

THE SUBSIDENCE EVOLUTION OF THE FORT WORTH BASIN IN NORTH CENTRAL
TEXAS, U.S.A.

by

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Abstract

THE SUBSIDENCE EVOLUTION OF THE FORT WORTH BASIN IN NORTH-CENTRAL TEXAS, U.S.A.

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Although the Fort Worth Basin in north-central Texas has become a major shale-gas production system in recent years, its subsidence history and dynamic relationship to the Ouachita fold-and-thrust belt have not been well understood. Here I study the sedimentation patterns, model the basin subsidence and thermal maturation histories to understand the evolution of the Fort Worth Basin. Depositional patterns show that the tectonic loading of both the Muenster Arch and the Ouachita fold-and-thrust belt influenced the subsidence of the basin as early as the middle-late Mississippian. Rapid subsidence of the basin initiated in the earliest Pennsylvanian in response to the propagation of the Ouachita fold-and-thrust belt. The rapid subsidence lasted into the Permian based on 2D flexure subsidence and thermal maturation modeling. The Pennsylvanian source rocks in the northeast part of the basin entered the gas maturation window with ~6.5 km of burial during the late Pennsylvanian-Permian.

Table of Contents

Acknowledgements	iii
Abstract	iv
List of Illustrations	vii
List of Tables	ix
Chapter 1 Introduction.....	1
1.1 Objectives	1
1.2 Geological Setting.....	3
1.3 Stratigraphy	5
1.4 Hypothesis	9
Chapter 2 Methods.....	10
2.1 Isopach and Structure Maps.....	10
2.2 Post-Pennsylvanian Exhumation and Burial History	11
2.3 1D Tectonic Subsidence	15
2.4 2D Flexure Subsidence	16
Chapter 3 Results	19
3.1 Isopach and Structure Maps.....	19
3.2 Post-Pennsylvanian Exhumation and Burial History	22
3.3 1D Tectonic Subsidence History	25
3.4 2D Flexure Subsidence Profile	27
Chapter 4 Discussion	30
4.1 Development of a Foreland Basin	30
4.2 Significance for regional tectonics and paleogeography	32
4.3 Significance for petroleum generation	33
Chapter 5 Conclusions	35

References.....	37
Biographical Information	47

List of Illustrations

Figure 1-1 Geological map of the Fort Worth Basin and its vicinity in southern United States.....	2
Figure 1-2 Generalized stratigraphic column of the Fort Worth Basin and the type log in the Jack County. Red wavy line represents unconformity. Lithostratigraphy of the type log is based on GR (gamma ray), and RES (resistivity) logs following Hentz et al. (2012). The stratigraphic column is modified from USGS (2003) and Pollastro (2003)	8
Figure 3-1 Generalized structure maps of the Fort Worth Basin. A: top of the Barnett Shale (318.1 Ma), B: top of the Marble Falls Group (310 Ma), C: top of the Bend Group (308 Ma), and D: top of the Strawn Group (306.5 Ma). The covered area of beige color in D represents the outcrop of the Strawn Group.	20
Figure 3-2 Generalized isopach maps of A: the Barnett Shale, B: the Marble Falls Group, C: the Bend Group, and D: the Wichita and Strawn Groups. Contour intervals are 50 m for A-C, and 100 m for D.	21
Figure 3-3 A: Scenario 1 of the burial and exhumation history of the Fort Worth Basin. Missi.: Mississippian, Pen.: Pennsylvanian, Neog.: Neogene. B: Modeled vitrinite reflectance data compared to measured vitrinite reflectance data (grey bars).....	23
Figure 3-4 A: Scenario 2 of the burial and exhumation history of the Fort Worth Basin. Missi.: Mississippian, Pen.: Pennsylvanian, Neog.: Neogene. B: Modeled vitrinite reflectance data compared to measured vitrinite reflectance data (grey bars).....	24

Figure 3-5 A: Reconstructed tectonic subsidence curves of the five studied sites; B: locations of the studied sites are represented by red crosses in the Fort Worth Basin	26
Figure 3-6 A: The flexural subsidence profile of the Fort Worth Basin during the late Pennsylvanian. The red crosses are the decompacted thickness from isopach map. The blue curve is the best-fit modeled flexural subsidence profile. D: flexure rigidity, EET: effective elastic thickness, h: load height, hw: load half width; B: location of the cross-section is represented by red line in the Fort Worth Basin	28
Figure 3-7 The flexural subsidence profile of the Fort Worth Basin during the late Pennsylvanian. D: flexure rigidity, EET: effective elastic thickness, h: load height, hw: load half width. A: the best-fit for scenario 1. B: the best-fit for scenario 2	29

List of Tables

Table 2-1 Parameters used for the calculation of tectonic subsidence and original strata thickness data in the five counties.	14
Table 2-2 Parameters used for the calculation of flexure subsidence	18
Table 3-1 Tectonic subsidence data in five counties	25

Chapter 1

Introduction

1.1 Objectives

The Fort Worth Basin is one of the several foreland basins of the Ouachita fold-and-thrust belt (Walper, 1982; Thompson, 1988; Erlich and Coleman, 2005; Elebiju et al., 2010) (Fig. 1-1). A foreland basin consists of four depozones, which are, from mountain front to distal basin, wedge-top, foredeep, forebulge, and back-bulge (DeCelles and Giles, 1996). The classic model of foreland basin suggests tectonic loading of the basin-bounding fold-and-thrust belt causes flexural subsidence to form a foreland basin and the sediments filled the foredeep depozone of the basin are predominantly derived from the fold-and-thrust belt (DeCelles and Giles, 1996). Several studies suggest that the Ouachita fold-and-thrust belt was the main sediment source of the Fort Worth Basin during the late Mississippian-late Pennsylvanian (Walper, 1982; Grayson et al., 1991; Noble, 1993; Pollastro, 2003), consistent with what the classic foreland basin model predicts. However, other studies suggest that the Muenster Arch to the north of the Fort Worth Basin was the primary sediment source during the early Pennsylvanian (Lovick et al., 1982; Thomas, 2003), and caused subsidence of the basin as early as the Mississippian (Loucks and Stephen, 2007). Furthermore, the structure orientations within the basin are variable, reflecting a more complex stress field that may not be explained by a single structure element, such as the Ouachita fold-and-thrust belt, or the Muenster Arch (Adams, 2003; Montgomery et al., 2005; Pollastro et al., 2007). Therefore, the subsidence history and mechanism of the Fort Worth Basin remain controversial. In addition to the tectonic significance, the subsidence history of the Fort Worth Basin may guide future hydrocarbon exploration and production. The basin has produced

approximately 2 Mbbl of oil and 7 tcf of gas from several late Paleozoic and Cretaceous formations (Pollastro, 2003; Thomas, 2003).

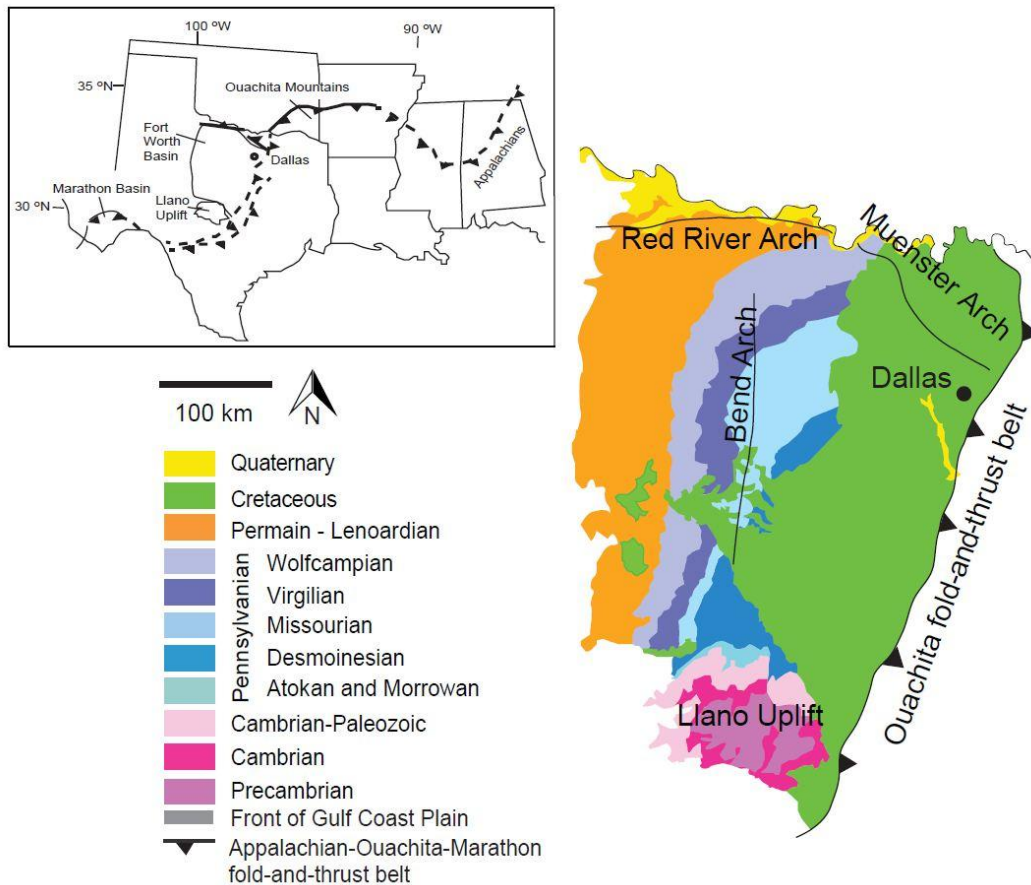


Figure 1-1 Geological map of the Fort Worth Basin and its vicinity in the southern United States

Up to today, only one research has studied the subsidence history of the Fort Worth Basin. Erlich and Coleman (2005) derived a subsidence rate of 130 m/Myr for the northern part of the basin, and 60 m/Myr for the southwestern part of the basin during the late Mississippian-Pennsylvanian. However, this study did not account for sediment compaction and loading, and overestimated tectonic subsidence rates. Decompaction to the late Mississippian-Pennsylvanian strata requires knowledge regarding the post-

Pennsylvanian burial and exhumation history of the Fort Worth Basin, which has not been understood because of limited preservation of the post-Pennsylvanian strata. The current understanding to the post-Pennsylvanian burial and exhumation history includes two schools of thought: 1) Grayson et al. (1991) and Montgomery et al. (2005) suggested that sediment accumulation occurred during the Permian, and no additional sedimentation occurred until the early Cretaceous; 2) Jarvie et al. (2005) and Ewing (2006) argued that basin exhumation occurred during the late Triassic-Jurassic as a result of rift-shoulder uplift during the opening of the Gulf of Mexico. Therefore, the post-Pennsylvanian burial and exhumation histories should also be constrained in order to adequately understand the subsidence history of the Fort Worth Basin.

The objective of this study is of three folds. First, I construct the isopach and structure maps of the basin fill to document the spatial patterns of sedimentation during the late Mississippian and Pennsylvanian. Second, I conduct thermal maturation modeling to constrain the post-Pennsylvanian burial and exhumation histories. At last, I reconstruct 1D and 2D tectonic subsidence histories of the Fort Worth Basin during the Mississippian and Pennsylvanian to constrain the flexural subsidence history of the basin. Results are put in regional geologic framework to constrain the geodynamic evolution of the Ouachita orogeny, and the dynamic relationship of the Fort Worth Basin to the Ouachita fold-and-thrust belt. This study improves our understanding to the subsidence evolution and mechanism of the Fort Worth Basin and guides future petroleum exploration.

1.2 Geological Setting

As the most important structural element in east-central Texas, the Fort Worth Basin is a shallow, asymmetric, north-south elongated sedimentary basin containing as much as ~3.7 km of sedimentary rocks (Montgomery et al., 2005). It is approximately

~320 km long and the width varies between ~160 km on the north end and ~16 km on the south end (Thompson, 1988) (Fig.1-1). The basin is bounded by the Red River and Muenster arches to the north, the Ouachita fold-and-thrust belt to the east, the Llano Uplift to the south, and the Bend Arch parallel to the Ouachita structural front to the west (Fig.1-1).

The Neoproterozoic rifting of the supercontinent Rodinia opened the proto-Atlantic (Iapetus) Ocean in the region of the present Gulf of Mexico and formed Laurentia and Gondwana continents (Keller and Cebull; 1973; Mosher, 1998). The southern margin of Laurentia evolved into a passive margin subsequently (Houseknecht and Matthews, 1985), and experienced rifting during the Cambrian, which formed the southern Oklahoma aulacogen (Burke, 1977; Perry, 1988). During the early Ordovician, the continental margin of Laurentia began to be subducted underneath Gondwana, associated with the development of volcanic arc and subduction complex (Keller and Cebull; 1973). The subduction continued through the middle Paleozoic and the hard collision of Laurentia and Gondwana may have occurred during the late Mississippian-early Pennsylvanian in the vicinity of the Fort Worth Basin (Keller and Cebull; 1973; Jurdy et al., 1995). During the subduction and hard collision of the two continents, the subduction complex was deformed and buried by the northward propagation of the Ouachita fold-and-thrust belt in the southeastern margin of Laurentia (Walper, 1982; Scotese and McKerrow, 1990). Basement-involved faults of the southern Oklahoma aulacogen were reactivated during the late Paleozoic compressional tectonics and formed northwest-striking Red River and Muenster arches as part of the Amarillo–Wichita uplift (Walper, 1982; Keller et al., 1989; Montgomery et al., 2005; Elebiju et al., 2010). Reactivation of the early Paleozoic normal faults during the compressional tectonics caused the initial uplift of the Llano Uplift (Erlich and Coleman, 2005). The uplift of the

Llano Uplift lasted to the late Pennsylvanian, which may have tilted the basinal fill in the Fort Worth Basin westward (Thomas, 2003).

The tectonic event that formed the Ouachita fold-and-thrust belt is named as the Ouachita orogeny (Graham et al, 1975; Wickham et al, 1976; Walper, 1977; Nelson et al, 1982), which is generally viewed as the westward extension of the Appalachian orogeny (Keller and Cebull, 1973; Loomis et al., 1994). The Ouachita fold-and-thrust belt extends from central Arkansas westward to southeastern Oklahoma, bends southward in eastern Texas, and joins the Marathon fold-and-thrust belt in central Texas (Graham et al., 1975; Houseknecht and Matthews, 1985; Loomis et al., 1994; Poole et al., 2005) (Fig.1.1). The Ouachita-Marathon fold-and-thrust belt is mostly buried underneath the Mesozoic and Cenozoic strata of the Gulf coastal plain (Houseknecht and Matthews, 1985; Loomis et al., 1994), and exposed only in the Marathon and Solitario uplifts in west Texas and in the Ouachita Mountains in Arkansas and Oklahoma (Thomas and Viele, 1983; Noble, 1993) (Fig.1.1).

1.3 Stratigraphy

The Paleozoic strata in the Fort Worth Basin are unconformably underlain by the lower Cretaceous (Fig.1-1). According to Montgomery et al. (2005), the total preserved Paleozoic basin fill reaches a maximum of ~3.7 km, and the strata can be roughly divided into three intervals: 1) Cambrian-upper Ordovician Wilberns, Riley, Hickory formations, Ellenburger and Viola groups, and Simpson Formation, which were deposited as carbonate platform in the passive continental margin of southern Laurentia (Walper, 1982); Devonian-Silurian is characterized by a regional depositional hiatus; 2) Middle-upper Mississippian Chappel Formation, Barnett Shale, and lower Marble Falls Member deposited in marine shelf environment; and 3) Pennsylvanian-lower Permian upper Marble Falls Member, Atoka, Strawn, Canyon, and Cisco groups, which were deposited

as interlayered marine carbonate and deltaic-fluvial siliciclastic sedimentary rocks (Fig.1-2). The interlayered carbonate and siliciclastic were broadly classified as deposits of marine transgression and regression (Cleaves, 1982; Thompson, 1988; Montgomery et al., 2005).

The Cambrian-upper Ordovician interval outcrops in the southern end of the basin, near the Llano Uplift (Turner, 1957). The Cambrian-lower Ordovician Wilberns, Riley, and Hickory formations are composed of yellow, brown, or red sandstone interbedded with thin lenses of claystone, dark-brown limestone, and calcareous sandstone. The upper Ordovician Ellenburger Group is composed of light gray, fossiliferous, dolomitic limestone, and cherty and crystalline limestone with a few intercalated shale beds (Turner, 1957; Montgomery, 2005). The thicknesses of these formations vary between ~300 m and ~950 m in the Fort Worth Basin (Turner, 1957). The Ordovician Simpson Group and Viola Limestone present only in the northeast part of the basin, and are composed of marine limestone, with maximum thickness of ~230 m along the Muenster Arch (Turner, 1957; Montgomery, 2005). In most area of the Fort Worth Basin, the Ellenburger Group is unconformably overlain by the Mississippian Barnett Shale.

The Mississippian deposits consist of alternating limestone and black, organic-rich shale. The total Mississippian interval thickens toward the Muenster arch, where the Barnett Shale is more than 300 m (Pollastro, 2003). The Mississippian Chappel Limestone underlies or intertongues with the Barnett Shale in the western and northern parts of the Fort Worth Basin. The Chappel Limestone, formed as reef core and inter-reef facies, is typically 30-50 m thick, but reaches ~120 m in the Montague County in the north part of the basin (Henry 1982). The lower Marble Falls Member (Morrowan stage) is composed of oolite shoals, with skeletal grainstone, packstone, and mudstone (Kier,

1980). The member reaches a maximum thickness of 70 m along the western margin of the Fort Worth Basin, and thins rapidly towards the south and west (Erlach and Coleman, 2005). The upper Marble Falls Member (Atokan stage) is composed of skeletal grainstone, siliceous limestone and shale, and organic carbon-rich black shale (Erlach and Coleman, 2005). It reaches 150 m in thickness, and thins toward the Llano Uplift (Erlach and Coleman, 2005).

The lower Pennsylvanian Atoka Group is composed of conglomerate, sandstone, shale, and thin layers of limestone (Turner, 1957; Thompson, 1988; Montgomery et al., 2005). The thickness of the Atoka Group ranges from ~76 m in the west part of the basin to ~1800 m in the east part of the basin (Turner, 1957). The Strawn Group is composed of thinly interbedded layers of limestone and shale, with some sandstone, conglomerate, and coal beds. The total thickness of the Strawn Group ranges from ~150 m in the west part of the basin to ~1370 m in the east part of the basin (Turner, 1957). The Canyon Group is composed of interlayered limestone and calcareous claystone, with minor

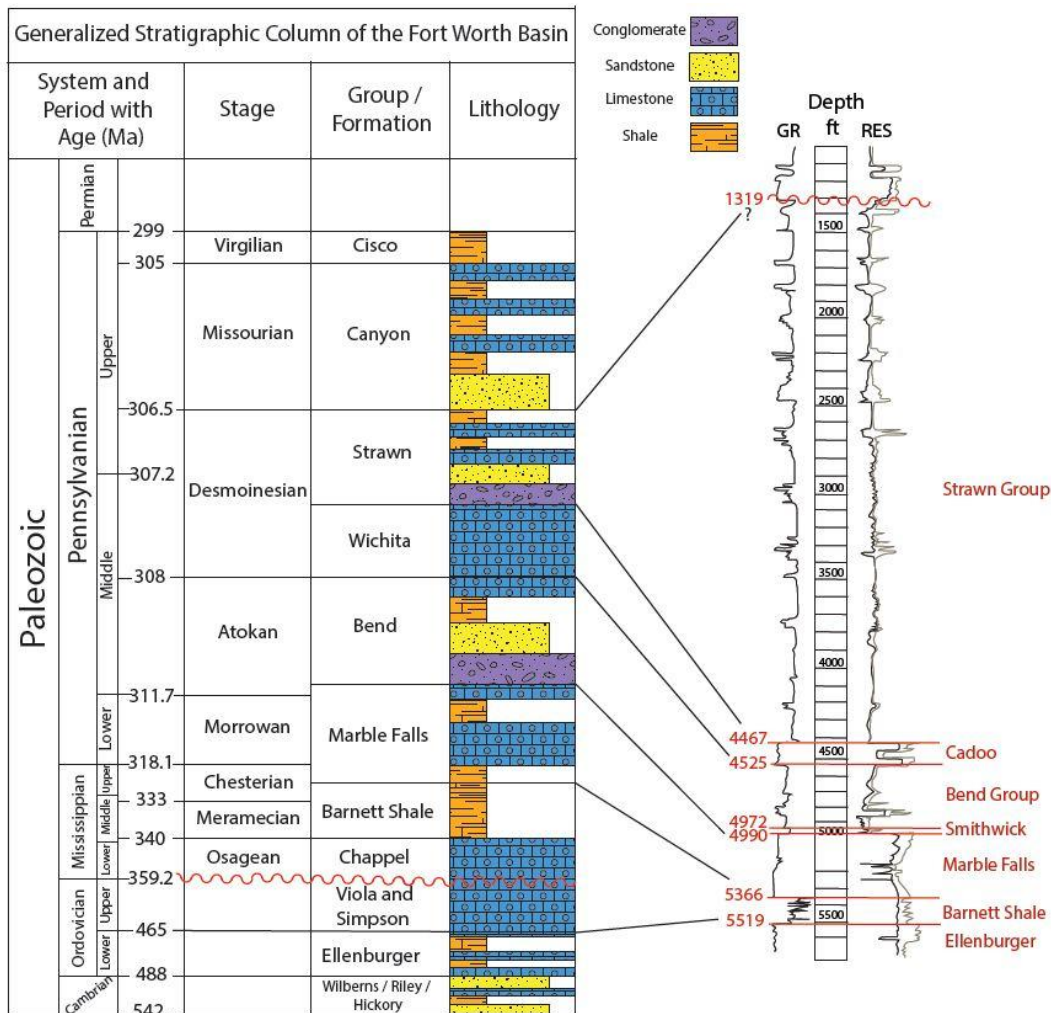


Figure 1-2 Generalized stratigraphic column of the Fort Worth Basin and the type log in the Jack County. Red wavy line represents unconformity. Lithostratigraphy of the type log is based on GR (gamma ray), and RES (resistivity) logs following Hentz et al. (2012). The stratigraphic column is modified from USGS (2003) and Pollastro (2003)

amount of sandstone lenses. The thickness ranges from ~600 m in the northeast part of the basin to ~150 m in the southwest part of the basin (Turner, 1957). The lowermost

Permian Cisco Group consists of gray thinly-bedded shale and is only preserved in the western part of the Fort Worth Basin, with maximum thickness reach ~300 m.

Cretaceous rocks of the Albian and Comanche series overlie the tilted Paleozoic sequence along the eastern part of the basin (Walper, 1982). Stratigraphic relationships and burial history reconstructions suggest that a significant thickness of the upper Permian-lower Cretaceous strata were eroded (Henry, 1982; Walper, 1982; Jarvie, 2003).

1.4 Hypothesis

I hypothesize that the Fort Worth Basin was a foreland basin that underwent flexural subsidence when the Ouachita fold-and-thrust belt was active, and the timing of the flexural subsidence reflects the timing of building the Ouachita fold-and-thrust belt during the suturing of Laurentia and Gondwana. Because the post-Pennsylvanian exhumation and burial history must be known in order to correctly decompact the Paleozoic strata, and because it is not clear when the subsidence of the Fort Worth Basin ceased due to the lack of preserved strata, I constrain the post-Pennsylvanian exhumation and burial history by modeling the thermal maturation of hydrocarbon. I hypothesize that post-Pennsylvanian thermal history can be calibrated with vitrinite reflectance data from the Paleozoic source rocks. I also conduct 1D tectonic subsidence and 2D flexural subsidence modeling of the basin in order to understand the subsidence history and infer the tectonic history.

Chapter 2

Methods

2.1 Isopach and Structure Maps

Previous stratigraphic analysis studies of the Fort Worth Basin have mainly focused on the distribution of the Barnett Shale. Turner (1957) published seven isopach maps of different formations and groups in the Fort Worth Basin based on outcrop measurements and the subsurface thickness data from a limited amount of wells. Because the outcrop exposures are limited to the west part of the basin, and the east part of the basin is covered by the Cretaceous strata, the isopach maps should be updated with more well controls. In this study, 70 well logs are used for stratigraphic correlation through the basin in order to construct structure and isopach maps. The main selection criteria for the well logs is to have continuous gamma-ray logs at least penetrating the base of the Barnett Shale. These well logs are loaded into Petra software for correlation based on previous studies of well-core comparison and well log cross-sections (Hackley et al., 2008; Hentz et al., 2012). Contours are produced in Petra and smoothed by hand. I divide the strata into four units including 1) the Mississippian Barnett Shale; 2) the Pennsylvanian Marble Falls Group; 3) the Pennsylvanian Bend Group; and 4) the Pennsylvanian Wichita and Strawn groups. The Wichita Group and the Strawn Group are lumped together because of the lack of distinctive log responses of the two groups (Hentz et al., 2012). Although the Canyon and Cisco groups are present in the western part of the basin only, most of the well logs in this area were not logged to the surface. For the ones that were logged to the surface, it is difficult to differentiate between the Wichita-Strawn groups from the lower Cretaceous strata in the western part of the basin because of the similarities of lithofacies. Therefore, isopach maps of the Canyon and Cisco can not be constructed without more core data.

2.2 Post-Pennsylvanian Exhumation and Burial History

Post-Pennsylvanian strata are not well preserved in the Fort Worth Basin. However, their thickness is important to the compaction of the pre-Pennsylvanian and Pennsylvanian strata. In order to estimate the post-Pennsylvanian strata thickness, and correctly account for compaction in 1D and 2D subsidence modeling, I conduct combined burial/exhumation modeling and hydrocarbon thermal maturation modeling using Schlumberger PetroMod 1D software, following the method of Poelchau et al. (1997), Yalcin et al. (1997), and Buker et al. (1999). The principle of the model is that hydrocarbon thermal maturation is determined by the exhumation and burial history of a basin. Hydrocarbon thermal maturation can be measured from reservoir rocks as, for example, vitrinite reflectance (%Ro). By varying the post-Pennsylvanian strata thickness and exhumation history and match the modeled %Ro to the measured %Ro, the best-fit scenario gives the burial and exhumation history of the basin. The main input parameters in the model include formation thickness, depositional ages, heat flow, lithology type, and the rock type of each formation.

Currently, the only area in the basin that has three published %Ro data in the Paleozoic strata is the Boonsville Field located in the northeast part of the basin (Hill et al, 2007). In the field, the %Ro of the Barnett Shale is 0.98-1.21, of the Smithwick Shale is 0.65-1.15, and of the Strawn shale is 0.80-0.85. To fit this group of vitrinite reflectance data, I read the formation thickness from a well log in the Wise County, which is within the Boonsville Field. Generally, heat flow increases during continental rifting due to lithospheric thinning and decreases to $\sim 50 \text{ mW/m}^2$ during post-rift thermal subsidence (Allen and Allen, 2005). I assume the heat flow of the Fort Worth Basin during the late Paleozoic was $\sim 50 \text{ mW/m}^2$ because the basin was formed near the failed Cambrian rift of the southern Oklahoma aulacogen. The formation thickness, ages, and lithology type are

summarized in Table 2-1. The initial porosity, lithology constants, and densities which are used in my 1D tectonic subsidence modeling are the average values based on different combinations of lithologies within a group or formation, and the end member values of conglomerate, sandstone, limestone, and shale (Angevine et al., 1993). Variations of lithology may bring some uncertainties to these parameters, however, the influence of the absolute values on the 1D tectonic subsidence is negligible.

The upper Pennsylvanian Canyon and Cisco groups are preserved only near and to the west part of the Bend Arch (Fig.1-1). It is not clear if the majority part of the basin had deposition during the Permian-early Cretaceous, and after the late Cretaceous. Two scenarios were given to model the burial and exhumation history of the Fort Worth Basin. Scenario 1 assumes that no preserved strata means no sedimentation. Although this scenario is most likely wrong, it brings insight to whether additional burial is required to cause thermal maturation of the source rocks. Scenario 2 assumes ~3 km of sedimentation of the Canyon and Cisco groups and ~3 km of the Permian strata. Although the Canyon and Cisco groups have no preservation in the main part of the basin, the estimate thickness was ~3 km by assuming the sedimentation rate of the groups is the same as the rate of the Wichita and Strawn groups. I also assume at least ~3 km of the Permian strata were deposited in the basin based on the thickness of the equivalent strata in the Permian Basin (Pranter, 1999). These assumption are also made because the result of my 2D subsidence modeling (present in 3.4) suggests that the Fort Worth basin continued to subside during the late Pennsylvanian and Permian. The preserved Cretaceous strata are ~500 m thick in the eastern part of the Fort Worth Basin (Perkins et al., 1971). Source rocks in the Cretaceous strata, including the Austin Chalk and Eagle Ford Shale in this area did not reach the hydrocarbon maturation window (DrillingInfo, 2011). Therefore, I assume there was not much post-Cretaceous

sedimentation. The basin experienced exhumation during the Triassic-early Cretaceous, and after Cretaceous, I vary the amount of exhumation to match the modeled vitrinite reflectance with the measured vitrinite reflectance. Although it appears that by varying the burial thickness, exhumation magnitude, and timings of burial and exhumation, several other scenarios may explain the observed hydrocarbon maturation, the histories represented by these scenarios are not supported by any geologic evidence, thus are not presented here.

Table 2-1 Parameters used for the calculation of tectonic subsidence and original strata thickness data in the five counties.

Formation name	Wichita and Strawn groups	Bend Group	Marble Falls Group	Barnett Shale
Age (Ma)	308.0 - 306.5	310.0 – 308.0	318.1 – 310.0	340.0 - 318.1
Lithology	Shale/ Limestone/ Sandstone/ Conglomerate	Shale/ Limestone/ Sandstone/ Conglomerate	Shale/ Limestone	Shale/ Limestone
Initial porosity	0.5	0.5	0.5	0.5
Lithology constant (/m)	0.0005	0.0007	0.0005	0.0006
Density (kg/m ³)	2.72	2.71	2.72	2.72
Water depth (m)	20	20	50	150
Relative sea-level (m)	60	40	20	0
Thickness in Archer County (m)	716	287	17	47
Thickness in Hill County (m)	1030	461	172	129
Thickness in Stephens County (m)	497	316	63	54
Thickness in Hamilton County (m)	614	454	85	54
Thickness in Wise County (m)	886	478	183	100

2.3 1D Tectonic Subsidence

Tectonic subsidence analysis produces a graphical representation of the vertical movement of a stratigraphic unit in a sedimentary basin to explain the subsidence process of the basin (van Hinte, 1978). Five wells across the basin are used to constrain the rates and spatial patterns of subsidence. The five wells are specifically located in the Archer, Hill, Stephens, Hamilton, and Wise counties. Thicknesses data are read directly from log picks. All data required for the 1D tectonic subsidence curve, including strata thickness, age, lithology, original porosity, original density, and the lithology constant are summarized in Tables.2.1.

The depositional ages of the stratigraphic units in the Fort Worth Basin have two types of uncertainties. One is related to the biostratigraphic and chronostratigraphic constraints of the strata, and the other is related to the geochronological time scale and the Global Boundary Stratotype Section and Point (GSSP). In this study, the age constraints are based on published biostratigraphic and Chronostratigraphic correlations (Pollastro, 2003; 2007; Boardman et al., 2012). The absolute ages are assigned based on the Paleozoic time scale of North America (Heckel, 2008).

The influences of sediment load, compaction, paleobathymetry, and sea-level changes must be removed in order to reconstruct the amount of tectonic subsidence (Angevine et al., 1990). In this analysis, I apply the concept of the Airy isostasy to remove the sediment load (backstripping) (Steckler and Watts, 1978). Decompaction is conducted based on empirically derived porosity-depth relationships for shale, sandstone, and limestone (Sclater and Christie, 1980). The post-Pennsylvanian strata is assumed to be ~2 km thick. Although the assumed thickness is small compared to the results of the thermal maturation modeling, the influence of compaction is less than 10% when the burial is more than 2 km because porosity loses exponentially as depth increases (Sclater and Christie, 1980). Paleobathymetry is difficult to estimate because of a paucity of unique depth

indicators in sedimentary rocks. My paleobathymetry estimates are based on the depositional environments, which are shallow marine and deltaic. Only the paleobathymetry of the Mississippian Barnett Shale has been discussed earlier with presumed water depth varying between ~100 m and ~300 m (Gutschick and Sandberg, 1983; Loucks and Ruppel, 2007). For simplicity, here I consider the water depth of the Barnett Shale to be 150 m, of the Marble Falls Group formed in inner shelf environment to be 50 m, and the shallow marine and deltaic Bend and Strawn groups to be 20 m. There are uncertainties associated with these estimates; however, they are small relative to the results of the tectonic subsidence in section 3.3.

Sea-level changes are based on the published global Phanerozoic sea-level curve in Snedden and Liu (2010). Relative sea-level decreased gradually to 0 m during the Mississippian, then increased to 60 m during the late Pennsylvanian. Although age controls, decompaction, paleobathymetry, and sea-level changes all bring uncertainties to the reconstructed 1D subsidence curves (Angevine et al., 1990; Xie and Heller, 2009), these uncertainties are small compared to the magnitude of tectonic subsidence.

2.4 2D Flexure Subsidence

Mountain plays as an external load to deflect lithosphere and form foreland basins. The depth and width of a foreland basin are determined by the size of the applied load and lithosphere strength (Allen and Allen, 2005). Typical foreland basins formed in association with thin-skinned fold-and-thrust belts, such as the Himalayan and Appalachian foreland basins, can be viewed as flexure of an infinite elastic plate (Allen and Allen, 2005). Although the lithosphere can be viewed as a broken elastic plate when basin-bounding structures penetrate the basement in the upper lithosphere (McDowell, 1997; Allen and Allen, 2005), because basement-involved structures are only limited to the north of the basin, and the depth of such structures are not well documented, the broken elastic model is not considered here. In this study, the Ouachita fold-and-thrust belt is considered as of

rectangular shape given the crustal shortening and thickening resulted from the long-distance propagation of fold-and-thrust belt. I then conduct 2D flexural subsidence modeling following the infinite elastic plate equation (EQ1) in Angevine et al. (1993).

$$W=(\rho_L * h_L / 2(\rho_m - \rho_s)) * [\exp((L-x)/\alpha) * \cos((x-L)/\alpha) + \exp((-L-x)/\alpha) * \cos((x+L)/\alpha)] \quad (\text{EQ1})$$

In the equation, W is the amount of subsidence. ρ_L , ρ_m , ρ_s are the densities of the load, mantle, and basin fill, respectively. I assume the density of the load is similar to the density of sandstone because the rocks that were deformed in the Ouachita fold-and-thrust belts should mainly include the subduction complex formed by the subduction of Laurentia shelf underneath Gondwana and Laurentia shelf deposits. The basin fill density is the initial sandstone density with 60% of grains and 40% of porosity filled by water. The density estimate based on sandstone should be representative to the combination of sandstone, conglomerate and shale. x is the distance to the load, h_L is the height of the load, and L is the half width of the load. α is the flexural rigidity of the lithosphere, which reflects lithosphere strength (Angevine et al., 1990; Allen and Allen, 2005). α is generally in the range of $10^{21} - 10^{25}$ Nm, with higher values occurring to old craton with large effective elastic thickness (Angevine et al., 1990; Allen and Allen, 2005). This equation shows that the amount of subsidence (W) decreases as distance to the load (x) increases. This equation also shows that the width and depth of a foredeep depozone are controlled by the height and width of the load and the lithosphere flexural rigidity (Allen & Allen, 2005).

2D flexural subsidence is conducted to the Pennsylvanian Bend, Wichita and Strawn groups (310-308 Ma). These are the youngest preserved units across the Fort Worth Basin. I combined the groups together because they were deposited when the basin experienced accelerated subsidence (result of 1D tectonic subsidence). The thickness of basin fill along a cross section perpendicular to the Ouachita fold-and-thrust belt is corrected for compaction in order to derive the 2D flexural subsidence profile. Here, I define this decompacted profile as the observed 2D flexural subsidence profile. By varying the height and width of the

Ouachita fold-and-thrust belt and the lithosphere flexural rigidity, I model the 2D flexural subsidence profile in order to match the observed 2D flexural subsidence profile. The best-fit model gives the height and width of the mountain load, and the lithosphere flexural rigidity. The parameters used for the 2D modeling are summarized in Table 2.2.

Table 2-2 Parameters used for the calculation of flexure subsidence

Density of load (kg/m ³)	2650
Density of basin fill (kg/m ³)	2000
Possion's ratio	0.25
Young modulus (N/m ²)	7×10^{10}

Chapter 3

Results

3.1 Isopach and Structure Maps

Structure maps of the tops of the Barnett Shale, Marble Falls Group, Bend Group, and Wichita-Strawn groups show that these tops are 750-2000 m below sea level in the northeast and east part of the basin, and shallow gradually to 250-1000 m in the west-central part of the basin (Fig. 3-1). These tops are shallowest around the Bend Arch (Fig. 3-1).

Isopach maps of the Barnett Shale, Marble Falls Group, Bend Group, and Wichita - Strawn groups generally thicken toward east and northeast, and thins to the west (Fig.3-2). The thickness of the Barnett Shale varies between 5 m and 150 m with the maximum in the northeast corner of the basin, adjacent to the Ouachita fold-and-thrust belt as well as the Muenster Arch (Fig.3-2A). This result is consistent with other published isopach maps of the Barnett Shale (Montgomery et al., 2005; Loucks and Ruppel, 2007; Pollastro et al., 2007; Zhao et al., 2007). The thickness of the Marble Falls Group varies between 10 m and 250 m (Fig.3-2B). The thickness of the Bend Group varies between 150 m and 650 m (Fig.3-2C). The isopach patterns of these two groups are similar to the Barnett Shale, showing thickening toward the east and northeast of the basin. The thickness of the Wichita-Strawn groups varies between 400 m and 1000 m with the thickest strata in front of the Ouachita fold-and-thrust belt, and the thinnest strata distributed in the southern end of the Bend Arch (Fig.3-2D).

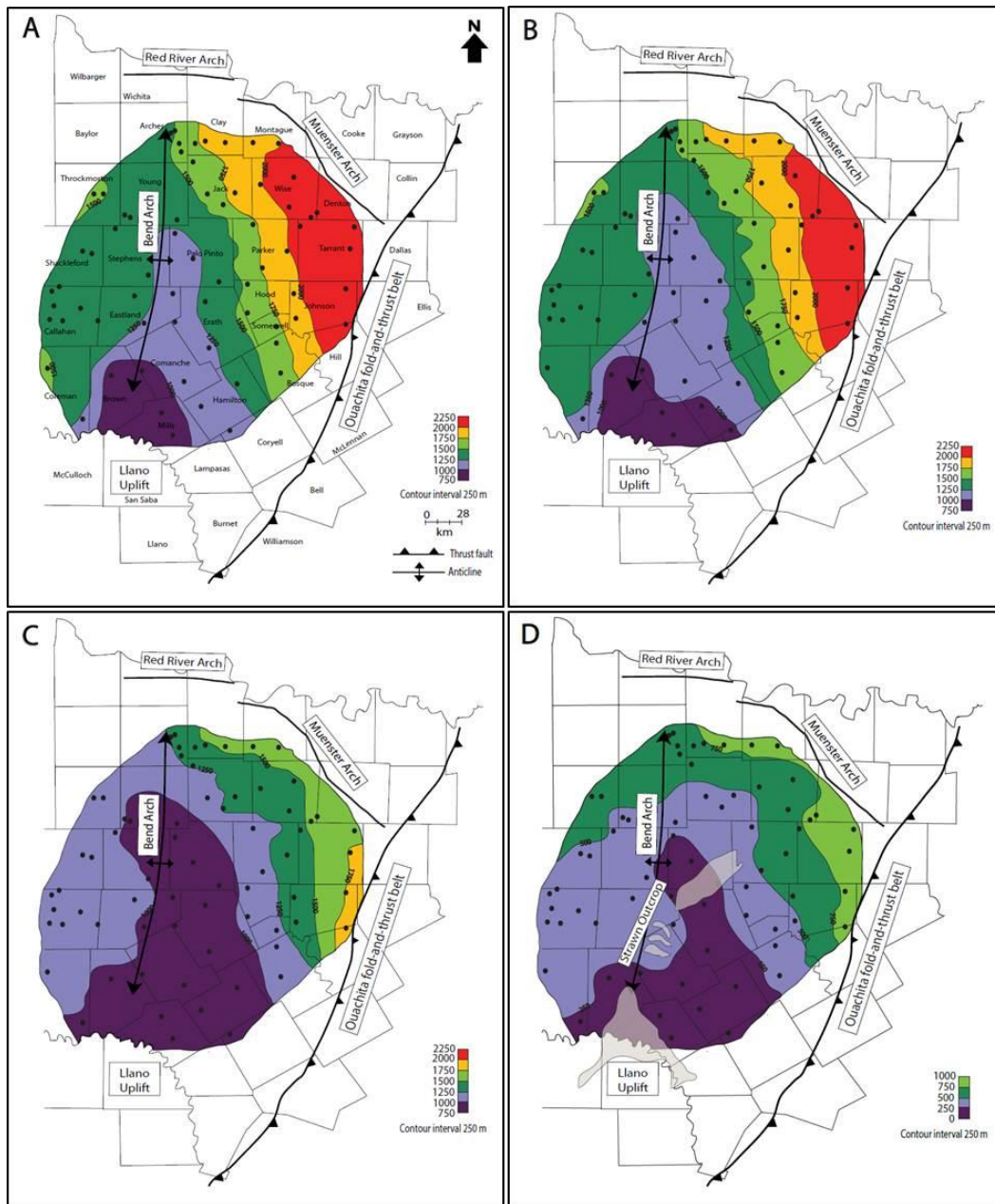


Figure 3-1 Generalized structure maps of the Fort Worth Basin. A: top of the Barnett Shale (318.1 Ma), B: top of the Marble Falls Group (310 Ma), C: top of the Bend Group (308 Ma), and D: top of the Strawn Group (306.5 Ma). The covered area of beige color in D represents the outcrop of the Strawn Group.

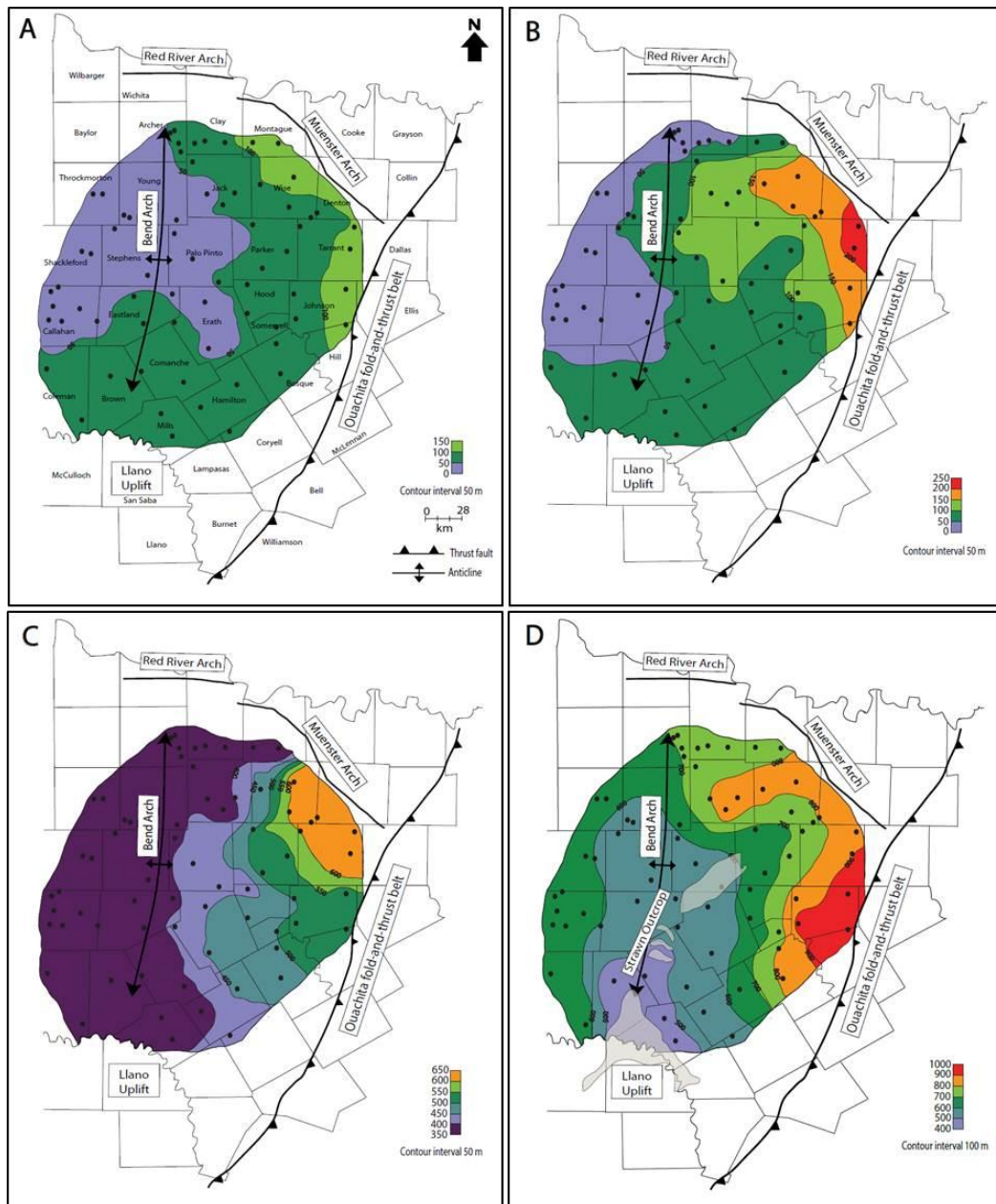


Figure 3-2 Generalized isopach maps of A: the Barnett Shale, B: the Marble Falls Group, C: the Bend Group, and D: the Wichita and Strawn Groups. Contour intervals are 50 m for A-C, and 100 m for D.

3.2 Post-Pennsylvanian Exhumation and Burial History

The first scenario of exhumation burial history, which only considers the preserved strata thickness, yields vitrinite reflectance values too small compared to the measured values (Fig. 3-3). Scenario 2, which gives a total of ~6.5 km of total burial during the Pennsylvanian and Permian, and ~2 km of Triassic-early Cretaceous exhumation, explains the measured vitrinite reflectance values (Fig. 3-4). The ~6.5 km of burial during the Pennsylvanian and Permian is necessary for the hydrocarbon maturation because the source rocks need to stay in elevated temperature long enough to reach the thermal maturation. Model results of Scenario 2 show that the exact timing of the exhumation during the Triassic-early Cretaceous does not matter, but the magnitude (~ 4 km) of exhumation is necessary to remove the overburden strata of the Mississippian-Pennsylvanian source rocks. Model results of Scenario 2 also show that the timing and magnitude of the Cretaceous burial and post-Cretaceous burial and exhumation do not influence the maturation of the upper Paleozoic source rocks when the total burial depth during the two periods is less than ~ 5 km. Although my thermal maturation modeling results suggest that the post-Strawn burial was ~ 5.5 km, I use 2 km for 1D and 2D decompaction because porosity loss is exponential and become negligible when the burial depth is more than 2 km thick (Sclater and Christie, 1980). Additionally the Strawn Group may have been well-cemented before Permian, and Permian sedimentation would not cause additional compaction.

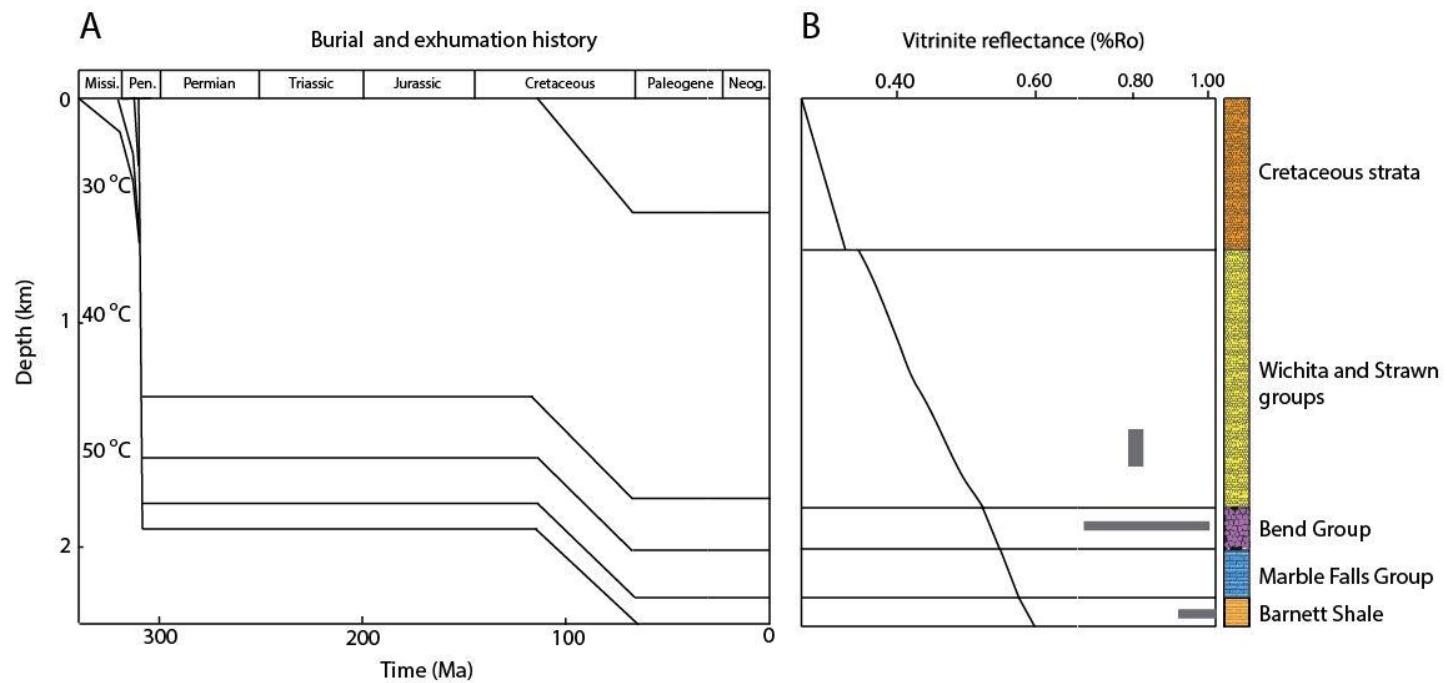


Figure 3-3 A: Scenario 1 of the burial and exhumation history of the Fort Worth Basin. Missi.: Mississippian, Pen.: Pennsylvanian, Neog.: Neogene. B: Modeled vitrinite reflectance data compared to measured vitrinite reflectance data (grey bars).

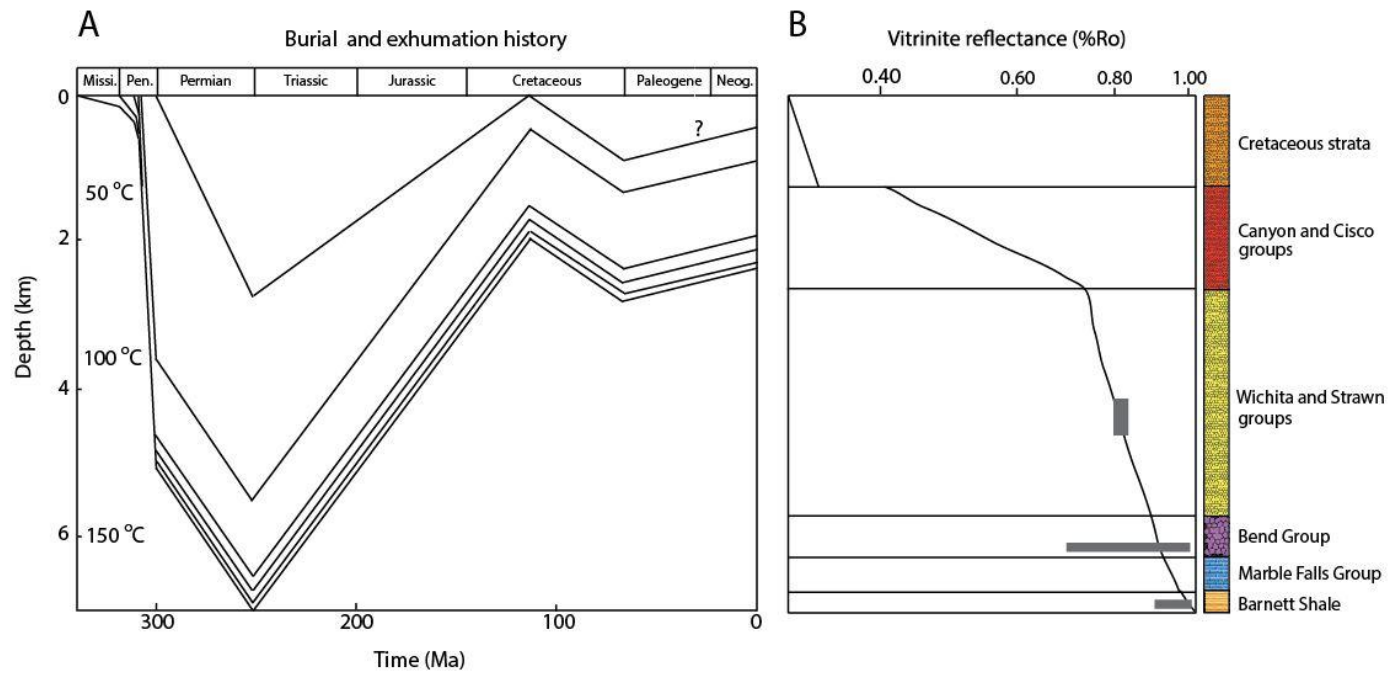


Figure 3-4 A: Scenario 2 of the burial and exhumation history of the Fort Worth Basin. Missi.: Mississippian, Pen.: Pennsylvanian, Neog.: Neogene. B: Modeled vitrinite reflectance data compared to measured vitrinite reflectance data (grey bars).

3.3 1D Tectonic Subsidence History

The five tectonic subsidence curves across the Fort Worth Basin all display a convex-up pattern (Fig.3-5), similar to the subsidence pattern of a typical foreland basin (Xie and Heller, 2009). The average tectonic subsidence rate increases from ~8 m/Myr during 340.0-310.0 Ma to ~91 m/Myr during 310.0-306.5 Ma. The rate is smaller than the subsidence rates in Erlich and Coleman (2005) because they did not account for sediment compaction and loading. The amounts of tectonic subsidence in the Archer, Stephens, and Hamilton counties are generally smaller than the amounts in the Wise and Hill counties located in the eastern part of the basin.

Table 3-1 Tectonic subsidence data in five counties

Strata thickness	Wichita and Strawn Groups	Bend Group	Marble Falls Group	Barnett Shale
Original Thickness (m): Archer County Hill County Stephens County Hamilton County Wise County	716 1030 497 614 886	287 461 316 454 478	17 172 63 85 183	47 129 54 54 100
Thickness after decompaction (m): Archer County Hill County Stephens County Hamilton County Wise County	998 1380 717 869 1208	467 720 503 699 740	30 294 107 146 310	84 227 95 97 180
Thickness after removing sediment load (m): Archer County Hill County Stephens County Hamilton County Wise County	252 348 181 219 305	120 185 129 179 190	8 74 27 37 78	21 57 24 24 45
Tectonic subsidence (m): Archer County Hill County Stephens County Hamilton County Wise County	468 732 429 528 686	282 450 314 375 447	200 303 222 233 295	171 207 174 174 195

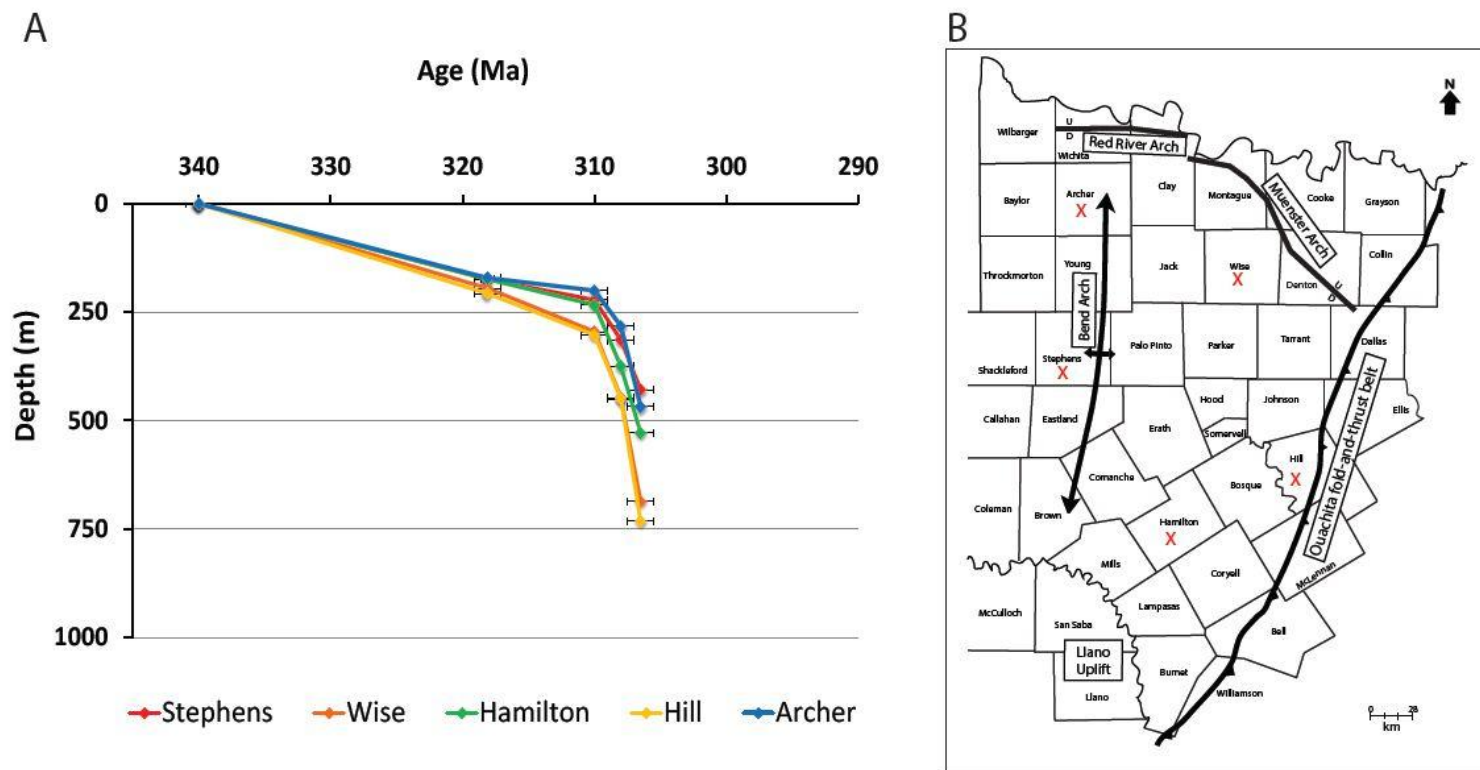


Figure 3-5 A: Reconstructed tectonic subsidence curves of the five studied sites; B: locations of the studied sites are represented by red crosses in the Fort Worth Basin

3.4 2D Flexure Subsidence Profile

The observed 2D flexural subsidence profile, with corrections for compaction and paleobathymetry, displays strata thickening toward the Ouachita fold-and-thrust belt. Flexure subsidence during the modeled time interval reached a maximum of ~ 1.2 km near the Ouachita fold-and-thrust belt. The wavelength of this flexure, which is the width of the foredeep, is ~ 2.5 km.

Because it is not clear if the front of the Ouachita fold-and-thrust belt was in its modern location during the early Pennsylvanian, I give two scenarios in the modeling. In Scenario 1, I assume the front of the Ouachita fold-and-thrust belt was in its modern location, when the modeled flexural subsidence profile matches the observed profile, the yielded lithosphere flexural rigidity and load size are the minima (Fig. 3-6). This scenario gives lithosphere flexural rigidity of $10^{23.45}$ Nm, which is equivalent to an effective elastic thickness of 36 km, and the height and half width of the mountain of 0.85 km and 130 km, respectively.

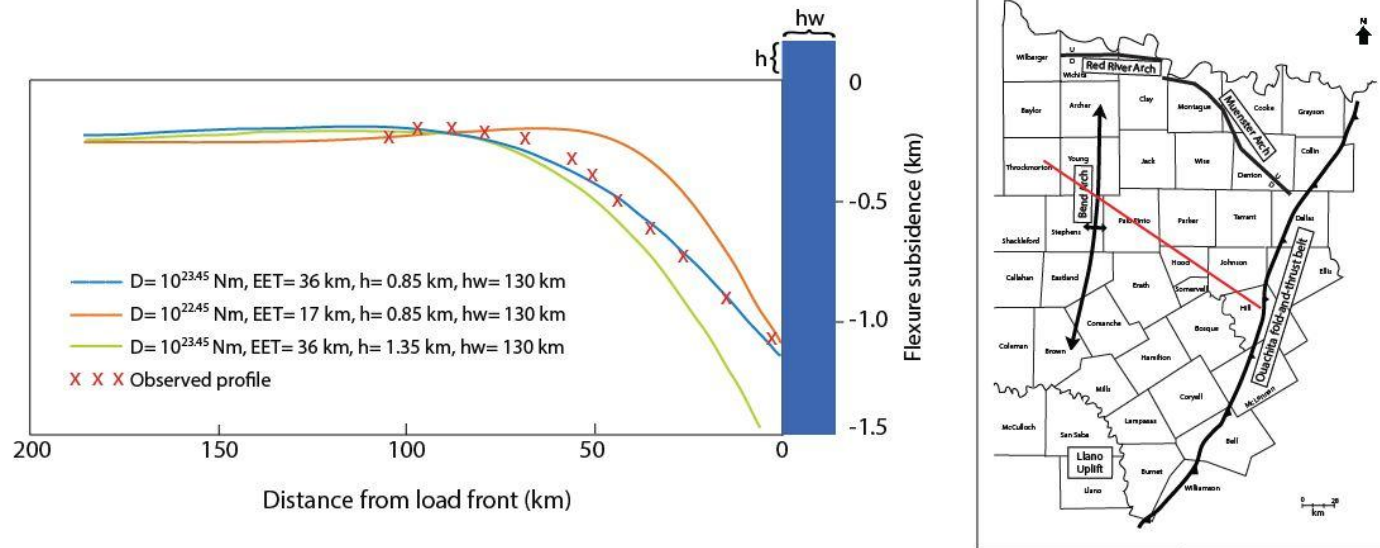


Figure 3-6 A: The flexural subsidence profile of the Fort Worth Basin during the late Pennsylvanian. The red crosses are the decompacted thickness from isopach map. The blue curve is the best-fit modeled flexural subsidence profile. D: flexure rigidity, EET: effective elastic thickness, h: load height, hw: load half width; B: location of the cross-section is represented by the red line

In Scenario 2, I assume the front of the Ouachita fold-and-thrust belt was 50 km to the east of its modern location (Fig. 3-7). This scenario increases the basin width and lithosphere flexural rigidity as well as the load size. The best-fit of lithosphere flexural rigidity is $10^{23.80}$ Nm, which is equivalent to an effective elastic thickness of 47 km and a mountain height of 1.4 km. An effective elastic thickness of 47 km is high compared to the effective elastic thickness of a region that has experienced flexural weakening, for example, the Himalayan foreland basin (Hetényi et al., 2006). It is also high compared to the modern effective elastic thickness in south-central U.S.A. (Bechtel et al., 1990). Therefore, the yielded lithosphere flexural rigidity and load size of Scenario 2 are the maximum.

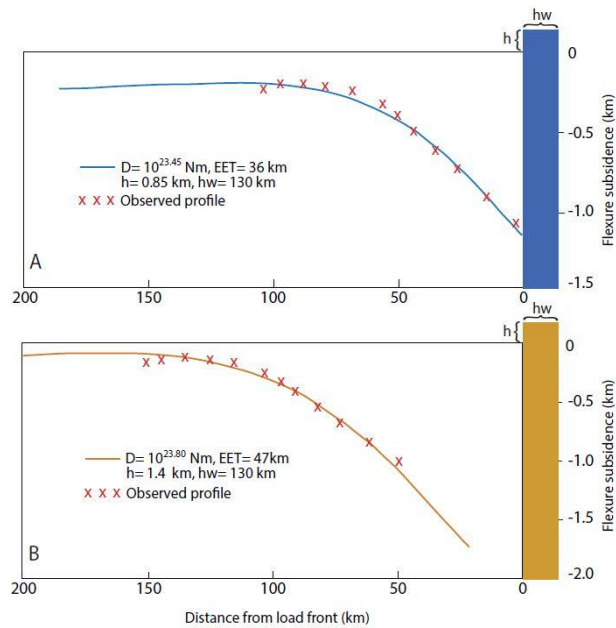


Figure 3-7 The flexural subsidence profile of the Fort Worth Basin during the late Pennsylvanian. D: flexure rigidity, EET: effective elastic thickness, h: load height, hw: load half width. A: the best-fit for scenario 1. B: the best-fit for scenario 2

Chapter 4

Discussion

4.1 Development of a Foreland Basin

Isopach maps display basin fill patterns, which can be used to decipher the timing of and the tectonic process by which accommodation space of the Fort Worth Basin was developed. The basin fill patterns suggest that the Fort Worth Basin was at its initial foreland basin stage in response to mountain loading to the north and east of the basin as early as the middle-late Mississippian (Fig. 3-2A). Many previous studies suggested that the basin was located in the stable Laurentian shelf during the late Mississippian (e.g., Turner, 1957; Burgess, 1976; Pollastro, 2003; Montgomery et al., 2005). Other studies suggested that during the late Mississippian, the subduction complex along the margin of Gondwana was thrust over the Laurentia margin to develop the Ouachita fold-and-thrust belt, and the Fort Worth Basin was covered by a shallow seaway and filled with flysch deposits (Graham et al., 1974; Walper, 1982; Arbenz, 1989; Keller et al., 1989; Viele, 1989). My results are consistent with the studies that suggest the Laurentia shelf became unstable during the late Mississippian due to the suture between Laurentia and Gondwana (Arbenz, 1989; Keller et al., 1989; Viele, 1989; Dickinson and Lawton, 2003). In addition, my result shows that the Muenster Arch to the north of the basin also played a major role in the basin subsidence. During the early Pennsylvanian (Morrowan), the depocenter of the Fort Worth Basin remained in the north and east part of the basin, and the forebulge depozone was not documented in the isopach maps.

The Ouachita fold-and-thrust belt became the only tectonic load of the Fort Worth Basin during the Desmoinesian. Started in the early-middle Pennsylvanian (Atokan), the depocenter of the Fort Worth Basin remained in the northeast, with accelerated basin

subsidence (Fig.3-5) initiated in response to the propagation of the Ouachita fold-and-thrust belt. Thick, synorogenic molass deposits of the Bend Conglomerate occurred in the northeast part of the basin and extended toward the Bend Arch (Lovick et al., 1982). During the late middle Pennsylvanian (Desmoinesian), the depocenter of the basin completely shifted to the east, parallel to the Ouachita fold-and-thrust belt, and the forebulge depozone occurred as the Bend Arch. The basin-fill pattern suggests the Ouachita fold-and-thrust belt was the only tectonic load controlling the subsidence of the basin after the Desmoinesian.

The Ouachita fold-and-thrust belt must have experienced additional vertical growth during the late Pennsylvanian and Permian. My 2D flexural subsidence modeling suggests that during the Desmoinesian, the height of the Ouachita fold-and-thrust belt was between 0.85 km and 1.4 km. This height is comparable to its modern topographic expression without considering the long-term erosion after the Pennsylvanian. However, it is small compared to some recent fold-and-thrust belts on the globe, such as the Himalayan, Zagros, and Sevier fold-and-thrust belts, which have a mean elevation of at least ~2 km (Alan, 1969; Chase et al., 1998; Qinye and Du, 2004). The small mountain height of the Ouachita fold-and-thrust belt suggests that the belt must have not been fully developed during the Desmoinesian, and the Fort Worth Basin must have had additional subsidence in response to the continuous tectonic loading during the late Pennsylvanian and Permian. Similar inference was made from my thermal maturation modeling which shows that ~5.5 km of late Pennsylvania-Permian sedimentation is necessary for the Pennsylvanian source rock maturation. My 2D modeling results also suggest that the front of the Ouachita fold-and-thrust belt was close to its modern location, thus the subsequent development of the belt should be characterized mainly by crustal thickening.

4.2 Significance for Regional Tectonics and Paleogeography

The rapid flexural subsidence of the Fort Worth Basin began during the Atokan, which was ~10 Ma younger than the timing of the increased sedimentation rate associated with rapid subsidence in the Arkoma Basin in Oklahoma (Shaulis et al., 2012), and ~5 Ma older than the documented initial foredeep development in the Marathon and Val Verde basins in west Texas (Wuellner et al., 1986). Therefore, a westward trend of flexural subsidence along the Ouachita-Marathon fold-and-thrust belt can be summarized from these studies. This trend is consistent with the westward development of the Ouachita-Marathon fold-and-thrust belt associated with the diachronous suturing of Laurentia and Gondwana (Dickinson and Lawton, 2003).

The existence of mountain loading to the north and east of the basin, however, is not completely consistent with the paleogeographic reconstructions in Gutschick and Sandberg (1983) and Blakey (2005). Both articles show that the Fort Worth Basin was located in a shallow seaway bounded by the Laurentia paleocontinent shelf to the north and west, and an island arc chain to the east. This island arc chain was formed by the subduction of the southern edge of Laurentia underneath Gondwana (Keller and Cebull, 1973). Although multiple ash beds derived from the volcanic arcs present in the early Mississippian Stanley Group in Oklahoma and Arkansas (Shaulis et al., 2012), the slightly younger Marble Falls Group and Barnett Shale in the Fort Worth Basin have no ash deposits. This observation indicates that the volcanic arcs were not active during the middle-late Mississippian in the vicinity of the Fort Worth Basin, implying the suturing of Laurentia and Gondwana has been accomplished in the vicinity of the Fort Worth Basin before the middle-late Mississippian.

The general strata thickening to the north and northeast of the Fort Worth Basin suggests the Amarillo-Wichita-Muenster Arch system was active as early as the middle-

late Mississippian. The Amarillo-Wichita-Muenster Arch system is one of the Ancestral Rocky Mountain basement-cored uplifts that are currently distributed in the southwestern and southern U.S.A. (Kluth, 1986; Perry, 1989; Robbins and Keller, 1990). Previous studies suggested the development of the Ancestral Rocky Mountains is related to the flat subduction of the southeastern Laurentia underneath the Gondwana, which reactivated old structures, particularly the normal faults formed during the Cambrian Oklahoma aulacogen (Ye et al., 1996; Barbeau, 2003; Dickinson and Lawton, 2003). This study shows that the basement-cored Amarillo-Wichita-Muenster structure developed in the foreland of the Ouachita fold-and-thrust belt synchronously, and ended before the rapid subsidence of the Fort Worth Basin in response to the fast propagation of the Ouachita fold-and-thrust belt. This observation suggests that the basement structures may be a far-field response of the initial collisional tectonics, and the movement of such structures may end when the stress is consumed by crustal thickening within the fold-and-thrust belt.

4.3 Significance for Petroleum Generation

The burial and exhumation history and heat flow of a basin influences the thermal maturation and hydrocarbon generation expectations of source rocks (Jarvie, 2004). Pollastro et al., (2003) generated a map of vitrinite reflectance values of the Barnett Shale across the Fort Worth Basin. The map shows a general trend of increasing thermal maturity toward the Ouachita fold-and-thrust belt, suggesting that the hydrocarbon maturation in the basin was controlled by the flexural subsidence of the basin, and the development of the Ouachita fold-and-thrust belt. Because my burial and exhumation history modeling suggest a continued foreland basin subsidence during the Permian, the maturation of the Mississippian and lower Pennsylvanian source rocks was thermally

matured during the Permian due to the flexural loading and denudation of the Ouachita fold-and-thrust belt.

My burial and exhumation history of the Fort Worth Basin is not consistent with the process of thermal maturation of the Barnett Shale suggested by Jarvie (2001) and Montgomery et al., (2005), which show the thermal maturation of the Barnett Shale occurred in three stages: rapid burial up to ~ 2.4 km during the Pennsylvanian and Permian; remaining in the elevated temperature (240–285 °F) during the late Permian to early Cretaceous; and erosion of ~ 1.9 km of the overburden strata during the late Cretaceous and Cenozoic. Gas maturation window is typically at 240 °F. The maturation of the Barnett Shale thus should have occurred during the early Permian. My modeling results show that the maturation of the Barnett Shale was reached by ~ 6.5 km of burial during the Pennsylvanian and Permian, ~2 km of erosion of the overburden strata during the Triassic, Jurassic and early Cretaceous, and ~ 0.9 km of burial during the middle and late Cretaceous (Fig. 3-4). Although the Cenozoic exhumation or burial history is not certain, a small amount of burial or exhumation (< 0.9 km) does not influence the maturation of the Barnett shale much. Therefore, the Barnett Shale reached the gas maturation window during the middle-late Permian. This conclusion is consistent with the results of Jarvie et al. (2005), which was conducted in the Montague County.

Chapter 5

Conclusions

This study integrates isopach maps, thermal maturation model, 1D tectonic subsidence, and 2D flexure subsidence modeling to understand the subsidence history of the Fort Worth Basin during the late Paleozoic. The isopach maps show that the strata thickens toward the Ouachita fold-and-thrust belt to the west as early as the middle-late Mississippian, suggesting the initial development of the Ouachita fold-and-thrust belt in response to the suturing of Laurentia and Gondwana that occurred by the middle-late Mississippian. The middle-upper Mississippian and lowermost Pennsylvanian strata also thicken toward the Muenster Arch to the north of the basin, suggesting the far-field stress of the convergent tectonics may have reactivated the Cambrian normal faults bounding the Oklahoma aulacogen, and formed the basement-cored Ancestral Rocky Mountains uplifts. Although the rapid foreland subsidence of the Fort Worth Basin initiated during the Atokan, the thermal maturation model suggests that the Mississippian and Pennsylvanian source rocks require ~ 6.5 km of total burial in order to reach the gas maturation window in the northwestern part of the basin, implying that the Ouachita fold-and-thrust belt experienced continuous development and the basin experienced additional subsidence during the Permian. This conclusion is consistent with the 2D flexural modeling, which shows that by the end of the early Pennsylvanian, the size of the Ouachita fold-and-thrust belt was relatively small, and continuous development of the belt caused additional flexural subsidence of the basin during the Permian. The concurrent development of the Amarillo-Wichita-Muenster Arch system and Ouachita fold-and-thrust belt suggests the basement-cored Ancestral Rocky Mountains structures were developed synchronously with the Ouachita fold-and-thrust belt during the suturing of the Laurentia and Gondwana. Flexural subsidence of the basin and thick burial denudes from the Ouachita fold-and-

thrust belt became the keys of the hydrocarbon maturation of the late Paleozoic source rocks, and the hydrocarbon went in the gas window during the Permian. This study elucidates the tectonic subsidence history of the Fort Worth Basin during the late Paleozoic, and sheds light to regional tectonics and hydrocarbon maturation within the basin.

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Biographical Information

Ohood Bader Al Salem was born on September 18, 1982 in the State of Kuwait. She joined Kuwait University in 2000 to start her undergraduate study in the Department of Earth and Environmental Sciences. She received her Bachelor of Science majoring in geology and minoring in petroleum geology in 2005.

Ohood maintained the highest GPA in the Department of Earth and Environmental Sciences during 2001-2005. She was honored to be the head of the students at the field trip to Oman in 2003, a member of the Society of Faculty of Science in Kuwait University in 2004, and a member of the Cultural Committee of the Deanship in the Faculty of Science in Kuwait University in 2004 and 2005. She was also recognized and awarded as the Ideal Student by the Society of Faculty of Science in 2005. Ohood joined Baker Hughes Incorporate immediately after her graduation.

In 2012, Ohood was awarded full education scholarship from Kuwait University to conduct her graduate studies at the University of Texas at Arlington. She joined the Department of Earth and Environmental Sciences at the University of Texas at Arlington for her master degree in petroleum geology in fall of 2012. Recently she was admitted into the PhD program at the University of Texas at Arlington, to continue her graduate study. Ohood is currently a member of the Honor Society and Golden Key International Honor Society based on her excellent academic achievement.

Ohood aims to become an academic professor and a researcher in Kuwait University upon finishing her PhD. She has always been dedicated and determined to achieve her ambitions. She is an active, energetic, sociable, and pleasant woman to work with. Her future is bright as long as she keeps her strong faith in herself.