THE SUBSURFACE DISTRIBUTION AND RESERVOIR PROPERTIES OF WIRELINE-LOG DEFINED DEPOSITIONAL CYCLES IN THE ATOKAN BEND GROUP

DENTON COUNTY,

FORT WORTH BASIN, TEXAS.

By

OLANIYI ADISA

Bachelor of Science in Geology

Oklahoma State University

Stillwater, Oklahoma

2008

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 2010

THE SUBSURFACE DISTRIBUTION AND RESERVOIR PROPERTIES OF WIRELINE-LOG DEFINED DEPOSITIONAL CYCLES IN THE ATOKAN BEND GROUP

DENTON COUNTY,

FORT WORTH BASIN, TEXAS.

Thesis Approved:

Darwin Boardman

Thesis Adviser

Anna Cruse

James Puckette

Gordon Emslie

Dean of the Graduate College

TABLE OF CONTENTS

LIST OF TABLES

Table

Page

LIST OF FIGURES

Figure

Page

CHAPTER 1

INTRODUCTION

Location

The Fort Worth Basin of North Central Texas (Figure 1) is a late Paleozoic foreland basin that was formed during the Early to Middle Pennsylvanian (Lahti, 1982). The basin is regarded as a mature basin in oil and gas exploration terms due to the discovery and exploration of hydrocarbons for over forty years in the Ellenburger limestone, Marble Falls limestone, Bend and Strawn conglomerates and recently in the Barnett Shale formation. The Fort Worth Basin generally trends north-south, is roughly 200 miles in length and deepens to the east (Pranter, 1989).

The study area, located in the north-east region of the Basin, is the area beneath the Muenster Arch in Denton County (Figure 2). Denton County is located in north central Texas and is within the Texas Railroad Commission District 9. The study covers an area that is located within several railroad surveys and is approximately 40 miles wide from east to west and roughly 28 miles wide from north to south.

The northern limit of the study is the Muenster Arch which represents a local source of terrigenous clastics during Atokan time (Thompson, 1982). The southern limit of the study corresponds to the boundary between Denton County and Tarrant County. The western limit is the Denton County – Wise County boundary and the Muenster Arch also serves as the eastern Boundary of the study.

The Bend Group sediments were deposited during the down warping of the basin in the early to middle Pennsylvanian by the westward progradation of terrigenous clastics sourced regionally from the Ouachita thrust belt and locally from the Muenster Arch. The Bend Group has a cumulative production history of over 160 million barrels (oil plus gas equivalent). Deposition of the Bend Group is very heterogeneous in nature and production and reservoir properties are facies controlled (Thompson, 1982).

The Bend Group is the primary reservoir of the prolific Boonsville gas field that is centered in Wise County and extends into parts of Jack, Parker and Denton Counties. Most of the oil and gas produced are from the fan-delta lobe facies of the Bend Group (Thompson, 1982). As a result of better completion techniques, increasing oil and gas prices and a realization that potential targets for exploration had been previously overlooked, there has been a recent surge by operators in the Boonsville field to recomplete previous wells, drill for new targets and exploit any by-passed pay potential in already drilled wells. Another reason for the renewed interest in the Bend Group is that it overlies the Mississippian Barnett Shale gas bearing formation of the Fort-Worth Basin and numerous gas shows have been noted in the Bend Group while drilling for the underlying Barnett Shale.

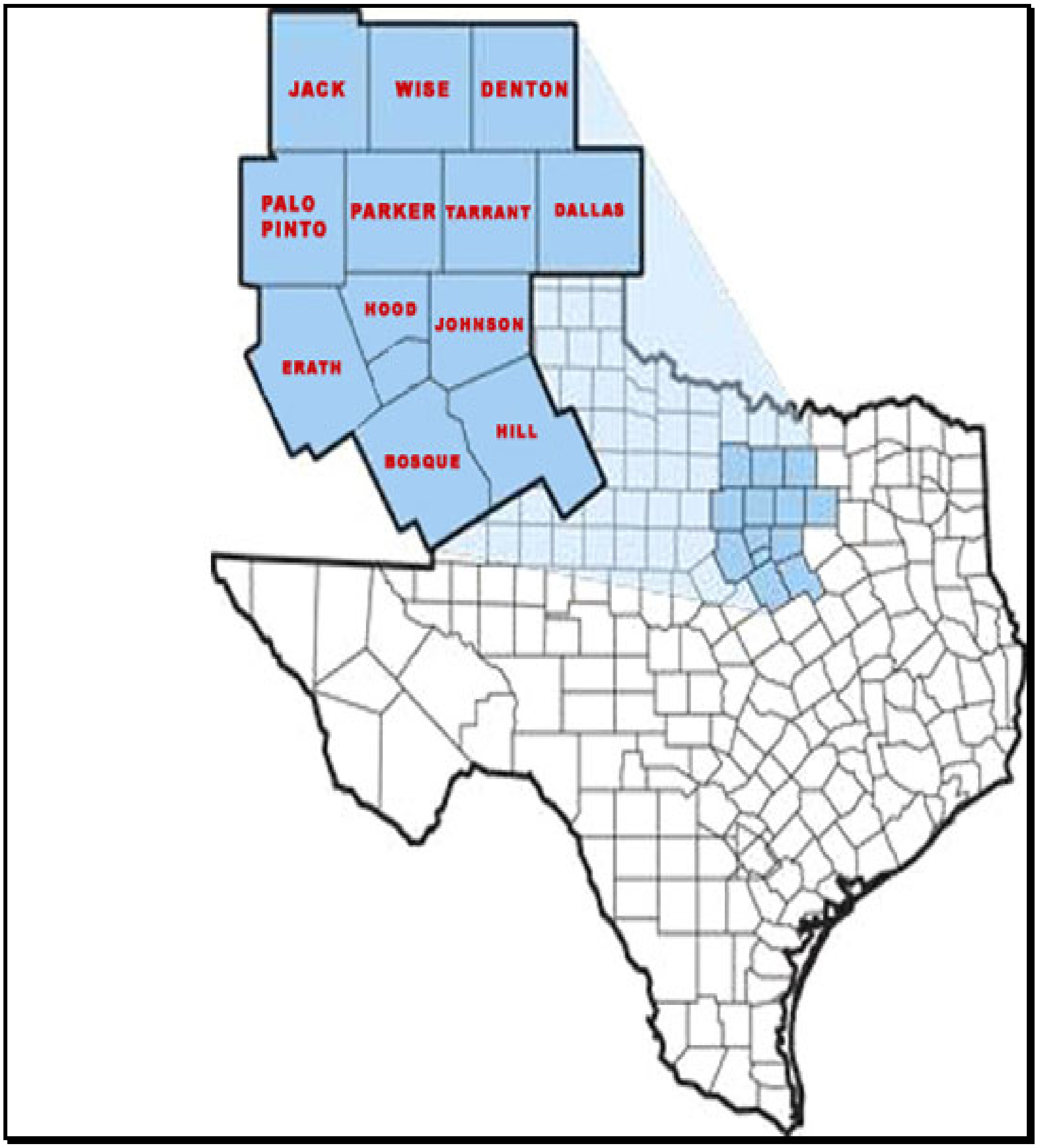

Figure 1: Map of Texas showing the location of the Fort Worth Basin.

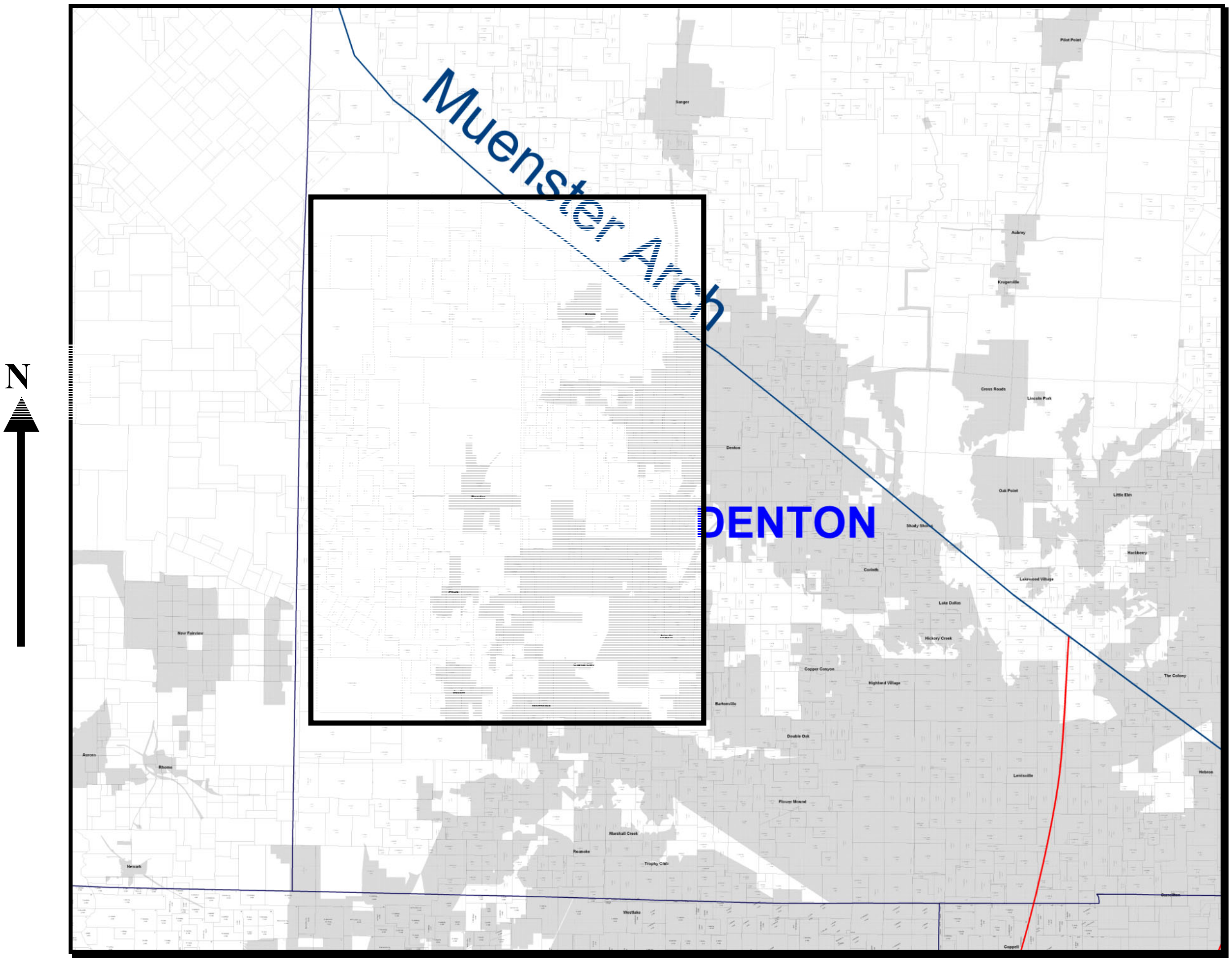

Figure 2: Map of Denton County showing the Muenster Arch and the study area (Area inside rectangle).

Objectives

The purpose of this study is to determine the various depositional cycles present in the Bend Group, interpret their depositional environments and facies relationships, map their distribution and better understand their reservoir properties. This information can help better understand the formation and distribution of facies within this fluvial dominated fan-delta, locate prime areas for oil and gas exploration and help identify previously overlooked targets because reservoir properties are facies controlled. The integration of wireline log analysis, core, thin-section microscopy, X-ray diffraction and scanning electron microprobe (SEM) analyses will aid in better understanding these cycles and their controls on reservoir properties like porosity and water saturation.

To determine the depositional and diagenetic processes that impact reservoir quality and hydrocarbon production from the Bend Group, the following objectives were laid out;

1) Perform a literature review of past studies on depositional environments, facies development and diagenetic processes of fluvial dominated deltas.
2) Establish depositional cycles within the Bend Group using core correlated well log attributes.
3) Construct cross sections and subsurface maps to illustrate structure, thickness, distribution and reservoir geometry of the different depositional cycles.
4) Perform petrophysical analysis on the various depositional cycles using well logs to determine porosity development and water saturation values for each elctrofacies.

5) Determine diagenetic and petrographic attributes of the Bend Group utilizing thin sections, SEM images, x-ray diffraction and well cuttings.
6) Perform detailed core analysis and develop a depositional model for the Bend Group in Denton County integrating core analysis with petrographic and petrophysical log analysis.

Methods

Various stages of investigations were carried out in order to meet the objectives that were set for this study.

- Firstly, a detailed literature search on the Fort-Worth Basin, the Bend Group and deltaic depositional environments was carried out.
- The second part of the investigation involved analyzing data on the subsurface obtained from wireline logs. The study area has a wealth of subsurface data including wireline logs and well-cuttings. Most Bend Group wells in Denton County were drilled on 40 acre spacing and wireline logs were run on them. Wireline logs were obtained from A2D technology with assistance from Chesapeake Energy. Well log analysis was performed on over 800 wireline logs to gather subsurface data on porosity development and water saturation. Several cross-sections were made with the aim of facies identification, correlation, distribution, structural attitude of strata and depositional model building.

- Subsurface structure and isopach maps were then constructed for the entire gross interval and also for each depositional cycle. This was done to determine the structural setting of the study area and interpret the depositional trend, reservoir geometry, and source direction.
- Core Analysis then followed. No core that penetrated the Bend Group in Denton County was available; however a core was obtained through the Bend Group in Parker County from the Bureau of Economic Geology (BEG) in Austin, Texas. The core is from the Bird #3 well, drilled by Stallworth Oil and Gas Company in Parker County. A cross section of the Bend Group was made from Denton to Parker County in order to correctly identify the Bend Group in Parker County based on wireline log correlation (Figure 3). The Bend Group and identified depositional cycles were observed in core and studied for sedimentary structure that helped build a depositional model.
- Cuttings from two wells in Denton County were obtained from the Bureau of Economic Geology (BEG) in Austin, Texas (Figure 4). The cuttings are from the Carter A.G, Allen #1 well and the Hall-Glasco, Carrol #1 well. Analyses performed on these cuttings included;

- (XRD) X-ray diffraction was carried out at the Chesapeake Reservoir Technology Center (RTC) in order to determine detrital mineralogy and authigenic constituents.
- (SEM) Scanning electron microscopy to determine mineralogy and reservoir properties like porosity and permeability.

- Petrologic well cutting and thin section analysis to examine reservoir properties, rock fabric, rock texture (grain size, sorting, rounding) and general composition.

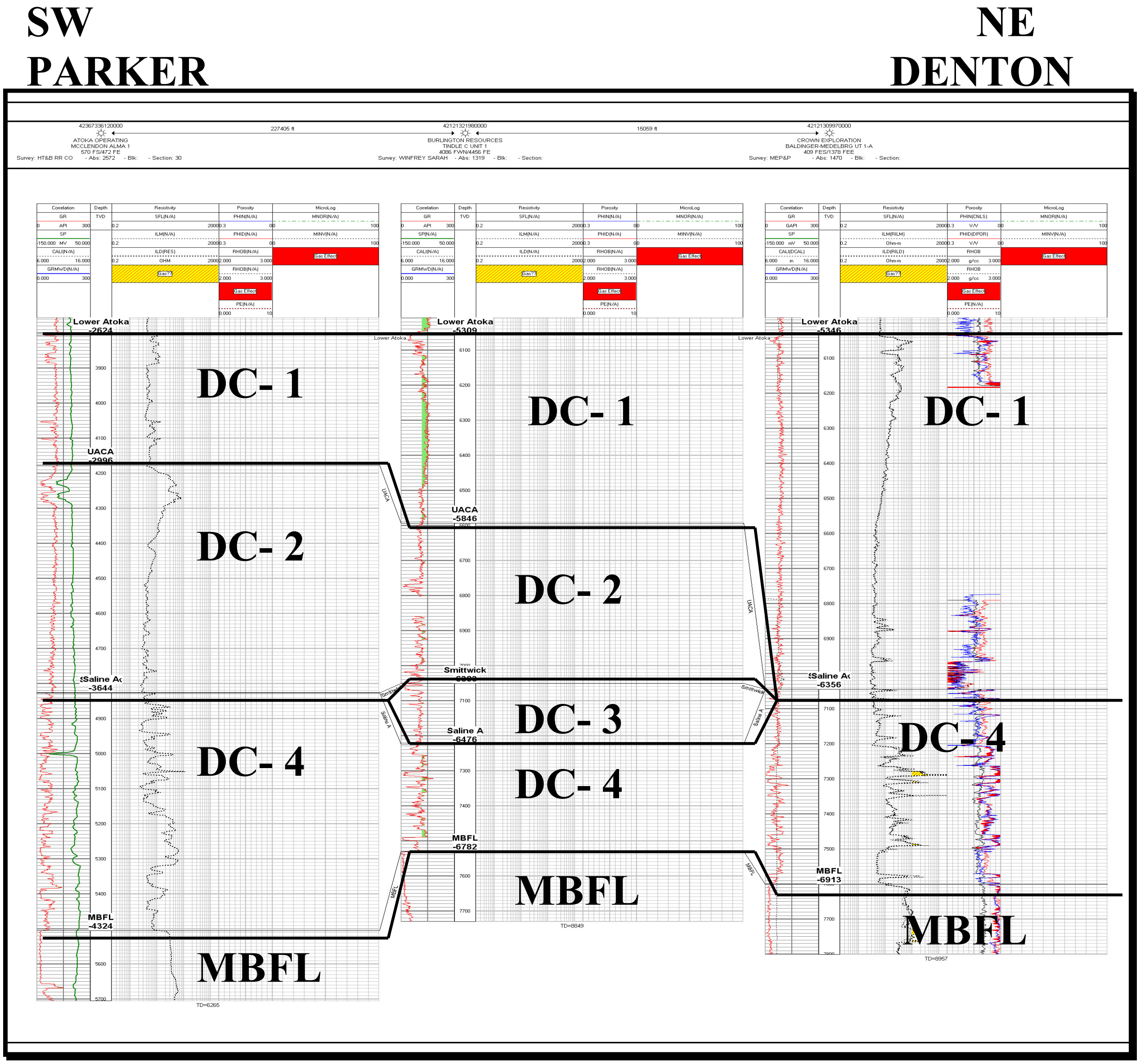

Figure 3: Cross-section illustrating stratigraphic relationships of the different depositional cycles from Parker County to Denton County. Datum is the top of the Bend Group. The different depositional cycles (DC1-4) identified here will be explained in subsequent chapters.

Figure 4: Map of study area showing the locations of well cuttings used in the study. Blue triangles indicate all the wireline logs used in the study. Red star indicates the location of the Allen #1 well while the yellow star indicates the location of the Carrol #1 well.

Previous Works

Several studies have been completed on the Fort Worth Basin and its stratigraphy and structure, with most of the studies focusing on the Mississippian Barnett shale (Pollastro, 2003). However, very few studies have focused primarily on the facies relationships within the terrigenous Bend Group sediments of Early- Middle

Pennsylvanian time and absolutely no work has been done to identify, characterize and map these facies in Denton County.

Lovick (1982) studied the sedimentary evolution of the Fort Worth Basin by analyzing the tectonic movements within the basin and identified several depositional environments and distribution patterns of the clastic sediments that make up the entire Bend interval. The identified environments were deltaic, fan-delta and marine.

Glover (1982) performed a study on the bend conglomerate, which is one of the informal names given to the Bend Group, in Jack Co. Texas. Several individual sand lenses within the Bend conglomerate interval were identified and mapped in this study. He determined that the individual sand lenses are difficult to correlate regionally and that the entire Bend conglomerate interval is an excellent producer with good porosity and poor permeability.

Lahti (1982) performed a study of the entire Bend Group of the Boonsville field area which includes the whole of Jack, Wise, Palo Pinto, Parker and Tarrant Counties. Parts of Montague, Cook, Denton, Johnson and Hood counties were also included in his work. Like most studies that have been performed on the Bend Group in this area, his work focused on the hydrocarbon producing formations and discusses the history and production of the field.

The most thorough paper that I have encountered on the Bend Group in the Fort Worth Basin is by Thompson (1982). She identified and analyzed several facies within the Bend Group and studied structural and stratigraphic controls on facies deposition. She also performed detailed petrophysical analysis on the facies identified in order to determine reservoir properties. Her work was more of a regional study that included the entire basin, and while Bend deposition is heterogeneous thereby making concise facies relationships hard to correlate over a wide area; her work does provide a general framework for facies analysis and depositional environment in the Early-Middle Pennsylvanian time in the Fort Worth Basin. She concluded that reservoir properties are facies controlled, the Bend Group has poor permeability and moderate to good porosity and deposition is heterogeneous.

Other studies concerned with the study of the Bend Group in the Fort Worth basin and fluvial deltaic deposition environments include Blanchard (1959) who studied the Natural gas production in the Atokan formations of the Fort Worth basin, Dutton (1980) who studied the depositional systems and hydrocarbon resource potential of the Pennsylvanian system in Palo Duro and Dalhart basins, Fisher (1969) who studied how deltaic systems can be explored in search of hydrocarbons, Solis (1972) who studied the subsurface geology of the central part of the Ft. Worth basin, Bates (1953) whose paper on delta formation is an invaluable asset when evaluating deltaic systems and Coleman (1976) who studied facies relationships within a delta.

CHAPTER II

GEOLOGIC SETTING

Regional stratigraphy

The sedimentary sequence in the Fort Worth Basin is represented by a wide variety of lithologic units ranging in age from Cambrian through Cretaceous (Figure 5). The early Paleozoic section of the Fort Worth Basin is mostly carbonates, while the middle to late Paleozoic sections are primarily clastics or mixed sequences of carbonate and clastic rocks.

The depositional record in the Fort Worth basin begins in the Cambrian with the transgressive sandstones and granite wash of the Riley and Hickory Formations that lies conformably on the Precambrian. These clastics are replaced by the carbonate rich Wilberns Formation higher in the section (Barnes, 1946). The shelf limestones and dolomites of the Wilberns Formation interfinger with the overlying Ordovician age Ellenburger Group and it is a difficult task to separate the Wilberns Formation from the Ellenburger Group (Turner, 1957). However, when insoluble residue studies are performed in the Ellenburger there is a significant decrease in the amount of silty, argillaceous material in the Ellenburger compared to the Wilberns Formation (Cole, 1942). Another way to differentiate the Wilberns from the Ellenburger is that the Wilberns is extremely richer in Glauconitic material than the Ellenburger (Turner, 1957).

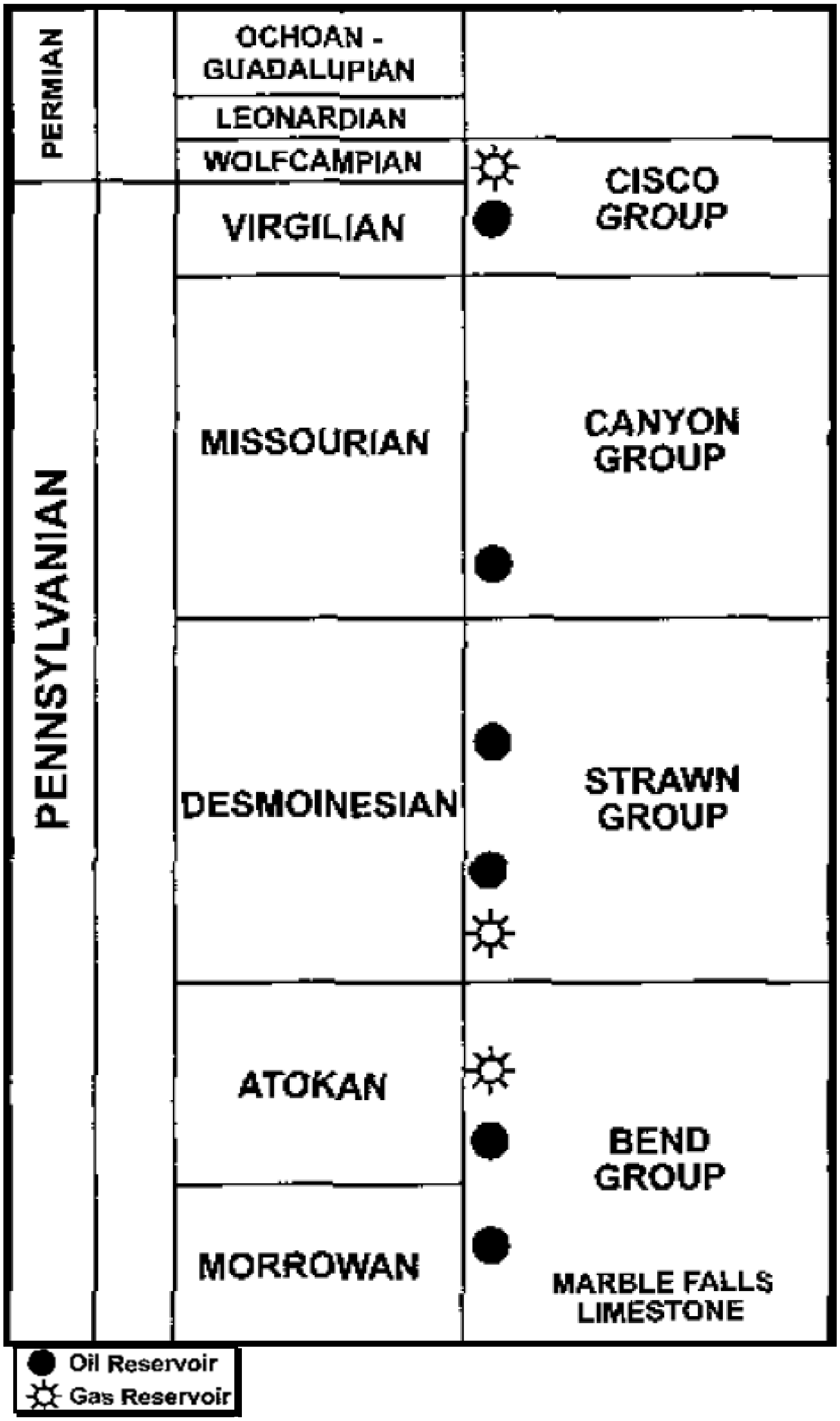

Figure 5: Subsurface stratigraphic column of Pennsylvanian and Permian strata, Fort Worth basin (Pollastro et al, 2003)

Upwarping of the Bend Arch during the Mid-Ordovician to the Lower Pennsylvanian resulted in a number of significant erosional unconformities in the Ellenburger (Cloud, 1942). The erosional surface of the Ellenburger has been studied extensively in outcrops and has been described as 'karstic'(Herkommer, 1982).The Ives member of the Ellenburger Group carries Early Mississippian fauna and is found in solution features and local synclinal areas (Herkommer, 1982). The Ordovician-Mississippian unconformity is easily recognizable in outcrops and cores due to significant lithologic differences between the two systems. At the unconformity, the Barnett Shale Formation is the basal unit of the Mississippian System. Barnett Shale is petroleum - yielding brown to black shale facies with some thin interbedded limestone and sandstone facies while the Viola limestone or the Ellenburger represents the top of the Ordovician and these are mostly limestone facies (Pollastro, 2003). The unconformity is also noticeable in the subsurface in wireline logs. The subsurface signature of the Barnett is an extremely high resistivity value, positive spontaneous potential (SP) value and a gamma ray reading that goes off scale while the Ellenburger has a low gamma ray signature and moderate SP and resistivity values.

The top of the Mississippian is usually recognized as the top of the Barnett Shale when the overlying slightly dolomitic, cherty and even textured Comyn Limestone is not present (Gee, 1976). In stratigraphic terms the Comyn is the same as the lower Marble Falls Limestone, and is usually darker colored then the upper Marble Falls Limestone. The upper Mable Falls Limestone, which represents the base of the Pennsylvanian, is Morrowan in age and consists of a siliceous gray limestone that contains glauconites near the Mississippian-Pennsylvanian boundary (Herkommer, 1982). The presence of glauconites in the Marble Falls can be used to differentiate the Marble Falls Formation from the underlying Comyn Formation.

Overlying the Marble Falls Limestone are Atokan age rocks of the Bend Group. The Bend Group strata of the Pennsylvanian system are informally called various names in the petroleum industry (Pranter, 1989). Some of these names include the Big Saline Conglomerate, Bend Conglomerate and Atoka Conglomerate. The Bend Group/Atokan age rocks are usually rich in glauconite and contain conglomerates which are typically arkosic in nature and this suggests a granitic source (Steward 1977). The Bend Group rocks are predominantly clastics with some interbedded limestone facies.

Within the middle Pennsylvanian series, the Desmoinesian age rocks of the Strawn Group overlie the Atokan rocks of the Bend Group. Lithologically, the Strawn Group consists of a gray shale to siltstone that contains pyrite and thin limestone and sandstone beds (Herkommer, 1982). The sandstone beds are informally referred to as Caddo "conglomerates" in the oil industry because the sandstones are generally fine to medium grained and bear some physical similarities with the older Bend Group (Lovick, 1982).

Structural Setting

Several factors contributed to the deposition of the Bend Group sediments in North-Central Texas and the Fort-Worth Basin as a whole. Sedimentation was greatly influenced by the structural development of the basin and Atokan deposition was contemporaneous with tectonic activity (Lahti, 1982).

The Fort-Worth Basin is an asymmetrical foreland basin that formed in response to the collision of the North American and proto-South American plates during early Pennsylvanian time (Dickinson 1978; Fischer 1976; Lovick, 1982). The Fort Worth Basin is bounded on the north by the Muenster Arch and the Red River arch, to the south by Llano uplift, on the west by Bend Arch and to the east by Ouachita structural belt (figure 6). The Fort-Worth Basin is about 200 miles in length and roughly 120 miles wide (Pranter, 1989). The Paleozoic s in the basin include Cambrian, Ordovician, Mississippian, Pennsylvanian and Permian age rocks with a maximum thickness of about 12,000 feet (Turner, 1957). The basin is a foreland basin to the Ouachita structural belt and the deepest part of the basin was near the Ouachita structural belt in western Dallas and southeastern Denton Counties (Flawn et al., 1961).

During the early Paleozoic, the Fort-Worth basin filled a broad shoreline indentation on the western edge of the Ouachita structural belt (Crosby, 1975), but became well defined in the Late Mississippian and Early to Middle Pennsylvanian as the basin subsided along the western margin of the Ouachita structural belt to form a foreland basin. Based on structural and paleogeological maps, the subsidence was more rapid during the Morrowan and Atokan time and reduced greatly during the Demoinesian and Missourian time (Lahti, 1982).

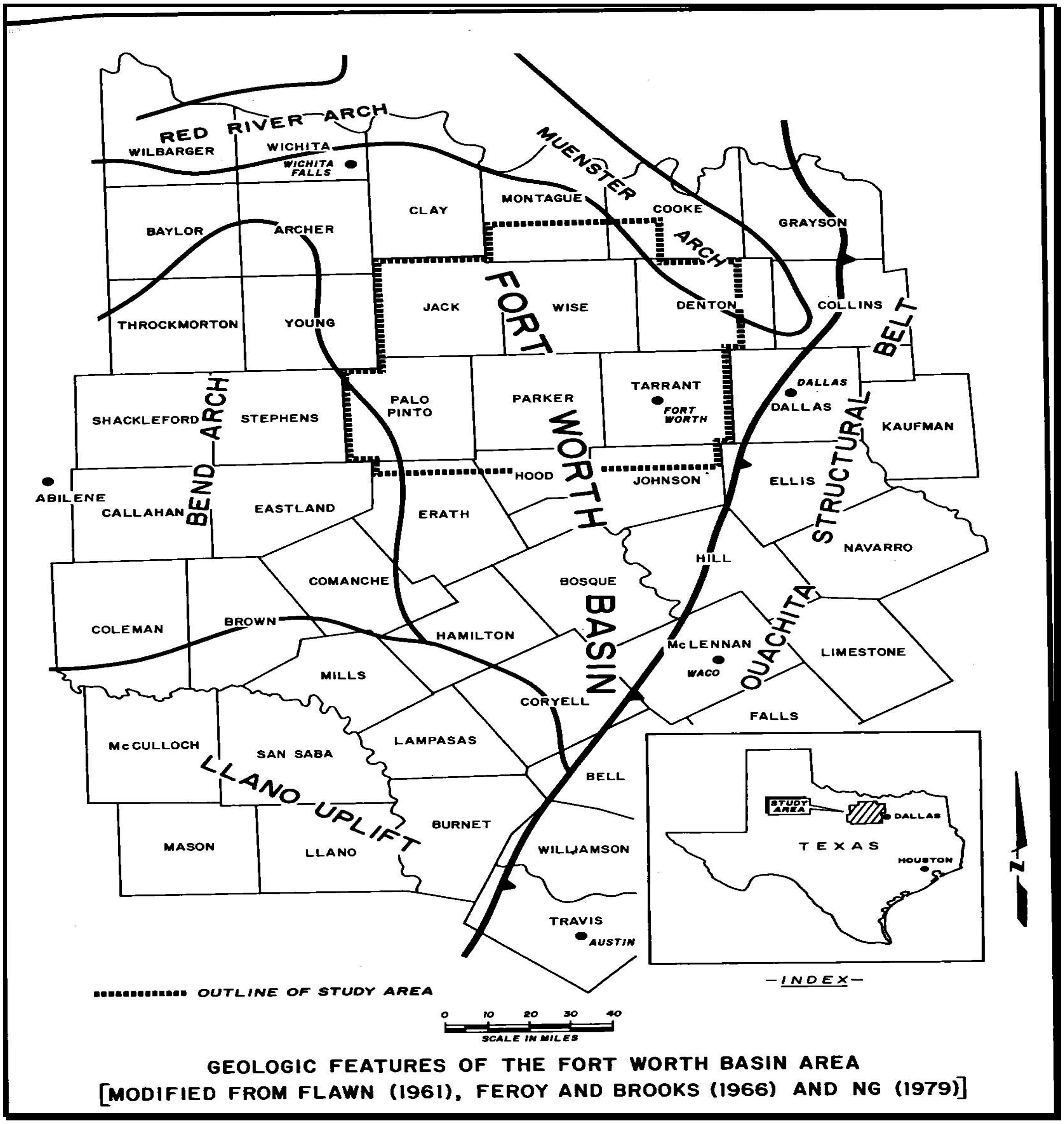

Figure 6: Geologic setting of the Fort Worth Basin (Lahti, 1982)

Within the Ouachita structural belt, Cambrian to middle Pennsylvanian sediments are preserved and tectonic activity accompanied by erosion of Ouachita chert and sandstone units during the Early to Middle Pennsylvanian time sourced the majority of the terrigenous sediments that filled the basin (Pranter 1989; Cleaves 1975).

The Muenster Arch is a northwest-southeast trending uplift of Pennsylvanian age that is fault bounded and now covered by sediments that were deposited after uplift occurred; hence it has not observable on surface. It is considered to have been range-like at the time of uplift and is a part of the Wichita mountain system (Eardley, 1962). The Fort-Worth basin and the Muenster Arch form one of the paired basins and uplifts that developed in the South Oklahoma-North Texas region due to the compressional stresses that occurred during the convergence of the North-American and proto- South American plates in Pennsylvanian time (Walper, 1977). These compressional stresses reactivated the boundary faults of the Southern Oklahoma aulacogen. The Muenster Arch uplift began in Late Mississippian and Morrowan (Early Pennsylvanian) time and occurred until Demoinesian (Middle Pennsylvanian). During this period the arch acted as a source area for the basin by shedding clastics. However, by Late Pennsylvanian time the uplift had ended and the arch was no longer active as a source area and Pennsylvanian aged deposits had already covered up the arch. Major clastic deposition from the Muenster arch occurred in Early Atokan and Early Demoinesian (Strawn) time (Flawn et al., 1961).

The Red River Arch is also a part of the Wichita mountain system and shares similar structural features with the Muenster Arch (Eardley 1962); it is also fault bounded and is an east-west trending uplift that occurred during the Pennsylvanian. The Red River Arch is considered to be a secondary source for the Atokan age clastics of the Fort-Worth Basin (Lahti, 1982).

Together, the Muenster Arch and the Red River Arch constitute a discontinued set of parallel fault blocks that appear to have been controlled by zones of weakness in the Precambrian that were reactivated during the Ouachita orogeny (Pranter, 1989). The Ouachita Structural Belt and the Wichita mountain system, especially the Muenster Arch, were the major source areas for the terrigenous Early to Middle Atoka (Bend Group) sediments in the Fort-Worth Basin.

The Llano uplift acts as the basin boundary to the south and was active during the Early to Middle Pennsylvanian time in response to the tectonic activity in the Ouachita Structural Belt; however the uplift is not considered to be a substantial source of clastics in the Fort-Worth basin (Wermund, 1975).

The Bend Arch is an expansive north trending arch that acted as the western shelf of the basin during Early Pennsylvanian time but was tilted westward during Late Pennsylvanian time to form the eastern shelf of the Midland basin due to the filling of the Fort-Worth basin (Eardley, 1962). The Bend Arch was not a source area during the Pennsylvanian because at this time it was either a carbonate shelf or a low relief area (Lahti, 1982).

Local Stratigraphy, Nomenclature and Structure

The Bend Group is a distinct subsurface rock in Denton County as in the whole of Fort-Worth Basin of north-central Texas. The Bend Group corresponds to the Big Saline Formation and is also called a host of informal names in the oil industry, some of which are- Bend conglomerates, Atoka conglomerates and Big Saline conglomerates. The Bend Group interval is that from the base of the Strawn Group to the top of the Marble Falls Limestone (figure 8). The Marble Falls top is identified on wireline logs as the first thick limestone below the Bend Group.

For the purposes of this study, the Bend Group is subdivided into four depositional cycles or packages each of which is believed to represent a pulse in the uplift of the Ouachita Structural Belt and a change in relative sea level. The depositional cycles are easily recognized in wireline logs and can be correlated with well cuttings and cores. Beginning at the base of the Bend Group, which also coincides with the top of the Marble Falls Formation, and moving up section the depositional cycles were identified as DC- 4 through 1(Figure 7). Typically, in any given well in the study area, two or more of the identified depositional cycles are identified with DC-1 and DC-4 present in every well.

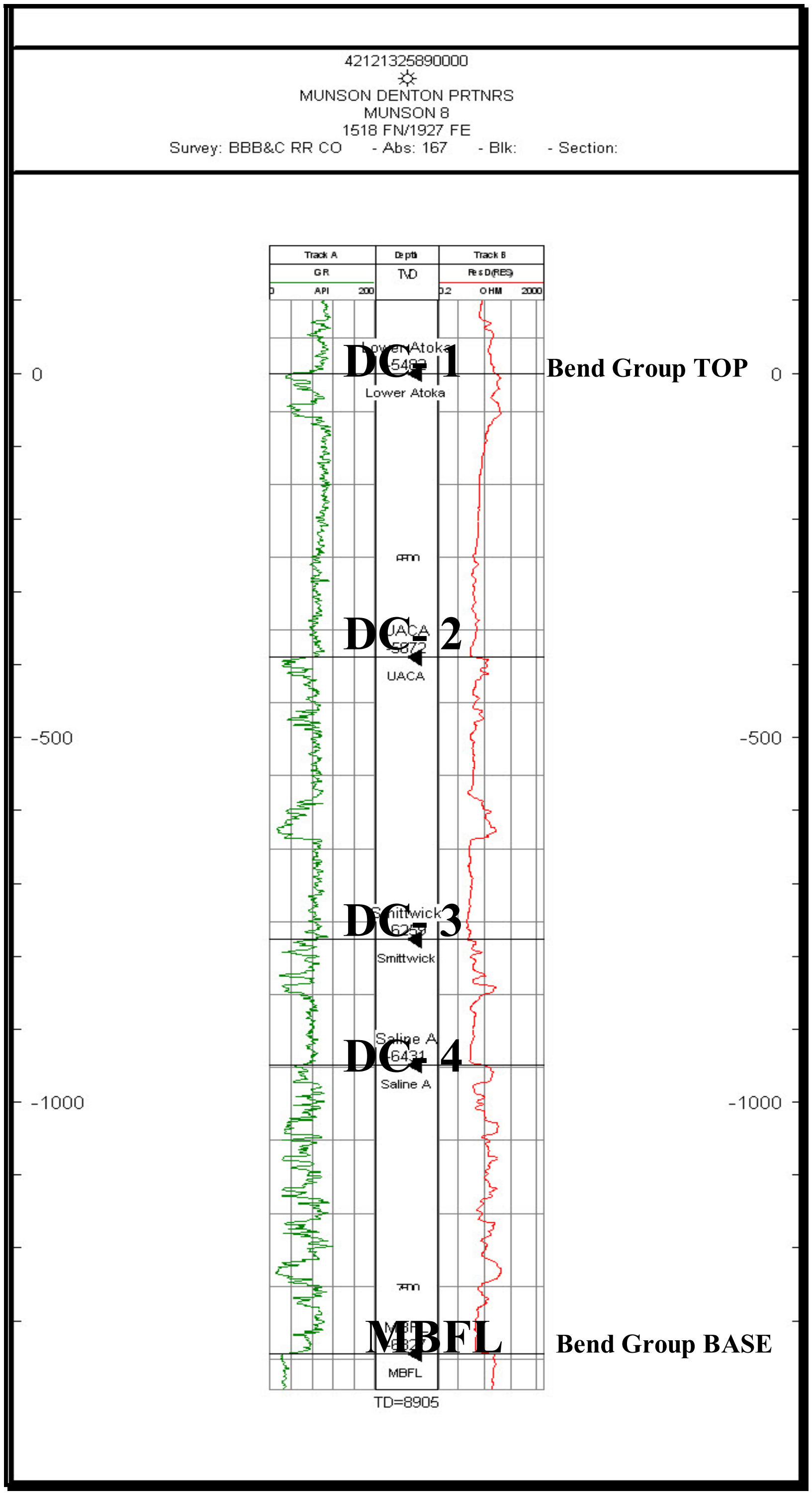

Figure 7: Type log illustrating the top of the Bend Group in Denton County with the associated depositional cycles identified in this study. The base of the Bend Group coincides with the top of the Marble Falls Formation (MBFL).

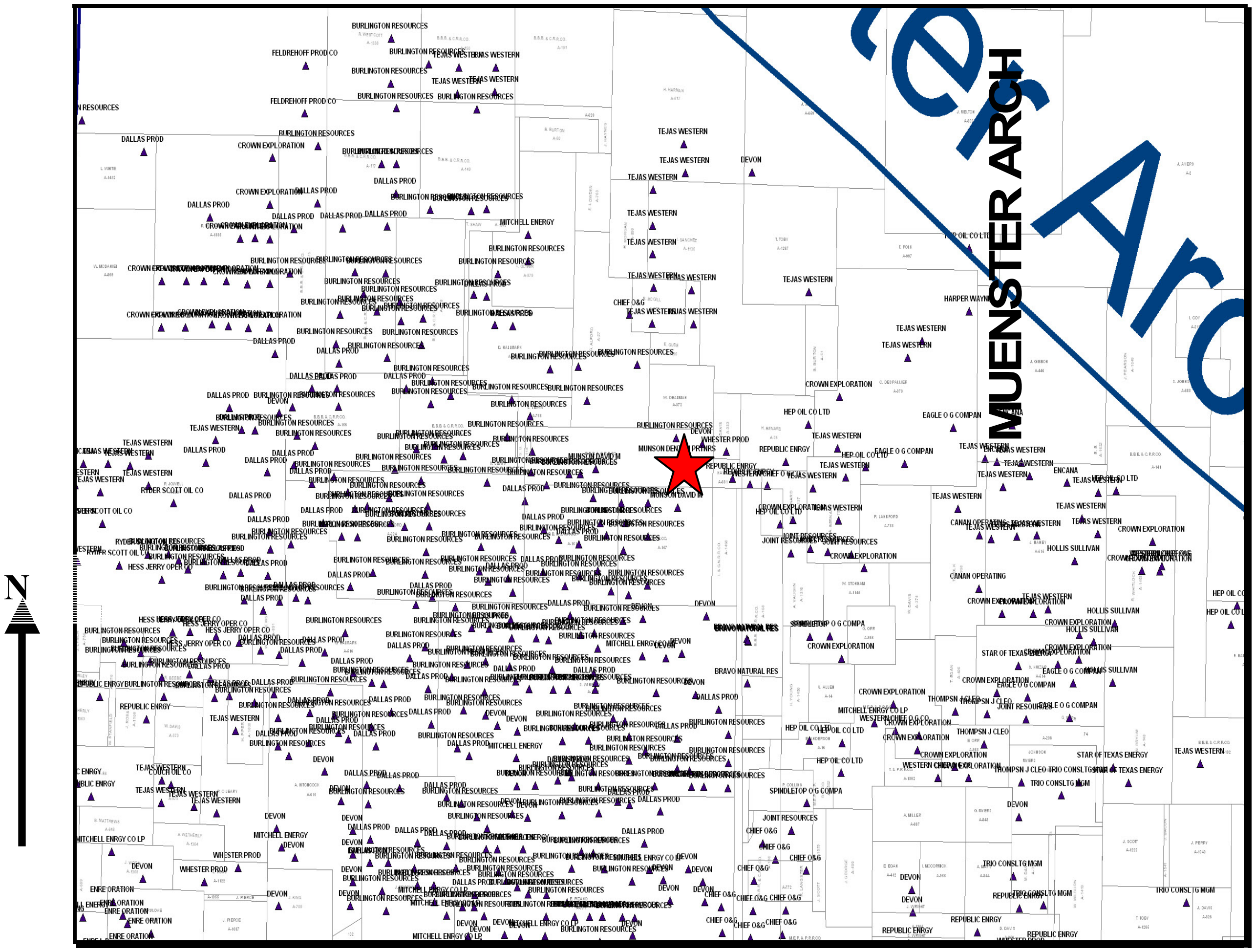

Figure 8: Base map of study area illustrating the location of the type log. Blue triangles indicate all the wireline logs used in the study.

The Bend Group is thickest adjacent to the Muenster Arch (Figure 9). An unconformity was observed in wireline logs, that occurs in the east-south east part of the study area adjacent to the Muenster Arch. Due to this unconformity, the DC-2 and DC-3 cycles are absent and the DC-1 package directly onlaps into the DC-4 package (Figure 10). Around this observed unconformity, the DC-1 and DC-4 cycles thicken considerably and account for most of the Bend Group thickening adjacent to the Muenster Arch. This thickening adjacent to the Muenster Arch and southward towards the Ouachita Structural

Belt in Early Pennsylvanian time coupled with the rapid decrease in depth of the underlying Marble Falls Formation close to the arch, also in Early Pennsylvanian time (Figure 12), indicates that the Muenster Arch and the Ouachita Structural Belt were active during Bend Group deposition and were sources of clastics in the study area.

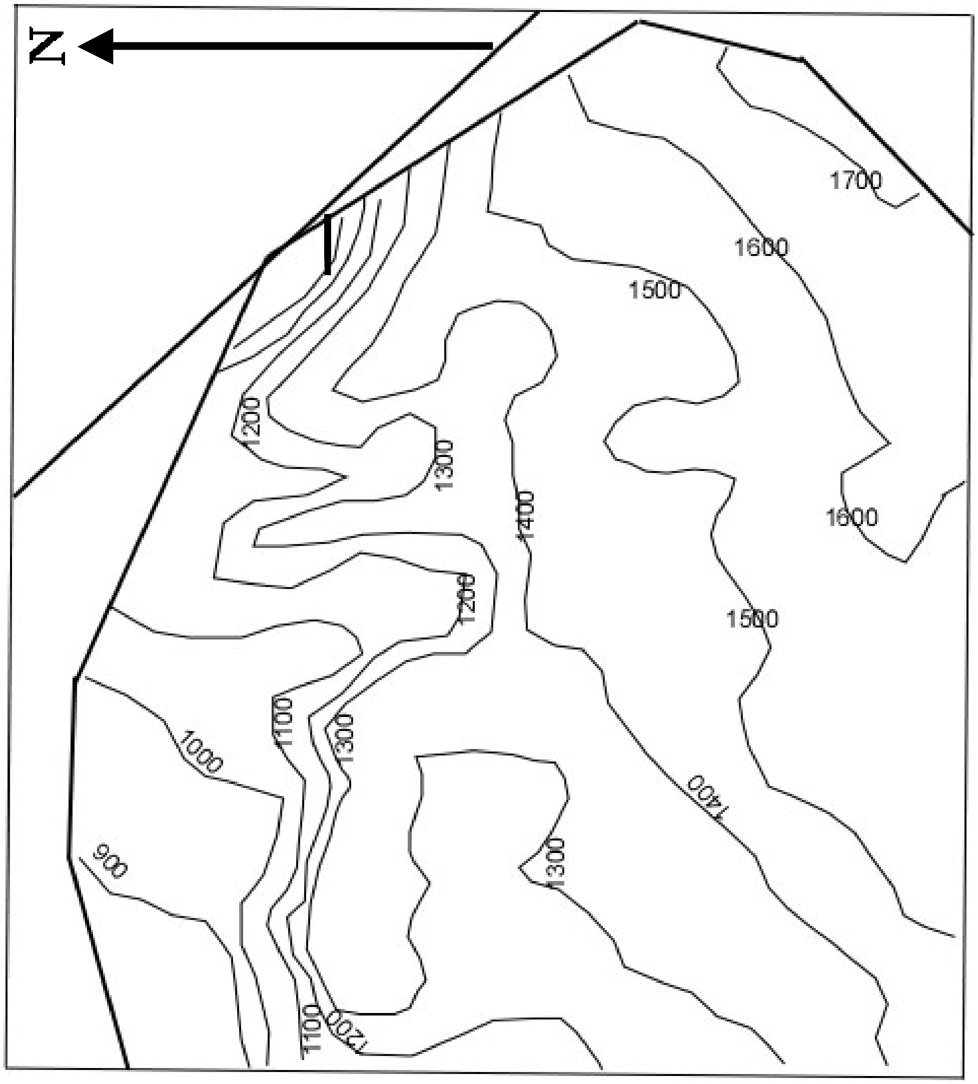

Figure 9: Gross Isopach map of the Bend Group in Denton County Texas.

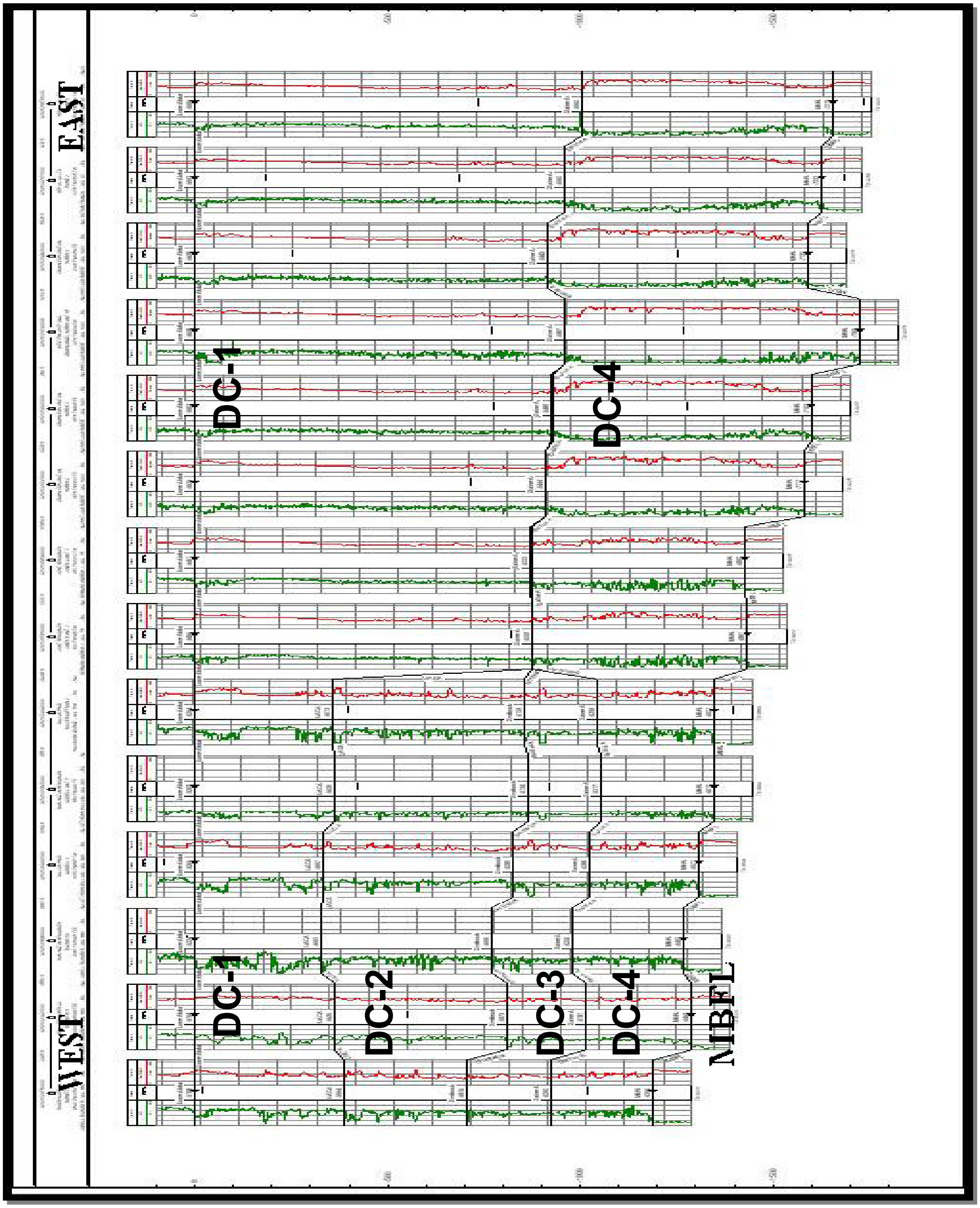

Figure 10: Stratigraphic cross-section illustrating the stratigraphic relationships between the different depositional cycles in study area. Datum is the top of the Bend Group (DC-1).

Figure 11: Map showing the index line for cross section shown in Figure 10.

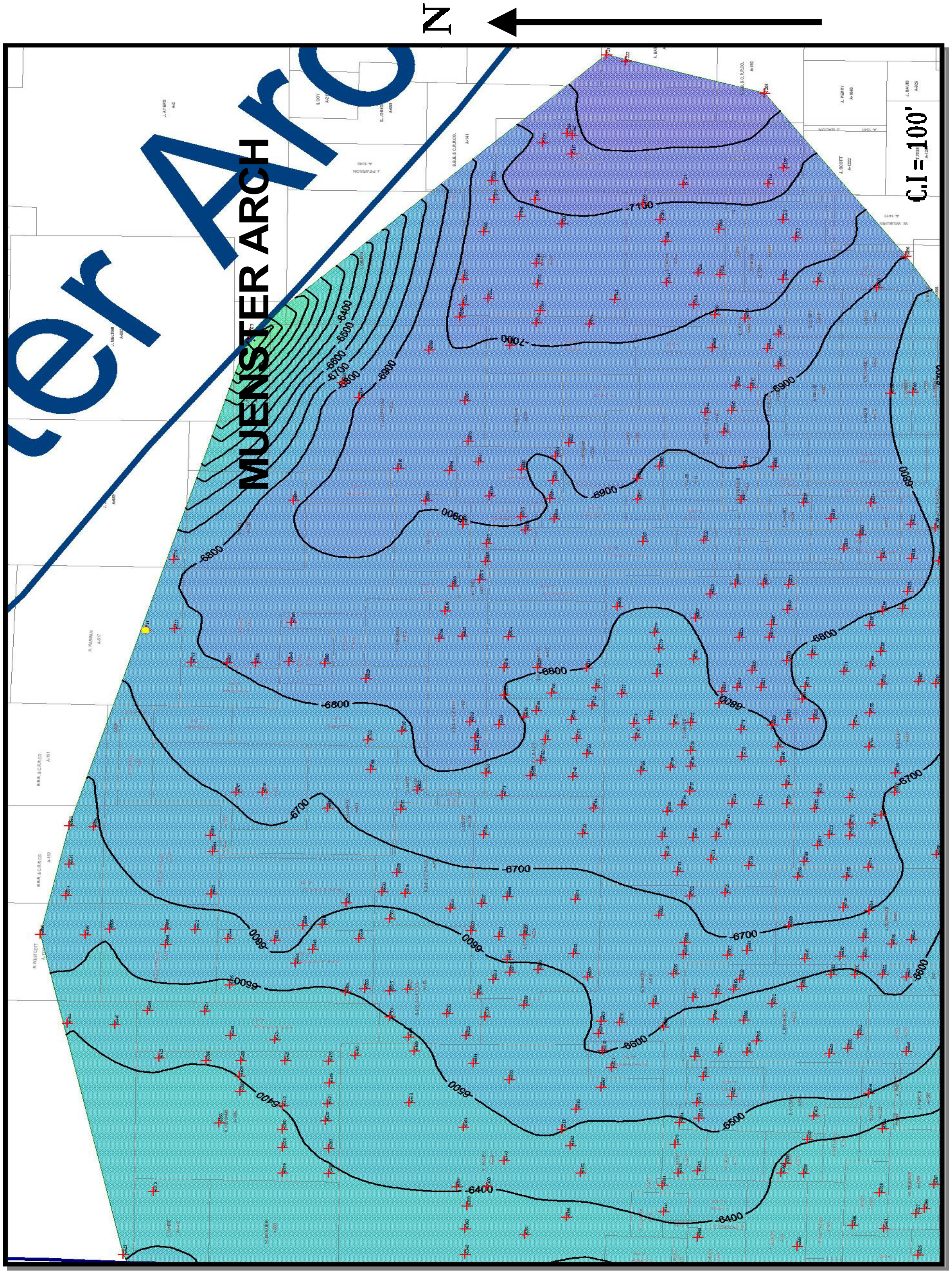

Figure 12: Subsurface structure map constructed on top of the Marble Falls Formation. Lighter colors indicate areas shallower depths relative to darker colors. Red crosses

indicate subsurface data (“picks”) used in map generation. Note that the only structural activity appears to occur around the Muenster Arch.

CHAPTER III

DEPOSITIONAL ENVIRONMENT AND DEPOSITIONAL CYCLES INTERPRETATION

Introduction

The process of depositional environment determination in this study used an integrated data set consisting of wireline log signatures, core, cross-sections, thin-section microscopy and isopach maps. Primarily, core analysis that showed the distribution of lithofacies and sedimentary structures was used in conjunction with wire-line logs and well cuttings to infer a depositional environment for the Bend Group. Then, the geometry of the different depositional cycles determined through isopach maps and thin-section microscopy confirmed the inferred depositional environment.

Since a core that penetrated the Bend Group could not be obtained in Denton County, a core was provided from the Bureau of Economic Geology (BEG) in Austin, Texas. The core is from the Stallworth Oil and Gas Company, Bird #3 well in Parker County. Parker County is located to the southwest of the study area (Figure 13). In an effort to correctly identify facies, a cross-section was made from Denton County to Parker County (Figure 3) and upon core examination the depositional cycles identified on wire-line logs through wire-line signatures were identified in the core.

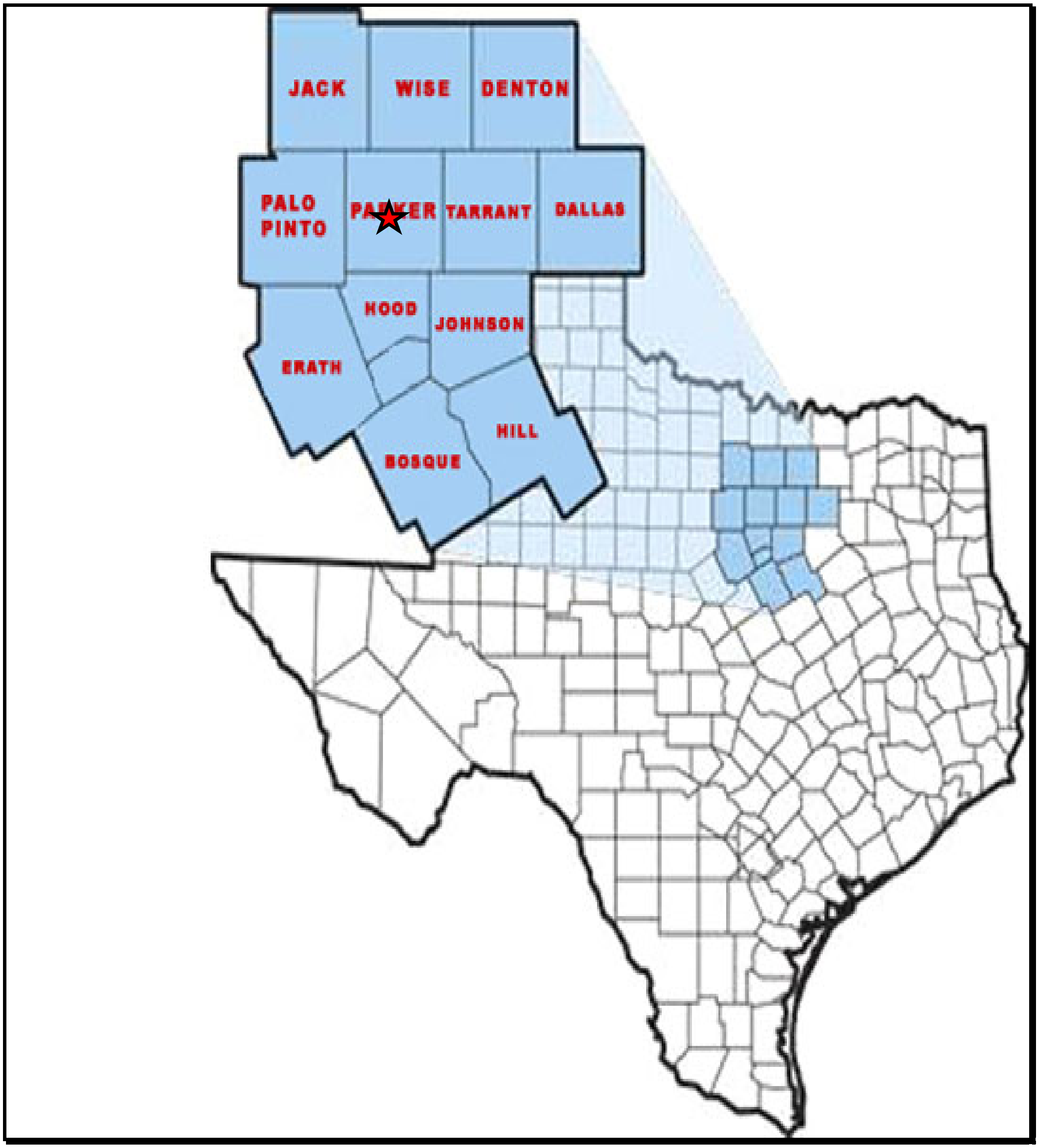

Figure 13: Location of Stallworth Oil and Gas Bird #3 core in Parker County.

Log Characteristics of Depositional Cycles

The onset of the different depositional cycles identified in the Bend Group coincide with periods of relative sea level rise. The Bend Group depositional cycles identified from wireline log signatures in the study area had deposits that included: proximal delta front/ distributary channel, delta front and prodelta deposits. The gamma-ray and resistivity characteristics of each of these deposits are summarized in Figure 14. Table 1 shows the interpretations of the deposits of the primary depositional cycles.

The spontaneous potential (SP) curve and the gamma ray curve can be used to indicate grain size profiles in sand-shale sequences (Wyllie, 1963). The SP deflection is controlled by permeability and the most negative deflection (leftward deflection) occurs in the most permeable interval. Since permeability increases with grain size, the S.P curve can be used to indicate grain size. The gamma ray curve also indicates grain size because clay content and radioactivity increases with smaller grain sizes (Wyllie, 1998).

The DC-4 package has a wireline signature that characterizes these deposits as distributary channel deposits. Overall these deposits exhibit low radioactivity (clean) and a blocky, well-developed gamma-ray response. Also, the spontaneous potential (SP) curve is usually well developed opposite the portions of the wireline log that indicate the sediments are sandstones and conglomerates. The tops and base of the gamma-ray response are sharp and this is consistent with gamma ray responses for channel deposits (Dutton, 1982). Some proximal delta-front deposits may be present underneath the channel deposits but for the most part the wireline signature and log characteristics of these deposits suggest that they are distributary channel deposits (Figures 14 and 15). The resistivity varies from 5 ohm-m in portions of the log with high gamma ray values to about 700 ohm-m in portions with low gamma ray readings but is generally high. Distributary channel deposits are mostly sandstones and conglomerates that signify deposition by high-gradient systems and exhibit a cyclical vertical variation in grain size as indicated by the gamma-ray signature (Figure 14). Fine- to very-fine-grained sandstones, siltstones, and silty shales are usually interbedded with the coarser-grained rocks (Alberta, 1987). This is also indicated by the cyclical nature of the gamma ray and resistivity log signatures for the DC-4 deposits (Figure 15). Distributary channel deposits are commonly oriented nearly perpendicular to the depositional strike of the marine strata.

Depositional Cycles	**DC-1**	**DC-2**	**DC-3**	**DC-4**
Interpretation	Pro-delta	Delta front	Pro-delta/Delta front	Distributary channel/Proximal delta front

Table 1: Tabular illustration showing the four identified depositional cycles and the interpretations of their associated deposits **based on wireline signature/log characteristics.**

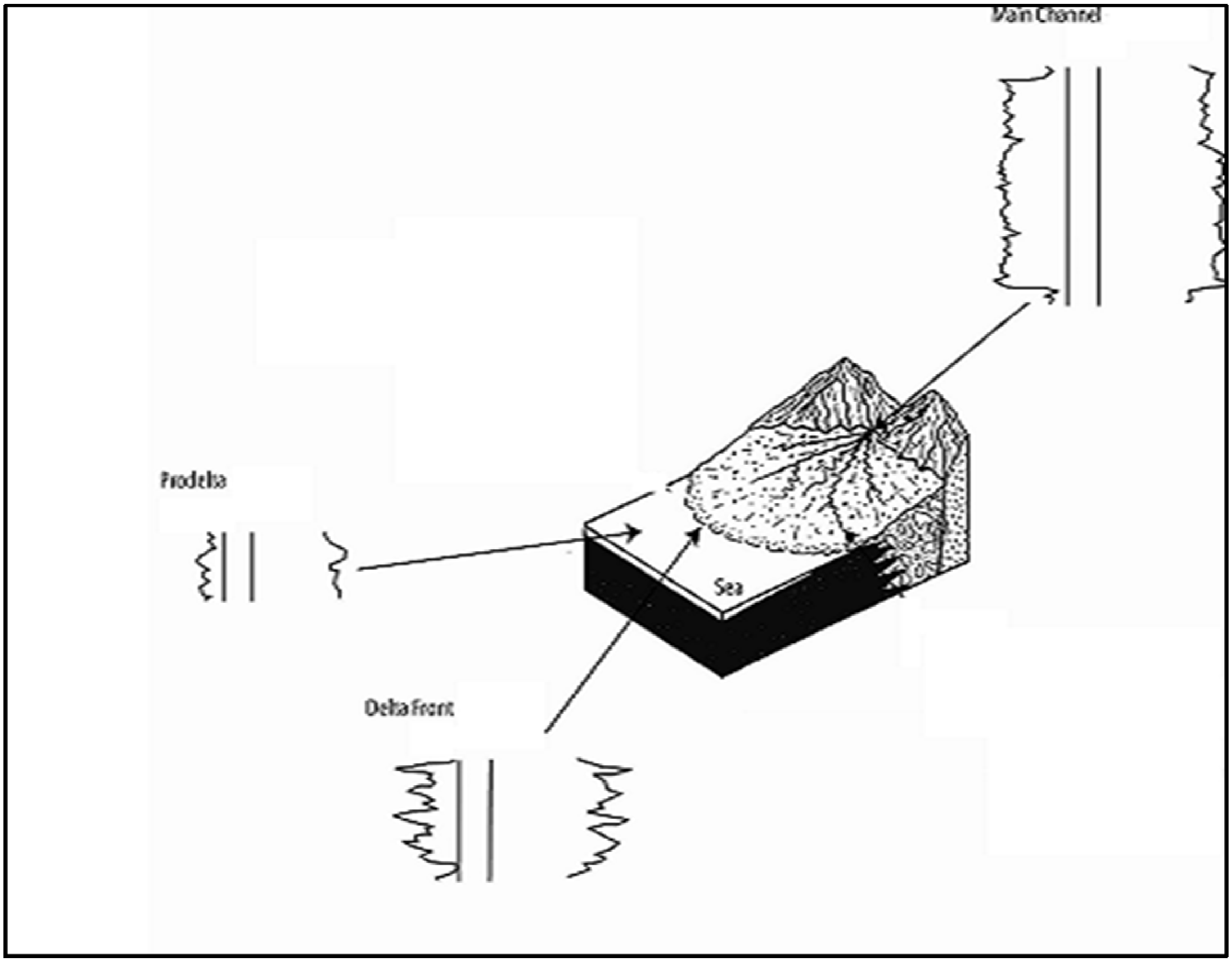

Figure 14: Gamma ray and resistivity log signatures of deltaic depositional facies (after Dutton, 1982 and Thompson, 2007)

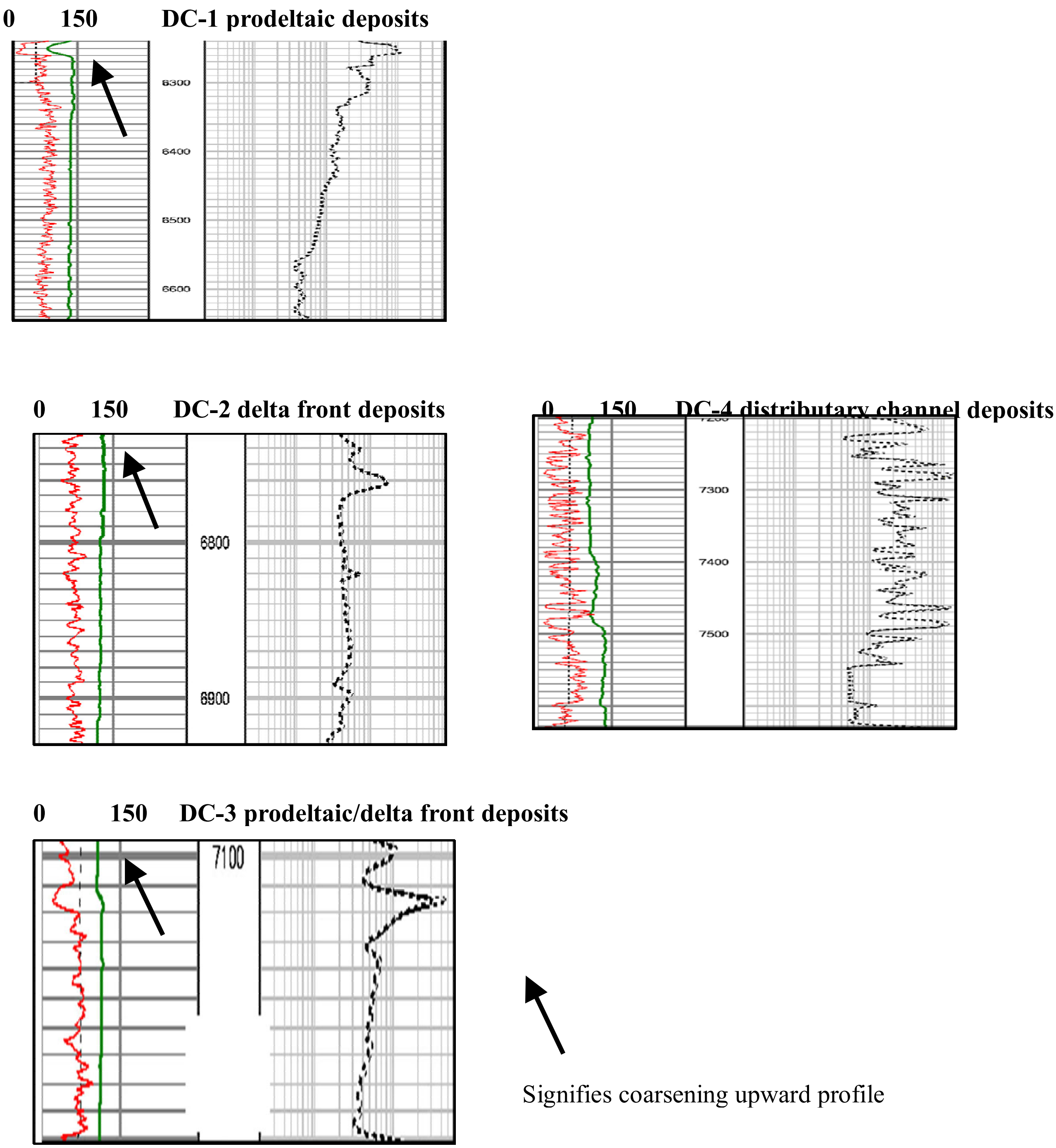

Figure 15: Wireline clipping of the four identified depositional cycles showing their log characteristics. Red lines represent the gamma ray curve, green lines represent the spontaneous potential (SP) curve and the black lines represent the resistivity curve.

The DC-3 package has a wireline signature that classifies these deposits as pro-deltaic/delta front deposits (Figures 14 and 15). The log characteristics (resistivity and gamma ray) for these deposits exhibit attributes consistent with pro-deltaic deposits at the base and then grade up to delta front deposits at the top. Prodelta deposits have variable thickness and usually have very low deflection on gamma-ray response. The curve appears serrated and has a "ratty" appearance because the gamma ray values are usually high (over 75 API) with no major deflections to the left. The resistivity curve generally records very low values compared to distributary channel deposits and is "spikey". The DC-2 deposits are interpreted to be delta front. Delta-front deposits have varying thicknesses but they show a progradational coarsening and cleaning-upward sequence due to a decrease in gamma-ray response from base to the top (Elphick, 1996). This indicates that there is an increase in quartz content towards the top of the package. The resistivity curve is variable throughout, ranging from 3ohm-m to 75ohm-m but overall has a moderate response. These deposits are characterized by interbedding of sandstone with shale and siltstone and repeated sequences of delta front deposits are common (Sneider at al., 1977). They exhibit a general upward decrease in the number of interbedded shale and siltstone beds and a general upward increase in grain size (Sneider et al., 1977), and this can be seen through the resistivity and gamma ray signatures of the DC-2 and 3 deposits (Figure 15).

The DC-1 package is inferred to be pro-deltaic based on wireline log signatures because its gamma ray and resistivity log characteristics are similar to those outlined above for pro-deltaic deposits.

Core Analysis

The core obtained from the BEG was used to determine lithofacies, identify sedimentary structures and establish the stratigraphic relationships between the depositional cycles identified through wire-line logs. The top of the core was at 3561’ and the bottom was at 5065’. The core had some section missing at various depths but the contacts between the depositional cycles were available, hence correlation between wireline logs and the core could still be carried out. The missing sections were analyzed with some degree of confidence using wireline logs and well cuttings.

The bottom section of the core (5050’-5063’) consists of a dark gray to black limestone that is micritic in nature (Figure 16). This section of the core effervescences readily with dilute hydrochloric acid. This interval is shaley towards the top (5050’) and contains interbedded shale beds that vary in thickness. This corresponds to the top of the Marble Falls Formation which is Morrowan in age and directly underlies the Bend Group in the Early Pennsylvanian System.

Above this interval lies a mixed terrigenous and carbonate facies assemblage from 4272’-5049’ (Figure 17). The base of this section consists of silty wackestones and interbedded black shales representing a transition from the shallow marine shelf environment of the underlying Marble Falls Limestone to a deltaic environment (Figure 18). The bedding is massive to cross-bedded and this section also effervescences readily with dilute hydrochloric acid. The core however has some section missing as these fine grained deposits begin to grade into sandstones and conglomeratic sandstones (4480’-4885’). The rest of the section is described with the help of well cuttings and wireline logs. This interval is identified in the wire-line logs as the DC-4 package that overlies the

Marble Fall Formation and signifies the onset of Bend Group deposition. The wire-line log signature in conjunction with other available data suggests that this interval coarsens upward and grain size increases up-section. This also corresponds well with Thompson (1982) who observes that this interval has light colored chert conglomerates and sandstones towards the top of the interval. These terrigenous deposits were likely sourced from the Muenster Arch locally and the Ouachita structural belt regionally, as both were active structural features during this period (Thompson, 1982).

The next interval is from 4247’-4272’ (Figure 19). This interval is primarily fine grained non-calcareous sandstone with some interbedded shale and interlamination. The thickness of these interbedded shale ranges from two inches to about eight inches. Horizontal bedding is present and the shale layers are very thin and light-dark grey in color. From wireline log to core correlation, this interval is determined to be the DC-2 package. As indicated in the gamma-ray and resistivity log signatures (Figure 15), the sandstone gets “cleaner” towards the top. This means that there is an increase in the quartz content relative to clay content at the top of the package.

On top of this interval lies non calcareous shale with interbedded very fine grained siltstone (Figure 20). This interval is from 4224’-4247’ and shows some evidence of burrowing. From wireline log to core correlation, this interval is recognized as the DC-1 package and is also the top of the Bend Group.

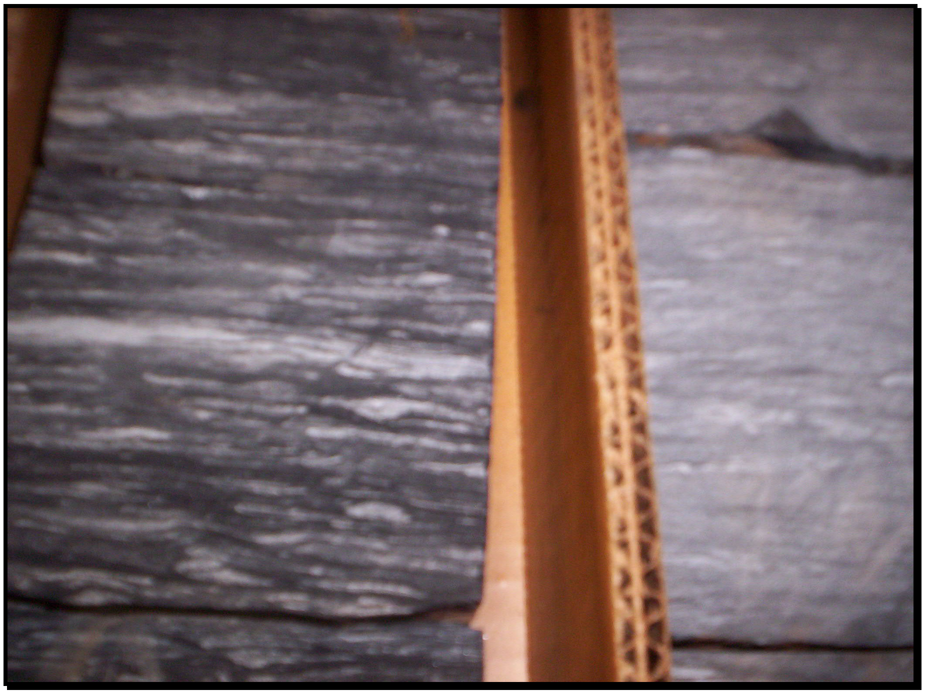

Figure 16: Core photograph of the micritic dark grey Marble Falls limestone underlying the Bend Group.

Figure 17: Core photograph of DC-4 deposits of the Bend Group showing some massive and planar bedding.

Figure 18: Core photograph showing the transition from a marine shelf environment to a more deltaic setting under which the Bend Group was deposited.

Figure 19: Core photograph of the delta front sands of the DC-2 package showing interbedded shale layers and interlamination.

Figure 20: Core photograph of the DC-1 pro-deltaic package showing horizontal bedding and interbedded silt.

Depositional Environment and Depositional Cycle Analysis

Core analysis and wireline signatures confirm previous hypothesis that the Bend Group was deposited in a fluvial dominated fan-delta system (Thompson, 1982). The top of the Marble Falls limestone, which marks the beginning of Bend Group deposition, represents the last episode of shallow water deposition in the shallow marine shelf system before the influx of clastics via a transgressive system consisting of numerous elongate deltas that prograded south from the Ouachita mountain system into the Fort Worth Basin (Lahti, 1982). Bend Group deposition has the properties of both a fan delta and a fluvial dominated delta system (Thompson, 1982). Fan deltas usually prograde into marine and lacustrine environments and are characterized by distributary channels, angular and coarse grained deposits, and terrigenous facies interbedded with carbonate facies (McGowen, 1970). The Bend Group was deposited as a result of a fan delta that prograded into the marine environment under which the Marble Fall limestone was deposited.

The DC-4 package is made up of distributary channel deposits and represents the fan-delta plain where river processes dominate (McGowen, 1970). The DC-4 package exhibits characteristics of sediments associated with a fluvial dominated fan-delta. From core, wire-line logs and well cutting analysis the DC-4 package was determined to be composed of light colored conglomerates interbedded with limestone stringers and conglomeratic sandstones in a fine-medium grained sand matrix. The deposition of this package occurred in a higher energy environment suggesting a fluvial dominated setting (Thompson, 1982). Fan deltas also occur in the vicinity of active tectonic sources like the

Ouachita structural belt and the Muenster Arch during early Pennsylvanian time (Lovick, 1982).

The remaining three depositional cycles (DC-3, DC-2 and DC-1) have sediments that exhibit characteristics associated with a prograding delta (Herkommer, 1982). The DC-3 and DC-2 cycles represent the delta front portion of a delta, where both fluvial and basinal processes occur (Walker, 1992). Fluvial deposits are characterized by large grain sizes, crossbedding and massive or planar bedding and signify a high energy environment while basinal deposits are characterized by pro-delta shales, horizontal bedding and interlamination and this signifies deposition in a low energy environment. As discussed in the core description, these deposits are fine grained non-calcareous sandstone with some interbedded shale and interlamination. The grain size is medium to fine grained and increases up-section. Horizontal beds are common and the inferred energy of deposition is moderate and signifies the interaction of fluvial and basinal processes. The delta front is where most of the active deposition in deltaic environments occurs especially at the mouths of distributaries where the coarsest sediments are deposited (Walker, 1992). A prograding delta lobe normally produces a sequence of coarsening upward delta front facies succession that transitions from the shaley deposits to sandier deposits. This is evidenced by the wire-line log signatures of the DC-2 and DC-3 package which are interpreted to be delta front deposits (Figures 14 & 15). Continued progradation of a delta lobe sometimes results in erosion of delta front deposits by the onlap of distributary channel deposits over its own mouth bar (Dutton, 1982). This may be the reason why the delta front deposits of the DC-2 and DC-3 cycles are absent adjacent to the Muenster Arch and the distributary channel deposits of the DC-4 package actually thicken in this area. Another explanation for this could be that the Muenster Arch and the Ouachita structural belt were both active during this time and were supplying coarse terrigenous clastics into the basin (Lahti, 1982). Hence this major supply of terrigenous clastics along with basin subsidence resulted in the deposition of the coarser grained distributary channel deposits in lieu of the finer grained delta front deposits.

The DC-1 deposits represent the pro-deltaic portion of the prograding delta where basinal processes dominate. Finer grained material settles quietly out of suspension in this area of the delta. There is little evidence of burrowing in the core and some silty lamination is also observed. This marks the influence of the delta and signifies that total bioturbation did not occur.

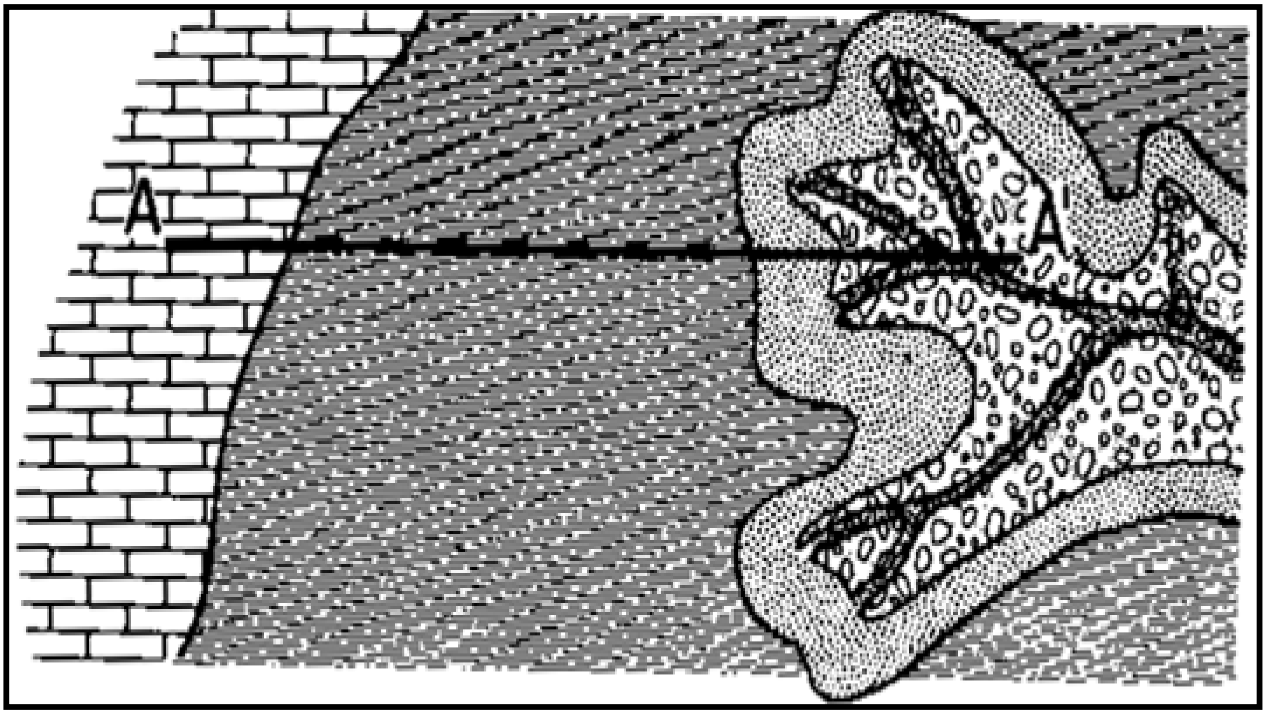

Figure 21: Depositional model for the Bend Group showing a prograding fan delta in a marine setting (After Thompson, 1982)

CHAPTER IV

DISTRIBUTION OF THE BEND GROUP

Regional Thickness

Lahti (1982) constructed a regional isopach map for the Bend Group in the Fort-Worth basin (Figure 22). The Bend Group ranges in thickness from 0' in the western parts of the basin to 3500' in the southeastern parts of the basin. The Bend Group is thickest along the southwestern flanks of the Muenster Arch because in "early" Atokan time, the Arch was uplifted and high angle faulting occurred on its southeastern flank (Lahti, 1982). This caused the basin to subside along the southwestern flank of the Muenster Arch with a great flow of coarse terrigenous sediments prograding southwards from the Muenster Arch. Also, large amounts of terrigenous sediments were shed from the rising Ouachita structural belt to the east of the basin during the early to middle Atokan time and this contributed immensely to the continued subsidence of the basin (Pranter, 1989). This increased subsidence in turn caused a hingeline to be formed in the basin, in Parker, Denton and Wise Counties (Figure 22), and the Bend Group thickens considerably adjacent to this hingeline as a result of increased deposition from the Ouachita Structural Belt.

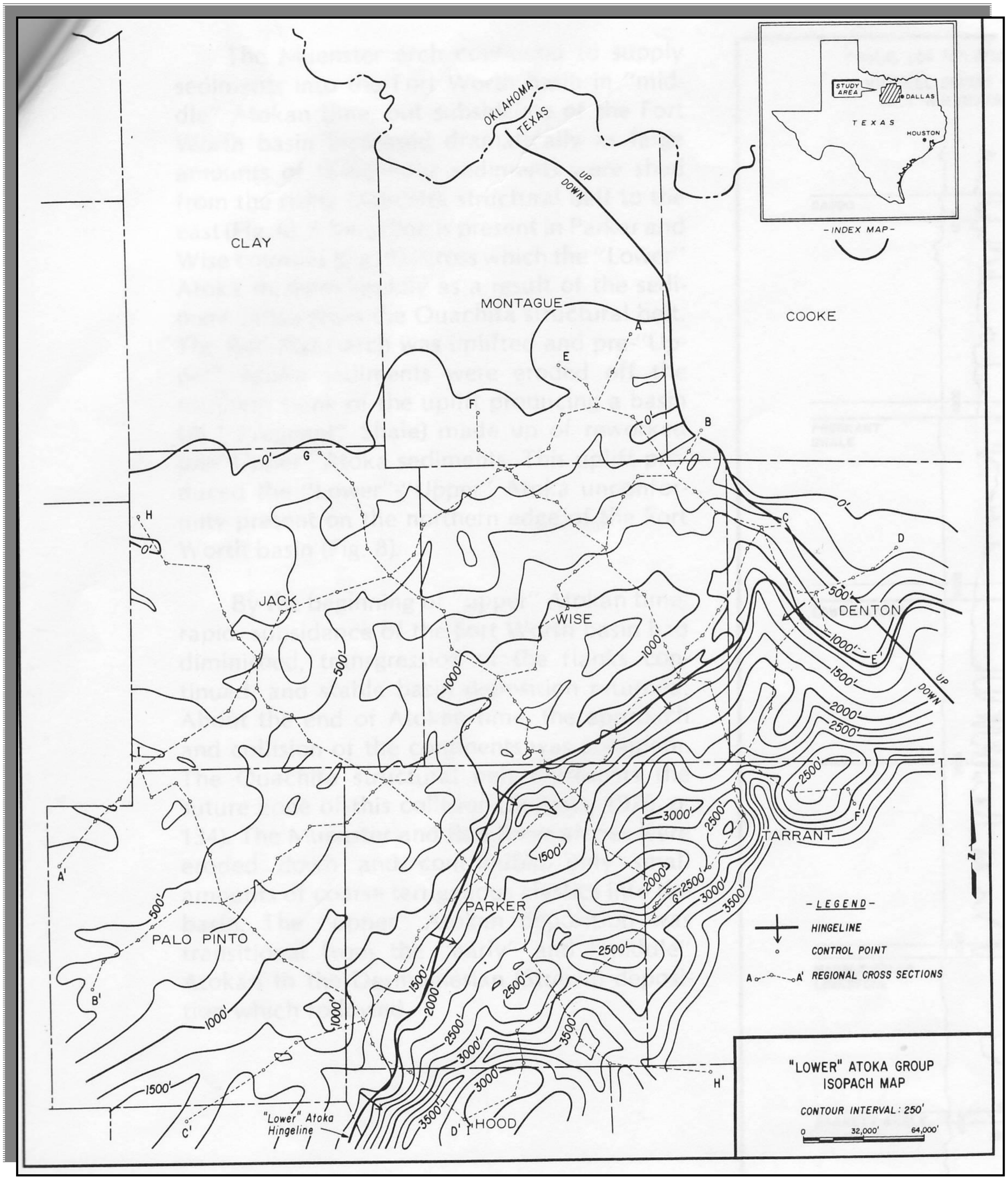

Figure 22: Regional isopach of the Bend Group (Lahti, 1982)

Bend Group Distribution in Denton County

To determine the distribution of Bend Group and identified depositional cycles (packages) in the study area, isopach maps were constructed for the entire Bend Group interval and also for each of the four identified depositional cycles (Figures 9, 23, 24, 26, and 27). The mapped distribution pattern supported the interpretation of a south and also an easterly source for all of the Bend Group deposits from the Ouachita Structural Belt and the Muenster Arch (Thompson, 1982). The lobate distribution geometry of the depositional cycles is consistent with the hypothesis that deposition occurred under deltaic influence, which supports the fluvial dominated fan delta depositional model.

Figure 9 is the isopach of the entire Bend Group Interval. As discussed earlier, the Bend Group is thickest adjacent to the Muenster Arch. The source directions appear to be to the south and also to the east; and the direction of transport to the north-northeast (arrows show transport direction). The deltaic lobes also trend to the north-northeast. As seen from Figure 9, the Bend Group deposits thicken toward the proposed south and easterly sources and they thin generally to the north. In the south-southeastern part of the study area, the thickness of the Bend Group deposits exceed 1600 feet, suggesting there was greater subsidence to the south and southeast and a considerable amount of tectonic activity supplying sediment to this area during deposition. The distribution pattern allows the interpretation that a fluvial dominated deltaic system transported sediments sourced from the Muenster Arch to the southeast and the Ouachita Structural Belt to the south while subsidence was occurring in the Early Pennsylvanian (“early” Atokan) time due to the uplift of the Muenster Arch and the reactivation of the Ouachita Structural Belt.

The DC-4 distributary channel/ proximal delta front deposits are the deepest of the Bend Group deposits and their distribution is shown in figure 23. The "DC-4" is thickest around the Muenster Arch; its sources still appear to be the south and easterly and the general direction of transport to the northeast (as indicated by the arrows). The deltaic lobes are also trending to the northeast. As seen from Figure 23, DC-4 deposits thicken toward the Muenster Arch to the east and thin moving basinward to the west, there is also no noticeable thickening towards the Ouachita Structural Belt to the south. This suggests that the while the Ouachita Structural Belt was a source for the DC-4 deposits along with the Muenster Arch, the Muenster Arch was likely more structurally active during the deposition of the DC-4 package as evidenced by the "bunching up" of contours close to the Arch.

The isopach map (Figure 24) shows the distribution of the DC-3 pro-deltaic/delta front package. From wireline logs, these deposits are determined to be mostly shale with some interbedded siltstone. The DC-3 package experiences a rapid "thinning" towards the Muenster Arch and is absent adjacent to it. A reasonable explanation for this is that since the Muenster Arch and the Ouachita structural belt were both active in Early Pennsylvanian time and they shed terrigenous rich clastic sediments into the basin, the more basinward pro-deltaic facies of the prograding delta were not deposited adjacent to these tectonically active features- instead the cherty conglomerates and fine to coarse grained sandstones of the distributary channel/proximal delta front facies (DC-4 package) were deposited here to fill the accommodation created by the continued subsidence . This accounts for the increased thickness of the DC-4 distributary channel/proximal delta front deposits around the Muenster Arch. This is also the probable cause of the unconformity mentioned earlier in the study that placed the DC-1 package just on top of the DC-4 package. The subsurface structure map constructed on top of the underlying DC-4 package show that the basin gets deeper moving east towards the Muenster Arch (Figure 25). Away from the Muenster Arch, the DC-3 package maintains a somewhat constant thickness of about 200 feet over a relatively large area. The source and transport direction is not easily discernable due to the widespread/blanket nature of these shaley deposits.

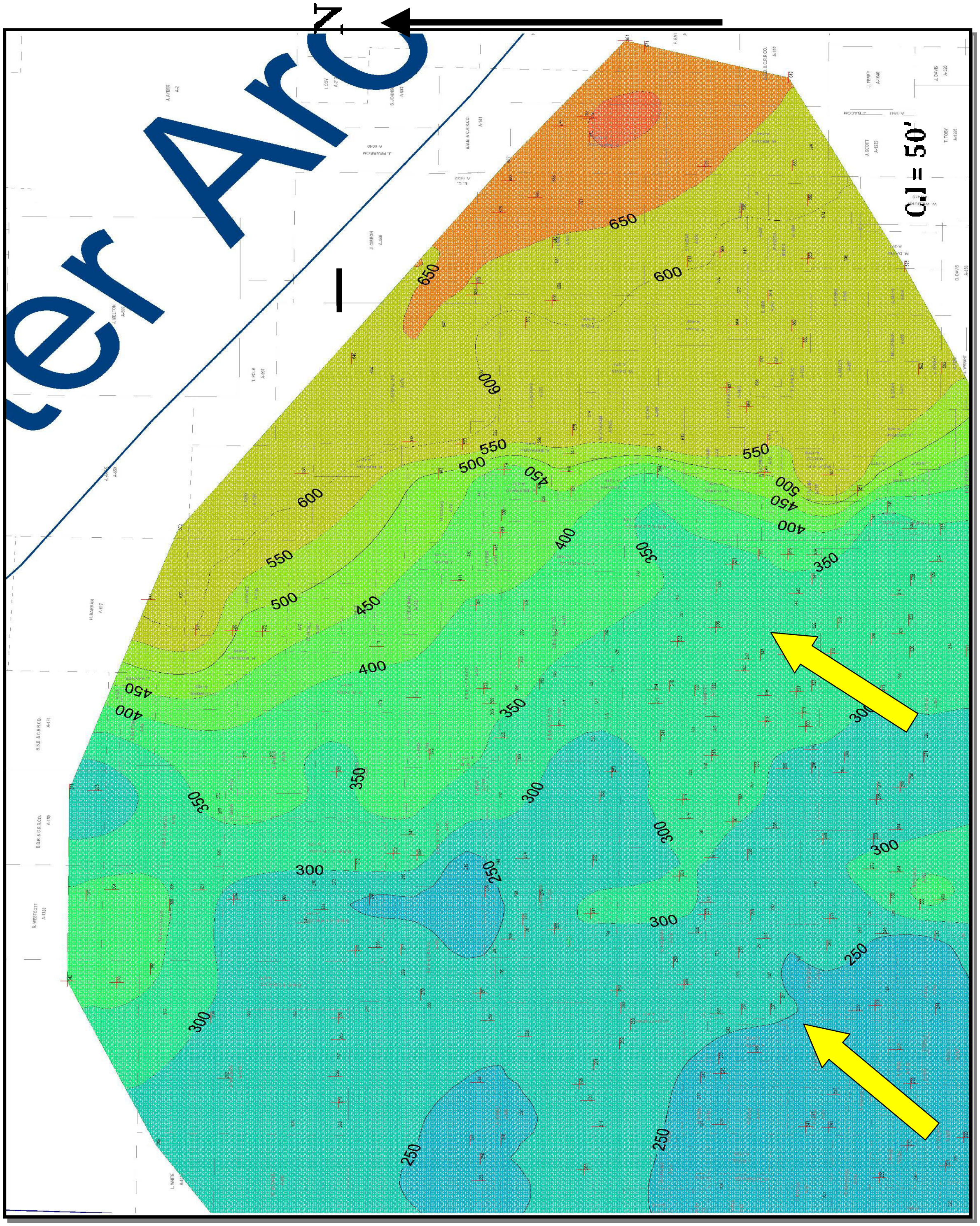

Figure 23: Isopach map of the DC-4 package in Denton County Texas. Lighter colors (blue) indicate areas of low thickness relative to darker colors (red). Red crosses indicate subsurface data ("picks") used in map generation.

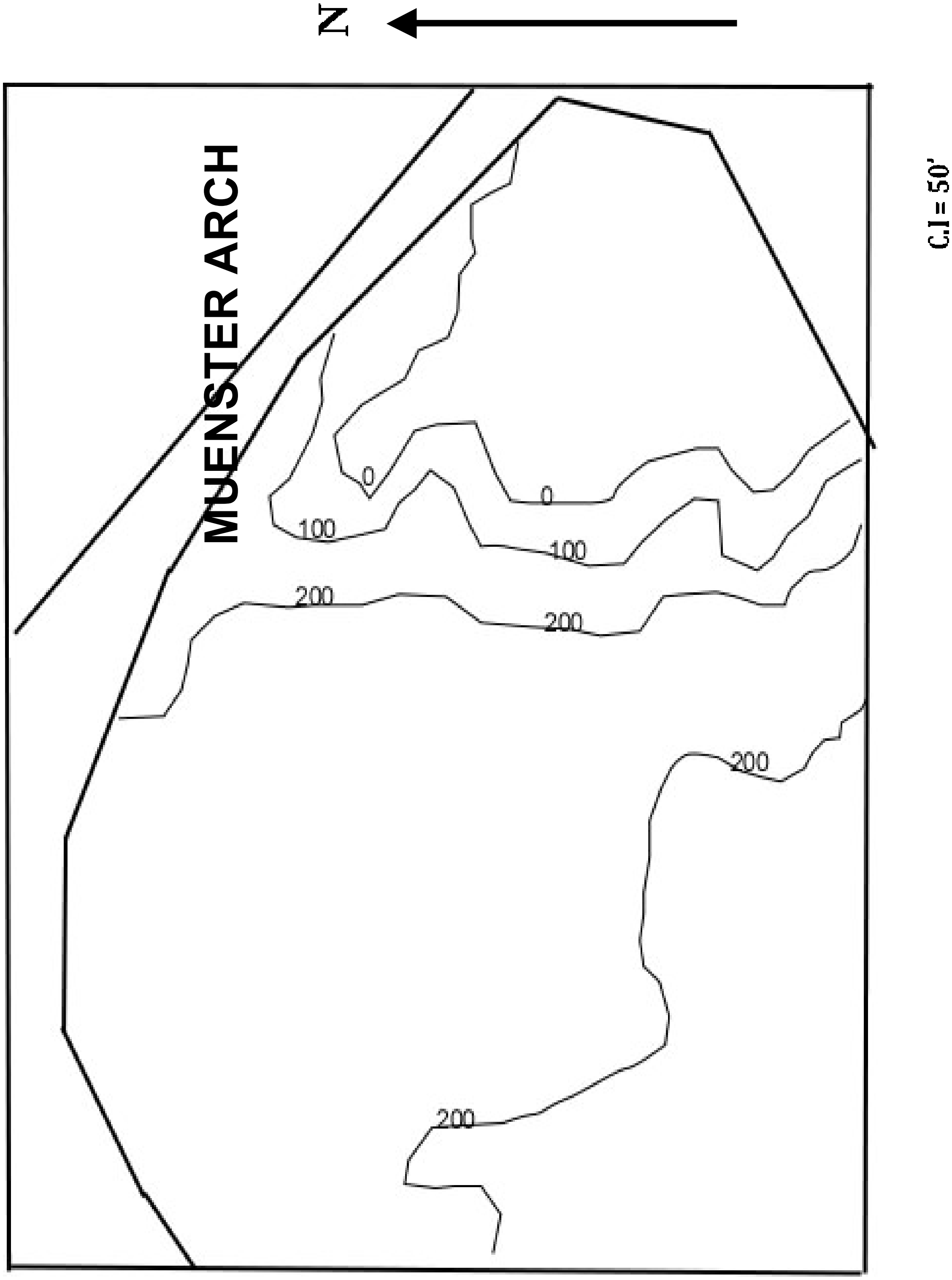

Figure 24: Isopach map of the DC-3 package in Denton County Texas.

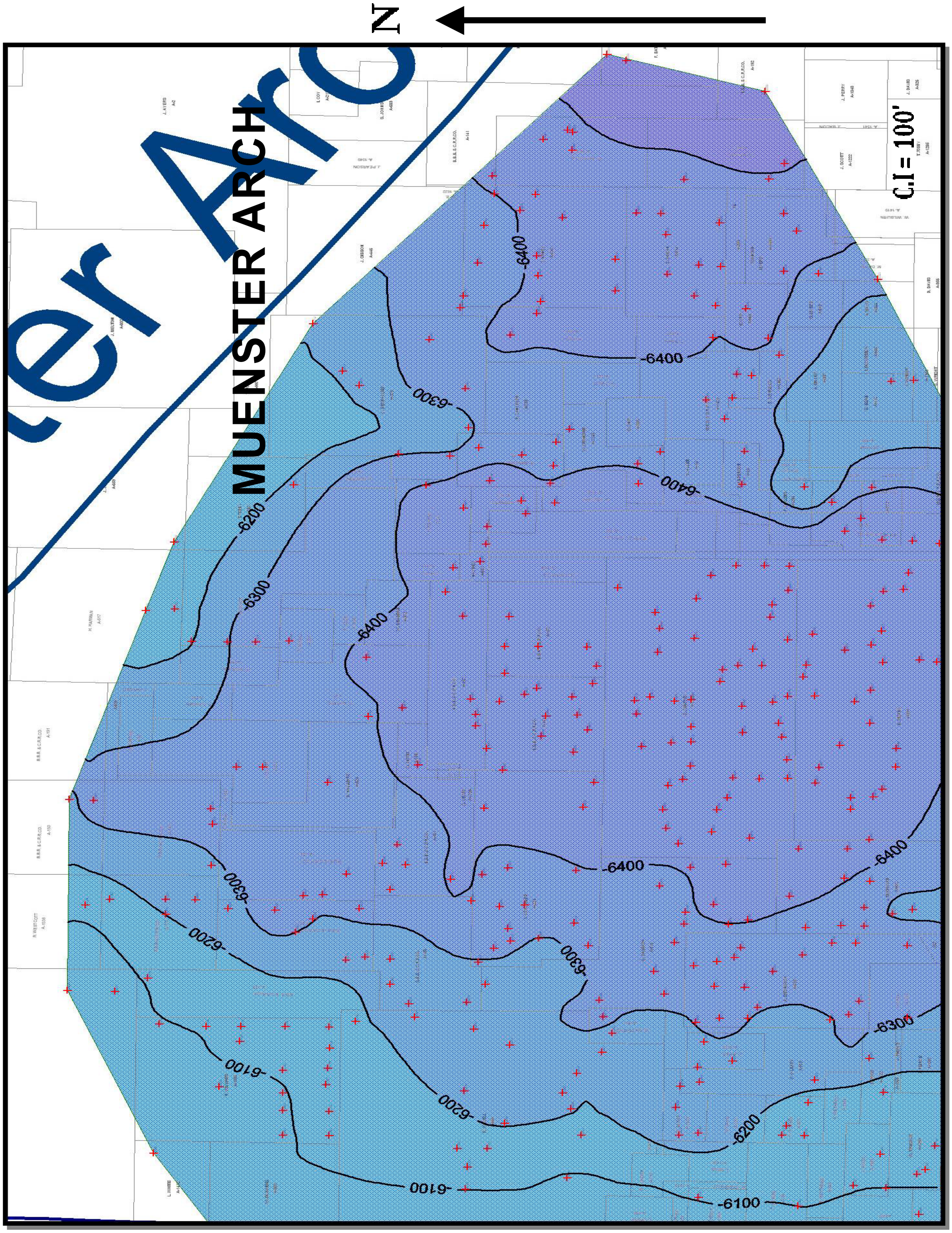

Figure 25: Subsurface structural contour map of the DC-4 package in Denton County Texas. Red crosses indicate subsurface data ("picks") used in map.

Figure 26 shows the distribution of the DC-2 delta front package. The DC-2 package like the underlying DC-3 package, experience a rapid “thinning” towards the Muenster Arch and are absent adjacent to it, which also indicates non deposition in this tectonically active area. Muenster Arch structural activity is evidenced in the map by the “bunching up” of contours in the vicinity of the Muenster Arch. The non deposition of these delta front deposits represents an unconformity in the current subsurface stratigraphic record. The source and transport direction of the DC-2 package appears to be the same as the entire Bend Group.

Figure 27 shows the distribution of the DC-1pro-deltaic package. The DC-1 package is stratigraphically the highest of the Bend Group depositional cycles and acts as the boundary between the Bend Group and the overlying Strawn sediments. The DC-1 package is present adjacent to the Muenster Arch suggesting that the structural activity that caused the non-deposition of the underlying DC-2 and DC-3 sediments occurred before the DC-1 sediments were deposited. Hence the uplift of the Muenster Arch was coming to an end if not over by then. This hypothesis is supported by the fact that the Muenster Arch was not active during the Late Pennsylvanian time (Brown, 1967) and Bend deposition occurred during the Early – Middle Pennsylvanian while the Muenster Arch and the Ouachita Structural Belt were active (Lahti, 1982). The source of the DC-1 package appears to still be the Ouachita Structural Belt and the Muenster Arch; however two transport directions were determined (as indicated by arrows). One is to the usual northeast direction and the other is to the south-south west. This is the first occurrence of a south-southwest trend in this study of the Bend Group and a possible explanation for it is that this might be an indicator of trend and/or transport direction in the Late

Pennsylvanian time since the DC-1 package represents the end of the Early Pennsylvanian time and Bend Group sedimentation.

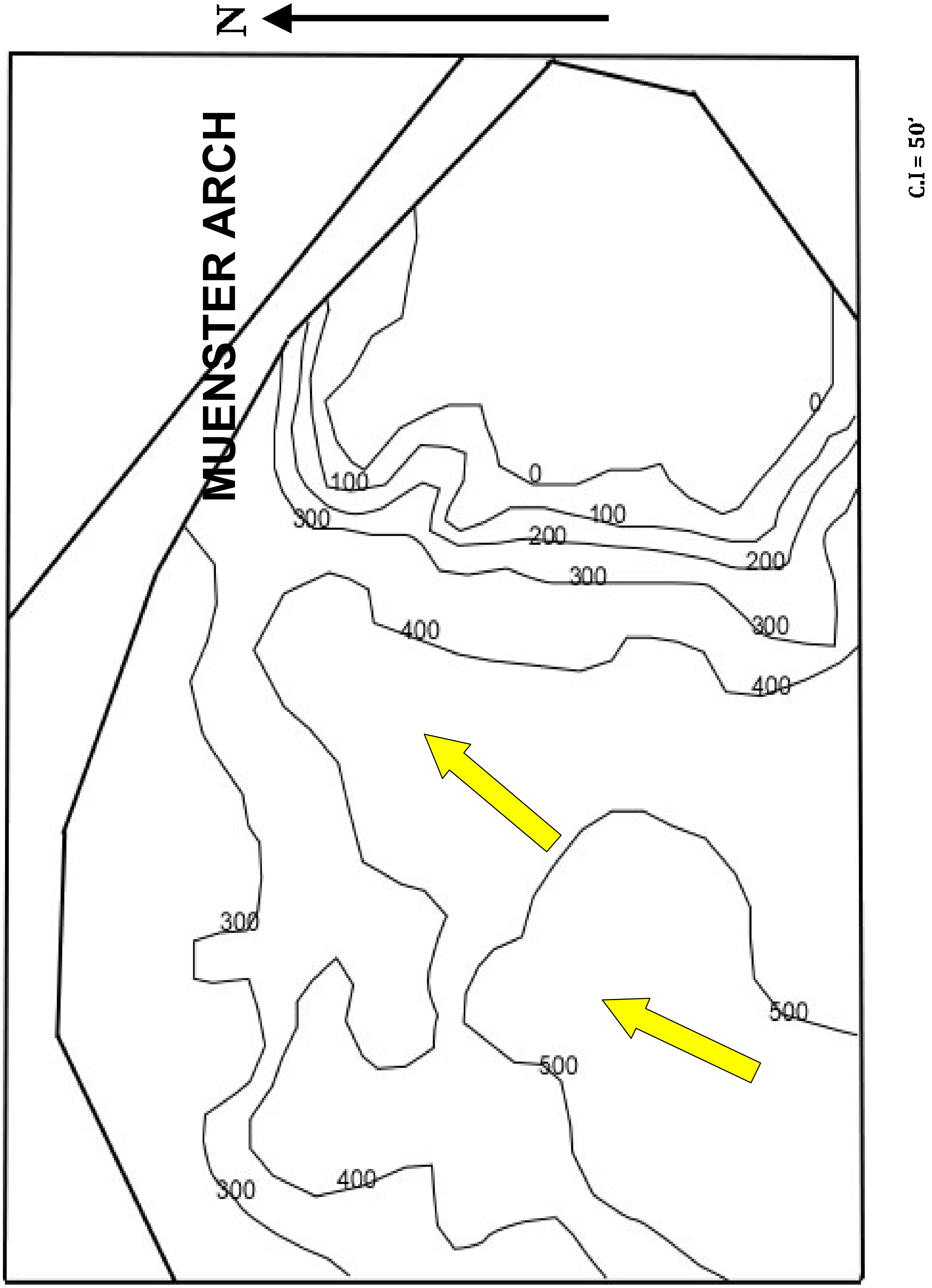

Figure 26: Isopach map of the DC-2 package in Denton County Texas.

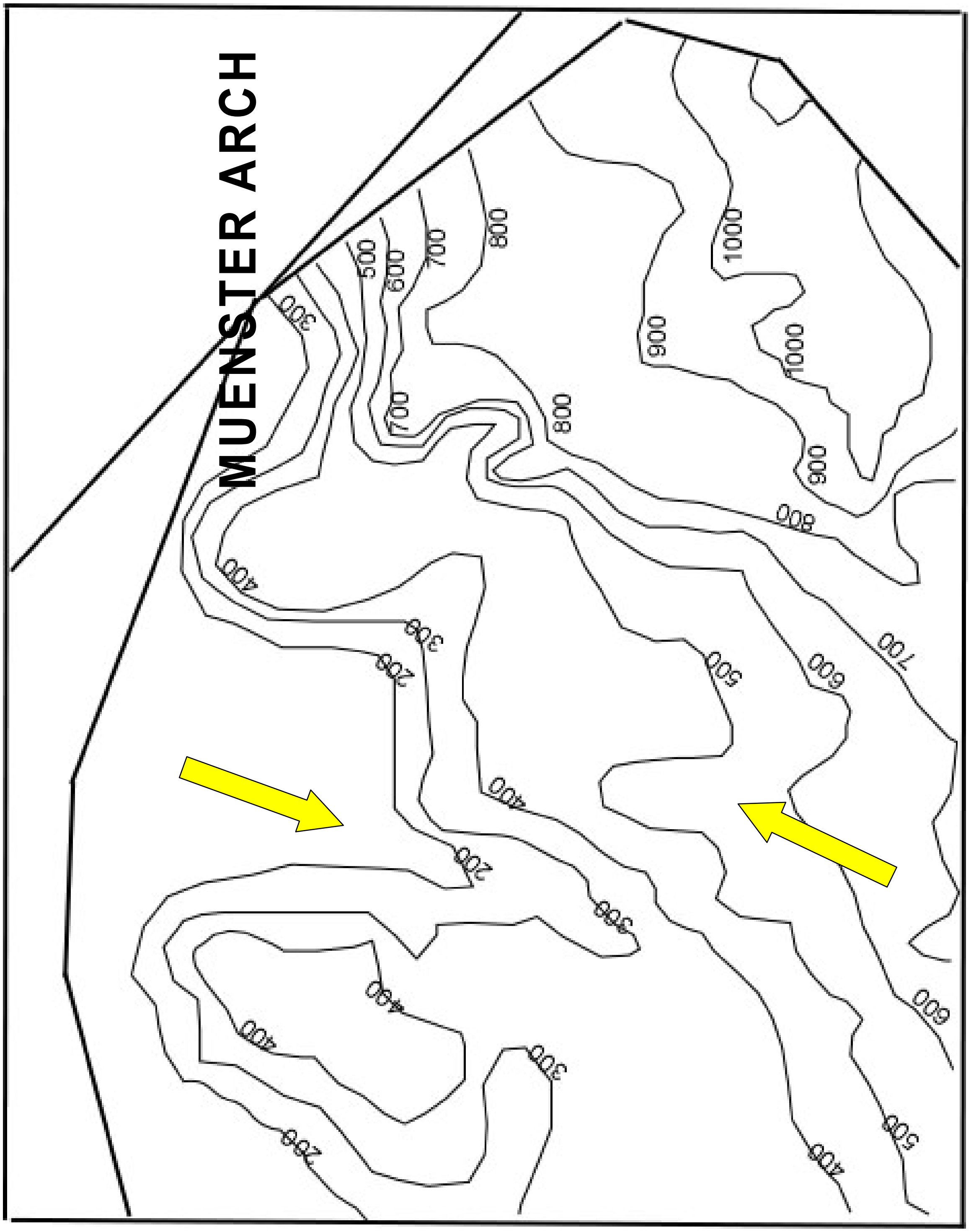

Figure 27: Isopach map of the DC-1 package in Denton County Texas

Bend Group Structure

A Structural contour map was constructed on top of the Bend Group using the formation tops obtained from wireline logs. The Top of the Bend Group also represents the top of the DC-1 deposits. The structure map for the Bend Group (Figure 28) indicates that the Bend Group strikes northwest-southeast and dips in a northeast to southwest direction.

The structure map indicates that the sub-sea depths for the Bend Group range from 4900’ feet to 5500’ in the study area. The shallower sub-sea depths for the Bend Group are observed towards the southwestern portion of the study area while the deeper depths for Bend Group are observed towards the north-northeastern portion of the study area. The location of the deeper parts of the Bend Group coincides with the general transport direction (northeast) observed for the Bend Group deltaic system and may explain why the Bend Group is generally thicker in these areas.

The Bend Group structural map also proves the earlier assertion that the Muenster Arch was not really active by the end of “early” Atokan time (which signifies the end of Bend Group sedimentation) because there is no significant structural activity observed in the vicinity of the Arch (Figure 28).

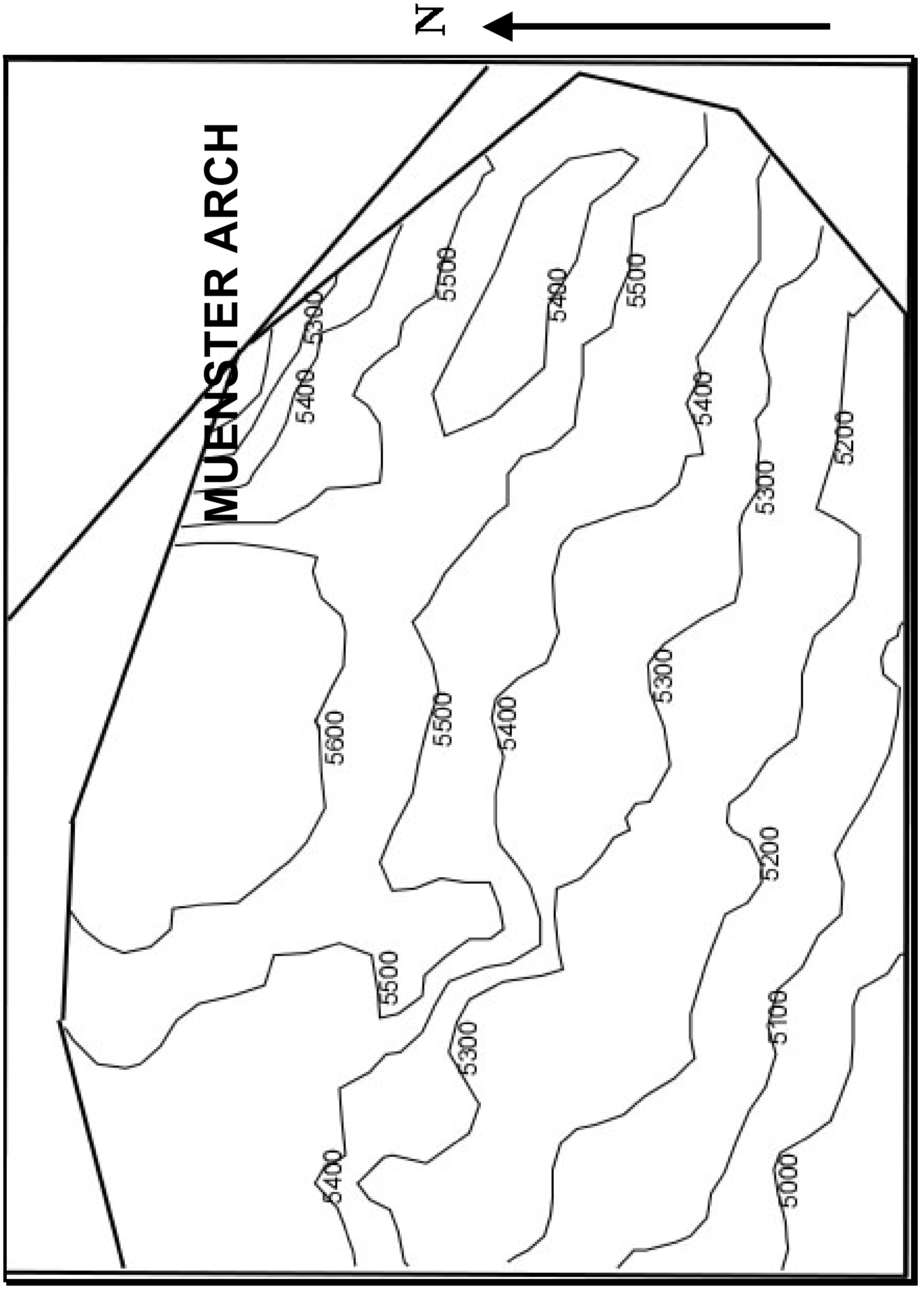

Figure 28: Subsurface structural contour map of the Bend Group in Denton County Texas.

CHAPTER V

DEPOSITIONAL CYCLES AND RESERVOIR QUALITY

Porosity and Water Saturation (S_w) Analysis of Depositional Cycles

Porosity and water saturation values were used as indicators of reservoir quality in this study. Based on the available data set, porosity and water saturation determination were the two analyses that could be performed on all the data through well log analysis, thin section microscopy, scanning electron microprobe and X-ray diffraction. The results of these analyses serve as good indicators of reservoir quality within the identified depositional cycles. Porosity was calculated directly from wireline logs and was also observed on thin section and SEM images. While water saturation was also calculated from wireline logs, clay content determined through SEM and XRD analysis also served as indicators of relative water saturation levels because clay minerals tend to attract water molecules. Clay content was also used as a rough estimate of permeability because clays usually reduce rock permeability.

The amount and distribution of porosity within the Bend Group depositional cycles were analyzed using the neutron-density porosity logs. Each primary depositional cycle was analyzed and an average porosity calculated. Average porosities were determined by averaging neutron and the density values for each two feet of section. There values were then averaged to obtain a composite porosity value for the depositional cycles (Table 2).

The porosity values were then used with resistivity values obtained from resistivity logs to calculate water saturation values for each primary depositional cycle using Archie's equation:

$$S_w = [\ (a / \Phi^m)*(R_w / R_t)\ ]^{(1/n)}.$$

Average water saturation values were also determined for every two feet of section. Table 2 also shows the average water saturation values for each depositional cycle. Figure 29 is a typical well log clipping containing a resistivity log and a compensated neutron-density log of the Bend Group depositional cycles, from which resistivity and porosity values were obtained.

	DC-1	DC-2	DC-3	DC-4
Average Porosity (%)	6.0	7.0	2.7	9.0
Average S_w (%)	60	50	76	41

Table 2: Table illustrating the different porosity and water saturation values for the primary depositional cycles.

The DC-4 distributary channel/proximal delta front deposits have a range of porosity between 4.8 -13.6% with an average of around 9% and this represents the highest average porosity of all the depositional cycles. The portions of the DC-4 deposits that exhibit the highest porosity and neutron-density crossover correspond with the cleaner, lower gamma-ray signatures and "robust" SP deflections to the left. Neutron-density crossover is usually called gas effect and occurs when the density porosity curve reads to the left of the neutron porosity curve. This usually indicates porosity, absence of clay minerals and the presence of natural gas. Likewise, the portions of the DC-4 deposits that have the lowest porosity and least amount of neutron-density crossover correspond with more radioactive, higher value gamma-ray signatures.

Above the DC-4 package are the prodelta silt - and clay-rich mudrocks of the DC-3 package. These prodelta deposits range in porosity from 0 to 6%, with an average of 2.7%. No neutron-density crossover is evident within these deposits, the neutron curve is much higher than the density, and the gamma ray curve reads to the right of the shale base line which indicates the presence of clay.

The DC-2 delta front deposits have a porosity range of 4%-9% with the average porosity approximately 7%. Like the DC-4 package, the portions of the DC-2 deposits with the highest porosity correspond with the “cleaner” (less clay content), less radioactive gamma-ray signatures.

The DC-2 deposits grade upward into the pro-deltaic deposits of the DC-1 package, which consists of sandstone and interbedded shales that coarsen, “clean”(less clay content), and thicken upward. The porosity of the DC-1 deposits range from 2.7% at the base of the package to 8% near the top. Average porosity is around 6%. There is some neutron-density crossover evident at the top of the package and this also corresponds to higher gamma ray signatures, moderate to “robust” SP deflection and higher resistivity values compared to the base of the package (Figure 29).

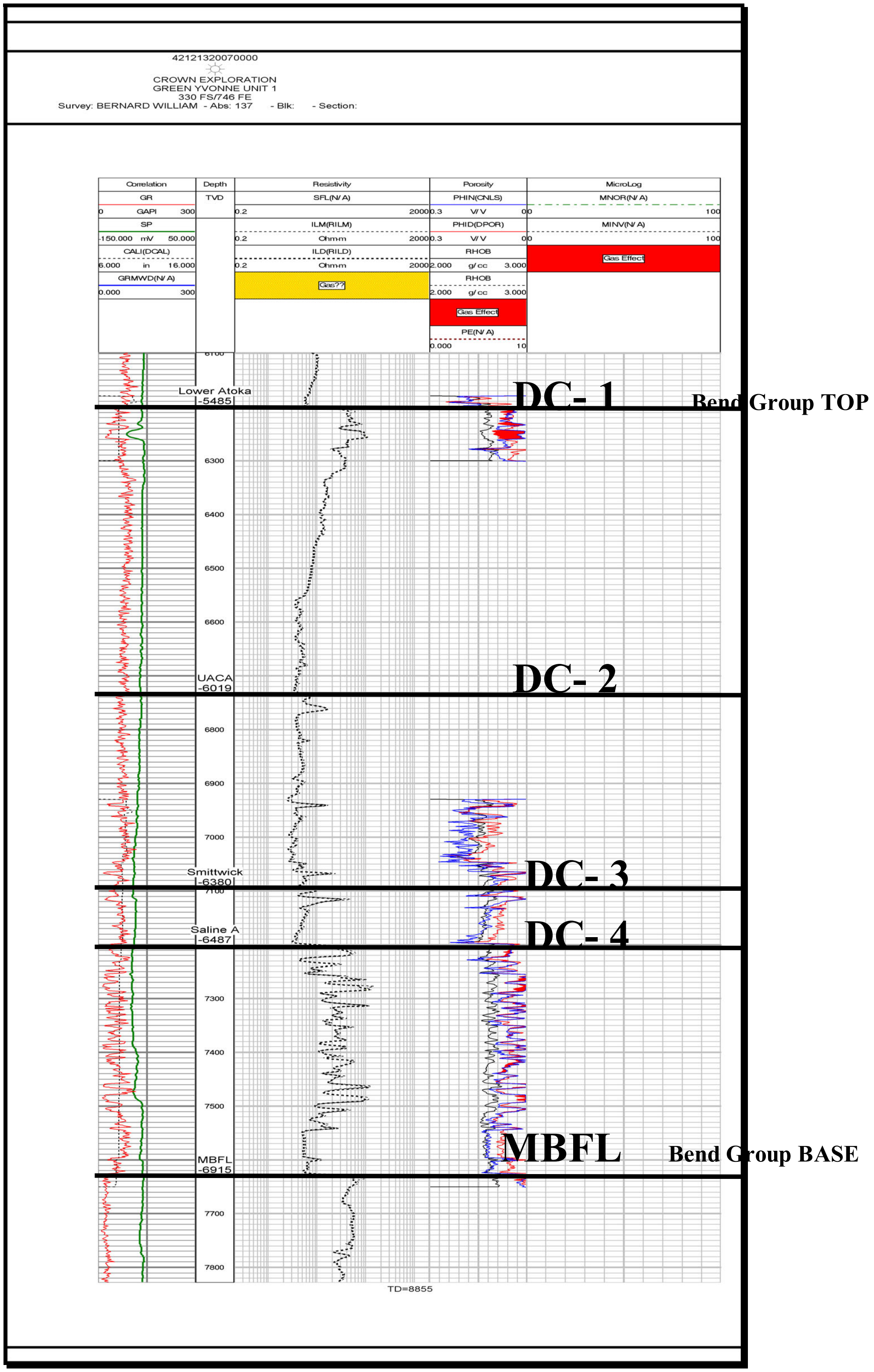

Figure 29: Well log clipping containing a resistivity log and a compensated neutron-density log of the Bend Group depositional cycles. Neutron porosity log is in blue while the density log is in red.

X-Ray Diffraction Analysis

X-Ray diffraction analysis (XRD) was carried out on the bit cuttings in order to determine the detrital mineralogy and authigenic constituents of the depositional cycles. The source area for Bend Group was the Ouachita Structural Belt which is located to the south – southeast of the study area and the Muenster Arch located to the east. Rock types in this area (Thompson, 1982) are predominantly quartz (55%) and feldspar (23%).

Depositional Cycles	Quartz (%)	Potassium Feldspar (%)	Plagioclase (%)	Calcite (%)	Illite/Mica (%)	Chlorite (%)	Kaolinite (%)	Mixed Smectite/Illite layer (%)
DC-1	32.2	0.1	1.4	4.3	39.8	2.0	8.5	9.5
DC-2	48.0	0.1	1.2	0.1	27	2.4	11.1	7.3
DC-3	25.3	0.2	2.7	3.6	43.9	1.7	7.6	11.0
DC-4	58	13	7	11	5.5	1.2	2.3	1.8

Table 3: Results of the XRD analysis carried out on the different depositional cycles.

The XRD data shows that the two depositional cycles (DC-4 and DC-2) identified earlier through wireline analysis as those with good reservoir potentials are those with higher percentages of non-clay minerals. The DC-4 distributary channel deposits have the highest percentage of quartz and lowest percentages of pore filling and lining clays like illite, chlorite and kaolinite. Hence they have good porosity and permeability development and a lower probability of water saturation. Feldspar is abundant in these deposits due to the terrigenous nature of the deposits and its proximity to a structurally active source. The high feldspar content of the DC-4 package (13%) compared to the other cycles confirms that the package was deposited in proximity to the source(s) and tectonic activity was occurring during deposition because feldspars and arkosic sandstones are normally deposited in proximity to tectonically active structures (Dutton, 1982).

The Pro-deltaic DC-3 and DC-1 deposits have the highest clay content and the lowest amount of quartz. This high clay content leads to high clay bound water saturation as indicated by wireline log analysis because the clay molecules attract water to their surfaces due to their atomic structure. Also, the clay molecules line and fill the pores of these deposits. This reduces the porosity and permeability potential of these deposits.

Thin Section Microscopy

Since there is no outcrop of the Bend Group in the study area and a core could not be obtained that penetrated the interval in Denton County, thin sections were made from well cuttings obtained from the BEG in Austin, TX. The thin sections were made from the Allen #1 well cuttings (Figure 4). While the thin sections made from the well cuttings enabled the determination of porosity, it was difficult to delineate sedimentary structures, detrital mineralogy and replacement features from the thin sections. X-ray diffraction analysis (XRD) was used to determine detrital mineralogy and authigenic constituents. Thin section analysis corroborated the interpretation through wireline log analysis that the DC-4 distributary channel package and the DC-2 delta front package show the most porosity potential. All images are in plane polarized light (PPL) and porosity is shown in pink because pink dye was to process the thin sections.

Several porosity types were determined for the DC-4 distributary channel deposits through thin-section microscopy. They include: 1) primary intergranular porosity, 2) secondary intragranular porosity, and 3) secondary microporosity. Fracture porosity found in detrital grains in the form of secondary intragranular porosity was the most common form of porosity present in the DC-4 package (Figure 30); this is likely the result of the extensive structural activity that was occurring in the basin in the early Pennsylvanian while these sediments were being deposited (Lahti, 1982). This type of porosity is often not captured in wireline porosity logs (Elphick, 1996). Hence the average porosities obtained for the DC-4 package using wireline porosity logs are probably higher in actuality. The second type of secondary intragranular porosity found in the DC-4 package was porosity due to dissolution of metastable feldspar grains, chert and limestone (Figure 32).

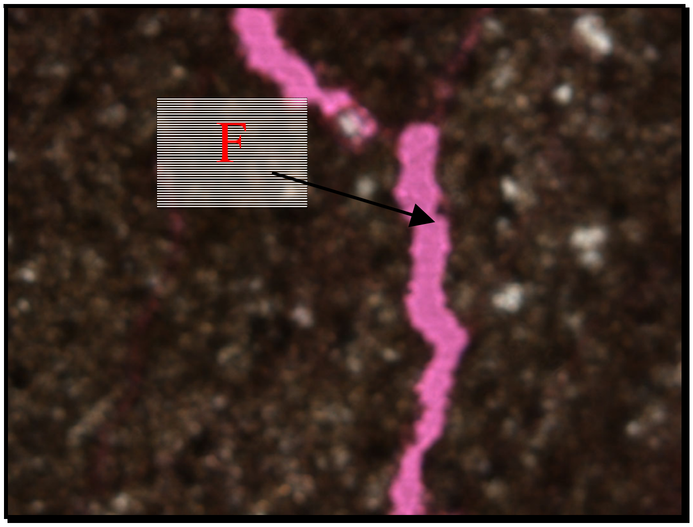

Figure 30: Photomicrograph of the DC-4 package showing secondary fracture porosity (F) .

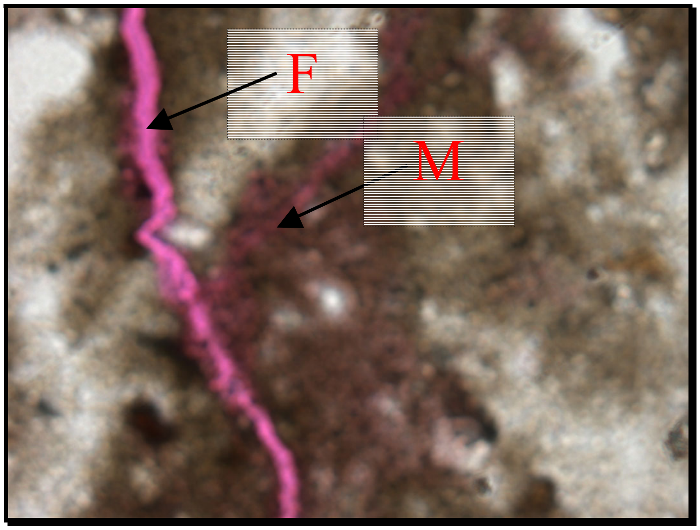

Figure 31: Photomicrograph of the DC-4 package showing secondary fracture porosity (F) and Intergranular secondary microporosity (M).

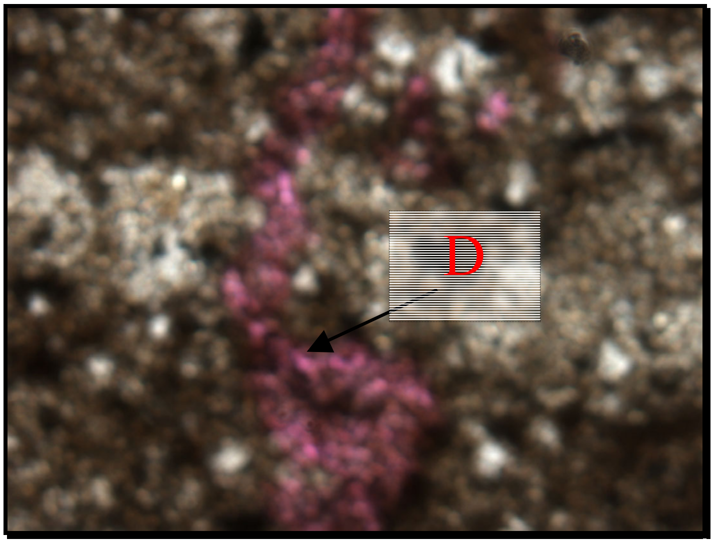

Figure 32: Photomicrograph of the DC-4 package showing secondary dissolution porosity (D).

Primary intergranular porosity also exists in the DC-4 package as primary pores that are preserved (Figure 33). This primary porosity has not been filled by authigenic clays or syntaxial silica cement and is critical to the development of secondary porosity as it provided the conduit for corrosive fluids to connect to metastable grains and dissolve them (Puckette, class notes). However, this type of porosity was not observed as frequently as secondary intragranular porosity as it is very difficult to detect this porosity type in bit cuttings because the rock tends to break along the plane of these large pores.

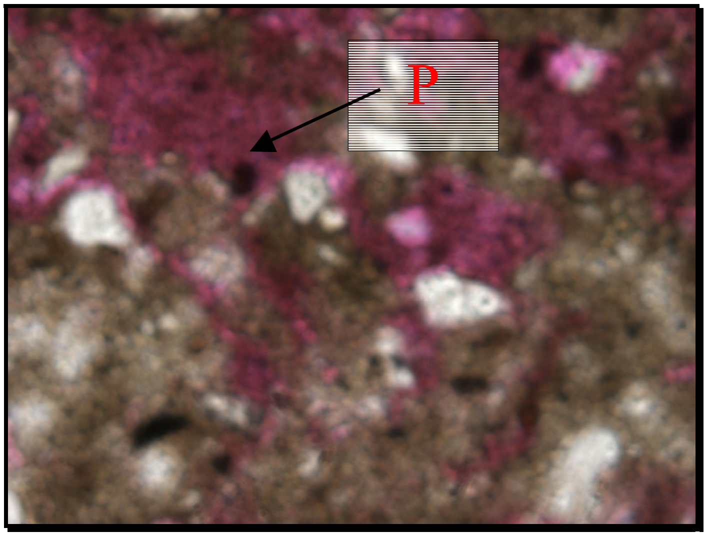

Figure 33: Photomicrograph of the DC-4 package showing primary intergranular porosity (P).

Microporosity occurs in the DC-4 package as the void spaces within authigenic clays and the micro pores within partially dissolved feldspar and chert grains. The intragranular microporosity is evident in metastable feldspar and chert grains (Figure 31). These micro pores host bound water and can cause resistivity readings to be lower than expected, which can affect water saturation calculations (Elphick, 1996).

The DC-3 pro-deltaic deposits do not show any primary intergranular porosity. The only porosity evident are very few secondary intragranular porosity in the form of fractures due to compaction (Figure 34). This is consistent with the findings from well log analysis and XRD analysis that the porosity values within this depositional cycle are low and these deposits are rich in clay minerals.

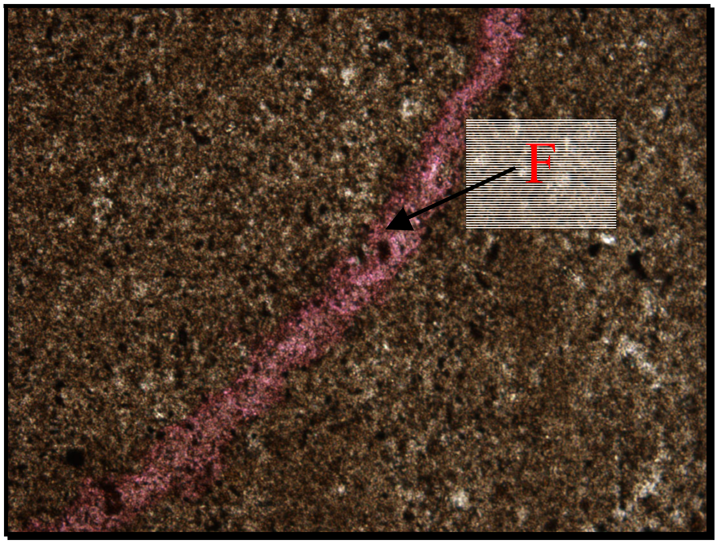

Figure 34: Photomicrograph of the DC-3 package showing secondary fracture porosity (F).

The DC-2 delta front deposits exhibited two porosity types; Primary intergranular porosity(Figure 35) and secondary intragranular porosity in the form of fractures and dissolution of metastable feldspar grains (Figures 36 and 37). The most common porosity type observed was secondary dissolution porosity. From thin section analysis, this depositional cycle has the second highest porosity occurrence corroborating wireline porosity analysis.

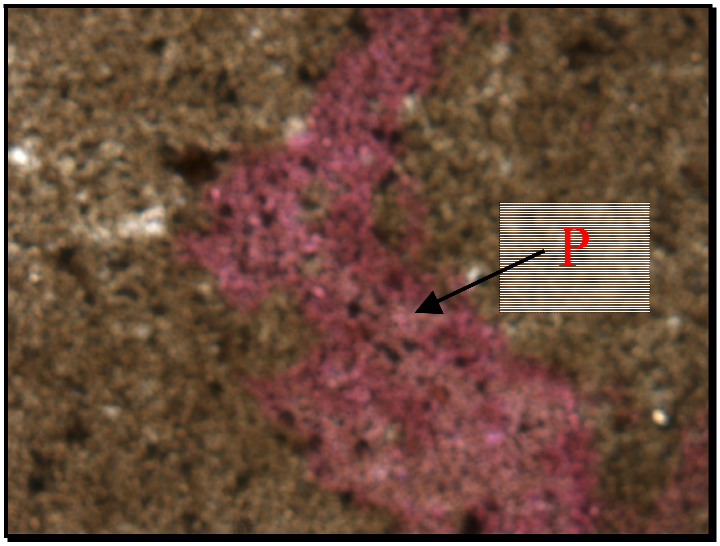

Figure 35: Photomicrograph of the DC-2 package showing primary intergranular porosity (P)

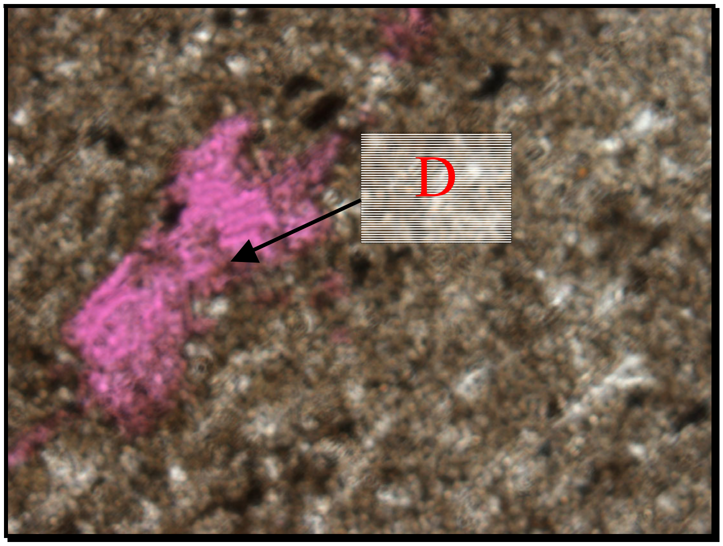

Figure 36: Photomicrograph of the DC-2 package showing secondary dissolution porosity (D)

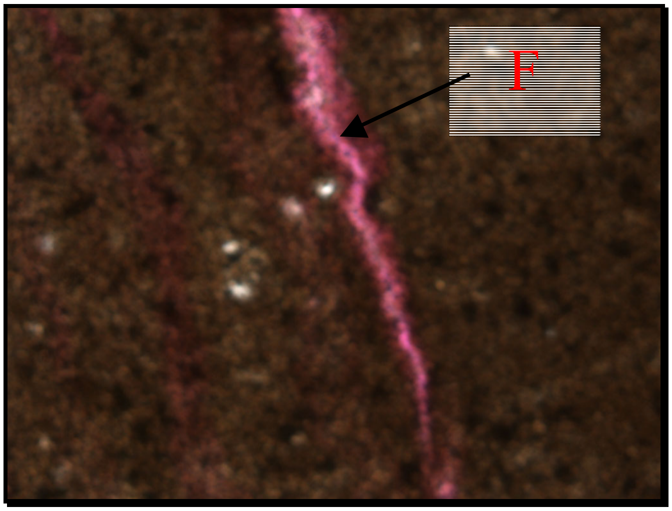

Figure 37: Photomicrograph of the DC-2 package showing secondary fracture porosity (F).

Like the DC-3 pro-deltaic deposits, the pro-deltaic DC-1 package does not exhibit much porosity in thin sections. The only observed porosity was secondary porosity due to fractures (Figure 38). The presence of primary intergranular porosity cannot be completely ruled out because it was not observed in thin section. As discussed earlier, it is very difficult to detect this porosity type in bit cuttings since the rock tends to break along the plane of these large pores.

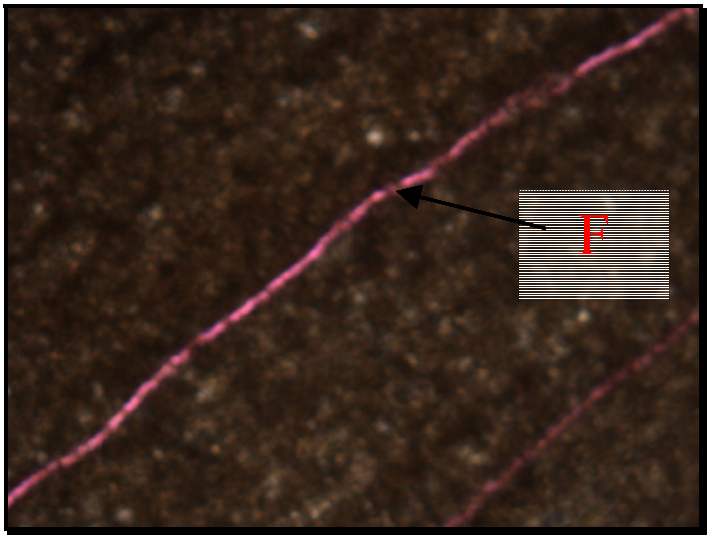

Figure 38: Photomicrograph of the DC-1 package showing secondary fracture porosity (F).

Scanning Electron Microprobe Analysis

Scanning electron microprobe analysis was used to confirm reservoir potential determined by thin section and wireline log analysis. The samples used for the SEM analysis are also from the Allen #1 well in Denton County. An electron microprobe is a microscope that allows the chemical analysis of small areas of a sample and produces an image when these samples are bombarded by a focused electron beam. These images were then analyzed for the presence of pore spaces indicating porosity and authigenic clays that would indicate water saturation. Accuracy for the electron microprobe is about +/- 1% and it has detection limits of about 50 ppm (Catlos, personal connunication).

The DC-4 distributary channel deposits show the most pore spaces from the derived SEM images, also a lot of calcite crystals were identified in the SEM images for this package confirming the hypothesis that this interval is a mixed terrigenous-carbonate interval (Figure 39). Fracture porosity observed in thin sections was also identified in the backscattered images for the DC-4 package (Figure 40).

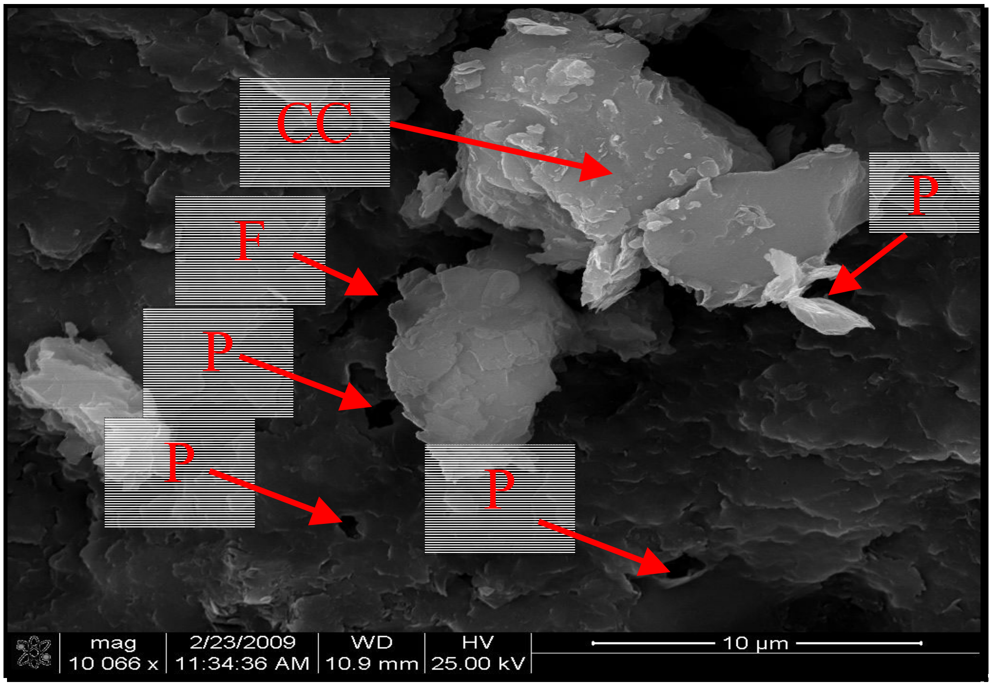

Figure 39: Backscattered image of the DC-4 package showing pore spaces (P), Fractures (F) and calcite crystals (CC) filling some of the bigger pore spaces.

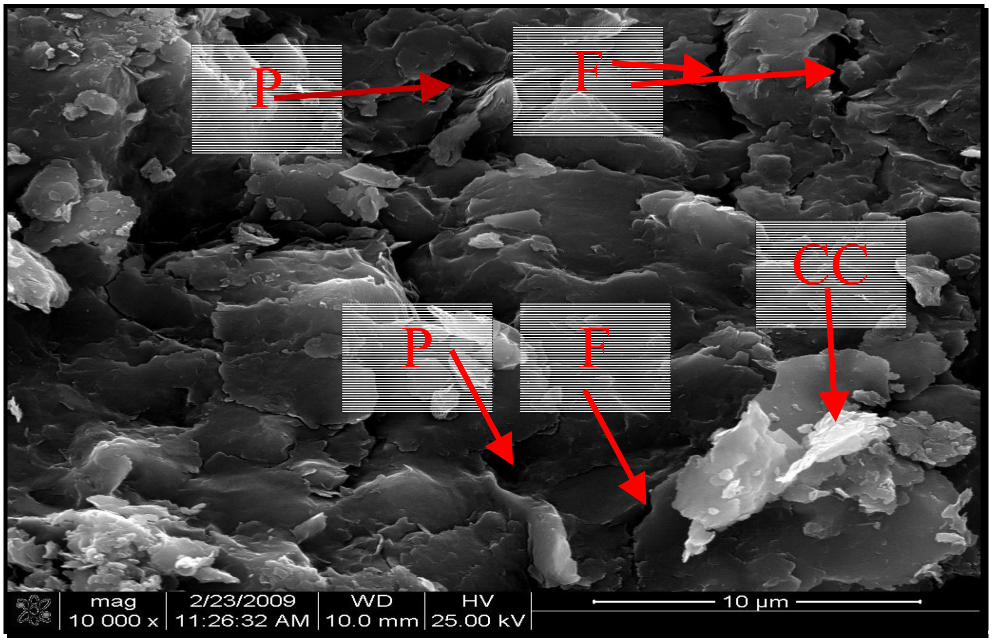

Figure 40: Backscattered image of the DC-4 package showing pore spaces (P), fracture (F) and calcite crystals (CC).

The backscattered images for the DC-3 package did not show pore spaces. From XRD analysis the sediments in this depositional cycle contain a lot of clay minerals in the form of Illite, Kaolinite and Chlorite. These clay minerals tend to line and fill pore spaces. This agrees with the conclusion through well log analysis and thin section microscopy that sediments in this depositional cycle do not exhibit much reservoir potential.

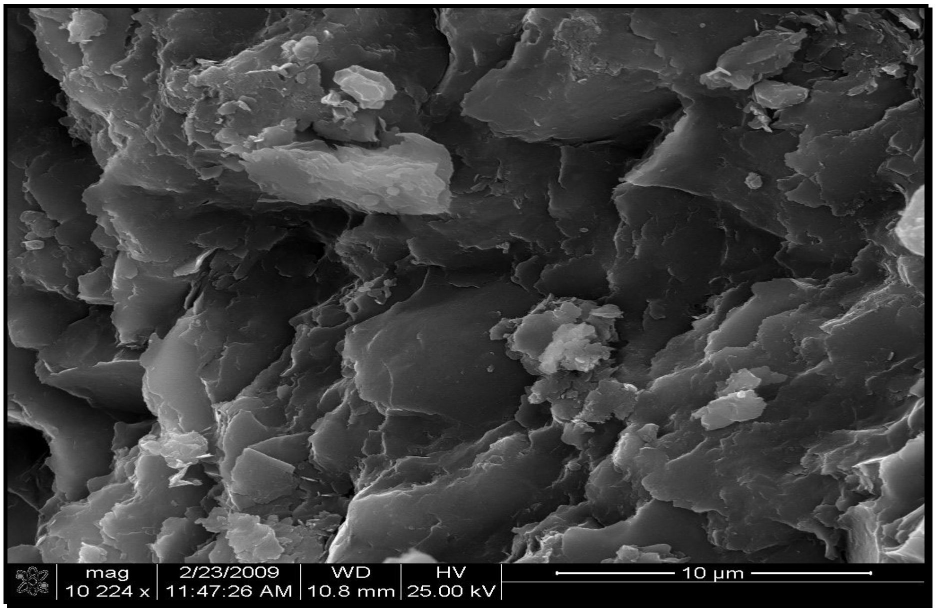

Figure 41: Backscattered image of the DC-3 package. Note the relative absence of pore spaces.

The DC-2 delta front deposits show some porosity in the backscattered image and some of these pores have been filled with clay minerals (Figures 42 and 43). From SEM analysis, this package shows the second highest porosity potential of all the identified depositional cycles.

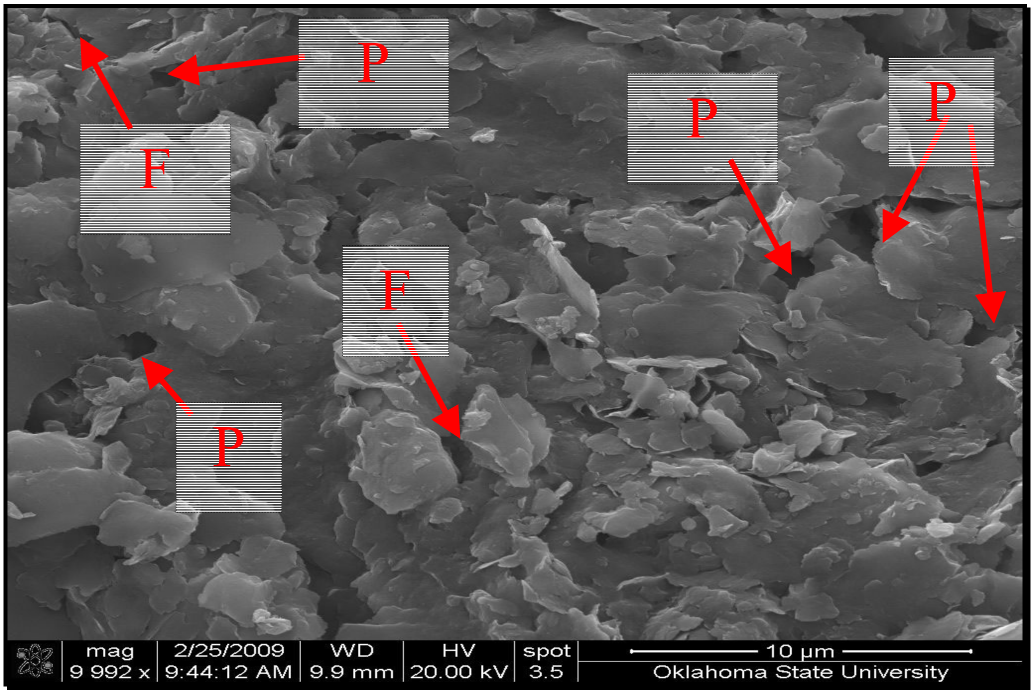

Figure 42: Backscattered image of the DC-2 package showing pore spaces (P) and fractures (F).

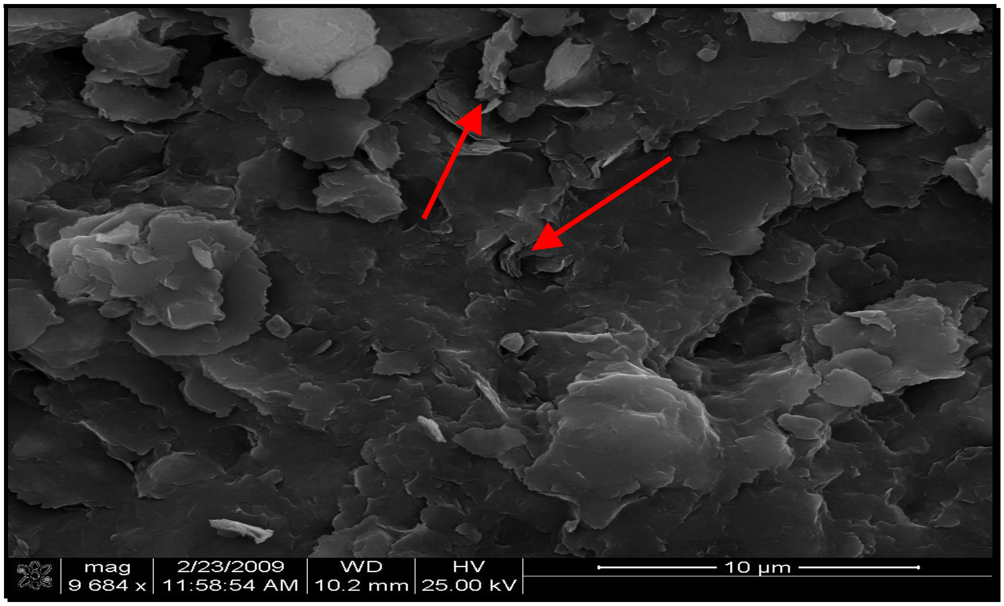

Figure 43: Backscattered image of the DC-2 package showing pore spaces filled with clay minerals (Illite).

The DC-1 pro-deltaic deposits show some minor porosity in the backscattered image and from XRD analysis, are composed primarily of silica and clay minerals (Figure 44).

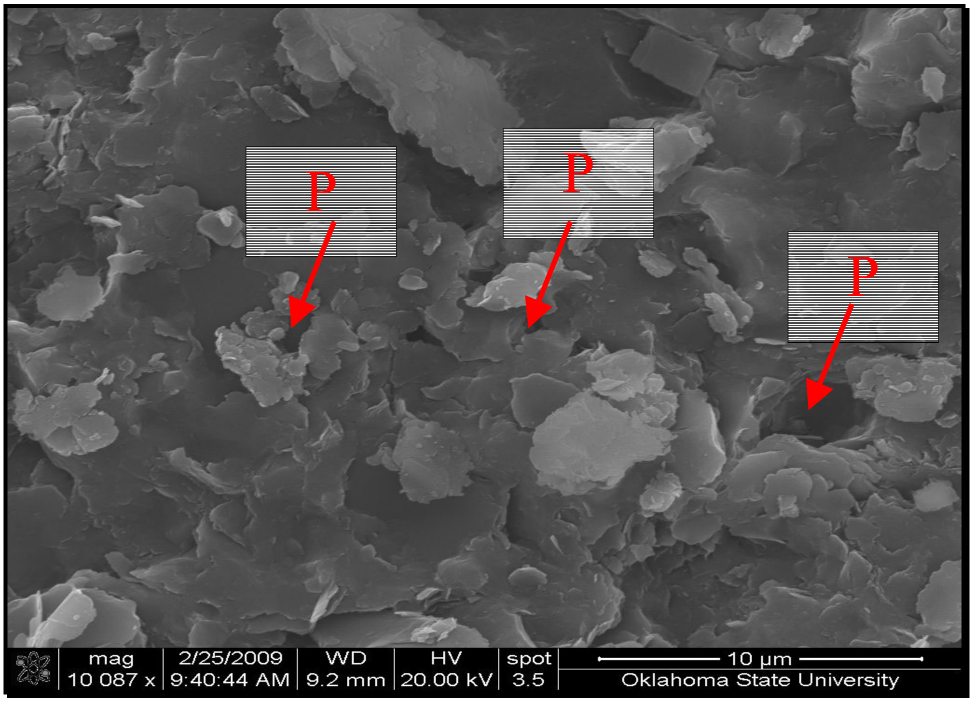

Figure 44: Backscattered image of the DC-1 package showing pore spaces.

Depositional Cycles and Reservoir Porosity Potential

In the Fort Worth Basin, the Bend Group is known for its “tight”, gas producing sandstones and conglomerates of the DC-4 distributary channel package (Lovick, 1982). Hydrocarbons are normally extracted from multiple stacked sandstone and conglomerate lenses; hence production is controlled stratigraphically since these lenses are not laterally continuous (Thompson, 1982). The distribution of porosity is erratic because these sandstones and conglomerates lenses are not homogenous. The porosity values of producing zones range from as low as 6% to as high as 22%. The producing zones are usually fractured with sand to generate more porosity and increase permeability. As evidenced by the thin section photographs and the backscattered SEM images (Figures 31, 32 and 41), the DC-4 package already has some associated fractures so these artificial fracture jobs tend to break the deposits along their fractured planes to create permeability (Pollastro, 2003).

Based on the examination of integrated wireline logs, thin-sections, SEM and XRD data, the DC-4 distributary channel deposits have the best porosity development and least water saturation, hence the best reservoir potential. Within the prograding fan-delta sequence, the DC-4 distributary channel package exhibits the highest sandstone porosity value. These channel deposits represent the thickest and cleanest sandstones within the progradational sequence. Thicker and "cleaner" distributary channel sandstones have higher porosity and lower water saturation values than thinner ones.

There appears to be permeability within each individual sandstone lens. However, these lenses are not laterally continuous; this reservoir heterogeneity coupled with the "tight" nature of the DC-4 package is the reason why oil and gas operators have recently began horizontal drilling of the Bend Group.

CHAPTER VI

CONCLUSIONS

Upon studying and analyzing the Bend Group and its associated depositional cycles, the following conclusions were reached:

1. The Bend Group was deposited in a prograding fluvial dominated fan delta environment during early-middle Pennsylvanian time while the basin was undergoing subsidence due to tectonic activity occurring at the Ouachita Structural Belt and the Muenster Arch which both served as source areas.

2. Four depositional cycles (DC1-4) were identified based on wireline log analysis with DC-4 being the base of the Bend Group and DC-1 being the top. These wireline log derived depositional cycles correlated well with the depositional facies observed in core, thin section analysis, SEM analysis and XRD analysis.

3. The DC-4 package is the proximal delta/distributary channel facies and it thickens considerably adjacent to the Muenster Arch, confirming the hypothesis that the Muenster Arch was active in early Pennsylvanian time and was a source of terrigenous rich clastics that were observed in the DC-4 facies. The DC-3 package is a pro-delta/delta front assemblage while the DC-2 package is primarily delta front deposits and the DC-1 package (the most distal facies) is prodelta silt, clay rich mudrocks and shale.

4. An unconformity was observed in wireline logs that placed the DC-1 package directly on top of DC-4 package adjacent to the Muenster Arch. The DC-2 and DC-3 sediments were not deposited during this time. This is because in early Pennsylvanian time at the onset of Bend Group deposition the Muenster Arch was active and was undergoing subsidence. It shed terrigenous rich coarse clastics into the basin and these clastics make up the DC-4 deposits and form the delta plain and distributary channel facies of the delta system. Hence, the delta front facies represented by the DC-2 and 3 cycles were not deposited adjacent to this tectonically active source.

5. Isopach maps show that the distinctive distribution patterns of each of the four depositional cycles have a general northern trend that suggests a source to south and transport in a northeasterly direction.

6. The reservoir potential of each of the depositional cycles was analyzed using several tools including wireline neutron-density porosity curves, SEM, thin section microscopy and XRD. The best reservoir potential was observed in the DC-4 distributary channel deposits; this package showed the best porosity development and the least water saturation in all the analyses carried out. The clay rich pro-deltaic cycles (DC-1 and DC-3) had the least reservoir potentials.

7. The DC-4 package has the widest distribution. It is the most proximal of the Bend Group facies and has numerous stacked sandstone and conglomerate lenses. These lenses are usually very “clean”, have “robust” SP deflections and the highest porosities in

the package are usually found within these sandstone and conglomerate lenses. This package is the primary target for hydrocarbons in the Bend Group.

8. The reservoir heterogeneity present in the Bend Group, due to the lateral discontinuity of the numerous stacked productive sandstone and conglomerate lenses, has caused several oil and gas operators to start evaluating bypassed and missed pay potential in the Bend Group. Most recently, improved drilling techniques like horizontal drilling has been employed due to the “tight” and heterogeneous nature of Bend Group reservoirs.

REFERENCES

Alberta, P. L., 1987, Depositional facies analysis and porosity development of the (Pennsylvanian) upper Morrow chert-conglomerate Puryear member, Roger Mills and Beckham Counties, Oklahoma: Oklahoma State University unpublished M.S. thesis, 135 p.

Barnes, V. E., Cloud, P. E., 1953, Upper Ordovician of central Texas: American Association of Petroleum Geologists Bulletin 5, v.37, p. 1030-1043.

Bates, C. C., 1953, Rational theory of delta formation: American Association of Petroleum Geologists Bulletin 9, v. 37, p. 2119-2162.

Blair, T., and McPherson, J., 1994, Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages: Journal of Sedimentary Research., Vol. A64. No. 3, pp. 450-489.

Blanchard, K. S., Denman, O., and Knight, A. S., 1959, Natural gas in Atokan (Bend) section of northern Fort Worth Basin, in Beebe, E. W., ed., Natural gasses of North America: American Association of Petroleum Geologists Memoir 9, v. 2, p. 1446-1454.

Brown, L. F., Jr., 1967, Virgil and lower Wolfcamp repetitive environments and depositional model, north-central Texas, In Elam, J.G and S. Chuber, eds., Cyclical sedimentation in the Permian Basin: West Texas Geological Society Guidebook, p 115-131.

Brown, L. F., Jr., Cleaves, A. W., II, and Erxleben, A. W., 1973, Pennsylvanian depositional systems in North-Central Texas, a guide for interpreting terrigenous clastic facies in a cratonic basin: The University of Texas at Austin, Bureau of Economic Geology Guidebook 14, 122 p.

Bull, W. B., 1972, Recognition of alluvial fan deposits in the stratigraphic record, in J. K. Rigby, and W. K. Hamblin, eds., Recognition of Ancient Sedimentary Environments: SEPM Spec. Pub. No. 16, pp. 63-83.

Casey, J. M., Depositional systems and basin evolution of the late Paleozoic Taos trough, northern New Mexico: Texas Petroleum Research Committee, Univ. Div., Austin, Texas, Rept. No. UT 80-1, 236 p.

Cleaves, A. W., II, 1975, Upper Desmoinesian-Lower Missourian depositional systems (Pennsylvanian) North-Central Texas: Ph.D. dissertation, University of Texas at Austin, 256 p.

Cole, T., 1942, Subsurface study of the Ellenburger Formation in West Texas: AAPG Bulletin 8, v.26, p. 1398-1043.

Coleman, J. M., and Prior, D. B., 1982, Deltaic Environments of Deposition, In Scholle P. A and D. Spearing, eds., Sandstone Depositional Environments: AAPG Memoir 31, v. 1, p. 139-178.

Crosby, E.J., and W. J. Mapel, 1975, Paleotectonic Investigations of the Pennsylvanian System in the ed States, Part I: Introduction and Regional Analyses of the Pennsylvanian System, Central and West Texas, in USGS Professional Paper 853, E.E Mckee and E.J Crosby, p. 197-232.

Derby, J. R., 2002, US DOE sponsored study of west Carney Hunton field, Lincoln and Logan Counties, OK: A preliminary report (part 1): Oklahoma City Geological Society 1, v. 53, p. 9-19.

Dickinson, W.R., 1978, Plate tectonic evolution of sedimentary basins, In Plate tectonics and hydrocarbon accumulations: AAPG Course Notes No. 1, p. 1- 56.

Dutton, S. P., 1980, Depositional systems and hydrocarbon resource potential of the Pennsylvanian System, Palo Duro and Dalhart Basins, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 80-8, 49 p.

Dutton, S.P., 1982, Pennsylvanian fan-delta and carbonate deposition, Mobeetie Field, Texas Panhandle: Amer. Assoc. Petrol. Geologist Bulletin, v. 66, no. 4, p. 389-407.

Eardley, A. J., 1962, Structural Geology of North America (Second Edition), Harper and Row Publishers, New York and Evanston, p. 743.

Edwards, A. R., 1958, Facies changes in Pennsylvanian rocks along north flank of Wichita Mountains, in J. W. Mayes, J. Westheimer, C. W. Tomlinson, and D. M. Putnam, eds., Petroleum geology of southern Oklahoma, a symposium, v. s: AAPG, p. 142-155.

Elphick, R.Y, Carr, D.L., Johns, R.A and Lancaster, D.E., 1996, A deterministic method for calculating facies from wireline logs: The log analyst, v. 37, no. 2, p. 125-142.

Fischer, J. F., 1976, Tectonic origin of the Delaware, Marfa, and Val Verde basins, in Sullivan, N.M., ed., Petroleum exploration – thrust belts and their adjacent forelands: West Texas Geological Society, p. 7-23.

Fisher, W. L., and McGowen, J. H., 1969, Depositional Systems in Wilcox Group (Eocene) of Texas and their relation to occurrence of oil and gas: American Association of Petroleum Geologist Bulletin, v. 53, p. 30-54.

Flawn, P. T., Goldstein, A. G., Jr., King, P. B., and Weaver, C. E., 1961, The Ouachita System: University of Texas, Austin, Bureau of Economic Geology Publication No. 6120, 401 p.

Frenzon, S. E., and Dixon, G. H., 1975, Texas Panhandle and Oklahoma, in E. D. McKee et al., Paleotectonic investigations of the Pennsylvanian System in the ed States: U. S. Geological Survey Prof, Paper 853, pt. 1, p. 177-194.

Galloway, W.E., 1985, Ancient alluvial fans and fan deltas, in R. M. Flores, ed., Recognition of Fluvial Depositional Systems and Their Resource Potential : SEPM Short Course No. 19, pp. 127-143.

Galloway, W.E., and Hobday , D.K., 1983, Terrigenous clastic depositional systems, New York, Springer-Verlag, 423 p.

Gardner, T. W., Paleohydrology and paleomorphology of a Caboniferous, meandering, fluvial sandstone: Journal of Sedimentary Petrology, v. 53, p. 991-1005.

Gee, D. E., 1976, The base of Pennsylvanian in the Fort Worth Basin – some regional comparisons above and below: Abilene Geological Society Geological Contributions, p. 6-9.

Glover, G., 1982, A Study of the Bend Conglomerate in S.E. Maryetta Area, Boonesville field, Jack County, Texas: in C.M. Martin, ed., Petroleum Geology of the Fort Worth Basin and Bend Arch Area, Dallas Geological Society, p. 97-127.

Handford, R. C., and Dutton, S. P., 1980, Pennsylvanian-Early Permian depositional systems and shelf-margin evolutiion, Palo Duro Basin, TX: Am. Assoc. Petro. Geol. Bull., Vol. 64, pp. 88-106.

Herkommer, M. A., and Denke, G. W., 1982, Stratigraphy and Hydrocarbons, Parker County, Texas: in C.M. Martin, ed., Petroleum Geology of the Fort Worth Basin and Bend Arch Area, Dallas Geological Society, p. 97-127.

Lahti, V. R., and Huber, W. F., 1982, The Atoka Group (Pennsylvanian) of the Boonesville Field Area, North Central Texas: in C.M. Martin, ed., Petroleum Geology of the Fort Worth Basin and Bend Arch Area, Dallas Geological Society, p. 377-399.

Lovick, G. P., Mazzine, C. G., and Kotila, D. A., 1982. Atokan Clastics – Depositional Environments in a Foreland Basin: in C.M. Martin, ed., Petroleum Geology of the Fort Worth Basin and Bend Arch Area, Dallas Geological Society, p. 193-211.

McGowen, J.H., 1970, Gum Hollow Fan Delta, Nueces Bay, Texas: The Univ. of Texas at Austin, Bureau of Economic Geology Report of Investigations. No. 69, 91 p.

Pollastro, R. M., 2003, Geologic and production characteristics utilized in assessing the Barnett Shale continuous (unconventional) gas accumulation, Barnett-Paleozoic total petroleum system, Fort Worth Basin, Texas: Barnett Shale Symposium, Ellison Miles Geotechnology Institute at Brookhaven College, Dallas, Nov. 12-13, 2003, p. 7-14.

Pranter, M. J., 1989, Facies analysis of the Strawn submarine fan complex: Fort Worth Bain, Central Texas: Baylor University M.S. thesis, 143 p.

Sneider, R. M., Richardson, F. H., Paynter, D. D., Eddy, R. E., and Wyant, L. A., 1977, Predicting reservoir rock geometry and continuity in Pennsylvanian reservoirs, Elk City Field, Oklahoma: Jour. Petro. Tech., July 1977, PP. 851-866.

Solis, R. F., 1972, Subsurface geology of the central part of the Fort Worth Basin:The University of Texas at Austin, Master's thesis, 91p.

Thompson, D. M., 1982, Atoka Group (lower to middle Pennsylvanian), northern Fort Worth Basin, Texas : Terrigenous depositional systems, diagenesis, and Reservoir distribution and quality : Bureau of Economic Geology, University Texas at Austin, Report of Investigations No. 125, 62 p.

Thompson, C. L., 2007, Electrofacies analysis and petrology of (Pennsylvanian) Cherokee granite wash, in parts of Roberts and Hutchinson Counties, Texas: Oklahoma State University unpublished M.S. thesis, 97 p.

Turner, G. L., 1957, Paleozoic stratigraphy of the Fort Worth Basin, in Conselman, F. B., ed., Abilene and Fort Worth Geological Society Guidebook, 1957 Joint Field Trip Guidebook, p 52-59.

Varnes, D.J., 1978, Slope movement types and processes, in Schuster, R.L. and Krizek, R.J., eds, Landslides, Analysis and Control: Washington D.C., Transportation Research Board, National Academy of Sciences, Special Report 176, pp. 11-33.

Walper, J. L., 1982, Plate tectonic evolution of the Fort Worth Basin, in Martin, C.A.,ed., Petroleum Geology of the Fort Worth Basin and Bend Arch Area: D Dallas Geological Society, p. 237-251.

Wermund, E. G., Upper Pennsylvanian Limestone Banks, North-Central Texas, Bureau of Economic Geology, The University of Austin at Texas, Geological Circular 75, p. 34.

Wescott, W.A., and Ethridge, F.G., 1980, Fan-delta sedimentology and tectonic setting – Yallahs fan delta, southeast Jamaica: Amer. Assoc. Petrol. Geologist Bull., Vol. 63, p. 374-399.

Wickham, J. W., 1978, The Southern Oklahoma Aulacogen, in Field Guide to the Structure and Stratigraphy of the Ouachita Mountains and the Arkoma Basin: Annual Meeting of Am. Assoc. Petro. Geol. Bull., Vol. 69, No. 8, p. 1320.

Wyllie, M. R. J., 1963, The fundamentals of electric log interpretation, 3rd ed. Academic Press, New York.

VITA

Olaniyi Kayode Adisa

Candidate for the Degree of

Master of Science

Thesis: DEPOSITIONAL CYCLES ANALYSIS, RESERVOIR PROPERTIES AND THE DISTRIBUTION OF THE BEND GROUP, DENTON COUNTY, FORT WORTH BASIN, TEXAS.

Major Field: Geology

Biographical:

Personal Data: Born in Ibadan, Nigeria, February 27, 1982; the son of Mr. and Mrs. I.A Adisa.

Education: Graduated from International School Ibadan, Nigeria in May of 1999; received Bachelors of Science degree in Geology from Oklahoma State University in July, 2008; completed requirements for the Masters of Science degree at Oklahoma State University in July, 2009.

Experience: Geological Intern, Chesapeake Energy, 2007-2008.

Professional Memberships: American Association of Petroleum Geologist; Society of Exploratory Geophysicists.

Name: Olaniyi Adisa Date of Degree: December, 2010

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study DEPOSITIONAL CYCLES ANALYSIS, RESERVOIR PROPERTIES AND THE DISTRIBUTION OF THE BEND GROUP, DENTON COUNTY, FORT WORTH BASIN, TEXAS

Pages in Study: 81 Candidate for the Degree of Master of Science

Major Field: Geology

Scope and Method of Study: The purpose of this study is to examine the Bend Group in Denton County, Fort Worth Basin TX. The objectives include: a discussion of fan-delta depositional processes, depositional cycles, and environment; the construction of maps to illustrate structure, geometry, trend, and source direction of the Bend Group and associated depositional cycles; recognize depositional cycles utilizing well log signatures; construct various cross sections to develop a depositional model; analyze porosity and water saturation of the various depositional cycles; and to evaluate petrographic and diagenetic characteristics of the Bend Group.

Findings and Conclusions: Four different depositional cycles were identified using well logs and correlated with core. Gross isopach maps of each of the four depositional cycles show lobate geometries that trend northeast indicating a northeasterly transport direction. Depositional cycles with the best porosity development and reservoir potential were distributary channels. Due to its better porosity development and widespread distribution, the DC-4 distributary channel package is the most suitable target for hydrocarbon exploration within the study area. The detrital mineralogy of the Bend Group is dominantly quartz with varying amounts of granitic rock fragments and feldspar. Porosity is mainly secondary and is the result of dissolution of rock metastable grains and fracturing.

ADVISER'S APPROVAL: Darwin Boardman