rector No. 1 well located approximately 1 mile northwest of the town of Forestburg in southeast Montague County. The interval he identified in that well is actually the lower Barnett calcareous unit identified in this study and the Forestburg limestone as it is defined herein lies stratigraphically above this interval from 6,947 to 7,191 feet. The Forestburg limestone discussed by Bowker (2003, 2007), Loucks and Ruppel (2007), and Pollastro *et al.* (2007) is equivalent to the Forestburg limestone identified and mapped in this study and is defined as the carbonate-rich interval that splits the Barnett Formation into upper and lower members in the area of the Newark East field. It is unclear how this interval mistakenly became known as the Forestburg limestone, but it is important to note that the Forestburg limestone as it is presently defined is not the same interval that was originally defined by Henry (1982). There may have been some confusion among the first Barnett workers who were unfamiliar with how the Forestburg limestone was originally defined, but the new modified definition of the Forestburg limestone has been used in all subsequent work and is continued herein.

The Forestburg limestone has only briefly been mentioned by previous workers because it’s a non-productive interval and the only real importance it has to exploration is as an impermeable upper barrier to the vertical growth of induced fractures during completion of horizontal lower Barnett Shale wells (Pollastro *et al.*, 2007). Pollastro *et al*. (2007) and Bowker (2007) are the only known publications to include a thickness map of the Forestburg limestone, which is incomplete because the map was excerpted from a hearing at the Texas Railroad Commission in 2003 and was created during the early stages of the Barnett Shale play when there was a limited number of deep wells that penetrated the Mississippian system. Despite the abundance of wells that have subsequently been drilled targeting the Mississippian Barnett Formation over the last 10-15 years, there have been no updated maps published on the Forestburg limestone and/or the Barnett Formation. The availability of modern well logs with deeper well control has presented the opportunity to evaluate and map the Forestburg limestone in greater detail to better understand the stratigraphic variations and depositional extent across the basin. There were no whole cores through the Forestburg limestone examined during this study and this work is based on extensive correlations of open-hole well logs, examination of micro-resistivity image logs, and data from two side-wall cores.

### Type Log and Well Log Characteristics

The Enervest Downe Arthur No. 4 (42-497-35049) well located along the eastern edge of Wise County serves as the type log for the Forestburg limestone which is defined as the interval from a measured depth of 7,406 to 7,738 feet (Figure 4-7). The Forestburg limestone was divided into three units informally defined as the lower Forestburg, middle Forestburg, and upper Forestburg. The type log was selected just to the south of where the Forestburg limestone reaches its maximum stratigraphic thickness in northeast Wise

County because the characteristics of these units are best represented on the open-hole well log provided (Figure 4-7). The lower Forestburg is defined as the interval from a measured depth of 7,651 to 7,738 feet, the middle Forestburg is defined as the interval from a measured depth of 7,484 to 7,651 feet, and the upper Forestburg is defined as the interval from a measured depth of 7,406 to 7,484 feet (Figure 4-7).

The limestone intervals within the Forestburg limestone sequence are composed dominantly of carbonate-rich sediments with high concentrations of calcite that gives it a vertically consistent well log response pattern with low GR, high ILD, and high PE (~5 b/e) values (Figure 4-7). The shale intervals are composed of higher concentrations of clay-rich sediments but also contain thin laminations of carbonate-rich sediments that make these intervals more calcareous with only slightly higher GR readings and slightly lower ILD and PE readings compared to the limestone intervals (Figure 4-7). The limestone and calcareous shale intervals within the Forestburg limestone sequence are gradational across most of the basin and are occasionally difficult to distinguish. However, they were correlated based on a thorough understanding of the regional stratigraphy. The limestone intervals were typically defined by GR values that range from 25 to 40 API, ILD values from 75 to over 200 ohm-m, RHOB values of 2.68 to 2.72 g/cm$^3$, DPHI values of 0.04 to 0.00 V/V, NPHI values of 0.06 to 0.02 V/V, and PE values from 4.5 to 5 b/e. The shale intervals have more sporadic well log response patterns, but they are typically defined by GR values that range from 70 to 90 API, ILD values from 10 to 25 ohm-m, RHOB values of 2.62 to 2.65 g/cm3, DPHI values of 0.03 to 0.08 V/V, NPHI values of 0.15 to 0.22 V/V, and PE values of 3.5 to 4.0 b/e.

Downe Arthur No. 4
(42-497-35049)

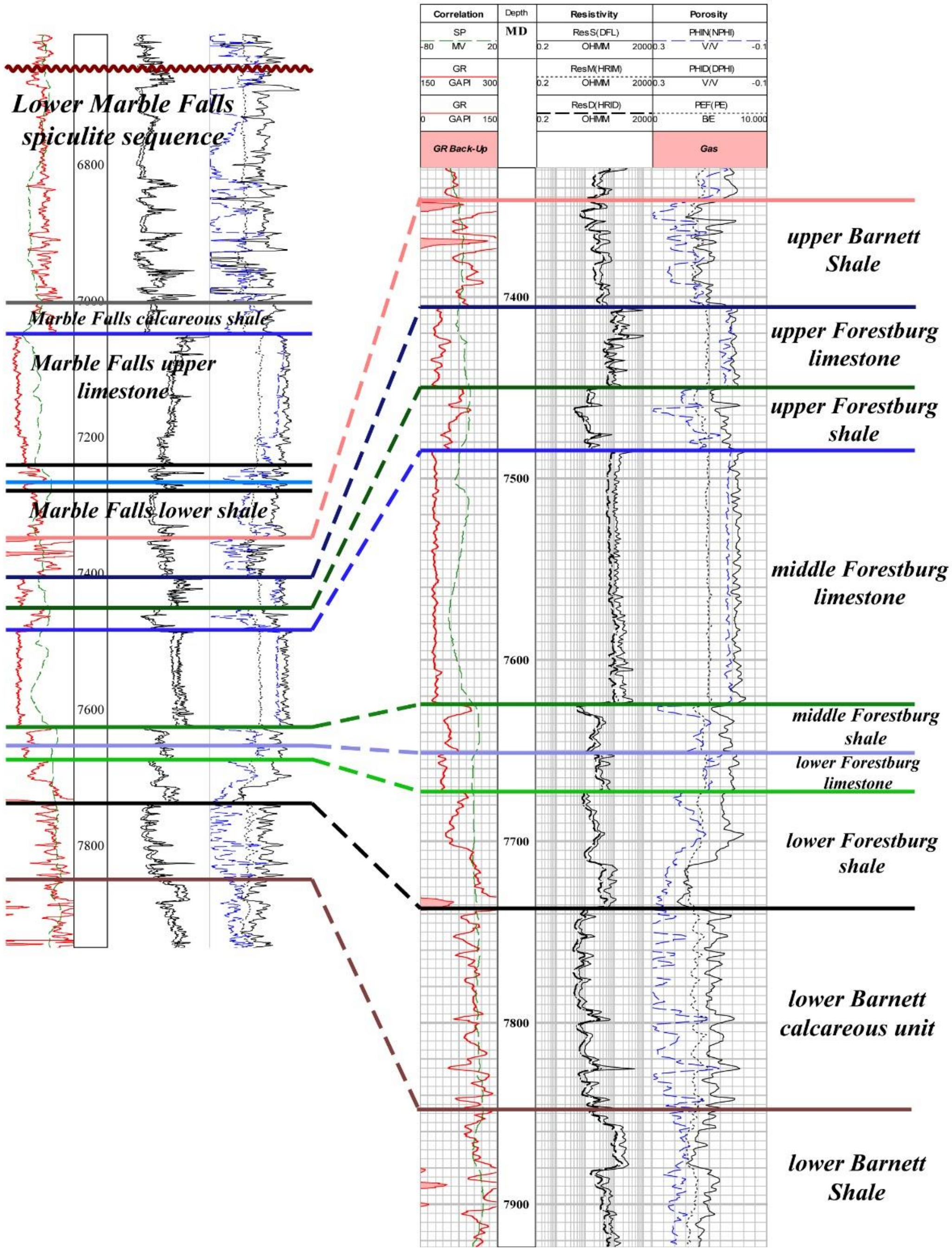



Figure 4-7. Type log of the Forestburg limestone displaying typical well log characteristics of interbedded limestone and shale intervals. Each unit of the Forestburg limestone was identified to the right of the expanded wireline log.

Lithofacies Description

The lithological characteristics of the Forestburg limestone were determined from side-wall core data, petrophysical data, and open-hole well logs. The author was not able to examine any whole cores through the Forestburg limestone, but the side-wall core data available for this study was compared to observations made by Loucks and Ruppel (2007) on various lithofacies within the Barnett Formation specifically those that comprise the Forestburg limestone. Loucks and Ruppel (2007) examined four whole cores from the Barnett Formation that were extracted from wells located in Erath and Wise counties. Only two of these cores sampled the Forestburg limestone including the Devon Energy Adams Southwest No. 7 in southwestern Wise County, and the Texas United Blakely No. 1 well in southeast Wise County. Loucks and Ruppel (2007) identified the carbonate-rich lithofacies that comprises most of the Forestburg limestone as a laminated argillaceous lime mudstone that is dominated by the mineral calcite and contains up to 21% dolomite, 30% clay and 28% other noncarbonated minerals. Papazis (2005) also examined the same cores and briefly discusses the high calcite content within this facies and mentions it can be classified as a limestone and categorized according to Folk's and Dunham's carbonate classification.

The carbonate-rich lithofacies of the Forestburg limestone was sampled with two side-wall cores at a measured depth of 5,960 feet and 6,000 feet in the Newark E&P Stewart No.1 well from eastern Jack County. The location of each side-wall core is shown in Figure 4-8 with a simplified mineralogy log displaying the characteristically high concentrations of calcite present in the Forestburg limestone. Unfortunately, there were only two side-wall cores taken from the middle limestone interval in this well and the shale intervals were not sampled. Thin section analysis reveal the limestone interval is composed pre-dominantly of an argillaceous dolomitic lime mudstone (A & B) and a slightly dolomitic limestone that contains minor amounts of detrital clays (C) (Figure 4-8). Image A and B shown in Figure 4-8 are photomicrographs from the 5,960 feet core sample in 50x and 200x magnification, respectively, and represent the argillaceous lime mudstone with the darker brown to black hue (A) signifying a higher concentration of clay. Image C is from the 6,000 feet core sample and represents the slightly dolomitic limestone lithofacies that contains abundant silt-size calcite crystals that are <0.02 mm in diameter and is therefore classified as a lime mudstone or micritic limestone (Figure 4-8). The mineral dolomite is present in variable amounts throughout the Forestburg limestone and is normally characterized by its light off-white to opaque, rhombohedral, euhedral crystals (Figure 4-8). Fossils are not an abundant constituent of the Forestburg limestone but there were various undifferentiated fossil fragments identified in thin sections (Figure 4-8). Both micro-resistivity image logs and thin sections have provided evidence that fractures commonly occur in the Forestburg limestone and while most of these are lithology-bound fractures, there are also mineral-filled fractures that are typically filled with calcite and more rarely with dolomite (Figure 4-8)

High-resolution micro-resistivity image logs were obtained over the entire Forestburg limestone interval and reveal that it is composed of interbedded laminations of mudstone and limestone that Loucks and Ruppel (2007) interpret as “interbedded layers of carbonate particles containing minor clay and carbonate particles with abundant clay.”

These high-resolution image logs were used to examine small-scale sedimentary features and thin laminated beds within the Forestburg limestone that could not be resolved with a standard open-hole well log. In Figure 4-9 there are two separate images presented from the Forestburg limestone, with image (A) representing typical characteristics of the limestone interval, and image (B) displaying the characteristics of a typical shale interval. The Forestburg shale intervals (B) are composed of clay-rich sediments that range from laminae to very thin (1-3 mm) to medium (10-30 mm) beds. The limestone intervals are compromised mostly of thick (30-100 mm) to very thick (100+ mm) carbonate-rich beds (Figure 4-9). An important observation that can be made from the images in Figure 4-9 is that the limestone interval on the left contains thin interbedded mudstone lithofacies among dominantly thicker carbonate-rich beds; and the shale interval on the right contains thin laminated beds of carbonate-rich sediments among dominantly clay-rich sediments (Figure 4-9). The typical 2 samples per foot of resolution from a standard open-hole was not able to distinguish thinner beds <0.5 feet, so when the carbonate-rich beds are thicker and more prominent the log-curve readings will appear as a limestone and when the clay-rich beds are more prominent the log-curve readings will display characteristics typical of a shale. Each of the three units that were identified within the Forestburg limestone are composed of clay-rich shale intervals that shallow-upward into thicker, more carbonate-rich sediments near the top. These sequences are typically bounded at the top by an erosional marine-flooding surface that represents an abrupt change in depositional facies (Figure 4-9).

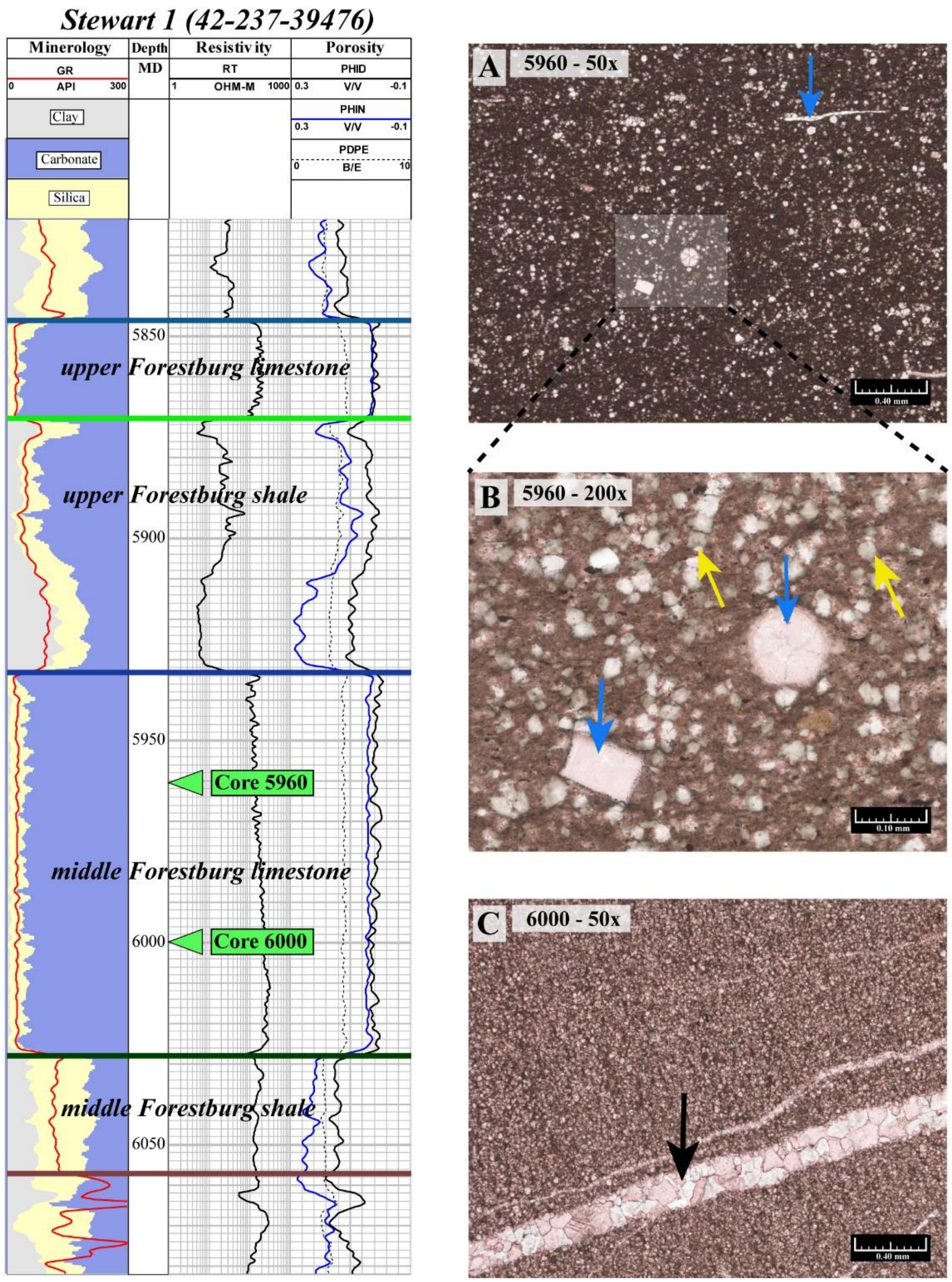



Figure 4-8. A simplified mineralogy log of the Newark E&P Stewart No. 1 on the left with locations of side-wall cores and photomicrographs on the right displaying common lithologies. A and B) slightly argillaceous, slightly dolomitic lime mudstone with yellow arrows indicating dolomite grains and blue arrows showing undifferentiated recrystallized fossil fragments. C) Slightly dolomitic limestone with high concentrations of calcite (stained red) and a calcite/dolomite filled fracture indicated by the black arrow.

**A** - limestone interval with thick carbonate-rich beds

**B** - shale interval with very thin clay-rich beds

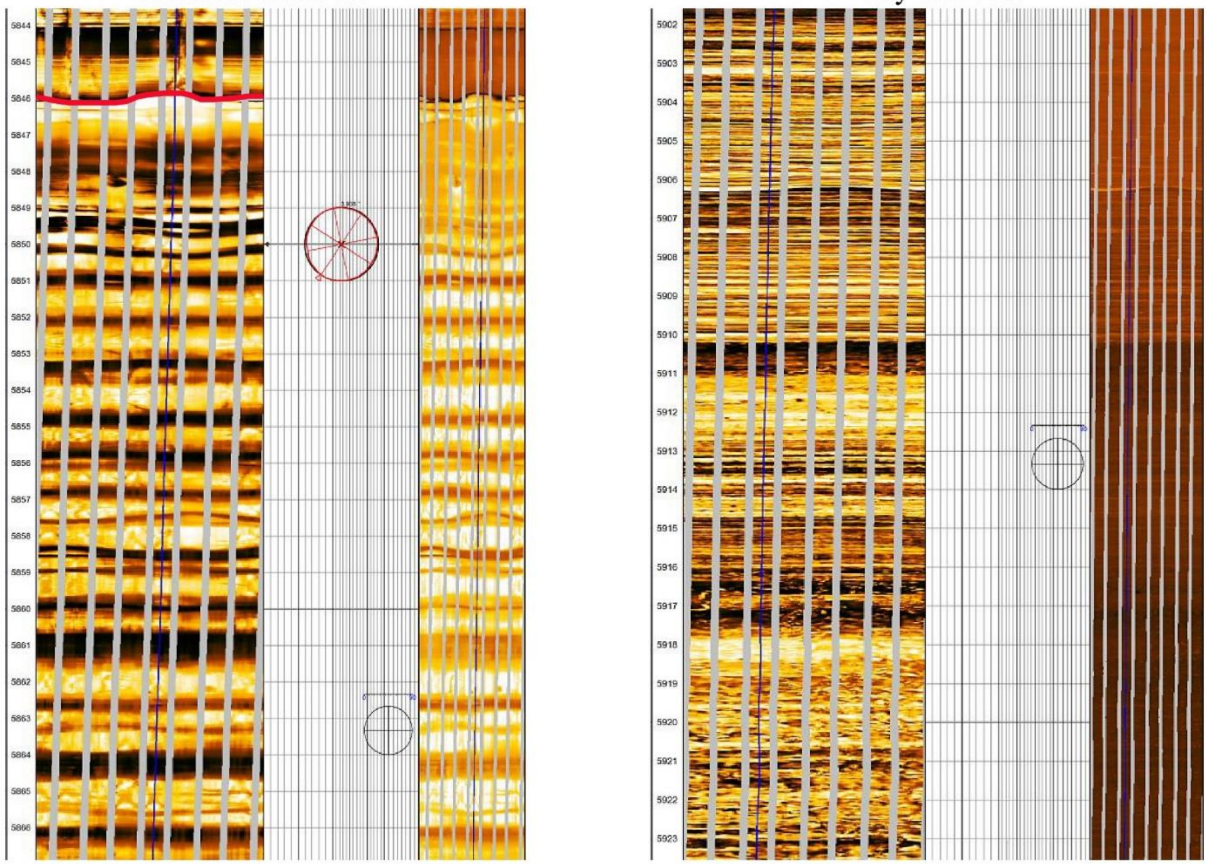


Figure 4-9. Two intervals of the image log from the Newark E&P Stewart No. 1 well displaying typical characteristics of a limestone interval on the left with thicker carbonate-rich beds and a shale interval on the right with thin laminae bedding; the red line at the top of the left image marks the top of the Forestburg limestone and represents an irregular and abrupt erosional contact with the overlying upper Barnett Shale.

Paleogeography

The Forestburg limestone is a sequence of interbedded limestone and mudstone that lies stratigraphically above the lower Barnett Shale or lower Barnett calcareous unit, and below the upper Barnett Shale or, the Marble Falls Formation where the upper Barnett is absent. The Forestburg limestone does not crop out at the surface and is only present in the subsurface in the northeastern edge of the FWB (Figure 1-1). It is less than a few feet thick in northeastern Palo Pinto County and along the northern edge of Parker and Tarrant counties where it splits the Barnett Formation into upper and lower members (Figure 4-10; Plate 3). It becomes progressively thicker to the north and northeast and reaches maximum stratigraphic thickness of >400 feet in northeast Wise County adjacent to the Muenster Arch (Figure 4-10; Plate 3; Plate 4). This thick section of the Forestburg limestone trends parallel to the Muenster Arch and extends from an area south of Bowie in southern Montague County to the southeast into western Denton County (Figure 4-10). The dashed blue line along the southeast corner of the isopach map marks the eastern limit of available control points due to the limited number of wells that have been drilled in this area (Figure 4-10). However, the Forestburg limestone most likely extends farther to the southeast and possibly reaches the Ouachita Thrust Front.

Along the northeastern edge of the isopach map near the town of Forestburg in southeastern Montague County, the Forestburg limestone becomes more difficult to distinguish from the underlying lower Barnett calcareous unit because nearly the entire Barnett section adjacent to the Muenster Arch is composed of a carbonate-rich facies (Figure 4-10; Plate 3). However, there is a distinct high-GR maximum flooding surface at the top of the lower Barnett calcareous unit that occurs across most of the area where the Forestburg limestone is present, and this contact marks the boundary between the Forestburg limestone and lower Barnett calcareous unit.

The northern subcrop boundary is controlled by a regional erosional unconformity that cut through the Forestburg limestone and was proposed by Henry (1982) to have been related to the Nocona - Saint Jo fault trending east to west through central Montague County. He discusses this regional unconformity and the fact that it is present at different stratigraphic intervals throughout the FWB and has cut through parts of the Lower Pennsylvanian and Mississippian strata (Henry, 1982). This work corroborates Henry's (1982) interpretation and this Atokan-age angular unconformity has been defined across northeastern Jack County and southern Montague County and the northernmost subcrop limits of the lower Barnett Shale, Forestburg limestone, and lower Marble Falls migrate progressively to the south as this unconformity erodes each of these stratigraphic units through times.

The Forestburg limestone gradually thins to the west and southwest away from the Muenster Arch and is interbedded with the Comyn limestone in south-central Jack County and northern Palo Pinto County where the two units are undifferentiated (Figure 4-10; Plate 4). There is a thicker stratigraphic trend in northeast Jack County that is bordered to the east by an unusually thinner area that both parallel the Muenster Arch (Figure 4-10). The Forestburg limestone was probably deposited uniformly throughout this part of the basin and the stratigraphic thinner area was exposed to erosion. There were limited data points in central and western Wise County but the Forestburg

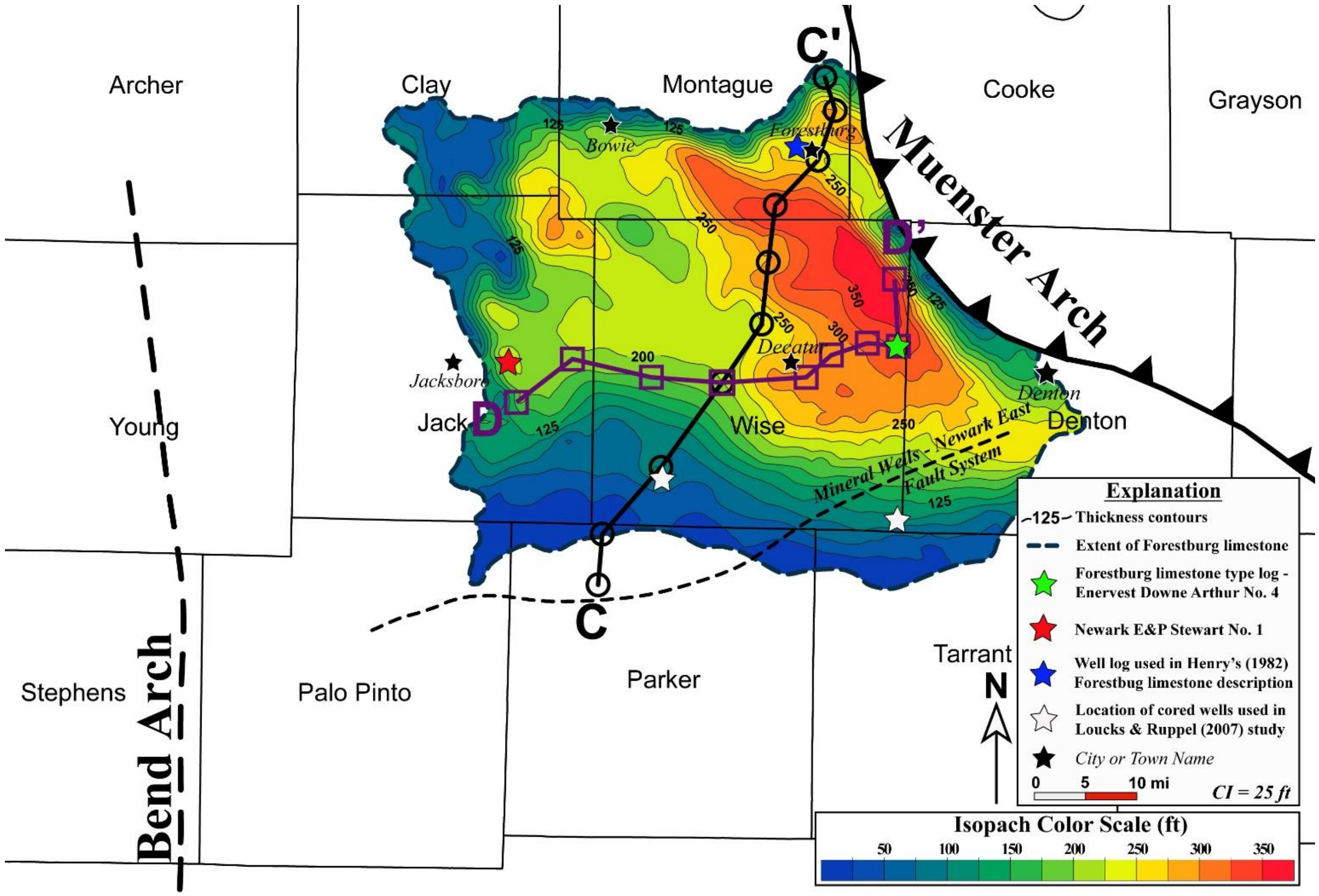



Figure 4-10. Isopach map of the Forestburg limestone displaying thickness trends and its paleogeographic extent across the northeastern part of the Fort Worth Basin. Locations of key wells are noted by the colored stars and referenced in the legend. A north-south cross-section line is shown in black with each circle representing the locations of well logs used in cross-section C – C' in Plate 3, and an east-west cross-section line is shown in purple with each square representing the locations of well logs used in cross-section D – D' in Plate 4.

limestone displays fairly uniform thicknesses of around 200 feet across most of this area (Figure 4-10; Plate 3; Plate 4). Along the eastern edge of Jack County the Forestburg limestone remains around 200 feet thick but just east of the town of Jacksboro it thins abruptly and is replaced by the overlying Marble Falls Formation (Figure 4-10).

In north-central Jack County and south-central Clay County, the Forestburg limestone becomes significantly thinner and grades upwards into the Marble Falls Formation, which makes it difficult to distinguish them on well logs. The Forestburg limestone is also interbedded with the lower Barnett calcareous unit in north-central Jack County and due to the complicated stratigraphy in this area, the various units of the Forestburg limestone were not correlated and the gross thickness was only included in the isopach map shown in Figure 4-10.

The lower unit of the Forestburg limestone is defined as the interval that lies above the lower Barnett Shale or lower Barnett calcareous unit, and below the middle Forestburg unit (Figure 4-7). It is gradational with the middle shale interval and was only correlated and mapped across an area where it could be distinguished from the overlying interval by a shallowing upward sequence that is capped by a marine flooding surface (Figure 4-7; Figure 4-11; Plate 4). It is composed of more clay-rich sediments compared to the overlying middle and upper Forestburg units that both contain massive limestones (Figure 4-7). The paleogeography of the lower unit extends southeast from Clay County into northern Wise County and pinches out in western Denton County (Figure 4-11). The thickest section of this unit was deposited in northeast Wise County where it is dominantly composed of mudstone-rich sediments that grades upwards into the middle

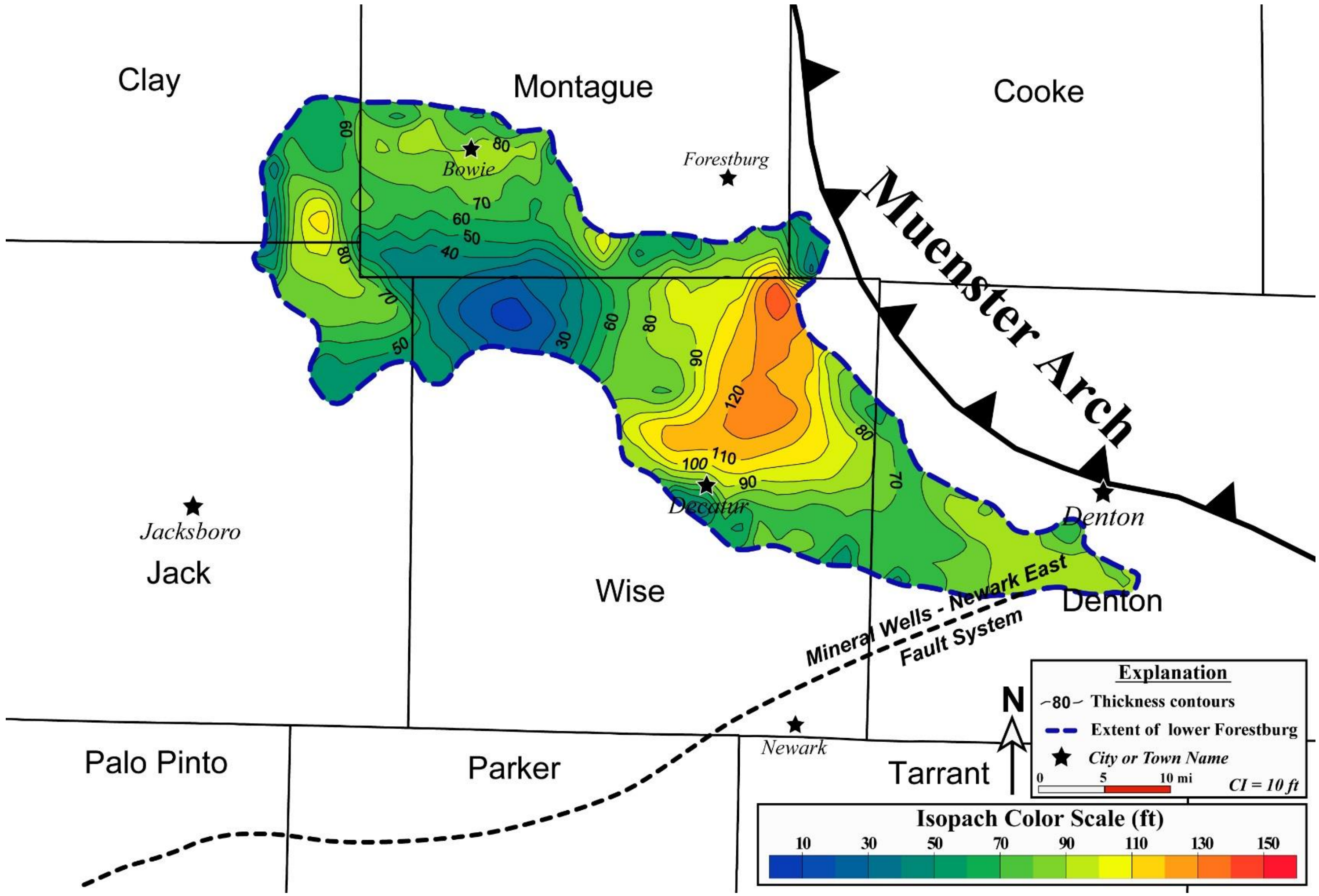



Figure 4-11. Isopach map of the lower Forestburg interval displaying thickness trends and its paleogeographic extent across the northeastern edge of the Fort Worth Basin.

shale interval (Figure 4-11; Plate 3). However, the lower Forestburg unit becomes progressively more calcareous toward the southeast and northwest of this area (Figure 4-11; Plate 4).

The middle unit of the Forestburg limestone is defined as the interval that lies above the lower Barnett Shale, lower Barnett calcareous unit, or the lower Forestburg unit and below either the upper Forestburg unit, upper Barnett Shale, or Marble Falls Formation (Figure 4-7). The middle Forestburg is composed dominantly of a limestone lithofacies with only a small fraction of the mudstone lithofacies present lower in the section. The middle unit of the Forestburg limestone covers approximately 4,560 $km^2$ (1,760 $mi^2$) across 5 counties and the thickest part of this unit was deposited over an area that extends from central Wise County toward the Muenster Arch to the northeast where it is composed entirely of a massive limestone interval that reaches maximum stratigraphic thickness of approximately 240 feet (Figure 4-12; Plate 4).

Throughout most of western Wise and eastern Jack counties this middle unit has consistent thicknesses of 80 to 120 feet, but thickens to the north and northeast and reaches thicknesses of >160 feet in northeast Jack County where it grades downwards into the lower Forestburg and upwards into the upper Forestburg (Figure 4-12). The three units within the Forestburg limestone are much harder to distinguish in southern Montague and northern Wise counties because they are vertically gradational, but the middle Forestburg interval is typically capped by a distinct high-resistivity limestone that is usually 10 to 40 feet thick (Plate 3). Along the southeast corner of Wise County and southwest corner of Denton County, the middle limestone interval thins rapidly to the

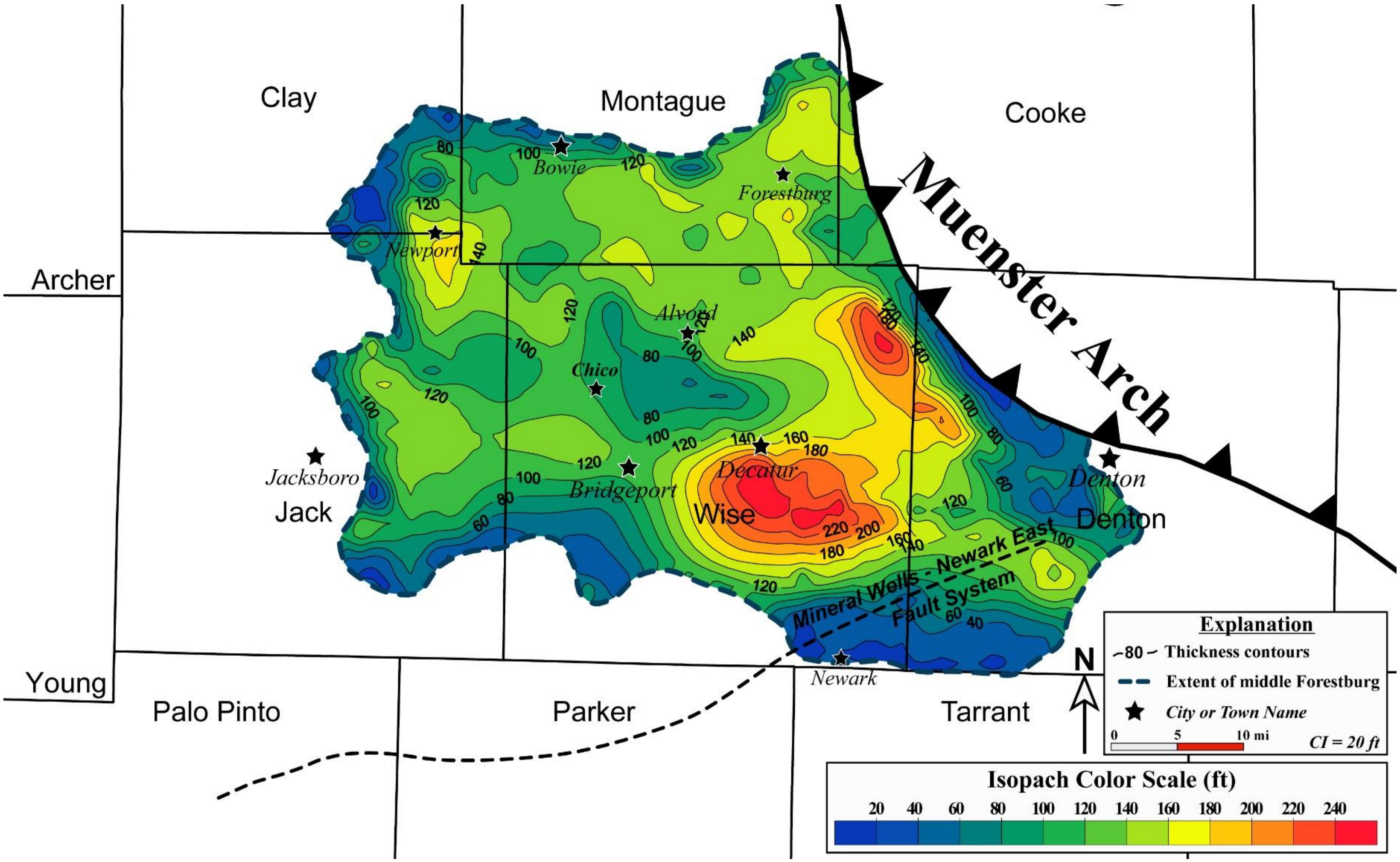



Figure 4-12. Isopach map of the middle Forestburg interval displaying thickness trends and its paleogeograhic extent across the northeastern edge of the Fort Worth Basin.

south over the Mineral Wells – Newark East fault system and is replaced by the upper Forestburg shale interval (Figure 4-12; Plate 3). This abrupt change in thickness of the middle limestone and upper shale intervals shows evidence that the fault was active during the time of deposition and influenced the distribution of sediments across this area.

The upper Forestburg limestone is defined as the interval that lies above the massive middle limestone or, where the middle limestone is absent, it lies directly on top of the lower Barnett Shale interval (Figure 4-7). It is bounded on the top by the upper Barnett Shale across most of the study area except along the eastern and northeastern edge of Jack County where it is overlain by the lower Marble Falls spiculite sequence (Figure 4-7). The upper unit of the Forestburg limestone is composed of a limestone and a shale interval that were distinguishable on well logs and were therefore correlated and mapped separately across the study area (Figure 4-14; Figure 4-15).

Stratigraphic variations of the upper Forestburg unit were greatly influenced by the Mineral Wells – Newark East (MW-NE) fault system, which indicates it was active at the time the upper unit was deposited (Figure 4-13; Figure 4-14; Figure 4-15). The upper unit of the Forestburg limestone thickens across the MW-NE fault in southeast Wise County and southwest Denton County (Figure 4-13), and most of this increase in thickness occurred in the upper shale interval as it replaced the middle limestone interval lying stratigraphically below (Figure 4-12; Figure 4-14). The upper Forestburg thins along the south side of the fault and is dominantly composed of the upper limestone interval in this area (Figure 4-13; Figure 4-15). The upper Forestburg limestone sits directly on top of the lower Barnett Shale in southeast Wise County and southwest Denton County and extends farther south into northern Parker and Tarrant counties compared to the middle unit (Figure 4-15).

The upper Forestburg thins along the north side of the MW-NE fault and it is < 20 feet thick near the town of Decatur where the upper limestone is completely absent and only the upper shale interval is present (Figure 4-13; Plate 3; Plate 4). It thickens again to the west and northwest of Decatur where it is more than 100 feet thick just north of the town of Bridgeport and is composed almost entirely of the shale interval (Figure 4-13; Figure 4-14; Plate 3; Plate 4). It also becomes stratigraphically thicker in northeast Wise County and southeast Montague County where the upper Forestburg is composed dominantly of the limestone interval (Figure 4-13; Figure 4-14; Figure 4-15; Plate 3; Plate 4). The upper Forestburg unit reaches maximum stratigraphic thickness of >140 feet in southeast Montague County approximately 6.5 miles southwest of the town of Forestburg (Figure 4-13; Plate 3).

The upper limestone interval is <20 feet thick across most of Wise County but thickens to the southeast parallel to the MW-NE fault and reaches thicknesses of >40 feet in southeast Wise County and southwest Denton County (Figure 4-15). The upper Forestburg also becomes more carbonate-rich along the northeastern edge of the FWB and the upper limestone interval reaches thicknesses of >100 feet in northeast Wise County and southeast Montague County adjacent to the Muenster Arch (Figure 4-15; Plate 3; Plate 4).

The extent of the upper shale interval is highly influenced by the thickness of the middle limestone interval and the isopach maps display evidence this (Figure 4-12; Figure 4-14). The upper shale interval is <30 feet thick across an area that trends from southeast Jack County into central and northeast Wise County (Figure 4-14). However, it thickens rapidly to the southeast as it replaces the middle limestone member and reaches thicknesses of >110 feet along the southwestern edge of Denton County and southeast Wise County (Figure 4-14). The upper shale interval also thickens to the west and northwest of Decatur and reaches maximum stratigraphic thickness of approximately 125 feet just north of the town of Bridgeport (Figure 4-14; Plate 4). The upper shale interval is highly calcareous across most of northeastern Jack County and northwestern Wise County (Plate 3).

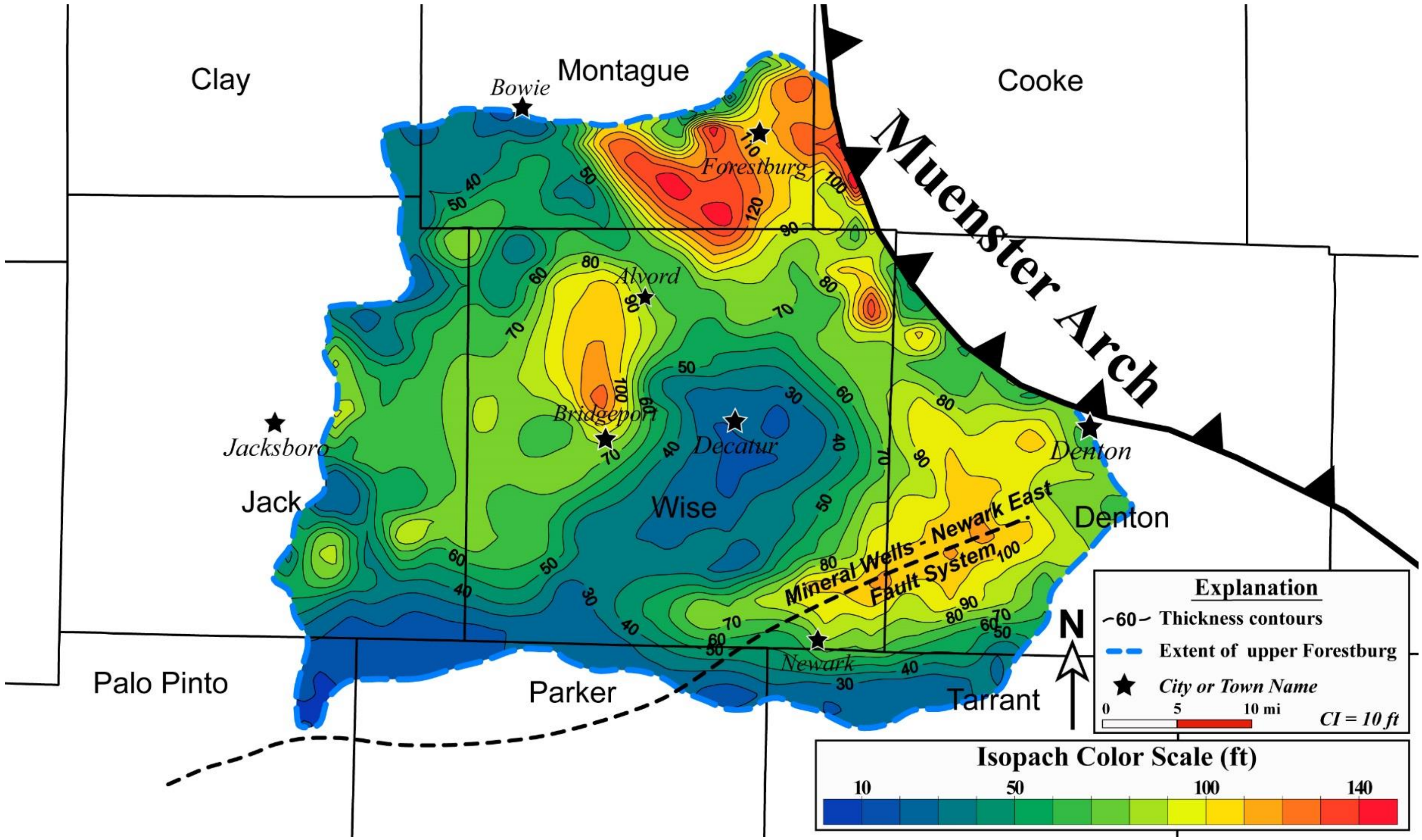



Figure 4-13. Isopach map of the upper Forestburg interval displaying thickness trends and its paleogeographic extent across the northeastern edge of the Fort Worth Basin.

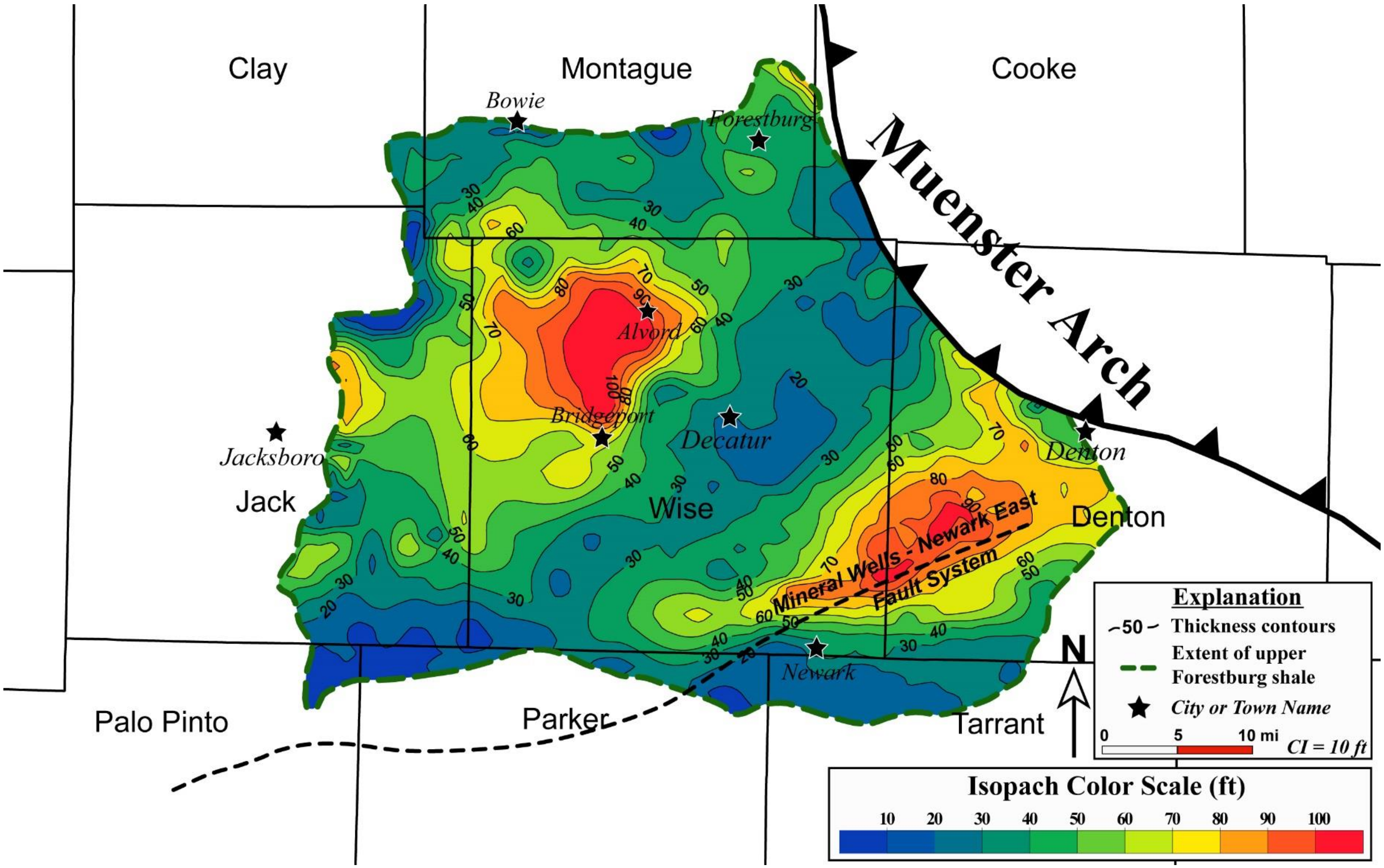



Figure 4-14. Isopach map of the upper Forestburg shale displaying thickness trends across the northeastern edge of the Fort Worth Basin.

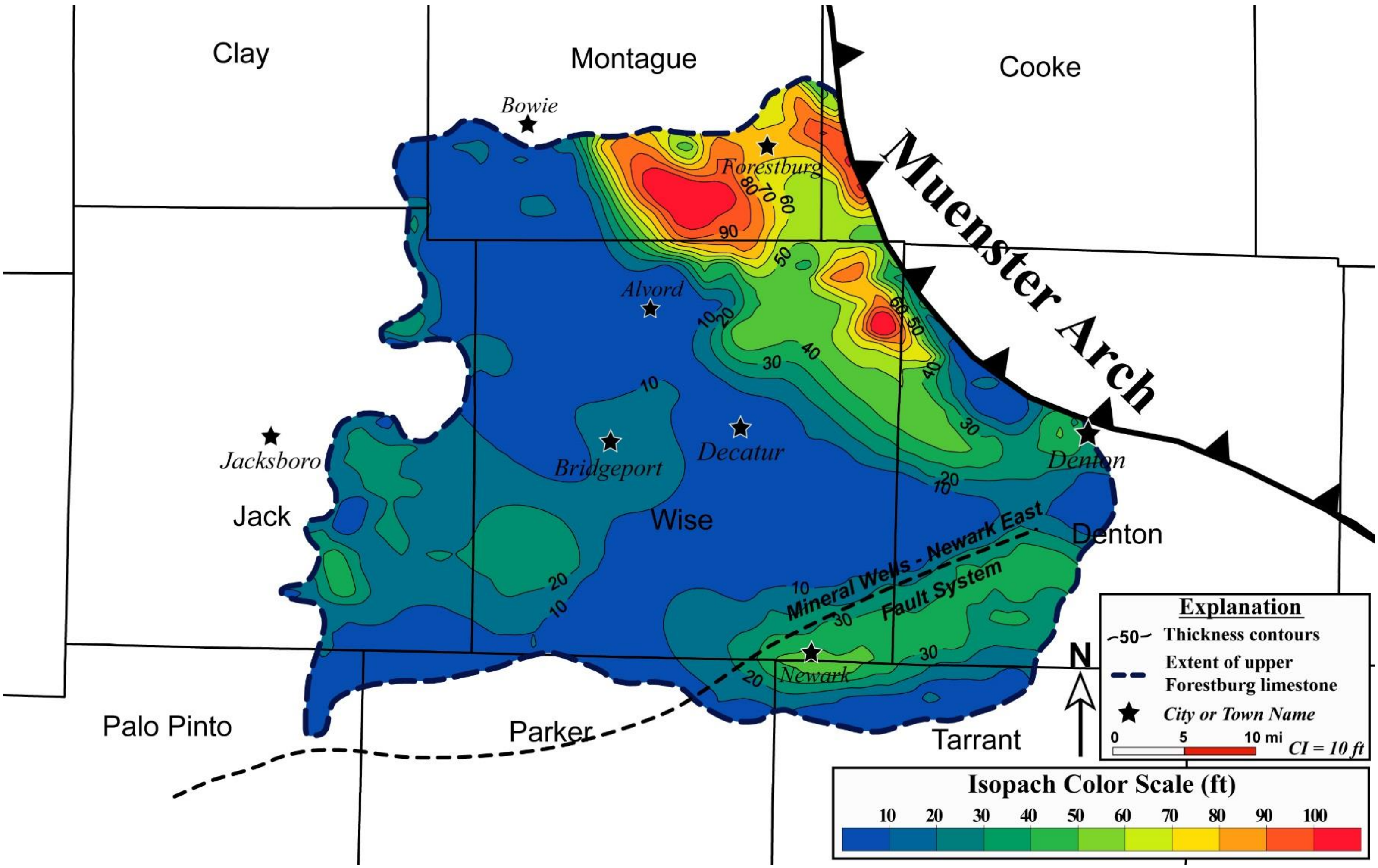



Figure 4-15. Isopach map of the upper Forestburg limestone displaying thickness trends across the northeastern edge of the Fort Worth Basin.

*Comyn Limestone*

The Comyn limestone (i.e. Comyn "formation") was first defined by Cheney (1940) as "that portion of the Marble Falls which occurs in the Ranger area" in northeast Eastland County. This unfortunate definition for the Comyn limestone was actually based on Goldman's (1922) descriptions of well cuttings that came from the Seaman No. 1 well drilled by the Roxana Petroleum Company along the western edge of Palo Pinto County. Cheney (1940) uses this well as the type subsurface section for the Marble Falls Formation even though he never examined the cuttings himself and states that "these samples were the subject of an exhaustive lithologic study by Goldman and are no doubt on file with state and national geological surveys." The interval from 4,132 to 4,320 feet in the Roxana Seaman No. 1 well that was proposed by Cheney (1940) as the Comyn formation is actually the lower part of the lower Marble Falls. The Comyn limestone, as it is defined in this study, is equivalent to Goldman's (1922) Unit K or the "Lower Bend" limestone from a measured depth of 4,320 to 4,372 feet. Unfortunately, the term Comyn limestone has been used inaccurately by geologist over the last 75 years because of the complicated nomenclature in the FWB and unfamiliarity with the origin of the name. There have been a number of studies published since the original definition in 1940 but they just briefly mention the Comyn limestone, and due to the complicated nomenclature issues it is unclear if they were referring to the same unit that was identified in this study. Farrar's (2010) thesis is the only available study on the present-day definition of the Comyn limestone and his interpretations were based on core and thin section analysis from the EOG Resources House No. 1 whole core in south-central Jack County. He describes the different lithologies and facies within the Comyn limestone but never mapped its geographic extent across the basin.

There are no maps published on the Comyn limestone that is known to the author and the large number of well logs available for this study has presented the opportunity to evaluate and map the Comyn limestone in greater detail to better understand the stratigraphic position, depositional environment, and paleogeographic extent across the basin. The upper part of the Comyn limestone interval, as well as the contact with the overlying lower Marble Falls was examined by the author in the House No. 1 whole core, but unfortunately EOG would not grant the author permission to share images associated with observations that were made from the core. However, there were a number of side-wall cores taken from the Comyn limestone in various wells scattered across the study area and thin section analysis from these cores show similar observations made by Farrar (2010). Petrophysical data was used to determine variations in lithological characteristics away from the wells with core data and ~6,950 well logs were used to correlate and map the Comyn limestone interval across the basin.

## Type Log and Well Log Characteristics

Although the term Comyn limestone has been used to describe various subsurface intervals within the FWB and should probably be discarded completely because of its erroneous definition by Cheney (1940), the author felt it was appropriate to continue with the term Comyn limestone because of its common usage currently among industry geologist and to avoid any further confusion with a newly proposed name. The Comyn limestone is defined as the carbonate-rich interval that lies above the lower Barnett Shale or lower Barnett calcareous unit where it is present and below the upper Barnett Shale, lower Marble Falls, or Atoka Group. The Frank Gilliam Sloan “A” No. 1 (42-237-34898) well located along the western border of Jack County serves as the type log for the Comyn limestone and is defined as the interval from a measured depth 4,870 to 5,244 feet (Figure 4-16). There are three separate units that were identified within the Comyn limestone and they are informally referred to as the lower Comyn, middle Comyn, and upper Comyn. The type log was selected from an area where the Comyn limestone reaches its near-maximum stratigraphic thickness, but also in an area where all three of these units were present and clearly defined in the log provided (Figure 4-16). The lower Comyn is defined as the interval from a measured depth of 5,192 to 5,244 feet, the middle Comyn is defined as the interval from 5,087 to 5,192 feet, and the upper Comyn is defined as the interval from 4,870 to 5,087 feet (Figure 4-16). Although three different units are defined on the type log, the lower unit is gradational with the middle Comyn and was only deposited over a small area in northwest Jack County so it was incorporated into the thickness of the middle unit.

The Comyn limestone is stratigraphically equivalent to the Forestburg limestone to the east and the limestone intervals display similar well log characteristics with high concentrations of calcite that gives it a vertically consistent well log response pattern with low GR, high ILD, and high PE (~5 b/e) values that is distinct from the typical higher-GR siliceous mudstone facies of the lower Barnett Shale (Figure 4-16). There are also various shale intervals within the Comyn limestone that are typically highly calcareous but contain higher concentrations of clay that causes the GR to read slightly higher and the PE and ILD to read slightly lower compared to the limestone intervals (Figure 4-7). The limestone and shale intervals are vertically gradational across the study area making it difficult to differentiate the two, but with the high-density well control various stratigraphic patterns were discovered that helped with these interpretations. The limestone intervals were typically defined by GR values that range from 25 to 40 API, ILD values from 75 to over 200 ohm-m, RHOB values of 2.68 to 2.72 g/cm$^3$ , DPHI values of 0.04 to 0.00 V/V, NPHI values of 0.06 to 0.02 V/V, and PE values from 4.5 to 5 b/e. The shale intervals contain a wider range of values due to the variability in concentrations of clay and calcite, but they are typically defined by GR values that range from 70 to 90 API, ILD values from 10 to 25 ohm-m, RHOB values of 2.62 to 2.65 g/cm3, DPHI values of 0.03 to 0.08 V/V, NPHI values of 0.15 to 0.22 V/V, and PE values of 3.5 to 4.0 b/e.

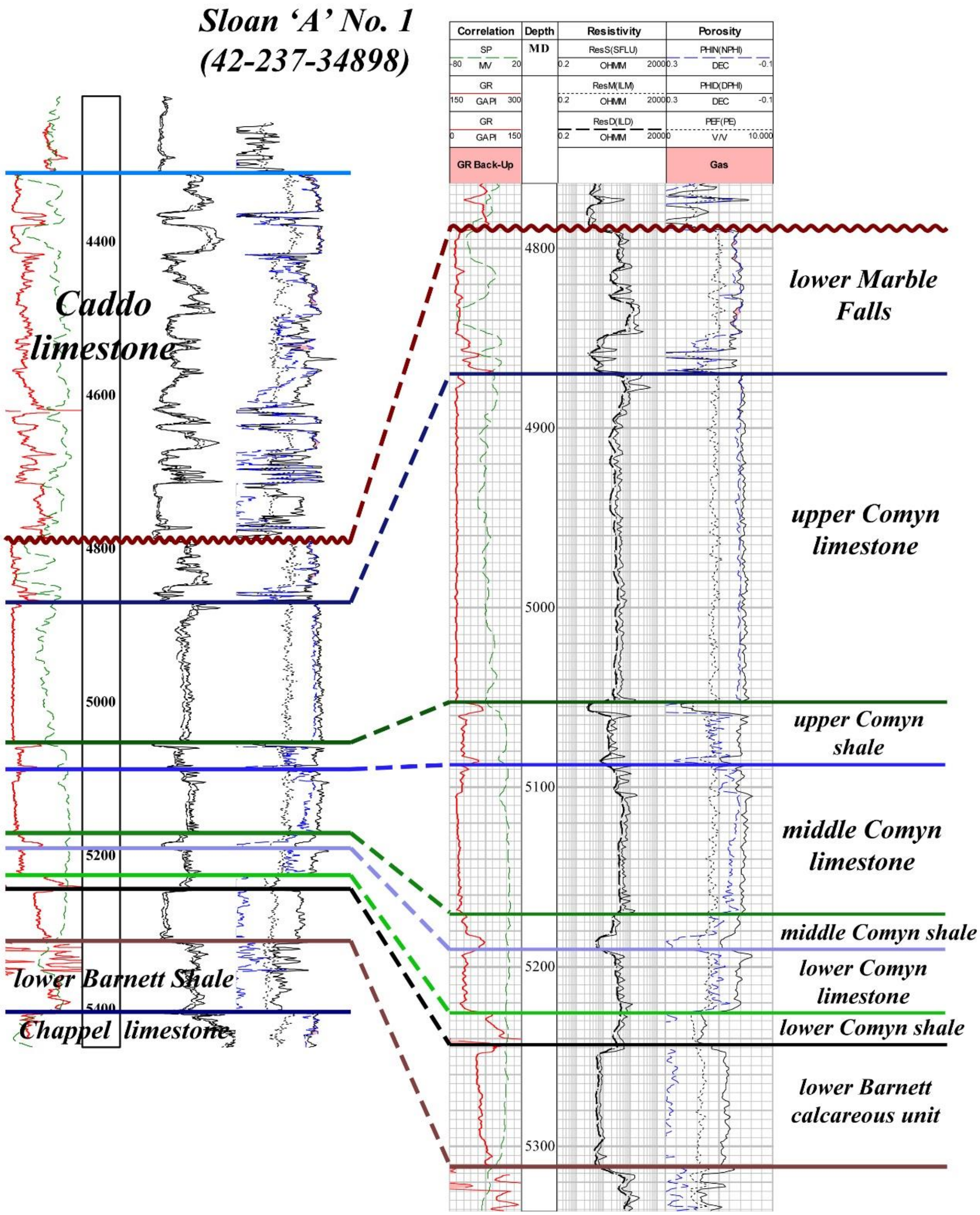



Figure 4-16. Type log of the Comyn limestone displaying typical well log characteristics of interbedded limestone and shale intervals. The different units were identified to the right of the expanded open-hole well log.

Lithofacies Description

The Comyn limestone interval is defined as a massive limestone on open-hole well logs, but when examined in more detail through micro-resistivity image logs and slabbed core it was discovered to contain thick beds of carbonate-rich sediments that are interbedded with thinner layers of clay-rich sediments (Figure 4-17). Farrar (2010) examined the EOG Resources House No. 1 whole core and interprets the carbonate-rich intervals as a micritic limestone and the clay-rich intervals as a dolomitic claystone. There were no thin sections analyzed from the House No. 1 whole core but the slabbed core was examined to compare with observations made from micro-resistivity image log data and thin sections taken from side-wall cores. The carbonate-rich beds are clearly distinguished from the clay-rich beds in the slabbed core and in image logs and are represented by the light grey to light bluish-grey color in the slabbed core and the yellow to white colors in image log (Figure 4-17). The clay-rich beds are not as prominent and only comprise a small portion of the Comyn limestone section, but they are identified in the slabbed core by the dark grey to dark brownish-gray color and in image logs by the brown to black colors (Figure 4-17). The House No. 1 whole core only sampled the upper interval of the Comyn limestone and did not sample any of the shale intervals that contain a higher percentage of clay-rich sediments.

The Comyn limestone was sampled with 8 side-wall cores from 3 different wells scattered across the study area and unfortunately all 8 of these samples were taken from the limestone intervals and none of shale intervals were sampled. Therefore, the lithological characteristics of the Comyn limestone is based on thin section analyses

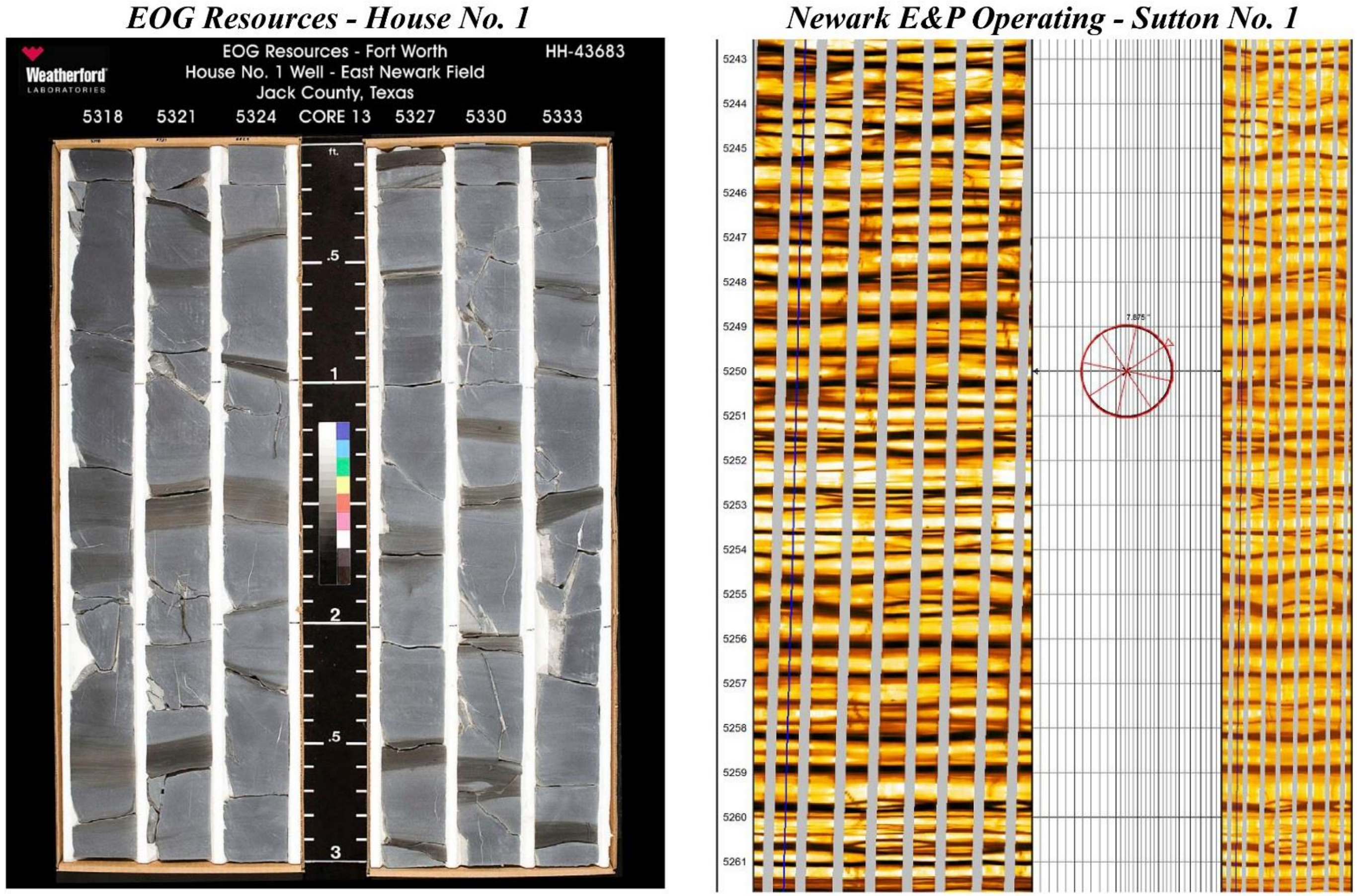



Figure 4-17. The image on the left was taken from Farrar (2010) and displays the Comyn limestone interval from the EOG Resources House No. 1 slabbed core with the light grey intervals representing the carbonate-rich sediments and the dark grey representing the clay-rich sediments. The image on the right is a micro-resistivity image log from the Newark E&P Sutton No. 1 well displaying similar characteristics of the Comyn limestone interval with the darker colors representing the clay-rich sediments and the lighter colors representing the carbonate-rich sediments.

from 7 side-wall cores taken through various limestone intervals in the Newark E&P Deck No. 1 located in southwest Jack County and the Newark E&P Hartnett No. 1 located in northwest Palo Pinto County.

The middle and upper limestone intervals were both present in the Newark E&P Hartnett No. 1 and were sampled with side-wall cores at a measured depth of 4,604 feet (upper), 4,626 feet (middle), 4,645 feet (middle), and 4,720 feet (middle) (Figure 4-18). Thin section analysis from the side-wall cores taken in this well reveal that most of the carbonate-rich beds of the Comyn limestone can be classified as micritic limestone with various amounts if silt, dolomite, and fossil fragments, and the clay-rich beds are defined as an argillaceous dolomitic mudstone. Photomicrographs A and B in Figure 4-18 are from the 4,604 feet core and 4,626 feet core and represent the micritic limestone with only minor amounts of non-carbonate constituents and abundant amounts of microcrystalline calcite (stained red) or micrite that is typically present in the Comyn limestone. The 4,645 feet core is represented by photomicrograph C and D and is characterized as a slightly silty/fossiliferous/dolomitic limestone with up to 10% euhedral dolomite grains present (Figure 4-18). Photomicrograph E & F are from the 4,720 feet core which was sampled from one of the clay-rich beds and is defined as an argillaceous dolomitic mudstone with up to 20% dolomite (Figure 4-18).

The middle and upper limestone intervals are also both present in the Newark E&P Deck No. 1 and were sampled with side-wall cores at a measured depth of 4,514 feet (upper), 4,546 feet (middle), and 4,620 feet (middle) (Figure 4-19). The Deck No. 1 location is 4 miles due north of the Hartnett No. 1 and the Comyn limestone does not

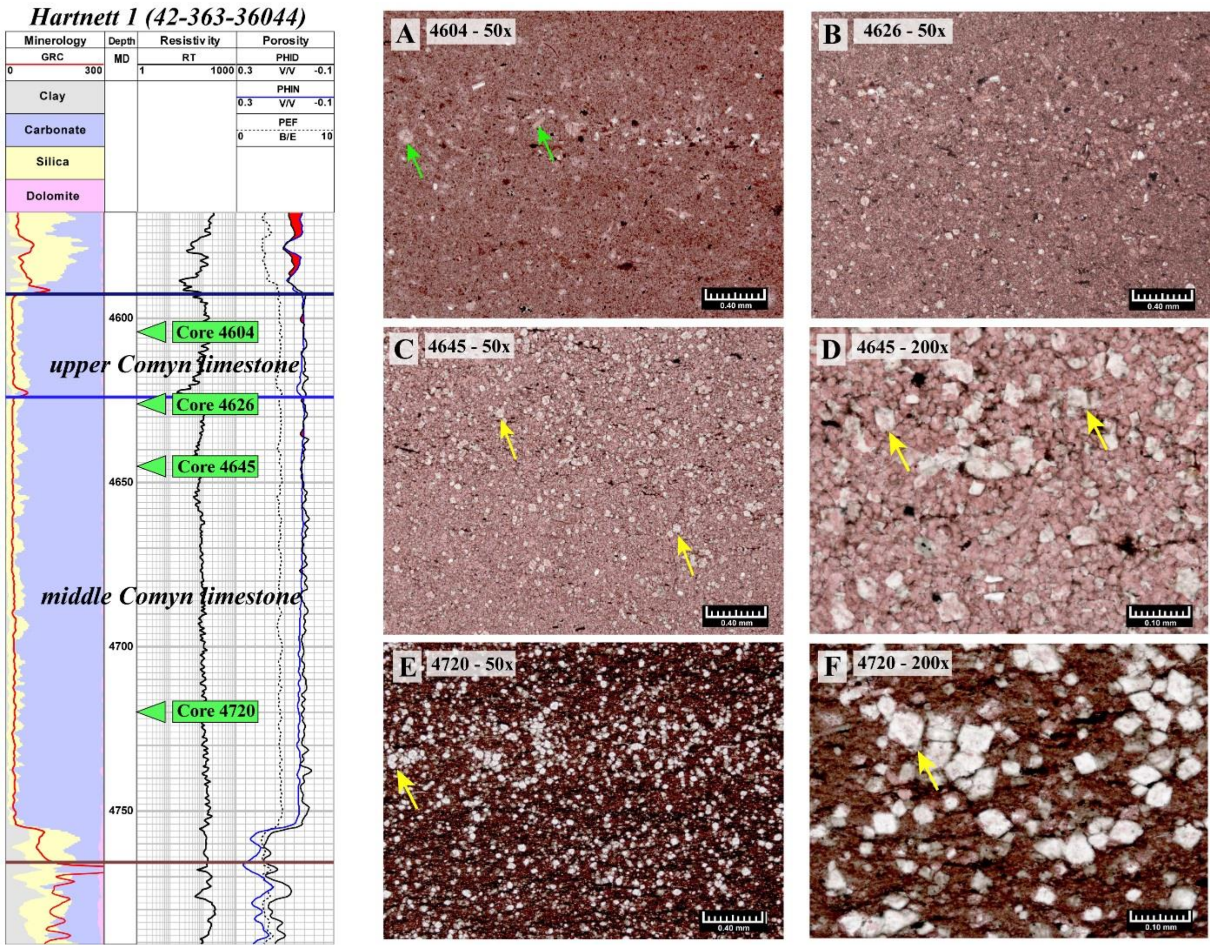



Figure 4-18. A simplified mineralogy log of the Newark E&P Hartnett No. 1 is shown on the left with depth locations of each side-wall core taken in the Comyn limestone. On the right is various photomicrographs displaying a slightly dolomitic limestone that is the most abundant lithofacies within the Comyn limestone. The green arrows indicate fossil fragments and the yellow arrows indicate dolomite crystals that are commonly present in the Comyn limestone section.

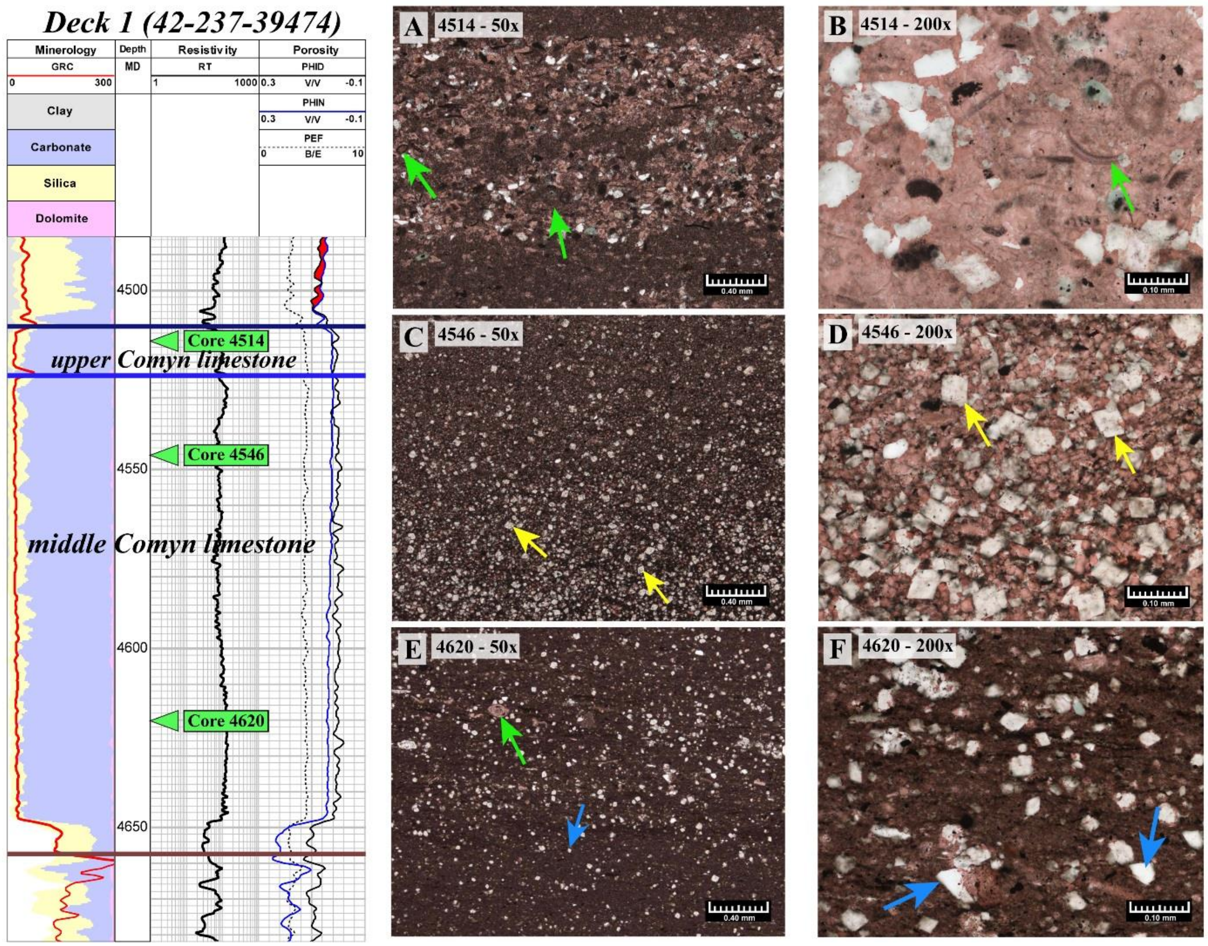



Figure 4-19. A simplified mineralogy log of the Newark E&P Deck No. 1 is shown on the left with depth location of side-wall cores and the photomicrographs A – F are displaying common lithologies present in the Comyn limestone. The bright green arrows indicate fossil fragments, the yellow arrows are identifying dolomite crystals, and the blue arrows are identifying silt-size quartz grains.

change much lithologically over this short distance. Therefore, thin section analysis from this well reveal similar results to the Harnett No. 1 with a micritic limestone comprising most of the Comyn limestone interval and containing significant amounts of dolomite and minor amounts of fossil fragments and silt-size quartz grains (Figure 4-19). Photomicrographs A and B are from the 4,514 feet core sampled from the upper limestone interval and represent a slightly silty / dolomitic / fossiliferous limestone (Figure 4-19). The 4,546 feet core represents a slightly argillaceous dolomitic limestone shown in photomicrograph C and D, and there were various parts of the thin section that contained more than 50% dolomite (Figure 4-19). The dolomite grains are mostly rhombic euhedral crystals that are displayed in photomicrograph D and denoted with the yellow arrows (Figure 4-19). The 4,720 feet core was sampled from one of the more clay-rich beds and represents a slightly argillaceous / fossiliferous / dolomitic / silty mudstone with silt-size quart grains indicated by the blue arrows and a foraminifera fossil indicated by the green arrow (Figure 4-18).

The Comyn limestone was deposited in an environment similar to the Forestburg limestone, and are composed of the same lithofacies as discussed above, but the high resolution micro-resistivity image logs also reveal similarities in bedding characteristics. The Comyn limestone succession contains both shale and limestone intervals that were defined using well log values and evaluating numerous image logs scattered across the study area. An example of the limestone interval is shown in Figure 4-17, Figure 4-18, and Figure 4-19 and is typically characterized by the occurrence of thick (30-100 mm) to very thick (100+ mm) carbonate-rich beds that are on average around 4 to 16 inches thick

(Figure 4-20). These limestone intervals also contain interbeds of clay-rich sediments but since they are typically < 2 inches thick the well logs do not have enough resolution to recognize them (Figure 4-20). An interesting discovery that was also made from the image logs was the fact that there was a slight change in the depositional environment from the middle limestone to the upper limestone with distinct differences in bedding characteristics and thicknesses. The upper limestone interval is composed of massive, continuous, planar bedding whereas the middle limestone is composed of thinner, non-parallel to parallel, discontinuous to continuous, even to wavy bedding (Figure 4-20). There were no shale intervals sampled with side-wall core or whole core, but image logs reveal these intervals are comprised mostly of thinner beds that range from lamina to very thin (1-3 mm) to medium (10-30 mm) in thickness and are even, parallel and continuous. A large percentage of the shale intervals are intensly bioturbated and contain exceptionally high concentrations of well bedded shell fragments that cause the PE curve to read higher than normal due to its calcareous nature.

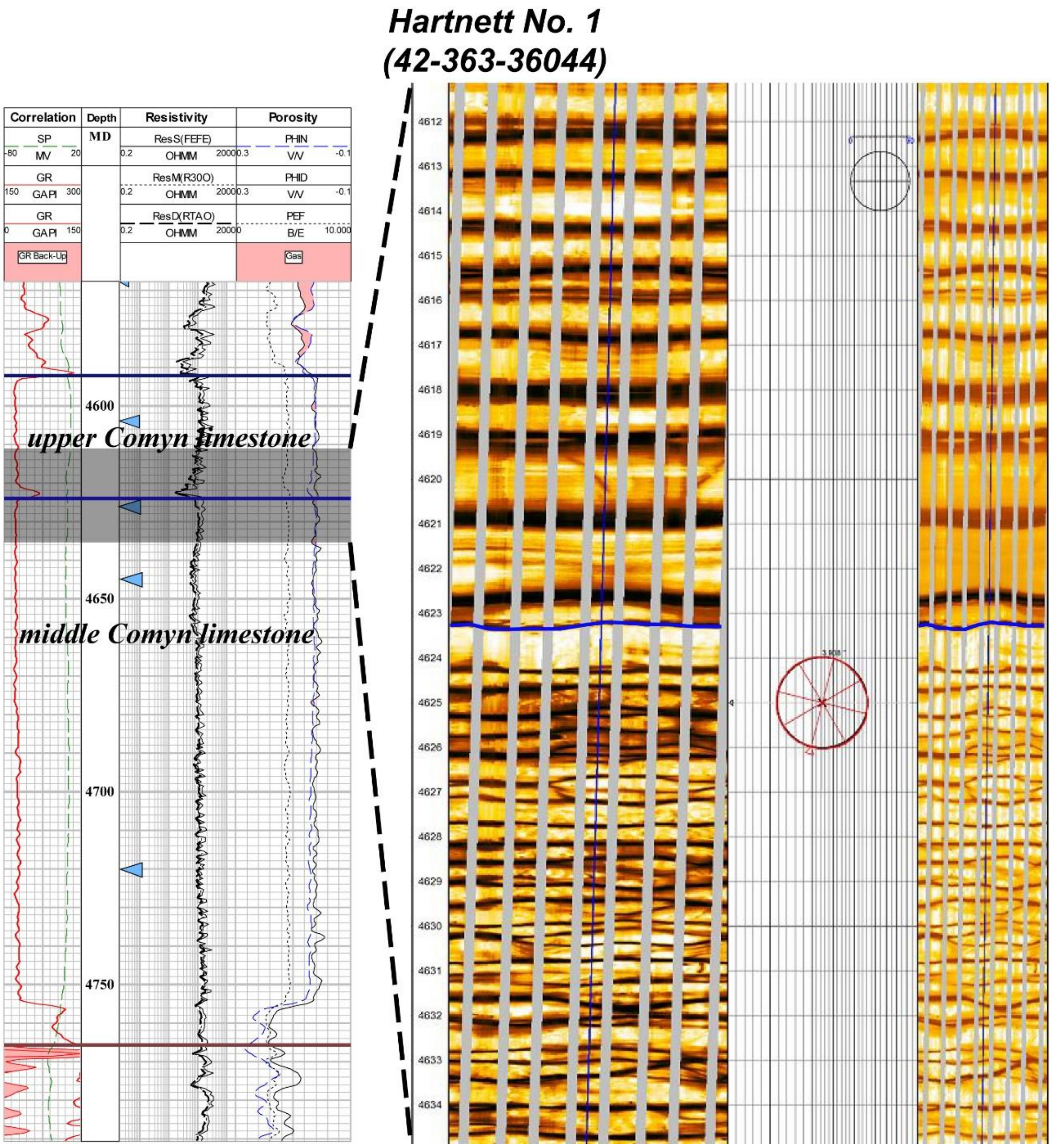



Figure 4-20. Newark E&P Hartnett No. 1 open-hole well log on the left with locations of side-wall cores and a section of the image log on the right from 4,611 to 4,635 feet displaying the contact between the middle limestone interval and upper limestone interval of the Comyn limestone.

Paleogeography

The Comyn limestone does not crop out anywhere at the surface and is not a subsurface equivalent member of any formations that outcrop around the Llano Uplift. It is only present in the subsurface in the northern part of the FWB and was deposited over an area of 7,730 $km^2$ (2985 $mi^2$) covering 8 different counties in North-Central Texas (Figure 4-21). It is probably Late Mississippian in age and is stratigraphically equivalent to the Forestburg limestone to the east, and like the Forestburg it is a carbonate-rich unit that splits the Barnett Formation into upper and lower members. The Comyn limestone also shows variations in gross thickness across the study area that are similar to the Forestburg limestone, and displays an overall thickening trend from the southwest to northeast. It is less than a foot thick along the southwestern subcrop boundary where it begins to develop in the upper part of the Barnett Formation and separates the Barnett into an upper and lower interval (Figure 4-21; Plate 5). The upper Barnett Shale is signicantly thicker over a small area along the eastern edge of Shackelford County and western edge of Stephens County, but as the underlying Comyn limestone thickens to the northeast it quickly replaces the upper Barnett Shale (Plate 5).

The Comyn limestone becomes progressively thicker to the northeast and reaches its maximum stratigraphic thickness of >400 feet along the border between Young and Jack counties near the small town of Jermyn, Texas (Figure 4-21; Plate 5). It thins abruptly to the east of this area along a north-south trend from >400 feet to <10 feet thick over a distance of approximately 4 miles (Figure 4-21). The Comyn limestone is thin across most of central Jack County and is completely absent north of the town of

Jacksboro where the overlying lower Marble Falls reaches maximum thicknesses (Figure 4-21; Plate 5). It is unclear what kind geological feature caused the Comyn limestone thickness to change so abruptly in this area, but it was most likely depositionally controlled because there is no evidence of a major erosional event occurring at the top of the Comyn sequence. Also, if there was an erosional unconformity that cut down through the section then the upper Comyn would be removed first and the middle Comyn would be removed farther east. However, there is no evidence of this occurring and both the upper and middle Comyn limestone units thin contemporaneously to the east and grade into a more mudstone-rich section that also eventually disappears to the east. The thinning of the Comyn limestone is not as intense in south-central Jack County and it intertongues with the Forestburg limestone to the east (Figure 4-21). It is also difficult to map the Comyn limestone in north-central Jack County and south-central Clay County because it is more gradational with the overlying Marble Falls Formation and intertongues with the lower Barnett calcareous unit and low-resistivity shale.

The northwestern and western subcrop boundaries represent where the Comyn limestone pinches out as it thins over the top of the Chappel limestone and a thin layer of lower Barnett Shale (Figure 4-21). There are a number of places where the thickness of the Comyn limestone is significantly thinner compared to offset wells, and these stratigraphic thinner intervals represent areas where there were prominent underlying Chappel reefs present (Figure 4-21. With higher resolution mapping of the Comyn limestone thickness it was discovered that the underlying Chappel limestone had significant influence on the thickness of the overlying Comyn limestone. Some of these

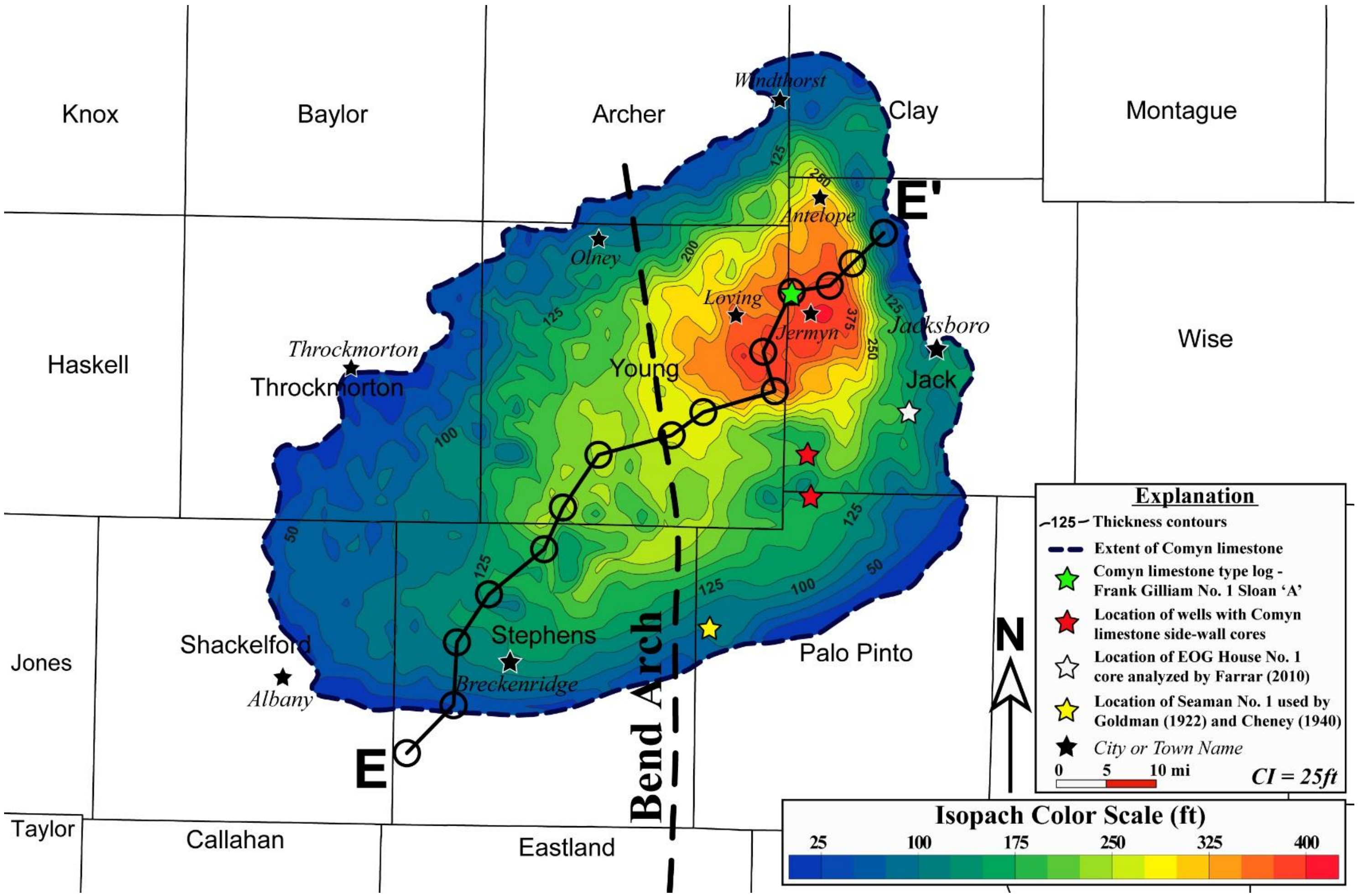



Figure 4-21. Isopach map of the Comyn limestone displaying gross thickness trends and its paleogeographic extent across the Fort Worth Basin. Locations of key wells are noted by the stars and referenced in the legend. A southwest to northeast cross-section line is shown in black with circles representing the locations of well logs used in cross-section E – E’ in Plate 5.

thinner areas are noted on the map in Figure 4-21 along the southern edge of Young County and along the border between southeastern Young and southwestern Jack counties. The Comyn limestone thickness was also influenced by the regional unconformity that typically occurs at the top of the lower Marble Falls, but where the Marble Falls was absent this unconformity continued to affect the upper surface of the Comyn limestone which was occasionally replaced by an erosional conglomerate.

The middle unit of the Comyn limestone is defined as the interval that lies stratigraphically above the lower Barnett Shale or lower Barnett calcareous unit and below either the upper Comyn unit, the lower Marble Falls, or the Atoka Group (Figure 4-16). In northeast Young County and northwest Jack County the middle unit grades downwards into the lower unit defined in the type log in Figure 4-16, but since this interval is only present across a small area it was incorporated with the thickness of the middle Comyn shown in the isopach map in Figure 4-22. The middle Comyn interval comprises most of the Comyn limestone sequence and covers a much larger area compared to the overlying upper Comyn interval. It is more than 200 feet thick across northern Stephens and southern Young counties and reaches maximum stratigraphic thicknesses of approximately 250 feet near the town of Graham (Figure 4-22). There are areas where the middle Comyn is significantly thinner and as mention previously, this is attributed to the presence of underlying Chappel reefs that cause the overlying formations to thin as they were deposited over these structural highs. Some of the variations in thickness in southeastern Young County and southwestern Jack County are thought to be fault controlled.

The middle Comyn is composed dominantly of carbonate-rich sediments of what is considered the middle limestone interval but there are also intervals with higher concentrations of clay and they were defined as the middle shale interval. Throughout the southern half of the isopach map shown in Figure 4-22 the middle Comyn is composed purely of a massive limestone interval that has a distinct low-GR, high ILD, high PE, and low NPHI and DPHI well log signature (Figure 4-16; Plate 5). The middle shale interval starts to develop lower in the section along an east-west strike through central Young County parallel to the 200 feet contour, and becomes progressively thicker to the north, east, and northeast as it replaces the carbonate-rich sediments of the limestone interval (Figure 4-22; Plate 5). The shale interval typically grades upward into the limestone interval and there is usually a slight change in well log characteristics that allow the two intervals to be distinguished from each other. However, as the middle Comyn thins to the north and northeast, the carbonate content gradually decreases and the limestone and shale intervals become interbedded into an argillaceous limestone and can no longer be separated. There is also another 30 to 60 feet limestone interval that has developed in the upper part of the middle Comyn along the northern edge of Young County and has distinct well log characteristics compared to the limestone interval to the south. This limestone interval was only present over a small area but it contained good SP deflection on well logs, which suggests higher permeability of a possible fracture zone.

The upper Comyn is defined as the carbonate-rich interval that lies above the massive middle Comyn limestone and below either the upper Barnett Shale, lower Marble Falls, or the Atoka Group (Figure 4-16). Similar to the middle Comyn there was

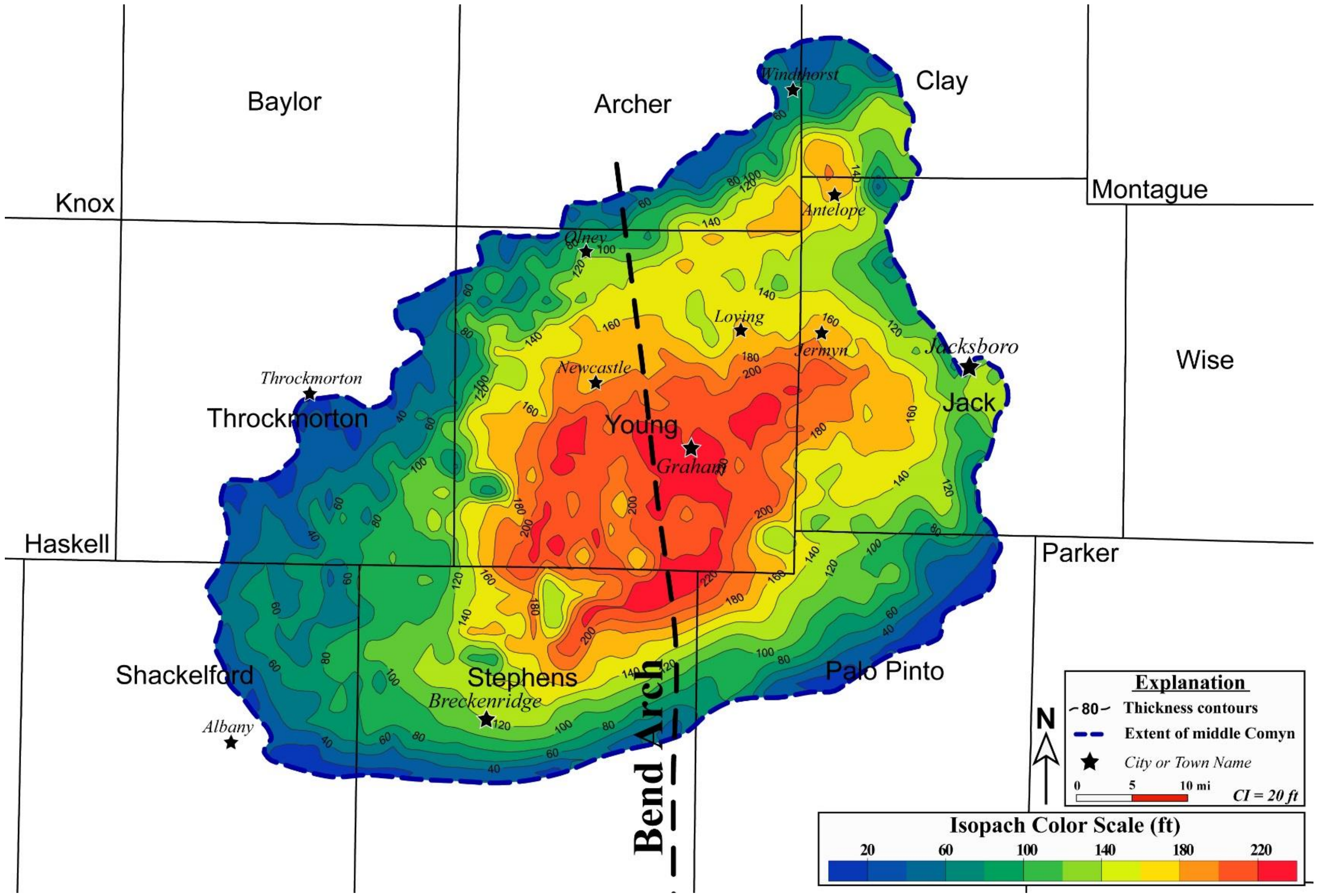



Figure 4-22. Isopach map of the middle Comyn limestone interval displaying thickness trends and its paleogeographic extent across the Fort Worth Basin.

both a limestone and calcareous shale interval identified that was mapped as a single unit defined herein as the upper Comyn unit (Figure 4-23). The upper Comyn is bounded on the top by the lower Marble Falls across most of its geographic extent, but the Marble Falls starts to pinch-out along a trend from the town of Antelope through Loving and Newcastle, and northwest of this subcrop the upper Comyn limestone is overlain by the Atoka Group (Figure 4-23). The upper Comyn was not deposited across as large of an area as the middle Comyn and only covers approximately 2,265km$^2$ (875 mi$^2$) throughout northeast Young and western Jack counties. The upper unit thickens from the southwest to northeast and reaches maximum stratigraphic thicknesses of approximately 250 feet along the northwestern edge of Jack County northeast of Jermyn (Figure 4-23).

The upper Comyn is significantly thinner (<50 feet) across most of southern Young County because the limestone interval is absent in this area and only the shale interval is present (Figure 4-23; Plate 5). The limestone interval does not develop in the upper Comyn until around the 60 feet contour just north of the town of Graham and becomes progressively thicker toward the northeast where it eventually grades into a massive limestone that comprises most of the Comyn limestone section around the town of Jermyn (Figure 4-23; Plate 5). This massive limestone interval thins to the northwest and pinches out along a subcrop that trends from north-central Young County into southeast Archer County (Figure 4-23). There is, however, a small area in southeast Archer County where the upper Comyn limestone develops into an unusually thick section >100 feet, but abruptly pinches out to the north (Figure 4-23). The upper limestone interval also thins abruptly to the east and northeast of Jermyn and the upper shale becomes progressively thicker as it replaces the upper and lower limestone intervals (Plate 5). Also, like the rest of the Comyn limestone sequence, the upper unit pinches out to the northeast and is completely replaced by the lower Marble Falls in north-central Jack County (Figure 4-23; Plate 5).

There is an area in the southeast Young County that was not included in the gross thickness map in Figure 4-23 because the upper Comyn was completely absent and only the underlying middle unit was present. There are a series of faults in this area that are sub-parallel to the main Mineral Wells – Newark East fault system and were possibly active during the Late Mississippian and influenced the deposition of the Comyn limestone sequence. There are also numerous Chappel reefs in this area that could have also influenced sedimentation patterns of the upper Comyn limestone section and prevented it from ever being deposited in this area (Figure 4-23).

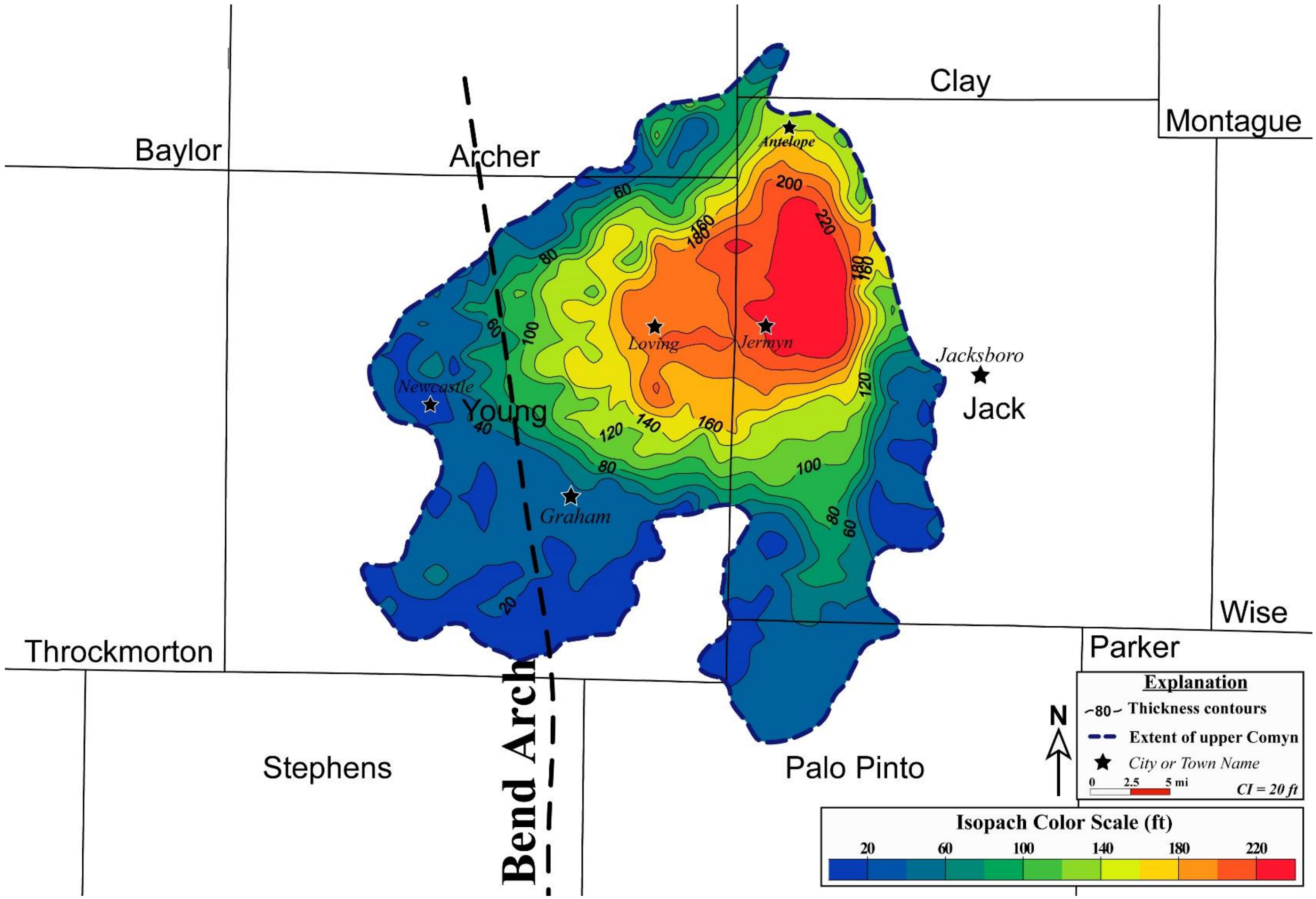



Figure 4-23. Isopach map of the upper Comyn limestone interval displaying thickness trends and its paleogeographic extent across the Fort Worth Basin.

*Paleogeography of Forestburg-Comyn Limestone*

The Forestburg limestone has previously been identified as a Mississippian-age carbonate-rich unit within the Barnett Formation (Pollastro *et al.*, 2007), and the Comyn limestone has been recognized by most previous workers as an Early Pennsylvanian limestone that is stratigraphically related to the Marble Falls Formation (Flippin, 1982). However, the original definitions of both these units are poorly understood and the terms "Forestburg" and "Comyn" have been used improperly over the last several decades and are no longer used today to define the same subsurface intervals the authors originally proposed (Cheney, 1940; Henry, 1982). This misunderstanding is mostly due to nomenclature issues that have been a problem throughout the FWB over the last century and the fact that most workers are unfamiliar with how these intervals were originally defined. There has also been very little work done on the Forestburg-Comyn limestone making this carbonate-rich unit poorly understood. Farrar (2010) is the only recent work known to discuss both of these units and recognized that they were stratigraphically equivalent, but even at the time he completed his thesis there was limited well control in south-central Jack County where the Forestburg and Comyn limestone intertongue. There have been significantly more wells drilled since that time and they were used here to confirm that the Forestburg and Comyn limestone are in fact stratigraphically equivalent and will be referred to hereafter as the Forestburg-Comyn limestone.

As mentioned previously, the Forestburg–Comyn limestone is a carbonate-rich unit that separates the Barnett Formation into upper and lower members and is only present in the subsurface in the northern part of the FWB. There has been no biostratigraphic work done on this carbonate unit but it is thought to be Mississippian in age because of its stratigraphic relationship with the Barnett Formation. The increase in drilling activity from the Marble Falls play over the last few years has made it possible to map the entire geographic extent of this unit with great accuracy using approximately 11,850 data points (Figure 4-24). It was deposited over an area covering more than 14,000 $km^2$ (5,405 $mi^2$) across 13 counties in North-Central Texas.

The map provided in Figure 4-24 displays regional thickness trends of the Forestburg-Comyn limestone across the northern part of the FWB, with the dashed black subcrop line representing where this unit pinches out or could no longer be identified. There are two notable areas along the Jack – Young County line and in northeastern Wise County where both the Comyn and Forestburg limestone thicken from southwest to northeast and reach their maximum stratigraphic thickness, respectively (Figure 4-24; Plate 6). Other observations that can be made from the isopach map in Figure 4-24 and the cross-section provided in Plate 6 is the fact that the Forestburg-Comyn limestone was deposited continuously from east to west across southern Jack County and thins toward the southeast into northeastern Palo Pinto County as one continuous unit. The Forestburg-Comyn limestone is <50 feet thick across the northern part of Parker and Tarrant counties, but thickens toward the northeast and most likely extends beyond the edge of the isopach map into southeast Denton, northeast Tarrant, and northwest Dallas counties where there is limited well control (Figure 4-24). There is also limited deep well control across most of western Wise County, but there were enough data points to accurately determine the thickness in this area.

The most interesting stratigraphic feature of the Forestburg-Comyn limestone, and certainly the most important to oil and gas exploration of the Marble Falls Formation in the northern part of the FWB, is the abrupt thinning of this carbonate-rich unit in central to north-central Jack County and south-central Clay County where it grades into a low-resistivity shale that sits below the lower Marble Falls and above the lower Barnett Shale (Figure 4-5; Figure 4-6; Figure 4-24; Plate 1; Plate 6). It is not entirely clear how this depositional feature formed or what geological processes controlled its extent, but it was most likely related to the Red River Arch to the north and played an important role in controlling the regional stratigraphy of the Mississippian and Lower Pennsylvanian strata. There is evidence from isopach maps that this feature migrated to the south through time and persisted across most of the Mississippian and into the Early Pennsylvanian. This feature is important because it had a significant influence on the depositional trends of the lower Barnett Shale, lower Barnett calcareous unit (Figure 4-5; Plate 1), and Forestburg–Comyn limestone (Figure 4-24; Plate 6). It also controlled thickness trends within the lower Marble Falls because the thinning of the Forestburg-Comyn limestone in central Jack County provided accommodation space for the lower Marble Falls to infill this area and reach thicknesses >400 feet (Figure 4-24; Plate 6).

The Forestburg-Comyn limestone thins from the east and west towards north-central Jack County and is completely absent north of the town of Jacksboro but is approximately 100 to 150 feet thick across south-central Jack County (Figure 4-24; Plate 6). The upper Comyn limestone interval thins rapidly from the west and pinches out before it reaches this area in south-central Jack County, but the middle Comyn limestone was present across the area and intertongues with both the middle and upper units of the Forestburg limestone to the east (Figure 4-24; Plate 6). The Forestburg-Comyn limestone thins toward the southeast from central Jack County and pinches out along the southern subcrop, but it can be correlated continuously from west to east across northeastern Palo Pinto County and southeastern Jack County (Figure 4-24). The stratigraphic position of the Forestburg-Comyn limestone has greatly influenced the thickness and distribution of depositional facies within the lower Marble Falls, which will be discussed in the next section.

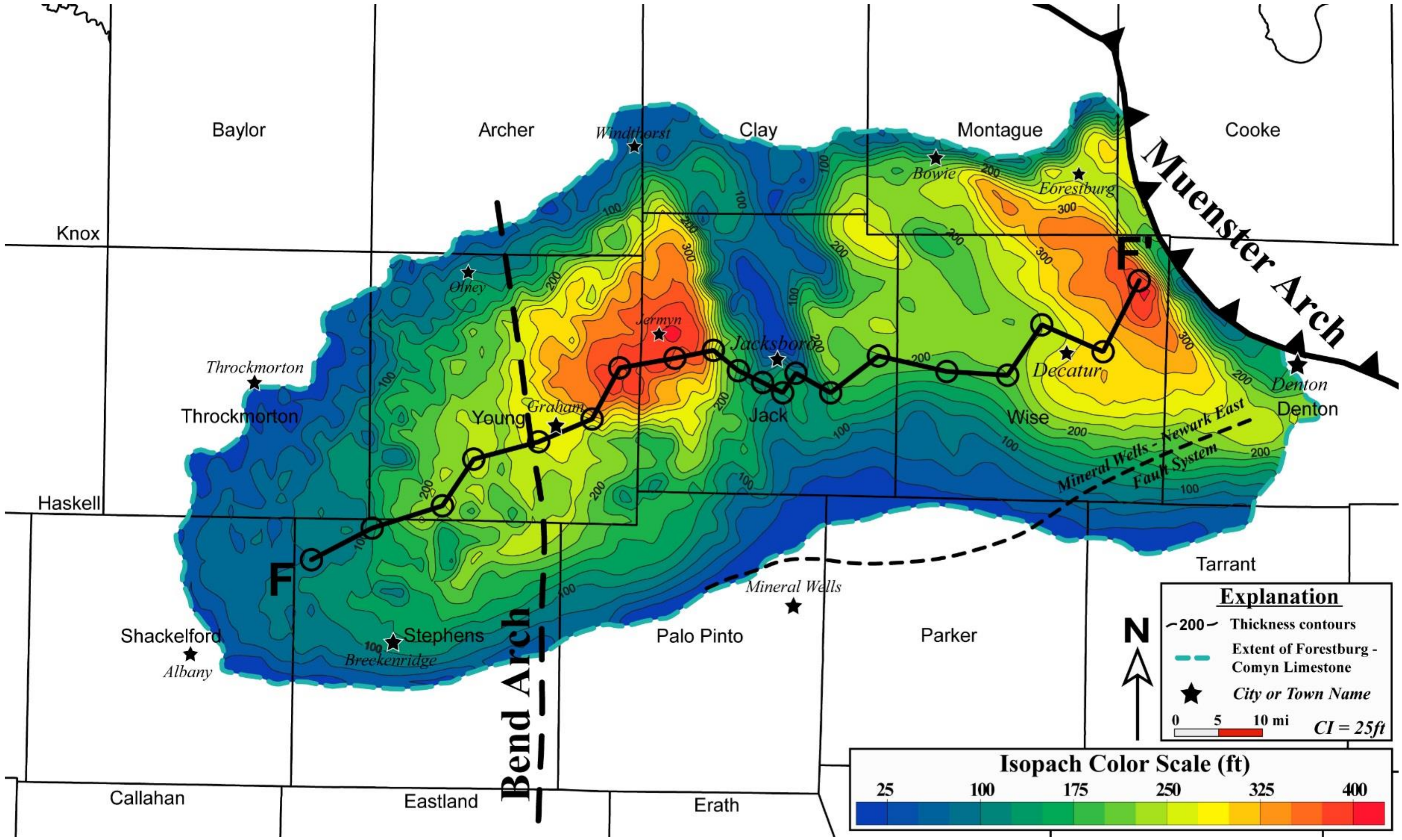



Figure 4-24. Regional isopach map of the Forestburg-Comyn limestone displaying thickness trends and its paleogeographic extent across the Fort Worth Basin. An east-west cross-section line is shown in black with circles representing the locations of well logs used in cross-section F – F' in Plate 6.

*Depositional Environment of Forestburg-Comyn Limestone*

The depositional environment of this carbonate-rich unit is poorly understood, but Bowker (2007) proposed that the Forestburg limestone was deposited as submarine debris flows with provenance in southern Oklahoma, and not as shoaling sequences as proposed by Johnson (2003). Part of Bowker's (2007) conclusion was based on the fact that the Forestburg reaches its maximum thickness near the Muenster Arch where the basin was structurally deepest (Bowker, 2007), but evidence from this work indicates the Forestburg-Comyn limestone is even thicker along the western edge of the FWB where it reaches thicknesses >400 feet (Figure 4-24;Plate 6). Loucks and Ruppel (2007) suggest that the sediments from the Forestburg limestone may represent fine-grained shelf carbonate debris that was transported deeper into the basin by turbidity flow and suspension processes. They proposed that there may have been a rise in sea level that triggered a transition in source area from a terrigenous-dominated source to a more distal carbonate-dominated source, and they suggested the Bend Arch to the west as a probable source area (Loucks and Ruppel, 2007). Farrar (2010) suggested that the sediments which comprise the Forestburg-Comyn limestone were derived from two different sources and intertongue along the border between Jack and Wise counties. He proposed that the Comyn sediments were sourced from the Chappel shelf to the west based on dip direction of beds and the thickening of this unit westward (Farrar, 2010), but he never mapped the Comyn limestone beyond western Jack County to observe that it actually thins to the west and southwest (Figure 4-24).

Evidence from thickness distributions and similarities in lithologies and bedding characteristics suggest that the Foresburg and Comyn limestones were deposited contemporaneously across the northern FWB in similar depositional environments that were separated in part by some type of depositional feature or incised valley present in central and north-central Jack County (Figure 4-24). As such, the Forestburg and Comyn limestones are herein interpreted to be laterally equivalent deposits that possibly represent a single unit. The interbedded clay-rich sediments and fine-grained carbonate-rich sediments within the Forestburg-Comyn limestone most likely represent deposits that were transported into the deeper basin from suspension settling or possibly dilute turbidity flow that were derived from the shallow-water shelf (Loucks and Ruppel, 2007). Based on thickness trends of the Forestburg-Comyn limestone and the fact that it pinches out almost uniformly across the entire southern subcrop suggest the source area was to the north in southern Oklahoma.

## Marble Falls Formation

### *Introduction*

The Marble Falls Formation has been studied extensively in outcrop and the immediate subsurface north of the Llano Uplift, but there has been limited subsurface work conducted in the central and northern parts of the FWB. Farrar (2010) discussed the facies within the lower Marble Falls based on core observations, but his work was concentrated in Jack and Wise counties and no attempt was made at correlating this portion of the Marble Falls to outcrop. There also have been no subsequent studies connecting Farrar's (2010) work to the various studies that have been conducted around the Llano Uplift. Therefore, this will be the first attempt to correlate and map the entire extent of the Marble Falls Formation across the FWB, including five different lithostratigraphic units that were only deposited in the northeastern part of the basin. This study utilizes the subsurface works of Brown (1983), Luker (1985), and Wood (2013) in the southern part of the FWB and the work of Farrar (2010) in the northern part of the basin to better understand the distribution of lithofacies within the Marble Falls Formation. In conjunction with the regional correlation and mapping efforts from this work, a stratigraphic framework is established for the Marble Falls Formation across the FWB and various units and parasequences are defined in the northern part of the basin. The upper member of the Marble Falls Formation (Atokan), discussed in previous sections, was also correlated and mapped across the southern part of the FWB (**Error! eference source not found.**), but details on the regional stratigraphy of this interval were not included in this study due to time constraints. This work concentrates on the lower member of the Marble Falls Formation because it was deposited over a much larger area and is the focus of a major oil and gas play emerging in the northern part of the FWB. It also presents much more complicated stratigraphic problems that need to be resolved, some of which were mentioned previously but will be discussed in more detailed in this section.

The lower Marble Falls was deposited in a carbonate ramp depositional system and is composed mostly of carbonate rocks along the Bend Arch in the western part of the FWB (Wood, 2013). These inner ramp carbonate units intertongue with middle to outer ramp deposits toward the east and northeast that are characterized by a thick sequence of spiculites. This spiculite facies is the most abundant facies within the lower Marble Falls and was discovered to have been deposited across the entire FWB. The spiculite deposits grade east into more mudstone-rich lithologies and in the northeastern part of the FWB the lower Marble Falls overlaps a series of calcareous shale and limestone units that are considered part of the Marble Falls Formation. However, it is important to note that there is evidence which will be presented later, that indicates these carbonate-rich sediments were probably deposited before the spiculite sequence (Morrowan), possibly during the Late Mississippian or Early Pennsylvanian, and originated from a different source area. Therefore, although it is possible these units may be similar in age, the carbonate-rich units are depositionally unrelated to the spiculite sequence to the west.

The Marble Falls Formation in the Newark East field area is composed of the lower Marble Falls spiculite sequence and five other limestone and shale intervals that are only present in the northeastern part of the FWB. In this same area, the entire Marble Falls succession reaches its maximum stratigraphic thickness of >800 feet in southwest Denton County and along the northern edge of Tarrant County. The various lithostratigraphic units of the Marble Falls Formation in the northern part of the FWB have been discussed briefly by previous authors (Pollastro *et al.*, 2007), but Farrar (2010) is the only work known to discuss and map each unit individually across Wise and Jack counties. However, each of these units extend beyond this area and it was important for this work to build upon Farrar's (2010) mapping efforts and define the paleogeography and thickness trends of each of these intervals across the FWB. Some of the same terms used by Farrar (2010) will also be used in this study and the Marble Falls Formation was informally divided into six units in the northeastern part of the FWB that include the following from the deepest stratigraphic interval to the shallowest: Marble Falls lower shale, Marble Falls lower limestone, Marble Falls upper shale, Marble Falls upper limestone, Marble Falls calcareous shale (defined in this study), and the lower Marble Falls spiculite sequence.

*Marble Falls Formation in Northeastern Portion of Study Area*

Type Log and Well Log Characteristics

The Devon Energy Smith Peggy Gas Unit No. 10 (42-121-31986) well located along the western border of Denton County serves as the type log for the Marble Falls Formation in the northeastern part of the FWB (Figure 4-25). This type log was selected from an area where all 6 units of the Marble Falls Formation were present and are distinctly defined in the log. The Marble Falls lower shale is defined as the interval from a measured depth of 7,303 to 7,347 feet in the type log shown in Figure 4-25. The base of this interval is marked by a sharp contact with the upper Barnett Shale, which is defined across the basin by a distinct increase in GR of over 200 API units. The lower shale interval is gradational with the overlying lower limestone interval and is characterized by slightly higher GR values that range from 45 to 90 API units and slightly lower resistivity values around 10 ohm-m (Figure 4-25). The Marble Falls lower limestone is defined as the interval from a measured depth of 7,246 to 7,303 feet in the type log shown in Figure 4-25 and is characterized by GR values that range from 30 to 45 API units, resistivity readings between 20 and 80 ohm-m, and PE values between 4.5 and 5 b/e. The upper contact of the lower limestone interval is gradational with the overlying Marble Falls upper shale interval and the contact between these units is typically marked by an increase in resistivity and decrease in GR at the top of the lower limestone. However, in areas where these two intervals are more gradational the contact is not as distinct as shown in the type log in Figure 4-25 and the top of the lower limestone is more interpretative and based on knowledge of variations in local stratigraphy

The Marble Falls upper shale interval is defined as the interval from a measured depth of 7,193 to 7,246 feet in the type log shown in Figure 4-25, and is characterized by log characteristics that are similar to the lower shale interval with GR readings ranging from 45 to 90 API units and resistivity readings ranging from 6 to 20 ohm-m. The contact of the upper shale with the overlying upper limestone is difficult to determine in parts of the basin because the upper shale becomes more calcareous toward the top as it grades upward into the upper limestone interval. However, the contact between these two units is typically marked by the first slight decrease in GR and increase in resistivity and PE values at the top of the upper shale, which indicates a transition from a mudstone-rich lithofacies to the more calcareous lithofacies of the upper limestone interval. The Marble Falls upper limestone is defined as the interval from a measured depth of 6,978 to 7,193 feet in the type log shown in Figure 4-25 and is a massive limestone that is characterized on well logs by GR values that range from 15 to 40 API units, resistivity readings that range from 40 to 100 ohm-m, PE values that range from 4.5 to 5 b/e, and NPHI / DPHI values from 0.06 to 0.00 V/V. The upper limestone interval is overlain by either the lower Marble Falls spiculite sequence or the calcareous shale interval and the contact of the upper limestone with each of these intervals is sharp and clearly defined by an increase in GR of over 100 API units (Figure 4-25).

The Marble Falls calcareous shale is defined as the interval from a measured depth of 6,861 to 6,978 feet in the type log shown in Figure 4-25 and is identified by its unusual well log characteristics that are distinct from any of the other Marble Falls lithostratigraphic units. It is characterized by GR values that range from 50 to 90 API units, resistivity values from 8 to 20 ohm-m, PE values from 3.5 to 4 b/e, NPHI values from 0.12 to 0.15 V/V, and DPHI values from 0.08 to 0.11 V/V (Figure 4-25). This calcareous shale interval was probably deposited in a similar environment to the limestone units lying below because it contains high concentrations of calcite that is evident in the slightly lower GR values and slightly higher ILD and PE values compared to a typical shale. The contact of the calcareous shale with the overlying lower Marble

Falls spiculite sequence is abrupt, with a maximum flooding surface (MFS) marking the top of the calcareous shale sequence which is represented by an increase in GR over 150 API units. (Figure 4-25). This MFS is present across most of the study area and is used as a correlative marker horizon to separate the spiculite sequence from the calcareous shale interval below. However, toward the west and southwest this MFS is not as distinct and the calcareous shale interval grades upwards into the lower Marble Falls spiculite sequence. The calcareous shale becomes more calcite-rich as it thickens towards the south and southeast and the log curve readings change significantly from the type log shown in Figure 4-25.

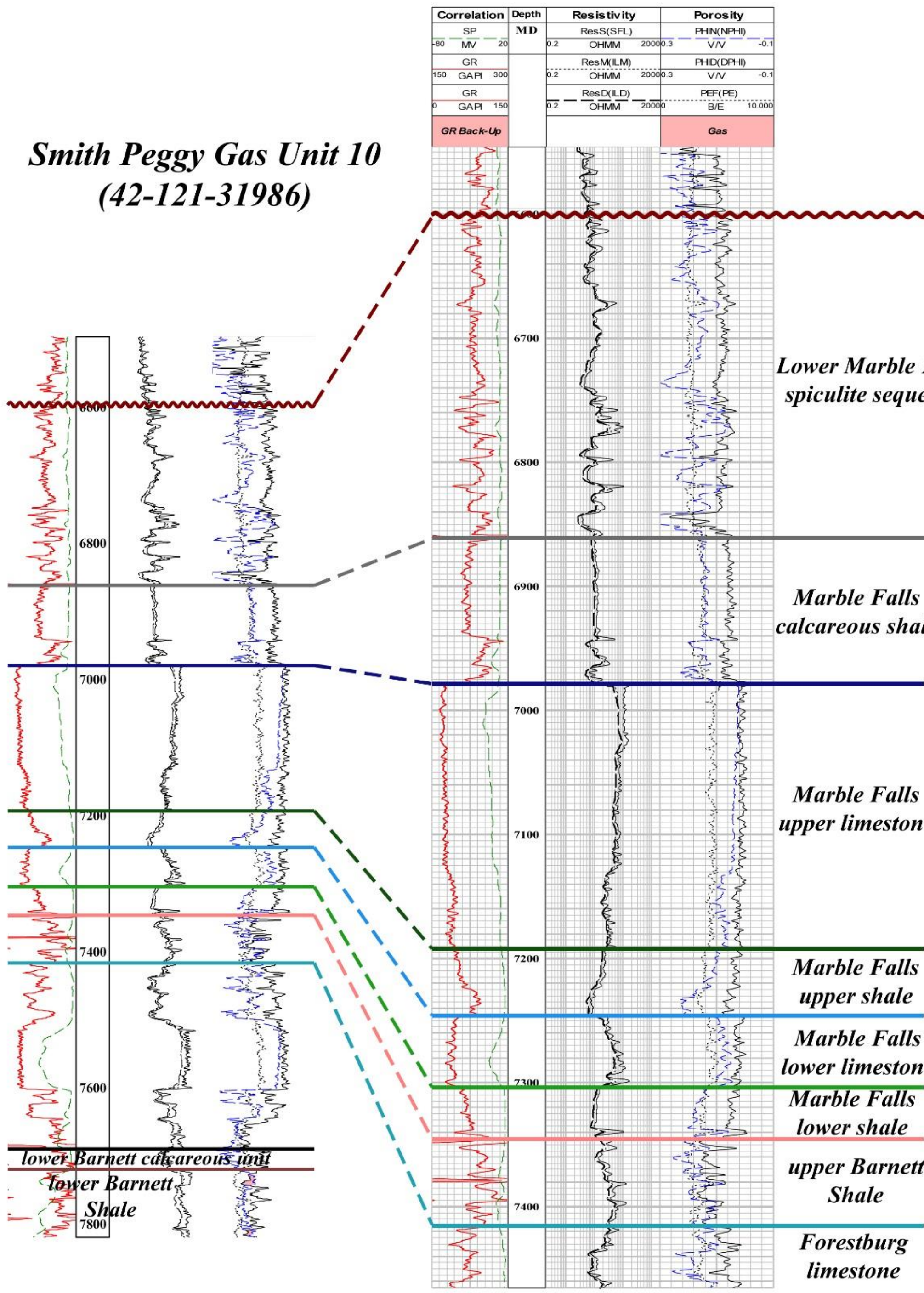



Figure 4-25. Type log for the Marble Falls Formation in the northeastern portion of the study area displaying typical well log characteristics of various units including the lower shale, lower limestone, upper shale, upper limestone, calcareous shale, and lower Marble Falls spiculite sequence.

Paleogeography of the Marble Falls Lower Shale

The Marble Falls lower shale lies unconformably above the upper Barnett Shale and is gradational with the overlying lower limestone interval. However, in areas where the lower limestone is absent, the lower shale grades upwards into the upper shale and the two units are difficult to distinguish on well logs. This occurs along the eastern and northern edges of Wise County where the lower limestone is thin to absent and in northwestern Wise County where the lower shale intertongues with the upper shale and forms a single shale unit that was defined as part of the upper shale. The lower shale reaches its maximum stratigraphic thickness of approximately 120 feet along an east-west trend in eastern Jack County and western Wise County where it is highly calcareous and grades upward into the lower limestone interval that contains only slight differences in well log characteristics from the lower shale (Figure 4-26; Plate 7). The lower shale unit also intertongues with the spiculite sequence to the west of this area in eastern Jack County and both the lower limestone and lower shale intervals replace the lower half of the spiculite interval (Plate 7).

The lower shale interval thins abruptly toward the south and is completely replaced by a massive lower limestone interval in southwest Wise County (Figure 4-26; Figure 4-27; Plate 7). However, the lower shale starts to thicken toward the east and northeast as it replaces the lower limestone interval which is only a couple feet thick adjacent to the Muenster Arch in northeast Wise County and western Denton County (Figure 4-26; Figure 4-27). Stratigraphic trends and thickness variations of the lower limestone and lower shale in Wise County were influenced by the Muenster Arch to the northeast and the Mineral Wells-Newark East (MW-NE) fault system to the south, and both of these structural features controlled the distribution of depositional facies throughout the Marble Falls succession. In the isopach map shown in Figure 4-26 there are notable northwest to southeast thickness trends in northeast Wise County that are parallel to the Muenster Arch, and these stratigraphic variations are possibly due to fluctuations in sea-level that caused changes in distance to the source area, or could have been tectonically controlled from subsidence of the FWB. The lower shale interval also thins abruptly to the southeast up against the MW-NE fault system and was not deposited on the south side of the fault (Figure 4-26; Plate 7), which suggests that the fault was active at the time of deposition and formed some type of barrier to deposition of the lower shale.

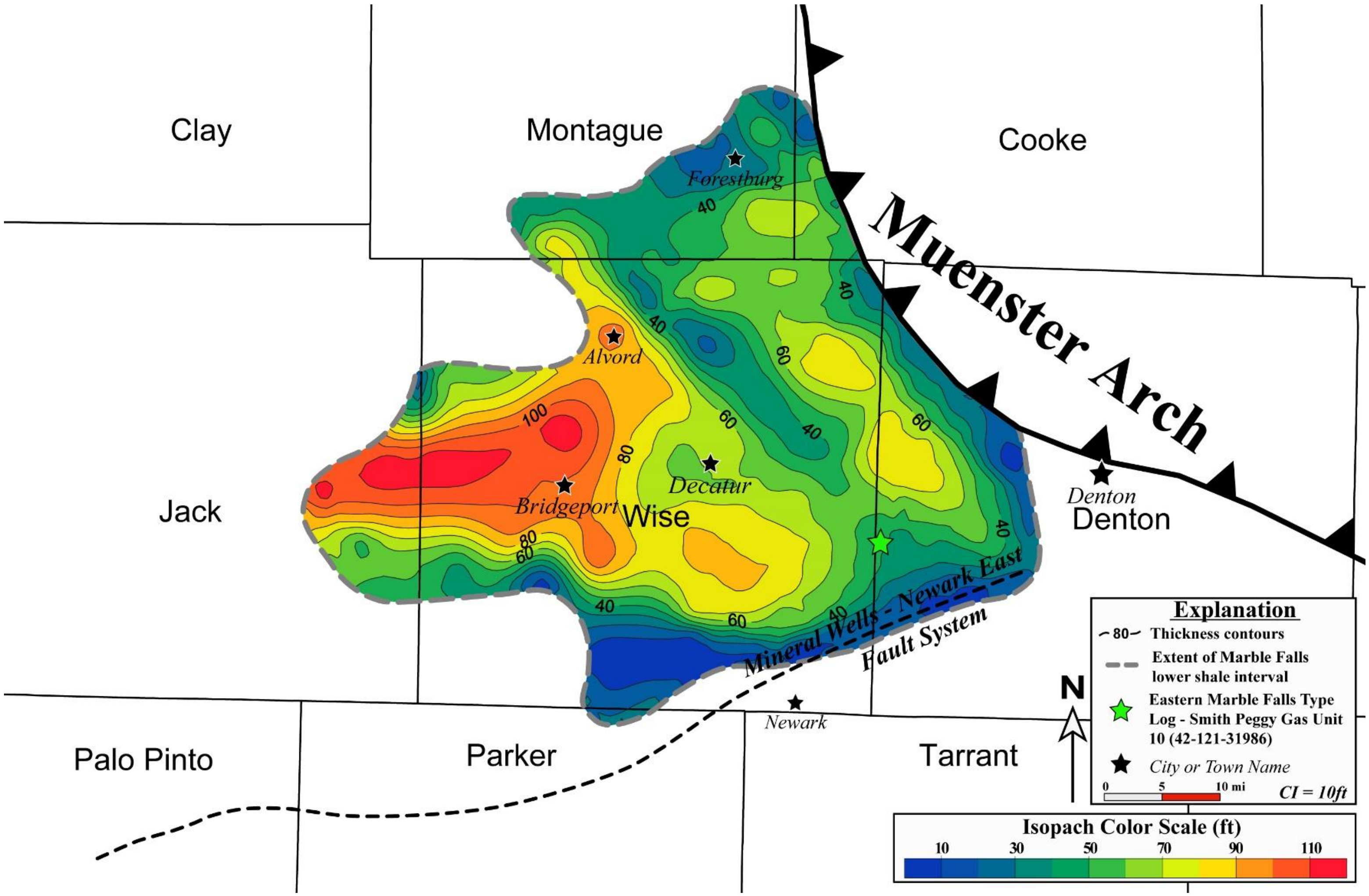



Figure 4-26. Isopach map of the Marble Falls lower shale interval displaying thickness trends and its paleogeographic extent across the northeastern edge of the Fort Worth Basin.

Paleogeography of the Marble Falls Lower Limestone

The Marble Falls lower limestone interval lies stratigraphically above the Marble Falls lower shale and below the Marble Falls upper shale, but south of the MW-NE fault system the lower shale is completely absent and the lower limestone lies directly on top of the upper Barnett Shale (Figure 4-25; Figure 4-26; Figure 4-27; Plate 7). The lower limestone interval is gradational with both the lower shale below and the upper shale above and is less than 100 feet thick across most of its extent in the northeastern part of the FWB (Figure 4-27). In southwest Wise County and southeast Jack County the lower limestone grades into a massive limestone interval that reaches a maximum stratigraphic thickness of approximately 215 feet (Figure 4-27; Plate 7). In northwest Parker County the lower limestone reaches thicknesses of 150 feet over a small area, but is abruptly replaced laterally in all directions by the spiculite sequence (Figure 4-27). The lower limestone intertongues with the lower part of the lower Marble Falls spiculite sequence in southeastern Jack County where it replaces most of the spiculite interval along a northwest to southeast trend (Figure 4-27). This trend corresponds to the abrupt change in thickness of the lower limestone interval from 200 feet to being completely absent over a distance of just 1500 feet. It is unclear if this abrupt change in thickness was structurally or depositionally controlled, but the fact that there are no major northwest to southeast trending faults identified in this area, suggests that it was depositionally controlled with the lower limestone having been deposited before the spiculite facies from a source area to the north or northeast.

The lower limestone interval thins toward the north and grades downwards into the lower shale interval until it is completely replaced by a thick upper shale interval in northwest Wise County (Figure 4-27). Both the lower shale and lower limestone intervals pinch out to the north along a southwest to northeast trend in southern Montague County (Figure 4-26; Figure 4-27). The lower limestone thins toward the east and northeast where it is gradually replaced by the lower shale interval and is <10 feet thick against the Muenster Arch in northeast Wise County and western Denton County (Figure 4-27). The depositional extent of the lower limestone interval was controlled by the MW-NE fault system, with the isopach map in Figure 4-27 displaying a stratigraphically thicker trend of the lower limestone parallel to the fault in southeastern Wise County (Plate 7). The lower limestone interval starts to thin on the south side of the MW-NE fault and is < 20 feet thick across most of northwest Tarrant County (Figure 4-27; Plate 7). The calcite content of the lower limestone also starts to decrease south of the MW-NE fault as it becomes more argillaceous and grades upwards into the upper shale interval.

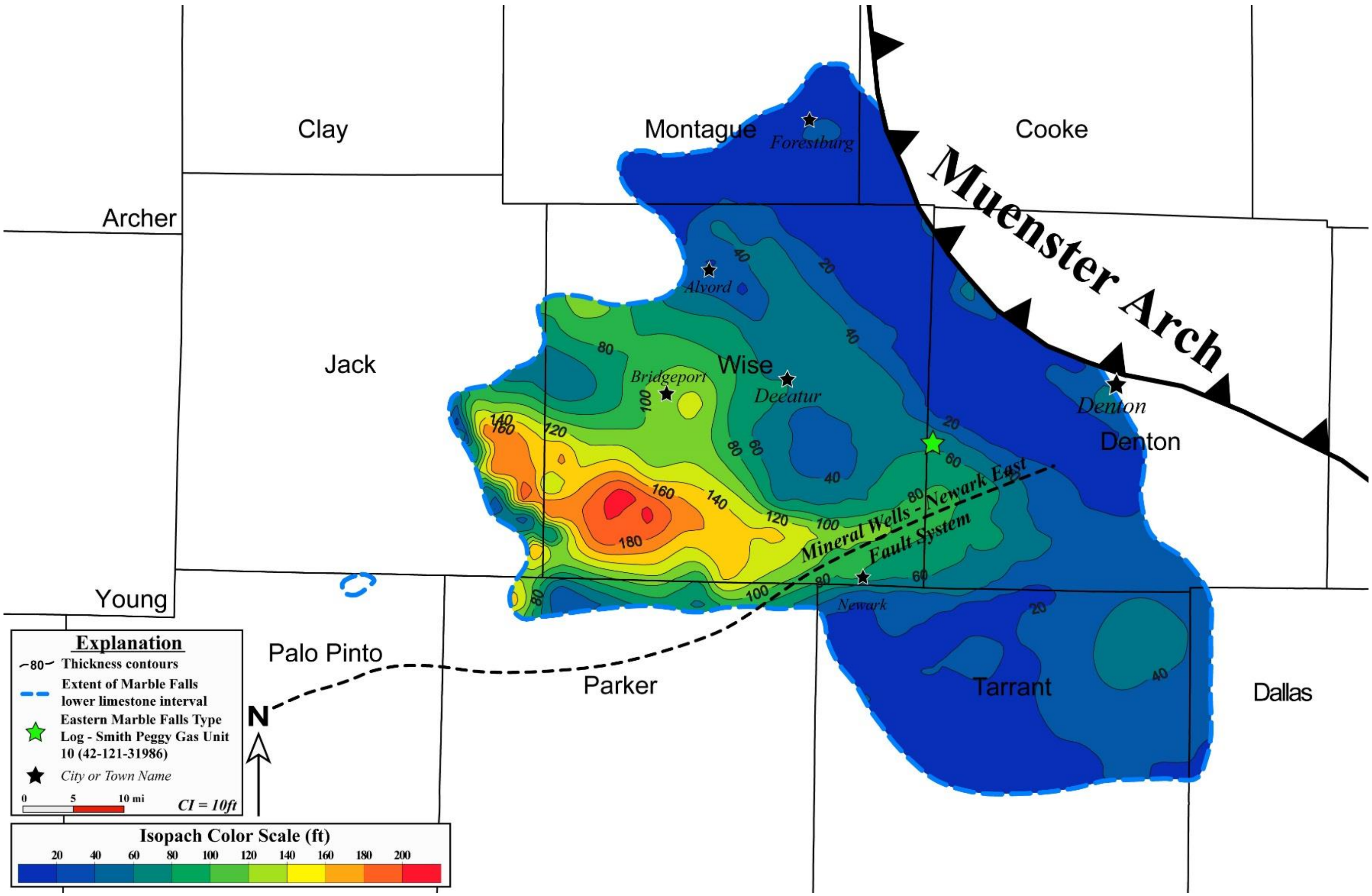



Figure 4-27. Isopach map of the Marble Falls lower limestone interval displaying thickness trends and its paleogeographic extent across the northeastern edge of the Fort Worth Basin.

Paleogeography of the Marble Falls Upper Shale

The Marble Falls upper shale lies stratigraphically above the lower limestone or lower shale and below the Marble Falls upper limestone or the lower Marble Falls spiculite sequence (Figure 4-25; Plate 7). The upper shale typically becomes more calcareous upward in the section and grades into the upper limestone interval where it is present, and grades downwards into the lower limestone interval south of the MW-NE fault (Figure 4-28; Plate 7). It also intertongues with the lower shale in northwest Wise County, and because the two intervals could not be distinguished on well logs this thick shale interval was included as part of the upper shale unit, which reaches thicknesses of more than 100 feet (Figure 4-28). The upper shale has a uniform thickness of approximately 40 to 60 feet across the rest of Wise County, but it gradually starts to thicken toward the MW-NE fault system to the southeast (Figure 4-28).

The isopach map in Figure 4-28 displays a stratigraphically thicker section of the upper shale that trends nearly parallel to the MW-NE fault from the northern part of Parker County to the northeast into central Denton County. This thick stratigraphic section of the upper shale occurs just south of where the thickest part of the lower limestone was deposited and the influx of clay-rich sediments most likely infilled an area of increased in accommodation space. Therefore, the distribution of sediments within the upper shale interval were also partially controlled by the MW-NE fault (Figure 4-28). The upper shale interval extends into northwest Parker County along the MW-NE fault and reaches thicknesses of nearly 150 feet near the town of Peaster (Figure 4-28). This is the only area in the northeastern part of the FWB where the Marble Falls upper limestone interval is completely absent and is replaced by the upper shale interval. The upper shale also thickens along the eastern edge of the MW-NE fault in south-central Denton County where it reaches a maximum stratigraphic thickness of approximately 150 feet (Figure 4-28; Plate 7). There were limited data points for correlating the Marble Falls Formation in southeast Denton County and northeast Tarrant County, but the upper shale interval generally thins to the south along an east-west strike and possibly extends farther east into southeast Denton County where there were no control points (Figure 4-28).

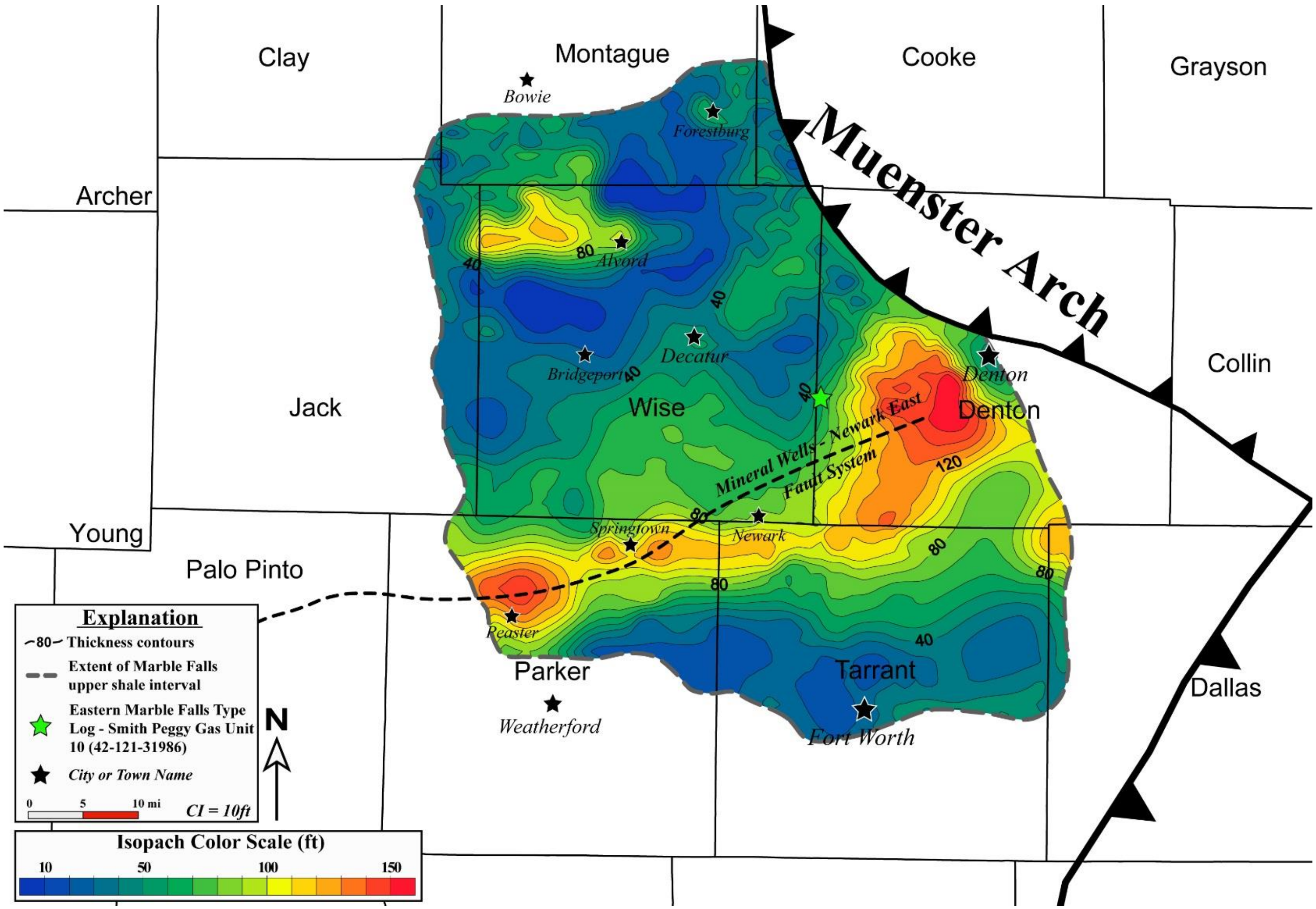



Figure 4-28. Isopach map of the Marble Falls upper shale displaying thickness trends and its paleogeographic extent across the northeastern edge of the Fort Worth Basin.

Paleogeography of the Marble Falls Upper Limestone

The Marble Falls upper limestone lies stratigraphically above the upper shale interval across most of the study area, but where the upper shale is absent, the upper limestone lies directly on top of the lower limestone interval or the upper Barnett Shale. It is overlain by either the lower Marble Falls spiculite sequence or the Marble Falls calcareous shale. With the exception of the spiculite sequence, the upper limestone unit is the thickest and most widely distributed interval in the Marble Falls succession in the northeastern part of the FWB and covers an area of approximately 6,520 $km^2$ (2,520 $mi^2$) (Figure 4-29). This interval is clearly identified on well logs as a massive limestone and contains uniform thicknesses across the study area that ranges from 150 to 200 feet (Figure 4-29; Plate 7). It reaches a maximum stratigraphic thickness of approximately 250 feet along a trend from central Denton County into the northern part of Tarrant County (Figure 4-29; Plate 7). Similar to other units within the Marble Falls Formation, the upper limestone interval most likely extends farther to the east and southeast into southeast Denton County and northwest Dallas County, but there were no control points to map these units in this area (Figure 4-29).

The paleogeographic extent of the upper limestone interval is controlled by the Muenster Arch to the northeast and the Saint Jo-Nocona fault to the north (Henry, 1982). Similar to the other units within the Marble Falls succession, the upper limestone pinches out to the north along an east-west strike through southern Montague County and was most likely eroded by the regional Atokan-age angular unconformity that was discussed by Henry (1982) (Figure 4-29). The upper limestone unit generally thickens toward the south and southeast across most of Wise County and into southwestern Denton County, but in northern Tarrant County the upper limestone unit thins abruptly to the south and is <20 feet thick near the city of Fort Worth (Figure 4-29).

The upper limestone interval also abruptly pinches out toward the west along a northwest to southeast trend from eastern Jack County into northwest Tarrant County (Figure 4-29; Plate 7). This abrupt change in thickness of the upper limestone unit occurs along a similar trend oriented in the same direction as the lower limestone interval, and both of these units were most likely controlled by the same geological processes. The upper limestone interval also occurs locally in northwest Parker County away from its principal subcrop similar to the lower limestone unit, and upper limestone reaches thicknesses >125 feet in this area (Figure 4-29).

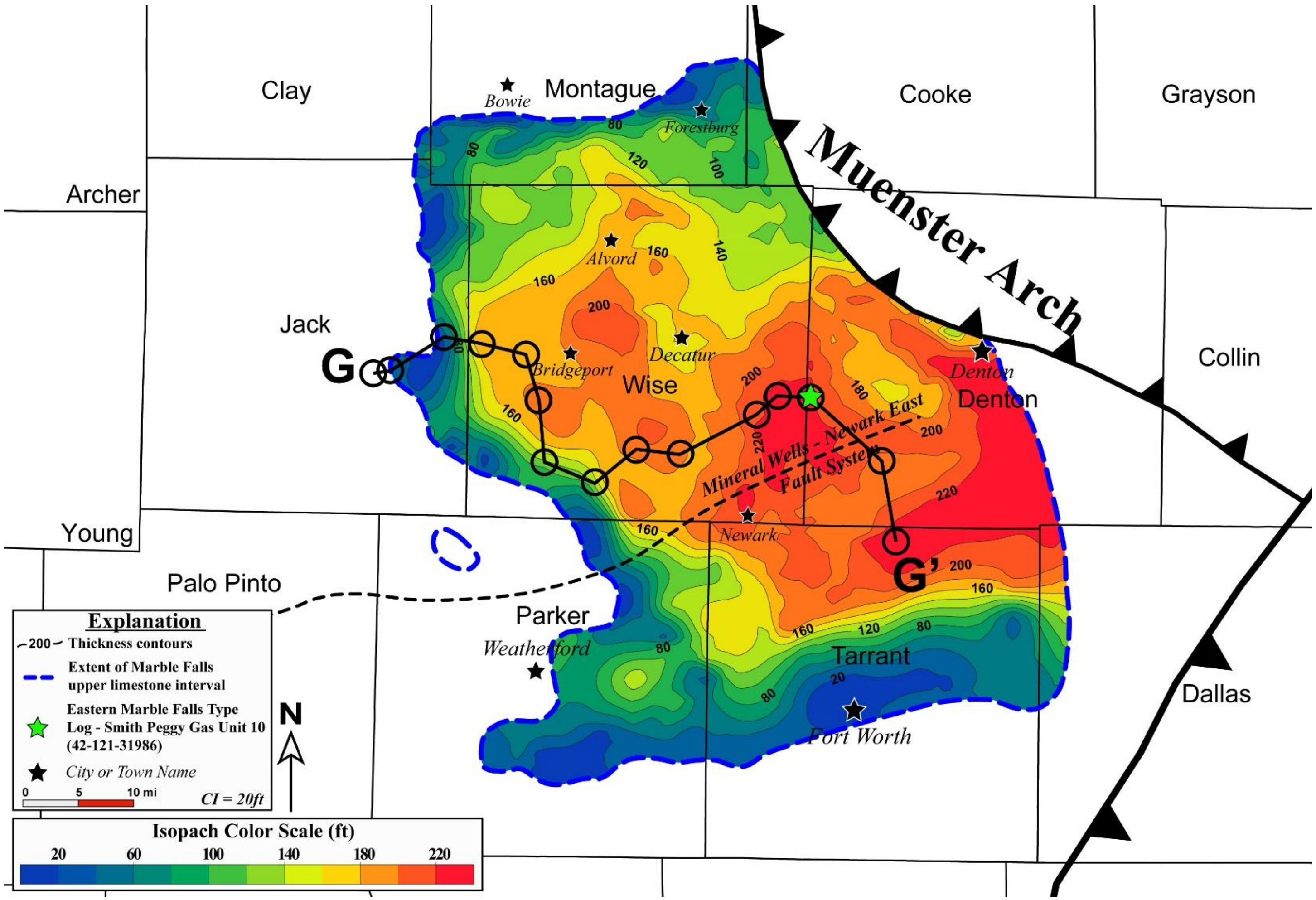



Figure 4-29. Isopach map of the Marble Falls upper limestone interval displaying thickness trends and its paleogeographic extent across the northeastern edge of the Fort Worth Basin. A west to east cross-section line is shown in black with circles representing the locations of well logs used in cross-section G – G' in Plate 7.

Paleogeography of the Marble Falls Calcareous Shale

The Marble Falls calcareous shale lies stratigraphically above the Marble Falls upper limestone interval or, where the upper limestone is absent, it lies directly on top of the upper Barnett Shale. It is overlain by the lower Marble Falls spiculite sequence and the contact between these two units is gradational across most of Parker County, but becomes more abrupt toward the east and northeast where a high-GR maximum flooding surface is present at the top of the calcareous shale (Figure 4-25; Plate 7). The calcareous shale interval was deposited farther south and southeast compared to the upper limestone unit and it reaches a maximum stratigraphic thickness of approximately 400 feet along the border between Tarrant and Dallas counties (Figure 4-30). There were limited data points for correlating the calcareous shale interval across Tarrant County, but there was enough control to define a distinct thinning of this unit to the southwest along the same trend as the upper limestone and lower limestone intervals (Figure 4-30).

The calcareous shale intertongues with the lower section of the spiculite sequence in parts of Parker County and these two units are difficult to distinguish in this area because of similarities in well log characteristics. The calcareous shale is also gradational with the spiculite facies in central and eastern Wise County where they thicken toward the northeast and grade into a thick limestone facies that cannot be distinguished on well logs. The calcareous shale interval thickens from <5 feet in central Wise County to the southeast where it reaches thicknesses >200 feet across southern Denton County and northern Tarrant,  and it becomes increasingly more calcareous toward the east and southeast (Figure 4-30; Plate 7).

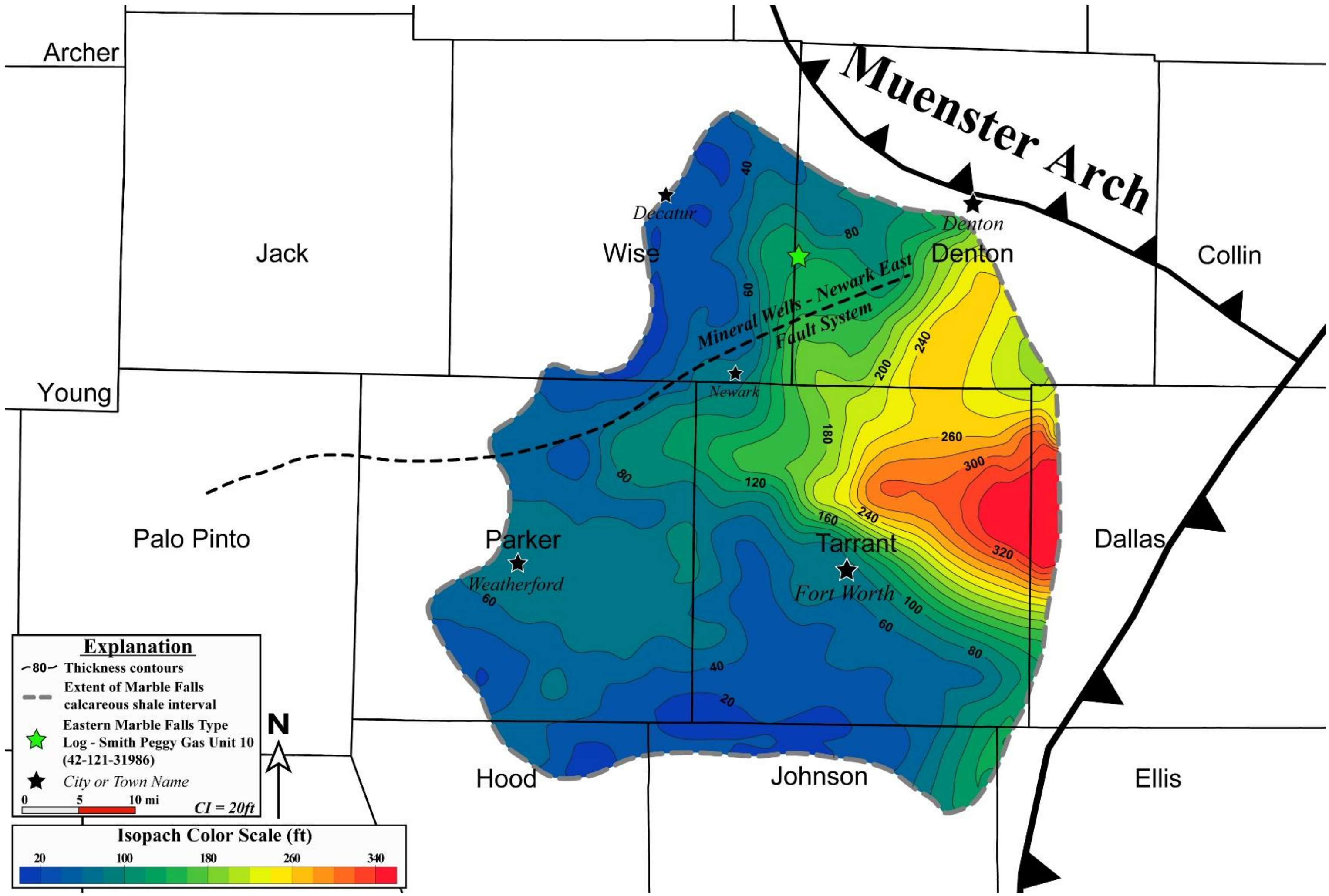



Figure 4-30. Isopach map of the Marble Falls calcareous shale displaying thickness trends and its paleogeographic extent across the northeastern edge of the Fort Worth Basin.

*Lower Marble Falls and the Lower Marble Falls Spiculite Sequence*

There has been no regional work conducted on the lower Marble Falls across the FWB, but the observations made by Brown (1983), Luker (1985), and Wood (2013) on the lower Marble Falls in the southern part of the basin were similar to the observations made by Farrar (2010) and this work in the northern part of the basin, and these similarities in lithologies and depositional facies show evidence that there was a broad depositional system that covered most of the FWB during the Early Pennsylvanian (Morrowan). The environment must have been ideal for sponge spicules to flourish during this time period because the lower Marble Falls contains a profusion of sponge spicules that were deposited as spiculites, or also referred to as the spiculite facies or spiculitic lithofacies. The possibility of the lower Marble Falls being deposited across the entire FWB and covering a much larger area than has previously been documented presented the opportunity to conduct a regional stratigraphic study, with the results and observations presented in subsequent sections. There were 5 lithostratigraphic units of the Marble Falls Formation discussed previously that are only present in the northeastern part of the FWB and contain carbonate-rich sediments that were most likely transported into the basin from a source area to the north.

The lower Marble Falls spiculite sequence is part of the lower member of the Marble Falls Formation that was deposited as a distally-steepened carbonate ramp along the Bend Arch in the western part of the FWB (Wood, 2013). This sequence of the lower Marble Falls is composed dominantly of siliceous to partly calcareous spiculites that extend across most of the FWB and overlap the carbonate-rich units to the northeast. It is this spiculite sequence of the lower Marble Falls that has historically been exploited for hydrocarbons from conventional stratigraphic traps along the western edge of the basin, and is currently the focus of an emerging unconventional fractured play in Jack and Palo Pinto counties. This sequence is poorly understood on a regional scale but the results from this study should provide a better understanding of the regional stratigraphy of the lower Marble Falls and the stratigraphic controls on reservoir quality.

### Lithofacies Description

There were several facies identified in the lower Marble Falls in the shallow subsurface north of the Llano Uplift that range from inner ramp carbonates to basinal mudstone facies (Wood, 2013). However, the most common and volumetrically significant facies within the lower Marble Falls succession in the southern part of the FWB is a spiculitic facies that comprises as much as 88% of the lower Marble Falls and contains an abundance of sponge spicules that are both siliceous and calcareous and constitute as much as 55% of the rock mass (Brown, 1983; Luker, 1985; Wood, 2013). The observations made by those authors on the lower Marble Falls in the southern part of the FWB are similar to what has been observed in the northern part of the basin. The lower Marble Falls consist of several lithofacies ranging from a fossiliferous limestone along the western edge of the basin to a calcareous mudstone along the eastern edge basin, but by far the most abundant facies in the lower Marble Falls succession in Jack and Palo Pinto counties is the spiculitic lithofacies. This facies contains an abundances of sponge spicules that are both siliceous and calcareous and comprise as much as 70% of the rock mass based on visual estimates from thin sections. It is unclear what percentage of the lower Marble Falls this spiculite facies comprises because most of the facies observations made in this work were based on thin section analysis from side-wall cores. However, Farrar (2010) performed a detailed whole core analysis of the EOG Resources House No.1 core and notes that approximately 70% of the core was composed of what he called a spiculitic siltstone and the other approximately 30% was composed of a laminated claystone to mudstone. The use of side-wall core data for determining various lithofacies in a formation is not as accurate as using whole core data, but in this work the thin sections from side-wall core were simply used to provide a general overview of the various lithofacies that are present in the lower Marble Falls. These observations are supported by well log characteristics, image log data, and previous investigations by Farrar (2010) and Ambrose *et al.* (2013). There were three common lithofacies observed in thin sections including a siliceous to partly calcareous spiculitic lithofacies, a calcareous mudstone, and a slightly argillaceous/fossiliferous packstone to grainstone,.

The spiculitic lithofacies was the most commonly observed facies within the lower Marble Falls succession and consist of a profusion of monaxon sponge spicules that were composed of both calcite and silica (Figure 4-31). The sponge spicules were the dominant allochem in this lithofacies but there were also various other unidentified fossil fragments present in varying amounts (Figure 4-31). The sponge spicules are randomly oriented in thin section and are commonly displayed in both transverse view where the central canal of the spicule is observed and in longitudinal views with some of the spicules reaching nearly 1 mm in length (Figure 4-31; Figure 4-32; Figure 4-33). The siliceous sponge spicules are more common than the calcareous spicules but they both typically occur in varying amounts throughout a single thin section (Figure 4-31). However, it was common for entire thin sections to be dominantly composed of either calcite or silica spicules allowing for the spiculitic lithofacies to be divide into sub-lithofacies consisting of a siliceous spiculitic limestone/chert (Figure 4-32), and a more calcareous spiculitic limestone (Figure 4-33). The siliceous lithofacies consist dominantly of sponge spicules that are composed of microcrystalline quartz and while this lithofacies can be considered a packstone to grainstone, the large quantities of silica comprising the sponge spicules make it a borderline chert lithofacies (Figure 4-32). It is important to note that when viewing this siliceous facies in drill cuttings under a standard binocular microscope it also has the textural appearance of a chert.

The calcareous spiculitic lithofacies consist dominantly of sponge spicules that have been nearly completely replaced by calcite or more rarely with dolomite, and this calcification process is evident in photomicrograph E and F of Figure 4-33 where the calcareous spicules are clumped together with the external structure of the spicules nearly unrecognizable. This calcification process has made the calcareous spiculitic limestone a poor reservoir quality lithofacies because any pore space that was present has been completely occluded and there was no visible porosity identified using standard petrographic observations. This calcareous spiculitic lithofacies is considered a packstone to wackestone and commonly contains varying amounts of silt, dolomite, organic-rich material (black color), and detrital clays (Figure 4-33).

The spiculitic lithofacies consist of randomly dispersed sponge spicules that are composed of either calcite or silica, but there are occasionally partially calcified spicules that contain a mixture of both silica and calcite (Figure 4-31). This is particularly common in photomicrograph E of Figure 4-31 where it appears that the calcite (stained red) was replacing the silica and occurs mostly along the edges of the spicules. Wood (2013) notes that these spicules were originally composed of opal-A and have been altered to calcite or microcrystalline quartz during diagenesis and these diagenetic processes are also observed in thin sections from the spiculitic lithofacies in the northern part of the basin (Figure 4-33). Silicification is common in the spiculitic lithofacies with the extent of this process varying from partial replacement of allochems to complete silicification to chert (Figure 4-34). While chert was commonly present in various thin sections it usually occurred in small quantities and never comprised a large portion of the total rock mass. However, a chert lithofacies does commonly occur in the lower Marble Falls spiculite sequence and was typically deposited near the top of high-frequence depositional cycles when there was a period of subaerial exposure. Other common constituents within the spiculitic lithofacies that occur in varying amounts include silt size quartz grains, dolomite, glauconite, pyrite, detrital clays, carbonaceous material, organic material, and commonly calcite-filled fractures are visible in thin section.

The spiculitic facies of the lower Marble Falls was observed by Brown (1983), Luker (1985), and Wood (2013) to be highly bioturbated and burrowed in the southern part of the FWB and Wood (2013) proposes they are *Chondrites* and *Zoophycos* burrows which exhibit a water depth of 200-2000 m. The burrows are typically distinguished from the surrounding material by their darker colors and are characterized by a higher clay and organic content (Brown, 1983; Wood, 2013). This intense bioturbation was also observed in the EOG Resources House No. 1 core in south-central Jack County and was noted by Farrar (2010) in his core description. The spiculitic lithofacies typically has a mottled appearance when viewed in a core and in drill cuttings and ranges from a creamy tan color to light gray to a darker gray and usually the higher concentrations of spicules correspond with the lighter rock whereas the darker colors represent the more clay-rich rocks. Other common features of the spiculitic lithofacies that was observed in the slabbed whole cores from the Cobra Oil and Gas Geer No. 1 and EOG Resources House No. 1 was the presence of soft-sediment deformation features, argillaceous lamina, stylolite, varying amounts of pyrite and glauconite, and common amounts of calcite-filled fractures.

The spiculitic lithofacies most commonly grades into, or is interbedded with, a calcareous mudstone lithofacies that Farrar (2010) interprets to comprise as much as 30% of the entire lower Marble Falls sequence. However, east and southeast of Jack and Palo Pinto counties the calcareous mudstone lithofacies comprises a significantly larger percentage of the lower Marble Falls spiculitc sequence due to a transition from a middle to outer ramp depositional environment in the central part of the FWB to a more basinal environment along the eastern part basin. The mudstone lithofacies within the lower Marble Falls is typically calcareous with varying amounts of silt, detrital clays, organic material, pyrite, recrystallized fossil fragments, dolomite, and glauconitic (Figure 4-35).

The calcareous mudstone lithofacies also commonly displays a laminated texture in thin section that is usually wavy to discontinuous (Figure 4-35).

The least commonly observed lithofacies in thin sections from side-wall cores in Jack and Palo Pinto counties was the limestone lithofacies that consist mostly of slightly silty/fossiliferous/argillaceous packstone to grainstone (Figure 4-36). There was also a micritic limestone identified with silt-size calcite crystals and only contained traces of silt, dolomite, and argillaceous material (Figure 4-36). The more carbonate-rich lithofacies within the lower Marble Falls succession typically increases in percentage toward the west in a more proximal inner ramp depositional environment.

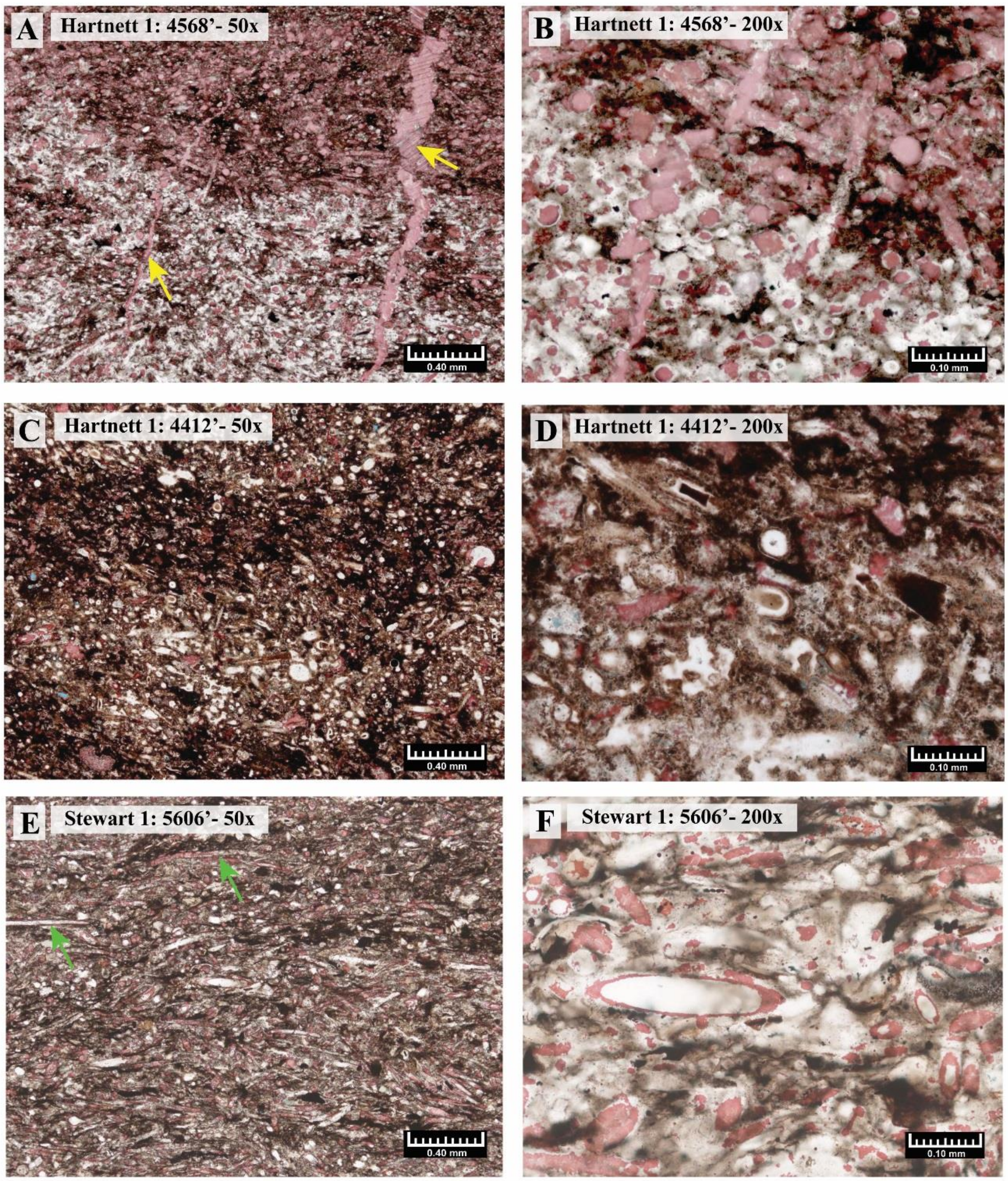



Figure 4-31. Photomicrographs of the spiculitic lithofacies displaying examples of randomly distributed calcified (stained red) and silicified (white) sponge spicules. The spicules are mostly randomly oriented but image E shows slight alignment possibly due to current reworking. Some of the longitudinal spicules reach nearly 1mm in length (green arrow). There is also a calcite-filled fracture displayed in image A (yellow arrow).

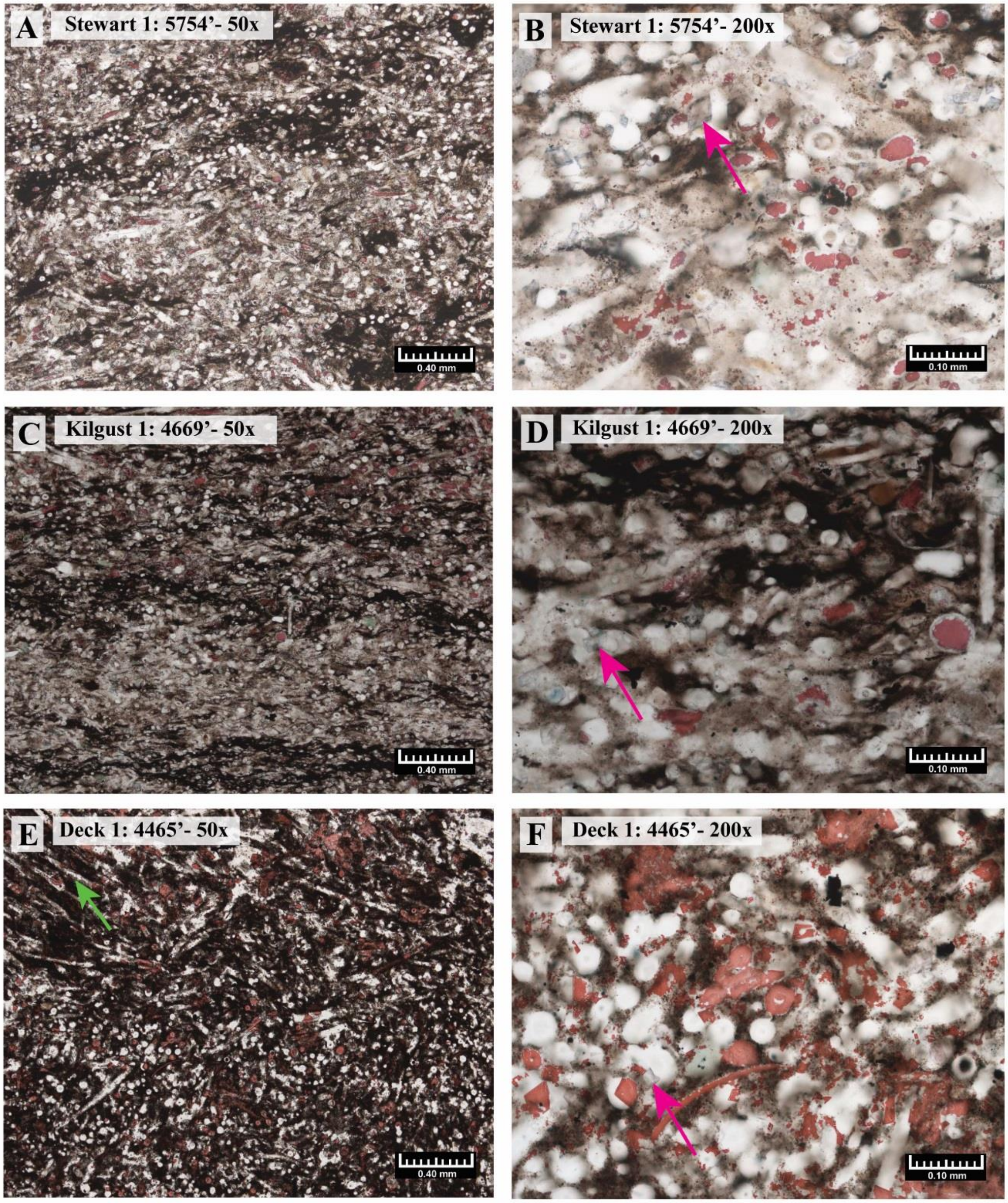



Figure 4-32. Photomicrographs of the siliceous spiculitic lithofacies displaying silicified sponge spicules (white) that dominate the thin sections. This lithofacies is typically slightly dolomitic (pink arrows) and argillaceous (black material). There is alignment of the spicules in the upper left corner of image E indicated by the green arrow.

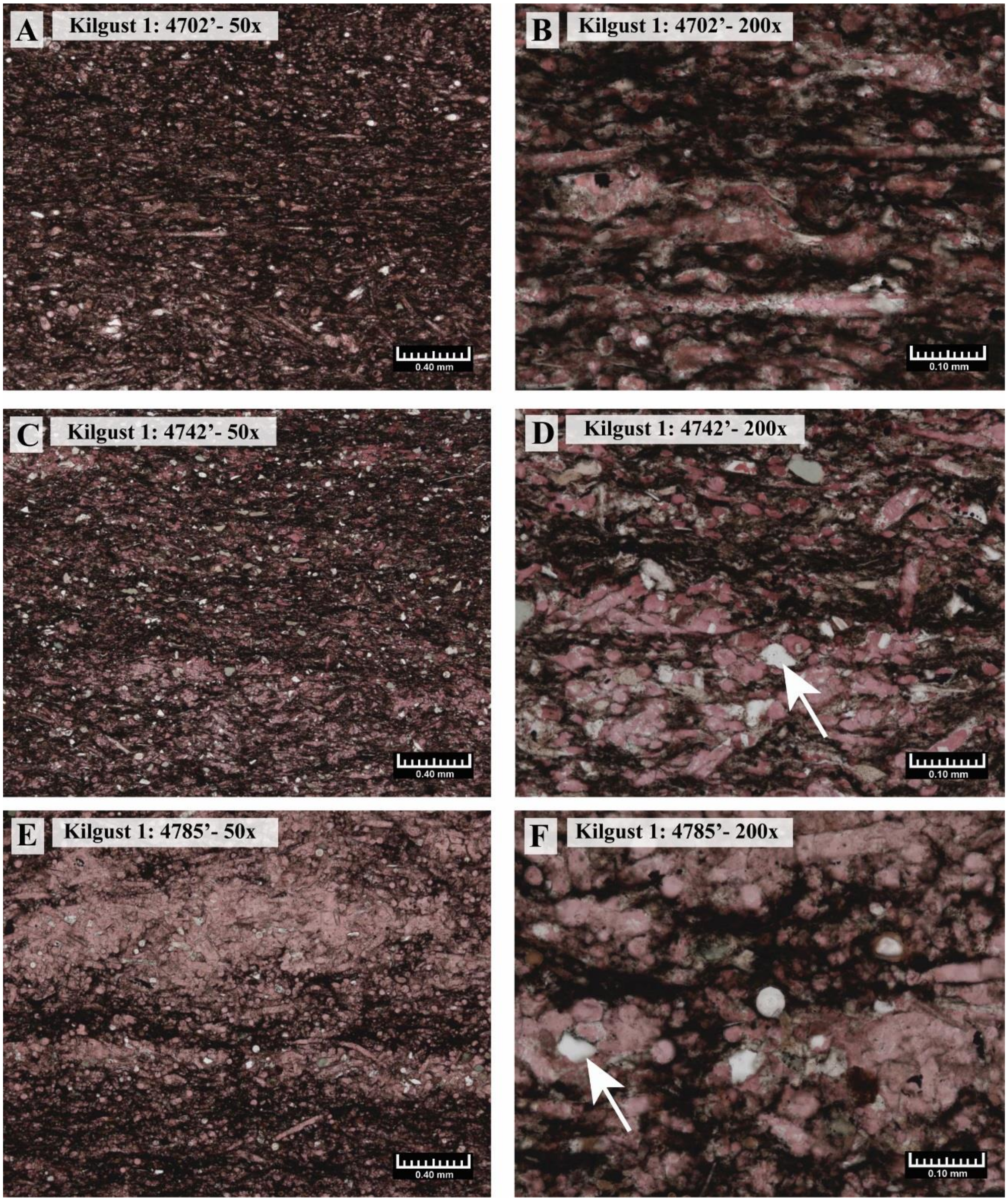



Figure 4-33. Photomicrographs of the argillaceous, calcareous spiculitic limestone displaying calcified (stained red) sponge spicules that dominate the thin sections. Note that the diagenetic calcification process has clumped the spicules together. These intervals are also slightly silty with quartz grains shown by the white arrow.

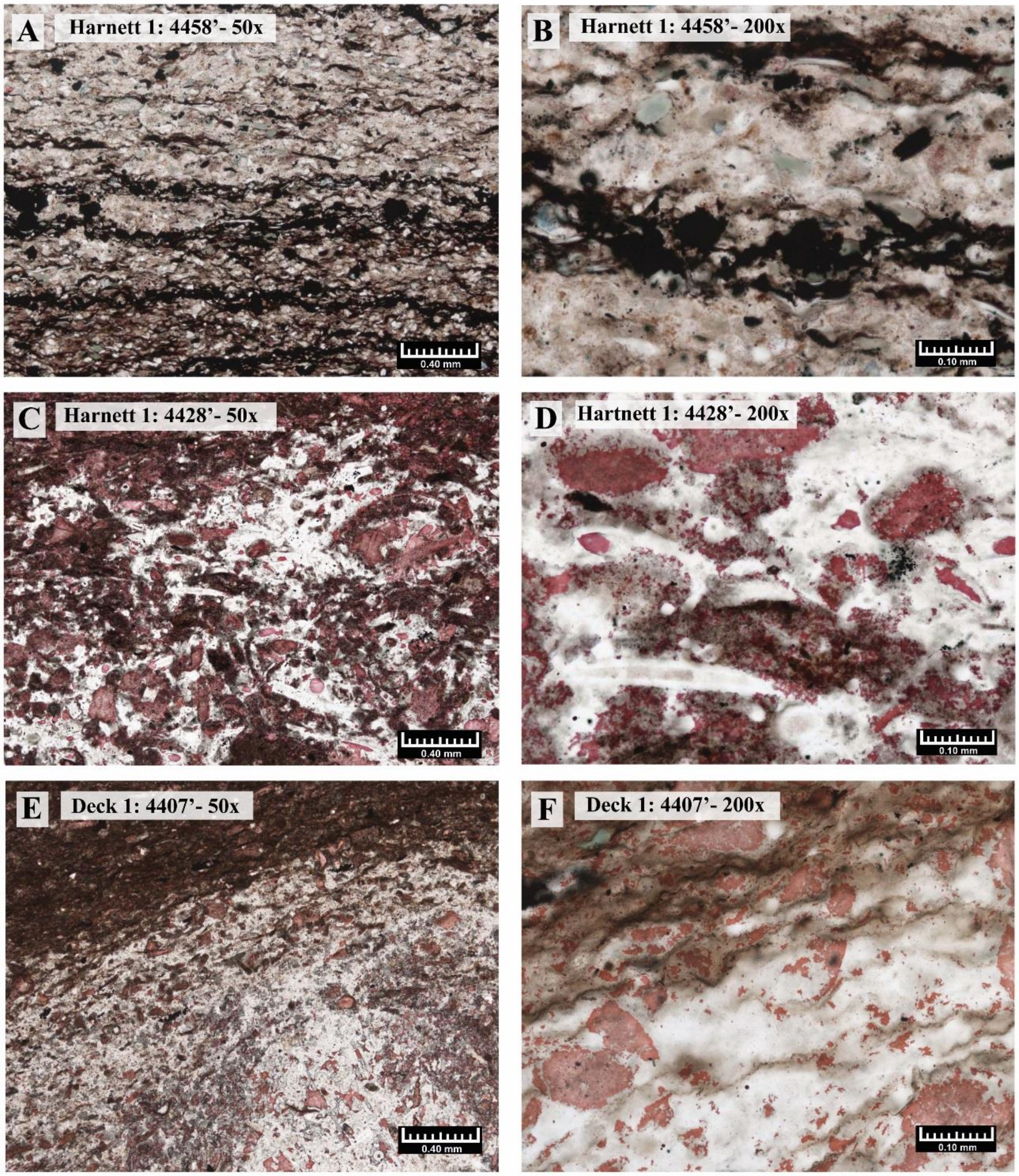



Figure 4-34. Photomicrographs displaying various examples of microcrystalline quartz or chert that commonly occurs in the lower Marble Falls. Note the presence of glauconite in image A and B represented by the green color.

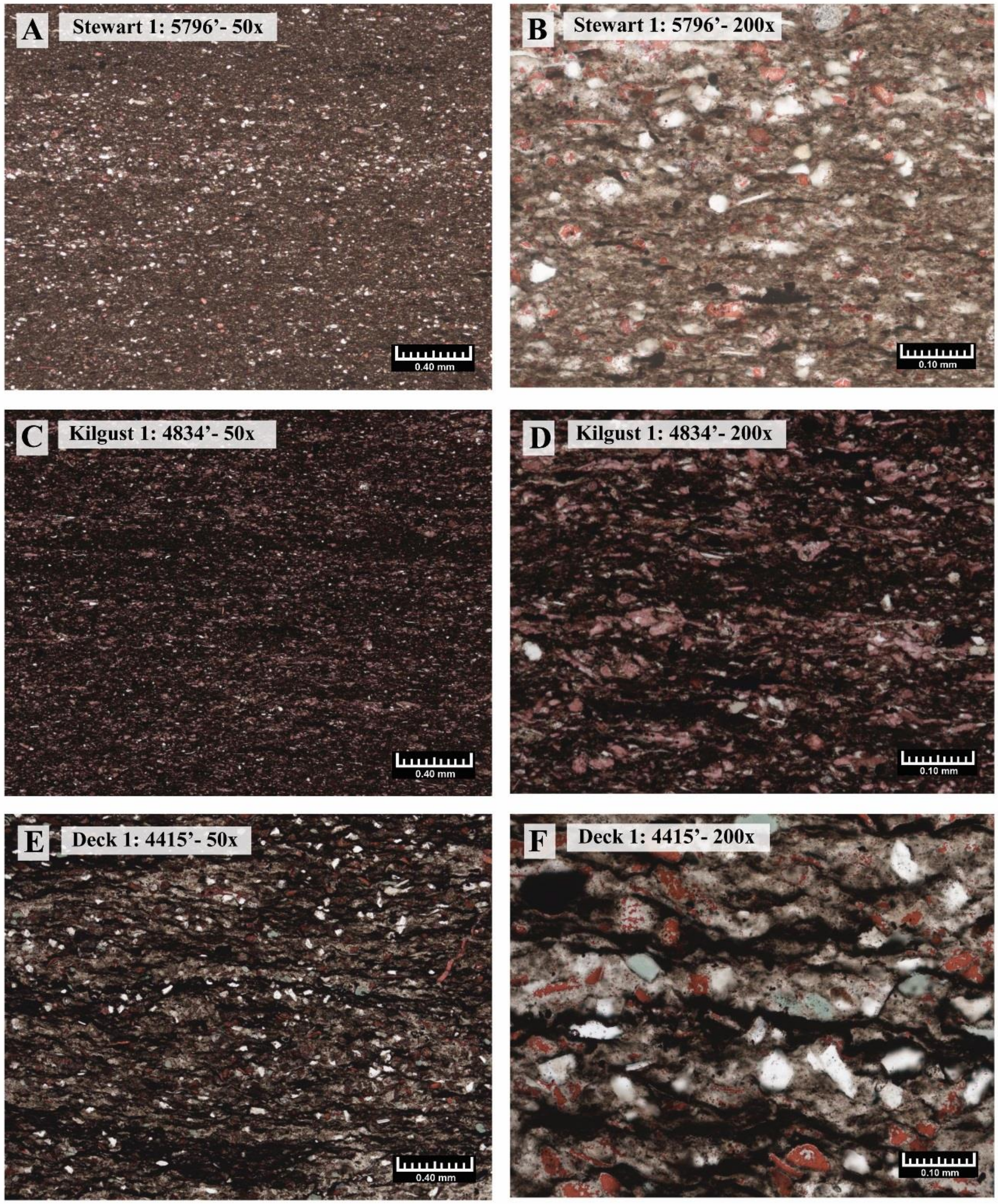



Figure 4-35. Photomicrographs displaying various slightly silty, calcareous mudstone lithofacies that commonly occur in the lower Marble Falls. Note the presence of glauconite in image E & F represented by the green colored grains and the abundance of argillaceous and carbonaceous material represented by the black colors.

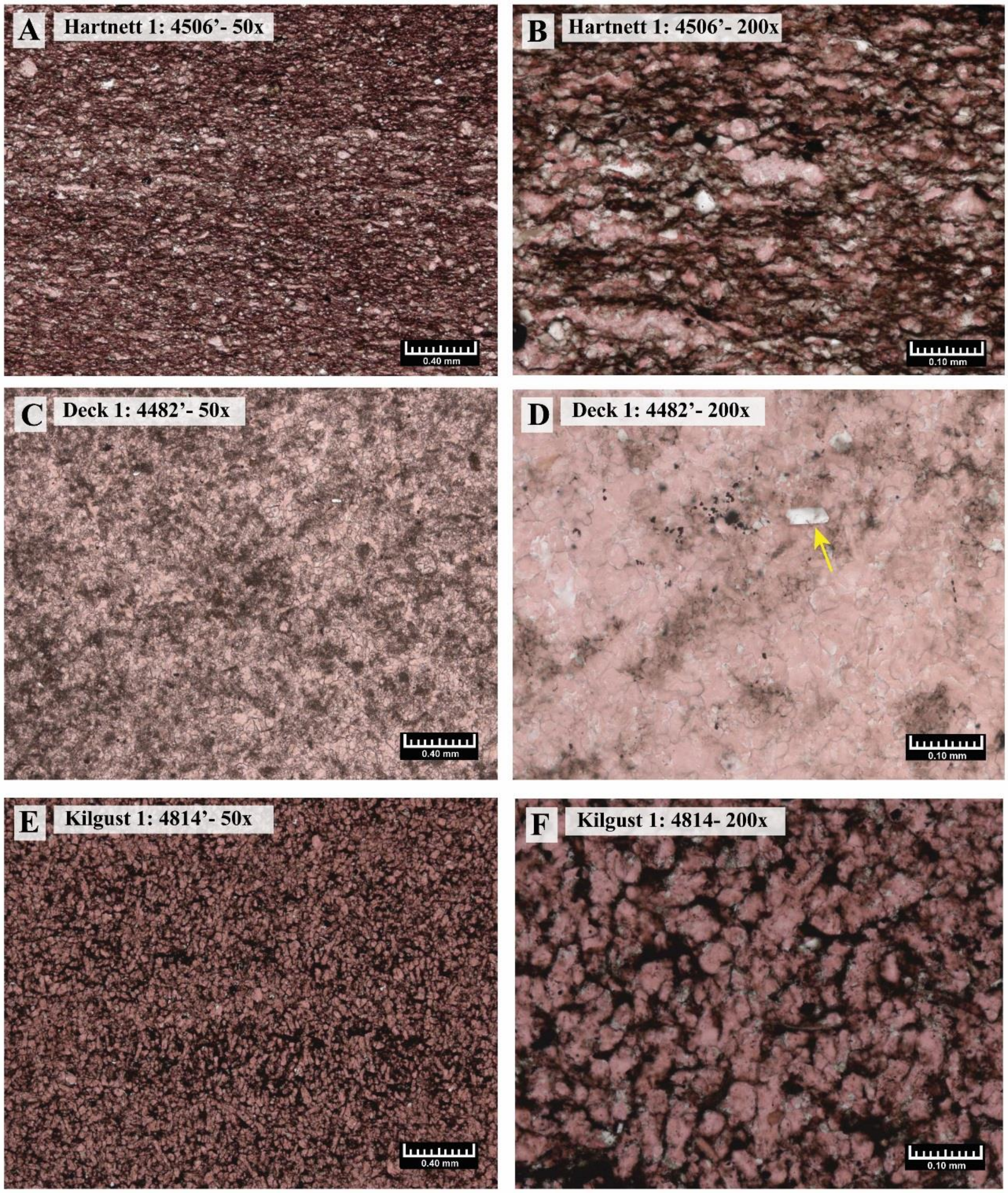



Figure 4-36. Photomicrographs displaying various limestone lithofacies with a packstone to grainstone (A, B, E, & F) being the most common texture, but a micritic limestone (C & D) was also observed. The limestone lithofacies are commonly slightly argillaceous (black material) and contain varying amounts of silt, dolomite (yellow arrow), and fossil fragments.

Type Log and Well Log Characteristics

The Early Pennsylvanian lower Marble Falls is defined as the interval that lies stratigraphically above the lower Barnett Shale, lower Barnett calcareous unit, Forestburg-Comyn limestone, upper Barnett Shale, or the carbonate-rich units of the Marble Falls Formation in the northeastern part of the basin, and is unconformably overlain by the Atokan strata represented by either the upper Marble Falls, Smithwick Shale, or the Atoka Group (Bend Conglomerate). The spiculite sequence comprises most of the lower Marble Falls and consist of sporadic well log patterns that are due to variations in silica and calcite content throughout the section. The type log for the spiculite sequence was selected from an area where it reaches a near-maximum stratigraphic thickness in the northern part of the basin and contained the greatest number of parasequences that were well defined in the log.

The Newark E&P Herring No. 1 (42-363-36156) well located along the northern edge of Palo Pinto County serves as the type log for the lower Marble Falls spiculite sequence and it is defined as the interval from a measured depth of 4,594 to 4,944 feet (Figure 4-37). It is bounded at the top by an unconformity and maximum flooding surface (MFS) that is identified by an increase in GR of over 200 API units and marks the upper contact with the overlying Atoka Group (Figure 4-37). It is also bounded at the base by an unconformity and MFS that marks the contact with underlying Upper Mississippian Forestburg-Comyn limestone or, where the limestone interval is absent, the Mississippian lower Barnett Shale (Figure 4-37). Both the lower Barnett Shale and Forestburg-Comyn limestone intervals contain well log characteristics that are distinct from the overlying lower Marble Falls and have made correlating these stratigraphic units across the FWB much simpler.

The lower Marble Falls spiculite sequence was influenced by Early Pennsylvanian sea-level fluctuations and foreland basin tectonics which is evident from the shallowing-upward high-frequency cycles (HFC), or parasequences that have been identified throughout the study area. A parasequence was defined by Van Wagoner *et al*. (1988) as a relatively conformable succession of genetically related beds or bedsets bounded by marine-flooding surfaces and their correlative surfaces. There were a total of 12 PS identified in Jack, Palo Pinto, and Parker counties, but only 8 of these have been correlated in detail and are present in the type log shown in Figure 4-37. Each of the parasequences were bounded by the correlative marine-flooding surfaces that were used to correlated and map each interval across the study area using open-hole wireline logs. PS 1 is defined as the interval from a measured depth of 4,900 to 4,944 feet, PS 2 is defined as the interval from 4,858 to 4,900 feet, PS 3 is defined as the interval from 4,806 to 4,858 feet, PS 4 is defined as the interval from 4,753 to 4,806 feet, PS 5 is defined as the interval from 4,714 to 4,753 feet, PS 6 is defined as the interval from 4,666 to 4,714 feet, PS 7 is defined as the interval from 4,606 to 4,666, and PS 8 is defined as the interval from 4,594 to 4,606 feet in the type log shown in Figure 4-37. The thickness distributions of each of these PS over an area where they could be mapped will be presented below.

The lower Marble Falls is a highly complex succession of interbedded siliceous to calcareous spiculites, carbonate-rich lithofacies, and mudstone lithofacies that are characterized by a wide range of well log values. The type log in Figure 4-37 displays the sporadic well log response patterns that are common in the lower Marble Falls spiculite sequence with the complex vertical variations in lithofacies expressed in the mineralogy log in track 1. The GR values do not change much between the calcareous intervals and siliceous intervals and typically range from 40 to 90 API units throughout the spiculite sequence with the marine-flooding surfaces of the parasequences reaching GR values over 90 API units (Figure 4-37). The SP curve is not typically used for correlation purposes or determining lithofacies characteristics, but it does provide a good indication of permeability throughout the spiculite sequence with a >20 mv negative deflection from the shale base line indicating a possible fractured zone. With the spiculite sequence being such a dense rock, the resistivity readings are typically high and frequently reach values greater than 200 ohm-m. Similar to the GR curve, the resistivity readings do not vary much between the siliceous and calcareous intervals and typically range from 20 to 200 ohm-m with a significantly lower reading throughout the mudstone-rich intervals (Figure 4-37).

The porosity curves are the most beneficial log for evaluating the reservoir quality of the lower Marble Falls spiculite sequence and distinguishing the siliceous-rich reservoir lithofacies from the calcareous non-reservoir lithofacies. The siliceous-rich spiculitic lithofacies are typically characterized by a cross-over of the DPHI and NPHI curves with a typical cross-plot porosity of 0.04 to 0.1 V/V (Figure 4-37). The RHOB values of the siliceous-rich intervals are usually around 2.5 to 2.6 g/cm$^3$ and the PE values typically range from 2 to 3 b/e (Figure 4-37). The calcareous-rich intervals are considered a non-reservoir rock because they typically do not contain as great a concentration of lithology-bound fractures compared to the siliceous-rich intervals and as mentioned previously, most of the pore space have been occluded by the diagenetic replacement to calcite. This calcareous lithofacies is typically characterized on well logs by NPHI values that range from 0.01 to 0.04 V/V, DPHI values from 0.02 to 0.05 V/V, RHOB values from 2.6 to 2.7 g/cm$^3$, and PE values from 3.5 to 5 b/e.

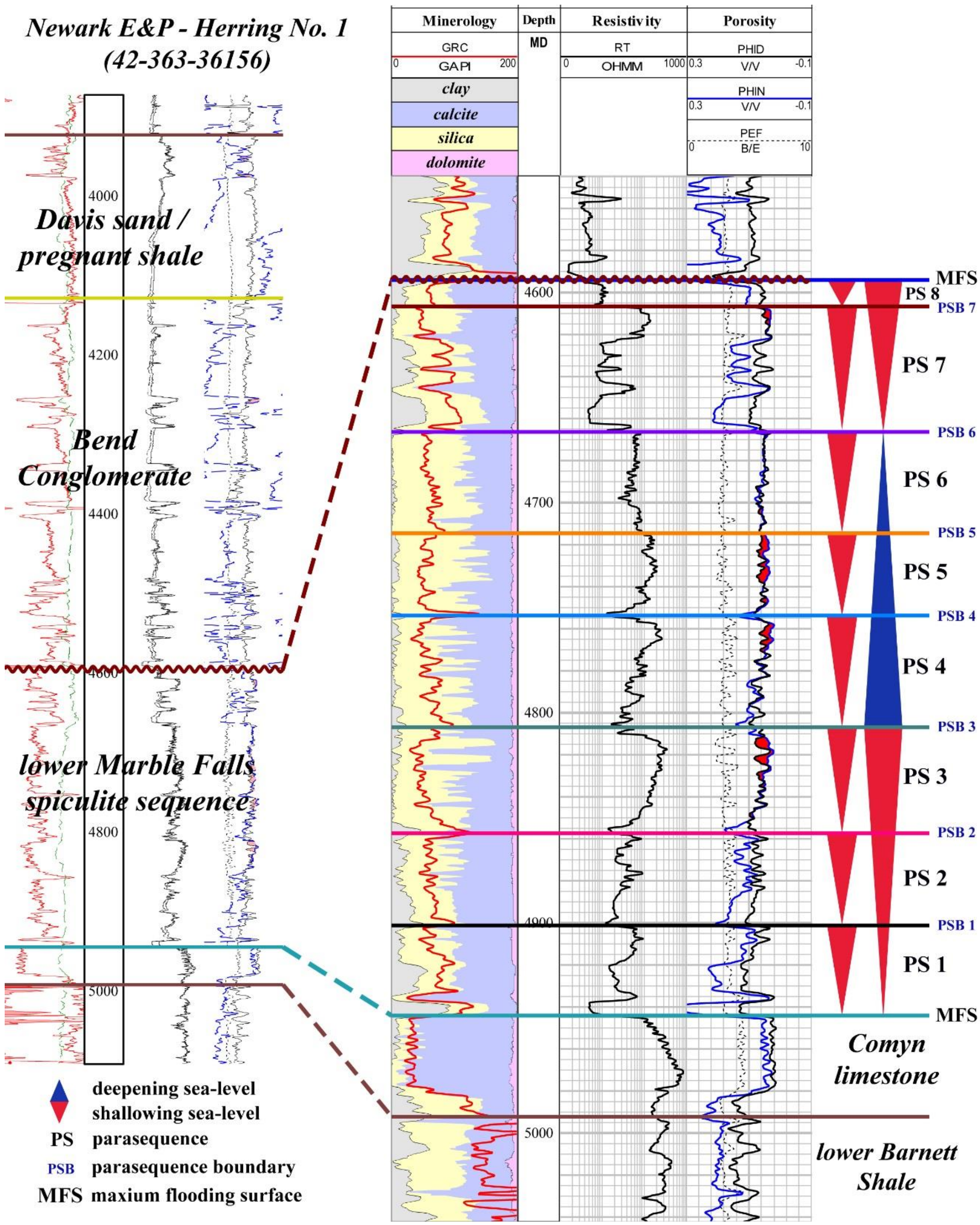



Figure 4-37. Type log for the lower Marble Falls spiculite sequence displaying typical well log characteristics and shallowing-upward parasequences that typically occur in this interval.

Bounding Surfaces

The top of lower Marble Falls is marked by an increase in GR that is usually over 150 API units and represents the upper maximum flooding surface (MFS) of the spiculite sequence (Figure 4-37). This increase in GR typically occurs at the top of the lower Marble Falls across most of the FWB and is used as a correlative marker horizon to aid in picking the top of the lower Marble Falls spiculite sequence on well logs. This sharp and non-gradational contact with the overlying Atoka Group is also a major unconformity surface that represents the regional Morrowan-Atokan unconformity present at the top of the lower Marble Falls across most of the FWB. This unconformity is typically defined as an angular unconformity because the structural dip of the lower Marble Falls beds commonly shift directions below this surface and the magnitude of dip depends on the proximity to a structural feature. More rarely there will be little to no shift in structural dip from the overlying beds and the erosional unconformity can be defined as a disconformity.

This high-GR flooding surface that marks the top of the lower Marble Falls is not present everywhere throughout the basin and the spiculite sequence is more gradational with the overlying Atoka Group along the northeastern edge of the basin where it becomes more difficult to pick the contact between these two formations on well logs. There is also commonly a conglomerate deposit that is more related to the Atoka Group but sits directly on top of the lower Marble Falls or occasionally erodes into the top and replaces part of the lower Marble Falls strata. This erosional conglomerate has well log characteristics that is similar to the overlying Bend Conglomerate intervals and is usually a highly porous reservoir rock that has been exploited for hydrocarbons throughout the FWB. There is also significant karsting that occurs at the top of the lower Marble Falls spiculite sequence that is identified on high-resolution image logs and signifies a drop in sea-level at the end of the Morrowan that subaerially exposed most of the lower Marble Falls throughout the FWB.

The base of the lower Marble Falls is typically identified by a distinct increase in GR of over 150 API units that represents a sharp contact with the top of the lower Barnett Shale or, the Forestburg-Comyn limestone or lower Barnett Shale where they are present in the northern part of the basin (Figure 4-37). There has been debate on whether the contact between the lower Marble Falls and the Barnett Formation is conformable or unconformable, but the work done by Brown (1983) and Luker (1985) in the shallow subsurface north of the Llano Uplift shows evidence that supports an unconformable Barnett-Marble Falls contact. This Mississippian-Pennsylvanian boundary was also discovered to be unconformable in the northern part of the basin with evidence from high-resolution image logs and whole core that display the following: 1) the contact is sharp, irregular and non-gradational; 2) rip-up clast from the underlying limestone are found within the basal lower Marble Falls; 3) the upper part of the boundary contains laminae of highly compacted shell fragments; 4) the lower part of the boundary contains exceptionally high concentrations of pyrite, glauconite, and phosphate material mostly in the form of pellets.

Paleogeography

The lower Marble Falls was discovered to extend from outcrop around the Llano Uplift to the northernmost edge of the basin where it is bounded by the Red River Arch to the north and the Muenster Arch to the northeast (Figure 4-38; Figure 4-39). The eastern edge of the isopach map in Figure 4-38 and the subsea structure map in Figure 4-39 is not necessarily a subcrop limit but represents more of a facies change where the lower Marble Falls grades almost entirely into a Pennsylvanian shale and could no longer be identified on well logs. The lower Marble Falls is bounded to the west by the subsurface structural high of the Bend Arch that influenced the depositional patterns of the lower Marble Falls and caused it to pinch-out along a subcrop boundary that trends north and south parallel to the Bend Arch (Figure 4-39). It was deposited over an area that covers more than 40,300 $km^2$ (15,565$mi^2$) across the FWB and generally thickens from west to east with thicknesses that range from <50 feet along the western edge of the basin to >500 feet along the eastern edge of Parker County and western edge of Tarrant County (Figure 4-38). Approximately 13,400 data points were used in the isopach map in Figure 4-38 to map the regional paleogeography of the lower Marble Falls, and approximately 20,900 data points were used in the subsea map in Figure 4-39 to map the structural trends of the top of the lower Marble Falls throughout the FWB.

In the southern part of the FWB there has not been any significant drilling over the last century so the data points for correlating and mapping the lower Marble Falls in this area were limited. However, as mentioned previously, the formation tops determined by Brown (1983), Luker (1985), and Wood (2013) in the 30 HOM cores were incorporated into the regional correlations of this study and used in the isopach map provided in Figure 4-38 and the subsea structure map in Figure 4-39. The lower Marble Falls lies stratigraphically above the Barnett Shale throughout the southern part of the basin and stratigraphically below the upper Marble Falls or, where the carbonates of the upper Marble Falls are absent it lies directly beneath the Smithwick Formation. The lower Marble Falls thickens from only a few feet along the southwestern edge of the FWB toward the east and southeast along a trend that is parallel to the Ouachita Thrust Belt (Figure 4-38). This southeast thickening trend of the lower Marble Formation in this area of the basin was highly influenced by the structural position and orientation of the Bend Arch. The subsea structure map at the top of the lower Marble Falls in Figure 4-39 displays the prominent structural high of the Bend Arch extending northeast from the Llano Uplift through the western edge of San Saba County and eastern edge of Brown County, then extending more to the north through Comanche and Eastland County.

The lower Marble Falls thickens from <20 feet along the eastern edge of Coleman County toward the east and southeast where it is >100 feet along eastern edge of Brown County, >150 feet across most of Comanche County, and reaches thicknesses of >250 feet along a northeast-trend from Somervell County through the northern part of Bosque County, most of Hamilton County, and the northern part of Coryell County (Figure 4-38; Plate 11; Plate 12). The lower Marble Falls is composed mostly of the spiculite sequence throughout this area and contains favorable reservoir quality rock that has similar well log characteristics to the northern part of the basin (Plate 13; Plate 14). The spiculite sequence starts to grade into a more mudstone-rich basinal lithofacies along a trend from central Coryell County to the northeast through central Bosque County and up through the southwestern part of Johnson County (Figure 4-38; Plate 11; Plate 12). The lower Marble Falls is >300 feet thick throughout the southern edge of Johnson County where it is composed dominantly of a mudstone lithofacies (Figure 4-38; Plate 11), and thins significantly to the south of this area into central Bosque County where the lower Marble Falls is <90 feet thick (Figure 4-38; Plate 12). The upper Marble Falls is also present throughout the southern part of the FWB and reaches thicknesses >250 feet along the northwest edge of Hamilton County (Plate 12), and >300 feet throughout the northern part of Brown County (Plate 11).

The thickness trends of the lower Marble Falls were also greatly influenced by the position of the Bend Arch throughout the central part of the FWB and this broad positive structural feature is orientated north to slightly northwest in this area (Figure 4-39). The lower Marble Falls is <100 feet thick along the western edge of the Bend Arch throughout the eastern edge of Callahan and Shackelford counties and has a uniform thickness of 100 to 150 feet across the axis of the Bend Arch (Figure 4-38; Plate 10; Plate 13). The lower Marble Falls thickens more toward the northeast along a northwest-trending strike in the central part of the basin and is around 150 feet thick along the western edge of Erath County and southwestern edge of Palo Pinto County, but thickens to >300 feet thick in the northeast corner of Erath County and eastern edge of Palo Pinto County (Figure 4-38; Plate 10). There were also two notably thicker areas of the lower Marble Falls trending east to west in central Palo Pinto County that was probably controlled by the Mineral Wells – Newark East fault, and in northern Erath County that was controlled by a series of northeast to southwest oriented faults (Figure 4-38; Figure 4-39).

There were no structural cross-sections provided but regional correlations reveal that the thickness of the lower Marble Falls does not significantly change much until the eastern edge of Stephens and Eastland counties where it progressively starts to thicken toward the east and northeast, and this trend corresponds with the structural deepening of the lower Marble Falls from the eastern edge of the Bend Arch toward the deep axis of the FWB to the east (Figure 4-38; Figure 4-39; Plate 10). The spiculite sequence comprises nearly the entire lower Marble Falls throughout the central part of the FWB with well log characteristics similar to those to the north and it does not grade into the mudstone-rich facies to the east until the central part of Tarrant County (Plate 10; Plate 13; Plate 14). Therefore, the stratigraphic thick section of the lower Marble Falls present in northern Hood County, northwest Johnson County, western Tarrant County, and across most of Parker County is composed dominantly of the spiculite sequence with lithological characteristics and reservoir properties similar to those in Jack County but with a more mudstone-rich interval in the lower part of this sequence (Figure 4-38; Plate 9; Plate 10; Plate 14).

The western subcrop of the lower Marble Falls trends directly north and south parallel with the axis of the Bend Arch, but along the southeastern edge of Throckmorton County and central Young County the lower Mable Falls pinches-out along a northeast-trending subcrop (Figure 4-38;Figure 4-39). Although this northwestern subcrop limit is somewhat erosionally control by the regional Morrowan-Atokan unconformity, the lower

Marble Falls was probably never deposited much farther north of this area because of the stratigraphic controls of the underlying Comyn limestone (Plate 9). The Comyn limestone reaches stratigraphic thicknesses >250 feet across most of Young County and the western part of Jack County (Figure 4-21), and this thick section of the Comyn limestone has significantly influenced the thickness, sequence stratigraphic framework, and distribution of depositional lithofacies within the lower Marble Falls throughout this area (Figure 4-38). The lower Marble Falls thins significantly over the top of the Comyn limestone and is composed dominantly of carbonates along east-central Young County and west-central Jack County that were deposited in a more proximal inner ramp depositional environment and intertongue with the outer-ramp spiculite facies to the south and east (Figure 4-38; Plate 9). These carbonate-rich rocks are distinguished from the spiculite facies on well logs by their distinct increase in PE and more vertically uniform GR readings that are slightly lower and resistivity readings that are slightly higher than the spiculite facies (Plate 9).

The thickest section of the lower Marble Falls was deposited throughout western Tarrant County, eastern Parker County, northwest Johnson County, and central Jack County and reaches thicknesses that average >300 feet but rarely exceed >500feet (Figure 4-38; Plate 13; Plate 14). The spiculite sequence comprises most of the lower Marble Falls throughout this thick section and its distribution in Jack County was controlled by the stratigraphic thicknesses of the Forestburg-Comyn limestone and lower Barnett calcareous unit that were discussed in previous sections. The limestone units of the Marble Falls Formation that were deposited throughout the northeastern edge of the basin have also greatly influenced the distribution of the lower Marble Falls spiculite sequence which is evident from the abrupt thinning of the spiculite sequence along a northwest-trend from eastern Jack County through the northeastern edge of Parker County and into north-central Tarrant County (Figure 4-38; Plate 14). The spiculite sequence reached much greater thicknesses where the lower limestone and upper limestone intervals were absent (Figure 4-27; Figure 4-29), but in the areas where they were present, the spiculite sequence would thin significantly and overlap these units (Figure 4-38; Plate 14). The spiculite sequence is <150feet along the western and southwestern edge of Wise County where both the lower limestone and upper limestone are present, and is <200feet in northeast Parker County where the upper limestone reaches thicknesses >160 thick (Figure 4-29; Figure 4-38; Plate 14). The spiculite sequence remains <250 feet across most of Wise County but starts to thicken toward the Muenster Arch to the northeast and reaches thicknesses >300 feet where there was more accommodation space in the deepest part of the basin (Figure 4-38).

The spiculite facies comprises most of the lower Marble Falls throughout the FWB with evidence from this study and the work done by Farrar (2010) that it is present in great quantities in Jack and Palo Pinto counties. It also comprises a significant portion of the lower Marble Falls in the southern part of the basin with evidence from three master's thesis that were conducted on 31 cores in the shallower subsurface north of the Llano Uplift (Brown, 1983; Luker 1985, Wood, 2013). Their observations were similar to those made from this work in the northern part of the FWB and they determined that the lower Marble Falls is composed dominantly of a spiculitic facies that is commonly interbedded with a calcareous shale or mudstone (Brown, 1983; Luker 1985, Wood, 2013) (Plate 13; Plate 14). Other similar observations that were made by these authors on the spiculitic facies within the lower Marble Falls include the following: 1) it contains an abundant of both siliceous and calcareous sponge spicules that were originally composed of chalcedony and were replaced by calcite and microcrystalline quartz; 2) it is highly bioturbated and burrowed; 3) it commonly contains lenses of chert; 4) and it generally thickens from west to east (Brown, 1983; Luker, 1985; Wood, 2013).

The spiculitic lithofacies was also discovered to have been deposited along the far eastern edge of the FWB where it comprises most of the lower Marble Falls. The lower Marble Falls reaches a stratigraphic thickness of approximately 200 feet along the northeastern edge of Bosque County where a whole core was taken in the ADEXCO No. 1P Walker Ranch well (Figure 4-38). The lower Marble Falls spiculite sequence was sampled from a measured depth of 6,526 feet to its base at 6,612 feet and thin sections from various intervals were prepared and analyzed. All of the thin sections from the lower Marble Falls were composed of an abundance of sponge spicules with the dominate lithofacies being a spiculite (grain supported) that was interbedded with a spiculitic mudstone lithofacies (mud-supported). Most of the sponge spicules were siliceous but were also commonly replaced by calcite and dolomite. The significance of this core containing similar spiculitic lithofacies compared to the northern and southern part of the basin further supports the idea that this lower Marble Falls spiculite sequence is present throughout the Fort Worth Basin (Figure 4-38; Figure 4-39; Plate 14; Plate 13).

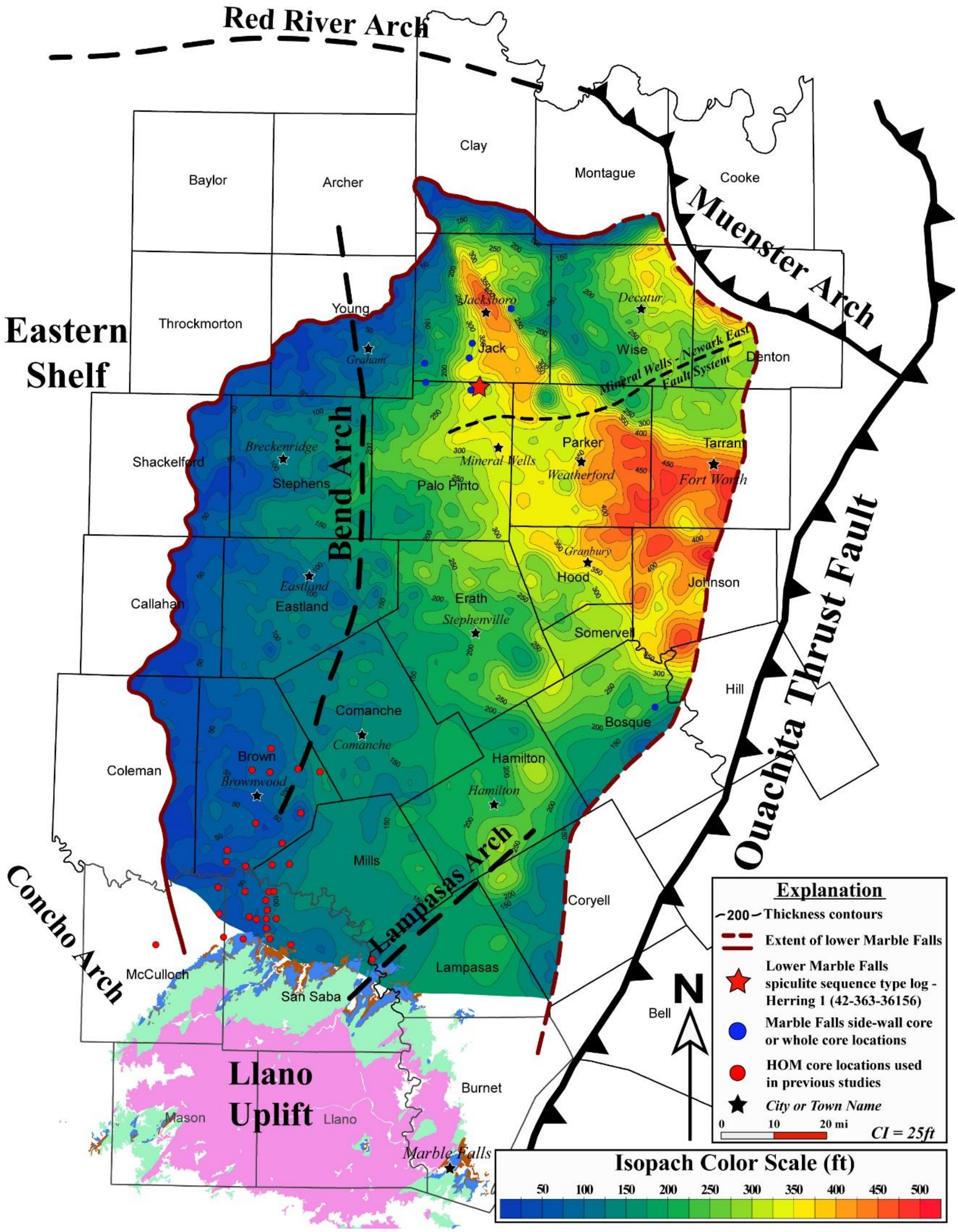



Figure 4-38. Isopach map of the lower Marble Falls displaying regional thickness trends and its paleogeographic extent across the Fort Worth Basin.

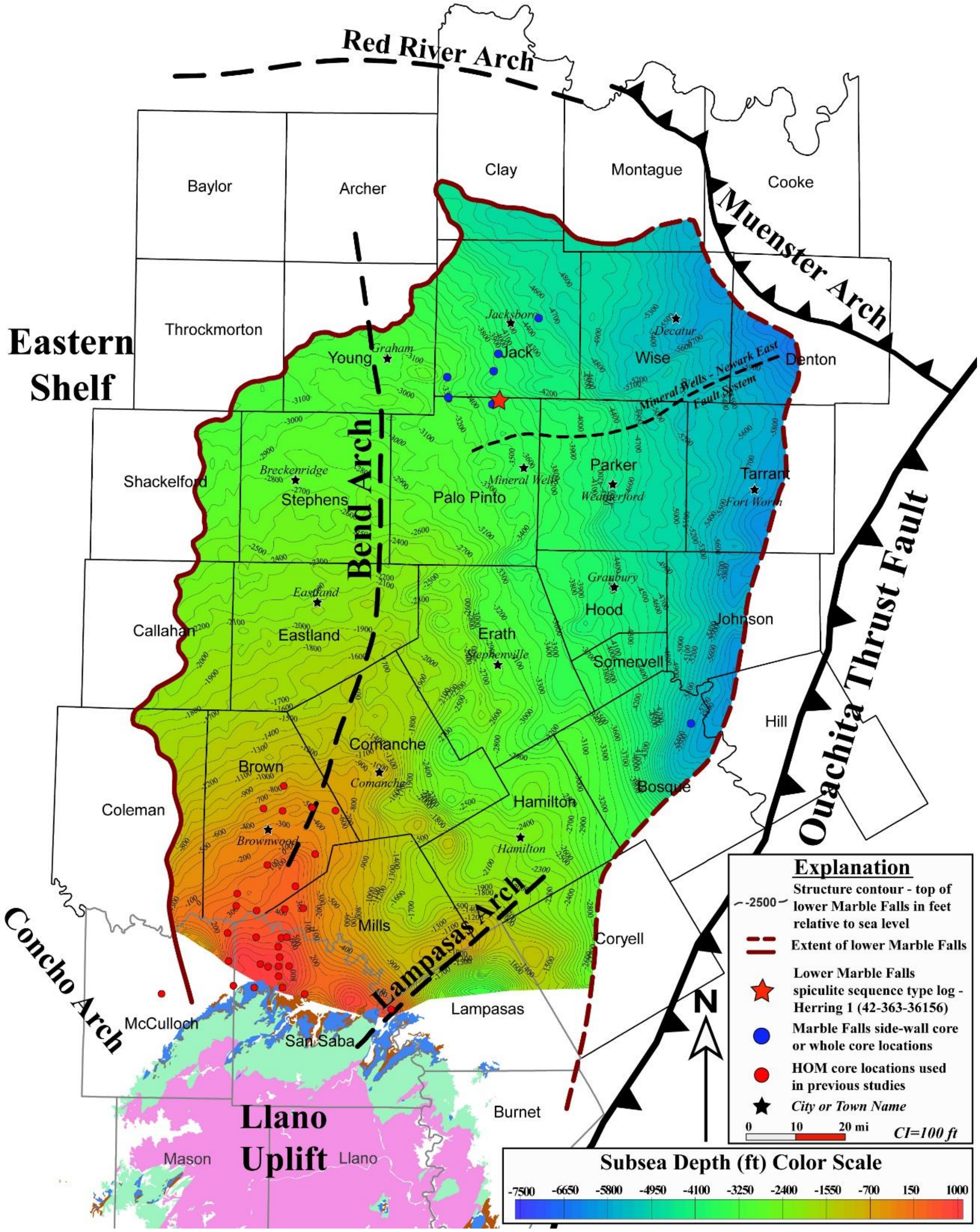



Figure 4-39. Subsea structure map at the top of the lower Marble Falls displaying regional structural trends and major structural elements throughout the Fort Worth Basin.

Parasequences

The lower Marble Falls in the southern part of the FWB is composed of a complex assemblage of facies that vary vertically and laterally over short distances (Kier, 1980), and Wood (2013) determined there were 3 high-frequency sequences present in the lower Marble Falls that were probably $4^{th}$ order cycles. Similar observations were made in the northern part of the basin and the distribution of lithofacies within the lower Marble Falls was discovered to be complex across most of the FWB due to the common occurrence and lateral variations of these high-frequency cycles (HFC). The spiculite sequence in the northern part of the basin contained numerous HFC or parasequences (PS) that were defined in the type log shown in Figure 4-37, but the intense cyclicity of the lower Marble Falls made it difficult to correlate these PS in detail across the study area. Throughout most of the basin there was not adequate well control to correlate the lateral variations of these parasequences and their bounding marine-flooding surfaces, but an attempt was made at mapping a number of them across the core area of the present Marble Falls play where there is a higher density of deeper well control. It is important to note that most of these parasequences extent beyond the mapped area but due to problems with well control it was not possible to correlate them any further beyond the limits designated in the isopach maps.

There were common depositional patterns observed when correlating these parasequences across the study area and they would occasionally form distinct stacking patterns that could be associated to systems tracts. Most of the PS were bounded by distinct marine-flooding surfaces that have vertically compartmentalized the reservoir in the lower Marble Falls spiculite sequence. These marine-flooding surfaces were commonly associated with minor erosional unconformities that were identified on image logs, and some of these unconformity surfaces were subaerially exposed for long periods of time and formed chert deposits that were typically productive. With better well control it is possible for a more detailed sequence stratigraphic study to be conducted in the future, but that is beyond the scope of this study and the following discussion is to provide a general overview of the parasequences that are present in the lower Marble Falls. However, because of the compartmentalization of this reservoir it is critical to learn more about the sequence stratigraphic framework of this spiculite sequence to better understand the reservoir heterogeneity of the lower Marble Falls and the stratigraphic control these HFC have on the distribution of reservoir lithofacies across the basin.

There were a total of 12 parasequences identified in the lower Marble Falls spiculite sequence throughout Jack, Palo Pinto, and Parker counties, but only 8 of these have been correlated in detail and will be presented below. The parasequences were identified from the deepest stratigraphic interval (PS 1) to the shallowest interval (PS 8) and were defined in the type log shown in Figure 4-37. The majority of these parasequences are shallowing-upward from a distal mudstone lithofacies to a more proximal spiculite lithofacies that is most commonly siliceous-rich and comprises the best reservoir lithofacies within the lower Marble Falls spiculite sequence. The parasequences become progressively younger and more mudstone-rich basinward to the east and southeast and represent an overall net regression of the lower Marble Falls spiculite sequence. Although these parasequences likely represent 4$^{th}$ or 5$^{th}$ order depositional cycles that range from <1m (3.28 feet) thick to >200m (60 feet) thick, they correspond closely with the 3rd order eustasy curves by Ross and Ross (1987) in Figure 4-40. These depositional cycles probably represent the high-amplitude glacio-eustatic fluctuations that commonly occurred during the Pennsylvanian and were controlled by the waxing and waning of Gondwanan ice sheets (Heckel, 1994).

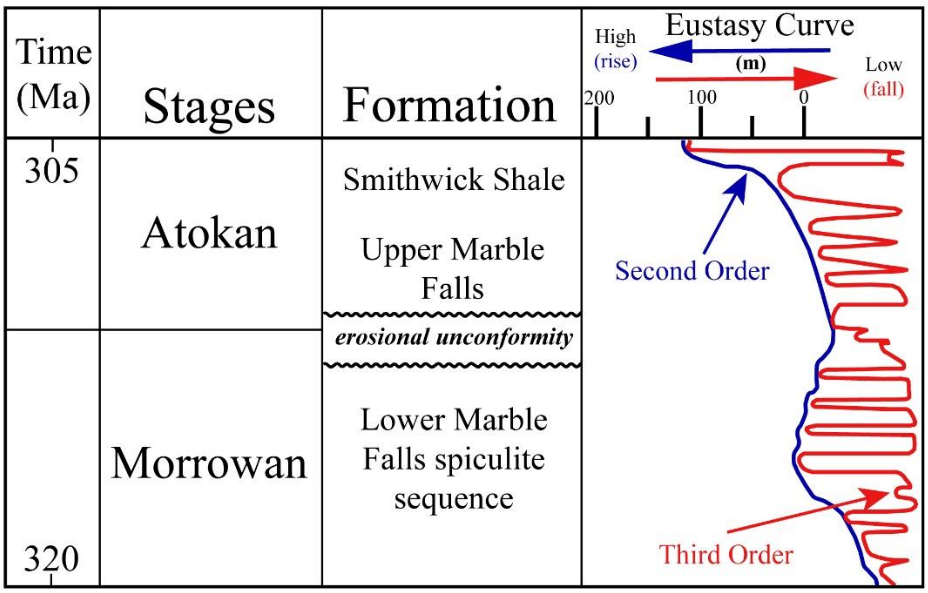



Figure 4-40. Early Pennsylvanian sea-level curves created from Ross and Ross (1987).

The deepest stratigraphic parasequence that lies directly above the Comyn limestone is PS 1 and it was deposited over a broad area and extends farther west than any of the other of the parasequences (Figure 4-41). It can be sub-divided even further into a number of higher amplitude HFC that have formed several stratigraphic traps along the southeastern edge of Young County. This PS 1 reaches maximum stratigraphic thicknesses of >120 feet in west-central Jack County and in southeast Young County where it comprises most of the lower Marble Falls spiculite sequence. The eastern subcrop boundary where this PS pinches-out is well defined, but it extends farther north, west, and south of the limit designated in the isopach shown in Figure 4-41 but due to difficulties with correlating it was not mapped. It was also challenging to correlate PS1, PS 3, and PS 6 in the southeast corner of Young County, southwest corner of Jack County, and northwest corner of Palo Pinto County because there were a series of penecontemporaneous faults that affected the distribution of parasequences across this area. PS 1 thins toward the west and northwest as it intertongues and overlaps several limestone units of the lower Marble Falls that are designated as ‘A’ and ‘B’ on the cross-section in Plate 15. PS 1 is characterized by a thick shallowing-upward cycle along the western and west-central part of Jack County where it comprises a large portion of the spiculite sequence, but starts to thin to the east and southeast and is <20 feet thick in northeastern Palo Pinto County (Figure 4-41; Plate 15). This parasequence becomes more mudstone-rich lower in the section but overall it contains a small percentage of shale that is mostly present to the southeast (Plate 15). It is dominantly composed of the spiculitic lithofacies across most of its extent with reservoir quality rock that exhibits good cross-over on the porosity logs and typically contains an abundance of LBF (Plate 15).

PS 1 is bounded at the top by a correlative marine-flooding surface that is designated as parasequence boundary 1 (PSB 1) in the type log shown in Figure 4-37 and lieing stratigraphically above this interval is either PS 2 or, where it is absent PS 3 overlies PS 1 (Plate 15). PS 2 is the least widely distributed parasequence in the spiculite sequence and was only deposited over a small area in southern Jack County and northern Palo Pinto with its subcrop boundary distinctly defined in the isopach map shown in image A of Figure 4-42. It starts to develop in the lower part of PS 3 and thickens from <5 feet just south of Jacksboro to the south where it reaches a maximum stratigraphic thickness of >40 feet in northern Palo Pinto County near the location of the type log (Figure 4-42; Plate 15). This parasequence is typically composed of laminated clay-rich beds that are interbedded with thin intervals of the spiculitic lithofacies and it is the thinnest parasequence within the spiculite sequence in the northern part of the basin (Figure 4-42). It rarely exhibits any type of reservoir quality rock on well logs and there were only minor LBF identified on image logs (Plate 15).

The top of PS 2 is marked by a correlative marine-flooding surface that separates it from the overlying PS 3 and this contact is designated as the PSB 2 on the type log shown in Figure 4-37. PS 3 lies stratigraphically above PS 1 throughout the western edge of Jack County and parts of eastern Young County, above PS 2 where it is present, and directly on top of the upper Barnett Shale along the eastern edge of the isopach map where PS 1 and PS 2 are both absent (Figure 4-42; Plate 15). There are various intervals that lie stratigraphically above PS 3 that include the following from northwest to southeast: Atoka Group, PS 6, PS 5, and PS 4 (Plate 15). There was a thicker section of PS 3 deposited along a northeast-trend in the western half of Jack County where it averages >80 feet thick and reaches maximum stratigraphic thicknesses >110 feet (Figure 4-42; Plate 15). This thick trend of PS 3 extends down into southwestern Jack County, northwestern Palo Pinto County, and northeastern Stephens County, but due to well control issues and faults that are present in this area it was difficult to correlate beyond the edge of the isopach (Figure 4-42). Throughout most of this thick trend along the western edge of Jack County, PS 1 and PS 3 comprise all of the lower Marble Falls spiculite sequence with similar shallowing-upward well log characteristics that is composed dominantly of the siliceous spiculitic lithofacies (Figure 4-42; Plate 15).

PS 3 thins abruptly toward the southeast where it is <30 feet thick throughout central Jack County and was replaced by the overlying PS 6 and PS 4 (Figure 4-42; Plate 15). However, it starts to thicken again toward the east and this is due to the fact that this parasequence can be split into two separate intervals with the lower interval not being present in the type log shown in Figure 4-37. The upper interval thins from northwest to southeast and is composed dominantly of the spiculitic lithofacies with low GR, high ILD, and low PE values. However it grades down into a lower interval that is composed of a calcareous mudstone with higher GR values, lower ILD values, and higher PE values and this interval starts to develop along the 40 feet contour in central Jack County and thickens toward the east and southeast where it eventually intertongues with the upper Barnett Shale and Forestburg limestone along the eastern edge of the isopach map (Figure 4-42; Plate 15). The spiculitic lithofacies of PS 3 exhibits good reservoir quality rock on open-hole logs and displays an abundance of LBF across most of the area, but the calcareous mudstone interval of this parasequence does not contain good quality reservoir properties.

The top of PS 3 is bounded by a marine-flooding surface that correlates with the MFS of the spiculite sequence along the western edge of Jack County and is designated as PSB 3 on the type log show in Figure 4-37 (Plate 15). PS 4 lies stratigraphically above PS 3 across most of the area except to the south and southwest where PS 3 is absent and

PS 4 lies directly above the Comyn limestone, and along the northeast edge of the isopach map where PS 3 is absent and PS 4 lies above the upper Barnett Shale, Forestburg limestone, Marble Falls lower limestone, or Marble Falls upper limestone (Figure 4-43). PS 5 or PS 6 lies stratigraphically above PS 4 and in northern Palo Pinto County these three parasequences coalesce to form a distinct stacking pattern that deepens-upward overall and may represent a highstand systems tract (Figure 4-37; Plate 15). The well log characteristics and thickness of PS 4 varies considerably across the study are but it generally thickens from west to east and is <50 feet across most of southern Jack County (Figure 4-38). It thickens toward the north where it reaches thicknesses >100 feet and also thickens toward the south where it reaches thicknesses >90 feet (Figure 4-43). The western and eastern subcrop boundaries for PS 4 in the isopach map in Figure 4-43 are closely estimated, but the southern boundary only marks where it could definitively be correlated and this thickness trend extends much farther south and southwest into central Palo Pinto County. The best reservoir quality of this parasequence is in the northern part of Palo Pinto County where it develops into a thick shallowing-upward sequence that is characterized by good reservoir properties of the siliceous spiculitic lithofacies (Figure 4-37; Figure 4-43; Plate 15). It becomes significantly more mudstone-rich with sporadic log responses toward the north and northeast of northern Palo Pinto County and does not exhibit as good a reservoir quality rock (Figure 4-43; Plate 15).

PS 4 is bounded at the top across most of the area by a correlative marine-flooding surface that is designated as PSB 4 in the type log shown in Figure 4-37. PS 5 lies stratigraphically above PS 4 and it lies stratigraphically below PS 6 throughout its entire extent (Plate 15). The marine flooding surfaces that separate these three parasequences are not always well developed and they occasionally coalesce to form one continuous parasequence set or stacking pattern that makes it difficult to distinguish PS 5 from PS 4 lying below and PS 6 lying above (Plate 15). This is especially common in northern Palo Pinto County near the area of the type log where PS 5 grades up into PS 6 (Figure 4-37; Plate 15). The western boundary of the isopach map in Figure 4-43 represents the estimated subcrop of PS 5 and it thickens abruptly toward the east where it reaches a maximum stratigraphic thickness of >100 feet just southwest of the town of Jacksboro (Figure 4-43). This thickness trend extends down into central Palo Pinto County where it became more difficult to map due to well control but it forms a distinct stacking pattern with PS 4 that displays good reservoir rock properties on well logs (Figure 4-43). PS 5 thins gradually from central Jack County toward the east where it overlaps the Marble Falls lower limestone and upper limestone units along the eastern edge of Jack County. PS 5 contains the best reservoir quality rock in south-central Jack County where it is composed of the spiculitic lithofacies and reaches greater thicknesses, but as it thins toward the southeast it becomes more mudstone-rich (Figure 4-43; Plate 15).

PS 5 is bounded at the top by a marine-flooding surface designated by PSB 5 on the type log in Figure 4-37 but this flooding surface is not present everywhere across the basin and PS 5 grades up into PS 6 in some areas. PS 6 was widely distributed across the basin and lies stratigraphically above PS 3, PS 4, or PS 5 and lies stratigraphically below

PS 7 or the Atoka Group along the western edge of the isopach map where PS 7 is absent (Figure 4-44; Plate 15). This parasequence can also be separated into a number of higher amplitude HFC that could be correlated across the study area but for simplification purposes they were incorporated together into one parasequence (PS 6) bounded by marine-flooding surfaces. The western boundary of the isopach map in Figure 4-44 is defined as the western subcrop of PS 6 where it abruptly develops above PS 3 and is <50 feet thick (Figure 4-44; Plate 15). It thickens significantly toward the east and southeast to form a northeast-trending thick section that averages around 100 feet thick and reaches thicknesses >175 feet in central Jack County near the town of Jacksboro (Figure 4-44; Plate 15). PS 6 comprises a large portion of the lower Marble Falls spiculite sequence throughout this area and it contains good quality reservoir rock that is composed dominantly of the spiculitic lithofacies (Plate 15). It also displays an overall constant well log pattern across most of Jack County that is neither shallowing-upward nor deepening-upward (Plate 15). This thick trend of PS 6 extends farther to the south into Palo Pinto County but could not be correlated due to sparse well control (Figure 4-44). It thins toward the east and southeast where it becomes more mudstone-rich and lies above a mudstone facies of PS 5 and below a mudstone facies of PS 7 (Figure 4-44; Plate 15).

PS 6 is bounded at the top by a marine-flooding surface that also represents a significant erosional surface and is designated as PSB 6 on the type log shown in Figure 4-37. PS 7 lies stratigraphically above PS 6 across most of its extent and lies stratigraphically below PS 8, PS 9, or the Atoka Group (Plate 15). Similar to the previous parasequences, the western boundary of isopach map A in Figure 4-45 represents the estimated subcrop of PS 7 where it starts to develop at the top of the lower Marble Falls spiculite sequence above PS 6 and thickens abruptly to the east as PS 6 thins (Figure 4-45; Plate 15). PS 7 is the thickest shallowing-upward cycle in the lower Marble Falls spiculite sequence and was deposited along a northwest to southeast trend from central Jack County into northwestern Parker County with thicknesses that average >150 feet and reach maximum thicknesses of >225 feet in an area southeast of the town of Jacksboro (Figure 4-45). Although PS 7 was mapped as one continuous unit, it is important to note that it represents a gradual shallowing-upward sequence that contains a thick non-reservoir shale section which was correlated separately from the spiculitic reservoir lithofacies (Plate 15). This shale interval is composed of thin laminated beds of clay-rich sediments and carbonate-rich sediments with no LBF or porosity, and in the area where PS 7 reaches maximum thickness >200 feet the shale interval comprises as much as 75% of the total section (Figure 4-45). This calcareous shale interval also comprises a significant portion of PS 7 throughout southeastern Jack County, northeastern Palo Pinto County, and northwestern Parker County (Figure 4-45; Plate 15). The upper part of PS 7 is composed of the spiculitic lithofacies with good reservoir quality rock and an abundance of LBF that make it a common target interval for completions (Plate 15). PS 7 thins toward the south and southwest but extends well beyond the southern limit of the isopach map in Figure 4-45 and could not correlated due to well control.

PS 7 is bounded at the top by a marine-flooding surface that is designated as PSB 7 in the type log shown in Figure 4-37. PS 8 lies stratigraphically above PS 7 throughout the mapped area and may overlie another interval toward the southeast where PS 7 eventually pinches-out (Plate 15). It lies stratigraphically below PS 9 across most of the area but where it's absent PS 8 lies directly below the Atoka Group and commonly intertongues with a lower Bend Conglomerate interval. PS 8 starts to develop in the upper part of the lower Marble Falls spiculite sequence along a trend just east of the subcrop of PS 7 (Figure 4-45; Plate 15). The western edge of the isopach map in Figure 4-45 represents the subcrop of PS 8 and it gradually thickens toward the east and southeast where it reaches a maximum stratigraphic thickness of 75 feet in northeastern Palo Pinto County. This thick trend of PS 8 extends farther to the south and southeast but could not be adequately correlated (Figure 4-45). PS 8 represents a distinct shallowing-upward cycle that is capped by a good reservoir quality spiculitic lithofacies that has been a conventional and unconventional target interval (Plate 15).

PS 8 is bounded at the top by a marine-flooding surface that is designated as PSB 8 or in the instance of the type log in Figure 4-37, it represents the maximum flooding surface of the lower Marble Falls spiculite sequence. PS 9 lies stratigraphically above PS 8 and starts to develop in the upper part of the lower Marble Falls spiculite sequence slightly east of the western subcrop boundary of PS 8 (Plate 15). There were three more parasequences that were defined in the lower Marble Falls spiculite sequence in Jack, Palo Pinto, and Parker counties but they could not be correlated in enough detail to create an isopach map due to inadequate well control. These parasequences include PS 10, PS 11, and PS 12 and similar to PS 7 through PS 9 each of these parasequences start to develop in the upper part of the lower Marble Falls spiculite sequence slightly east to southeast of the previous one and are shallowing-upward from a mudstone lithofacies to a spiculitic lithofacies (Plate 15).

These parasequences occur throughout the FWB and have greatly controlled the distribution of reservoir lithofacies due to the complicated lateral variations. There are typically only 1 to 3 parasequences present in a single well along the Bend Arch to the west, but as the lower Marble Falls spiculite sequence thickens to the east there are as much as 8 parasequences present in a single well. These parasequences vary significantly over short distances with changes in thickness or lithological characteristics from well to well. Therefore, these HFC or parasequences are a critical part in understanding the complex stratigraphic framework and reservoir heterogeneity of the lower Marble Falls spiculite sequence across the entire FWB.

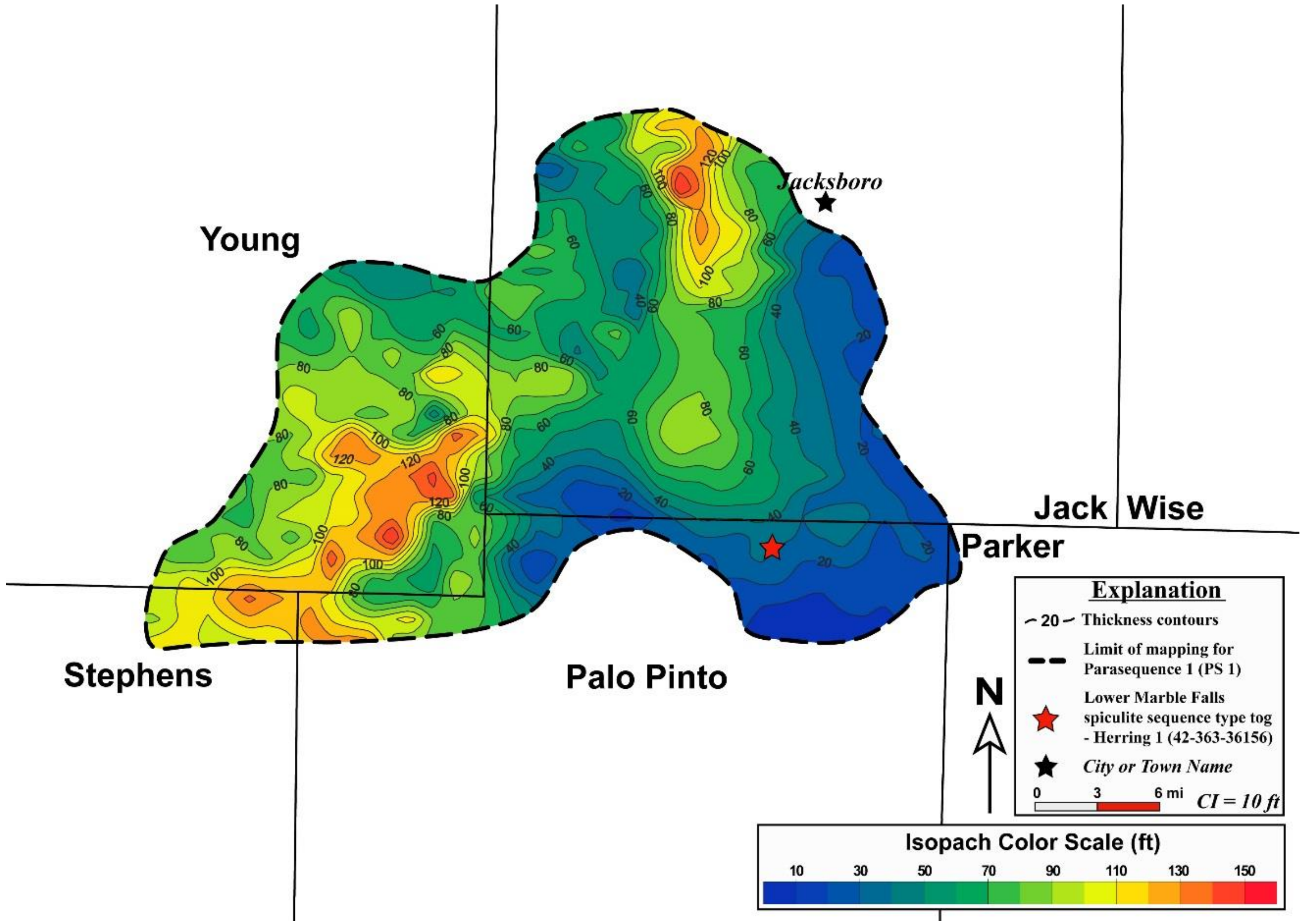



Figure 4-41. Isopach map of parasequence 1 (PS 1) displaying thickness distributions across the study area.

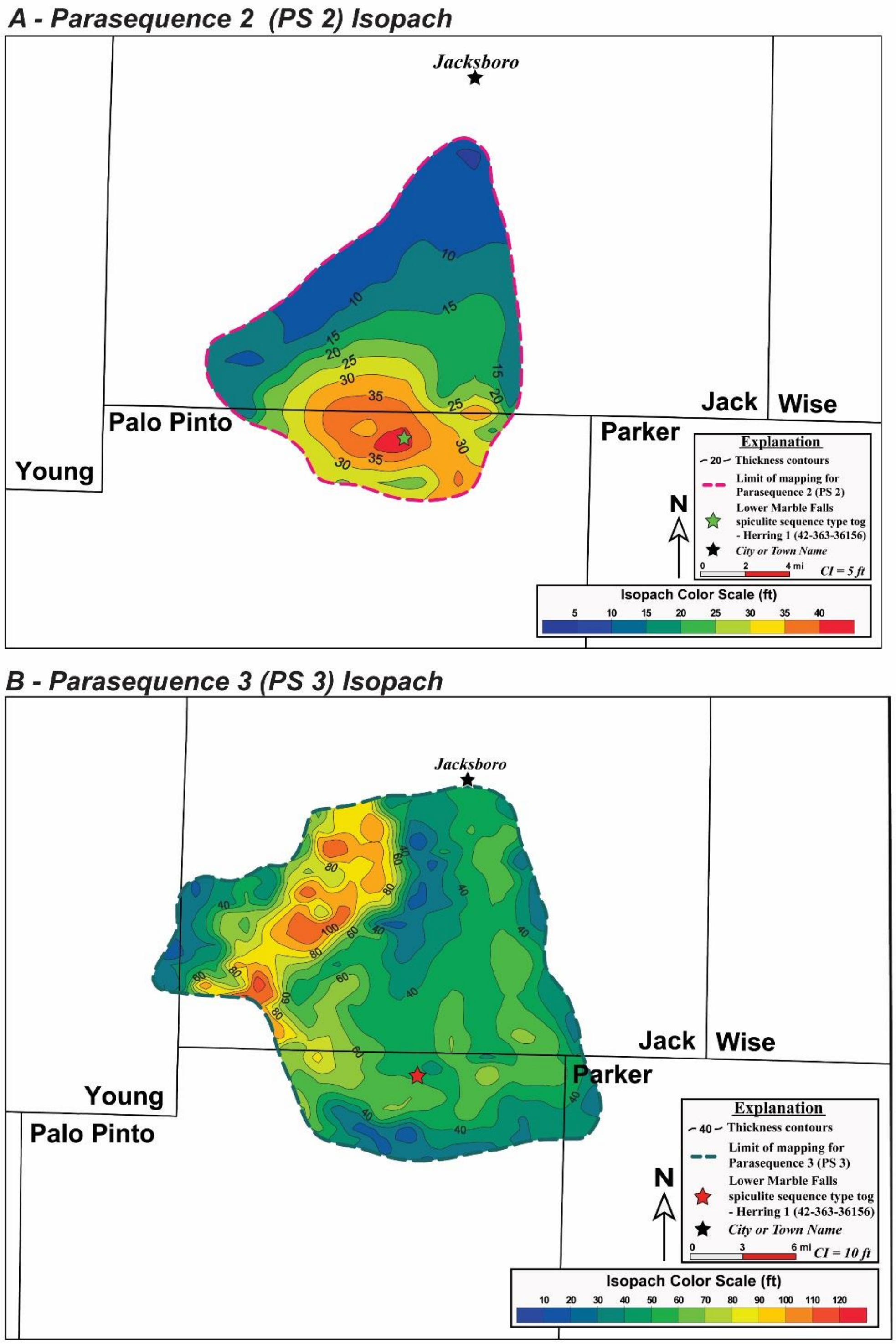
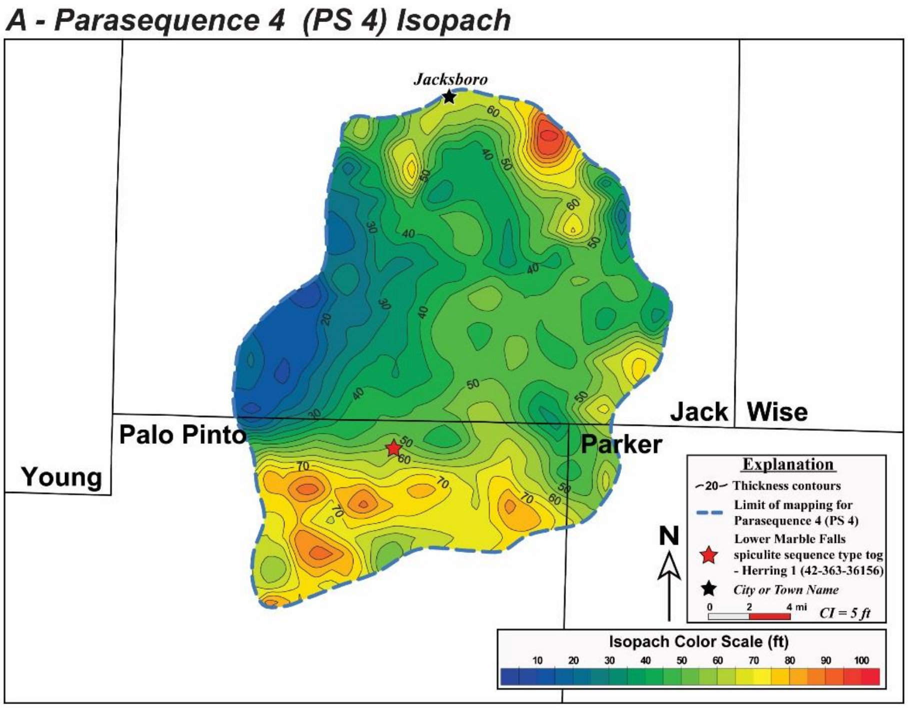



Figure 4-42. Isopach maps of parasequence 2 (A) and parasequence 3 (B) displaying thickness distributions across the study area.



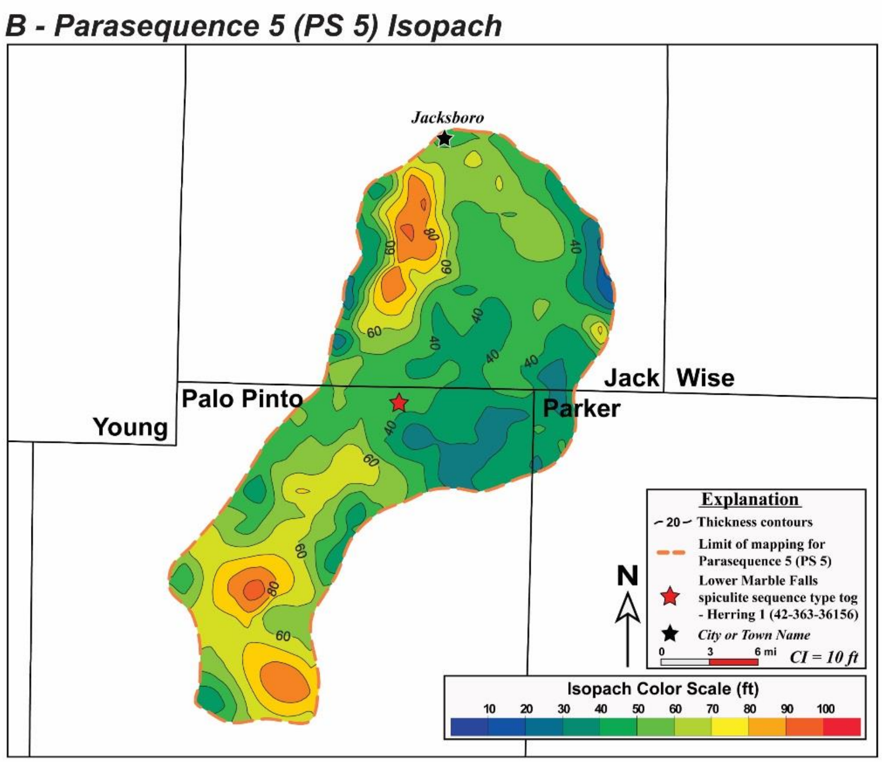




Figure 4-43. Isopach maps of parasequence 4 (A) and parasequence 5 (B) displaying thickness distributions across the study area.

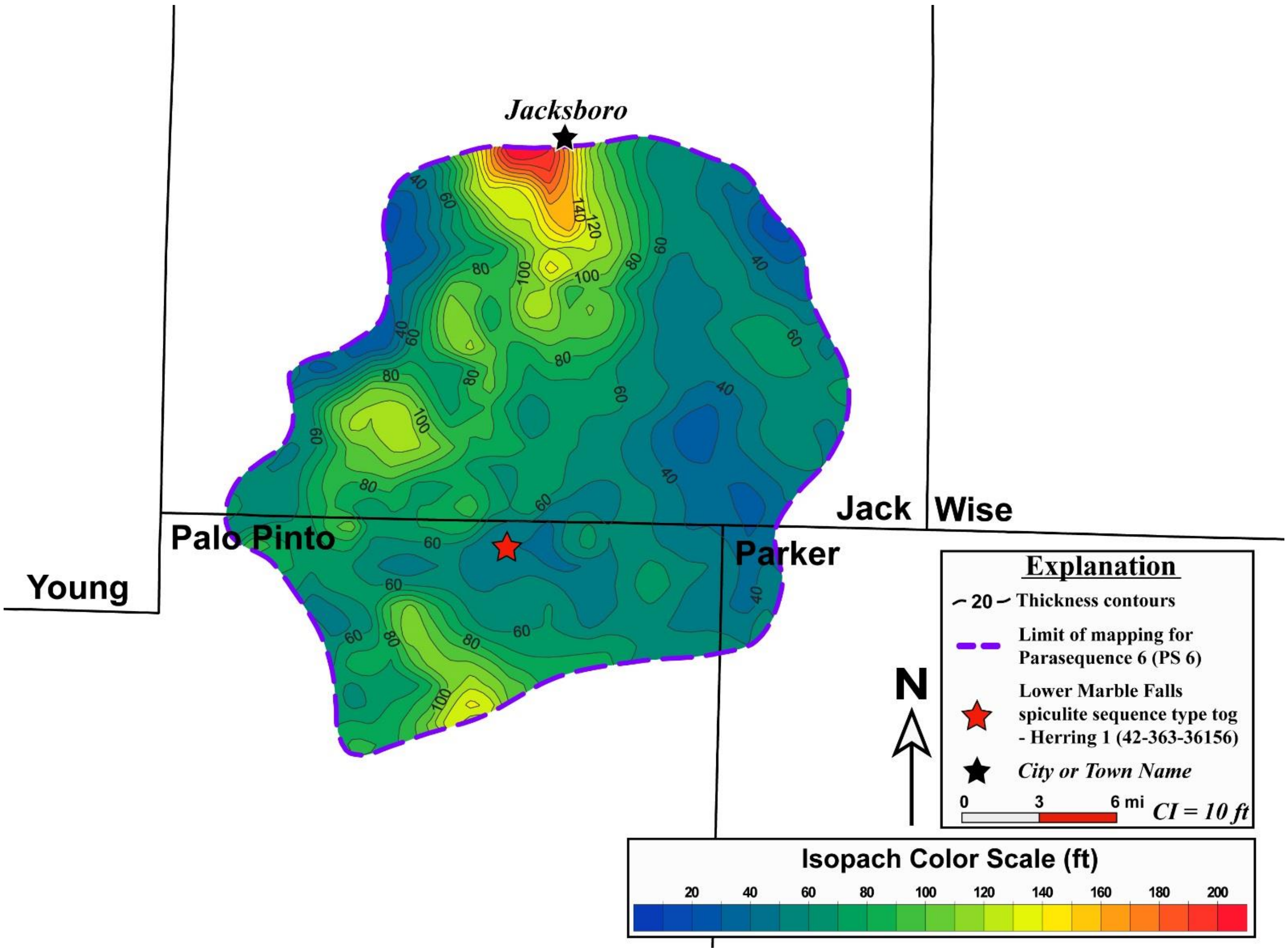



Figure 4-44. Isopach map of parasequence 6 displaying thickness distributions across the study area.

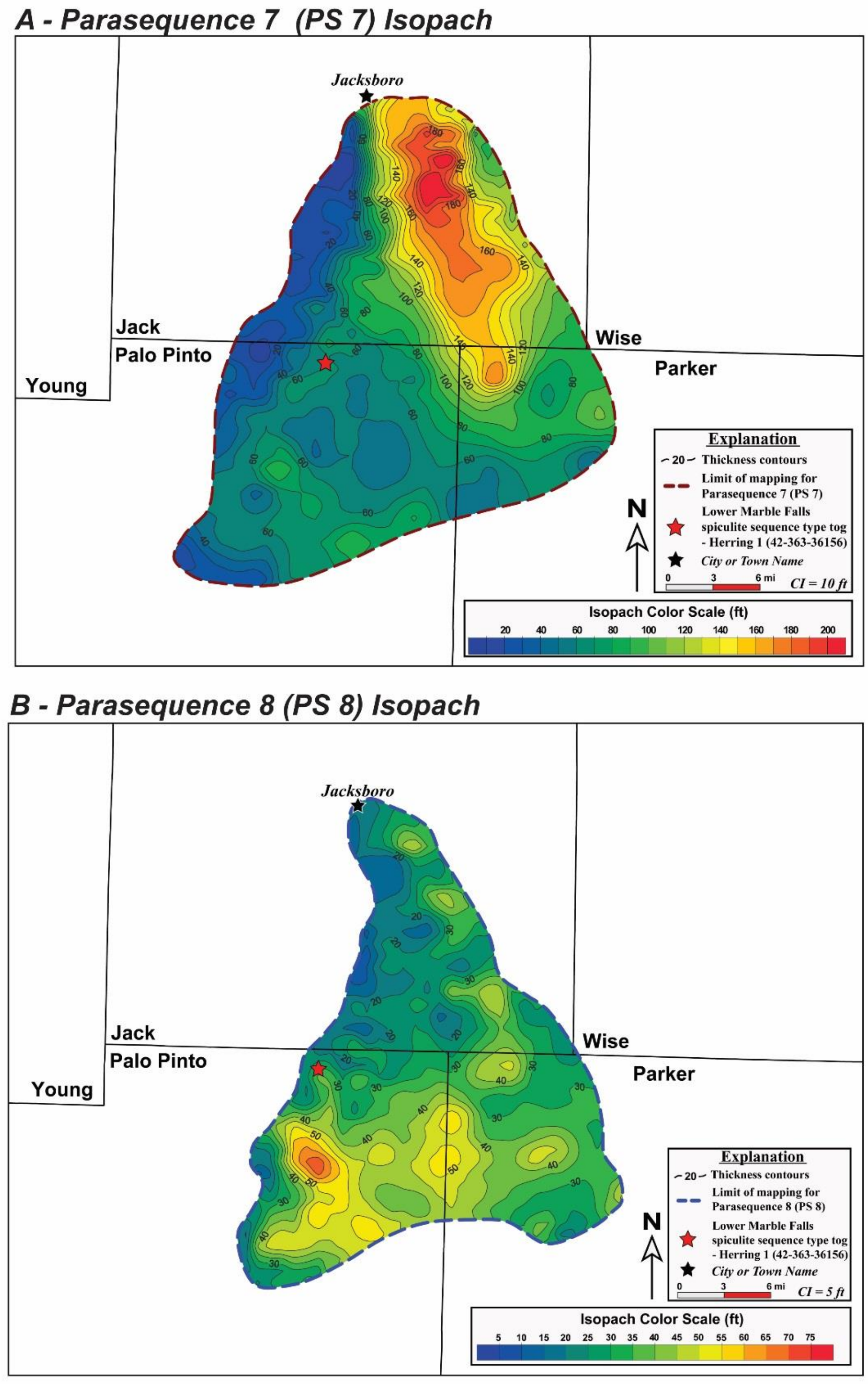



Figure 4-45. Isopach maps of parasequence 7 (A) and parasequence 8 (B) displaying thickness distributions across study area.

Historical Production and Reservoir Quality

The lower Marble Falls has historically been exploited for hydrocarbons across the FWB since the early- to mid-1900's and there have been nomenclature issues and discrepancies in reporting completion and production data since that time. Public data sources have reported nearly 7,000 wells producing from the Marble Falls Formation without distinguishing between the upper Marble Falls and lower Marble Falls (DrillingInfo). There were also numerous wells (~1,700) and entire fields that produced from the lower Marble Falls but were reported under various other names with the most common being the "Duffer", "Duffer Lime", "upper Duffer", or "lower Duffer." Additionally, there were numerous geologist that would lump every stratigraphic interval between the Barnett Shale (Mississippian) and the Smithwick Shale (Atokan) and call it the Marble Falls Formation. Therefore, public data sources were not reliable for determining wells that specially produced from the lower Marble Falls and the only way to define an accurate distribution of production across the FWB was to manually determine if the reported perforations were located within the lower Marble Falls stratigraphic interval. A year-long correlation project was undertaken to go through every well in the entire FWB to determine which stratigraphic interval each well was actually completed in and keep a manual record of all the lower Marble Falls wells. A list of some of the fields that were reported by public data sources as Marble Falls production are shown in Table 4.2 and the column "Producing Formation" designates the formations or intervals that were manually determined to have been completed in that specific field .

Table 4.2. Marble Falls fields reported by public data sources with producing formations or intervals determined from well logs and completion data

| Marble Falls Field Names on Record | Source | Location (County) | Discovery Date | Producing Formation | # of wells (DI) |
|---|---|---|---|---|---|
| Ranger, Ranger NW & Ranger South (MF) | Reeves, 1922 | north-central Eastland | 1917 | upper MF cong/Bend cong & lower MF | 639 |
| Desdemona, Desdemona N. & Desdemona E. (MF) | DrillingInfo | western Erath/ NE Comanche/ SE Eastland | ~1918 | upper MF carbonates/cong | 274 |
| Santa Anna, Santa E. & Santa Anna S. (MF) | Namy, 1982; Rothrock, 1957 | eastern Coleman & western Brown | 1928 | upper MF carbonates | 269 |
| Pottsville & Pottsville South (MF) | Namy, 1982; Munn & Riddle 1957 | western Hamilton | 1936 | upper MF carbonates | 30 |
| Sipes Springs (MF) | DrillingInfo | NW Comanche & SE Eastland | ~1938 | upper MF carbonates | 71 |
| X-Ray (MF) | Flippin, 1982 | NW Erath | 1949 | "Big Saline"/ Bend conglomerate | 148 |
| Sidney (MF) | Hailey, 1976 | west-central Comanche | 1950 | upper MF carbonates | 9 |
| Kirk (MF) | DrillingInfo | NE Comanche/SE Eastland | ~1950 | upper MF conglomerate | 31 |
| Mittie (MF) | DrillingInfo | north-central Comanche | ~1953 | upper MF carbonates | 143 |
| Walton (MF) | Harmon, 1957 | SE Eastland | 1953 | upper MF carbonates/cong | 5 |
| Lake Brownwood (MF) | DrillingInfo | western Brown | ~1957 | upper MF carbonates | 29 |
| Duster NE (MF) | DrillingInfo | north-central Comanche | ~1963 | upper MF carbonates | 89 |
| Strawn, NW (MF) | DrillingInfo | southwest Palo Pinto | ~1964 | Bend conglomerate | 173 |
| Stuart (MF) | DrillingInfo | southwest Palo Pinto | ~1965 | Bend conglomerate | 31 |

Table 4.2 - *Continued*

| Marble Falls Field Names on Record | Source | Location (County) | Discovery Date | Producing Formation | # of wells (DI) |
|---|---|---|---|---|---|
| J.S. Lewis (MF) | Jackson, 1980 & DI | Central Brown | ~1969 | upper MF carbonates | 109 |
| Weedon (MF) | DrillingInfo | central Brown | ~1972 | upper MF carbonates | 20 |
| Pickwick (MF) | DrilingInfo | NE Palo Pinto | ~1975 | lower Marble Falls | 45 |
| Street & Stewart (MF Cong) | Martin, 1982 | NW Jack | 1979 | MF cong & lower MF | 28 |
| Morgan Mill (MF) | Flippin, 1982 | NE Erath | 1978 | lower MF | 90 |
| Beattie & Beattie N (MF) | Hailey, 1976 | north-central Comanche | 1973 | upper MF carbonates | 68 |
| Foster (MF) | DrillingInfo | SW Eastland | ~1975 | upper MF carbonates/cong | 357 |
| BBB&C, BLK. 3 (MF) | DrillingInfo | NE Brown | ~1976 | upper MF carbonates & lower MF | 102 |
| Blind Hog (Duffer & Ranger) | DrillingInfo | SW Eastland/northern Brown | ~1977 | upper MF carbonates/cong & lower MF | 90 |
| Poolville SW (MF) | Herkommer & Denke, 1982 | NW Parker | ~1977 | lower Marble Falls | 9 |
| Palo Davis (Duffer & Ranger) | Jackson, 1980 & DrillingInfo | NW Brown | ~1978 | upper MF carbonates & lower MF | 52 |
| Magnum (CONGL) | DrillingInfo | NW Brown | ~1978 | upper MF carbonates & lower MF | 58 |
| Moby Dick (MF) | Herkommer & Denke, 1982 | southwest Parker | ~1979 | lower Marble Falls | 12 |
| Rebecca (MF) | DrillingInfo | north-central Eastland | ~1981 | upper MF cong | 36 |
| Reb (MF) | DrillingInfo | north-central Eastland | ~1982 | upper MF cong/lower MF | 505 |
| Johnston Gap (MF) | DrillingInfo | southwest Palo Pinto | ~1983 | Bend conglomerate | 24 |
| Morenco (MF) | DrillingInfo | SE Eastland | ~1983 | upper MF carbonates | 34 |
| C.B. Long (MF) | DrillingInfo | southwest Palo Pinto | ~1984 | Bend conglomerate | 45 |

The map in Figure 4-46 displays the cumulative oil and gas bubbles of all the wells (~3,500) across the FWB that were determined to have produced or is producing from the lower Marble Falls stratigraphic interval. A vast majority of these wells along the Bend Arch in the western part of the basin produced from highly porous chert deposits that formed from an extended period of subaerial exposure that affected most of the lower Marble Falls carbonate ramp during the Late Morrowan (Figure 4-46). Some of these productive chert deposits along the western subcrop boundary would completely replace the lower Marble Falls where subaerial exposure was more intense, but the majority of these chert intervals would only occur at the top of the lower Marble Falls where it was affected by the regional Morrowan-Atokan unconformity. It was also common for a porous and productive chert intervals to form at the top of various parasequences within the spiculite sequence that were also due to an extended period of subaerially exposure. Occasionally, the porous chert lithofacies would occur randomly throughout the lower Marble Falls section and this was probably due to diagenetic silicification of the abundant siliceous sponge spicules that are present.

The high-frequency cycles present in the northern part of the basin are also commonly present in the lower Marble Falls along the Bend Arch and across most of the FWB, and the high degree of lateral variability in these cycles have formed numerous oil and gas fields across the basin. Most of the production in these fields are contributed to porous stratigraphic traps where these parasequences would pinch-out up-dip or where they were subaerially exposed with significant diagenetic processes contributing to porosity development. There are also a number of fields along the western edge of Jack

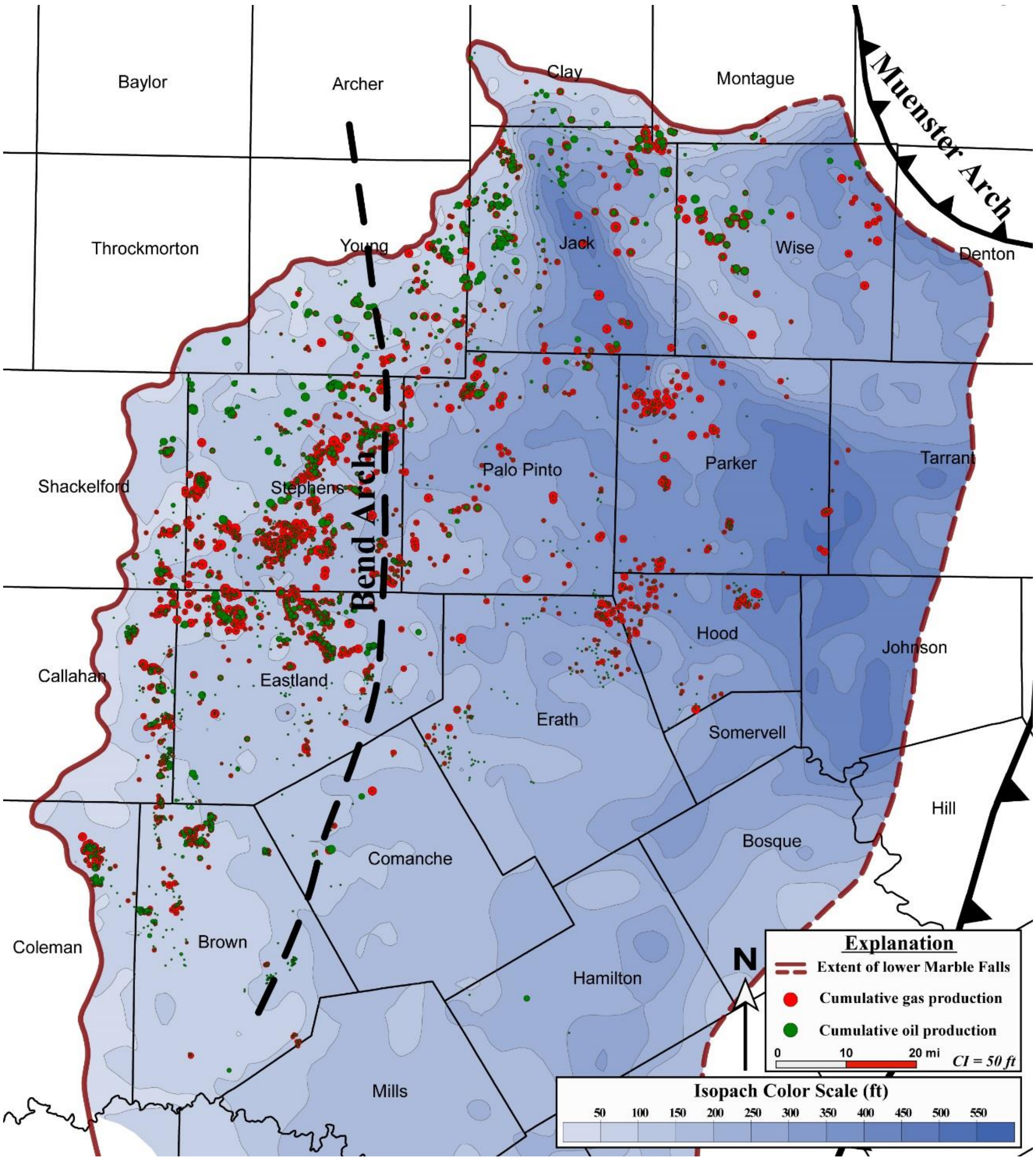



Figure 4-46. Lower Marble Falls production map displaying historical cumulative oil and gas production bubbles of wells that have been completed in the lower Marble Falls interval. Approximately 3,500 historical producers were manually determined.

County and eastern edge of Young County that produced from limestone intervals within the lower Marble Falls and these carbonate-rich sediments accumulated over the top of the thick underlying Comyn limestone interval and were normally productive. There is an erosional conglomerate interval above the lower Marble Falls that industry geologist call the "Marble Falls conglomerate" or MBLFG and has historically been highly productive, but because of the common occurrence of this conglomerate 30 to 50 feet above the lower Marble Falls, it was not included in the cumulative production bubble map in Figure 4-46. This same conglomerate interval occasionally erodes and replaces the top of the lower Marble Falls and although it is more lithologically similar to overlying Atoka Group, it is most likely related to the erosional regional unconformity at the top of the lower Marble Falls.

Most of the lower Marble Falls production along the Bend Arch can be contributed to conventional high porosity reservoirs, but there are other areas scattered across the FWB where the lower Marble Falls has historically been productive. Most of these fields east of the Bend Arch contain low porosity reservoirs and the production is related to the complex network of fractures that are present in the lower Marble Falls. These fractures most likely occurred from Ouachita deformation and the regional flexure of the Bend Arch as it migrated progressively westward through time and caused stresses in the lower Marble Falls spiculites that were already deposited to the east. The fields that are known to have historically produced from fractured intervals within the lower Marble Falls include areas in Erath, Hood, Parker, Palo Pinto, Wise, and Jack counties. Although the present Marble Falls play in Jack and Palo Pinto counties is using new technologies to extract hydrocarbons from the lower Marble Falls fractured reservoir, geologist have known for decades that the Marble Falls was a fractured-driven reservoir. Jackson (1980) discusses the lower Marble Falls in Brown County as having low matrix porosity with production enhanced by fracture development and solution-gas drive. Recent results from the modern Marble Falls play in the northern part of the basin are similar to the results that were observed by Jackson (1980) in the southern part of the FWB and he notes that the fracture development causes good initial potentials but the production drops rapidly to 10 or 15 percent of the original production levels. Turney (1982) also notes that production is dependent on the presence of natural fractures in Erath County and discusses the importance of properly determining where these fractured zones occur within the lower Marble Falls section. There was also an area in northwest Jack County where the lower Marble Falls was identified as a fractured reservoir by Martin (1982).

The current Marble Falls play situated in Jack and Palo Pinto counties is targeting a thick section of the lower Marble Falls spiculite sequence that is a dense, siliceous-rich rock with very little primary porosity or permeability (Figure 4-47; Figure 4-48; Figure 4-49; Figure 4-50). However, the complex network of lithology-bound fractures (LBF) that occur in the spiculite facies is contributing to the reservoir in this area and hydraulic fracturing is used to connect this network of fractures as well as create new fractures to increase the permeability of the rock and allow hydrocarbons to flow to the well-bore (Figure 4-51). These new technologies has allowed operators to make economic wells from a low porosity/low permeability fractured reservoir with the possibility of expanding the lower Marble Falls play into other parts of the basin in the future.

The siliceous-rich spiculitic lithofacies was discovered to be the best reservoir lithofacies due to a number of factors including the fact that the only visible porosity in thin sections from the spiculite sequence was the rare occurrence of moldic porosity that formed in the canals of the sponge spicules. The more siliceous-rich intervals also revealed better reservoir quality on well logs with a common 4 to 10% porosity cross-over between the NPHI and DPHI curves, whereas the calcareous intervals had no porosity visible in thin sections and little to no porosity on open-hole logs (Figure 4-51). Although LBF due occur in all lithofacies present in the lower Marble Falls section, they have been discovered to occur in much greater abundances in the more siliceous–rich intervals which is possibly due to the brittleness of the rock preserving fracture development (Figure 4-51). The fractures occur on a micro- to macro-scale that are observed in thin sections and on image logs and most of these fractures are filled with calcite but there are occasional open fractures. The siliceous-rich spiculite lithofacies typically contains the highest porosity and greatest concentration of LBF and is therefore considered the best reservoir lithofacies with these interval typically targeted during completions. It is critical for future development of the Marble Falls Formation to better understand the lateral variations of the parasequences previously mapped to more accurately predict the distribution of this siliceous spiculitic lithofacies across the FWB (Figure 4-51).

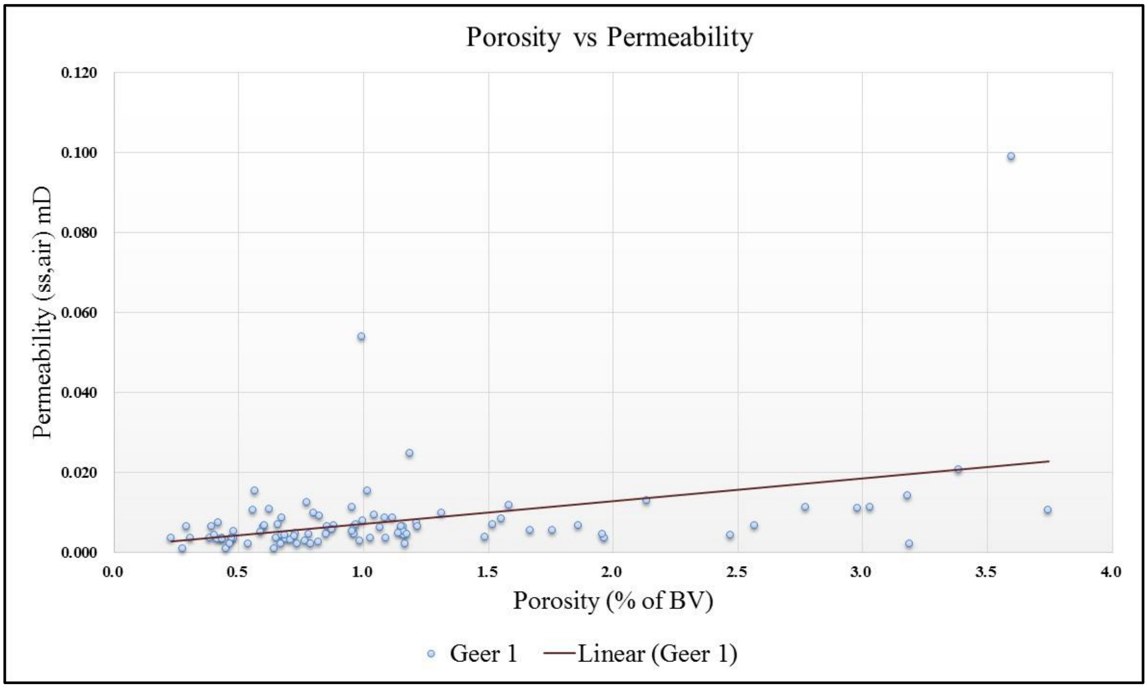



Figure 4-47. Cross plot of porosity versus permeability measured from the Geer No. 1 core plugs. Chart was created from data provided by Ambrose *et al.* (2013).

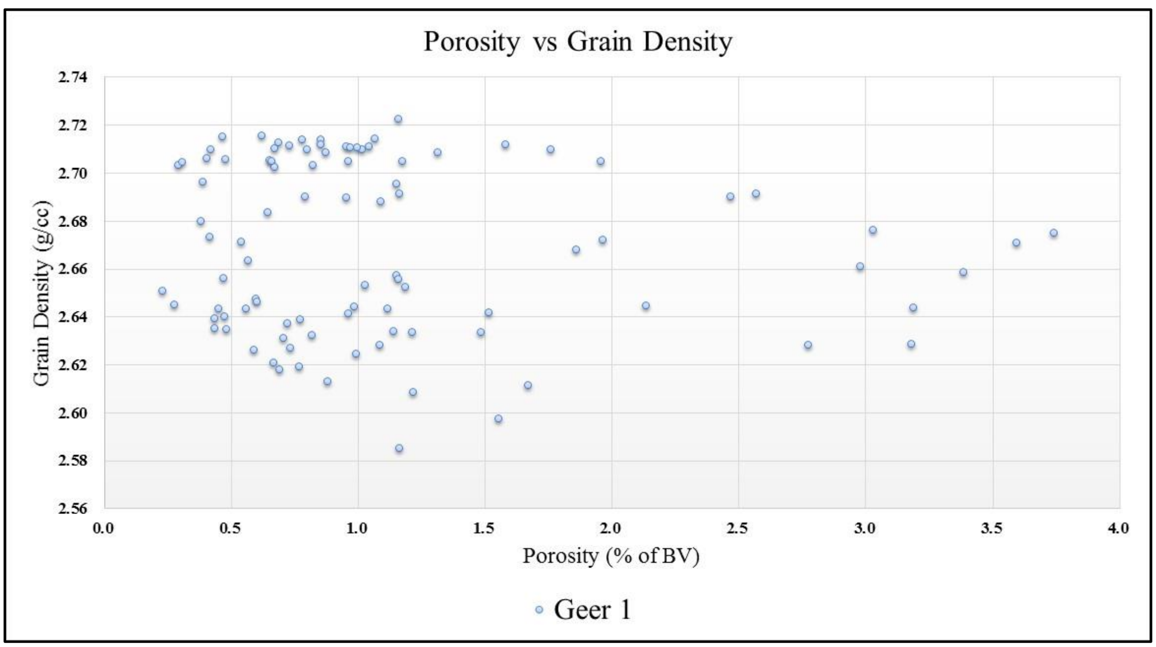



Figure 4-48. Cross plot of porosity versus grain density measured from the Geer No. 1 core plugs. Chart was created from data provided by Ambrose *et al.* (2013).

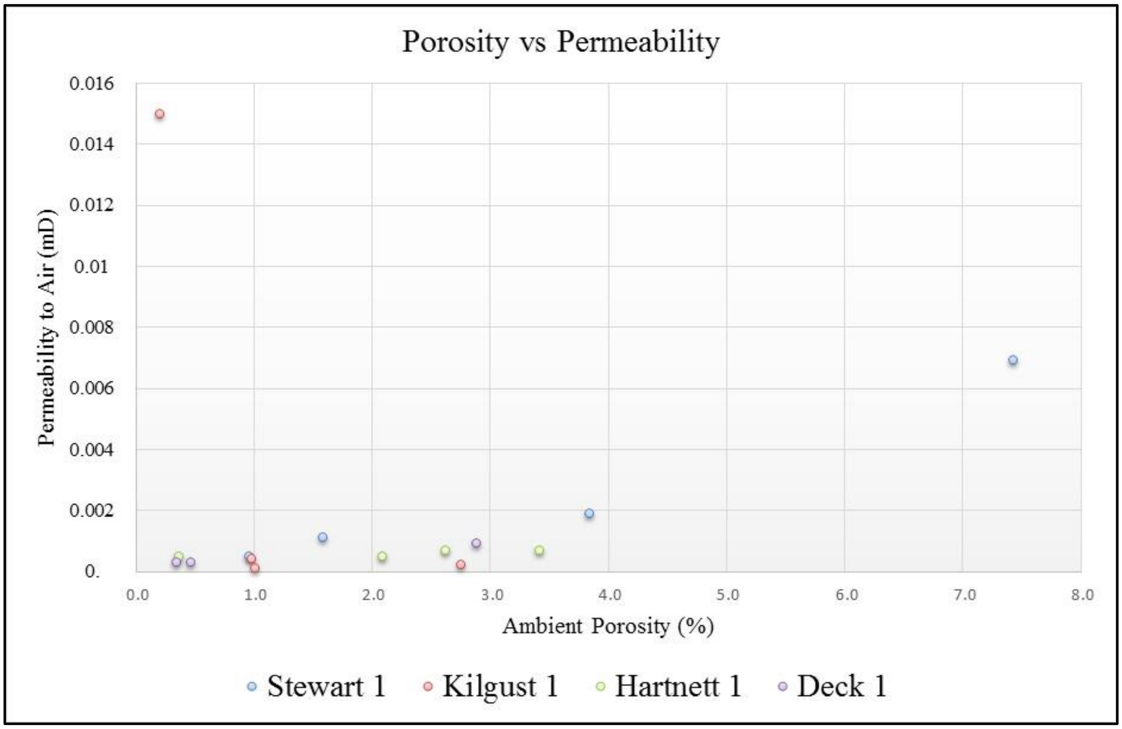



Figure 4-49. Cross plot of porosity versus permeability measured from various side-wall cores taken in four different wells.

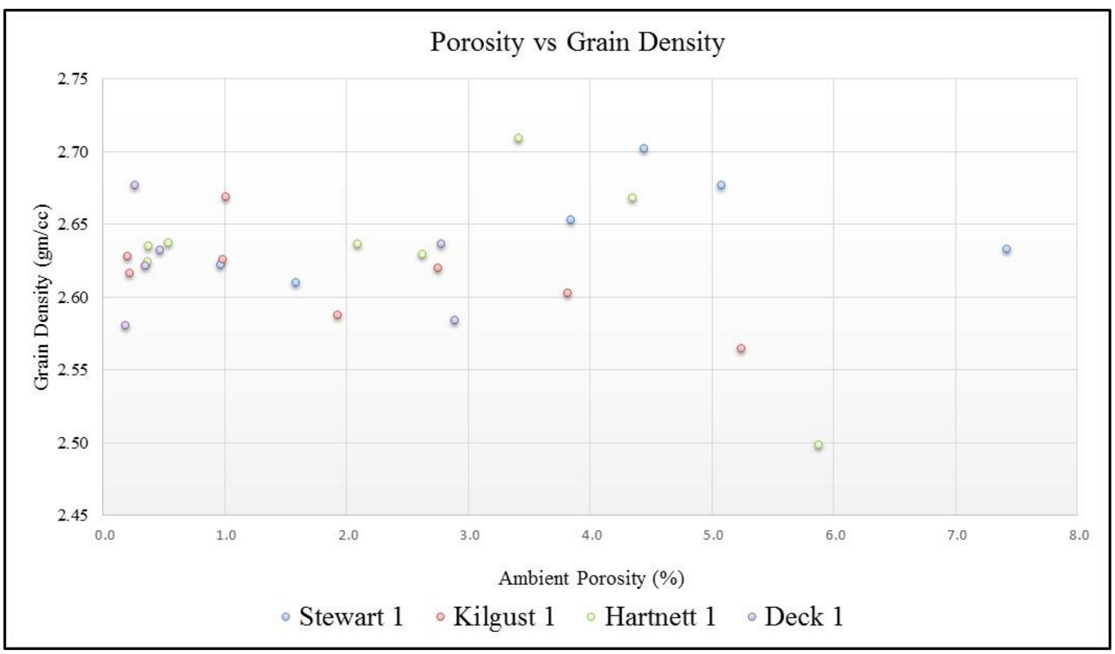



Figure 4-50. Cross plot of porosity versus grain density measured from various side-wall cores taken in four different wells.

***Newark E&P - Herring No. 1***
***(42-363-36156)***

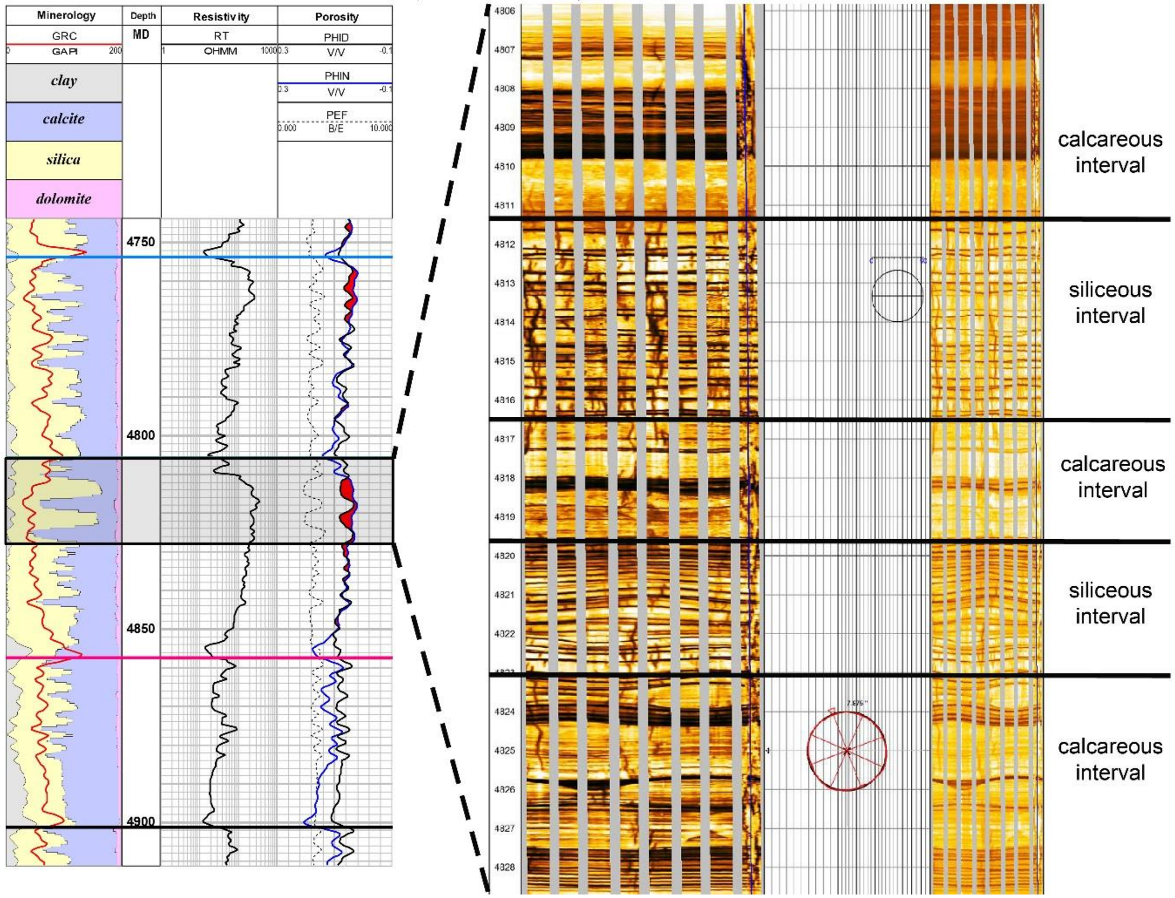



Figure 4-51. Newark E&P Herring No. 1 mineralogy log on the left from a portion of the lower Marble Falls spiculite sequence displaying interbedded siliceous intervals and calcareous intervals with the image log on the right revealing the abundance of lithology-bound fractures in the siliceous intervals and significantly less fractures in the calcareous interval.

# Chapter 5

## Discussion

The Early Pennsylvanian lower Marble Falls is present throughout the Fort Worth Basin from outcrop around the Llano Uplift in Central Texas to the northernmost edge of the basin in North Texas, and from the Bend Arch along the western edge of the basin to the Ouachita thrust belt to the east. The lower Marble Falls was deposited in a carbonate ramp system and consists of a complex assemblage of interbedded carbonate rocks of the inner ramp to spiculites of the outer ramp and calcareous mudstones of a more basinal environment. The spiculite facies is the most abundant depositional facies within the lower Marble Falls succession and was deposited across an enormous area that covered most the FWB. This spiculite facies most commonly occurs in the upper part of a series of shallowing-upward parasequences that comprise the lower Marble Falls and are well defined in southern Jack and northern Palo Pinto counties (Figure 4-37). This sequence of spiculitic sediments was termed the lower Marble Falls spiculite sequence and has been the focus of an emerging fractured-driven resource play in the northern part of the basin, and due to the highly cyclical nature of this sequence it has also formed numerous conventional stratigraphic traps that have historically been exploited for hydrocarbons along the western edge of the basin.

The lower Marble Falls spiculite sequence was deposited uniformly and undisturbed from west to east across the FWB basin with a gradual thickening trend toward the northeast that was controlled tectonically by the subsiding FWB to the east and northeast and the western-migrating forebulge of the North American Craton to the west, which developed into the present-day Bend Arch (Walper, 1982) (Figure 4-39). The combination of these tectonic events had a significant influence on the distribution of the lower Marble Falls sediments across the FWB. The increase in accommodation space over time allowed for the spiculite facies to accumulate across the entire basin and reach thicknesses >400 feet throughout Jack, Parker, Tarrant, Hood, and Johnson counties (Figure 4-38). The location of this stratigraphically thicker section of the lower Marble Falls is unusual because it seems more likely for it to reach maximum stratigraphic thicknesses in the northeastern part of the basin adjacent to the Muenster Arch where the basin was structurally deepest during the Early Pennsylvanian (Walper, 1982). Also, the carbonate platform was being deposited contemporaneously along the eastern side of the forebulge as it migrated westward through time so the lower Marble Falls should have reached maximum thicknesses along the easternmost edge of its extent. However, it is herein revealed that this did not occur and that there were other controls on the distribution of the lower Marble Falls spiculite sequence that were not tectonically-driven and explains why this thick northwest-trending accumulation occurs where it does.

The extensive correlation and mapping efforts from this work reveal that the lower Marble Falls spiculite sequence was stratigraphically controlled by the underlying carbonate-rich units in the northeastern part of the FWB. The lower Barnett calcareous unit, Forestburg-Comyn limestone, Marble Falls lower limestone, Marble Falls lower shale, Marble Falls upper limestone, Marble Falls upper shale, and Marble Falls calcareous shale all contain carbonate-rich sediments that were only deposited in the northern or northeastern part of the FWB and contain maximum stratigraphic thicknesses that migrated progressively toward the south and southeast through time (Figure 5-1; Figure 5-2). The distribution of these intervals across the northeastern edge of the FWB suggests that they were all deposited from the same carbonate-dominated source area that was most likely located to the north in southern Oklahoma. There were no image logs or core data available through the lower Barnett calcareous unit or the carbonate-rich units of the Marble Falls Formation which made it difficult to determine if these rocks were depositionally similar to the dolomitic limestone of the Forestburg-Comyn limestone. However, similarities in well log characteristics provides evidence that the carbonate-rich sediments of these 7 units may represent redeposited, finely crystalline, carbonate debris that was transported into the basin from a carbonate-dominated source to the north.

The paleogeography and distribution of these carbonate units were mapped in detail across the northern FWB and they all contain both limestone and calcareous shale intervals which suggest that there were alternating fluctuations of dominantly carbonate sedimentation (limestone intervals) and episodes when there was an influx of clay-rich sediments with high-concentrations of calcium carbonate still present in the system (shale intervals). There is also evidence from the isopach maps that suggest the Mineral Wells – Newark East fault system was active during the Late Mississippian and Early Pennsylvanian and affected the distribution of these sediments across the area (Figure 5-2). The lower shale, lower limestone, upper shale, and upper limestone of the Marble Falls Formation are gradational and were deposited continuously with no hiatus observed that would suggest a period of erosion or non-deposition. The similarities in log characteristics and paleogeography of the carbonate-rich units in the Marble Falls

Formation with those of the Forestburg-Comyn limestone and the lower Barnett calcareous unit, and the fact that the lower Marble Falls spiculite sequence is Morrowan in age, suggest that all of these carbonate units in the northeastern part of the basin are possibly Mississippian in age. There is also a maximum flooding surface that occurs at the top of the Marble Falls upper limestone or, where present, at the top of the Marble Falls calcareous shale and separates these units from the overlying lower Marble Falls spiculite sequence which also possibly represents the Mississippian-Pennsylvanian boundary. However, more work is needed to support this interpretation and more detailed biostratigraphic work needs to be conducted to determine the exact ages of each of these units.

There is also evidence which revealed that the Marble Falls lower limestone, upper limestone, and calcareous shale all thin abruptly to the west along a trend that is oriented in the same direction that the Forestburg-Comyn limestone and lower Barnett calcareous unit also thin (Figure 5-1; Figure 5-2). This area of non-deposition of these carbonate-rich units created accommodation space for the lower Marble Falls spiculite sequence to infill from the west and reach thicknesses >450 feet (Figure 5-2). The stratigraphic control of these carbonate-rich units explains why the thickest section of the lower Marble Falls spiculite sequence trends northwest where these units have thinned abruptly in Tarrant, Parker, and Jack counties (Figure 5-2). The spiculite sequence also thins significantly to the northeast along this same northwest-trend as it overlaps the carbonate-rich units.

The lower Marble Falls spiculite sequence accumulated into a thick wedge-shaped feature in central Jack County that was controlled by the underlying carbonate-rich units as well (Figure 5-1). The Forestburg-Comyn limestone and lower Barnett calcareous unit extend across most of the northern part of the FWB, but are completely absent through north-central Jack County and south-central Clay County (Figure 5-1). It is unclear if the carbonate-rich sediments were never deposited in this area or if there was an erosional feature that cut through the carbonates allowing deposition of clay-rich sediments (low-resistivity shale). Whichever was the case, this geological feature was probably related to the Red River Arch to the north and isopach maps reveal it was present over a significant time period affecting sedimentation patterns from the Mississippian into the Early Pennsylvanian. The lower Marble Falls spiculite sequence reaches thicknesses >450 feet in north-central Jack County where this feature has eroded the Forestburg-Comyn limestone and lower Barnett calcareous unit or prevented the carbonate sediments from being deposited in this area (Figure 5-1; Figure 5-2; Plate 9).

The underlying Forestburg-Comyn limestone also influenced depositional trends of the lower Marble Falls spiculite sequence across most of Jack County. In the southern part of Jack County where the underlying limestone unit is present and averages around 100 feet thick, the lower Marble Falls spiculite sequence is characterized by a succession of distinct shallowing-upward parasquences that represent Early Pennsylvanian sea-level fluctuations (Heckel, 1994); (Plate 5; Plate 15). However, just north of the town of Jacksboro where the Forestburg-Comyn limestone is completely absent, these high-frequency depositional cycles could not be defined and the lower Marble Falls is characterized by a thick (>450 feet) sequence of undifferentiated spiculite deposits that were probably deposited as debris-flows transported from the south or southwest (Ambrose *et al*., 2013); (Plate 9).

The position and thickness of the Late Mississippian Forestburg-Comyn limestone is also thought to have influenced the overall sedimentation patterns and stratigraphic framework of the lower Marble Falls throughout the northern FWB. This interpretation is based on the fact that the lower Marble Falls carbonate ramp extends over 125 miles from west to east across the central part of the basin from inner-ramp carbonates along the Bend Arch to basinal mudstones to the east. However, in the northern part of the basin this transition in depositional facies occurs over a distance of approximately 15 miles, and the lower Marble Falls is composed dominantly of inner-ramp carbonate rocks along western Jack County that grade abruptly into the outer-ramp spiculite facies in central Jack County and eventually grade into a dominantly calcareous mudstone facies along the eastern edge of Jack County. These observations show evidence that the carbonate ramp of the lower Marble Falls was widespread across the southern and central part of the basin but narrows significantly in the northern part of the basin. These sedimentation patterns were partially tectonically influenced by the position of the Bend Arch, but the stratigraphic position of the Foresetburg-Comyn limestone also had a significant influence on the distribution of depositional facies within the lower Marble Falls in the northern part of the FWB.

The western migrating forebulge, now known as the Bend Arch, had a significant influence on the distribution of depositional facies, reservoir lithofacies, and thickness of

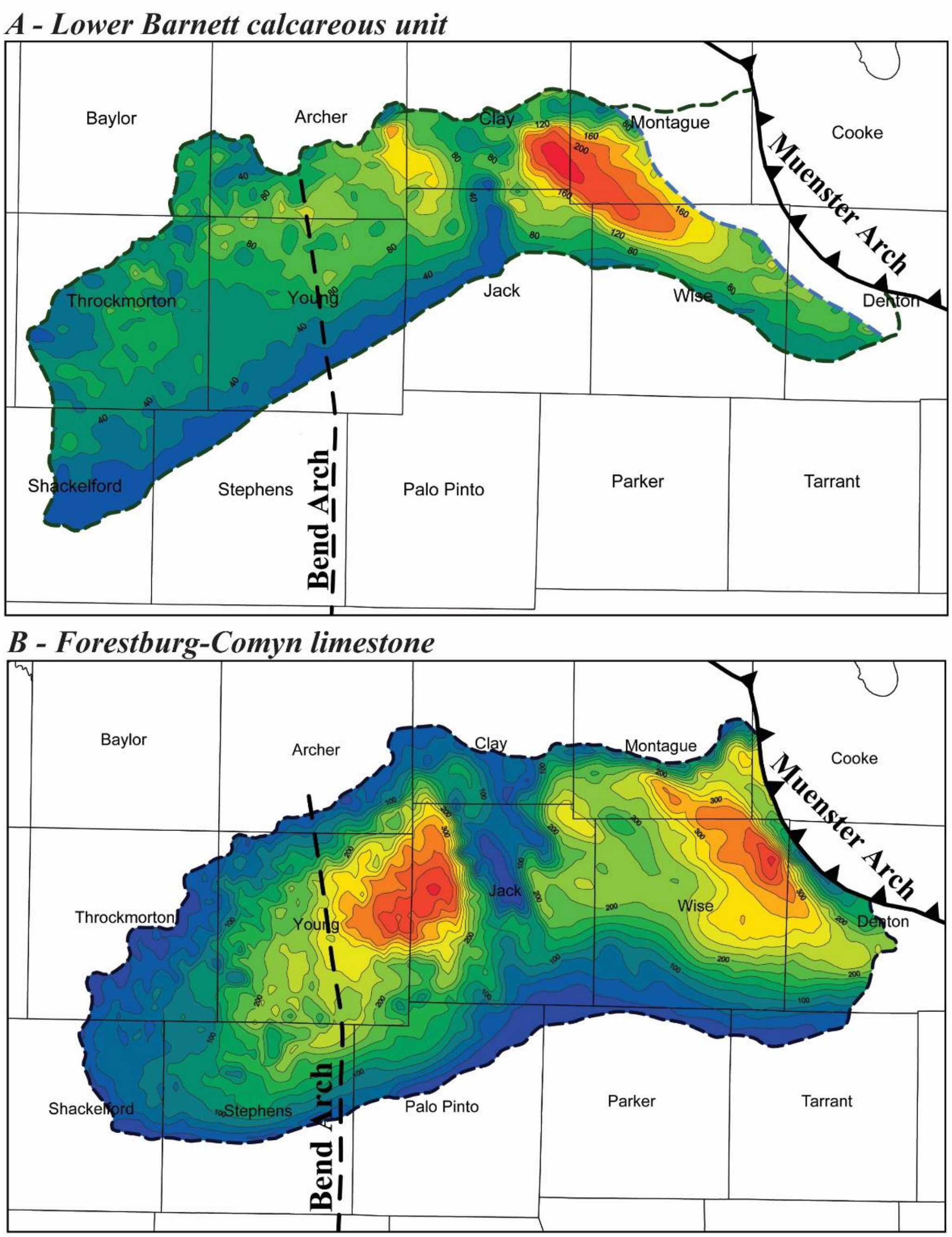



Figure 5-1. Comparison of the lower Barnett calcareous unit isopach map (A) and the Forestburg-Comyn limestone isopach map (B) displaying stratigraphic variations across the northern part of the Fort Worth Basin and the migration of carbonate sedimentation toward the south and southeast .

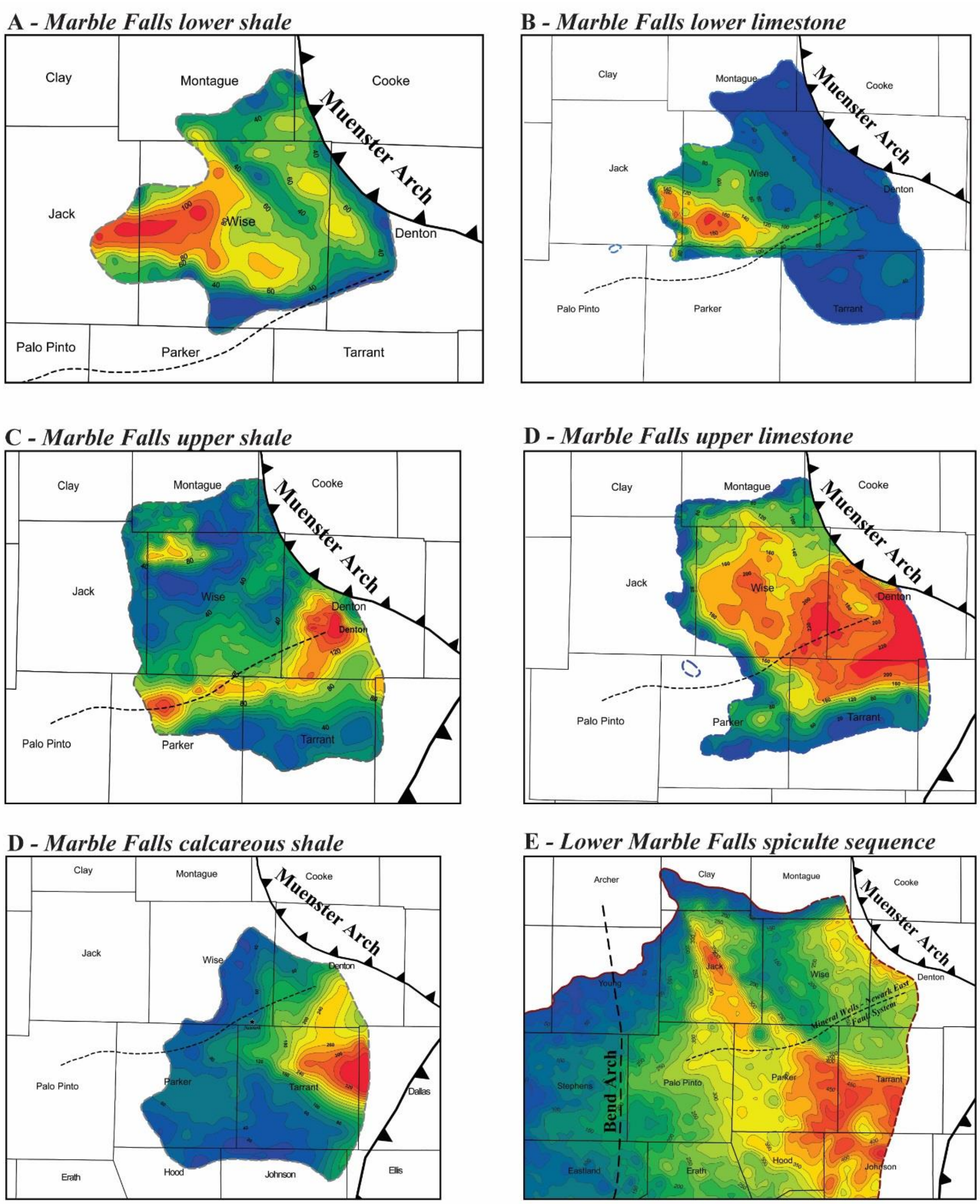



Figure 5-2. Comparison of isopach maps of the Marble Falls lower shale (A), lower limestone (B), upper shale (C), upper limestone (D), calcareous shale (E), and the lower Marble Falls spiculite sequence (E). Note the thickest section of each unit from A to D is migrating progressively toward the south and southeast and the spiculite sequence thins over the top of these units along a northwest-trend.

the lower Marble Falls across most of the FWB. A major drop in sea-level at the end of the Morrowan subaerially exposed most of the lower Marble Falls carbonate ramp which is evident by the regional erosional unconformity that occurs at the top of the lower Marble Falls across most of the FWB. However, the area to the west along the axis of the Bend Arch was especially affected by this drop in sea level because it was located in a more proximal carbonate shelf environment and was significantly thinner compared to the lower Marble Falls deposits basinward to the east (Figure 4-38; Figure 4-39). The subaerially exposure of this carbonate ramp along the western edge of the FWB formed widespread chert deposits that occur at the top of the lower Marble Falls in parts of Eastland, Stephens, and southern Young counties (Plate 9; Plate 10). Siliceous sponge spicules are abundant in the lower Marble Falls with evidence of silicification of the sponge spicules commonly occurring. Therefore, the chert deposits were probably sourced from the silica that compose the sponge spicules with evidence from other studies that discuss siliceous sponge spicules as a source of diagenetic silica (Pittman, 1959). These chert deposits become significantly more abundant toward the subcrop to the west and eventually comprise most of the lower Marble Falls in eastern Coleman, Callahan, and Shackelford counties, the southeastern edge of Throckmorton County, and in parts of the western Stephens and Young counties (Figure 4-38; Plate 9; Plate 10; Plate 11). The chert deposits that comprose the lower Marble Falls along the western edge of the FWB have historically been exploited for hydrocarbons over the last century.

The regional Morrowan-Atokan unconformity that separates the lower and upper members of the Marble Falls Formation was traced across most of the basin using a high-GR flooding surface, and the contact between the lower Marble Falls and overlying upper Marble Falls or Atoka Group is abrupt, irregular, and occasionally represents an angular unconformity. The drop in sea level represented by this boundary was visibly more significant along the western edge of the basin where there were widespread chert deposits and erosional conglomerates that occurred at the top of the lower Marble Falls. Erlich and Coleman (2005) estimated 10-20 m of the lower Marble Falls was removed during this drop in sea level and also suggested that a rock interval equating to 2.1 Ma is missing from the Morrowan and up to 0.5 Ma is missing from the base of the Atokan at this unconformable surface. However, along the eastern edge of the basin there were no erosional deposits or abrupt contacts that would suggest the presence of an unconformity which makes it difficult to distinguish the top of the lower Marble Falls because it is gradational with the overlying Atoka Group. This was probably due to sea level falling just enough to expose the lower Marble Falls carbonate ramp along the western half of the basin but not enough to affect the deeper-water outer ramp to basinal deposits to the east.

The lower Marble Falls spiculite sequence contains a succession of shallowing-upward parasequences that were mapped in northern Palo Pinto and southern Jack counties, but they commonly occur throughout the FWB and influenced the heterogeneity of the lower Marble Falls reservoir. The intense cyclicity of the lower Marble Falls spiculite sequence is also expressed in complicated lateral variations of these high-frequency cycles that have influenced the distribution of lithofacies. The variability in these high-frequency cycles likely play a critical role in controlling the sequence stratigraphic framework of the lower Marble Falls spiculite sequence and distribution of reservoir lithofacies, but at the time of this study there was not enough data to conduct such a study. The regional stratigraphy and paleogeography of the lower Marble Falls indicates that the overall thickness of this unit was mostly tectonically controlled by the development of the FWB, but the thicker northwest-trending section in Jack, Parker, Tarrant, Johnson, and Hood counties was stratigraphically controlled by the distribution of the underlying carbonate-rich units. The parasequences that compose the lower Marble Falls spiculite sequence across the FWB were controlled by high-amplitude glacio-eustatic sea-level fluctuations that commonly influenced Pennsylvanian sedimentation across North America (Heckel, 1994).

The lower Marble Falls has historically been exploited for hydrocarbons across much of the FWB and Bend Arch area, with most of the production attributed to porous chert reservoirs or conventional stratigraphic pinch-outs along the western edge of the basin. However, there is still significant potential in the FWB for exploiting the lower Marble Falls spiculite sequence because it is a highly variable system that is composed of complex stacking patterns and high-frequency parasequences which have formed stratigraphic traps that may have been by-passed in areas where there is a lack of deep well control. Also, the lower Marble Falls spiculite sequence is known to be a fractured reservoir in Jack and Palo Pinto counties, but there is evidence that also shows it is fractured elsewhere in the basin (Jackson, 1980). Determining the regional stratigraphy and distribution of the lower Marble Falls across the FWB has also presented evidence that reveals the spiculite sequence contains similar well log characteristics to the lower Marble Falls in the northern part of the basin where the present play is located (Plate 13; Plate 14). The lower Marble Falls covers more than 15,000 square miles and has been historically productive across much of the Bend Arch and parts of the FWB, which suggests that this new fractured-driven Marble Falls play may have significantly greater potential for expansion than has been previously realized. However, much work still needs to be done in a number of disciplines including geochemistry, fracture/structure, sequence stratigraphy, biostratigraphy, and a more detailed depositional analyses.

# Chapter 6

## Conclusions

The Marble Falls Formation has been studied extensively in outcrop and the shallow subsurface north of the Llano uplift, where it was informally divided into a lower member (Morrowan) and an upper member (Atokan) that are separated by the regional Morrowan-Atokan unconformity. The Marble Falls Formation also occurs in the deep subsurface in the northern part of the FWB, but until this work it has not been determined in published literature whether this section of the Marble Falls Formation was part of the lower or upper member, or if it was even stratigraphically related to the Marble Falls Formation in outcrop. This study is the first comprehensive work to correlate the Marble Falls Formation across the entire FWB to better understand the regional stratigraphy and controls on sedimentation patterns.

The Marble Falls Formation in Jack County was shown to be part of the lower member of the Marble Falls Formation defined in outcrop and this sequence covered a much larger area than has been previously defined. The regional Morrowan-Atokan unconformity is also shown to be present at the top of the lower Marble Falls in the northern part of the basin, just as it is in outcrop. This major erosional unconformity was identified throughout the basin by a high-GR flooding surface, porous chert and conglomerate deposits associated with subaerial exposure, karst features, and by the abrupt and irregular contact with the overlying Atoka Group or upper Marble Falls.

The extensive regional correlation of the lower Marble Falls revealed it was deposited over an area >15,500 square miles (40,140 km$^2$) across the FWB and contains abundant siliceous to partly calcareous sponge spicules that have undergone significant diagenetic alteration. Evidence from conventional whole cores and rotary side-wall cores indicate that this spiculite facies comprises most of the lower Marble Falls across the FWB, which indicates that the environment was ideal for these siliceous sponges to flourish over a large paleogeographic area. The spiculite facies was deposited in an outer ramp environment and normally occurs in the upper part of shallowing-upward parasequences that are common across the basin and comprise the lower Marble Falls spiculite sequence.

This spiculite sequence was correlated and mapped across the FWB and Bend Arch area using >20,000 well logs and the overall thickening trend of this interval from west to east was tectonically controlled by the subsidence of the FWB and westward migration of a forebulge now known as the Bend Arch. It is approximately 100 feet thick along the axis of the Bend Arch but thins to the west and is <20 feet thick near the western subcrop boundary where it has been nearly completely replaced by highly porous chert deposits. The lower Marble Falls spiculite sequence thickens toward the axis of the FWB to the east and northeast and reaches maximum stratigraphic thicknesses of >450 feet throughout parts of Hood, Johnson, Tarrant, and Parker counties. This thick section of the spiculite sequence is herein shown to be stratigraphically controlled by five underlying carbonate-rich units of the Marble Falls Formation that were only deposited in the northeastern part of the FWB. All five units were correlated and mapped in the northeastern part of the basin and the well log characteristics and paleogeography of these units suggests that they were all deposited in a similar environment with sediments sourced from the same carbonate-dominated area to the north. The lower Marble Falls spiculite sequence also reaches thicknesses >450 feet in Jack County and this thick stratigraphic section was influenced by the underlying Forestburg-Comyn limestone and a newly described lower Barnett calcareous unit. Both of these carbonate-rich units were correlated and mapped and are herein shown to have only been deposited across the northern part of the FWB. They are both completely absent in north-central Jack County where the lower Marble Falls spiculite sequence accumulated to greater thicknesses.

The Marble Falls Formation was deposited during the Early Pennsylvanian and influences of glacio-eustatic sea-level fluctuations were evident by high-frequency cycles that commonly occur in the lower Marble Falls spiculite sequence. Numerous parasequences were defined within the lower Marble Falls in southern Jack and northern Palo Pinto counties, the lateral variability of which stratigraphically control reservoir quality and the distribution of lithofacies across much of the FWB. The regional stratigraphic thickness of the lower Marble Falls combined with historical production trends and the fact that it contains reservoir quality rock throughout the FWB, suggests that it has the potential to be further exploited for hydrocarbons across most of the FWB using both conventional and unconventional technologies.

# Appendix A

## Cross-Sections

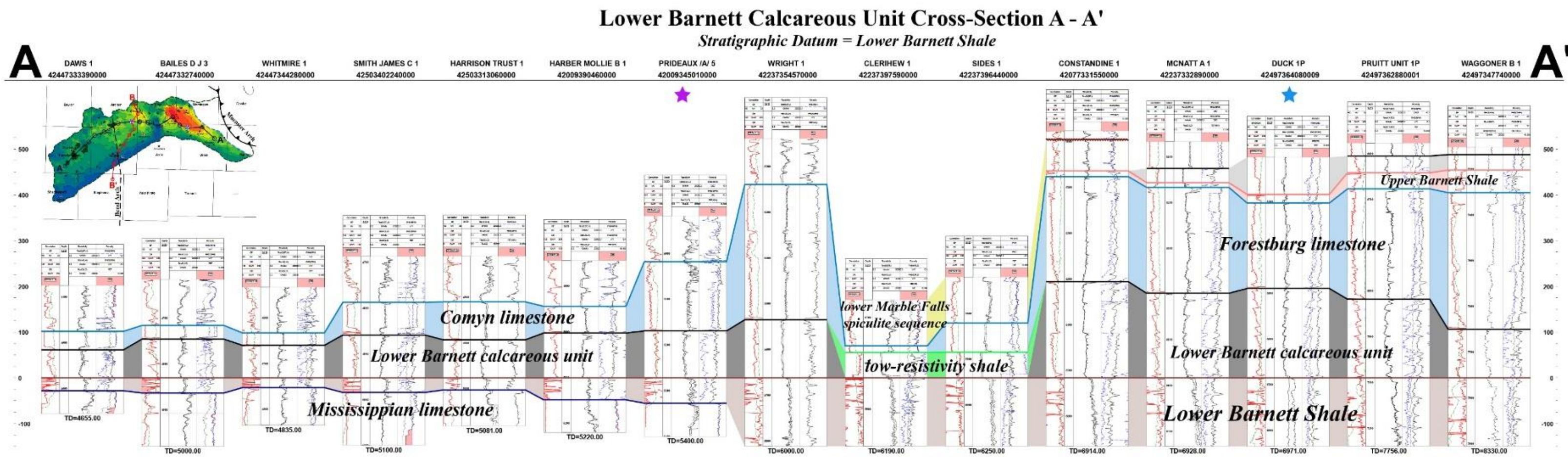



Plate 1. A – A' cross-section from the Bend Arch to the west toward the Muenster Arch to the east showing thickness distribution and characteristic log response patterns of the calcareous unit and low-resistivity shale.

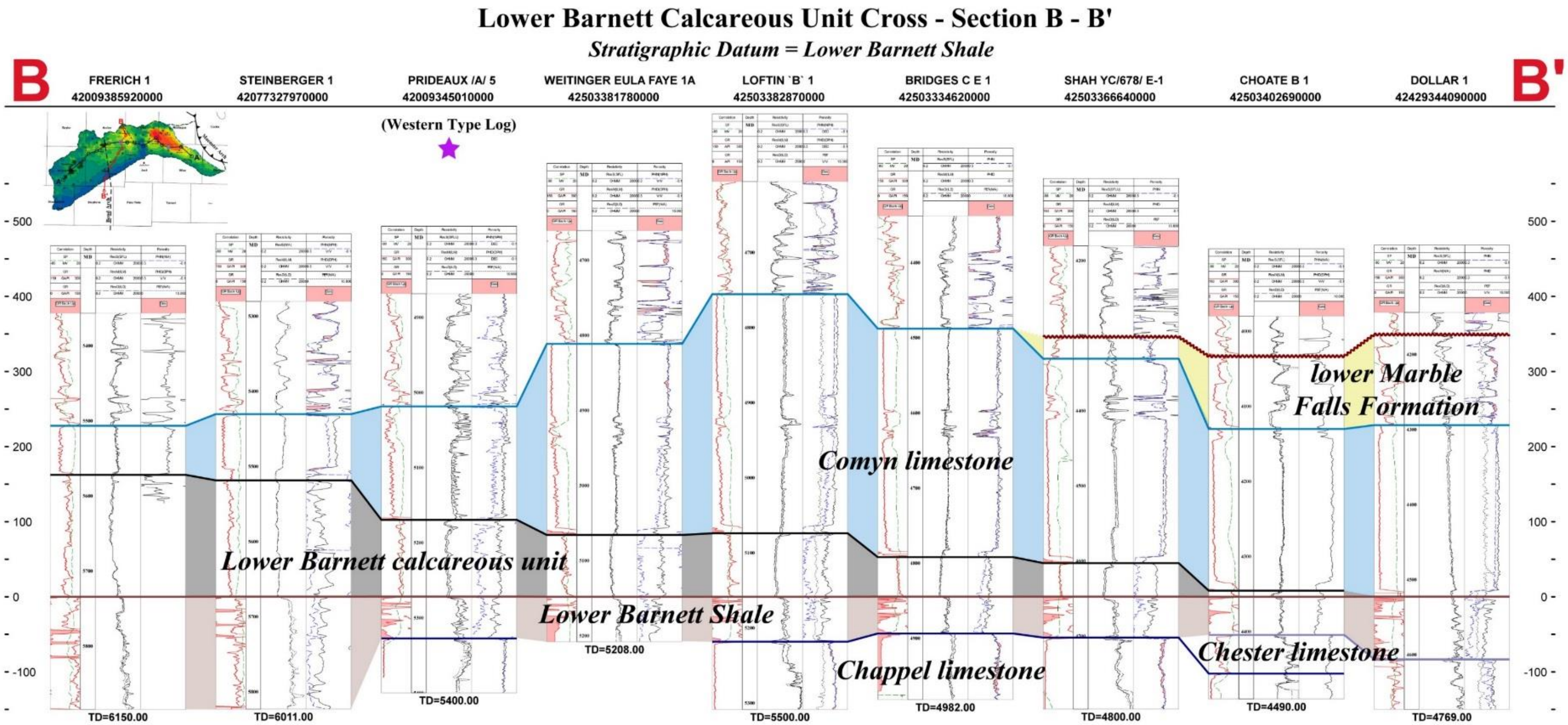



Plate 2. B – B' cross-section showing the thickest part of the western calcareous unit in eastern Archer County and its thickness distribution and log response patterns as it thins toward the south and is completely absent in northeastern Stephens County .

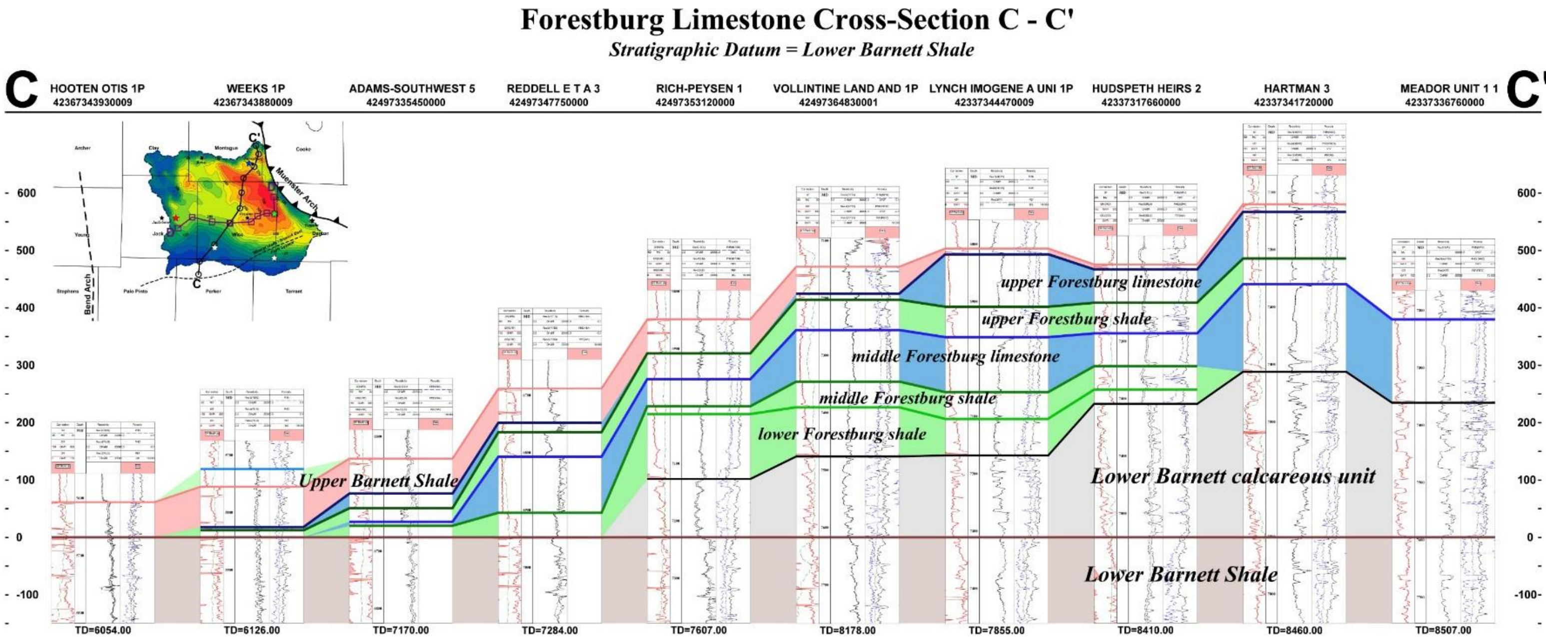



Plate 3. C – C' cross–section from the northern limit of the Forestburg limestone in eastern Montague County to its southern limit in northern Parker County.

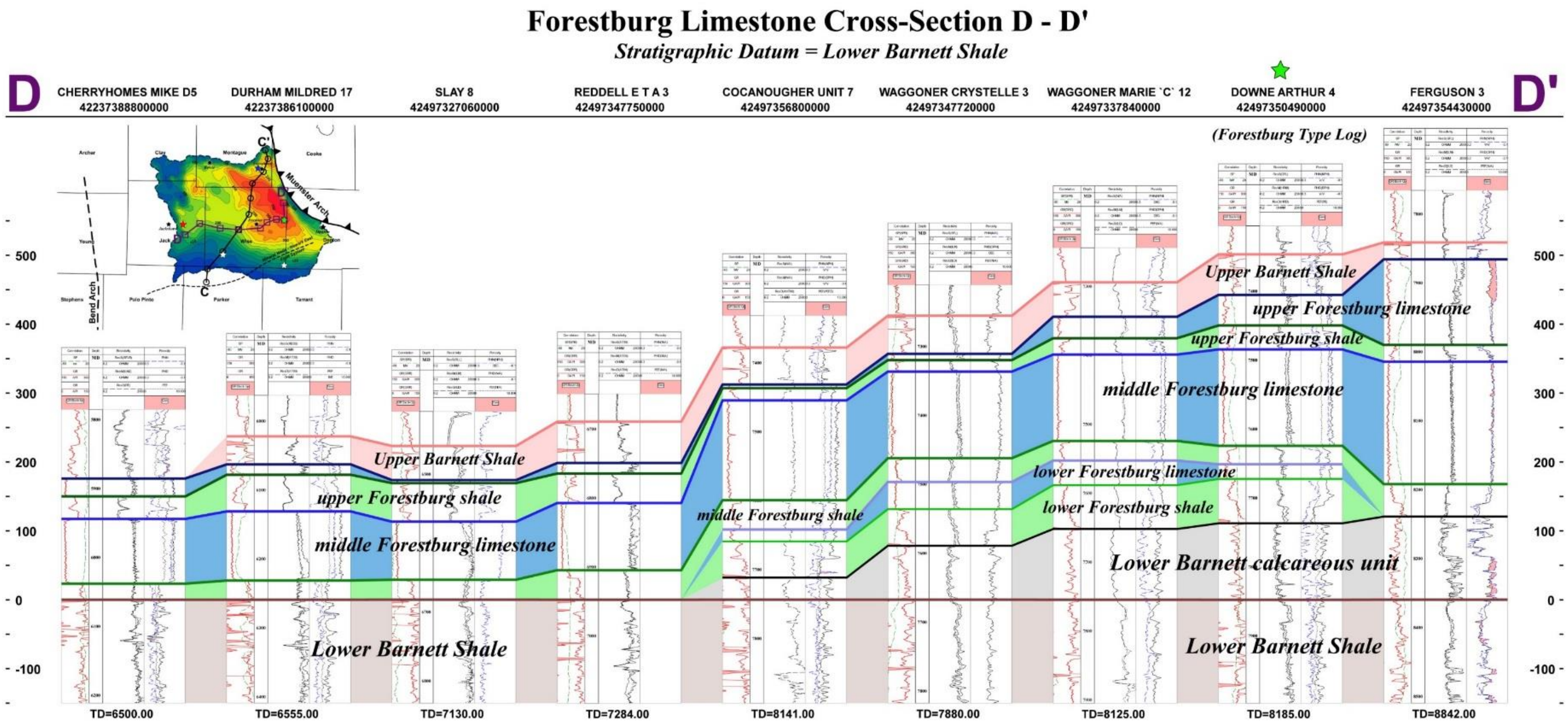



Plate 4. D - D’ cross-section from the western limit of the Forestburg limestone in eastern Jack County to its thickest section in northeastern Wise County.

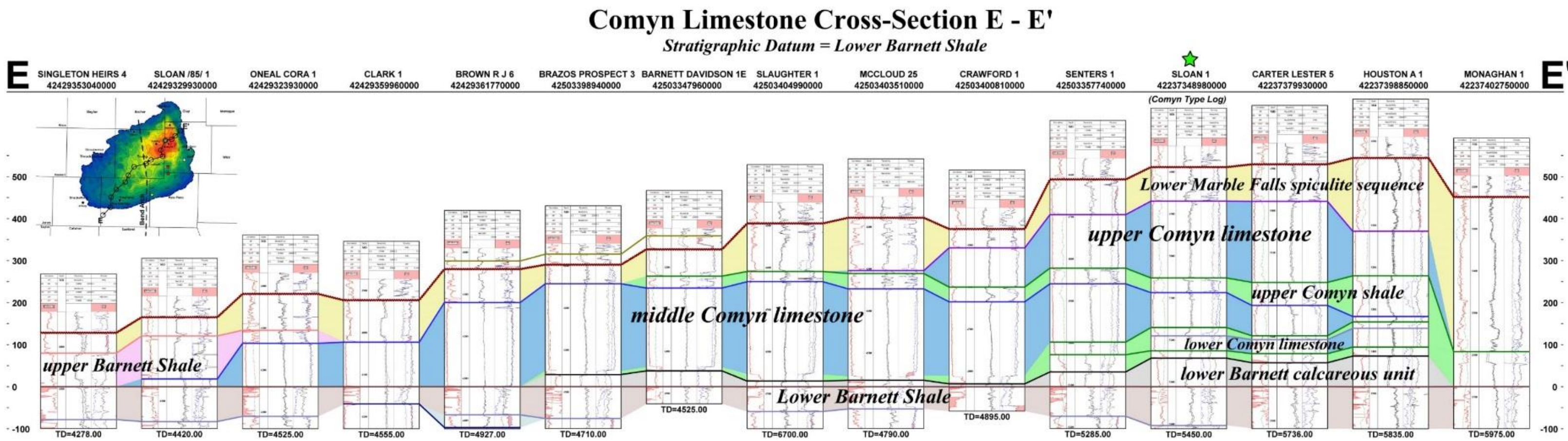



Plate 5. E – E' cross-section from the southernmost Comyn subcrop limit in southwestern Stephens County to the eastern limit in north-central Jack County displaying the Comyn limestone stratigraphy and thickness variations across the Fort Worth Basin.

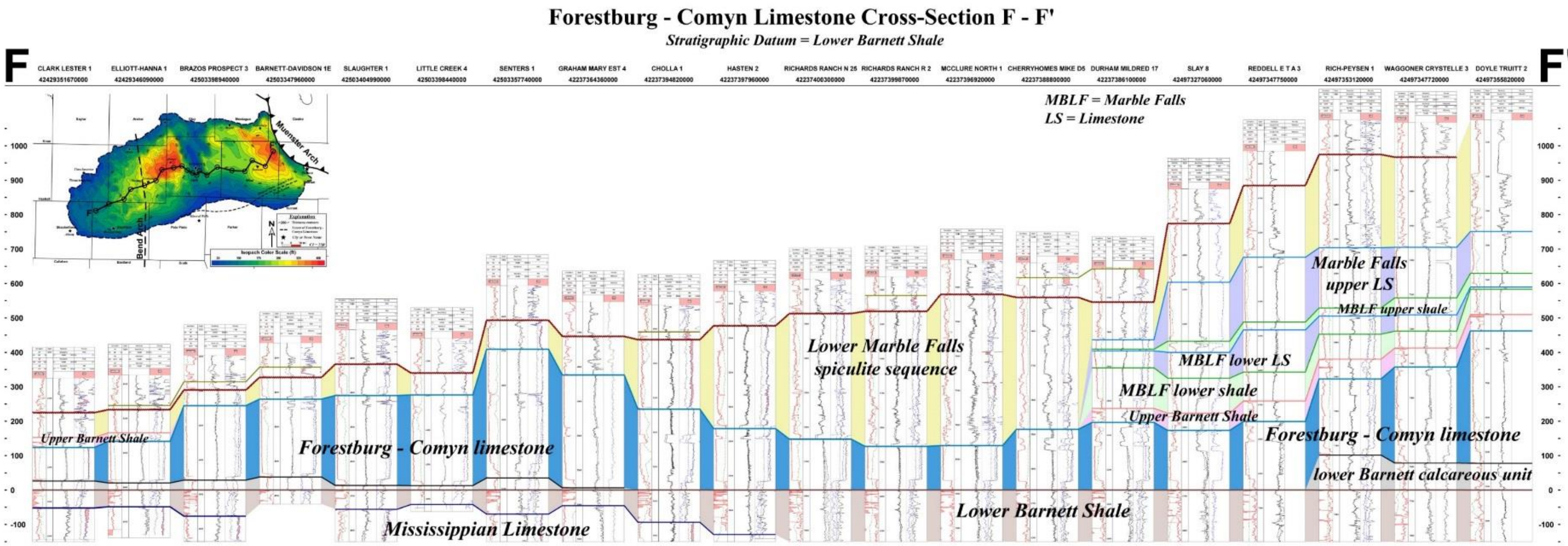





Plate 6. F – F' cross-section from the Bend Arch along the western edge of the Fort Worth Basin to the northeastern edge of the basin adjacent to the Muenster Arch displaying regional stratigraphy of the Forestburg – Comyn limestone section and thickness variations across the basin.

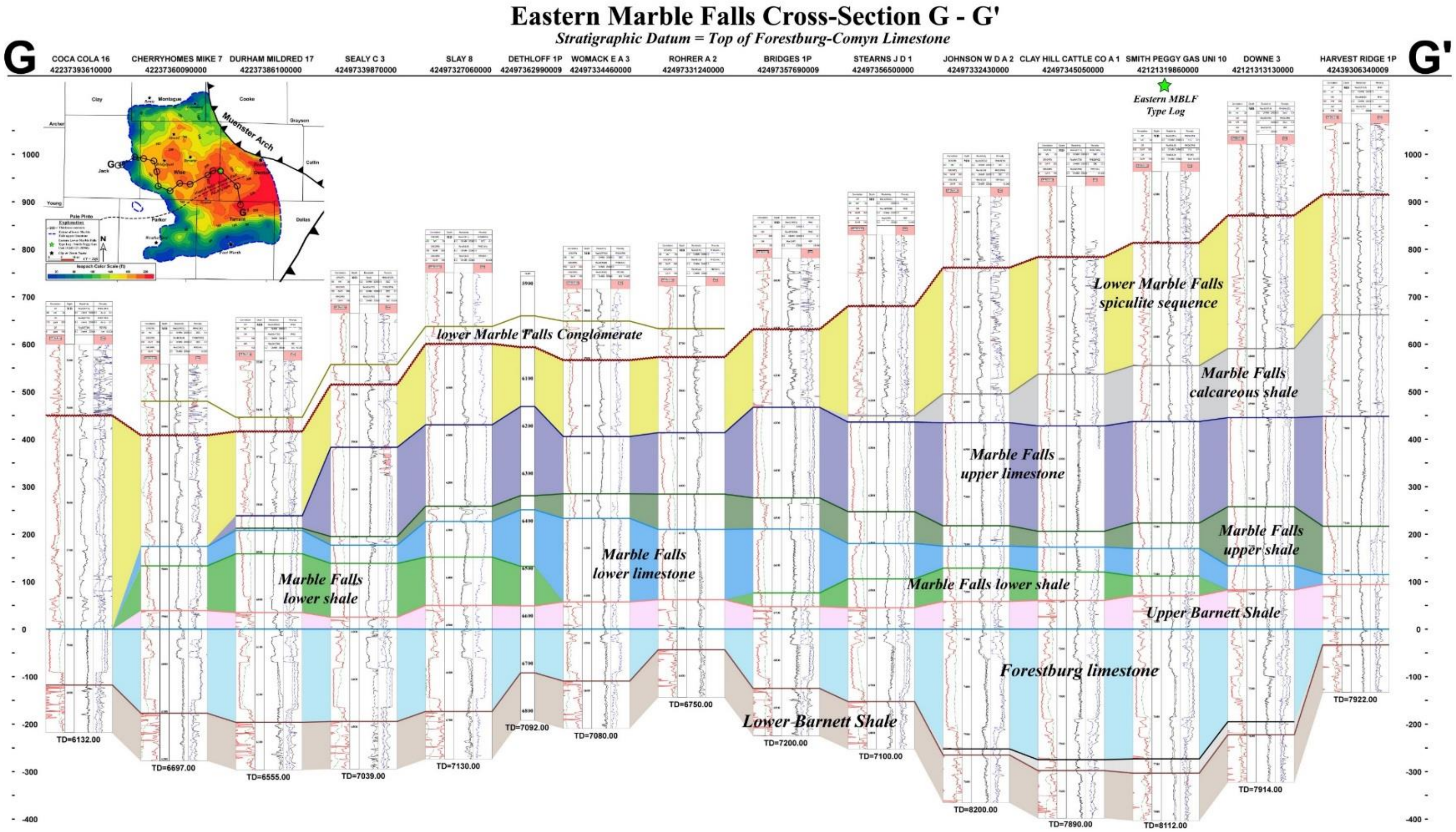



Plate 7. G – G' cross-section from the eastern edge of Jack County to the far northern edge of Tarrant County displaying the Marble Falls stratigraphy in the northeastern part of the Fort Worth Basin. The calcareous shale, upper shale, and upper limestone units generally thicken toward the southeast. The thickest section of the lower shale and lower limestone units are along the eastern edge of Jack County and western edge of Wise County and thin toward the east. The spiculite sequence thins along the eastern edge of Jack County where the lower limestone is thickest and thickens toward the southeast as the lower limestone thins.

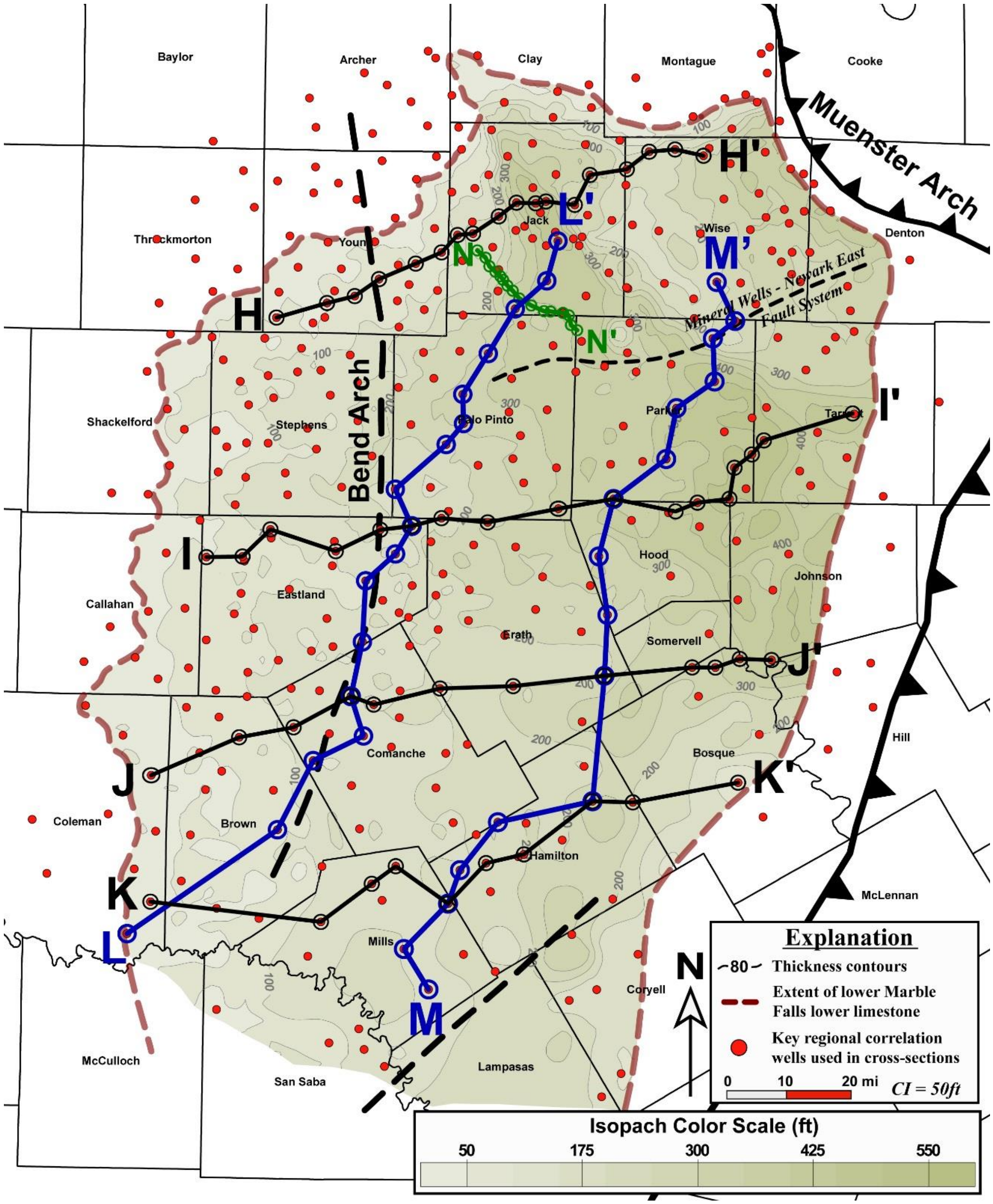



Plate 8. Map of regional lower Marble Falls correlations displaying cross-section lines associated with the appropriate cross-sections below.

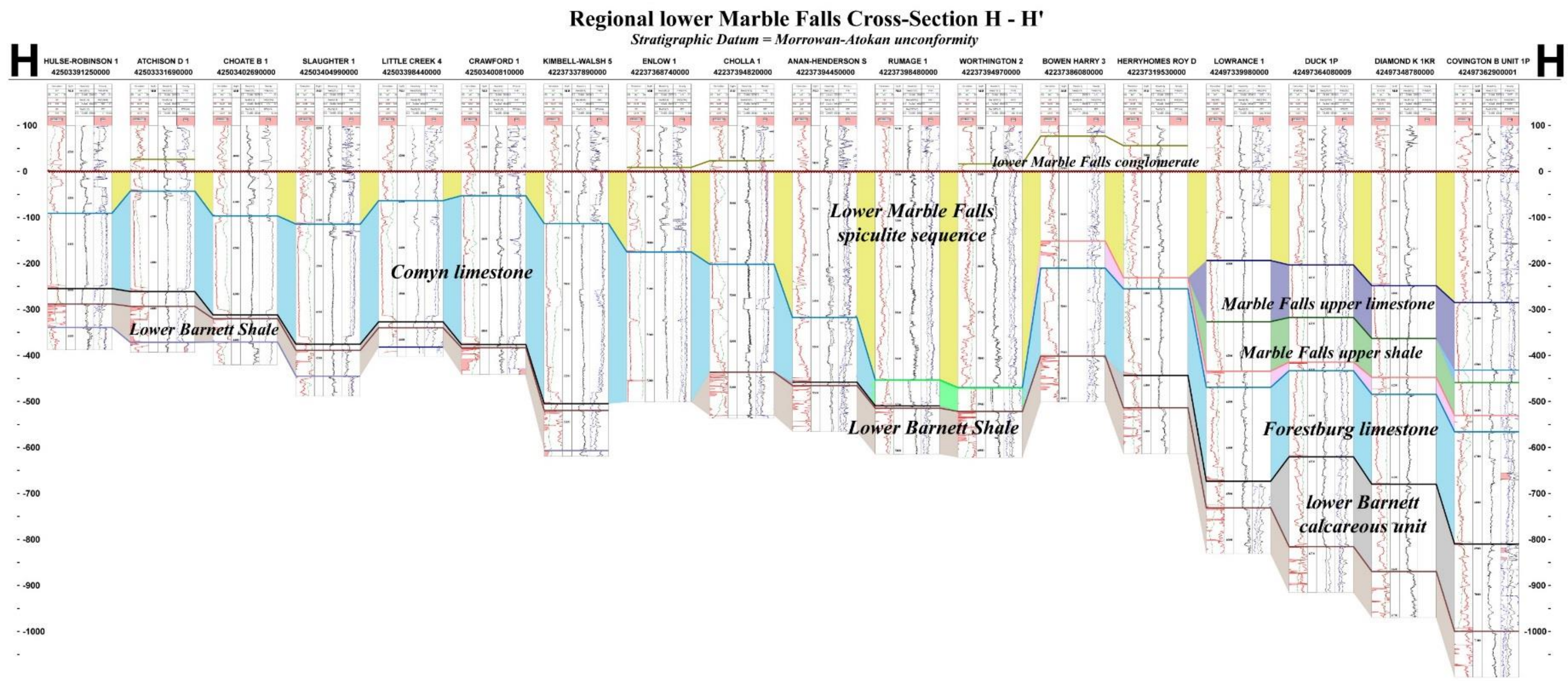



Plate 9. H – H' cross-section from southwestern Young County along the Bend to north-central Wise County along the northeastern part of the basin displaying the regional distribution of the lower Marble Falls spiculite sequence.

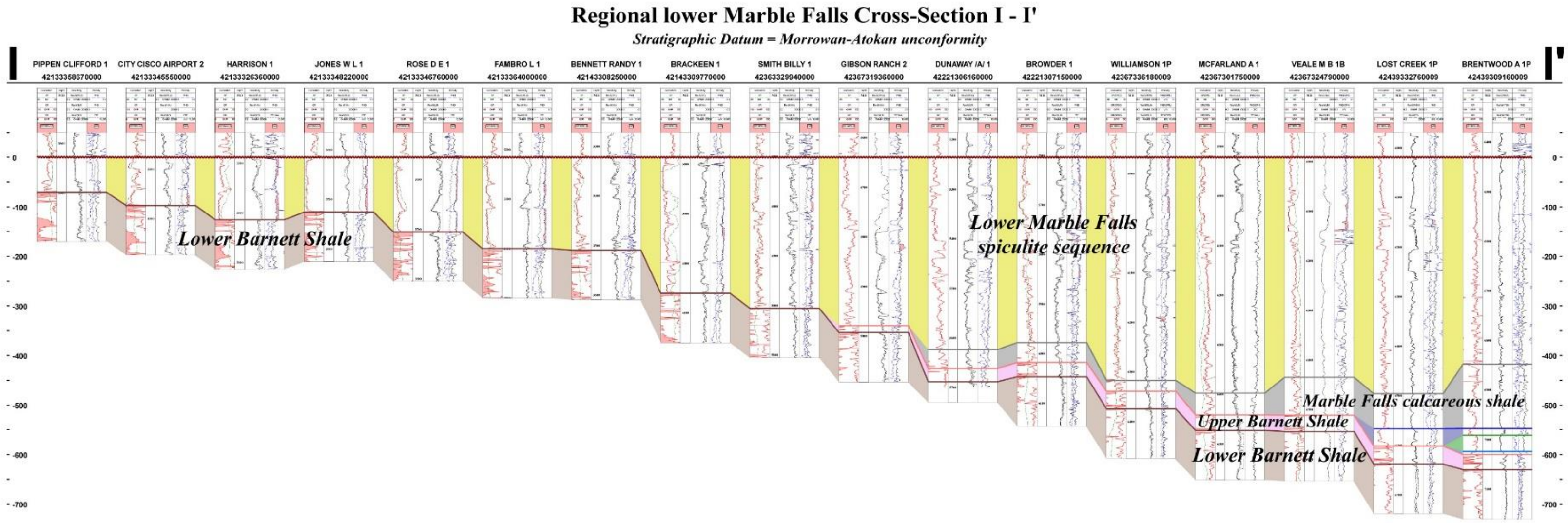



Plate 10. I – I’ cross-section from the western edge of Eastland County along the Bend Arch to central Tarrant County in the northeastern part of the basin displaying the regional distribution of the lower Marble Falls spiculite sequence across the Fort Worth Basin.

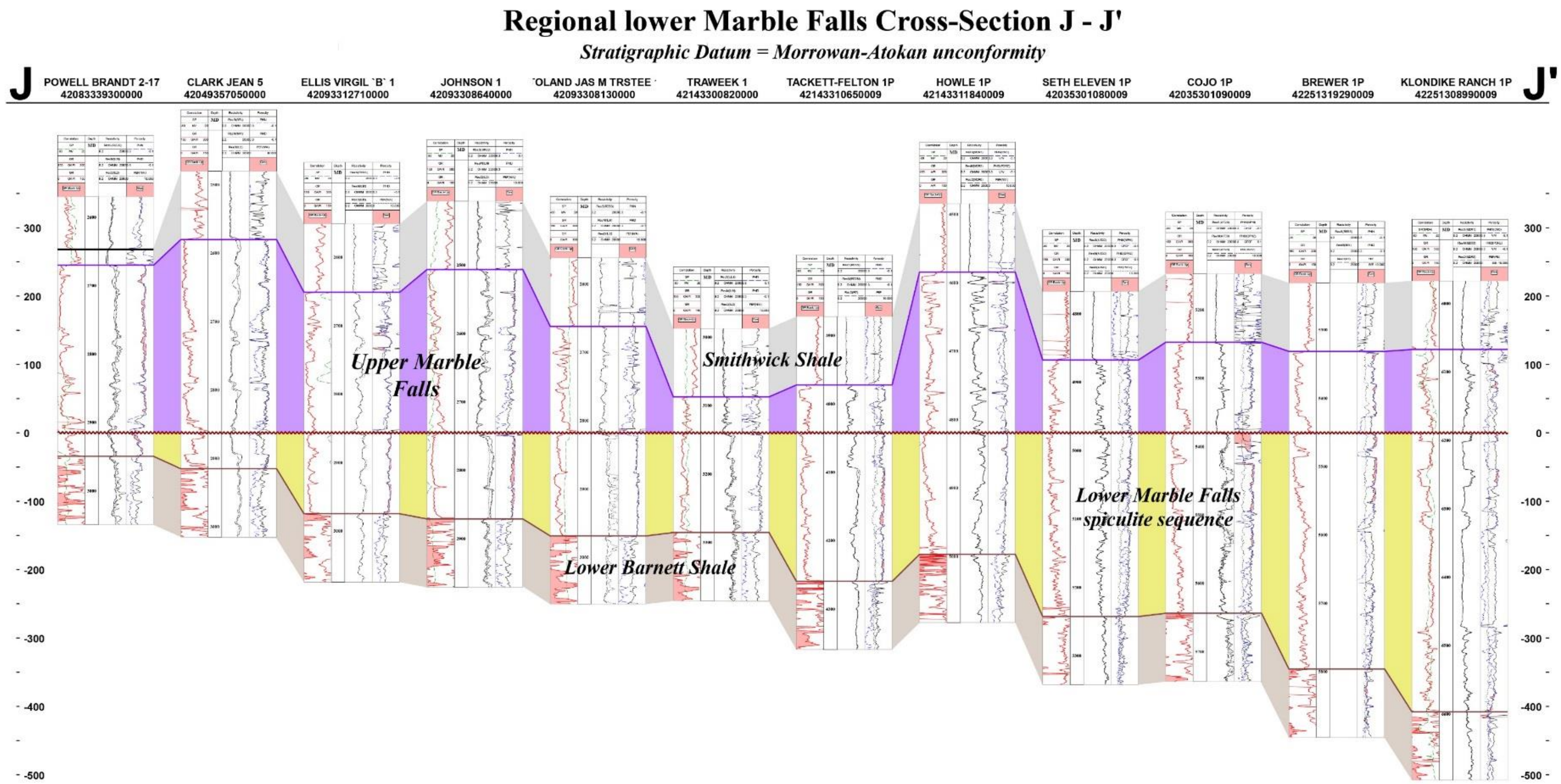



Plate 11. J – J' cross-section from eastern Coleman County along the western edge of the basin to southern Johnson County along the eastern edge of the basin displaying the regional distribution of the lower Marble Falls spiculite sequence across the Fort Worth Basin.

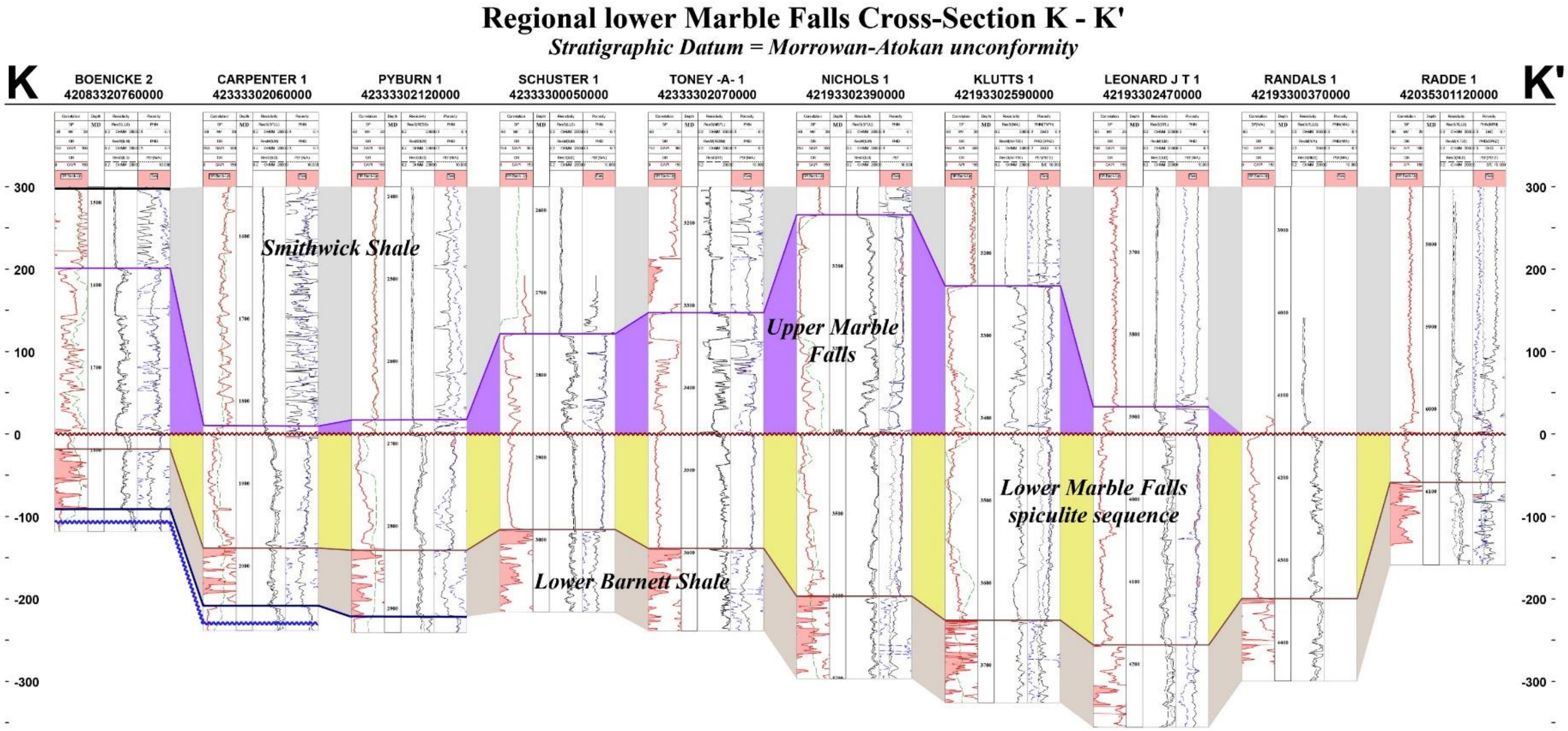



Plate 12. K – K' cross-section from southeastern Coleman County along the western edge of the basin to central Bosque County in the eastern part of the basin displaying the distribution of the lower Marble Falls spiculite sequence across the southern part of the Fort Worth Basin.

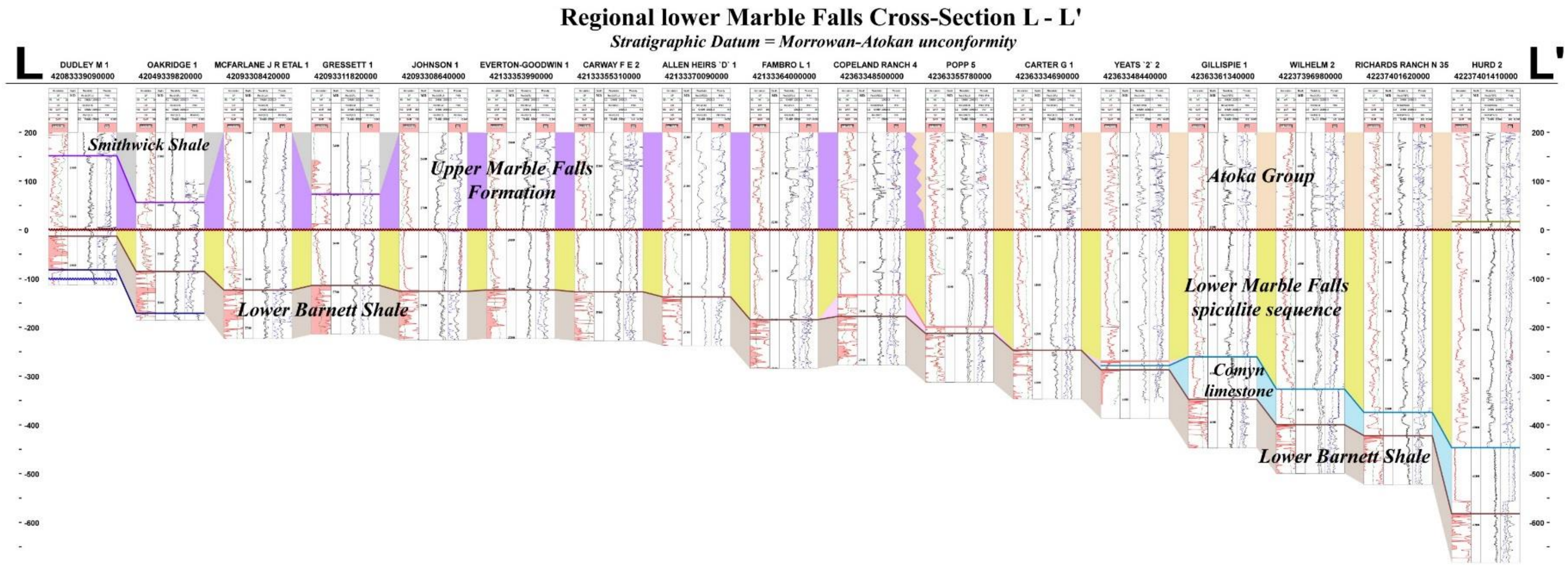



Plate 13. L – L' cross-section from southeast Coleman County to central Jack County displaying the regional distribution of the lower Marble Falls spiculite sequence across the Fort Worth Basin.

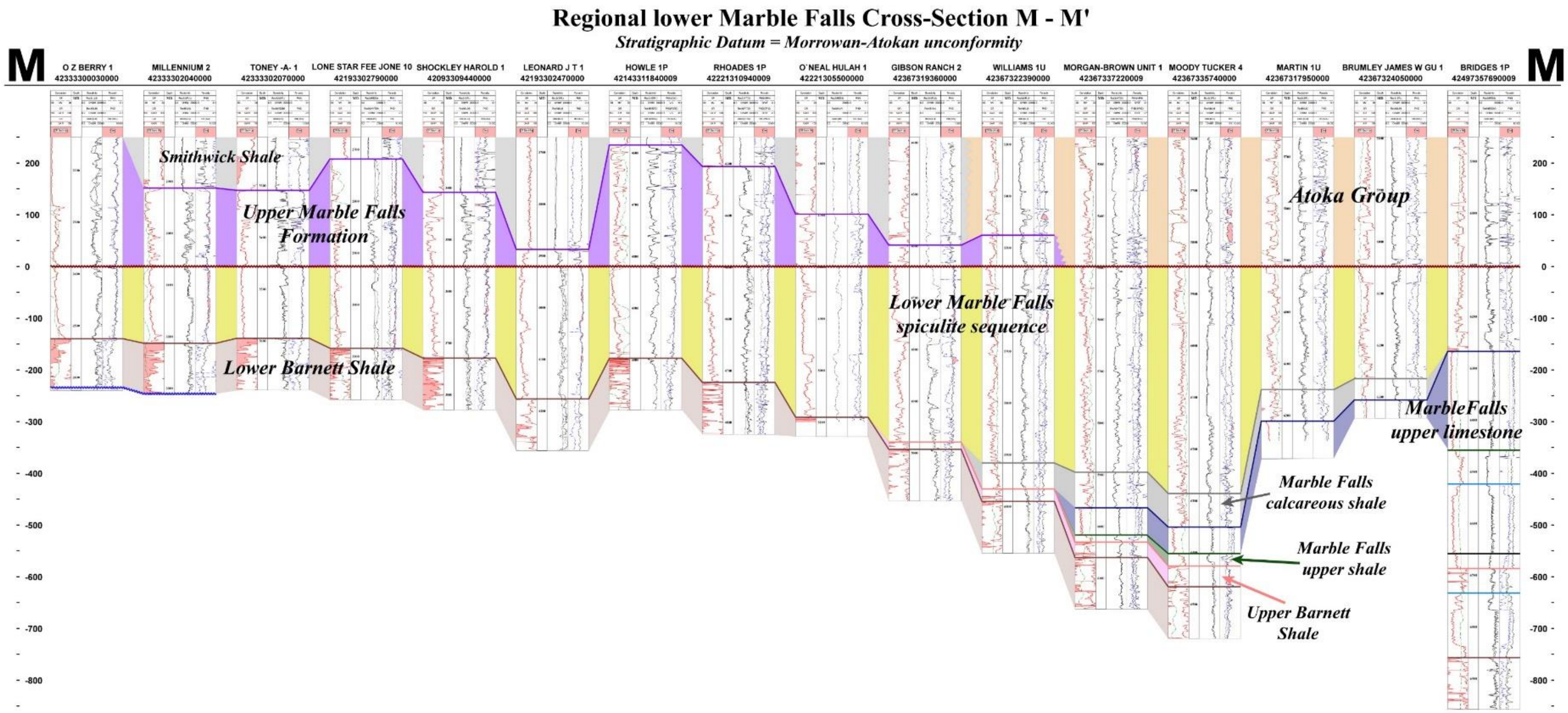



Plate 14. M – M' cross-section from southeastern Mills County to south-central Wise County displaying the regional distribution of the lower Marble Falls spiculite sequence across the Fort Worth Basin.

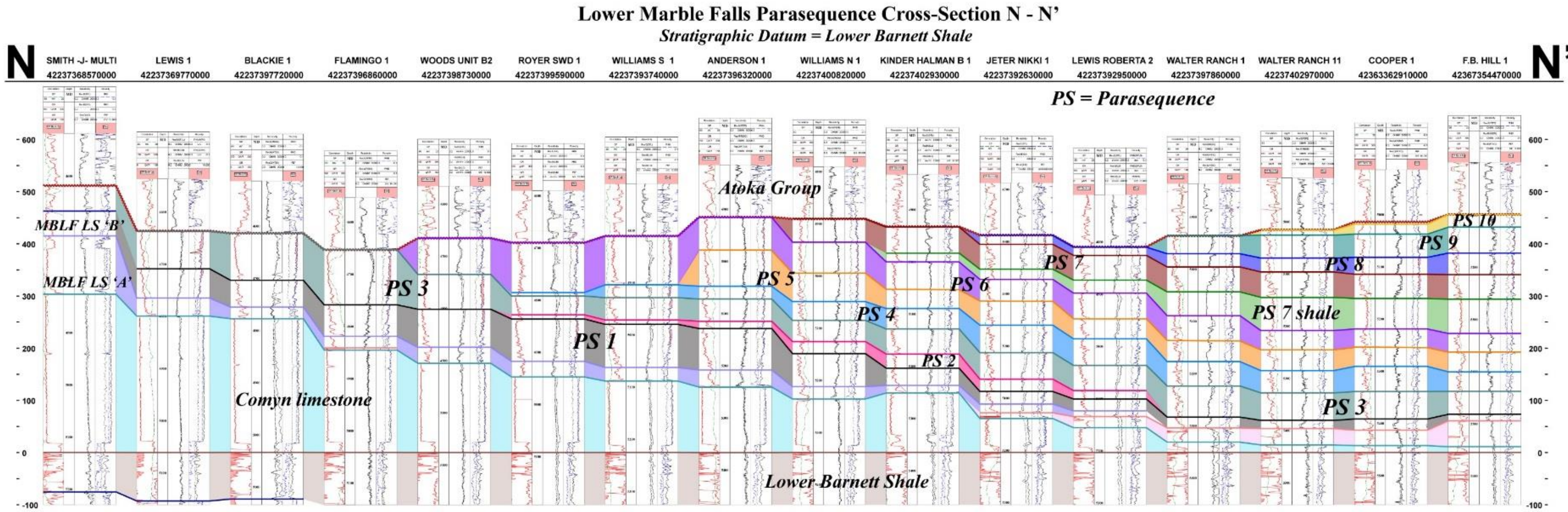





Plate 15. N – N' cross-section from the western side of Jack County to northeastern Palo Pinto County displaying the distribution of parasequences across the study area.

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## Biographical Information

Beau Berend was raised in the small town of Windthorst, TX where he spent most of his time playing sports, hunting, and enjoying the great outdoors with friends and family. He attended Tarleton State University in Stephenville, Texas where he received a Bachelor of Science in Geoscience in 2010. Berend then worked for a few years in the oil and gas industry and gained experience as a well-site geologist and mud logger before going back to school and pursuing a graduate degree. He was hired as a part-time geology intern for Newark E&P Operating while pursuing his Master of Science degree at The University of Texas at Arlington. Berend has been working as a full-time Operations Geologist for Newark E&P Operating since November of 2013 and has been a vital part of the technical team exploiting the Marble Falls Formation in North-Central Texas. He is particularly interested in sequence stratigraphy and the role dynamic depositional environments play in controlling reservoir quality. Over the last few years, Berend has gained an exceptional understanding of the Carboniferous stratigraphy of the Fort Worth Basin and plans to use this knowledge in his future career as a Petroleum Geologist.