FAULTS IN NORTHEASTERN OKLAHOMA: THEIR OCCURRENCE AND RELATIONSHIP TO HYDROCARBON PRODUCTION AND MODERN SEISMIC ACTIVITY

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Title of Study: FAULTS IN NORTHEASTERN OKLAHOMA: THEIR OCCURRENCE AND RELATIONSHIP TO HYDROCARBON PRODUCTION AND MODERN SEISMIC ACTIVITY

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Abstract: This study examines known fault systems in northeastern Oklahoma, analyzing their relationship to producing reservoirs and their link to the recent increase in seismic activity. By collecting fault information from previous publications and unpublished industry maps, this study, using GIS techniques, compiled a detailed fault map for northeastern Oklahoma, including the type of faulting, where possible. The Nemaha, West Stillwater – Ramsey – Labette, Wilzetta, and Keokuk fault zones are the more prominent in the area of study; characterized by highly faulted networks that show a conjugate pattern and an almost orthogonal pattern. Although most faults in northeastern Oklahoma are reported to be normal in terms of apparent displacement, high-angle reverse faults have been mapped along the major fault zones. During multi-tectonic events, strike-slip displacement is an essential component for the fault systems in north-central Oklahoma.

A comparison of the age of the producing reservoirs maps with the interpretive fault map reveals that the predominance of production from Lower Paleozoic reservoirs is from structure-related traps. There is significant production from stratigraphic traps in Pennsylvanian reservoirs. It seems clear that Pennsylvanian and Permian producing reservoirs reflect reactivation of pre-existing faults and vertical migration of hydrocarbons through faults to shallower reservoirs.

A comparison of the distribution of earthquake foci with the fault map and the top of basement in northeastern Oklahoma shows that the majority of earthquakes have occurred well below the basement and that most of these earthquakes occurred between the major fault systems. The three earthquakes with moment magnitudes (Mw) of 5.0 or greater occurred quite near major fault zones, but apparently along their individual branches.

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CHAPTER I

INTRODUCTION

1.1 Previous Works

In northeastern Oklahoma, even though fault occurrences are rather well-documented, recent studies suggest that the area is even more highly faulted than generally thought (Gay, 2003a, 2003b). Luza and Lawson (1980) considered previously recognized vertically faulted uplifts to be responsible for the formation of significant structures in northeastern Oklahoma. Major fault systems, associated with strike-slip movements (e.g., Nemaha Fault Zone, Wilzetta Fault Zone, and Keokuk Fault Zone), have been proposed as being responsible for the complex fault patterns resulting from multi-tectonic events (Gay, 1999; Dycus, 2013; Dudek, 2014). As illustration, along the Nemaha Fault Zone in Kay County, Oklahoma, several smaller fold-fault structures have been proposed to be the result of strike-slip faults (Davis III, 1985).

The current fault databases of Oklahoma, available from the Oklahoma Geological Survey (OGS), show known faults and some of their attributes in Oklahoma. The fault information has been significantly updated through various Oklahoma Fault Maps published since 2014 (e.g., Holland, 2015; Marsh and Holland, 2016).

In this study, faults in the existing Oklahoma fault databases, were compiled with unpublished faults and others not shown in the existing databases, thereby providing more information on faults in northeastern (and north-central) Oklahoma, in order to have an up-to-date map of faults mapped in northeastern Oklahoma.

Although the relationship between the occurrence of hydrocarbon traps and fault patterns along major fault zones in Oklahoma is generally understood (Dolton and Finn, 1989), the relationship of producing reservoirs and fault systems in northeastern Oklahoma, especially Pennsylvanian-Permian reservoirs and the role of vertical migration of hydrocarbons, is less well known.

Added to distribution of faults and their association with producing reservoir is the relatively recent high occurrence of earthquakes in northeastern, central, and north-central Oklahoma, especially after 2009. Most studies (e.g., Keranen et al., 2014; Hough and Page, 2015; Walsh and Zoback, 2015; Boak, 2018) propose the earthquakes are possibly related to waste-water injection; this study focuses on the relationship between the recent earthquakes and existing fault systems.

1.2 Objectives

The objectives of this study are to: (1) compile, using GIS techniques, the most accurate map of faults in northeastern Oklahoma possible from all available maps in the study area, make a reasonably sound interpretive map, and determine the relation of the faults to two groups of producing reservoirs (pre-Pennsylvanian and Pennsylvanian-Permian) and (2) relate recent earthquakes to the mapped faults, to producing reservoirs, and to the basement.

1.3 Significance

This research will further contribute to the completion of the fault system information in northeastern Oklahoma and advance our understanding of the occurrence and nature of the fault systems in northeastern Oklahoma. The study of the distribution pattern of producing reservoirs in different ages relative to the fault systems will help us to understand more clearly the distribution of hydrocarbon reserves and thereby lead to a better predictor of undiscovered oil and gas reserves remaining along the fault zones in northeastern Oklahoma.

Knowing the relation of earthquakes to the mapped faults and to previously unknown faults should improve the understanding of the seismicity of the area. The relation of the foci to the top of the basement (base of the sedimentary section) should help in determining with more accuracy the relation of petroleum exploration and production in generating earthquakes.

1.4 Study Area

As shown in Figure 1, the study area is within the Cherokee Platform, which is bounded by the Ozark Uplift to the east, and the Nemaha Uplift to the west. The major tectonic structural elements of southern Oklahoma, the Wichita, Arbuckle, and Ouachita uplifts, are associated with its southern boundary, and they had a structural influence on the Cherokee Platform (Johnson, 2008). The study area lies north of the Arkoma Basin and the southernmost part of the Cherokee Platform, and the Kansas border delineates its northern limit. Fourteen counties are included within it. The Nemaha Fault Zone and Wilzetta Fault Zone are two of the major fault zones in the study area.

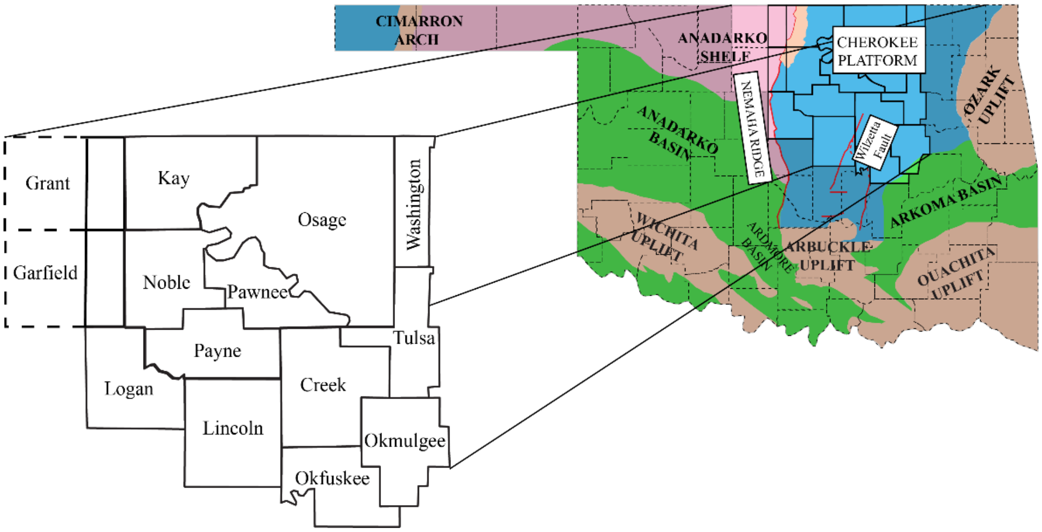

Figure 1: Study area in relation to the major tectonic provinces of Oklahoma (modified from Johnson, 2008). Dashed areas of Grant and Garfield Counties are located at the west of Nemaha Fault Zone and fault information in these areas are briefly collected.

1.5 Stratigraphy

The strata in the study area formed from sediments deposited mainly during the Paleozoic Era (Figure 2a and Figure 2b; Dolton and Finn, 1989; Boyd, 2008). They are usually divided into two segments: pre-Pennsylvanian strata consisting primarily of dolomites, limestones, and shale, with fewer siliciclastic deposits, and Pennsylvanian-Permian strata. The latter are known for their cyclic deposits containing terrigenous deposits and marine deposits (carbonates and shales, primarily) (Dolton and Finn, 1989). Pre-Pennsylvanian and Pennsylvanian-Permian strata are separated by a major unconformity at the close of the Mississippian. Furthermore, tectonic movements during the Ordovician and Devonian resulted in regional unconformity(ies) and local erosion on structural highs.

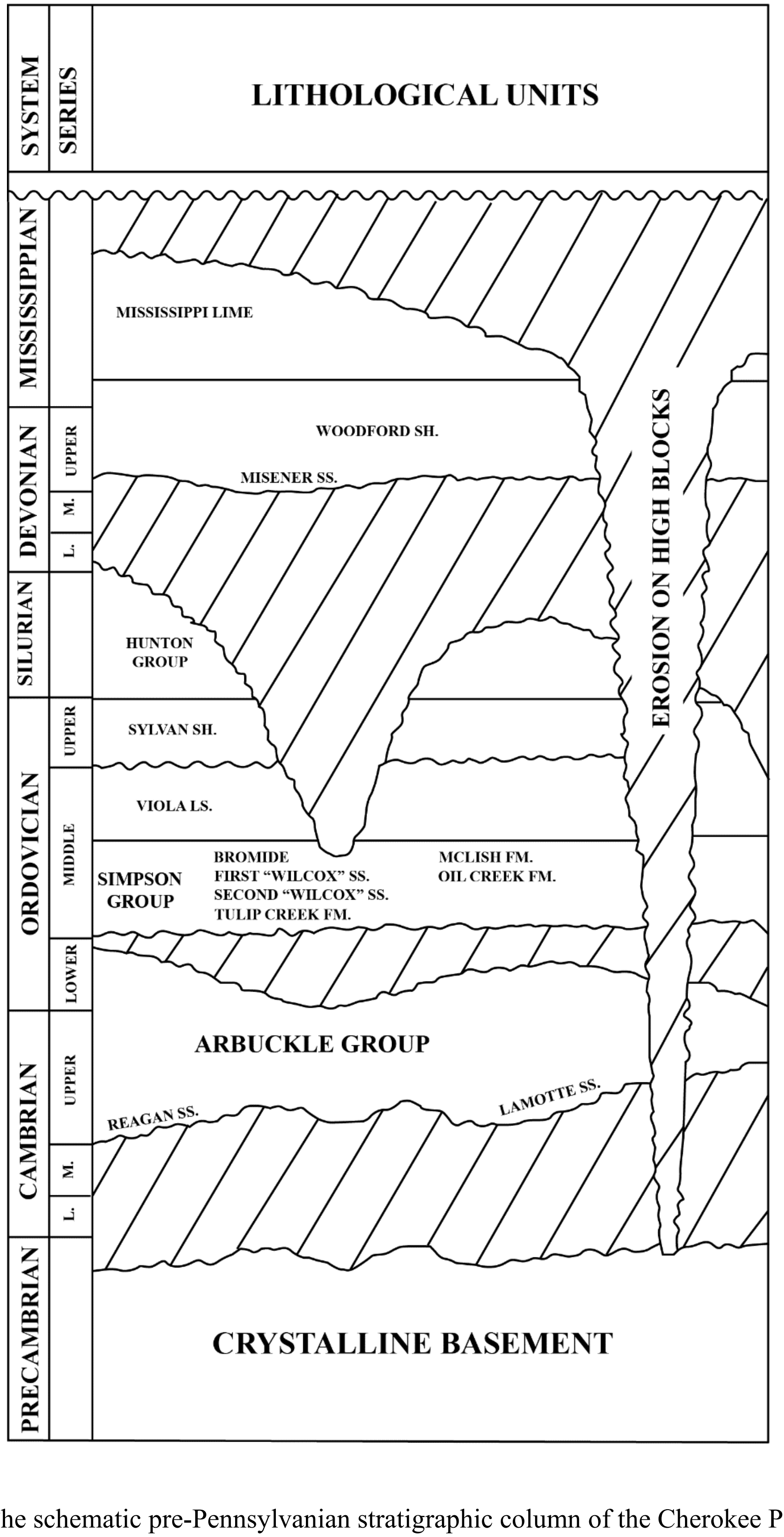

Figure 2a: The schematic pre-Pennsylvanian stratigraphic column of the Cherokee Platform in northeastern Oklahoma (adapted and modified from Dolton and Finn, 1989; Boyd, 2008).

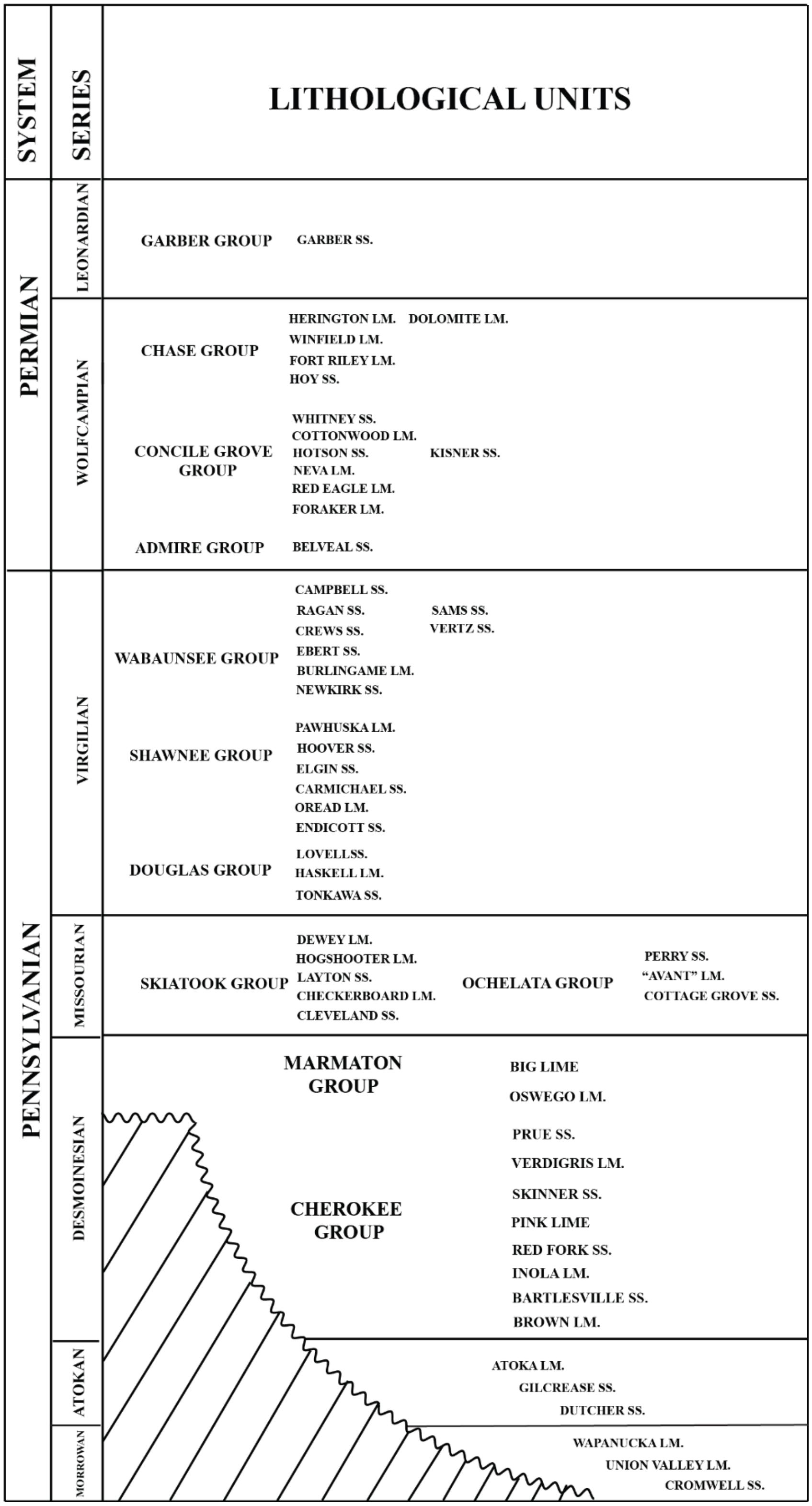

Figure 2b: The schematic Pennsylvanian-Permian stratigraphic column of the Cherokee Platform in northeastern Oklahoma (adapted and modified from Dolton and Finn, 1989; Boyd, 2008).

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CHAPTER II

TECTONIC HISTORY OF STUDY AREA

2.1 Late Mesoproterozoic Mid-Continent Rift in Central Oklahoma

Around 1.1 Ga, the Laurentia supercontinent underwent intracratonic rifting in the present-day midwestern United States, forming the Mid-Continent Rift System (MRS). Rifting started around Lake Superior and extended southward across Minnesota, Iowa, southeastern Nebraska, and northeastern Kansas (Whitmeyer and Karl, 2007). Some studies (Berendsen and Blair, 1986; Keller et al., 2016) indicate the continuation of the MRS into central Oklahoma, as the initial trace of the Nemaha Fault Zone; volcanic intrusions and deep Precambrian sedimentary basins in Osage County provide some evidence for the rift zone in Oklahoma (Elebiju et al., 2011). Additionally, gravity and well-log data suggest further a southward extension of the MRS under the Anadarko Basin and into Texas (Keller et al., 2016).

2.2 Middle Ordovician, Middle to Late Devonian Regional Uplift in Oklahoma

After development of the WNW-trending Southern Oklahoma Aulacogen during the Cambrian (e.g., Ham et al., 1964; Keller, 2014), there was movement along the Nemaha Fault Zone, probably during middle Ordovician and middle to late Devonian; included were rejuvenated fault activities in Oklahoma (Johnson, 2008), such as at the Oklahoma City Field Uplift (McGee and Jenkins, 1946) and localized uplifts in Noble and Kay County (Davis III, 1985; Tarr et al., 1965). In the uplifted areas, the Hunton Limestone underwent erosion; in some locations, erosion extended through the Wilcox Sand to the Cambro-Ordovician Arbuckle Group (McGee and Jenkins, 1946; Tarr et al., 1965). The widespread Woodford Shale lies unconformably on eroded earlier Paleozoic units.

2.3 Late Mississippian and Pennsylvanian Orogenic Events in Oklahoma

During late Mississippian and early Pennsylvanian, the Wichita Orogeny of southwestern Oklahoma, the Nemaha Uplift of central Oklahoma and Ozark Uplift of northeastern Oklahoma were active (Johnson, 2008). The Nemaha and Ozark Uplifts faulted and deformed pre-Pennsylvanian strata in north-central and northeastern Oklahoma (Jordan, 1962). The Ouachita Orogeny of southeastern Oklahoma probably started during the Mississippian and was active during early to middle Pennsylvanian up to the end of the Desmoinesian (Johnson, 2008). The last major orogenic event in Oklahoma, the Arbuckle Orogeny, occurred during the Virgilian and ceased at the end of the Pennsylvanian (Johnson, 2008). After the Pennsylvanian, there were minor uplift and reactivation of faults and folds in Oklahoma (Johnson, 2008).

CHAPTER III

METHODOLOGY

The study began by collecting information on faults, particularly their surface and/or subsurface extents, from fourteen counties in northeastern Oklahoma using all available publications and publically available data.

Arc GIS 10.4 software, a geographic information system for map compilation and geographic information analysis, was used effectively to compile all available information on faults, thereby providing a visual template for studying the relationship between the location of faults, distribution of oil fields, and earthquake foci.

In ArcMap, the World Geodetic System (WGS) 1984 was used as the project coordinate system. The land survey system in Oklahoma is the Public Land Survey System (USGS, 2019). The Oklahoma County Map (Oklahoma Office of Geographic Information, 2019) is added into the project as a reference map. Previous structure maps showing fault extents were scanned into digital files and imported into the ArcMap Project. By using the Arc GIS georeference tool, the township boundaries in the scanned maps were georeferenced with respect to township outlines in the Oklahoma County Map; the real position of a fault was defined and digitized (Figure 3). Then, information from the faults, including their attributes, were input into a database.

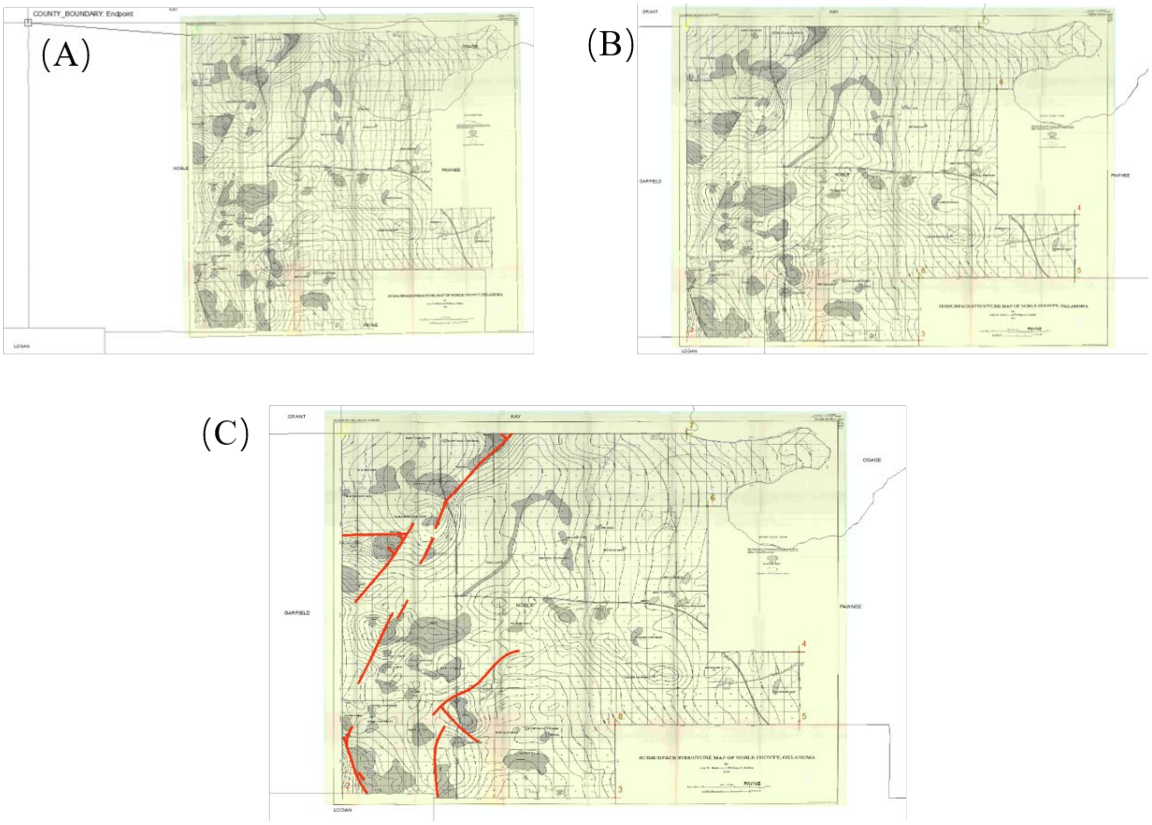


Figure 3: Georeference of a scanned geologic map by Shelton et al. (1979) into ArcGIS.

(A) Georeferenced a Noble County structure contour map to the county location in ArcMap; (B) Georeferenced boundary of the scanned Noble County structure contour map to match the Noble County boundary in ArcMap; (C) Digitized fault traces in ArcMap, red lines show the fault traces digitized from scanned Noble County structure contour map.

The Index Maps to surface and subsurface mapping in Oklahoma (Roberts, 1981; Roberts et al., 1981; Luza et al., 1983; Jordan and Roberts, 1986) were examined for calibration in collecting detailed published and unpublished references of the geological mapping in the study area. In addition to the fault information collected from the literature from local studies, the following represent critical sources of information:

U.S. Geological Survey:

- A Digital Geologic Map Database of Oklahoma (Heran et al., 2003);

Oklahoma Geological Survey:

- Comprehensive Fault Database and Interpretive Fault Map of Oklahoma (Marsh and Holland, 2016),
- Oklahoma Fault Database Contributions from the Oil and Gas Industry (Holloway et al., 2016),
- Preliminary Fault Map of Oklahoma (Holland, 2015).

All of these sources were used in the compilation and comprised the comprehensive database for the ArcMap project basic to this study.

After fault compilation and interpretation, primarily for deletion of duplication, information relating to oil and gas fields was plotted on the interpretive fault map. Sources for the information on oil and gas fields are:

- Map of Oil and Gas Field in Oklahoma by Reservoir Age (Boyd, 2002a),
- Map of Oklahoma Oil and Gas Fields (Boyd, 2002b),
- Herndon Maps,
- Other related publications (Akin, 1964; Schramm, 1965; Chenoweth, 1966, Harris, 1975; Bloesch, 1987; Lyons, 1987; Dolton and Finn, 1989).

Because of the pre-Pennsylvanian tectonic activity, the producing reservoirs were divided into two groups, Cambro-Ordovician Arbuckle Group, Ordovician Simpson Group, Siluro-Devonian Hunton Group and Mississippi Lime, and Pennsylvanian to Permian reservoirs.

By integrating the fault map and field locations in ArcMap, two maps that were generated (Figure 7 and Figure 8) show relationships between faults and the occurrence of hydrocarbon production from two mega - stratigraphic intervals Cambro - Ordovician - Mississippian and Pennsylvanian - Permian.

To relate fault occurrences and recent earthquake activity, two sources were used.

Oklahoma Earthquakes from 09/10/1918-10/31/2019, Database in:

- Oklahoma Geological Survey,
- U.S. Geological Survey.

From these databases, earthquake foci were loaded into ArcGIS for plotting the location of earthquakes, with their attributes (location, time, depth, and magnitude). The map of earthquake distribution (location) includes magnitude and depth, and it is combined with the fault map (Figure 9) to analyze the spatial relationship between the earthquake parameters and faults in the study area. Additionally, faults estimated from the earthquake (seismic) data (Figure 10, McNamara et al., 2015a, 2015b) are also shown with the fault map to use in showing the relationship between recent earthquakes and mapped fault systems in the study area. The structural contour map on the top of the basement in northeastern Oklahoma by Denison (1982) was digitized and the earthquake foci and basement surface are shown in 3D/front views, utilize Petra software to aid in analyzing the spatial relationship between earthquakes and the basement.

CHAPTER IV

RESULTS

4.1 Faults in Northeastern Oklahoma

The comprehensive fault map of northeastern Oklahoma (Plate I) shows the fault database built in this study (red) with the fault database from Oklahoma Geological Survey (blue). An interpretive fault map of northeastern Oklahoma (Plate II) is interpreted based on these databases.

Major fault zones in the study area (Plate II) are the Nemaha Fault Zone (NFZ, red color), West Stillwater – Ramsey – Labette Fault Zone (WSRLFZ, orange color), Wilzetta Fault Zone (WFZ) with parallel faults (dark-blue color) to the east, and East-West-trending faults between NFZ and WFZ (green color). Most of the faults in the study area are high-angle normal faults. However, reverse faults are reported along the Nemaha Fault Zone, West Stillwater – Ramsey – Labette Fault Zone in Pawnee County, Wilzetta Fault Zone in Lincoln County, and Weleetka Fault Zone east of the study area (Appendix I, Plate II). In some cases, the reverse faults, thought to extend upward from the basement displace shallow Pennsylvanian to Permian strata (Appendix I). In addition to the major fault systems, shallow-rooted en echelon fault zones (grey color, plate II) but associated in most cases with deep-seated faults show several trends; the dominant trend is northwest-southeast, especially in the west, and northeast-southwest trend in the easternmost area (Arbenz, 1956). They commonly are clues (trend and direction of relative movement) to the underlying strike-slip faults.

4.1.1 Nemaha Fault Zone (NFZ)

The Nemaha Fault Zone (Figure 4) extends beyond the study area, along or near the western boundary of the area, from Oklahoma City into western Logan County, easternmost Garfield County, through Kay County into Kansas. In Oklahoma, the NFZ broadly is convex westward. To the north into Kansas it trends NNW. The NNW-SSE-trending major Nemaha Fault trace in western Logan County is mapped by Holloway et al. (2016) using 2D seismic data; a reverse fault is reported at a branch fault of the major Nemaha Fault Zone (Gay, 2003b). Although the NFZ is generally down-to-the-west (Ford, 1955; Luza and Lawson, 1980); in the northwestern corner of Logan County (T19N R4W), the fault is down-to-the-east (Luza and Lawn, 1980).

The Nemaha Fault Zone in Kay and Grant Counties is adapted mainly from Rogers (2001), who provides an interpretation at the top of the Mississippian. In these counties, the Nemaha Fault Zone is trending NE to NNE, and the major Nemaha Fault trace splits into several subparallel-trending faults. In addition, there are parallel northeast-southwest-trending faults in Noble and Garfield Counties (Luza and Lawson, 1980; Northcutt and Campbell, 1995). Other fault traces are mapped from Ford (1955), Bross (1961), Shelton et al. (1979), Gay (1999), and Holloway et al. (2016). Most of the mapped faults are normal faults. However, there are eight reverse fault locations reported from Gay (2003b) (Plate II).

In summary, the Nemaha Fault Zone primarily consists of high-angle normal faults (Ford, 1955; Gatewood, 1970; Gay, 1999; Gay, 2003a, 2003b) with localized high-angle reverse faults (Gay, 2003b). It has been interpreted to have left-lateral movement (Blair and Berendsen, 1988; Berendsen and Blair, 1995); however, recent studies propose a more right-lateral nature to the NFZ (Toelle et al., 2008; Chopra et al., 2018). The displacement of the Nemaha Fault is reported from dozens of feet to over 500 feet (Bross, 1961). Currently, the literatures have not constrained the actual strike-slip displacement along the Nemaha.

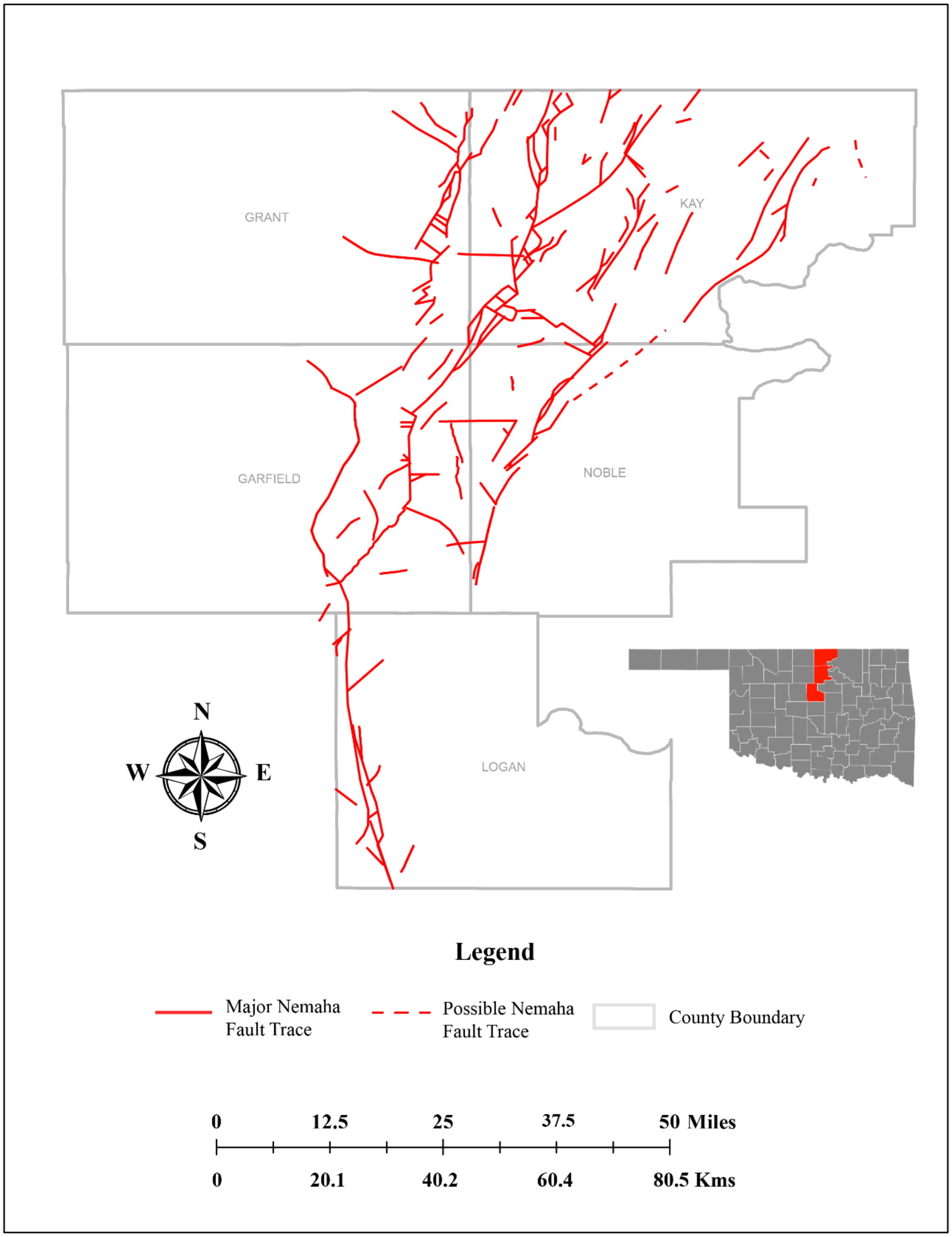


Figure 4: Interpretive Fault Map of Nemaha Fault Zone (NFZ) (after Ford, 1955; Bross, 1961; Shelton et al., 1979; Gay, 1999; Rogers, 2001; Gay, 2003b; Holloway et al., 2016).

The earliest movement of the Nemaha Fault Zone probably occurred during the late-Mesoproterozoic Mid-Continent Rift event (Berendsen and Blair, 1986; Keller et al., 2016), underwent reactivation during the Ordovician, more intense reactivation during the end of Mississippian and early Pennsylvanian, and reactivated again during middle-Pennsylvanian and post-Permian time (Gay, 2003b).

4.1.2 West Stillwater – Ramsey – Labette Fault Zone (WSRLFZ)

Located east of the Nemaha Fault Zone, the West Stillwater – Ramsey – Labette Fault extends northeastward from easternmost Logan County into Payne County into Pawnee County, where it is referred to as the Labette Fault Zone, which probably continues its northeastward trend into Kansas (Figure 5).

The major fault traces of WSRLFZ were mapped from Luza and Lawson (1980), Shelton et al. (1985), Holloway et al. (2016), J. Puckette (2016, personal communication), and Matson (2015). Also, the dash-grey line included in Figure 6 is a lineament shown by Matson (2015), which may be related to WSRLFZ. The northeast-southwest trending Labette Fault (Figure 5; Holloway et al., 2016) represents the northern extension of the WSRLFZ. It has been proposed to correspond to a boundary separating Upper Proterozoic metarhyolite to the northwest and Upper Proterozoic rhyolite, dacite, and andesite flows to the southeast (Sims, 1987). The Watchorn Fault (Figure 5, green color; Gearhart, 1958; Holloway et al., 2016) intersect with West Stillwater – Ramsey – Labette Fault Zone in northwestern Pawnee County.

It has been proposed that the West Stillwater – Ramsey Fault is a high-angle normal fault, with the downthrown block to the southeast, and with left-lateral strike-slip movement (Mckenny, 1955; Umpleby, 1956; Hollrah, 1979). To the north, reverse faults have been reported at Morrison field and along the East Watchorn Fault (Gearhart, 1958).

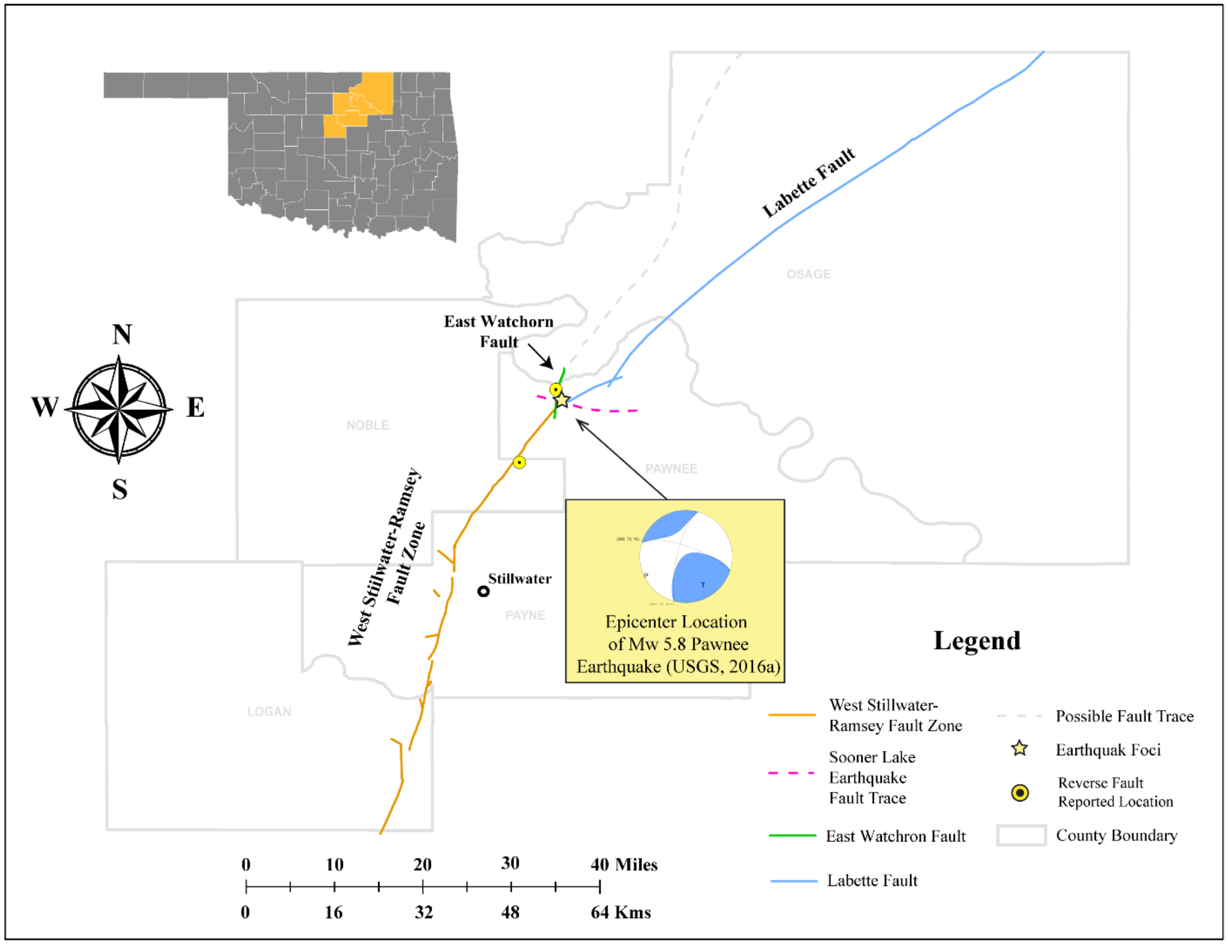


Figure 5: Interpretive Fault Map of West Stillwater – Ramsey – Labette Fault Zone (WSRLFZ), along with north-trending East Watchorn Fault (Green). Fault that intersects the WSRL Fault Zone in northwest Pawnee County (after Gearhart, 1958; Luza and Lawson, 1980; Shelton, 1985; Matson, 2015; Holloway et al., 2016; J. Puckette, 2016, personal communication). The Mw 5.8 Pawnee earthquake (yellow star; USGS, 2016a) occurred along the previously unmapped NW-SE trending Sooner Lake Fault (pink dashed line) (Pennington and Chen, 2017).

In the Ramsey Oilfield the Mississippian and Viola Limestones have approximately 700 feet of left-lateral slip (Umpleby, 1956), or five times more than its vertical displacement. Umpleby (1956) concluded that horizontal movement there was prior to the deposition of the Pennsylvanian Inola Limestone and after Mississippian deposition. There was a brief episode of rejuvenation of the faulting during Middle Pennsylvanian and a vertical movement of the West Stillwater – Ramsey Fault between the deposition of the Inola Limestone and the deposition of the Oswego Limestone.

On September 3rd, 2016, the Mw 5.8 Pawnee Earthquake occurred at the junction of the WSRLFZ and the East Watchorn Fault, which activated a previously unmapped fault, the Sooner Lake Fault (Figure 5, pink dashed line; Pennington and Chen, 2017). The focus of that earthquake is 5.6 km, and the movement has been interpreted as left-lateral along a northwest-southeast-trending strike-slip fault (USGS, 2016a). This earthquake likely resulted from the effects of numerous wastewater disposal wells in the area that changed the basement stress field (Keranen et al., 2013; Keranen et al., 2014; Kolawole et al., 2017; Pennington and Chen, 2017).

4.1.3 Wilzetta Fault Zone (WFZ) with Parallel Fault Zones to the East

A series of northeast-southwest trending fault zones (Figure 6) are mapped in the eastern part of the study area. From west to east, they are the Wilzetta Fault Zone (dark blue), Keokuk Fault (green), Wewoka Fault (brown), Weleetka Fault (yellow) and East Mountain Fault system (black). In addition, several belts of en echelon faults occur along these fault zones (Plate II). The belts trend N to NNE, parallel to the Nemaha uplift, and are composed of faults that strike NW. The faults that make up the en echelon belts strike N45-70°W and dip 50 to 65° either northeast or southwest. All are normal faults. The longest is about 5 km and the greatest throw about 40 m. The fault belts parallel the strike of Upper Pennsylvanian strata in this part of Oklahoma. Mapping of these faults tied to what may be the earliest recognition of strike-slip faulting in the

American Midcontinent, by Fath (1920) and Foley (1926). Using simple clay models for analogues, Fath and Foley proposed that the en echelon zones are the surface expression of **left-lateral** movement on faults in Precambrian basement. Phanerozoic strike-slip faulting in the continental interior platform of the United States: examples from the Laramide Orogeny, Midcontinent, and Ancestral Rocky Mountains (Marshak et al., 2003).

4.1.3.1 Wilzetta Fault Zone (WFZ)

Wilzetta Fault Zone (Figure 6; Dycus, 2013; Holloway et al., 2016) is a northeast-trending fault zone in Lincoln County. In Creek County, it splits into two fault traces. One fault extends northeastward, and the other trends northwest for approximately 5 miles, where it intersects with the major fault that extends northeastward. Further north, in southeasternmost Pawnee County, it shows a more northerly direction, which is characteristic in Osage County.

The WFZ has a complex fault nature which includes normal faults (Cutolo-Lozano, 1970; Pulling, 1979, Verish, 1979; Baurenfeind, 1982; Way, 1983; Hopper, 2005), and reverse faults (Gay, 2003b), as vertical expressions of the strike-slip faults (Verish, 1979). Dycus (2013) characterized the movement as right-lateral. The structure patterns along WFZ may be divided into three parts: Southern Seminole-Cushing Ridge WFZ, Cushing Uplift WFZ, and northern north-south trending WFZ with surface en echelon faults (Dycus, 2013).

The southern part of the WFZ is characterized by almost vertical dip, with the downthrown block to the northwest (Joseph, 1986), and it offsets strata up through the Pennsylvanian Verdigris Limestone. Detailed mapping and interpretation by Dycus (2013) show that the major Wilzetta Fault trace trends N 30° E and is associated with minor east-northeast normal faults. Near the Cushing structure, WFZ is a high-angle normal fault zone with up to 700 feet of vertical separation, and it consists of several fault blocks (Bennison, 1964; Witt et al., 1971).

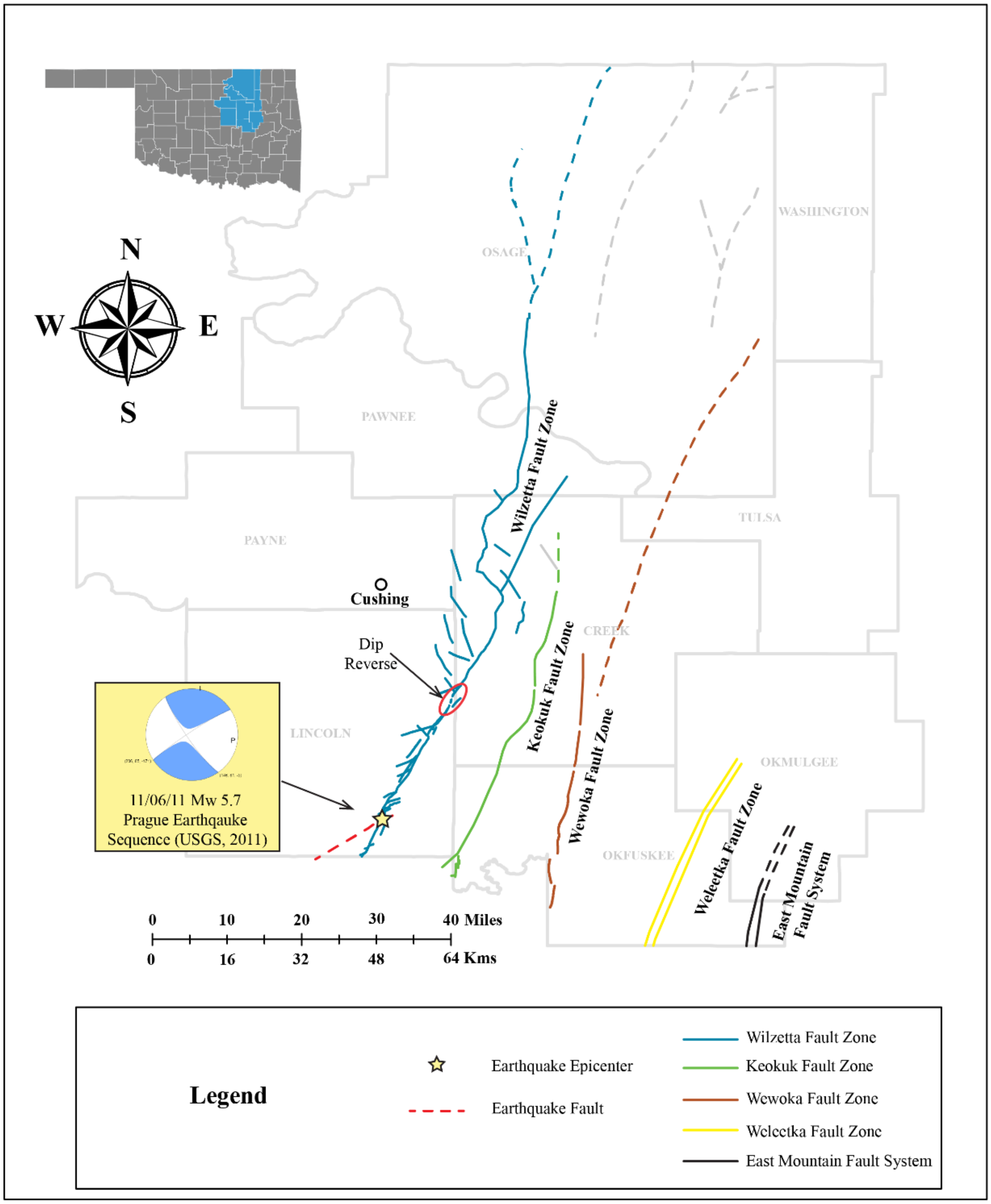


Figure 6: Interpretive Fault Map of Wilzetta Fault Zone and Parallel Fault Zones to the east (Dycus, 2013; Dude, 2014; Holloway et al., 2016; Toelle et al., 2008): Keokuk Fault Zone (green), Wewoka Fault Zone (brown), Weleetka Fault Zone (yellow) and East Mountain Fault System (black). The red dashed line represents the Mw. 5.7 Prague Earthquake Fault (from after-shocks). Earthquake foci is shown (USGS, 2011; Dycus, 2013) as yellow star. Red circle marks the location of dip reversal.

The northern extension of the Wilzetta Fault Zone is not well constrained, and the faults are mapped following the surface north-south trending en echelon faults (Plate II, Fath, 1920; Luza and Lawson, 1980; Way, 1983; Dycus, 2013; Matson, 2015). Fath (1920) proposed that the en echelon faults were possibly generated from the shearing of crystalline basement faults.

Early movement of the Cushing structure occurred during the deposition of the Ordovician Arbuckle Group (Bennison, 1964), due to the earliest movement of Wilzetta Fault. Later faulting and associated structures resulted during the Middle Devonian (post-Hunton) (Bennison, 1964; Pulling, 1979; Dycus, 2013). Influenced by the Ouachita Orogeny, major fault movement of WFZ occurred from the Mississippian to the Desmoinesian. According to Pulling (1979) and Dycus (2013) movement of Paul's Valley Uplift during Early Pennsylvanian changed the local stress directions and activated east-west trending fault and folds along the Wilzetta Fault Zone. From middle to late Pennsylvanian and from the Permian to the Cretaceous, minor reactivation of pre-existing faults further attenuated the faults and folds along the WZF (Arbenz, 1956; Pulling, 1979; Bauernfeind, 1982).

On November 6th, 2011, the Mw 5.7 Prague earthquake occurred along the Wilzetta Fault Zone, seemingly forming new northeast-southwest-trending Meeker-Prague Fault (Figure 6, red dashed line**,** Dycus, 2013). The earthquake focal depth is 5.5 km, well below the top of the basement (Figure 6, USGS, 2011; Dycus, 2013). It is thought that the earthquake resulted from wastewater injection by oil and gas production in this area (Keranen et al., 2013; McNamara, et al., 2015a, 2015b; Walsh and Zoback, 2015).

4.1.3.2 Keokuk Fault Zone (KFZ)

The Keokuk Fault Zone (KFZ; Figure 6) is a north-northeast-trending high-angle normal fault zone with the downthrown block(s) to the east (Blumenthal, 1958; Cutolo-Lozano, 1970; Dudek, 2014). Detailed interpretation of the southern KFZ fault by Dudek (2014) shows a right-stepping

NNE-SSW en echelon normal fault zone. The fault probably originated in the basement and extends upward and dies out in a Middle Pennsylvanian limestone (Dudek, 2014). Associated north-south trending folds become subtle upward (Dudek, 2014). Evidence from the en echelon faults and folds suggest left-lateral movement (Fath, 1920; Miser and Oakes, 1954; Tanner, 1956; Oakes and Jordan, 1959). The Keokuk Fault Zone was active during Middle Devonian and from the end of the Mississippian to the Permian (Tanner, 1956; Dudek, 2014).

4.1.3.3 Wewoka Fault Zone, Weleetka Fault Zone, and East Mountain Fault System

Wewoka Fault Zone (Figure 6; Holloway et al., 2016) is a north-northeast-trending fault zone parallel to, and east of, the Keokuk Fault Zone. Reverse separation is reported along the southern part of Wewoka Fault Zone (Dudek, 2014). The Weleetka Fault Zone (Figure 6; Toelle et al., 2008) east of the Wewoka Fault Zone, is mapped as a northeast-trending graben system with left-lateral strike-slip movement. Further to the east, the East Mountain Fault System (Figure 6; Toelle et al., 2008) is composed by NNE-SSW-trending high-angle normal faults to form a horst. These faults cut Lower Pennsylvanian strata (Musgrove, 1967; Toelle et al., 2008). The paralleling trend of Wewoka, Weleetka, and East Mountain Fault zones suggest a similar history to the Wilzetta and Keokuk Fault Zones.

4.2 Faults and Producing Reservoirs in Northeastern Oklahoma

In northeastern Oklahoma, producing reservoirs range from Cambrian to Permian, mainly including the Cambro-Ordovician Arbuckle Group, Ordovician Simpson Group, Siluro-Devonian Hunton Group, Mississippi Lime, and Pennsylvanian-Permian sandstones (Figure 2a and Figure 2b; Dolton and Finn, 1989; Boyd, 2008). Two maps show the relationship of these producing reservoirs and the fault zones in the study area: reservoirs coupled with the fault map have been completed: (1) Fault Map and Pre-Pennsylvanian Producing Reservoir Map (Figure 7) and (2) Fault Map and Pennsylvanian to Permian Producing Reservoir Map (Figure 8).

4.2.1 Fault Map with Map of Pre-Pennsylvanian Producing Reservoirs

The primary producing reservoirs (Figure 7) include the Cambro-Ordovician Arbuckle Group (purple color), middle Ordovician Simpson Group (orange color), Siluro-Devonian Hunton Group (olivine yellow color), Mississippi Lime (blue color) and unassigned pre-Pennsylvanian reservoirs in structurally controlled traps (dark green color, Lyons, 1987).

Along the Nemaha Fault Zone, pre-Pennsylvanian reservoirs produce along or near faults, in fault- and/or fault-related folds. These include a trap-door structure at Billings field in Noble County and a prominent structure at the intersection of the West Stillwater-Ramsey and an east-west fault in Payne County (Shelton, et al., 1979). Major production has been a significant feature of the Nemaha and Wilzetta fault zones. The Mississippian Lime probably has the poorest relation to faults of the pre-Pennsylvanian reservoirs, although in Osage County, basement highs in Osage County, with associated production, are generally considered paleo-topographic features (e.g., Rottmann, 2018).

In summary, there are four typical distribution trends of pre-Pennsylvanian producing reservoirs. First of all, large oil fields are created by structural traps at the upthrown blocks of the major fault zones (Nemaha Fault Zone, Wilzetta Fault Zone, West Stillwater-Ramsey Fault Zone and East-West Trending Fault Zone). For example, Arbuckle producing reservoirs and Simpson producing reservoirs of Cushing Oilfield occur in the western upthrown fault block of Wilzetta Fault Zone. Also, the structurally controlled plays (dark green color) along the East-West trending faults at the north of Logan County (Lyons and Dobrin, 1972; Lyons, 1987). Secondly, smaller producing fields are distributed along the junctions of major faults and subsidiary faults in the Nemaha Fault Zone and Wilzetta Fault Zone. For example, the upthrown blocks at the junctions of N 60° E faults and the N 30° E major fault traces of the WFZ. Thirdly, the typical location producing reservoirs is where the East-West striking faults terminate against the NFZ and WFZ.

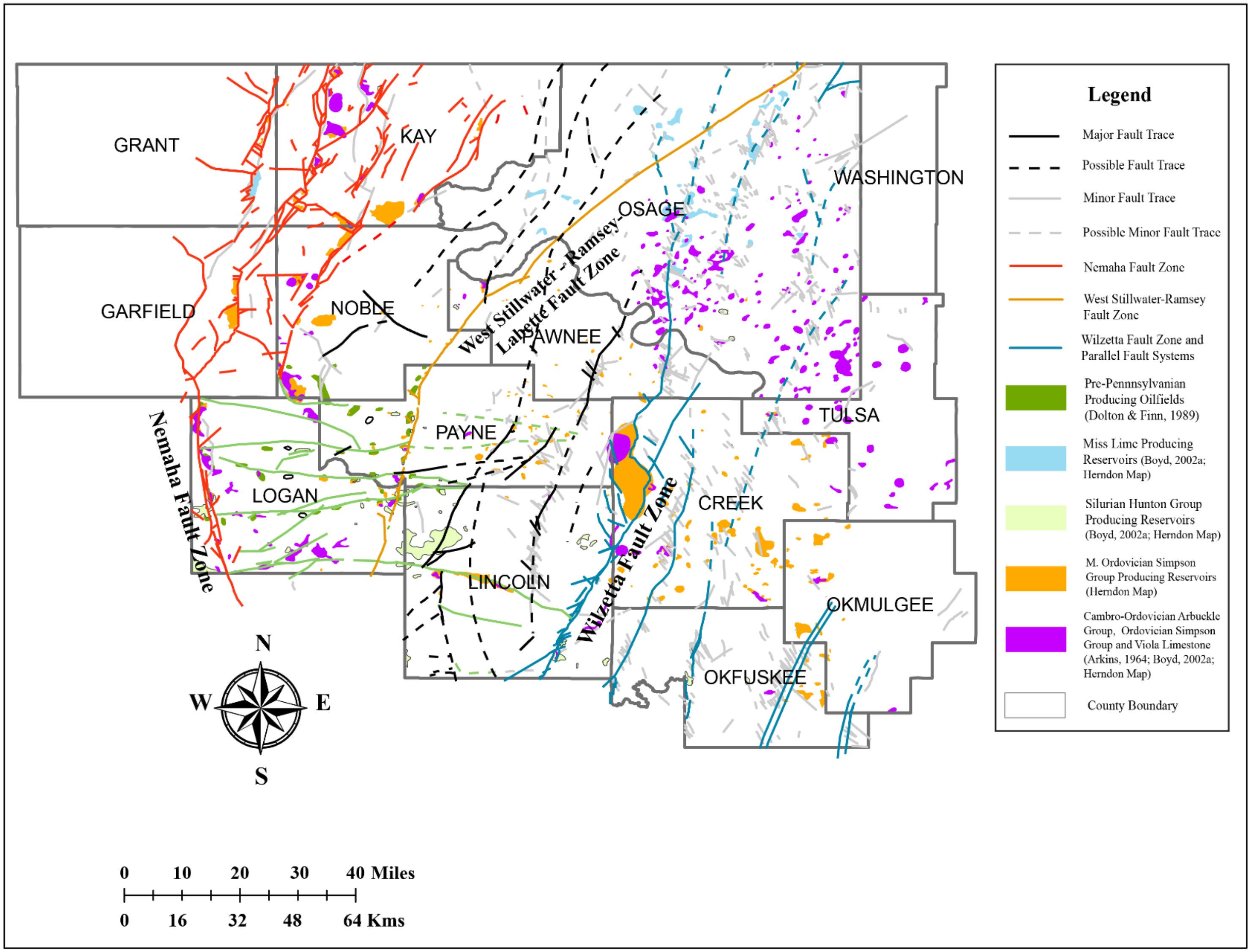


Figure 7: Fault map with map of pre-Pennsylvanian producing reservoirs.

The upthrown blocks in the junctions between the East-West Trending Fault and the Nemaha Fault Zone or the Wilzetta Fault Zone are ideal locations to form structural traps for hydrocarbon accumulation. The last major producing reservoir type is the Arbuckle Group producing reservoirs distributed in Osage County and Tulsa Counties. They are controlled by basement highs, normally referred to Tulsa Ridges or Tulsa Mountains, which form the structural highs for overlying sediments.

4.2.2 Fault Map with Map of Pennsylvanian to Permian Producing Reservoirs (Figure 8)

The major fault systems in northeastern Oklahoma probably do not play a role in the distribution of Morrowan age producing reservoirs in northeastern Oklahoma.

Pennsylvanian reservoirs produce from both structural traps, basically resulting from faulting, and stratigraphic traps. The former has in most cases resulted in larger reserves, whereas the latter seemingly are more numerous. Permian production in the study area is insignificant, compared to the Pennsylvanian.

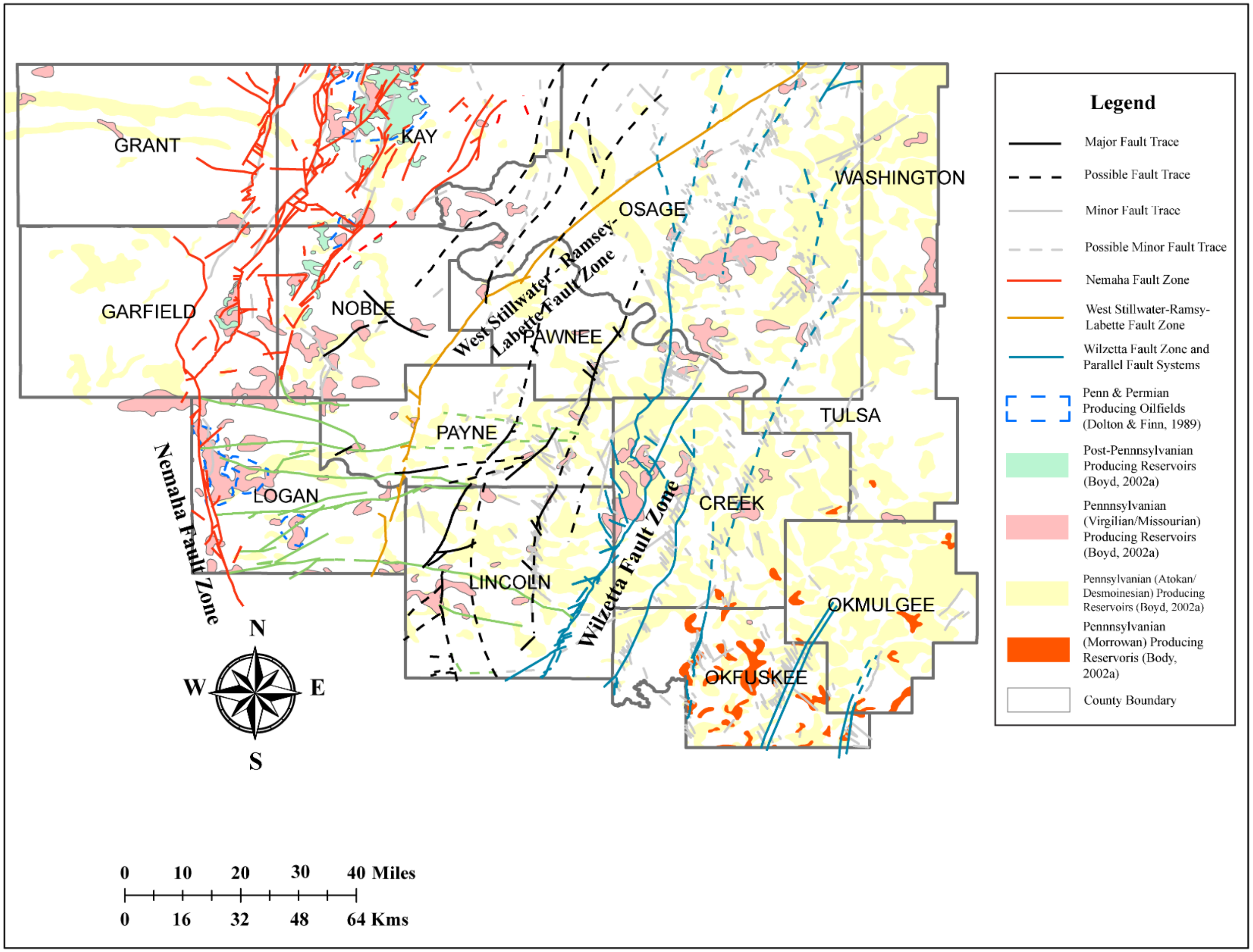


Figure 8: Fault map with map of Pennsylvanian to Permian producing reservoirs.

4.3 Faults and Earthquake Occurrences in Northeastern Oklahoma

4.3.1 Faults and Earthquake Occurrences

The comprehensive map of faults with an overlay of earthquake foci (Figure 9) shows the foci of the earthquakes in the study area from 1918-2019. The fault map is the compilation from all available fault databases. The earthquakes have occurred mainly between Nemaha Fault Zone and Wilzetta Fault Zone. Most of the earthquakes have occurred between the major fault systems; relatively few have occurred directly on the fault traces of the major fault zones in the study area. Three earthquakes with Mw of 5.0 or greater have been recorded in the study area; they occurred at depths between 4km to 6km. They are the Mw 5.7 Prague earthquake (Figure 6 and Figure 9; USGS, 2011), the Mw 5.8 Pawnee earthquake (Figure 5 and Figure 9; USGS, 2016a) and the Mw 5.0 Cushing earthquake (Figure 9; USGS, 2016b). The Prague earthquake occurred at a previous unmapped northeast-southwest-trending fault in the Wilzetta Fault Zone (USGS, 2011; Dycus, 2013). The Cushing earthquake occurred on a southwest-northeast-trending fault that intersects a prominent NNE-SSW trending fault east of Wilzetta Fault Zone (McNamara et al., 2015a). The Pawnee earthquake occurred at the intersection of West Stillwater-Ramsey Fault Zone, Labette Fault Zone and Watchorn Fault and on a previously unmapped northwest-southeast fault (Sooner Lake Fault) (Pennington and Chen, 2017). These high magnitude earthquakes occurred on or near previously mapped major faults and apparently formed new subsidiary faults that intersect the major fault traces. However, for the earthquakes below magnitude five, most do not show a significant relationship with the north-south-trending fault zones, but with the easterly trending (unnamed) fault zones.

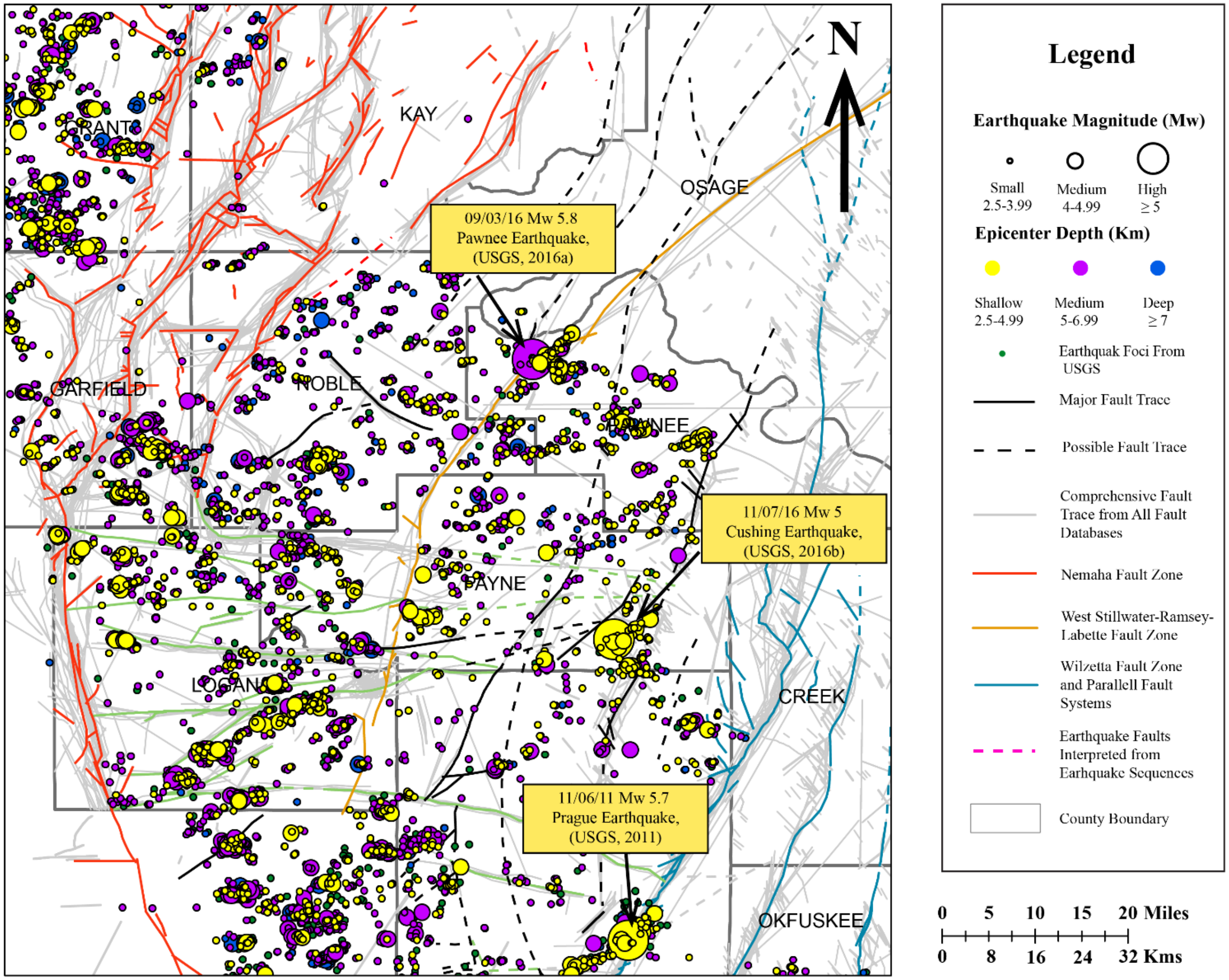


Figure 9: Faults with earthquake foci in northeastern Oklahoma. In order to avoid the duplication of the earthquake foci from USGS and OGS, only earthquake foci from OGS are shown in detailed information.

4.3.2 Fault Map and Earthquake Fault Map

Earthquake faults (Figure 10) are interpreted from (1) “the distribution of seismicity and focal mechanism nodal plane” by McNamara (2015b) or (2) the distribution of seismicity using the 1918-2019 earthquake information. The interpretive fault zones in the study area are the mapped faults from all databases compiled in the study area. Most earthquake fault trends are consistent with the N 53° E and N 113° E optimal fault orientations given the maximum horizontal stress of N 80°-90° E estimated by Alt and Zoback (2016). Apparently, most of the earthquake faults do not directly coincide with the geologically mapped faults.

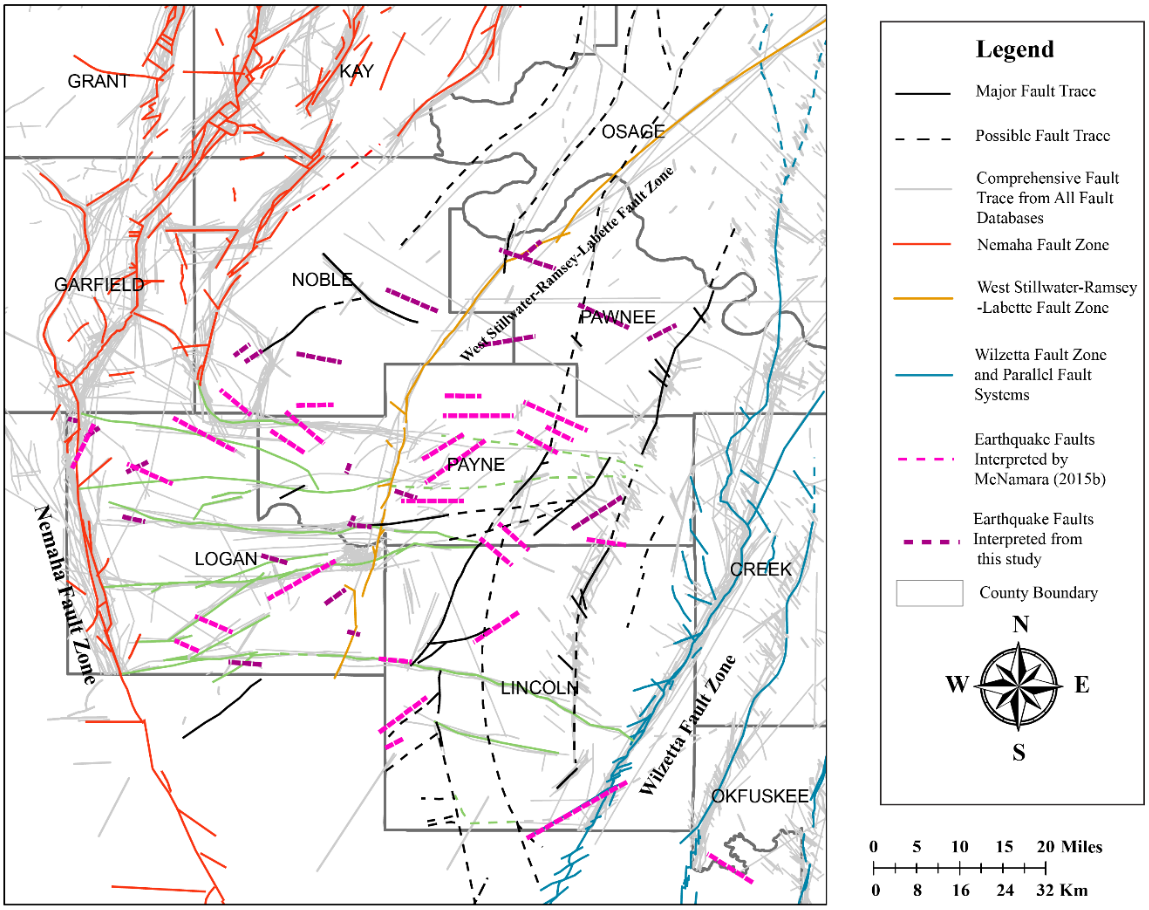


Figure 10: Geologically determined faults and seismically determined faults in northeastern Oklahoma.

4.3.3 Earthquake Foci and the Top of the Basement in Northeastern Oklahoma

After combining earthquake foci and the map of the top of the basement (Denison, 1982) of the study area, we projected the foci and top of the basement into 3D view (Figure 11) and front view (Figure 12). It shows that most earthquakes were generated below the top of the basement, whereas only a few originated above the basement.

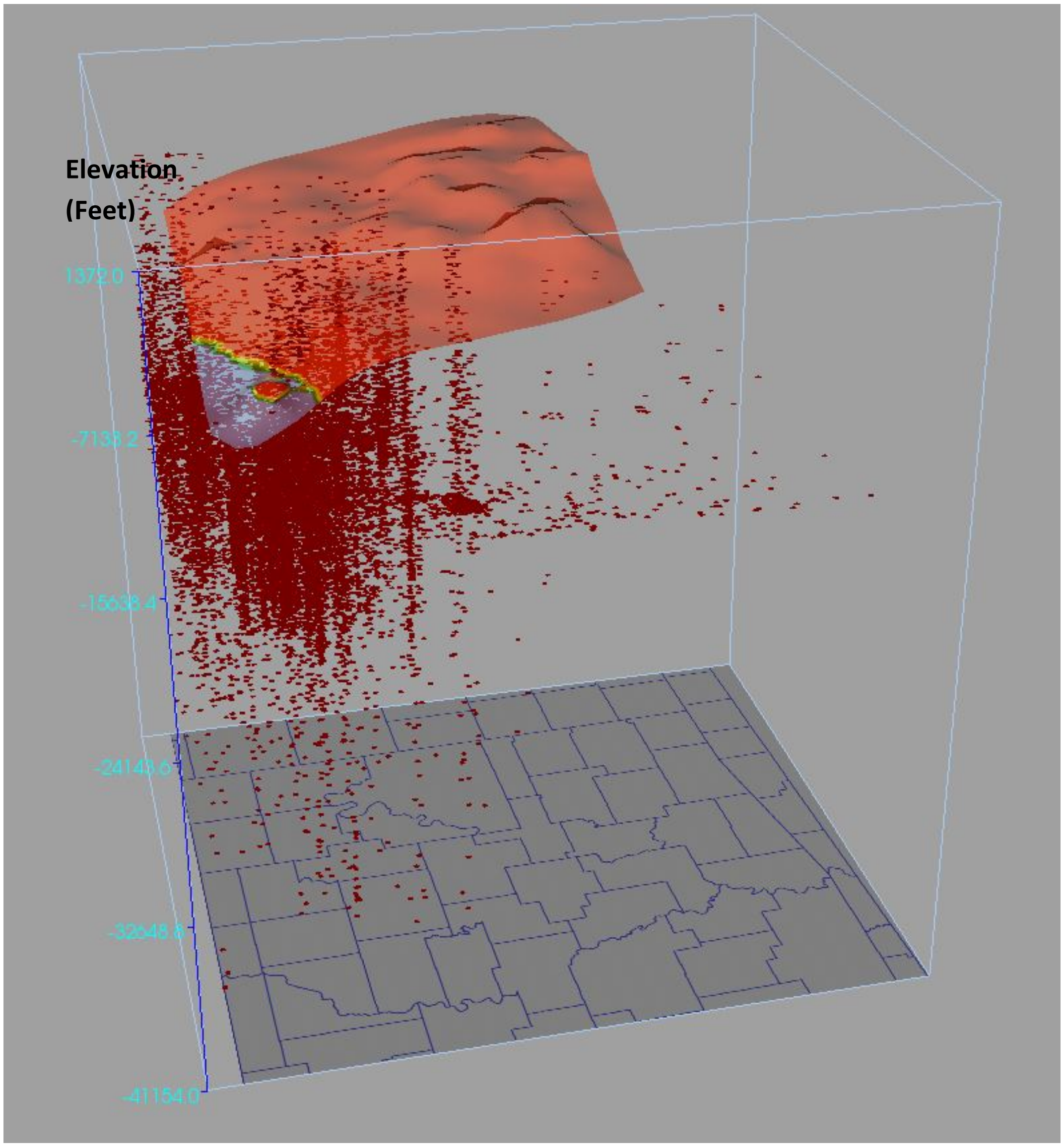
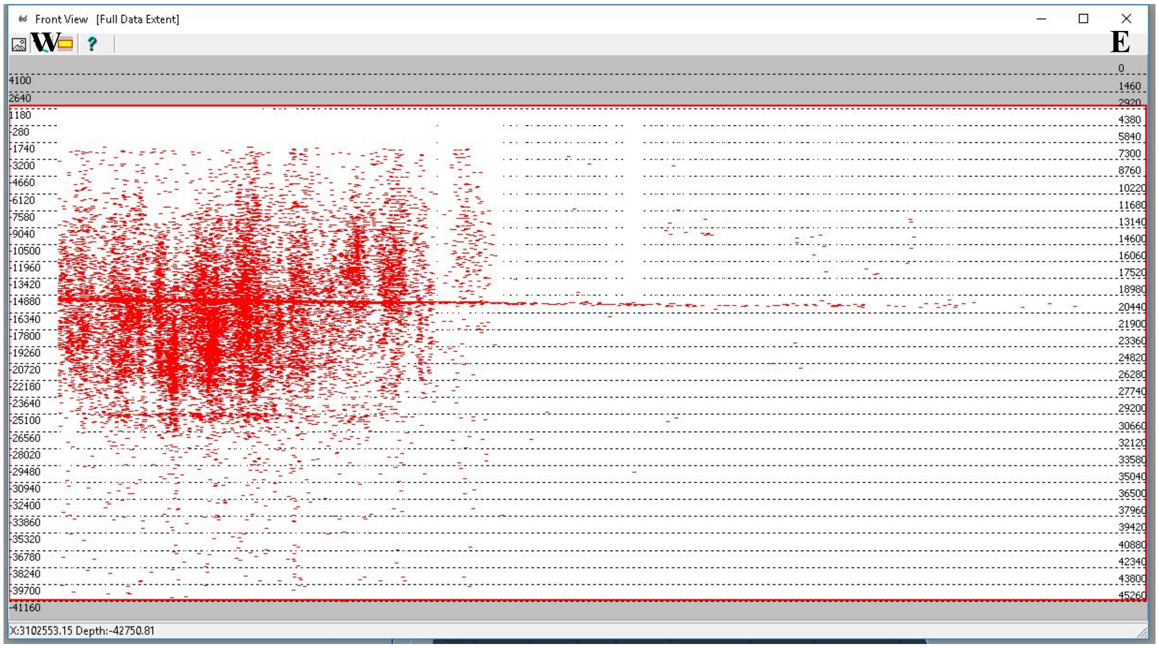


Figure 11: 3D view of earthquake foci (OGS), top of the basement (Denison, 1982) and surface topography in northeastern Oklahoma.



X:3102553.15 Depth:-42750.81

Figure 12: Front view of earthquake foci (OGS) distribution (left vertical axis shows the elevation of foci in feet and the right vertical axis shows the depth of foci in feet).

CHAPTER V

DISSCUSION AND CONCLUSION

5.1 Strike-Slip Feature of the Fault Systems in Northeastern Oklahoma

Strike slip, as the dominant movement along faults in the study area is based on: high-angle to vertical fault surfaces, change in dip direction along the same fault, reverse as well as normal separation, en echelon surficial faults, pop-up, flower (Figure 13), and trap-door structures, and Riesel fractures (due to recent earthquake-induced faulting).

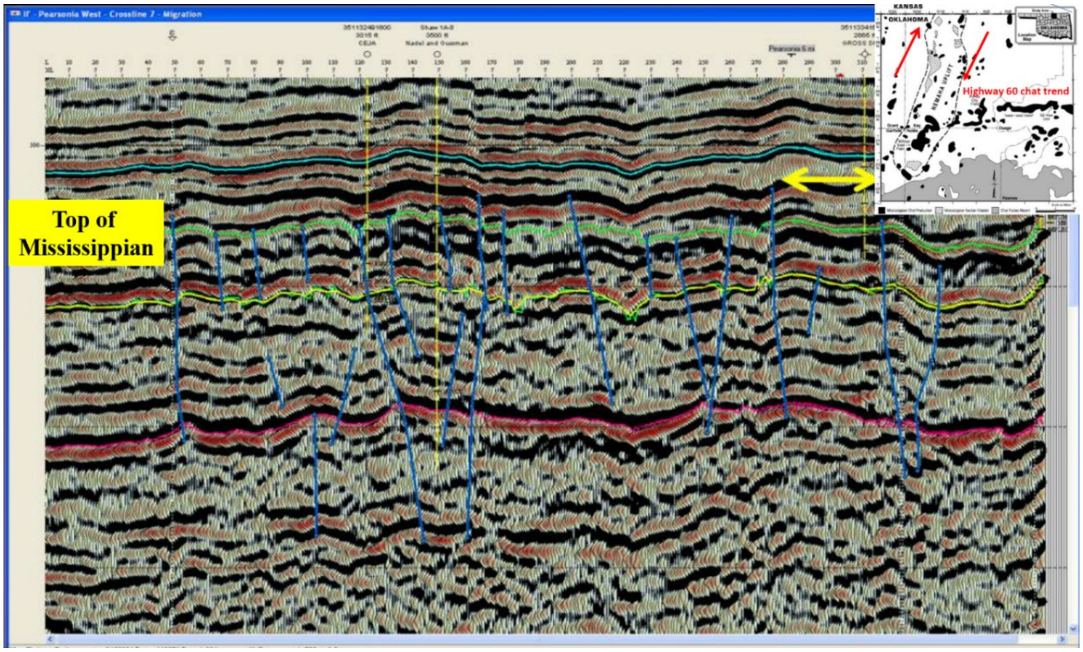


Figure 13. E-W Seismic Section (8 miles width) of HW 60 Trend, Osage County, Oklahoma (Matson, 2013; Watney, 2014).

5.2 Relationship between Pennsylvanian-Permian Producing Reservoirs and Pre-Pennsylvanian Producing Reservoirs

Comparison of the Fault Map with Pre-Pennsylvanian and with Pennsylvanian Reservoirs shows that the former produce dominantly in fault-related traps, whereas the latter produce from some of the same traps as the former, but also produce from stratigraphic traps. The common trapping feature indicates reactivation of the faults over a long period of time. It also implies a common dominant source rock, the Devonian Woodford Shale.

5.3 Association of Earthquakes with Paleozoic Faults in Northeastern Oklahoma

The Fault and Earthquake Fault Map (Figure 10) shows that the earthquake faults are not strongly associated with the currently known faults in northeastern Oklahoma. However, there is correlation when the stronger earthquakes are considered (magnitude of Mw 4.6 and above 4.6, Figure 14). The majority of the earthquakes originated well below the top of the basement (Figure 11, 12). A recent study by (Shah and Crain, 2018) based on aeromagnetic data showed some earthquake faults in northeastern Oklahoma were associated with the basement faults. In addition, R. J. Springman (2018, personal communication) confirmed that one earthquake occurrence coincides with a fault based on seismic data that was acquired before the earthquake. Therefore, earthquake faults might be the reactivation of basement faults. It is likely that basement faults are much more common than subsurface geologic data permits, as suggested by Gay (1999, 2003a, 2003b). It is also conceivable that some of the earthquakes represent new faults associated with changes in the stress field.

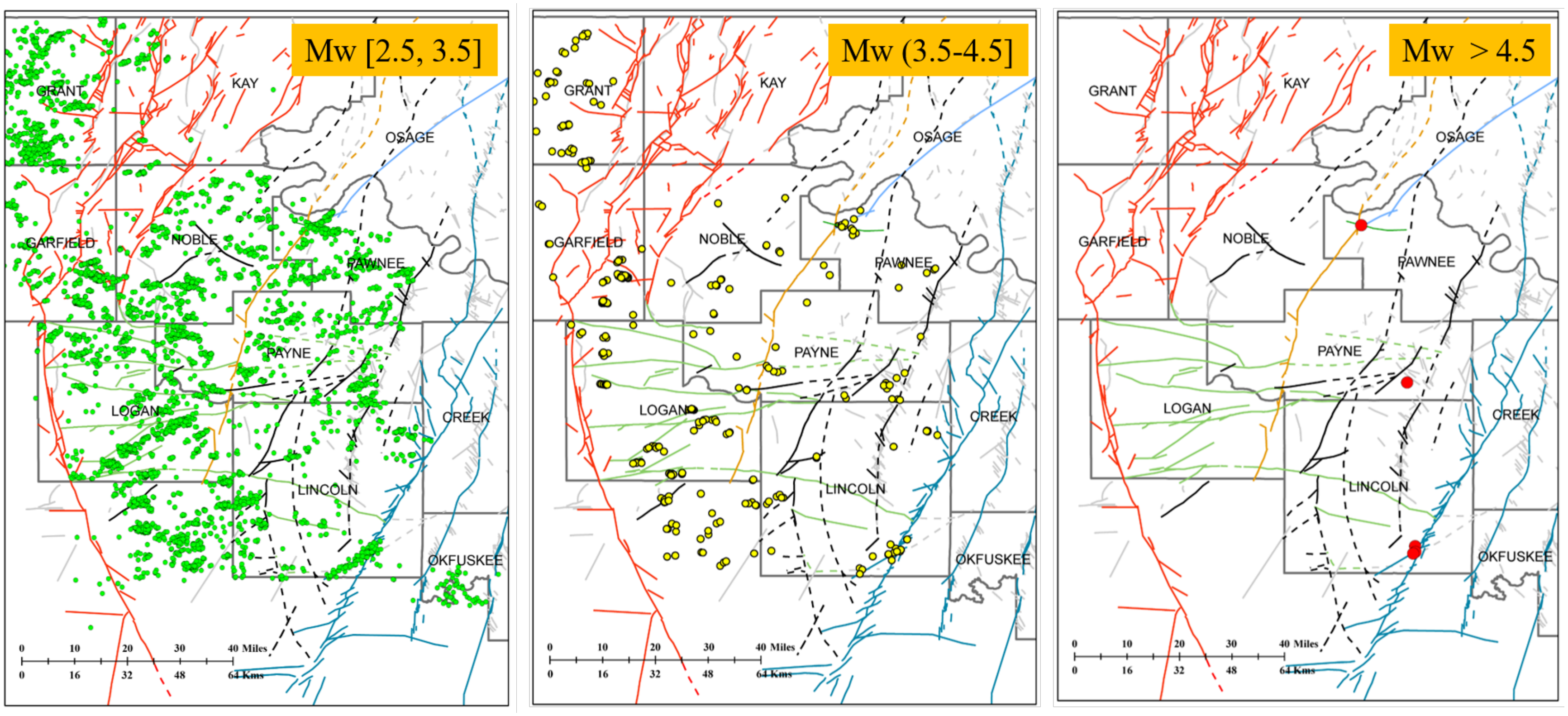


Figure 14. Earthquake foci in different movement magnitudes with faults. From left to right, diagrams are earthquake foci of Mw 2.5-3.5 (green), Mw greater than 3.5 and less than or equal to 4.5 (yellow), and Mw greater than 4.5 (red).

5.4 Conclusions

1. The fault information collected from this study shows complex fault patterns in northeastern Oklahoma. The most dominant fault zones are the Nemaha Fault Zone (NFZ) and the Wilzetta Fault Zone (WFZ). Other major zones that are named are the West Stillwater – Ramsey – Labette, Keokuk, Wewoka, and Weleetka. Strike-slip is the primary fault movement, and its associated fault systems. Essentially, strike-slip movement is one of the most important components of these fault systems.

2. Pre-Pennsylvanian reservoirs produce largely from structural traps associated with the fault zones noted above. Yet, several potential traps exist along fault zones that are interpreted from the databases utilized and others interpreted from earthquake data.

Pennsylvanian producing reservoirs also occur in fault-related traps, but they also are present in stratigraphic traps. Additional production potential is likely in the presence of traps along fault zones delineated in this study and in those interpreted from the earthquakes themselves.

3. Earthquakes that occurred recently in northeastern Oklahoma were predominantly less than 3 Mw magnitude. However, three were 5.0-5.8 Mw. Those three show a relation to the major faults, seemingly along or forming subsidiary faults. The foci from most of the earthquakes were below the top of the basement. Overall, the map of earthquake faults and geologically mapped faults in the study area does not show strong link between the faults and the earthquakes. Yet this would indicate that a large number of pre-existing faults have not been mapped or unmapped faults were recently generated, as recorded by a large number of the earthquakes. It seems reasonable to think that fractures, indeed faults, are present at least in the basement and may extend to the overlying sedimentary section.

5.5 Future Study

The following are features related to this study in northeastern Oklahoma that are recommended for future study:

- Depth of open fractures in the basement,
- History of injection pressure in wells in areas of Mw greater than 4.5,
- Delineation of faults, with aid of considerable seismic data in Osage County,
- Relation of faults to “buried hills”,
- Permeability of rock into which fluids are injected.

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APPENDICES

Appendix I. Reported reverse fault locations.

References	Location	Comments
Gay (2003b)	sec. 21, R. 1 W., T. 29 N.	Braman North Field-Horst block showing 400+ ft of uplift on the west.
	sec. 9, R. 2 W., T. 25 N.	Thomas field
	R. 2E., T. 25 N.	Ponca City Field-Magnetic data by Applied Geophysics, Inc. show west dip to fault, hence reverse throw.
	sec. 7, R. 2W., T. 24 N.	Three Sands field
	sec. 33, R. 4 W., T 17 N.	Crescent field
	R. 3 E., T. 8 N. to R. 7 E., T. 17 N.	"Wilzetta" fault. Extends 55 mi from north central Pottawatomie Co. to western Creek Co.
Dudek (2014)	sec. 23, R. 11 N, T. 18 E.	A reverse fault mapped from Viola to Pre-Atokan Unconformity, the fault dips to the east.
Greer (1961)	NE 1/4 SE 1/4 NE 1/4 sec. 9, T. 14 N, R. 6 E.	The well encontered Mississppian rocks two times, so the repeat sections indicates reverse fault in this area.
Robbins (1979)	sec. 12, 24, 25 R. 5 E, T. 18 N & sec. 7, 17, 18, 30 R. 6 E, T. 18 N.	The cross sections of the fualts show high angle reverse fault cutting upper Pennsylvanian strata.
Gearhart (1958)	Marrison (?) Fault, sec. 28, 32, 33, R. 3 E, T. 22 N, sec. 5, 8, R. 3 E, T. 21 N; East Watchorn Fault, sec. 13, 24, 25, 36, R. 3 E, T. 23 N.	The down dip sides of Marrison (?) Fault and East Watchorn Fault have been upthrown.

Appendix II Fault references in this study, list by County (continues to next page).

Creek	**Kay**	**Lincoln**	**Logan**
Bauernfeind (1982)	Bradshaw (1959)	Andrews (2003)*	Bebout et al. (1993)*
Bennison (1964)	Clark & Cooper (1927)#	Bauernfeind (1982)	Bross (1961)
Busch (1956)*	Clark & Daniels (1929)	Beckwith (1927)*	Cardott et al. (1985)*
Buttram (1914)#	Clements (1961)	Blumenthal (1958)#	Ford (1955)#
D'Lugosz et al. (1986)*	Davis III (1985)	Cole (1958)#	Gay (1999)#
Fath (1920)	D'Lugosz et al. (1986)*	D'Lugosz et al. (1986)*	Heinzelmann (1967)
Gay (1999)#	Gay (1999)#	Ferguson (1964)	Hollrah (1979)
Hanke (1967)	Jordan (1962)	Gay (1999)#	Jordan (1962)
Hyde (1957)	Luza & Lawson (1980)#	Greer (1961)	Kousparis (1979)
Jordan (1962)	Matson (2013)	Heinzelmann (1967)	Luza & Lawson (1980)#
Luza & Lawson (1980)#	Matson (2015)	Hollrah (1979)	Lyons (1987)
Matson (2013)	Mikkelson (1966)*	Hyde (1957)	Matson (2013)
Matson (2015)	Murray (2014)*	Jordan (1962)	Matson (2015)
Miser & Oakes (1954)#	Northcutt & Campbell (1995)#	Joseph (1986)#	McKenny (1955)#
Murray (2014)*	Querry (1958)	Luza & Lawson (1980)#	Mcnamara (2015b)
Northcutt & Campbell (1995)#	Ratre (2017)	Masters (1958)	Miller (1959)
Oakes & Jordan (1959)*	Rogers (2001)	Matson (2015)	Murray (2014)*
Ratre (2017)		Mcnamara (2015b)	Nolte (1951)
Toelle et al. (2008)		Miser & Oakes (1954)#	Northcutt & Campbell (1995)#
		Murray (2014)*	J. Puckette (2016, personal communication)
		Northcutt & Campbell (1995)#	Ratre (2017)
		J. Puckette (2016, personal communication)	Shah & Crain (2018)
		Ratre (2017)	Toelle et al. (2008)
		Rottmann (2000)	
		Shah & Crain (2018)	
		Smith (1948)	
		Toelle et al. (2008)	
		Verish (1979)	
		West (1961)	

* Fault references of Comprehensive Fault Database of Oklahoma (Marsh and Holland, 2016).

Fault references of fault database of this study and Comprehensive Fault Database of Oklahoma (Marsh and Holland, 2016).

Appendix II Fault references in this study, list by County (continues to next page).

Noble

Chandler (1979)#
Clark & Cooper (1927)#
Clements (1961)
Denison (1982)*
Gay (1999)#
Gearhart (1958)
Jordan (1962)
Luza & Lawson (1980)#
Lyons (1987)
Matson (2013)
Matson (2015)
McDuffie (1964)
Mcnamara (2015b)
Murray (2014)*
Northcutt & Campbell (1995)#
Page (1955)#
Pennington & Chen (2017)
J. Puckette (2016, personal communication)
Ratre (2017)
Rogers (2001)
Shah & Crain (2018)
Shelton et al. (1979)#
Ward (1958)

Okfuskee

Andrews (2003) *
Andrews et al. (1998)*
Blumenthal (1958)#
Cutolo-lozano (1970)
D'Lugosz et al. (1986)
Dudek (2014)
Gay (1999)#
Jordan (1962)
Luza & Lawson (1980)#
Matson (2013)
Matson (2015)
Miser & Oakes (1954)#
Murray (2014)*
Musgrove (1967)
Northcutt & Campbell (1995)#
Ratre (2017)
Ries (1954)#
Smith (1948)
Tanner (1956)*
Toelle et al. (2008)

Okmulgee

Andrews (2003) *
Clark (1926)*
Hamric (1961)
Hemish & Beyma (1988)
Jordan (1962)
Luza & Lawson (1980)#
Matson (2015)
Miser & Oakes (1954)#
Musgrove (1967)
Oakes & Motts (1963)
Toelle et al. (2008)

Osage

Beckwith (1927)*
Bingham & Bergman (1980)
Blakeley (1959)
Denison (1982)*
D'Lugosz et al. (1986)
Fath (1920)
Gay (1999)#
Gearhart (1958)
Hyde (1957)
Jordan (1962)
Luza & Lawson (1980)#
Matson (2013)
Matson (2015)
Millikan (1920)
Miser & Oakes (1954)#
Pennington & Chen (2017)
Ratre (2017)
Rountree (1994)#
Sims (1987)
Stanley (2010)*
Tanner (1956)*

* Fault references of Comprehensive Fault Database of Oklahoma (Marsh and Holland, 2016).
\# Fault references of fault database of this study and Comprehensive Fault Database of Oklahoma (Marsh and Holland, 2016).

Appendix II Fault references in this study, list by County (continues to next page).

Pawnee	Payne	Tulsa	Washington
Baker (1958)	Backer (1958)	Bennison (1972)	Hemish (1990)
Bingham & Bergman (1980)	Dalton (1960)	Bingham & Bergman (1980)	Jordan (1962)
Blakeley (1959)	D'Lugosz et al. (1986)	Fath (1920)	Matson (2013)
Denison (1982)	Gay (1999)#	Hemish (1990)	Matson (2015)
D'Lugosz et al. (1986)	Graves (1958)#	Jordan (1962)	Oakes (1940)
Fath (1920)	Heinzelmann (1967)	Luza & Lawson (1980)#	
Gay (1999)#	Hollrah (1979)	Matson (2013)	
Gearhart (1958)	Hyde (1957)	Matson (2015)	
Greig (1959)	Jordan (1962)	Miser & Oakes (1954)#	
Hyde (1957)	Luza & Lawson (1980)#	Oakes (1952)	
Jordan (1962)	Lyons (1987)	Ratre (2017)	
Luza & Lawson (1980)#	Matson (2013)	Reeder (1976)	
Matson (2013)	Matson (2015)	Stanley (2010)*	
Matson (2015)	McKenny (1955)#	Stanley et al. (2011)*	
Miser & Oakes (1954)#	Mcnamara (2015b)	Toelle et al. (2008)	
Pennington & Chen (2017)	Miser & Oakes (1954)#		
J. Puckette (2016, personal communication)	J. Puckette (2016, personal communication)		
Ratre (2017)	J. Puckette (2016, personal communication)		
Rountree (1994)#	Ratre (2017)		
Shah & Crain (2018)	Robbins (1976)		
Sims (1987)	Rottmann (2000)		
Toelle et al. (2008)	Rountree (1994)#		
	Shah & Crain (2018)		
	Shelton et al. (1985)		
	Shipley (1976)		
	Stringer (1958)#		
	Umpleby (1956)*		

* Fault references of Comprehensive Fault Database of Oklahoma (Marsh and Holland, 2016).
# Fault references of fault database of this study and Comprehensive Fault Database of Oklahoma (Marsh and Holland, 2016).

Appendix II Fault references in this study, list by County.

Garfield	**Grant**
Fritz (1978)	Gay (1999) #
Luza & Lawson (1981)	Luza & Lawson (1981)
Lyons (1987)	Matson (2013)
Matson (2013)	Matson (2015)
Matson (2015)	Rogers (2001)
McDuffie (1964)	
Rogers (2001)	
Toelle et al. (2008)	

* Fault references of Comprehensive Fault Database of Oklahoma (Marsh and Holland, 2016).
# Fault references of fault database of this study and Comprehensive Fault Database of Oklahoma (Marsh and Holland, 2016).

Appendix III Regional fault references and fault databases of northeastern Oklahoma.

Region Fault References	Fault Database of OGS	Fault Database of USGS
Arbenz (1956)	Holland (2015)	Heran et al. (2003)
Bingham & Bergman (1980)	Holloway (2016)	Miser & Oakes (1954)*
Fath (1920)	Marsh & Holland (2016)	
Fritz (1978)		
Gay (1999)		
Jordan (1962)		
Luza & Lawson (1981)		
Matson (2013)		
Matson (2015)		
Northcutt & Campbell (1995)		
Shah & Crain (2018)		
Tarr et al. (1965)		
Toelle et al. (2008)		

* Fault references of Comprehensive Fault Database of Oklahoma (Marsh and Holland, 2016).

VITA

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Biographical:

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Professional Memberships: AAPG

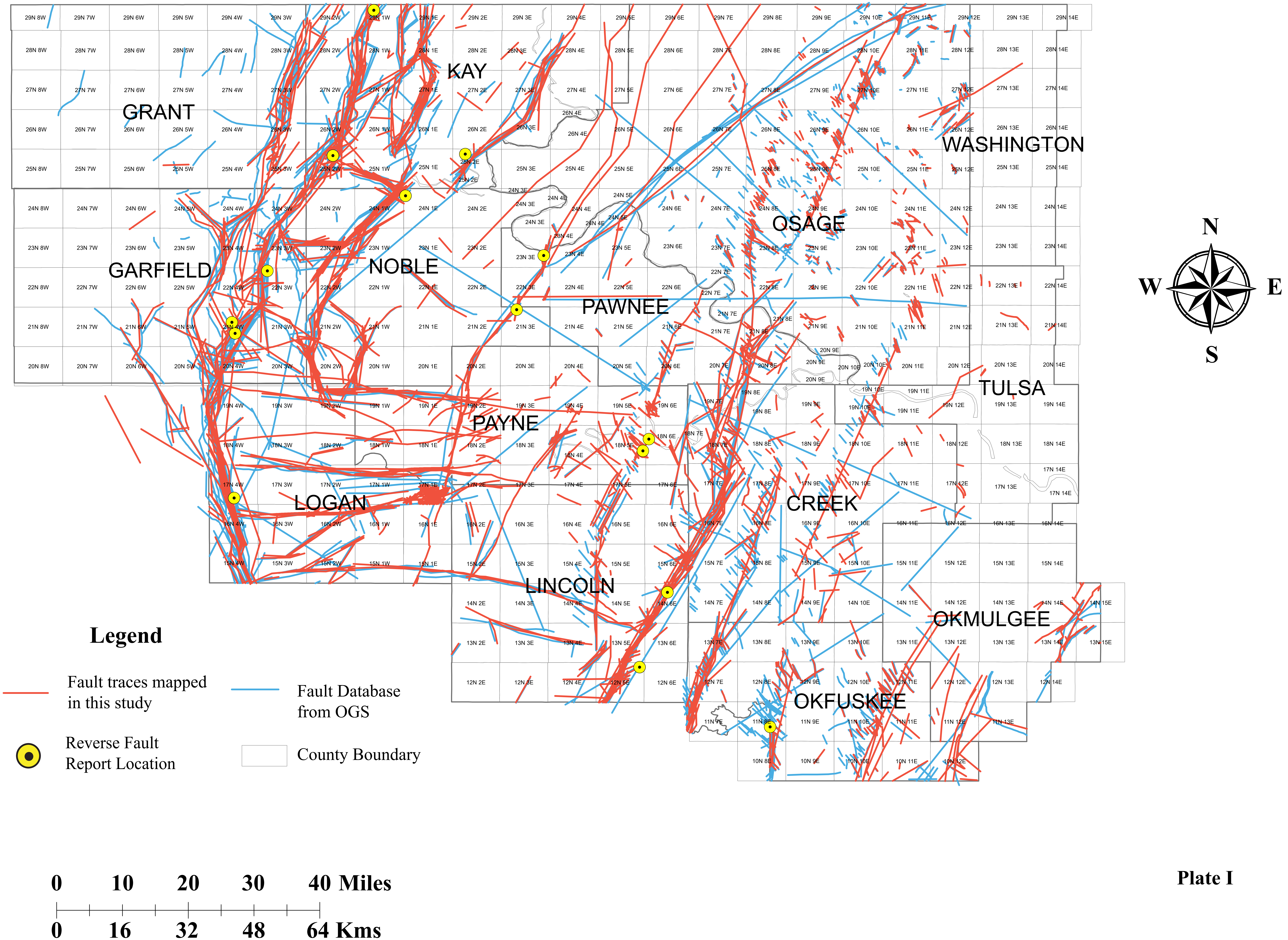
GRANT
KAY
GARFIELD
NOBLE
OSAGE
WASHINGTON
PAWNEE
PAYNE
TULSA
LOGAN
CREEK
LINCOLN
OKMULGEE
OKFUSKEE
N
W
E
S
Legend
Fault traces mapped in this study
Fault Database from OGS
Reverse Fault Report Location
County Boundary
0
10
20
30
40 Miles
0
16
32
48
64 Kms

Plate I

Interpretive Fault Map of Northeastern Oklahoma

By

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Plate II