Faults in Northeastern Oklahoma: Their Occurrence, Relation to Modern Seismic Activity and to Producing Reservoirs*

James Puckette[1] and Xitong Hu[1]

Search and Discovery Article #30675 (2020)
Posted January 4, 2021

*Modified from Oklahoma State University M.S. Thesis, 2019, by Xitong Hu, who appreciates the technical support of Jingyao Gong and John Shelton. Manuscript received February 27, 2020. Manuscript accepted June 25, 2020.

[1]Oklahoma State University, Stillwater, OK (jim.puckette@okstate.edu)
[1]Oklahoma State University, Stillwater, OK (xhu@okstate.edu)

Abstract

This study of faults in Northeastern Oklahoma focuses on their distribution, their relation to earthquakes of the last decade and to oil and gas production. A map of fault distribution was prepared by GIS-based compilation of faults presented in the literature, in theses, and in unpublished work. An interpretive fault map derived from the compilation, as expected, shows reasonable correlation with the major earthquakes. The weaker earthquakes show a more random distribution, suggesting that the mapped faults are but a fraction of the total faults, with minor faults remaining undetected by well and surface data. The Nemaha, Noble-Kay Counties, West Stillwater-Ramsey-Labette, Yale, Wilzetta, Keokuk, Wewoka, and East Mountains fault zones, along with east-trending fault zones, are the most prominent in the area of study. The study area is characterized by a complex pattern, suggesting conjugate relations together with an almost orthogonal pattern. Although most faults in Northeastern Oklahoma are reported to be normal in terms of apparent vertical displacement, high-angle reverse faulting has been mapped along the major fault zones. Yet, during multi-tectonic events, strike-slip is the dominant component of displacement of the fault systems in Northeastern Oklahoma.

Comparison of the earthquake foci with the fault map and with the top of the basement of Northeastern Oklahoma shows that most of the earthquakes have originated well below the top of the basement. Although most of the earthquakes have occurred between the major fault systems, the three earthquakes with moment magnitudes (M_w) of 5.0 or greater occurred near major fault zones, apparently along branches. The earthquakes unrelated to recorded faults undoubtedly reflect a high density of faults, albeit with minor displacement in most cases.

By comparing maps of the producing reservoirs with the interpretive fault map, it is apparent that the predominance of production is from structurally related traps. There is some significant production from stratigraphic traps, especially in Pennsylvanian reservoirs. It seems clear that these reservoirs reflect reactivation of older faults and vertical migration of hydrocarbons along faults into shallower reservoirs, along with lateral migration.

Introduction

Although in Northeastern Oklahoma (Figure 1) fault occurrences are rather well documented, recent studies suggest that the area is even more highly faulted than generally thought (e.g., Gay, 2003a, b). It widely accepted that the major fault systems (e.g., Nemaha Fault Zone, Wilzetta Fault Zone, and Keokuk Fault Zone in the study area) are characterized predominantly by strike-slip movements and that the complex fault patterns resulted from multi-tectonic events (e.g., Gay, 1999; Dycus, 2013; Dudek, 2014). Fault information has been significantly updated by various maps published since 2014 (e.g., Holland, 2015; Marsh and Holland, 2016).

In this study, we utilized GIS methods to compile a map of all faults previously mapped in the study area (Figure 1) and available to us. This technique insured the map to be as accurate as the data from which it was prepared. In numerous cases a particular fault is shown in the compilation as more than one trace, due in part to differences in original interpretations, differences in selection of stratigraphic positions for mapping the fault(s), and the complex nature of a fault zone. From this compilation, an interpretive map was prepared; it is considered to be the more definitive document for comparison with earthquake data.

The rather high occurrence of earthquakes in Northeastern Oklahoma, especially after 2009, is represented, according to intensity, on the fault map. Most studies (e.g., Keranen et al., 2014; Hough and Page, 2015; Walsh and Zoback, 2015) propose the earthquakes are possibly related to waste-water injection. This study focuses on the relationship between the recent earthquakes (their occurrence and depths of origin) and the fault systems.

The relationship between the occurrence of hydrocarbon traps and fault patterns along major fault zones in Oklahoma is generally understood (Dolton and Finn, 1989). However, the role of vertical and lateral migration of hydrocarbons, especially into Pennsylvanian reservoirs, is less well known.

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 Arbuckle, Ouachita, and even the Wichita province are associated with its southern boundary; 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. Twelve counties are included within it. The Nemaha Fault Zone and Wilzetta Fault Zone are the better known major fault zones in the study area.

Stratigraphy

Strata in the study area are Paleozoic in age (Figure 2; Dolton and Finn, 1989; Boyd, 2008); they may be divided into groups corresponding to unconformity-bounded sequences of Sloss (e.g., 1963, 1984). Here they are divided into pre-Pennsylvanian strata, consisting primarily of dolomites, limestones, and shale, with some coarser clastic deposits, and Pennsylvanian-Permian strata. The latter are known for their cyclic deposits containing both terrigenous and marine deposits (Dolton and Finn, 1989).

Tectonic History

In Late Precambrian, the supercontinent Laurentia underwent intracratonic rifting in the present-day Midwestern United States, forming the Mid-Continent Rift System (MRS). It is thought that the rifting, which started in the Lake Superior area, extended southward into Northeastern Kansas (Whitmeyer and Karlstrom, 2007) and into central Oklahoma (Berendsen and Blair, 1986; Keller et al., 2016), as the initial trace of the Nemaha Fault Zone. Gravity and well-log data suggest a farther southward extension of the MRS into north Texas (Keller et al., 2016).

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 counties (Tarr et al., 1965). In the uplifted areas, the Hunton Limestone underwent erosion; in some locations, erosion extended through the Wilcox Sand into the Cambro-Ordovician Arbuckle Group (McGee and Jenkins, 1946; Tarr et al., 1965). The widespread Woodford Shale lies unconformably on the eroded older Paleozoic units.

During Late Mississippian and Early Pennsylvanian, the Wichita Mountains of southwestern Oklahoma, the Nemaha Uplift of central Oklahoma, and Ozark Uplift of Northeastern Oklahoma experienced movement (Johnson, 2008). The Nemaha and Ozark uplifts were faulted, deforming pre-Pennsylvanian strata in north-central and Northeastern Oklahoma (Jordan, 1962). The Ouachita Orogeny of southeastern Oklahoma probably began 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 (Johnson, 2008). After the Pennsylvanian, there were, or has been, minor uplift and reactivation of faults and folds in Oklahoma (Johnson, 2008). The Ouachita Orogeny most likely modified the Wichita and Arbuckle orogens, which in turn affected the propagation of the Nemaha Uplift into central and perhaps southern Oklahoma.

Methodology

Arc GIS 10.4 software, a geographic information system for map compilation and geographic information analysis, was used effectively to compile available information on faults, thereby providing a visual template for determining the location of faults and studying the relationship between their locations and earthquake epicenters, as well as the distribution of oil and gas fields. Maps with faults were scanned into digital files and imported into the ArcMap Project. By using the Arc GIS georeference tool, the position of a fault was defined precisely, was in digital format (Figure 3), and included in a database. The main literature sources are as follows:

- Index Maps to surface and subsurface mapping in Oklahoma (Roberts, 1981; Roberts et al., 1981; Luza et al., 1983; Jordan and Roberts, 1986)
- Currently published Oklahoma fault database by U.S. Geological Survey: A Digital Geologic Map Database of Oklahoma (Heran et al., 2003)
- Oklahoma Geological Survey's 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. The comprehensive fault map (Figure 4) was prepared from the database, and the interpretive fault map (Figure 5) was prepared by editing of the comprehensive map, which contains considerable duplication in some areas by virtue of compiling all reported faults. Information of recent earthquake activity has been plotted on the interpretive map (Figures 6, 7, 8, 9, and 10). Also, oil and gas fields were plotted on the interpretive fault map (see Figures 14 and 15).

The relation of fault occurrences and recent earthquake activity is based on the Oklahoma Earthquake Database to the end of 2019, relocated by the HypoDD method (Waldhauser, 2001), the Oklahoma Geological Survey, and data posted online by the U.S. Geological Survey.

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, International Oil Scouts (1931)
- Other related publications (including Akin, 1964; Schramm, 1965; Chenoweth, 1966. 1983; Harris, 1973; Bloesch, 1987; Lyons, 1987; Dolton and Finn, 1989).

From these databases earthquake epicenters and foci were loaded into ArcGIS for plotting the earthquakes, with their attributes (location, time, depth, and magnitude). As noted above, maps of earthquake data are combined with the fault map (Figures 6, 7, 8, 9, and 10) to analyze the spatial relationship between the earthquake parameters and faults in the study area. Additionally, faults estimated from recent earthquake (seismic) data (e.g., McNamara et al., 2015a,b) are incorporated into the fault map to aid in showing the relationship between recent earthquakes and fault systems in the study area, and those earthquakes with M_w 5 or greater and associated interpreted faults are shown in Figure 11.

The probable close spacing of faulting in the entire area is illustrated in Figure 12, a seismic section from the northernmost part of the study area, published by Matson (2013) and by Watney (2014). These faults generally show limited vertical separation, and they "die-out" upward.

The structural contour map on the top of the basement in Northeastern Oklahoma by Denison (1981) was digitized and used in preparation of cross-sectional views of earthquake foci and top of the basement surface (Figure 13). ArcScene software was used as an aid in analyzing the spatial relationship between the foci and the basement in the study area.

As noted above, the Paleozoic strata were divided into two groups: (1) Cambro-Ordovician Arbuckle Group, Ordovician Simpson Group, Siluro-Devonian Hunton Group, and Mississippi Lime and (2) Pennsylvanian.

By combining the fault map and field locations in ArcMap, two maps (Figures 14 and 15) show relationships between faults and the occurrence of hydrocarbon production from the two groups (Cambro-Ordovician - Mississippian and Pennsylvanian (or Sauk-Tippecanoe-Kaskaskia and Absaroka sequences, respectively [Figure 2; Sloss, 1963]).

Faults in Northeastern Oklahoma

The predominant fault zone in the study area is the Nemaha (NFZ), which extends from southeastern Nebraska through Kansas to central Oklahoma and separates the Anadarko Basin on the west (and Anadarko Shelf in the north) from the Cherokee Platform to the east. Yet there are other major fault zones in the study area (Figures 4 and 5). They include northeast- to north-northeast-trending faults, such as the West Stillwater-Ramsey-Labette (WSRLFZ), Yale (YFZ), Wilzetta (WFZ), Keokuk (KFZ), and East Mountain (EMFZ) in an eastward direction, along with several other fault zones, and easterly trending fault zones, especially prominent in the southern part of the area. between NFZ and WFZ. The faults are dominantly strike-slip in nature. Most in the study area show normal separation. However, reverse separation is reported locally along a number of them. In addition to the major fault systems, shallow-rooted en echelon fault zones, associated with deep-seated faults, are dominantly northwest- trending, but other trends are present in the study area. They, of course, are indicators of the trend and direction of relative movement of the underlying strike-slip faults.

The extent of horizontal separation along the strike-slip faults is not known. With the scale of the maps, the effects of fault intersection were not considered, and lengths of individual faults composing major fault zones also were not studied separately.

Nemaha Fault Zone

The Nemaha Fault Zone extends beyond the study area, along or near the western boundary of the study area, from Cleveland County into western Logan County, easternmost Garfield County, through Kay County into Kansas (e.g., Figure 5). In the southernmost part of the study area, largely in McClain County, there is a splay of faults, and the most prominent north-northeast faults comprise the Central Oklahoma Fault Zone (Northcutt and Campbell, (1995), with the northernmost part being the McClain County Fault Zone (e.g., Chenoweth, 1983). This termination of NFZ or its change in configuration may well be due to movement of the three tectonic elements to its south, southwest, and southeast (Arbuckle, Wichita, and Ouachita orogens, respectively). Broadly, the NFZ is convex westward. To the north it trends NNE into Kansas. Although the NFZ is generally down-to-the-west, the fault is down-to-the-east in northwestern Logan County (Ford, 1955; Luza and Lawson, 1980). The Nemaha Fault Zone in Garfield and Kay counties splits into several subparallel-trending faults, which may be considered either as separate zone(s) or as part of NFZ.

Surficial en echelon faults are not present along NFZ, but Blair and Berendsen (1988, 1995) have mapped, in the subsurface, northwest-trending, en echelon faults in Kansas that suggest left-lateral strike-slip faulting; yet Chopra et al. (2018) show northeast-trending, en echelon faults offsetting Mississippian-Devonian strata suggestive of right-lateral strike-slip faulting. 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), and it underwent reactivation several times during the Paleozoic, even in post-Permian time (Gay, 2003b).

Noble and Kay Counties Fault Zone

A rather complex, braided fault system lies immediately east of NFZ in the northwestern part of the study area (Figure 5). The north- to north-northeast-trending Noble and Kay Counties Fault Zone (NKCFZ) is prominent in western Kay and western Noble counties and is closely related to NFZ. As noted above, it is included as part of NFZ by some workers. Two other significant faults, trending northeast, are shown east of northern part of NKCFZ and west of the Watchorn Fault (WAFZ) (Figure 5).

West Stillwater–Ramsey-Labette Fault Zone (WSRFZ)

Located east of the Nemaha Fault Zone, the West Stillwater-Ramsey–Labette Fault Zone extends northward from Oklahoma County, north-northeastward from easternmost Logan County into Payne County, and northeastward into Pawnee and Osage counties (e.g., Figure 5), where it is referred to as the Labette Fault Zone. Its Northeastern trend continues into Kansas (Gearhart, 1958, Holloway et al., 2016).

At least two faults, Watchorn (WAFZ) and Foraker (FFZ) are significant branches of the WSRLFZ (Figure 5). Segments of WSRLFZ were mapped by Luza and Lawson, (1980), Holloway et al. (2016), Puckette (2016b), and Matson (2015). Sims (1987) proposed that the Labette Fault corresponds to a boundary separating Upper Proterozoic metarhyolite to the northwest and Upper Proterozoic rhyolite, dacite, and andesite flows to the southeast. The north-northeast-trending fault at Watchorn Field in northwest Pawnee County branches from, or intersects, West Stillwater-Ramsey–Labette Fault Zone. Normal separation characterizes the southern part of WSRLFZ (McKenny, 1955; Umpleby, 1956; Hollrah, 1979), whereas reverse separation has been reported in the Morrison field and along the Watchorn Fault (Gearhart, 1958).

In the Ramsey Oilfield, at the intersection of WSRLFZ and a prominent east-trending fault, the Mississippian and Viola Limestones show approximately 700 feet of left-lateral slip (Umpleby, 1956), or five times the vertical displacement. There was movement prior to and during the Pennsylvanian (Umpleby, 1956).

On September 3, 2016, the Pawnee Earthquake, with moment magnitude (M_w) of 5.8, occurred at the junction of the WSRLFZ and the Watchorn Fault (WAFZ) due to the development or activation of a fault, the Sooner Lake Fault of some workers (e.g., Kolawole et al., 2017; Pennington and Chen, 2017) (Figures 5 and 11A). The focus of that earthquake was calculated as 5.6 km (18,400 ft), and USGS (2016) favors left-lateral movement along the west-northwest-trending fault and waste-water disposal as the likely triggering cause, as do other workers (e.g., Kolawole et al., 2017; Pennington and Chen, 2017).

Yale Fault Zone

Yale Fault Zone (YFZ) (Figure 5) is closely related to the Wilzetta Fault Zone (WFZ); yet it is shown to extend northward from southernmost Lincoln County, to intersect both WSRLFZ and FFZ, and to continue into Kansas. It may branch from WFZ at its southernmost extremity, and some workers have included it in WFZ, especially in southern Osage County, where the two zones are juxtaposed.

It is most noteworthy that earthquakes occurred in October 2014 and in November 2016 in the Cushing area (Figures 5 and 11), an area that is known for petroleum storage; the magnitude of the 2014 earthquakes was recorded as M_w 4.0 and 4.3. The 2016 earthquake was M_w 5.0; the focus was calculated to be 5 km (16,400 ft) .

Wilzetta Fault Zone

A group of northeast-southwest-trending fault zones extending beyond the southern boundary of the study area (Figure 5) is mapped in the eastern or southeastern part of the study area. From west to east, they are the Wilzetta, Keokuk, Wewoka, and East Mountain zones.

Wilzetta Fault Zone (WFZ) is a northeast- to north-northeast-trending fault zone that extends from Pottawatomie County, in the south, into Kansas north of Osage County (Figure 7; Dycus, 2013; Holloway et al., 2016). In Creek County, in the Cushing oil field area, it splits into at least two faults, one of which is the Whitettail (McBee, 2003; Toelle et al., 2008). Farther north, in southeasternmost Pawnee County, it shows a more northerly trend that extends through southern part of Osage County, north of which it seemingly trends north-northeast.

The WFZ shows both normal separation (Cutolo-Lozano, 1970; Pulling, 1979; Verish, 1979; Baurenfeind, 1982; Way, 1983) and reverse separation (Gay, 2003b). The southern part of the WFZ is characterized by steep, almost vertical, dip, with the vertical separation being down to the northwest (Joseph, 1986), offsetting strata as young as the Pennsylvanian Verdigris Limestone. Reverse separation is reported in the southern extremity of WFZ (Figure 5; Gay, 2003b). In vertical section, WFZ in the area of the Cushing structure is a high-angle normal fault zone with several fault blocks (Bennison, 1964; Witt et al., 1971) and up to 700 feet of vertical separation being down to the east.

Early movement of the Cushing oil field structure and the Wilzetta Fault occurred during deposition of the Ordovician Arbuckle Group (Bennison, 1964). Later faulting and other associated structural development occurred during the Middle Devonian (post-Hunton) (Bennison, 1964; Pulling, 1979; Dycus, 2013) and again in Late Mississippian to Desmoinesian (Pulling, 1979; Dycus 2013). Later movements further attenuated the faults and folds of the WZF (Arbenz, 1956a,b; Pulling, 1977; Bauernfeind, 1982).

On November 6, 2011, the M_w 5.7 Prague earthquake occurred along the Wilzetta Fault Zone, seemingly forming the new northeast-southwest-trending Meeker-Prague Fault (Figure 11; Dycus, 2013). The earthquake focal depth is 5.5 km (18,000 ft), well below the top of the basement (Figures 5 and 11; USGS, 2011; Dycus, 2013). It is thought that the earthquake resulted from wastewater injection associated with oil and gas production in this area (Keranen et al., 2013; McNamara et al., 2015a,b; Walsh and Zoback, 2015.

Keokuk Fault Zone

The Keokuk Fault Zone (KFZ; Figure 5) is a north-northeast-trending high-angle normal fault zone (in vertical section) 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 zone with normal separation. Keokuk Fault Zone was also active during Middle Devonian, and the fault extends upward into a Middle Pennsylvanian limestone (Dudek, 2014).

Wewoka and East Mountain Fault Zones

The Wewoka and East Mountain Fault zones are successively east of the Keokuk Fault Zone in the southeastern part of the study area (Figure 5); they are essentially parallel to the Keokuk Fault Zone. Reverse separation is reported along the southern part of the Wewoka Fault Zone (Dudek, 2014). Farther east, the East Mountain Fault Zone (Figure 5; Toelle et al., 2008) is composed of NNE-SSW-trending, high-angle faults that form a horst. These faults cut Lower Pennsylvanian strata (Musgrove, 1964; Toelle et al., 2008). It is suggested that these fault zones had a similar history to the Wilzetta and Keokuk fault zones.

East- Trending Fault Zones

Based on available maps, east-trending faults are more common in the southern part of the study area than in the northern part (Figure 5). The southern limit of the clearly defined Nemaha Fault Zone is marked by east-trending faults along or near the southern boundary of the study area. These faults are commonly present between NFZ and WFZ. Some faults, especially in the more central part of the study area, shown a broad arcuate pattern, convex to the northeast. The east-trending faults tend to be more common in the area where NFZ, which effectively forms the western boundary of the study area, changes trend from north-northwest in the south to north-northeast in the northern part of the study area.

The east-trending faults are more compatible with the maximum horizontal stress of approximately N85^{o}W (McNamara et al., 2015) and orientation of (possibly extension) fractures (N70^{o}E) in a well in the Mississippi Lime play in the northern part of the area (Matson, 2013) than with the orientation of the north, north-northwest, north-northeast, and northeast fault zones. In terms of possible related tectonic elements, to the east lies the broad Ozark Uplift, and to the east of it is the New Madrid Seismic Zone and the associated Reelfoot Rift.

Faults and Earthquake Occurrences

Earthquake Occurrences (Figures 6, 7, 8, 9, and 10)

The Interpretive Map of faults together with epicenters (Figure 6) of the earthquakes in the study area to the end of 2019 shows that the earthquakes have occurred mainly between Nemaha Fault Zone (NFZ) and Wilzetta Fault Zone (WFZ). Most earthquakes with M_w of 3.5 or greater (Figure 8) have occurred between the major fault systems; relatively few have occurred directly on the major faults, although several have occurred in the Edmond area along NFZ. Also, the three earthquakes with M_w 5.0 or greater are associated with WFZ, Yale (YFZ), and West Stillwater–Ramsey–Labette (WSRLFZ) (Figure 10). They are the M_w 5.7 Prague earthquake at or near WFZ, the M_w 5.0 earthquake at or near YFZ, and the M_w 5.8 Pawnee earthquake along or near WSRLZ (Figure 11A,B). The Prague earthquake occurred at a previous unmapped northeast-trending fault in the WFZ (Dycus, 2013). Along or near the YFZ, five earthquakes Mw 4.0 or greater, but less than 5.0, preceded by more than one year the M_w 5.0 Cushing earthquake of November 2015 (Figure 11C; McNamara et al., 2015a; Yeck et al., 2017). It occurred at a depth of 5 km (16,400 ft). The earlier earthquakes are interpreted to have occurred along a west-northwest fault, whereas the 2015 earthquake was interpreted to have occurred along a northeast-trending fault, perhaps in a conjugate relationship. As noted above, the Pawnee earthquake occurred at the intersection of WSLFZ and Watchorn Fault (WAFZ) along a previously unmapped northwest-southeast fault

(Sooner Lake Fault) (Pennington and Chen, 2017). These M_w 5 and greater earthquakes, which occurred on or near previously mapped major faults, apparently utilized unmapped, subsidiary faults that intersect the north- to northeast-trending major fault traces. Perhaps, these faults may be considered by some workers as Riedel shears.

Some earthquakes with M_w less than 5 show a relationship with the easterly trending (unnamed) fault zones rather than the northerly trending fault zones. Most earthquakes occur below a depth of 4 km (13,000 ft), and they do not have a strong relationship with the currently known mapped faults (basically from surface and subsurface geologic data) in the study area.

McNamara (2015b) inferred faults "from the combined analysis of the spatial distribution of seismicity and focal mechanism nodal planes," in preparing a fault map of central Oklahoma. This map shows NE and NW average orientations of faults associated with recent earthquakes and to be within calculated maximum horizontal stress of N85^{o}W (McNamara (2015b; Alt and Zoback, 2016). An occasional earthquake corresponds to east-west-trending faults.

A recent study by (Shah and Crain, 2018), based on aeromagnetic data, shows relationship of earthquakes in Northeastern Oklahoma with basement faults. In addition, Springman (2018) noted that one earthquake coincides with a fault delineated by seismic data acquired before the delineation by the earthquake. It is likely that basement faults, ones which have experienced periods of activity, are much more common than subsurface geologic data indicate, as suggested by Gay (1999, 2003a,b) and demonstrated by Matson (2013; Figure 12). It is also conceivable that some of the earthquakes represent new faults associated with changes in the stress field.

Earthquake Foci and Top of the Basement

The earthquake foci and the top of the basement (Denison, 1981) in the study area are combined into diagrammatic, cross-sectional views (Figure 13). They show that most of the earthquakes were generated well below the top of the basement and commonly significantly below the positions of injection of wastewater. Relatively few foci originated above the basement.

Matson (2013) reported that a well in the Mississippi lime play in the northern part of the study area contains very abundant open fractures at depths greater than 3200 ft. Dickey and Cox (1977) note that "many, if not most, oil and gas reservoirs in the Mid-Continent area had subnormal pressure." Most operators of injection wells in Northeastern Oklahoma are familiar with a reservoir in an injection well "taking fluid on a vacuum." The above comments suggest that fluid flow during and following injection into some reservoirs, karstic and/or highly fractured, are experiencing Newtonian flow as opposed to Darcy flow. Further, with increase in pore pressure, perhaps even below overpressure threshold, the reduction of strength of the rock allows for faulting (and earthquakes) where the rock is under significant differential stress before injection. The Prague and Pawnee earthquakes are in areas where water injection had occurred for considerable periods of time (probably greater than 20 years) as the reservoirs were being "dewatered."

Faults and Producing Reservoirs in Northeastern Oklahoma

In Northeastern Oklahoma, primary producing reservoirs are the Cambro-Ordovician Arbuckle Group, Ordovician Simpson Group, Siluro-Devonian Hunton Group, Mississippi Lime, and Pennsylvanian Sandstones (Figures 14 and 15; Dolton and Finn, 1989, Boyd, 2008). Oil/gas fields in which each group of reservoirs (Pre-Pennsylvanian and Pennsylvanian) is productive are shown on the interpretive fault map. Major production has been a significant feature of the Nemaha and Wilzetta fault zones.

Along the Nemaha Fault Zone, pre-Pennsylvanian reservoirs produce along or near faults, in faulted and/or fault-related folds (Figure 14). These include the Oklahoma City and West Edmond fields. A trap-door structure is the trap at Billings field in Noble County, and a prominent structure at Ramsey field in Payne County is at the intersection of the West Stillwater–Ramsey-Labette and an east-west fault. The Mississippian Lime probably has the poorest relation to faults of the pre-Pennsylvanian reservoirs, although in Osage County, basement highs, with associated production, are generally considered paleotopographic features (e.g., (Rottmann, 2018), but faulting may have been a contributing factor. In general, there are four types of fault-related traps: (1) large oil fields in the upthrown blocks of the major fault zones (NFZ, WSRLFZ, and WFZ), (2) smaller producing fields along the junctions of major faults and subsidiary faults in the NFZ and WFZ, (3) upthrown fault blocks in the junctions between an east-west-trending fault and the major fault zones, and (4) basement-high-related traps, especially in Osage and Tulsa counties, controlled by basement highs, which form the structural highs for overlying sediments.

Pennsylvanian reservoirs produce from both structural traps, basically resulting from faulting, and stratigraphic traps (Figure 15). The former traps have in most cases resulted in larger reserves, whereas the latter seemingly are more numerous. Burbank field in Osage County is an outstanding exception. Permian production in the study area is insignificant, compared to the Pennsylvanian.

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 there is major production from stratigraphic traps. The common trapping feature for structural traps is reactivation of the faults over a long period of time. It also implies a common dominant source rock, the Devonian Woodford Shale, and a strong element of vertical migration. Yet a large number of the stratigraphic traps and some of the structural traps, especially at shallow depths, reflect significant horizontal migration.

It is interesting to observe empirically the large to giant fields that lie generally east of the area where orientation of NFZ changes from NNW to NNE; i.e., Ramsey, Cushing, and Glenn Pool (Creek and Tulsa counties). Also, in the study area, concentration of Pennsylvanian fields is east of the concentration of recorded earthquakes.

Conclusion

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 Noble and Kay Counties,

Watchorn, Foraker, Stillwater-Ramsey-Labette, Yale, Keokuk, Wewoka, and East Mountain. These have a strong northerly component in orientation. Other significant faults have an easterly orientation, and they are more common in the southern part of the study area, especially between the Nemaha and Wilzetta fault zones. Strike-slip is the primary fault movement with its resulting fault systems. Normal separation is more common than reverse separation.

2. Earthquakes that have occurred recently in Northeastern Oklahoma were predominantly less than M_w 3.5 in magnitude. However, three were M_w5.0-5.8. Those three show a relation to the major faults, seemingly along or forming subsidiary faults. The foci from most of the earthquakes were well below the top of the basement. Overall, the earthquakes and mapped faults in the study area do not show a strong link or relationship. Yet this might suggest 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 consider that rather complex systems of fractures, indeed faults, are present in the basement.

3. The depths of the foci of the more intense earthquakes, well below the position of water injection, suggest that (a) fractures are open to focal depths or (b) considerable time, in terms of petroleum production, is required before fluid injection results in faulting (and earthquake generation).

4. Pre-Pennsylvanian reservoirs produce largely from structural traps associated with the fault zones noted above. The potential exists for future production of that type of trap and high-resolution stratigraphic traps. Pennsylvanian producing reservoirs also occur in fault-related traps, but they also are present in stratigraphic traps. There is potential also for both types of traps in Pennsylvanian strata.

Selected References

Akin, R., 1964，Map of Arbuckle Pools of Oklahoma: Tulsa Geological Society Digest, v. 32, p. 36.

Alt, R.C. and Zoback, M.D., 2016, In situ stress and active faulting in Oklahoma: Bulletin of the Seismological Society of America, v. 107, p. 216-228.

Andrews, R.D., 2003, Cromwell Play in Southeastern Oklahoma: Oklahoma Geological Survey Special Publication 2003-2, 87p.

Andrews, R.D., Cardott, B.J., Storm, T., 1998, The Hartshorne Play in Southeastern Oklahoma: Regional and Detailed Sandstone Reservoir Analysis and Coalbed-Methane Resources: Oklahoma Geological Survey Special Publication 98-7.

Arbenz, J.K., 1956a, Tectonic Map of Oklahoma: Oklahoma Geological Survey, Geologic Map 3.

Arbenz, J.K., 1956b, Tectonic Framework of Oklahoma: AAPG Bulletin, v. 40, p. 423-424.

Baars, D.L., Watney, W.L., Steeples, D.W., and Brostuen, E A. 1993, Petroleum: A Primer for Kansas: Kansas Geological Survey, Educational Series 7.

Baker, D.A., 1958, Subsurface Geology of Southwestern Pawnee County, Oklahoma: University of Oklahoma, M.S. Thesis.

Bartram, J.G., Imbt, W.C., and Shea, E.F., 1950, Oil and gas in Arbuckle and-Ellenburger formations, Mid-Continent region: AAPG Bulletin, v. 34, p. 682.

Bass, N.W., Leatherock, C., Dillard, W.R. and Kennedy, L.E., 1937, Origin and distribution of Bartlesville and Burbank shoestring oil sands in parts of Oklahoma and Kansas: AAPG Bulletin, v. 21, p. 30-66.

Bauernfeind, P.E., 1982, The Misener Sandstone in portions of Lincoln and Creek Counties, Oklahoma: The Shale Shaker Digest X, v. 32, p. 1-30.

Bebout, D.G., White, W.A., and Hentz, T.F., 1993, Atlas of Major Midcontinent Gas Reservoirs, Gas Research Institute, p. 1-85.

Beckwith, H.T., 1927, Geology of Osage County: Oklahoma Geological Survey Bulletin 40-T. 62p.

Bellis, W.H., 1961, Distribution and thickness of pre-Desmoinesian rock units in south-central Oklahoma: University of Oklahoma, M.S. Thesis.

Bennison, A., 1964, The Cushing field, Creek County, Oklahoma: Tulsa Geological Survey Digest, v. 32, p. 158-159.

Bennison, A.P., Chenoweth, P.A., Desjardins, L. and Ferris, C., 1972, Surface Geology and Bouguer Gravity of Tulsa County, Oklahoma: Tulsa Geological Society Digest, v. 37, p. A1-A1.

Berendsen, P., and Blair, K.P., 1986, Subsurface structural maps over the Central North American Rift System (CNARS), central Kansas, with discussion: Kansas Geological Survey, Subsurface Geology Series 8.

Berendsen, P. and Blair, K.P., 1995, Structural development of the Nemaha tectonic zone in Kansas: Oklahoma Geological Survey Circular, v. 97, p. 208-214.

Bingham, R.H., and Bergman, D.L., 1980, Reconnaissance of the water resources of the Enid Quadrangle, north-central Oklahoma: OGS Hydrologic Atlas 7.

Blair, K.P. and Berendsen, P., 1988, Subsurface structural geology of the Nemaha tectonic zone, Kansas (abstract): Geological Society of America South Central Section Meeting Abstracts with Programs, v. 20, p. 91.

Blakeley, D.C., 1959, Subsurface geology of north-central Pawnee County: University of Oklahoma, M.S. Thesis.

Bloesch, E., 1987, Arbuckle Production in Northeastern Oklahoma: Tulsa Geological Society Special Publication No. 3: Petroleum Geology of the Mid-Continent, p. 35-36.

Blumenthal, M., 1958, Subsurface Geology of the Prague-Paden Area, Lincoln and Okfuskee Counties, Oklahoma: Shale Shaker Digest II, v. 8, p. 155-170.

Borden, J.L., and Brant, R.A., 1941, East Tuskegee pool, Creek County, Oklahoma, in Stratigraphic Type Oil Fields: AAPG, p. 436-455.

Boyd, D.T., 2002a, Oklahoma Oil and Gas Fields (by reservoir age) (map, 1:500,000): Oklahoma Geological Survey, Geologic Map 38.

Boyd, D.T., 2002b, Map of Oklahoma Oil and Gas Fields (Distinguished by Coalbed Methane and Field Boundaries): Oklahoma Geological Survey, Geologic Map 37.

Boyd, D.T., 2002c, editor, Finding and Producing Cherokee Reservoirs in the Southern Midcontinent, 2002 Symposium: Oklahoma Geological Survey Circular 108.

Boyd, D.T., 2008. Stratigraphic Guide to Oklahoma Oil and Gas Reservoirs: Oklahoma Geological Survey, Special Publications 2008-1.

Bradshaw, R.D., 1959, The Autwine Field, Kay County, Oklahoma: University of Oklahoma, M.S. Thesis.

Bross, G.L., 1961, Distribution of Layton Sandstone (Pennsylvanian) Logan County, Oklahoma: The Shale Shaker Digest III, v. 11, p. 327-337.

Burg, J.-P., 1986, Strike-slip and oblique-slip tectonics: Website accessed August , 2020, available at http://www.files.ethz.ch/structuralgeology/JPB/files/English/5wrench.pdf.

Busch, D.A., 1956, General Subsurface Geology along the Turner Turnpike, Lincoln County, Oklahoma; Oklahoma Geological Survey Guidebook 4, 76p.

Buttram, F., 1914, The Cushing oil and gas field, Oklahoma, Oklahoma Geological Survey Bulletin 18.

Bryan, R.C., 1950, Subsurface geology of the Deer Creek, Webb and North Webb oil pools, Grant and Kay Counties: University of Oklahoma, M.S. Thesis.

Cary, L.W., 1954, The subsurface geology of the Garber area, Garfield County, Oklahoma: Shale Shaker Digest I, p. 384-403.

Cardott, B.J., and Lambert, M.W., 1985, Thermal maturation by vitrinite reflectance of Woodford Shale, Anadarko basin, Oklahoma: AAPG Bulletin, v. 69, p. 1982-1998.

Carver, Jr., G.E., 1948, Arcadia-Coon Creek oil pool, Oklahoma and Logan Counties, *in* Structure of Typical American Oil Fields: AAPG., v. 3, p. 319-340. (book)

Chandler, C.E., 1979, Subsurface Stratigrapic Analysis of Selected Sandstones of the "Cherokee" Group Southern Noble County, Oklahoma: The Shale Shaker Digest IX, v. 29, p. 1-16.

Chenoweth, P.A.,1966, Viola oil and gas fields of the Mid-Continent, Tulsa Geological Society Digest Symposium on the Viola, Fernvale and Sylvan, v. 34, p. 110-118.

Chenoweth, P.A., c1983, Principal structural features of Oklahoma (map): PennWell Publishing Company.

Chopra, S., Marfurt, K.J., Kolawole, F., and Carpenter, B.M., 2018, Nemaha Strike-Slip Fault Expression on 3-D Seismic Data in SCOOP Trend, Search and Discovery Article #42235 (2018).

Clark, R.W., 1926, Geology of Okmulgee County, Oklahoma: Oklahoma Geological Survey Bulletin 40-F, 52 pages, 7 figures, 8 plates.

Clark, G.C., and Cooper, C.L., 1927, Geology of Kay, Grant, Garfield, and Noble Counties: Oklahoma Geological Survey Bulletin 40-H.

Clark, S.K. and Daniels, J.I., 1929, Relation Between Structure and Production in the Mervine, Ponca, Blackwell, and South Blackwell Oil Fields, Kay County, Oklahoma:SP 3: Structure of Typical American Oil Fields, v. 1, p. 158-175.

Clements, K.P., 1961, Subsurface Study of the Skinner and Red Fork Sand Zones (Pennsylvanian) in Portions of Noble and Kay Counties, Oklahoma: University of Oklahoma, M.S. Thesis.

Cole, J.A., 1958, Subsurface Geology of East Central Lincoln County, Oklahoma: The Shale Shaker II, v. 8, p. 79-96.

Cook, K.L., 1956, Regional gravity survey in Northeastern Oklahoma and southeastern Kansas: Geophysics, v. 21, p. 88-106.

Cronenwett, C.E., 1958, A subsurface study of the Simpson Group in east-central Oklahoma: Shale Shaker Digest II, p. 171-187.

Cutolo-Lozano, F., 1970, Subsurface Geology of the Seminole Area: Seminole, Pottawatomie, and Okfuskee Counties, Oklahoma: The Shale Shaker Digest VI, v. 20, p. 100-112.

D'Lugosz, J.J., McClaflin, R.G., and Marcher, M.V., 1986, Geohydrology of the Vamoosa-Ada aquifer, east-central Oklahoma: Oklahoma Geological Survey Circular 87, 42 p.

Dalton, D.V., 1960, The subsurface geology of northeast Payne County. Oklahoma: University of Oklahoma, M.S. Thesis.

Dapples, E.C., 1955, General lithofacies relationship of St. Peter Sandstone and Simpson Group: AAPG Bulletin, v. 39, p. 444-467.

Davis III, H.G., 1985, Wrenching and Oil Migration, Mervine Field Area, Kay County, Oklahoma: The Shale Shaker Digest XI, v. 35, p. 145-158.

Denison, R.E., 1981, Basement rocks in Northeastern Oklahoma: Oklahoma Geological Survey Circular 84, 84 p.

Dickey, P.A., and Cox, W.C., 1977, Oil and gas in reservoirs with subnormal pressures: AAPG Bulletin, v. 61, p. 2134–2142.

Dillard, W.R., 1941. Olympic pool, Hughes and Okfuskee counties, Oklahoma, *in* Stratigraphic Type Oil Fields: AAPG, p. 456-472.

Dille, A.C.F., 1956, Paleotopography of the Precambian Surface of Northeastern Oklahoma: Tulsa Geological Society Digest, v. 24, p. 122 – 126.

Dolton, G.L., and Finn, T.F., 1989, Petroleum geology of the Nemaha uplift, central mid-continent: Dept. of the Interior, US Geological Survey, Open-File Report 88-450-D.

Dudek, J.E., 2014, Understanding the Geologic Structure and Kinematics of the Keokuk Fault Zone in East-Central Oklahoma: University of Tulsa, Doctoral dissertation.

Dycus, M., 2013, Structural characterization of the Wilzetta fault zone: Lincoln, Pottawatomie, and Creek Counties, Oklahoma: University of Tulsa, M.S. thesis.

Elebiju, O.O., Shane, M., Keller, G.R., and Marfurt, K.J., 2011, Integrated geophysical studies of the basement structures, the Mississippi chert, and the Arbuckle Group of Osage County region, Oklahoma: AAPG Bulletin v. 95, p. 371-393.

Fath, A.E., 1920, The origin of faults, anticlines, and buried granite ridge of the northern part of the Mid-Continent oil field: U.S Geological Survey Professional Paper 128-C, p. 75-84.

Ferguson, D.B., 1964, Subsurface Geology of Northern Lincoln County, Oklahoma: The Shale Shaker Digest IV, v. 14, p. 444-458.

Fritz, R.D., 1978, Structural contour map of Oklahoma on the Pennsylvanian Wapanucka Limestone, Oswego Limestone, base of the Hoxbar group, and Checkerboard Limestone: Oklahoma State University, M.S. Thesis.

Ford, W.J., 1955, The subsurface geology of southwest Logan County, Oklahoma: The Shale Shaker Digest I, v. 5, p. 327-343.

Gatewood, L.E., 1970, Oklahoma City field-anatomy of a giant, *in* M.T. Halbouty, Geology of Giant Petroleum Fields, AAPG Memoir 14, p. 223-254.

Gay, Jr., S.P., 1995, Basement control of selected oil and gas fields in Kansas as determined by detailed aeromagnetic data, *in* N.L Anderson,., and D.E. Hedke, editors, Geophysical atlas of selected oil and gas fields in Kansas: Kansas Geological Survey Bulletin 237, p. 10-16.

Gay, Jr., S.P., 1999, Strike-slip, compressional thrust-fold nature of the Nemaha system in eastern Kansas and Oklahoma: Transactions of the 1999 AAPG Midcontinent Section Meeting (Geoscience for the 21st Century).

Gay, Jr., S.P., 2003a, The Nemaha Trend - A system of compressional thrust-fold, strike-slip structural features in Kansas and Oklahoma, Part 1: The Shale Shaker, v. 54, p. 9-17.

Gay, Jr., S.P., 2003b, The Nemaha Trend - A system of compressional thrust-fold, strike-slip structural features in Kansas and Oklahoma, (Part 2, conclusion): The Shale Shaker, v. 54, p. 39-49.

Gleen, D.H., 1963, Mississippian Rocks in the Subsurface of the North Tulsa Area.: University of Oklahoma, M.S. Thesis.

Gearhart, H.L., 1958, Subsurface Geology of Northwestern Pawnee County, Oklahoma: University of Oklahoma, M.S. Thesis.

Greer, J.K., 1961, Subsurface Geology of East Central Lincoln County. Oklahoma: University of Oklahoma, M.S. Thesis.

Greig, P.B., 1959, Geology of Pawnee County: Oklahoma Geological Bulletin 83, 188p.

Ham, W.E., Denison, R.E., and Merritt, C.A., 1964, Basement Rocks and Structural Evolution of Southern Oklahoma: Oklahoma Geological Survey Bulletin 95, 302p

Hamric, B.E., 1961, Hoffman gas area, Okmulgee and McIntosh counties, Oklahoma: The Shale Shaker Digest III, v. 11, p. 433-445.

Hanke, H.W., 1967. Subsurface stratigraphic analysis of the Cherokee Group in north-central Creek County, Oklahoma: The Shale Shaker Digest V, v. 17, p. 177-194.

Harris, S.A., 1973, Hydrocarbon Accumulation in" Meramec-Osage"(Mississippian) Rocks, Sooner Trend, Northwest Central Oklahoma: University of Oklahoma, Doctoral Dissertation.

Heinzelmann, , Jr., G.M., 1967, Mississippian rocks in the Stillwater-Chandler area: The Shale Shaker Digest V, v. 17, p. 195-207.

Hemish, L.A., 1990, Coal Geology of Tulsa, Wagoner, Creek, and Washington Counties, Oklahoma: Oklahoma Geological Survey, Geological Map 33.

Hemish, L.A., and Beyma, K.N., 1988, A Stratigraphic and Structural Study of the Eram Coal and Associated Strata in Eastern Okmulgee County and Western Muskogee County, Oklahoma: Oklahoma Geological Survey, Geologic Map 30.

Heran, W.D., Green, G. and Stoeser, D.B., 2003, A Digital Geologic Map Database of Oklahoma: U. S. Geological Survey Open File Report 03-247.

Holland, A.A., 2013, Optimal fault orientations within Oklahoma: Seismological Research Letters, v.84, p. 876–890,

Holland, A.A., 2015, Preliminary Fault Map of Oklahoma: Oklahoma Geological Survey, Open-File Report, OF3-2015.

Holloway, S., Holland, A., and Keller, G.R., 2016, Oklahoma Fault Database Contributions from the Oil and Gas Industry: Oklahoma Geological Survey, Open-File Report, OF1-2016.

Hollrah, T.L., 1979, Subsurface lithostratigraphy of the Hunton Group in parts of Payne, Lincoln and Logan counties, Oklahoma: The Shale Shaker Digest IX, v. 29, p. 76-91.

Hopper, J.F., 2005, Computer-assisted Mapping of "Cherokee" Sandstone Trends, by Reference to Spontaneous Potential Curves, in Parts of Creek, Lincoln, and Payne Counties, Oklahoma: Oklahoma State University, M.S. thesis.

Hough, S.E. and Page, M., 2015, A century of induced earthquakes in Oklahoma?: Bulletin of the Seismological Society of America, v. 105, p. 2863-2870.

Hu, X., 2019, Faults in Northeastern Oklahoma: Their Occurrence, Relationship to Hydrocarbon Production, and Modern Activity: Oklahoma State University M.S. Thesis, 79p.

Hyde, J.C., 1957, Mississippian Rocks of the Drumright Area, Oklahoma: University of Oklahoma, M.S. Thesis.

International Oil Scouts Association, and Society of Petroleum Engineers of AIME, 1931, International Oil and Gas Development, Review.

Ireland, H.A., 1955, Pre-Cambrian surface in Northeastern Oklahoma and parts of adjacent states: AAPG Bulletin, v. 39, p. 468-483.

Ireland, H.A., and Warren, J. H., 1946, Maps of Northeastern Oklahoma and parts of adjacent states showing the thickness and subsurface distribution of Lower Ordovician and Upper Cambrian rocks below the Simpson group: USGS Oil and Gas Investigations Preliminary Map no. 52.

Jackson, N.A., 1955, A subsurface study of the lower Pennsylvanian rocks of east central Oklahoma: The Shale Shaker Digest I, v. 5, p. 47-53.

Johnson, C.L., 1992. Burbank Field-USA Anadarko Basin, Oklahoma, *in* C. L. Johnson, editor, Treatise: Stratigraphic Traps III: AAPG, p. 333-345.

Johnson, K., 2008, Geologic history of Oklahoma: Oklahoma Geological Survey, Educational Publication 9.

Jordan, L., 1962, Geologic map and section of pre-Pennsylvanian rocks in Oklahoma: Oklahoma Geological Survey, Geological Map, GM-5.

Jordan, L., and Roberts, J.F., 1986, Index to subsurface geologic mapping in Oklahoma, 1940–1966 [second edition]: Oklahoma Geological Survey, Geological Map, GM- 29.

Joseph, L., 1986, Subsurface analysis, "Cherokee" group (Desmoinesian), portions of Lincoln, Pottawatomie, Seminole, and Okfuskee Counties, Oklahoma: The Shale Shaker Digest XII, v. 37, p. 87-112.

Keller, G.R., 2014, The Southern Oklahoma aulacogen: It's a classic, *in* N. Suneson, editor, Igneous and Tectonic History of the Southern Oklahoma Aulacogen: Oklahoma Geological Survey Guidebook 38, p. 390-391.

Keller, G. R., Buening, J., Stein, S., Stein, C.A., Holland, A., and Luza, K., 2016, Extension of the Mid-Continent Rift System into the southern Mid-Continent region: Possible implications for exploration and natural hazards: Search and Discovery Article # 30450.

Keranen, K.M., Savage, H.M., Abers, G.A. and Cochran, E.S., 2013, Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 M_w 5.7 earthquake sequence: Geology, v. 41, p. 699-702.

Keranen, K.M., Weingarten, M., Abers, G.A., Bekins, B.A. and Ge, S., 2014, Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection: Science, v. 345, p. 448–451.

Kitchen, E.W., 1963, Mississippian rocks in the subsurface of the Bartlesville area: University of Oklahoma, M.S. Thesis.

Kolawole, F., Atekwana, E.A. and Ismail, A., 2017, Near‐surface electrical resistivity investigation of coseismic liquefaction‐induced ground deformation associated with the 2016 M 5.8 Pawnee, Oklahoma Earthquake: Seismological Research Letters, v. 88, p. 1017-1023.

Kousparis, D., 1979, Quantitative geophysical study of the Cleveland sand reservoir (Pennsylvanian) in the eastern part of Logan County, Oklahoma: Shale Shaker, v. 29, p. 92-107.

Kuykendall, M.D. and Matson, T.E., 1992, Glenn Pool Field--USA Northeast Oklahoma Platform, Oklahoma, *in* N. H. Foster and E. A. Beaumont, editors, Stratigraphic Traps III: AAPG Treatise, p. 155-158.

Logsdon, T., and Brown, A.R., 1970, 'Hunton'--Hottest play in Oklahoma: The Shale Shaker Digest VI, v. 20, p. 195-202.

Luza, K.V., Ham, E.A., and Sanders, P.R., 1983, Indexes to surface and subsurface geologic mapping in Oklahoma, 1977–1979: Oklahoma Geological Survey, Geological Map GM- 26.

Luza, K.V., and Lawson, Jr, J.E., 1981, Seismicity and Tectonic Relationships of the Nemaha Uplift in Oklahoma, Part III: Oklahoma Geological Survey Special Publication 81-3. Website accessed August 6, 2020, http://ogs.ou.edu/docs/specialpublications/SP81-3.pdf.

Lyons, P.L., and Dobrin, M.B., 1972, Seismic exploration for stratigraphic traps: Geophysical exploration methods, *in* Stratigraphic Oil and Gas Fields--Classification, Exploration Methods, and Case Histories: AAPG Memoir 16, p. 225-243.

Lyons, P.L., 1987, Gravity and magnetic expression of the tectonic framework of the Mid-Continent, *in* B. Rascoe, Jr., and N.J. Hyne, editors, Petroleum Geology of the Mid-Continent: Tulsa Geological Society Special Publication No. 3, p. 15-18.

Marsh, S., and Holland, A., 2016, Comprehensive fault database and interpretive fault map of Oklahoma, Oklahoma Geological Survey, Open-File Report, OF2-2016.

Masters, K.E., 1958, Geology of the Prague area, Lincoln and Pottawatomie counties, Oklahoma: Shale Shaker Digest II, v. 6-8, p. 227-234.

Martin, M.G., 1943, The structural conditions of the Crescent Pool, Logan County, Oklahoma: University of Oklahoma, M.S. Thesis.

Matson, S.E., 2013, Mississippi Lime play: From outcrop to subsurface-The evolution of a play: Search and Discovery Article #110170 (2013). Website accessed August 6, 2020.

Matson, S., 2015, The Mississippian Lime: Kinematics of a play—Structure, reservoir characterization and production performance of the horizontal Mississippian play: Search and Discovery Article #110184 (2015). Website accessed August 6, 2020.

McBee, Jr., W., Nemaha Strike-Slip Fault Zone: Search and Discovery Article #10055 (2003). Website accessed July 30, 2020.

McDuffie, R.H., 1964, Mississippian rocks in the subsurface of Garfield and western Noble Counties, Oklahoma: The Shale Shaker Digest IV, v. 14, p. 129-144.

McGee, D.A. and Jenkins, H.D., 1946, West Edmond oil field, central Oklahoma: AAPG Bulletin, v. 30, p. 1797-1829.

McKenny, J.W, 1955, Subsurface Geology of Northeastern Logan County, Oklahoma: The Shale Shaker Digest I, v. 5, p. 149-166.

McNamara, D.E., Benz, H.M., Herrmann, R., Bergman, E.A., Earle, P., Holland, A., Baldwin, R., and Gassner, A., 2015a, Earthquake hypocenters and focal mechanisms in central Oklahoma reveal a complex system of reactivated subsurface strike-slip faulting: Geophysical Research Letters, v. 42, p. 2742-2749.

McNamara, D. ., Rubinstein, J.L., Myers, E., Smoczyk, G., Benz, H.M., Williams, R.A., Hayes, G., Wilson, D., Herrmann, R., McMahon, N.D., and Aster, R.C., 2015b, Efforts to monitor and characterize the recent increasing seismicity in central Oklahoma: The Leading Edge, v. 34, p. 628-639.

McNamara, D.E., Hayes, G.P., Benz, H.M., Williams, R.A., McMahon, N.D., Aster, R.C., Holland, A., Sickbert, T., Herrmann, R., Briggs, R. , Bergman, E., Smoczyk, G.,and Earle, P., 2015c, Reactivated faulting near Cushing, Oklahoma: Increased potential for a triggered earthquake in an area of United States strategic intrastructure: Geophysical Research Letters, v. 42, p. 2742-2749.

Mikkelson, D.H., 1966, The origin and age of the Mississippian “chat” in north-central Oklahoma: Oklahoma City Geological Society. Shale Shaker Digest V, v. 15-17, p.255-265.

Miller, J.H., 1959, Subsurface geology of the east Columbia area, Kingfisher and Logan counties, Oklahoma: University of Oklahoma, M.S. Thesis.

Millikan, C.V., 1920, Inter-relations of the folds of Osage County, Oklahoma: AAPG Bulletin, v. 4, p. 151-158.

Miser, H.D., 1954, Geologic map of Oklahoma: U.S. Geological Survey / Oklahoma Geological Survey.

Murray, K.E., 2014, Class II Underground Injection Control Well Data for 2010-2013 by Geologic Zones of Completion, Oklahoma: Oklahoma Geological Survey Open-File Report (OF1-2014).

Musgrove, C.D., 1967, Petroleum Geology of the Bryant Area, Okmulgee Okfuskee and Mclntosh Counties, Oklahoma, The Shale Shaker Digest V, v. 17, p. 266-279.

Nolte, C.J., 1951, Geology of the subsurface formations of northern Logan County, Oklahoma: University of Oklahoma, M.S. Thesis.

Northcutt, R.A. and Campbell, J.A., 1995, Geologic provinces of Oklahoma: The Shale Shaker, v. 46, p. 99-103.

Oakes, M.C., 1940, Geology and mineral resources of Washington County, Oklahoma: Oklahoma Geological Survey Bulletin 62, p. 1-208.

Oakes, M.C. and Jordan, L., 1959, Geology and mineral resources of Creek County, Oklahoma: Oklahoma Geological Survey Bulletin, v. 81, p. 5-25.

Oakes, M.C. and Motts, W.S., 1963, Geology and water resources of Okmulgee County, Oklahoma: Geological Survey Bulletin 91.

Pennington, C. and Chen, X., 2017, Coulomb stress interactions during the M_w 5.8 Pawnee sequence: Seismological Research Letters, v. 88, p. 1024-1031.

Puckette, J.O., 2016a, Structure of Ordovician Viola Limestone, 14N-21N, R3E-6E (parts of Payne, Noble, Lincoln and Pawnee counties): Unpublished map.

Puckette, J.O., 2016b, Structure of Ordovician Viola Limestone, 14N-21N, R2W-2E (parts of Oklahoma, Logan, Payne, and Noble counties): Unpublished map.

Puckette, J.O., and Al-Shaieb, Z., 2002, The Red Fork sandstone: Overview of marine and deep-marine reservoirs: Oklahoma Geological Survey Circular 108, p. 119-133.

Pulling, D.M., 1979, Subsurface stratigraphic and structural analysis, Cherokee Group, Pottawatomie County, Oklahoma: Shale Shaker, v. 29, p. 124-136.

Querry, J.L., 1958, Subsurface geology of south-central Kay County, Oklahoma: The Shale Shaker Digest II, v. 8, p. 388-408.

Ratre, P., 2017, Integrated geophysical study for subsurface characterization of basement in the Cherokee Platform, Northeastern Oklahoma, The University of Tulsa, M.S. Thesis.

Reeder, L.R., 1976, The control of potential Arbuckle hydrocarbon traps in Northeastern Oklahoma by Precambrian topography: The Shale Shaker Digest VIII, v. 26, p. 176-186.

Ries, E.R., 1954, Geology and mineral resources of Okfuskee County, Oklahoma: Oklahoma Geological Survey Bulletin 71.

Roberts, J F., 1981, Index to Subsurface Mapping in Oklahoma, 1967-1970: Oklahoma Geological Survey, Geological Map 22.

Roberts, J.F., Luza, K.V. and Corff, J.A., 1981, Index to surface geologic mapping in Oklahoma (through 1976): Oklahoma Geological Survey, Geological Map 21.

Robbins, Jr, G.D., 1976, Geology of the Yale Southwest Quadrangle, Payne County, Oklahoma: Oklahoma State University, M.S., Thesis.

Rogers, S.M., 2001, Deposition and diagenesis of Mississippian chat reservoirs, north-central Oklahoma: AAPG bulletin, v. 85, p. 115-129.

Rottmann, K., 2000, Prairie Gem Field Hunton Reservoir Study: Oklahoma Geological Survey Speccial Pulication 2000-2, p. 88-114. Website accessed August 11, 2020, http://ogs.ou.edu/docs/specialpublications/SP2000-2.pdf.

Rottmann, K., 2018, Well-Log Characterization of the Arbuckle Group in Central and Northern Oklahoma: Interpretation of the Impact of its Depositional and Post-Depositional History on Injection Induced Seismicity: Oklahoma Geological Survey, Open-File Report 21-2018.

Rountree, J.H., 1994, Petroleum Geology of the Arbuckle Group, Southern Osage and Eastern Pawnee Counties, Oklahoma:(Part I): The Shale Shake Digest XIII, v. 44, p. 207-221.

Schloeder, F X. III, 1998, Geological surprises with 3D[seismic] – Nemaha Ridge, Kay and Noble Counties, Oklahoma, and Sumner County, Kansas, *in* Abstracts with program, 3D-Seismic Symposium: Rocky Mountain Association of Geologists.

Schramm Jr., M.W., 1965, Distribution of Simpson production, central Mid-Continent Region: Tulsa Geological Digest, v. 33, p. 130-133.

Shah, A.K. and Crain, K., 2018, Aeromagnetic data reveal potential seismogenic basement faults in the induced seismicity setting of Oklahoma: Geophysical Research Letters, v. 45, p. 5948-5958.

Shelton, J.W., Jenkins, W.A. and Bingham, R.H., 1979. Geology and mineral resources of Noble County: Oklahoma Geological Survey Bulletin 128.

Shelton, J.W., J.S. Ross, A.J. Garden, and J.L. Franks, 1985, Geology and Mineral Resources of Payne County, Oklahoma: Oklahoma Geological Survey Bulletin 137.

Shipley, R.D., 1976, Local Depositional Trends of "Cherokee" Sandstones, Payne County, Oklahoma: Shale Shaker, Digest IX, v. 27, p. 173-191.

Sims, P.K., 1987, Precambrian Basement Map of the Northern Mid-Continent USA, *in* B. Rascoe, Jr. and N. J. Hyne, editors, Petroleum Geology of the Mid-Continent: Tulsa Geological Society Special Publication 3, p. 10-12.

Sloss, L.L. 1963. Sequences in the cratonic interior of North America: GSA Bulletin, v.74, p. 93-114.

Sloss, L.L., 1984, Comparative anatomy of cratonic unconformities, *in* Interregional Unconformities and Hydrocarbon Accumulation, AAPG Memoir 36, p. 1-6.

Smith, E.W., 1955, Subsurface geology of eastern Kay County, Oklahoma and southern Cowley County, Kansas: Shale Shaker, v. 5, p. 434-448.

Smith, J.C., 1948, Garden Grove Pool, Okfuskee and Lincoln Counties, Oklahoma: Tulsa Geological Society Digest, v. 16, p. 65-69.

Springman, R.J., 2018, personal communication.

Stanley, T.M., 2010, Geologic Map of the Wekiwa 7.5 Quadrangle, Osage, Pawnee, and Tulsa Counties, Oklahoma: Oklahoma Geological Survey Quadrangle Map 80.

Stanley, T.M., and Chang, J.M., 2011, Geologic Map of the Lake Sahoma 7.5 Quadrangle, Creek and Tulsa Counties, Oklahoma: Oklahoma Geological Survey Quadrangle Map 82.

Stringer, Jr., C.P., 1958, Subsurface Geology of Western Payne County, Oklahoma: Oklahoma City Geological Society, The Shale Shaker Digest II, v. VI-VIII, p. 258-273.

Swesnik, R.M., 1948. Geology of West Edmond oil field, Oklahoma, Logan, Canadian, and Kingfisher Counties, Oklahoma, *in* R. M. Swesnik, editor, Structure of Typical American Oil Fields: AAPG, v. 3, p. 359 -398.

Sylvester, A.G., 1988, Strike-slip faults: Geological Society of America Bulletin, v. 100, p. 1666-1703.

Tanner, W.F., 1956, Geology of Seminole County, Oklahoma: Oklahoma Geological Survey Bulletin, v. 74.

Tarr, R.S., Jordan, J., and Rowland, T.L., 1965, Geological Map and Section of Pre-Woodford Rocks in Oklahoma: Oklahoma Geological Map GM-9.

Toelle, B., Sitchler, J., and Pfannenstiel, R., 2008, Pannotian breakup (Iapetan Opening) features in central Oklahoma, *in* SEG Technical Program Expanded Abstracts 2008, Society of Exploration Geophysicists, p. 929-932.

Umpleby, S.S., 1956, Faulting, accumulation, and fluid distribution in Ramsey pool, Payne County, Oklahoma: AAPG Bulletin, v. 40, p. 112-139.

USGS, 2011, M 5.7 Prague Earthquake, Oklahoma: Earthquake Hazards Program. Website accessed August 11, 2020, https://earthquake.usgs.gov/earthquakes/eventpage/usp000jadn/executive.

USGS, 2016, M 5.8 - 14km NW of Pawnee, Oklahoma: Earthquake Hazards Program. Website accessed August 11, 2020, https://earthquake.usgs.gov/earthquakes/eventpage/us10006jxs/executive.

Verish, N.P., 1979, Reservoir trends, depositional environments, and petroleum geology of "Cherokee" sandstones in T11-13N. R4-5E, central Oklahoma: Shale Shaker, v. 29, p. 209.

Waldhauser, F., 2001, HypoDD: A computer program to compute double-difference earthquake locations: USGS Open File Rep., 01-113.

Walsh, F.R., and Zoback, M.D., 2015, Oklahoma's recent earthquakes and saltwater disposal: Science Advances, v.1, p. 1-9.

Ward, F.D., 1958, The subsurface geology of Noble County: University of Oklahoma, M.S. Thesis.

Watney, W.L., 2014, Fluid migration and accumulation within the Mississippian: Why 2% oil cut here, 15% oil cut one mile away: AAPG Mississippian Lime Forum, v. 20.

Way, H.S.K., 1983. Structural Study of the Hunton Lime of the Wilzetta Field T12-13N, R5E, Lincoln County, Oklahoma, Pertaining to the Exploration for Hydrocarbons: Oklahoma State University, Doctoral Dissertation.

Weirich, T.E., 1953, Shelf principle of oil origin, migration, and accumulation: AAPG Bulletin, v. 37, p. 2027-2045.

West, A.E., 1961, Geology of Northeastern Lincoln County, Oklahoma: The Shale Shaker Digest III, v. 11, p. 342-352.

White, S.B., 1941, Davenport field, Lincoln County, Oklahoma, *in* Stratigraphic Type Oil Fields: AAPG, p. 386-407.

Whitmeyer, S.J., and Karlstrom, E.K., 2007, Tectonic model for the Proterozoic growth of North America: Geosphere, v. 3, p. 220-259.

Witt, W.J., Allred, O.B., Denney, P.P., Garrity, S.R., Gatewood, L.E., Givens, D.B., Perkins, J.M., and Sundholm, A.W., 1971, Cross-section of Oklahoma from SW to NE corner of State: Oklahoma City Geological Society, Stratigraphic Committee, p. 1-1.

Yeck, W.L., G.P. Hayes, D.E. McNamara, J.L. Rubinstein, W.D. Barnhart, P. S. Earle, and H. M. Benz, 2017, Oklahoma experiences largest earthquake during ongoing reginal wastewater injection hazard mitigation efforts: Geophysical Research Letters: v. 44, p. 711-717. Website accessed August 3, 2020, https://agupubs.onlinelibrary.wiley.com/doi/pdfdirect/10.1002/2016GL071685.

Zoback, M.L., 1992, First-and second-order patterns of stress in the lithosphere: The World Stress Map Project. Journal of Geophysical Research: Solid Earth, v. 97, p. 11703-11728.

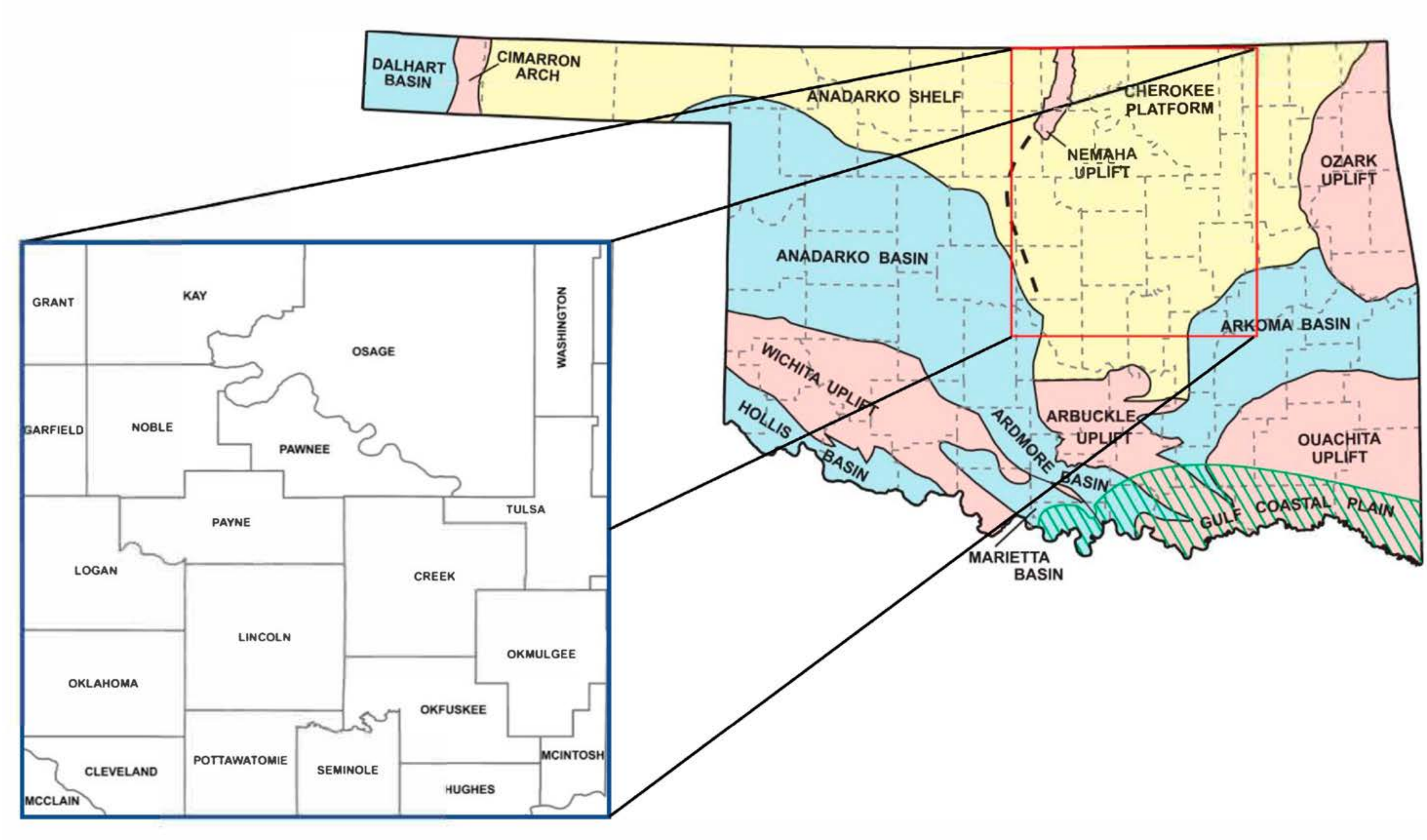


Figure 1. Study area in relation to the major tectonic provinces of Oklahoma (modified after Johnson, 2008).

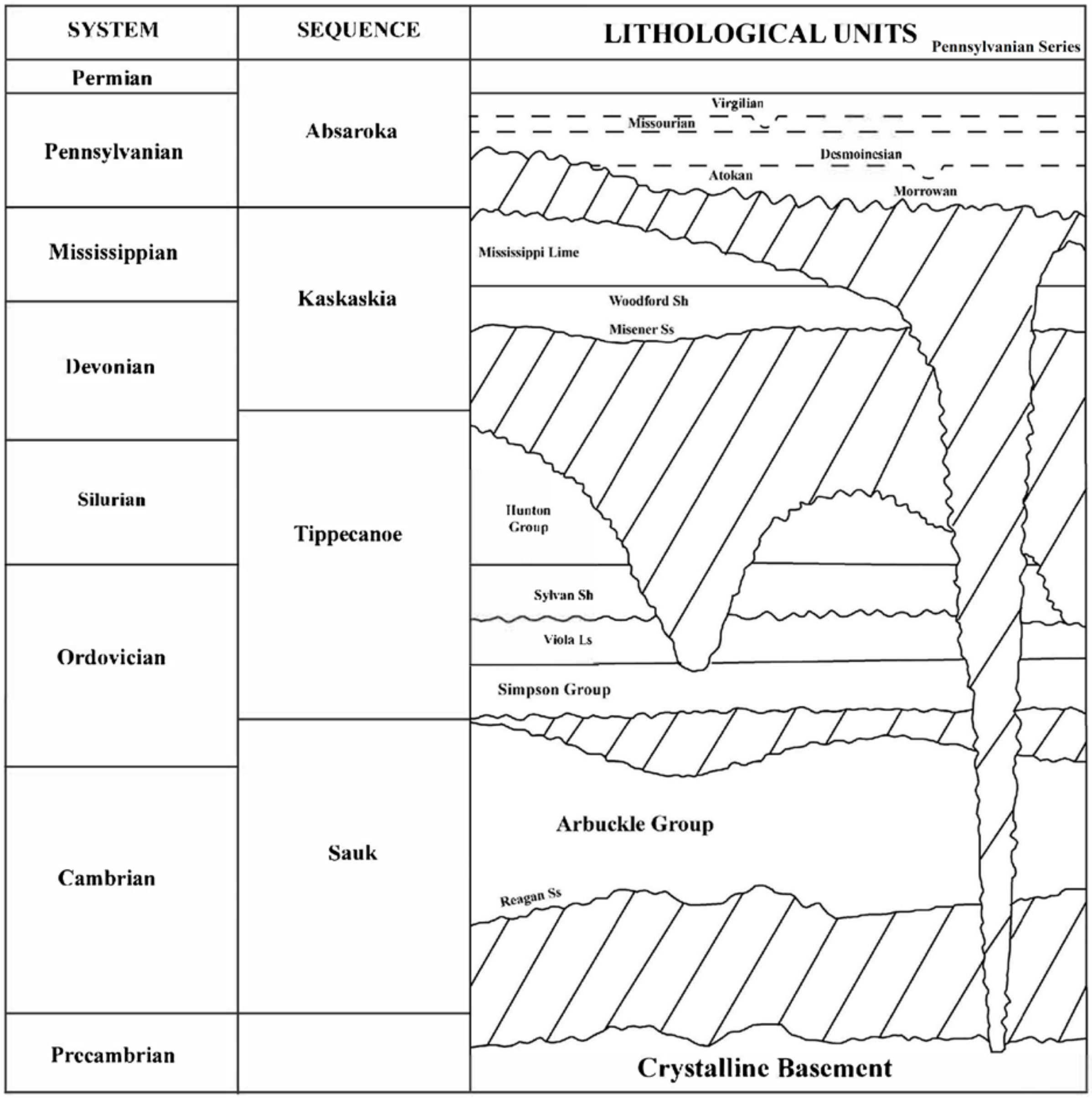


Figure 2. Schematic stratigraphic column of the Cherokee Platform in Northeastern Oklahoma (modified after Dolton and Finn, 1989; Boyd, 2008).

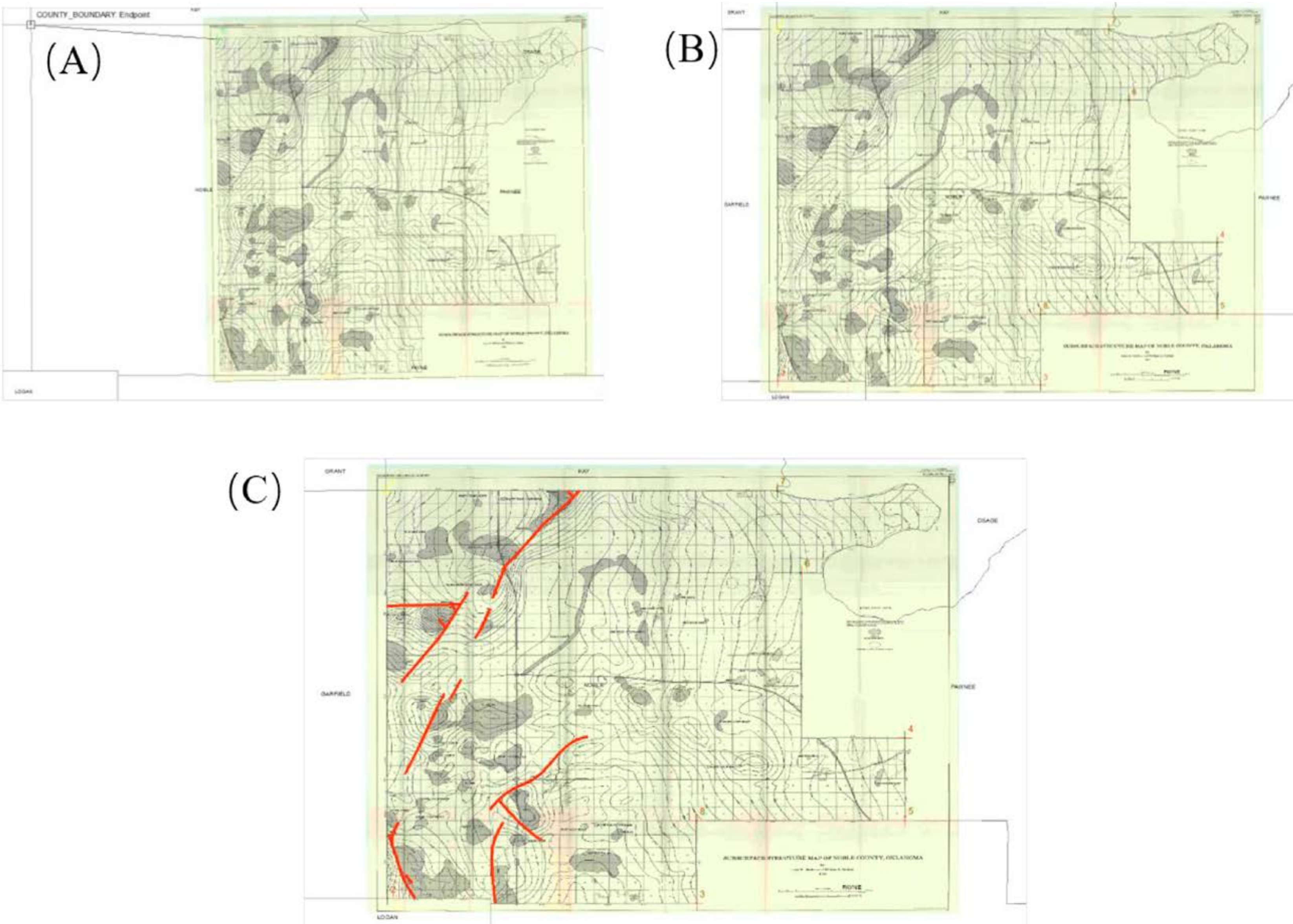


Figure 3. Georeference of Noble County structural contour map by Shelton et al. (1979) into ArcGIS. (A) Georeference of a Noble County structure contour map to the county location in ArcMap; (B) Georeference of boundary of the scanned map to match the Noble County boundary in ArcMap; (C) Digitized fault traces in ArcMap; red lines show the fault traces digitized from scanned map.

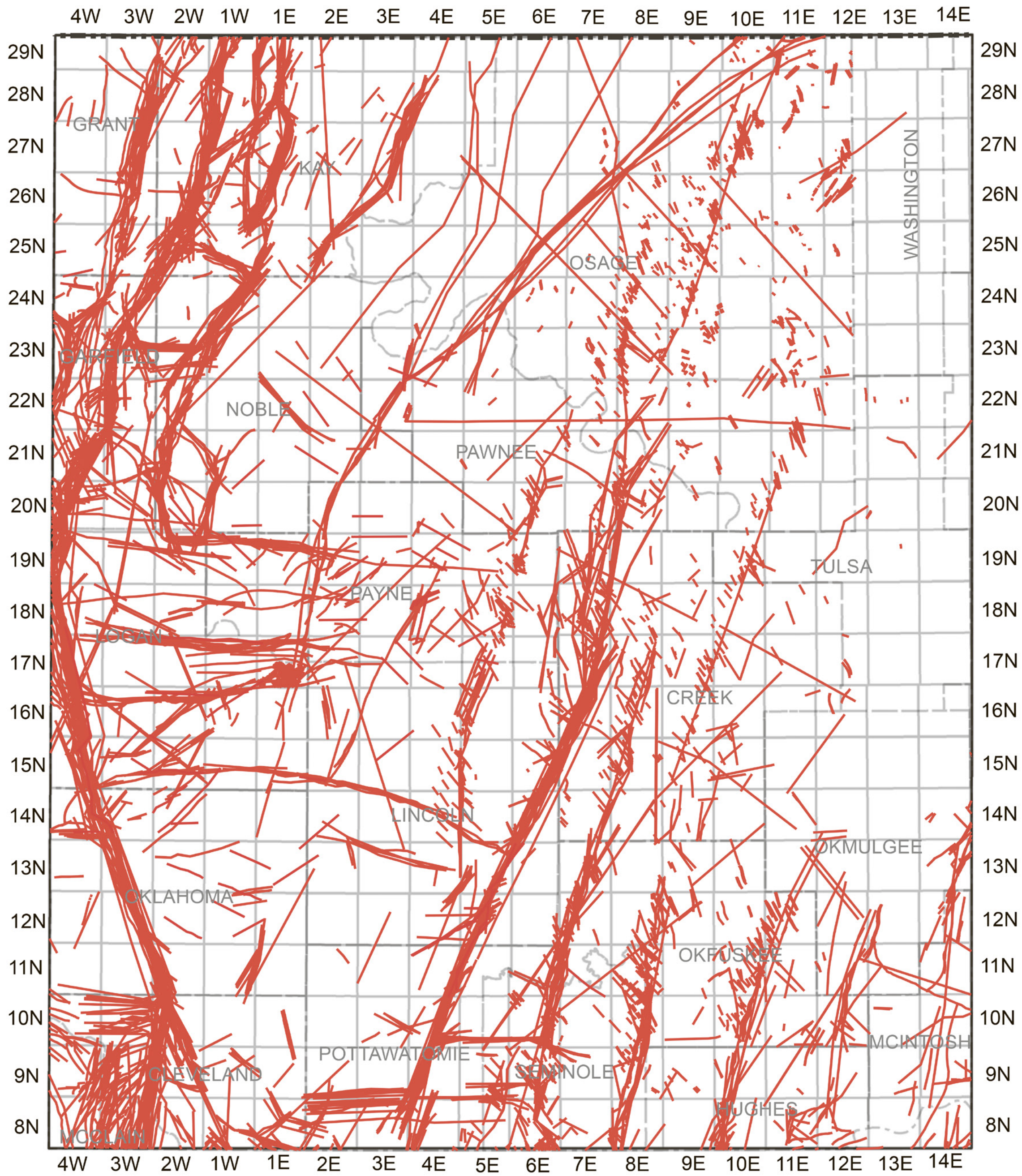


Figure 4. Comprehensive fault map of study area in Northeastern Oklahoma.

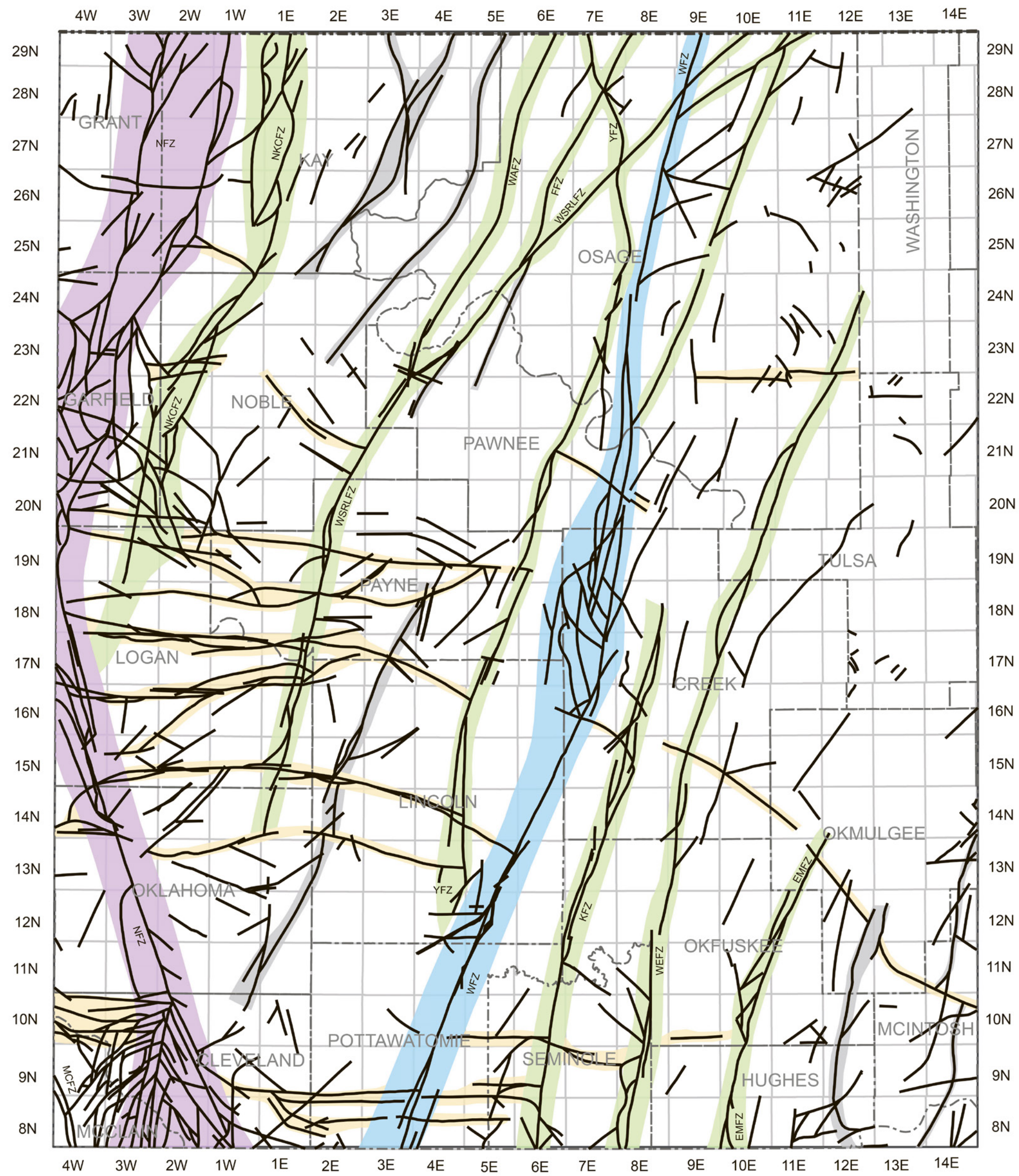


Figure 5. Interpretive fault map of study area in Northeastern Oklahoma. NFZ=Nemaha Fault Zone; NKCFZ=Noble-Kay Counties Fault Zone; WAFZ=Watchorn Fault Zone; FFZ=Foraker Fault Zone; WSRLFZ=West Stillwater – Ramsey – Labette Zone; YFZ=Yale Fault Zone; WFZ=Wilzetta Fault Zone; KFZ=Keokuk Fault Zone; WEFZ=Wewoka Fault Zone; EMFZ=East Mountain Fault Zone; MCFZ=McClain County Fault Zone.

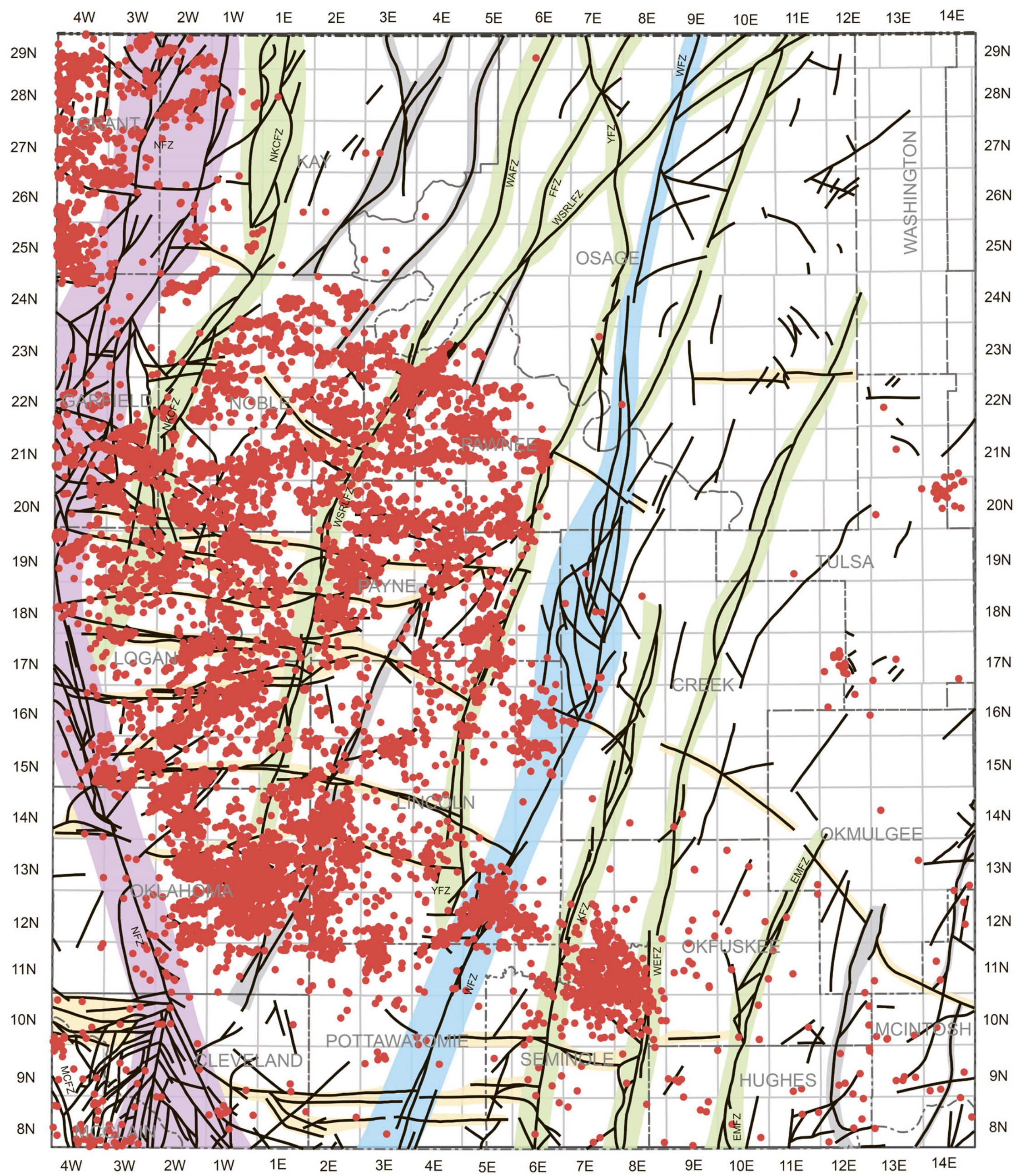


Figure 6. Interpretive fault map and earthquake epicenters in Northeastern Oklahoma. To avoid duplication, the data are taken from one source, Oklahoma Geological Survey.

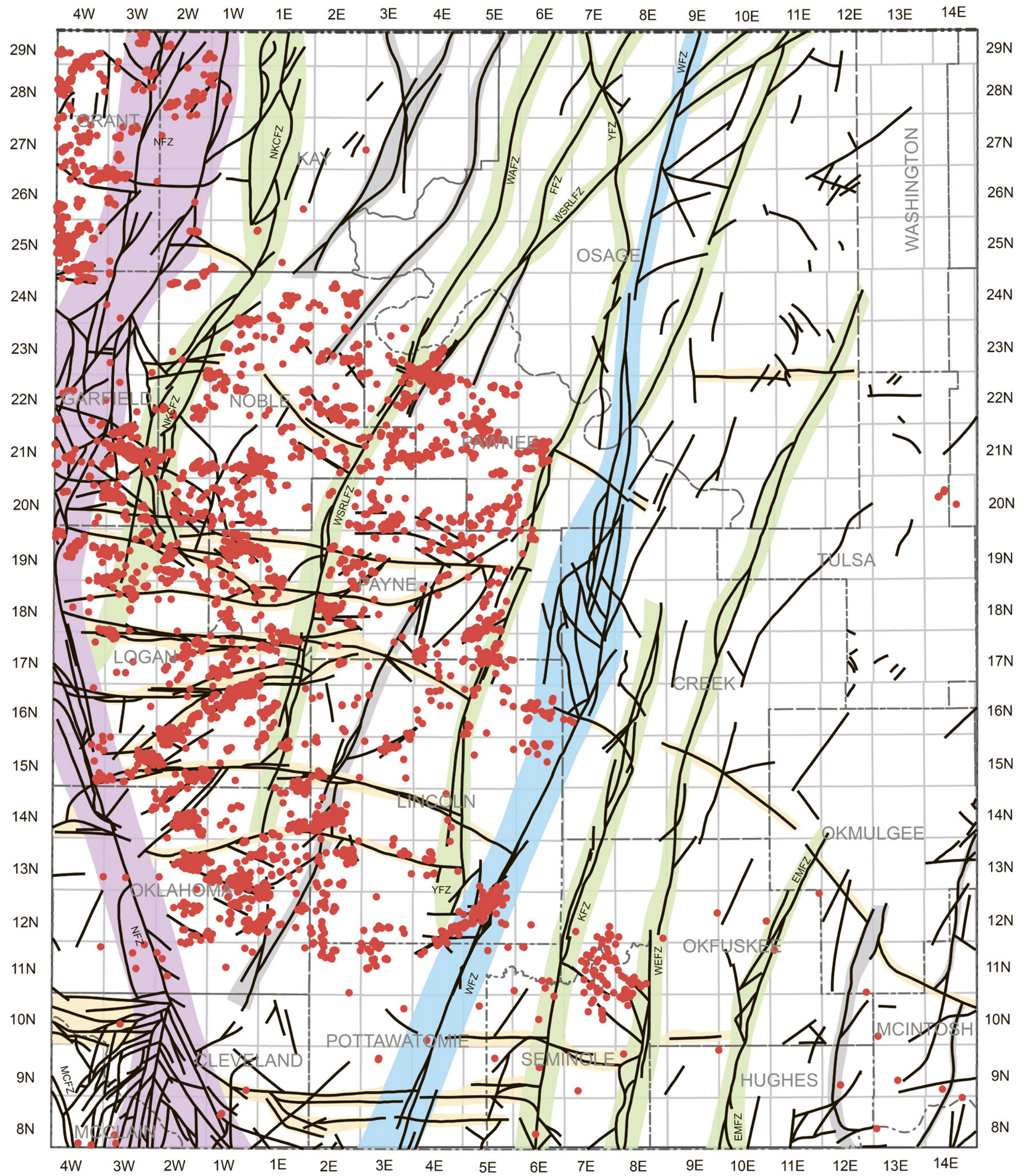


Figure 7. Interpretive fault map and epicenters of earthquakes with intensity of M_w 2.5+.

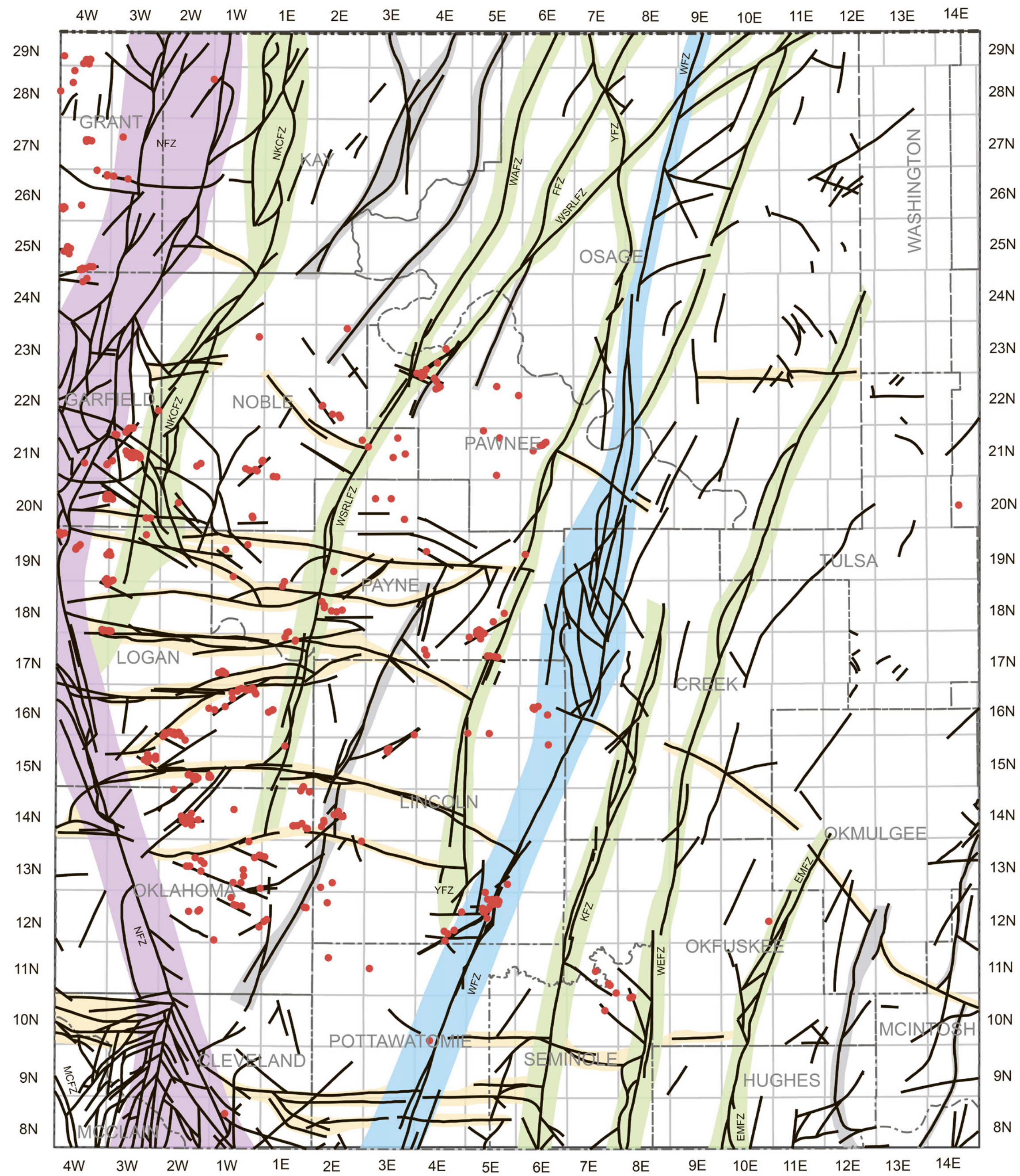


Figure 8. Interpretive fault map and epicenters of earthquakes with intensity of M_w 3.5+.

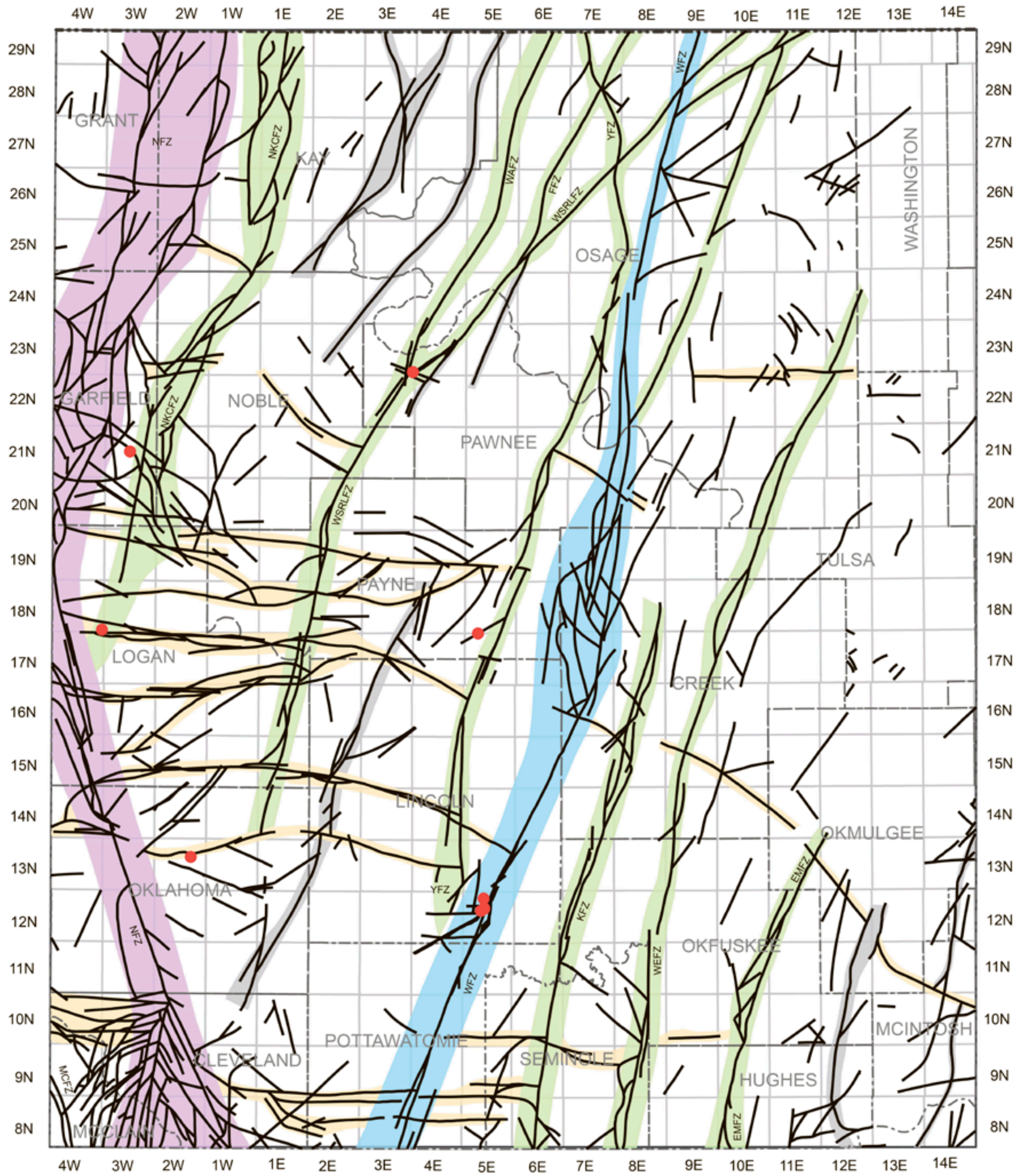


Figure 9. Interpretive fault map and epicenters of earthquakes with intensity of M_w 4.5+.

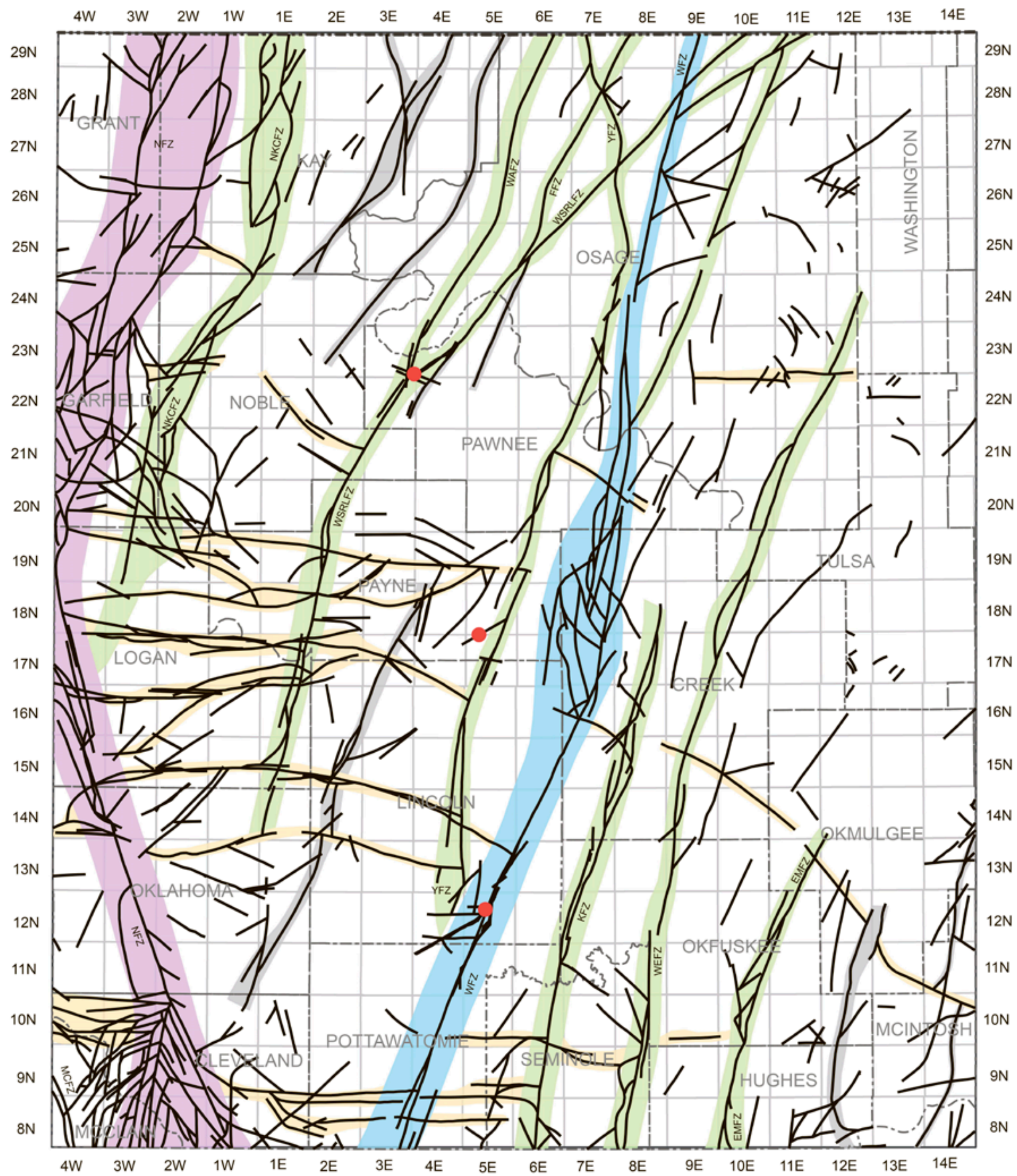
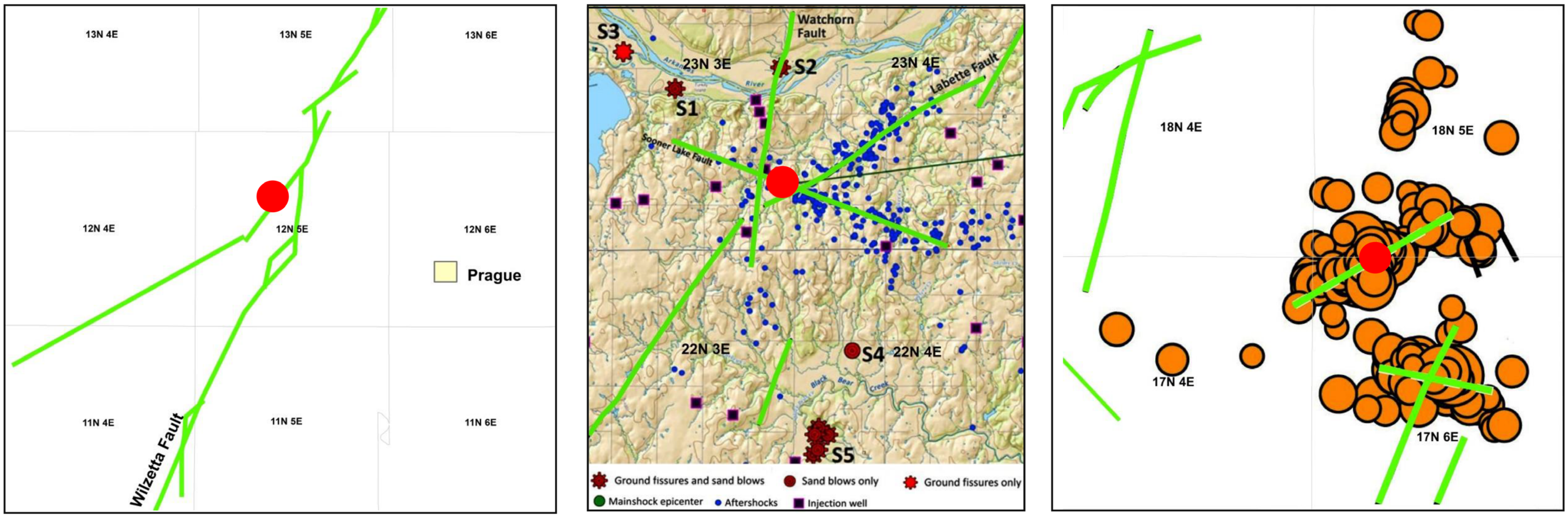


Figure 10. Interpretive fault map and epicenters of earthquakes with intensity of M_w 5.0+.



A B C

Figure 11. Faults and epicenters of earthquakes of M_w 5.0+. A. Faults and main Prague earthquake (M_w 5.6; after McNamara, 2015a). B. Faults, including Sooner Lake Fault, and main Pawnee earthquake (M_w 5.8; S1-S5=sand blows / ground fissures; modified from Kolawole et al., 2017). C. Faults and Cushing earthquakes, with M_w 5.0 earthquake in red (modified after Yeck et al., 2016).

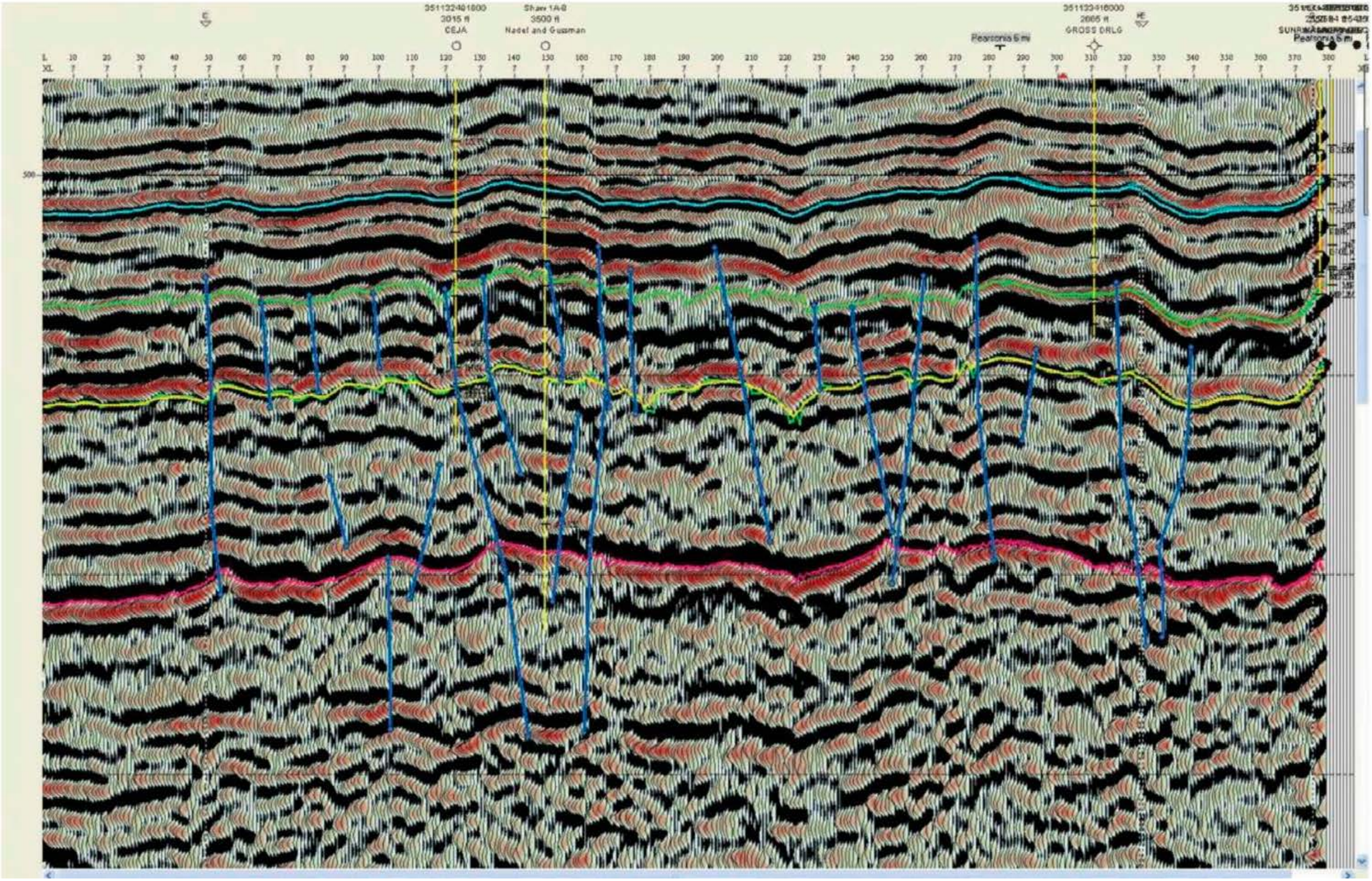


Figure 12. E-W seismic section of HW 60 Trend, Osage County, Oklahoma (from Matson, 2013; Watney, 2014), showing abundant, tightly spaced faults, which die out upward in Pennsylvanian strata. Length of section 8 miles.

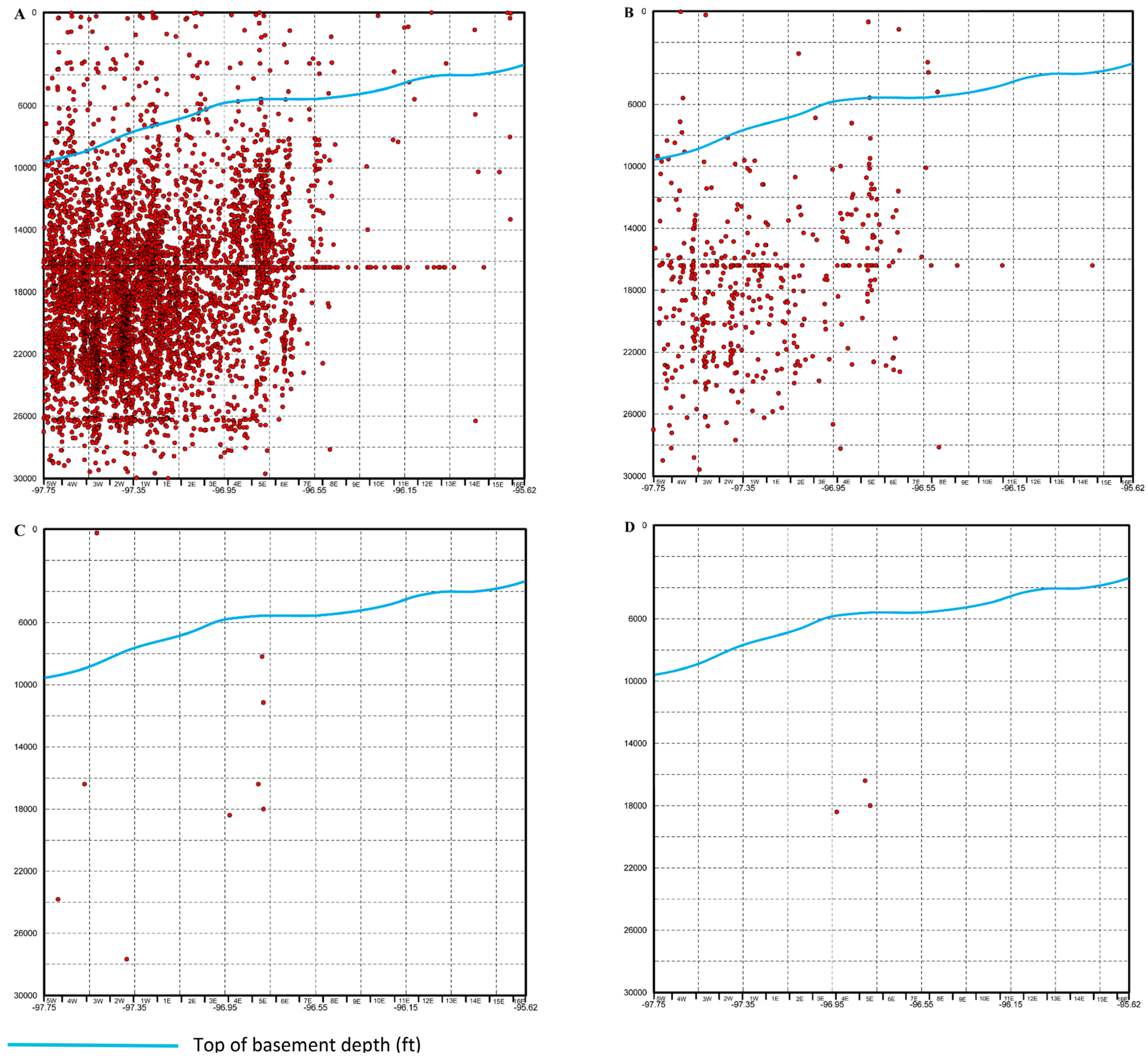


Figure 13. Generalized diagrammatic, cross-sectional views of earthquake foci in relation to top of basement mapped by Denison (1981). A. Earthquakes with intensity of M_w 2.5+. B. Earthquakes with intensity of M_w 3.5+. C. Earthquakes with intensity of M_w 4.5+. D. Earthquakes with intensity of M_w 5.0+.

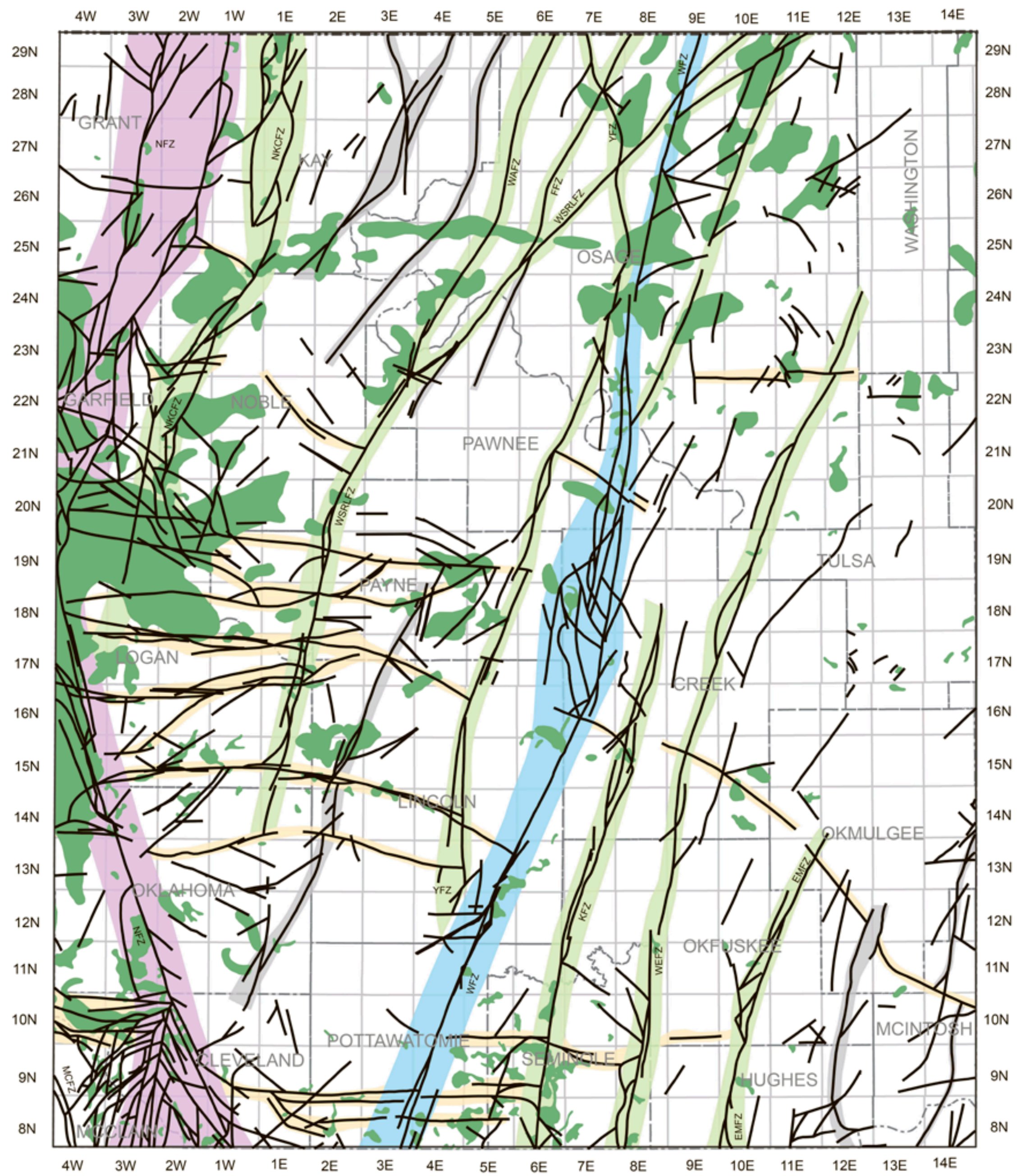


Figure 14. Interpretive fault map with map of Pre-Pennsylvanian producing reservoirs (fields after Boyd, 2002a,b).

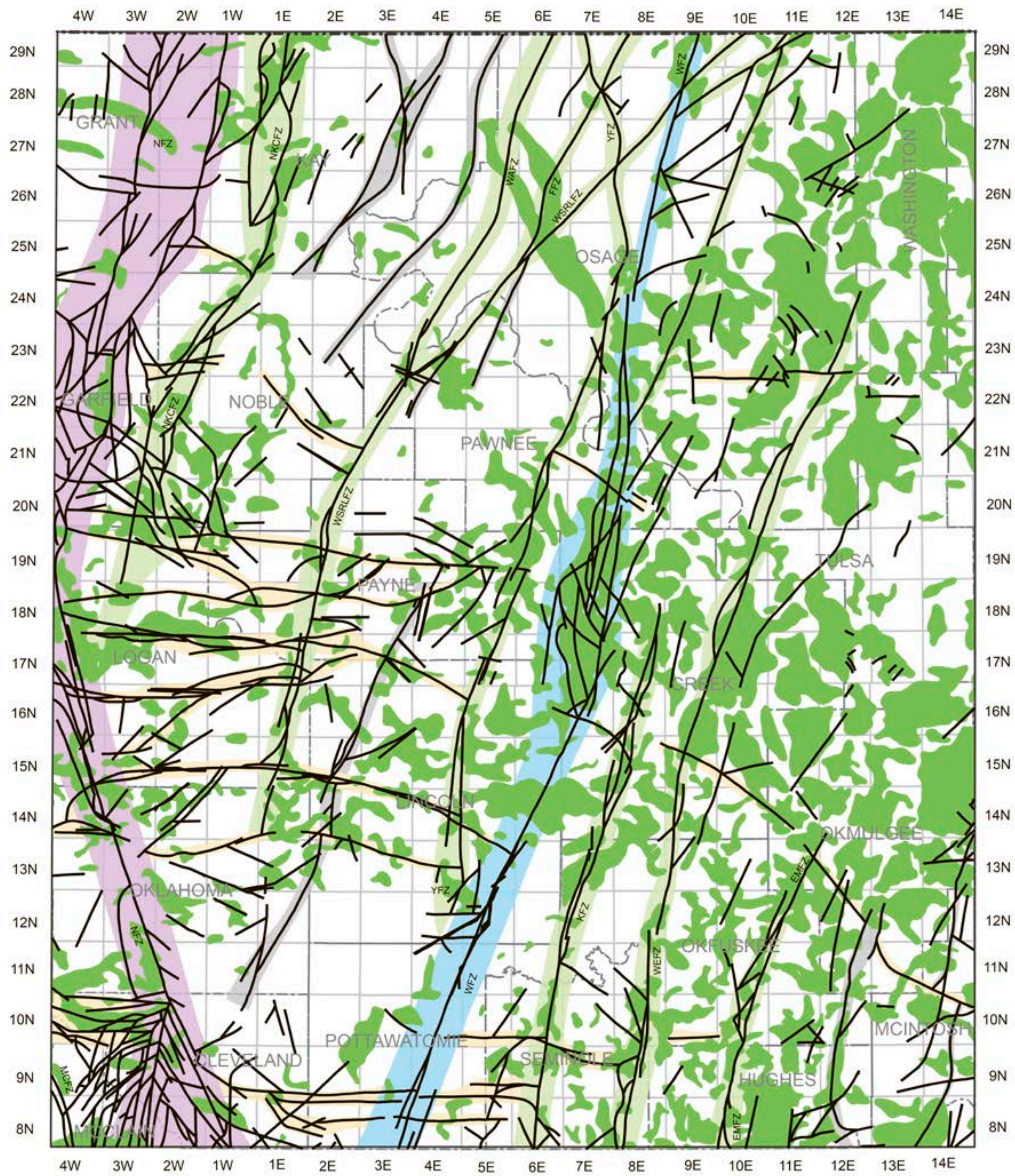


Figure 15. Interpretive fault map with map of Pennsylvanian producing reservoirs (fields after Boyd, 2002a,b).