Kansas Geological Survey

Stratigraphic and Structural Evaluation of the Lower and Middle Pennsylvanian Subsystem in the Cherokee-Forest City Basin of the U.S. Midcontinent

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Abstract

The Cherokee-Forest City Basin (CFCB) has drawn recent attention due to the potential critical mineral (CM) endowment of the basin's many Pennsylvanian-aged black shales, coals, and interbedded clay horizons. These lithologies have the potential to contain CM resources that are essential for an array of modern technologies, national security, and regional economic vitality. Much of our general understanding of the CFCB's geometry, stratigraphic architecture, and structural framework was established in the early-to-mid 20th century and predates modern tectonic and sequence stratigraphic concepts The objective of this work is to improve upon these historical interpretations through establishment of new stratigraphic correlations in wireline logs for fifteen stratigraphic horizons using 7,785 oil and gas wells spanning southwestern Iowa to northeastern Oklahoma. Isochore maps, regional petrophysical cross sections, and structural interpretations highlight elements of the Carboniferous-aged evolution of the basin with focus on the Lower and Middle Pennsylvanian series. With these data, this study aims to refine our understanding of Carboniferous basin geometries in the CFCB at the subsystem and/or subgroup level; identify regional subsurface units for refined stratigraphic determination and assess their viability in basin-wide correlation (particularly those of the Lower Pennsylvanian Cherokee Group); characterize the accommodation and infilling of the Forest City portion of the basin in Northeastern Kansas; track the migration of depocenters through the Lower and Middle Pennsylvanian age in the dynamic, tectonically active CFCB; and evaluate the significance of both well and lesser known structural elements that were active during deposition.

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Table of Contents

Abstract ... 3
Acknowledgements ... 4
List of Figures ... 7
List of Tables ... 9
Introduction ... 10
Background ... 12
 Regional Geology ... 12
 Structural Framework of the CFCB ... 13
 Stratigraphic Framework ... 15
Methodology ... 20
 Stratigraphic Correlation ... 20
 Cross Sections, Isochore, and Structural Surfaces ... 24
Results ... 24
 Stratigraphic Correlation ... 24
 Cross Sections ... 26
  WE-1 ... 28
  WE-2 ... 28
  WE-3 ... 29
  WE-4 ... 29
  WE-5 ... 30
  WE-6 ... 30
  NS-1 ... 30
  NS-2 ... 31
  NS-3 ... 31
  NS-4 ... 32
  NS-5 ... 32
  NS-6 ... 33

NS-7 ... *34*
NS-8 ... *35*
Isochore Maps ... 35
i0: Mississippian Carbonates (Base Chouteau Limestone to top Mississippian Subsystem) *36*
i1: Krebs Subgroup (Top Mississippian Subsystem to Base Tebo Shale) ... *37*
i2: Lower Cabaniss Subgroup: (Base Tebo Shale to Top Mecca Quarry Shale) ... *38*
i3: Upper Cabaniss Subgroup (Top Mecca Quarry Shale to Top Excello Shale) ... *38*
i4: Fort Scott Subgroup (Top Excello Shale to Top Anna Shale) ... *39*
i5: Appanoose Subgroup (Top Anna Shale to Top Lake Neosho Shale) ... *40*
i6: Lower Holdenville Subgroup (Top Lake Neosho Shale to Top Hushpuckney Shale) ... *40*
i7: Upper Holdenville/Lower Bronson Subgroups (Top Nuyaka Creek Shale to Top Hushpuckney Shale) ... *41*
i8: Kansas City, Lansing, and Douglas Groups (Top Hushpuckney Shale to Top Heebner Shale) ... *42*
Depth Structure Surfaces ... 43
Discussion ... 47
Mississippian Stratigraphic Challenges ... 47
Depositional Trends ... 49
Inference of Structural Elements ... 53
Conclusions ... 59
Considerations for Future Research ... 60
References ... 61
Appendix 1. CoreCM Interstate Nomenclatural Scheme ... 68
Appendix 2. Wireline Well Log Correlation ... 70
References ... 75
Appendix 3. Full Page Isochore Maps (i0-i8) ... 76
Appendix 4. Full Page Surface Maps (S0-S9) ... 87

List of Figures

Figure 1: A) Upper Pennsylvanian Midcontinent Sea (LPMS) paleogeographic reconstruction, modified from Blakey (2007). Paleo-equator is from Oborny et al. (2017) as defined by Heckel (2013). B) Area of interest that encompasses the Western Region Coal Field (WRCF; grey area, approximately) spanning across several states and the Osage Nation (ON), composed by the Forest City Basin (FCB), Cherokee Basin (CB), and Arkoma Basin (AB). Structural features in/adjacent to the study area include the Midcontinent Rift System (MRS), Thurman-Redfield Fault Zone (TRFZ), Nemaha Uplift (NU), Humboldt Fault Zone (HFZ), Nemaha Tectonic Zone (NTZ), Central Plains Mega-shear Zone (CPMZ), Central Missouri Tectonic Zone (CMTZ), Bolivar-Mansfield Tectonic Zone (BMTZ), Chesapeake Tectonic Zone (CTZ), Fall River Tectonic Zone (FRTZ, Bourbon Arch, and Ozark Uplift (figure provided by Dr. S.C. Oborny) 10
Figure 2: Sea-level curve for Upper Desmoinesian through Lower Virgilian cyclothems in the CFCB (from Heckel, 2013)........ 14
Figure 3: Generalized cyclothem from the Kansas-Iowa outcrop belt (modified from Oborny et al., 2017, after Heckel, 1994). Note discussion in text outlining various interpretations regarding assignment of systems tracts........ 15
Figure 4: A) KU graduate student analyzing Pennsylvanian Age outcrop in Bourbon County, KS (Photo courtesy of KGS); B) Cross-polarized and reflected light photomicrographs of a sample taken at 2387' from Peterson Trust well #8-31 (Krebs Subgroup), depicting an illite matrix with interbedded amorphous organic matter (Oborny and Bream, 2025); and C) Peterson Trust well #8-31 core sample from 2360' to 2420' measured depth (Krebs Subgroup, Oborny and Bream 2025)........ 16
Figure 5: CFCB Nomenclature for the State of Kansas. Left): stratigraphic nomenclature presently recognized for use by the state of Kansas. Middle): nomenclature proposed by recent works. Right): combined nomenclatural schemes of Layzell et al. (2021; Marmaton Group) and Oborny et al. (2025; Cherokee Group). Isochore intervals (i0-i8) and structural surfaces (S0-S9) are identified at far right. Blue = coal, Red = black shale (figure provided by Dr. S.C. Oborny and slightly modified to include isochore and structural surface details........ 19
Figure 6: Project oil and gas well distribution overlain with prior regional fault interpretations. Fault layer was compiled by Alan Peterson at the KGS and published in Mohammadi et al. (2022)........ 21
Figure 7: Gamma-ray type log and lithological description of the Douglas County Core Hole #1 in Douglas County, Kansas (modified from Newell and Bailey; 2012). Isochore intervals i0-i8 are denoted at left. Stratigraphic units delineated by this work are at right........ 23
Figure 8: Cross section distribution........ 26
Figure 9: Representative sample from cross section WE-3 centered on the Excello Shale (orange) depicting the Base Chouteau Limestone (red) through Stark Shale Interval (top blue) as it traverses the NTZ/HFZ in Marion through Morris Counties. Full cross sections in poster format can be found in Supplementary File 2........ 27

Figure 10.0: Mississippian Carbonates Isochore 36
Figure 10.1: Krebs Subgroup Isochore 37
Figure 10.2: Lower Cabaniss Subgroup Isochore 38
Figure 10.3: Upper Cabaniss Subgroup Isochore 39
Figure 10.4: Fort Scott Subgroup Isochore 39
Figure 10.5: Apanoose Subgroup Isochore 40
Figure 10.6: Lower Holdenville Subgroup Isochore 40
Figure 10.56: Undifferentiated Appanoose and Lower Holdenville Subgroup Isochore 41
Figure 10.7: Upper Holdenville/Lower Bronson Subgroup Isochore 42
Figure 10.8: KC, Lansing, and Douglas Group Isochore 42
Figure 11.1: At left, isochore Maps i0 (base Chouteau Limestone to top Mississippian Subsystem) and i1 (top Mississippian Subsystem to base Tebo Shale). At right, surface maps showing depth relative to MSL for upper unit of both isochores. 44
Figure 11.2: At left, isochore Maps i2 (base Tebo Shale to top Mecca Quarry Shale) and i3 (top Mecca Quarry Shale to top Excello Shale). At right, surface maps showing depth relative to MSL for upper unit of both isochores. 45
Figure 11.3: At left, isochore Maps i4 (top Excello Shale to top Anna Shale) and i5 (top Anna Shale to top Lake Neosho Shale). At right, surface maps showing depth relative to MSL for upper unit of both isochores. 46
Figure 12: Collection of isochore maps spanning i0-i7 with focus on the CB portion of the CFCB. Lettering discussed in text. 51
Figure 13: At left, isochore Map i8 (top Hushpuckney Shale to top Heebner Shale). At right, surface map showing depth relative to MSL for Heebner Shale. 55
Figure 14: Interpreted NW-SE trending fault lineaments interpreted from all data; underlain by i0 isochore for the Mississippian Carbonate, accompanying isochore well distribution, and documented faults. Previously documented faults were compiled by Alan Peterson and presented in Mohammadi et al. (2022). The red circle on the FRTZ corresponds closely to the Rose and Silver City Domes and denotes an area of complexity that makes fault interpretation difficult to interpret.. 57

List of Tables

Table 1: Regional names assigned to two correlative hot-gamma spikes in Cherokee Group. ... 20
Table 2: Established marker bed tops/bases in stratigraphic order. A total of 64,796 new delineations were generated by this effort 25
Table 3: Statistical information for cross sections 27
Table 4: Isochores generated by this study in stratigraphic order. 35
Table 5: Statistical data for isochores in stratigraphic order. 36
Table 6: Statistical data for structure maps in stratigraphic order. 43

Introduction

The Cherokee-Forest City Basin (CFCB) spans a broad geographic area, covering eastern Kansas, northeastern Oklahoma and the Osage Nation within Oklahoma, western Missouri, southwestern Iowa, and southeastern Nebraska (Figure 1). The basin exists within what the U. S. Geological Survey (USGS) defines as the "Western Region Coal Field" (WRCF), which represents the Forest City (FCB), Cherokee (CB), and Arkoma (AB) basins combined (Tully, 1996; East, 2013). The CFCB encompasses approximately 80% of the WRCF's total area (~125,000 mi^2).

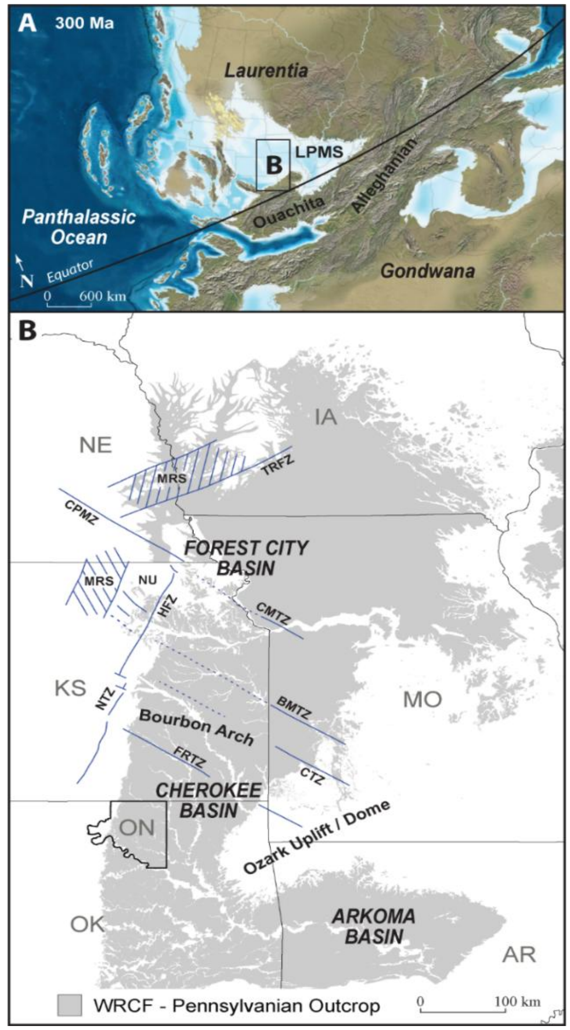

Figure 1: A) Upper Pennsylvanian Midcontinent Sea (LPMS) paleogeographic reconstruction, modified from Blakey (2007). Paleo-equator is from Oborny et al. (2017) as defined by Heckel (2013). B) Area of interest that encompasses the Western Region Coal Field (WRCF; grey area, approximately) spanning across several states and the Osage Nation (ON), composed by the Forest City Basin (FCB), Cherokee Basin (CB), and Arkoma Basin (AB). Structural features in/adjacent to the study area include the Midcontinent Rift System (MRS), Thurman-Redfield Fault Zone (TRFZ), Nemaha Uplift (NU), Humboldt Fault Zone (HFZ), Nemaha Tectonic Zone (NTZ), Central Plains Mega-shear Zone (CPMZ), Central Missouri Tectonic Zone (CMTZ), Bolivar-Mansfield Tectonic Zone (BMTZ), Chesapeake Tectonic Zone (CTZ), Fall River Tectonic Zone (FRTZ, Bourbon Arch, and Ozark Uplift (figure provided by Dr. S.C. Oborny).

Interest in characterizing and improving upon the stratigraphic framework of the CFCB has recently increased due to its potential for hosting and producing critical minerals (CMs), which are essential for innovations in batteries, photovoltaics, fuel cells, and other emerging technologies (Schulz et al., 2017; Oborny and Bream, 2025). Currently, the U.S. relies heavily on foreign imports of CMs, leaving the supply chain vulnerable to disruptions. Efforts at basin-wide interstate characterization have historically been hindered by inconsistent unit boundary definitions and nomenclature across states and tribal agencies. These challenges are compounded by the complex internal architecture of individual cyclothems, the presence of disconformities, and by poorly understood structural features in the basin (Figure 1; Appendix 1; e.g., Layzell et al., 2021; Oborny et al., 2025). Additionally, differing interpretations of depositional trends and facies belts within the CFCB (c.f., Heckel, 2013; Oborny et al., 2025) further limit our ability to evaluate and predict CM content and distribution in this geologically complex depositional setting and stratigraphic framework.

This study develops regional subsurface stratigraphic correlations within the CFCB by integrating both published and newly acquired subsurface data, primarily petrophysical well log data (gamma ray, neutron, and resistivity). The objective of this work is to identify regionally correlative subsurface units for refined stratigraphic characterization and to test the hypothesis that marker beds, typically used for local correlation (e.g., Brown, 2003; Johnson, 2004; Newell and Stalder, 2014; Oborny et al., 2025), exist within the Pennsylvanian succession and are suitable for basin-wide interstate correlation via petrophysical wireline data. Such marker beds may elucidate depositional and structural trends in the basin. Prior to this work, the black shales of the Lower- to Middle-Pennsylvanian Cherokee Group succession (~16 Mys, or ~77% of Pennsylvanian time; Schmitz and Davydov, 2012) had not previously been correlated at this regional scale.

As a critical first step toward evaluating and predicting CM content and distribution, this study provides new basin-wide and interstate isochore maps, structural surface maps, and stratigraphic cross-sections at subsystem (Mississippian) and subgroup (i.e. subgroups within the Pennsylvanian) levels. These products refine our understanding of Carboniferous-aged basin geometry, sites of accommodation and stratigraphic trends, and include the first basin-wide interpretations for stratigraphic differentiation of the Pennsylvanian Cherokee Group.

Background

Regional Geology

During the Carboniferous, the Gondwanan and Laurasian landmasses were converging to form the supercontinent Pangea (Murphy et al., 2010), with the CFCB existing north of the AB along the southwestern margin of the Laurentian paleocontinent (Figure 1; Blakey, 2007; Lawton et al., 2021). During the early Mississippian the area that would later encompass the CFCB was located south of the equator at ~10-20° latitude (Gutschick and Sandberg, 1983; Witzke, 1990). Throughout the remainder of the Mississippian and into the middle-to-late Pennsylvanian, the Pangean landmasses drifted northward placing the CFCB north of the equator at ~5-10° latitude (Witzke, 1990; Heckel, 2013; Oborny et al., 2017). Though several orogenic events were occurring at that time, two that strongly influenced the CFCB were the Ouachita Orogeny to the south and Alleghenian Orogeny to the southeast (Figure 1). Throughout deposition of the lower and into the middle part of the Cherokee Group, several hundred feet of predominantly siliciclastics were deposited within the FCB, which was separated at that time from the CB by a west-east trending (present-day orientation) anticline named the Bourbon Arch (Lee, 1943). During upper middle Cherokee Group deposition, accommodation within the FCB was limited and shifted primarily to the CB with modern-day west-east facies belts and southward thickening of strata into Oklahoma (e.g., Lee, 1943; Joeckel et al., 2007; Heckel, 2013; Heckel, 2023). During times of sea-level highstand, these basins existed within a broad epicontinental sea referred to as the Late Pennsylvanian Midcontinent Sea (Figure 1; Algeo and Heckel, 2008). Recent works have proposed a competing interpretation where these facies belts instead trend southwest-northeast with southeastward thickening of strata into Missouri and Arkansas towards the AB (Oborny and Hasiuk, 2022; Oborny et al., 2025).

Structural Framework of the CFCB

The northern margin of the CFCB is defined by the Thermon-Redfield Structural and/or Fault Zone (TRFZ), which extends eastward from east-central Nebraska into Iowa (Figure 1). This zone consists primarily of high angle faulting that bounds the southern flank of the Midcontinent Rift System (MRS), and/or Midcontinent Geophysical Anomaly (MGA) in Iowa (Van Eck et al., 1982; Witzke et al., 2010). The structural features observed along the northern margin of the CFCB in Iowa are considered to be a continuation of those along the basin's western margin in Kansas; however, these elements are structurally juxtaposed within Nebraska by an apparent left-lateral shear zone termed the Central Plains Megashear Zone (CPMZ) and/or Central Missouri Tectonic Zone (CMTZ; McBee, 2003). The basin's southeastern and southern margins are defined by the Ozark Uplift or Dome in Missouri (Killen, 1986) and as an area of basinward deepening in Oklahoma, respectively (e.g., Lee, 1943; Joeckel et al., 2007; Heckel, 2013; Heckel, 2023).

The CFCB is bound to the west by the Nemaha Tectonic Zone (NTZ), an area of structural complexity that contains strike-slip, normal, and reverse high-angle faults extending from southeastern Nebraska to northcentral Oklahoma. The NTZ is considered the relict eastern boundary to the Precambrian aged Midcontinent Rift System (MRS) and is further defined as encompassing the Nemaha Uplift (NU; Moore and Haynes, 1917), which is flanked on its eastern edge by the Humboldt Fault Zone (HFZ; Condra, 1927; Condra and Reed 1943). The NTZ (or

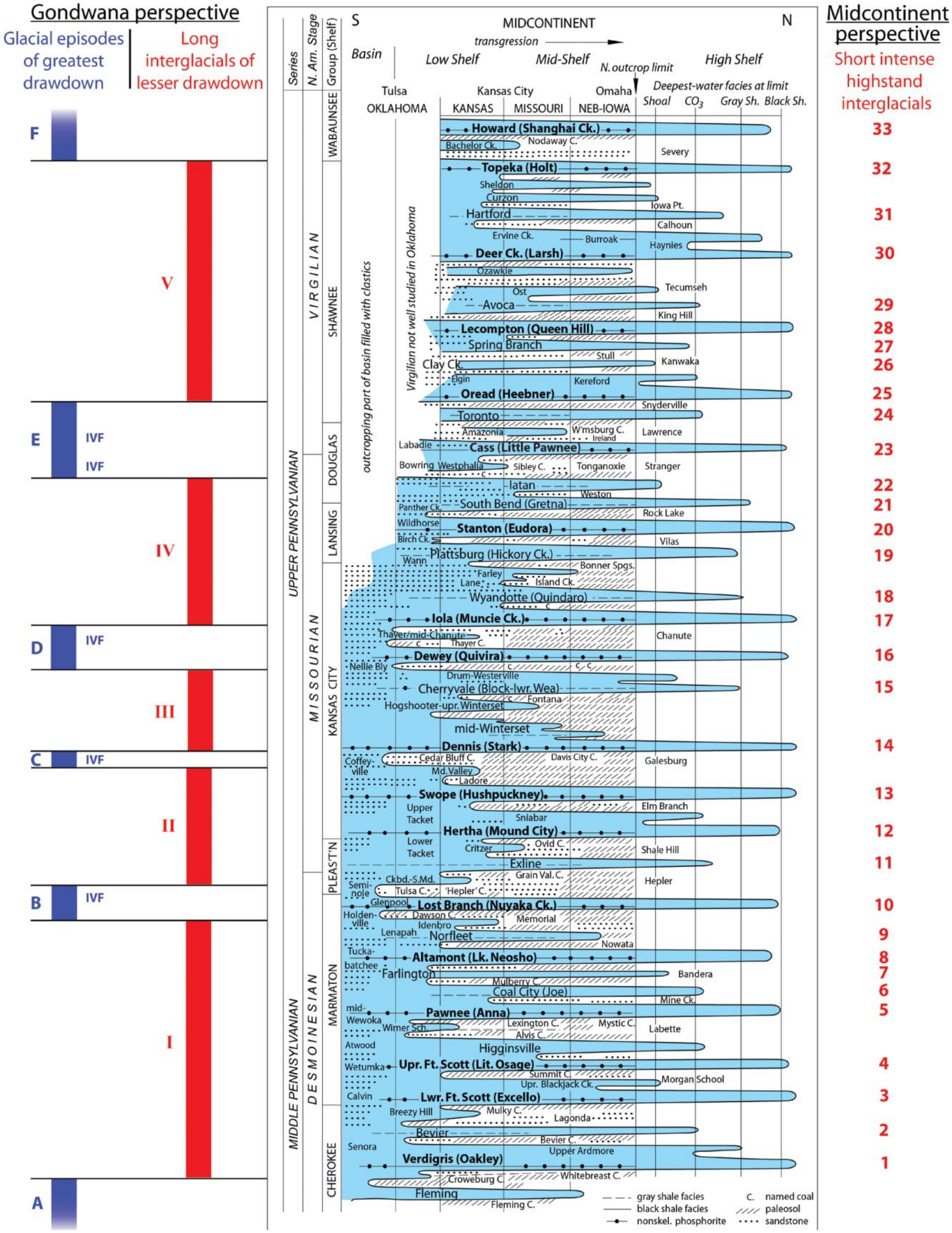

Figure 2: Sea-level curve for Upper Desmoinesian through Lower Virgilian cyclothems in the CFCB (from Heckel, 2013).

HFZ in the FCB) acts as the primary structural divide to the CFCB's western margin (Berendsen and Blair, 1986). Several northwest-southeast trending tectonic zones are documented traversing the CFCB (Figure 1). The most notable of these systems are (in order from south to north) the Fall River, Chesapeake, Bolivar-Mansfield, and Central Missouri Tectonic Zones (FRTZ, CTZ, BMTZ, and CMTZ). These faults are interpreted as having measurable left-lateral sinistral displacement (Berendsen and Blair, 1986; McBee, 2003); though, right-lateral dextral displacement has also been variably postulated (Baars and Watney, 1991; Cox, 2009; Oborny et al., 2025). Along these major fault zones, deposition of the Pennsylvanian succession was complicated by syn-depositional structural activity (Heckel, 1994; Wilson and Berendsen, 1998; Cox, 2009; Oborny et al., 2025).

Stratigraphic Framework

The Pennsylvanian age was a time of rapid global sea-level fluctuations caused by rhythmic changes in temperature and ice volume (Figure 2; Heckel, 2013). This waxing and waning in ice volume resulted in the deposition of repetitive stratigraphic packages referred to as cyclothems, consisting of sandstone, paleosols, gray and black shale or fine-grained mudstone, limestone, and coal (Figure 3, Heckel, 1994; Figure 4). Of these, black shales are commonly high in organic material which tends to accumulate

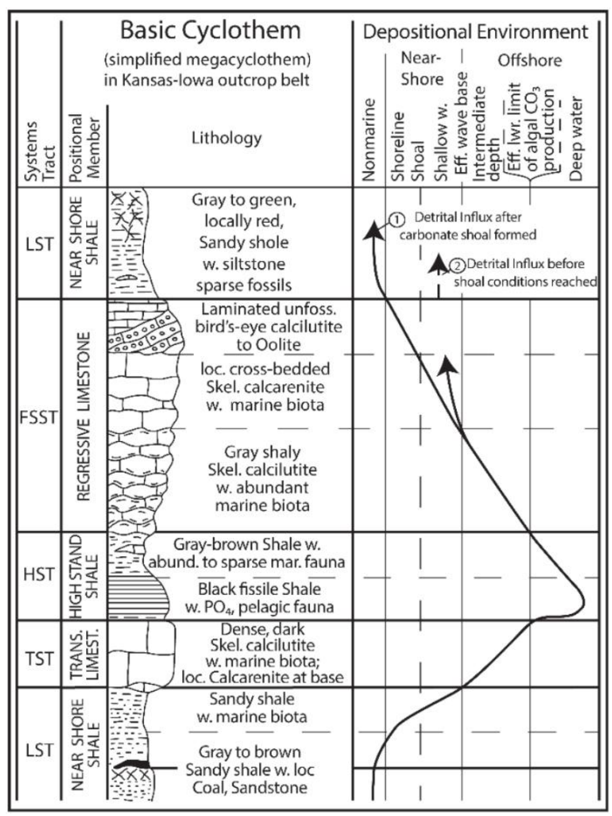

Figure 3: Generalized cyclothem from the Kansas-Iowa outcrop belt (modified from Oborny et al., 2017, after Heckel, 1994). Note discussion in text outlining various interpretations regarding assignment of systems tracts.

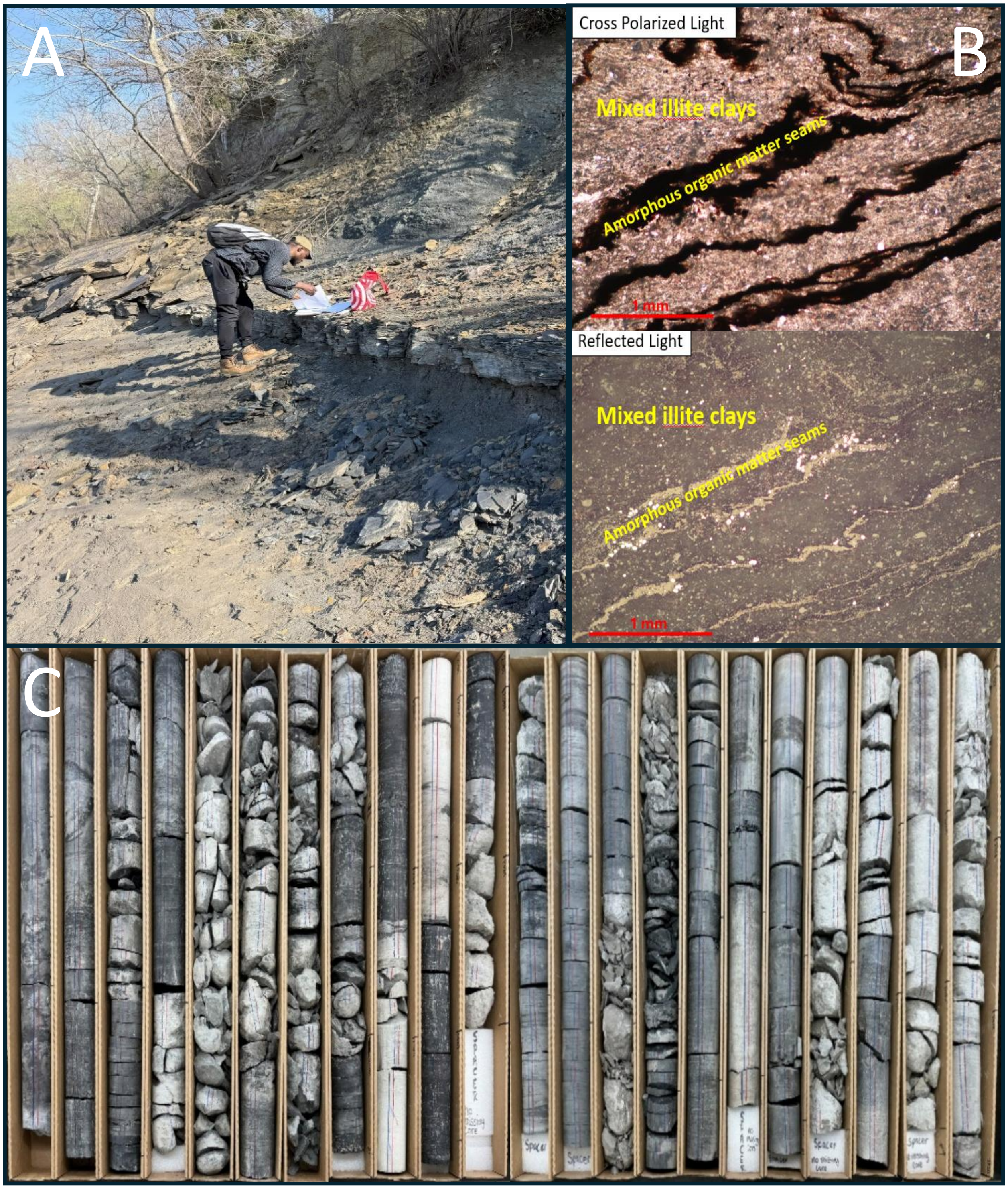

Figure 4: A) KU graduate student analyzing Pennsylvanian Age outcrop in Bourbon County, KS (Photo courtesy of KGS); B) Cross-polarized and reflected light photomicrographs of a sample taken at 2387' from Peterson Trust well #8-31 (Krebs Subgroup), depicting an illite matrix with interbedded amorphous organic matter (Oborny and Bream, 2025); and C) Peterson Trust well #8-31 core sample from 2360' to 2420' measured depth (Krebs Subgroup, Oborny and Bream 2025).

uranium, resulting in characteristically high gamma-ray signatures that can provide a reliable means for subsurface stratigraphic correlation within petrophysical logs. The presence of clay minerals rich in potassium within these fine-grained mudstones can also contribute to their high gamma-ray signatures (Doveton, 1989; Oborny and Hasiuk, 2022).

Black shale facies in the basin are typically phosphatic and deposited under anoxic or euxinic environmental conditions. These redox conditions have historically been explained through homogenous depositional models in which the black shales are associated with times of either sea-level highstand, (e.g., Algeo and Heckel, 2008; Heckel, 2013) or transgression (Wignall and Maynard, 1993). Evidence for both interpretations exist in the Midcontinent, including the transgressive Excello and Mecca Quarry shale members in the Illinois Basin (Coveney and Martin, 1983), and highstand Hushpuckney and Heebner shale members in the CFCB (Coveney et al., 1991; Algeo et al., 2004). Greater than twenty-two phosphatic black shales are documented in the Pennsylvanian succession in the CFCB (Heckel, 2013; S. C. Oborny, personal communication, Sept. 2022); most of which are the result of globally extensive sea-level highstands (Schmitz and Davydov, 2012).

Nomenclature

Frequent eustatic fluctuations during the Pennsylvanian, combined with the inherent stratigraphic complexity of cyclothems, disconformities, and poorly understood structural features in the CFCB, have produced confusing and sometimes contradictory nomenclatural frameworks that complicate basin-wide correlation (e.g., Layzell et al., 2021, Oborny et al., 2022; Oborny et al., 2025). This issue is compounded by the use of similar yet varying nomenclatural schemes between the States and tribal nations hosting CFCB strata. In particular, unit hierarchy, unit recognition, and unit boundary definitions vary significantly throughout the

CFCB. Recently proposed standardized interstate nomenclatural schemes for the Marmaton and lower Kansas City groups were adopted for the purpose of this investigation (Layzell et al., 2021). Nomenclature and unit definitions assigned to the Cherokee Group (i.e., consisting of strata between the Mississippian Subsystem and Marmaton Group) were not regionally standardized at the start of the present research (S. C. Oborny, personal communication, May 2022). We provide in Figure 5, nomenclature presently recognized for use in Kansas, and within Appendix 1, the combined interstate nomenclatural scheme established by Oborny et al. (2025).

While establishing lithological descriptions of drill cores throughout the basin, 4 fissile, phosphatic, and black fine-grained mudstones were identified within the Cherokee Group by Oborny et al. (2025). The authors observed that the lower and upper-most of these phosphatic units typically have distinct petrophysical characteristics with high gamma-ray signatures comparable to other black shales in the Pennsylvanian succession. The upper-most of these units has informally been referred to as the V-Shale in Kansas (Newell and Grisafe, 2004; Newell and Johnson, 2005, 2006; Newell et al, 2006). However, the KGS does not formally differentiate either shale unit by name within the Cherokee Group, nor is there an agreed upon nomenclature applied by other states (Table 1). Given that Cherokee Group strata are best exposed in the state of Missouri, nomenclature accepted by the Missouri Geological Survey was used to define these phosphatic shale members (Oborny et al., 2025). In ascending order, these are the Tebo and Mecca Quarry shale members, respectively. Additionally, Oborny et al. (2025) used these shale units to differentiate the Cherokee Group into three intervals tentatively recognized as subgroups. In ascending order, these are: Krebs, lower Cabaniss, and upper Cabaniss. The authors defined the lower and upper contacts of the Krebs at the subsystem boundary and at the

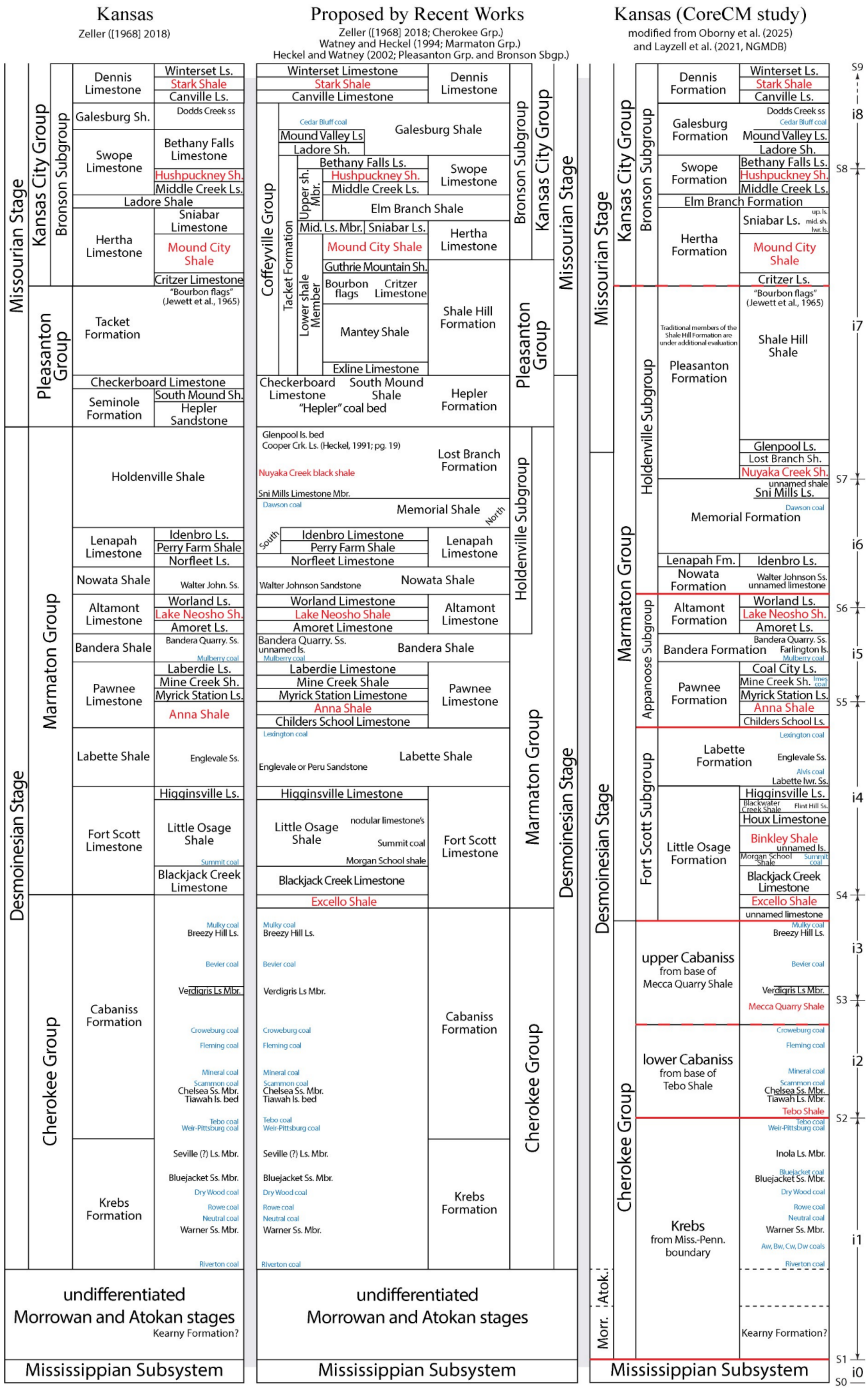

Figure 5: CFCB Nomenclature for the State of Kansas. Left): stratigraphic nomenclature presently recognized for use by the state of Kansas. Middle): nomenclature proposed by recent works. Right): combined nomenclatural schemes of Layzell et al. (2021; Marmaton Group) and Oborny et al. (2025; Cherokee Group). Isochore intervals (i0-i8) and structural surfaces (S0-S9) are identified at far right. Blue = coal, Red = black shale (figure provided by Dr. S.C. Oborny and slightly modified to include isochore and structural surface details

base of the high gamma-ray signature associated with the Tebo Shale Member, respectively (i.e., the Krebs-lower Cabaniss Subgroup boundary). The assignment of the Krebs-lower Cabaniss Subgroup boundary is in close stratigraphic proximity to the Krebs-Cabaniss Subgroup and/or Group boundary as presently recognized in Kansas, Missouri, and Oklahoma (Appendix 1). The definition for the Cabaniss stratigraphic interval remained largely unaltered from its presently recognized use in Kansas apart from redefinition of the interval's lower boundary. Given the correlative nature of the Mecca Quarry Shale (informally referred to as the V-Shale in Kansas) in subsurface data between Kansas and Missouri the Cabaniss interval was further divided into the lower and upper Cabaniss (Oborny et al., 2025).

State	Lower Member	Upper Member
Iowa	Belinda Shale	Oakley Shale
Kansas	unnamed	V-Shale (informal)
Nebraska	Belinda Shale	Oakley Shale
Missouri	Tebo Shale	Mecca Quarry Shale
Oklahoma	unnamed	Oakley Shale
Osage Nation	unnamed	unnamed

Table 1: Regional names assigned to two correlative hot-gamma spikes in the Cherokee Group.

Methodology

Stratigraphic Correlation

Stratigraphic correlations were generated with Petra software (Version 3.15.3, academic license to KGS from S&P Global) by picking key stratigraphic horizons based on wireline log character—primarily gamma-ray but also using neutron and resistivity, and other data where they were available—from 7,785 individual oil and gas wells across the CFCB (Figure 6). A detailed explanation of petrophysical log analyses is provided in Appendix 2. Individual well data is retrievable via online databases hosted by each state or tribal nation, or through agencies within those jurisdictions (Kansas Geological Survey; Missouri Department of Natural Resources; Nebraska Oil and Gas Conservation Commission; Oklahoma Corporation Commission; and Osage Mineral Data Repository). Approximately 6,400 rasterized well-logs were each depth calibrated and saved with a .lic calibration file. These depth calibrated raster logs were then integrated with ~1,400 wells containing digital .LAS files downloaded from the KGS Oil & Gas Database.

Oil and Gas Well Distribution for Wells Evaluated by this Study

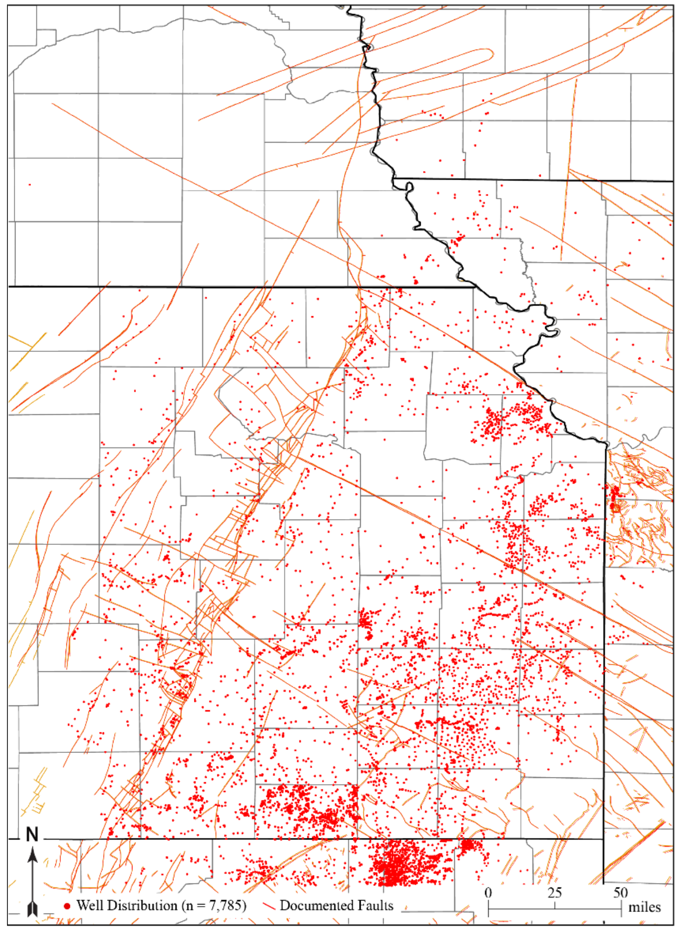

Figure 6: Project oil and gas well distribution overlain with prior regional fault interpretations. Fault layer was compiled by Alan Peterson at the KGS and published in Mohammadi et al. (2022).

When necessary, stratigraphic correlations were compared to prior published works and agency reports that include lithostratigraphic, petrophysical, and drill core data interpretations (e.g., Underwood, 1984; Knight, 1985; Sutton, 1985; Killen, 1986; Staton, 1987; Heckel, 1991; Hemish, 2002; Brown, 2003; Lange, 2003; Johnson, 2004; Newell and Bailey, 2012; Newell and Stalder, 2014; Oborny and Hasiuk, 2022; Oborny et al., 2025). The vertical reference elevation datum for all Kansas wells in the Petra project was set to 1-meter resolution LIDAR data (KGS, 2021), which accompany on-line KGS well records. This approach maximized the number of usable wells and reduced uncertainties associated with incomplete or inaccurate well records, particularly for older wells with less documentation. We note that geospatial coordinates for some older wells are based on PLSS (section, township, range) and assigned using centroid methodologies, which place wells at the center of their respective sections. While this introduces localized inaccuracies in interpolations and surface maps, the effect is considered minor given the scale of this study.

Fifteen stratigraphic horizons spanning the Carboniferous System were selected for correlation—with primary focus on the coal-bearing Pennsylvanian succession—and used in constructing cross-sections, isochore maps, and structural surfaces for further study. The two stratigraphically lowest horizons were used in defining the "Mississippian Carbonate" and are assigned to the basal contact of the Chouteau Limestone Formation, and Mississippian-Pennsylvanian subsystem boundary (see Zeller, [1968] 2018; Figure 7). These contacts are lithologically abrupt, thick shale-to-carbonate and thick carbonate-to-shale, respectively, and are readily correlatable apart from some key challenges as noted below. The top Mississippian correlation is important because: 1) the interval may elucidate underlying regional structures, and 2) the antecedent topography may inform depositional trends in the overlying Pennsylvanian succession.

Thirteen lithostratigraphic members overlying the Mississippian carbonates and consisting lithologically of fissile, phosphatic, black fine-grained mudstone were selected for use in establishing the stratigraphic container for the Pennsylvanian succession (Figure 7). These members are, in ascending order: the Tebo Shale, Mecca Quarry Shale, Excello Shale, Binkley Shale, Anna Shale, Lake Neosho Shale, Nuyaka Creek Shale, Hushpuckney Shale, Stark Shale, Eudora Shale, Heebner Shale, Queen Hill Shale, and Larsh-Burroak Shale. Each of these units may at times have lower or upper gray shale facies that do not maintain high gamma-ray signatures like what is characteristic of the black shale facies (typically >150 API).

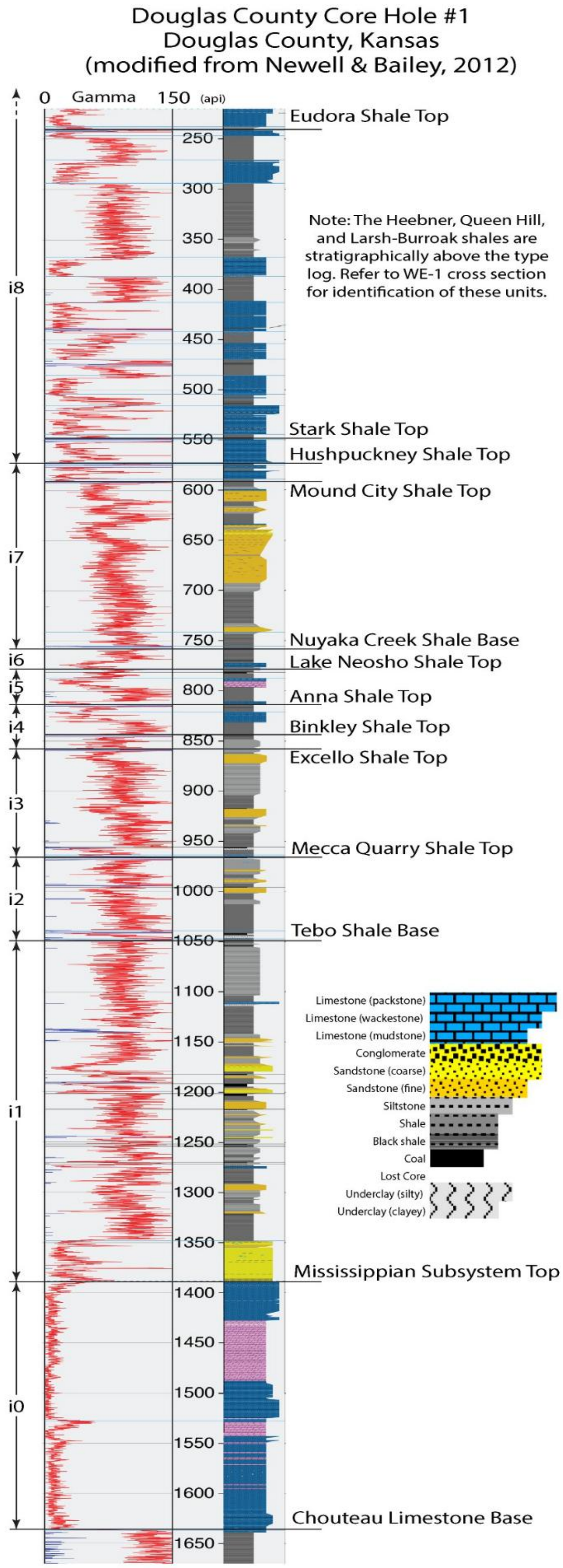

Figure 7: Gamma-ray type log and lithological description of the Douglas County Core Hole #1 in Douglas County, Kansas (modified from Newell and Bailey; 2012). Isochore intervals i0-i8 are denoted at left. Stratigraphic units delineated by this work are at right.

For consistency, we assign our correlations of these shale units at either the increasing or decreasing inflection point of the high-gamma signature; coincident with the contact of the fissile, phosphatic, black fine-grained mudstone facies.

Cross Sections, Isochore, and Structural Surfaces

Isochores and structural surface interpolations were generated in ESRI ArcGIS. Stratigraphic data were exported from Petra into ArcGIS and grids were created using kriging methodology (variable search of 12 nearest neighbors/points). Contouring was established at 10, 25, or 50 feet for isochores, depending on overall thickness, and 50 feet for structural surfaces. All interpolations were then overlain with respective well distributions. Stratigraphic cross-sections were generated within Petra and then exported into Adobe Illustrator for final graphic design. The datum in all cross sections is established at the top of the Excello Shale Member. Inset structural profiles were included in cross sections using relative distance between wells.

Results

Stratigraphic Correlation

Through combined use of interstate nomenclatural schemes established by Layzell et al. (2021) and Oborny et al. (2025), 64,768 stratigraphic marker bed delineations were newly assigned and cross-evaluated (Table 2, Supplemental File 1). Most wells drilled within the CFCB reach total depth (TD) above, or within, the uppermost Mississippian Subsystem and do not penetrate the lowest stratigraphic unit of this study, the Chouteau Limestone. Similarly, due to erosion along the Pennsylvanian outcrop belt the Eudora, Heebner, Queen Hill, and Larsh-Burroak shales are not present in all parts of the basin. For these reasons, there are fewer occurrences of these units in our database.

Although locally correlative units were observed within the Cherokee Group (e.g., Verdigris Limestone), only the Tebo and Mecca Quarry shales could be regionally correlated with confidence. This includes an evaluation of two phosphatic black shales previously reported in the middle part of the lower Cabaniss, between the Tebo and Mecca Quarry shales. While these two shales often display prominent gamma-ray signatures, they cannot be correlated with confidence due to their frequent absence in petrophysical data. For example, in Butler County, Kansas, cross section WE-5 shows strong gamma-ray responses for the two intermediate shales between 2,620 and 2,670 ft in wells 15-015-22920 and 15-015-22829. However, the gamma-ray response diminishes eastward in the same cross section.

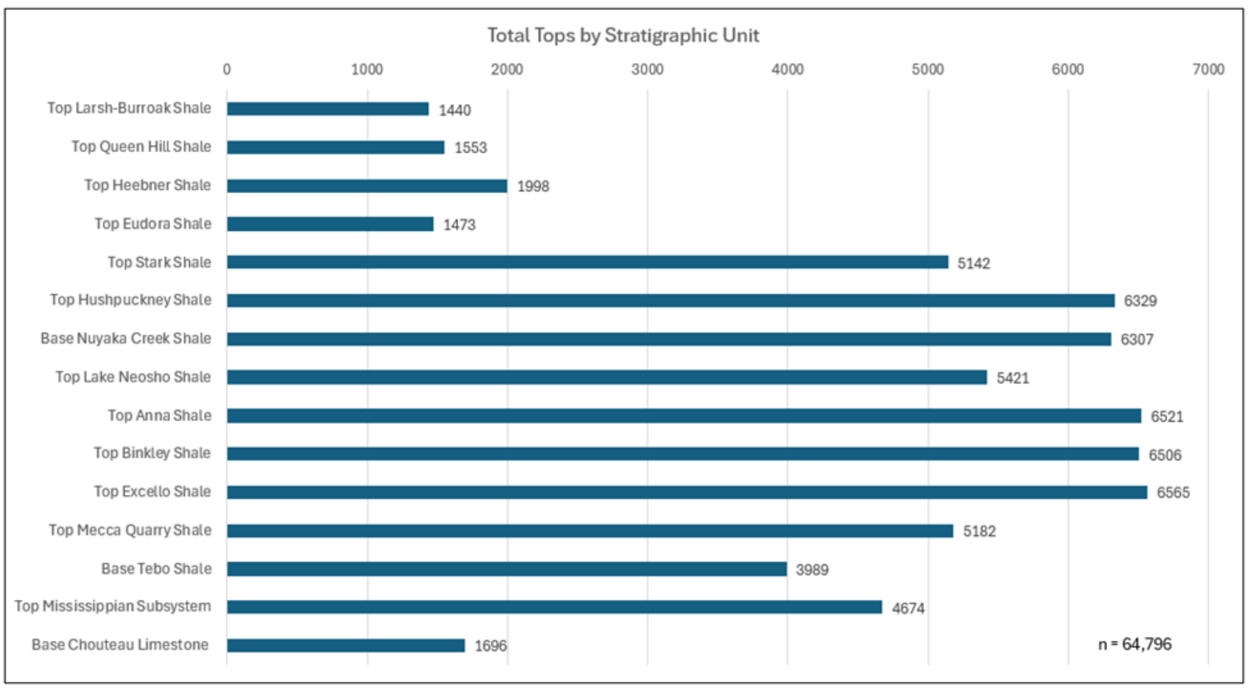

Table 2: Established marker bed tops/bases in stratigraphic order. A total of 64,796 new delineations were generated by this effort

Cross Sections

A total of 14 cross sections spanning the CFCB were generated from stratigraphic correlations made in Petra (Table 3; Figure 8; Supplemental File 2; finer details of the cross sections are not visible in this format). Six cross sections trend west-to-east, whereas the remaining 8 trend north-to-south. Structural elements of the HFZ and NTZ are identifiable in all west-east cross sections, and in north-south cross sections 1 through 3. These features coincide with apparent east-side-down structural juxtaposition or folding, thinning of lower Paleozoic or Cherokee Group strata, or both.

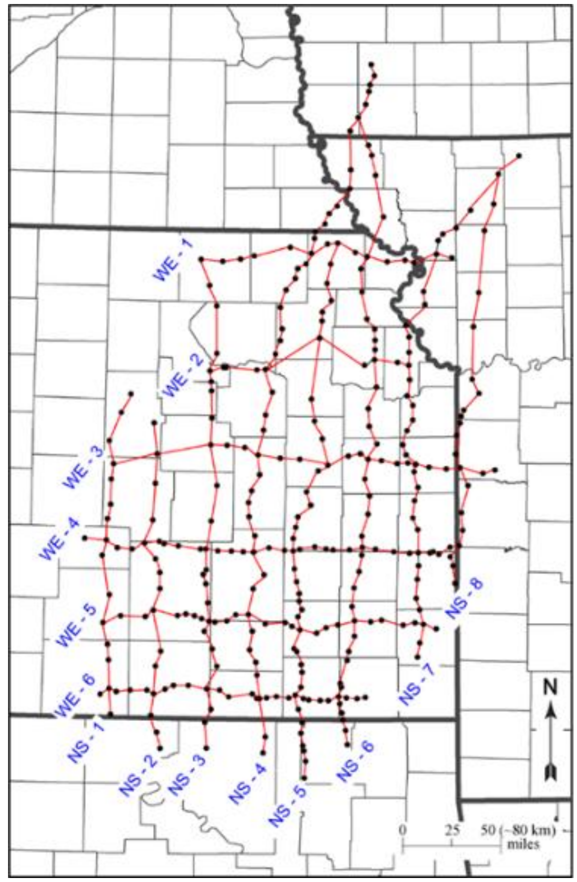

Figure 8: Cross section distribution.

Atop the NU, the Upper Pennsylvanian lies in close contact with Precambrian basement, whereas the Lower and Middle Pennsylvanian and underlying Paleozoic strata are better preserved to the south. Correlations, particularly NS-5 through NS-8, indicate the northwest-southeast trending FRTZ, CTZ, and BMTZ extend westward from Missouri into Kansas. The cross sections also highlight the presence of Pennsylvanian aged depocenters within the CFCB. The earliest and most prominent of these depocenters trends northeast-southwest east of the HFZ from Jackson County, Kansas, to at least Montgomery County, Iowa, and encompasses the Krebs interval. This depocenter reaches a maximum thickness of approximately 625 ft between Brown County, Kansas and Holt County, Missouri. Following deposition of the Krebs interval, the

Pennsylvanian succession generally thickens southeastward, with localized thinning observed in the upper Cabaniss Subgroup (NS-2 through NS-5, and WE-5 through WE-6), approximate Appanoose Subgroup (NS-2 through NS-6), and approximate Holdenville-Bronson Subgroups (NS-2 through NS-5, and WE-5 through WE-6).

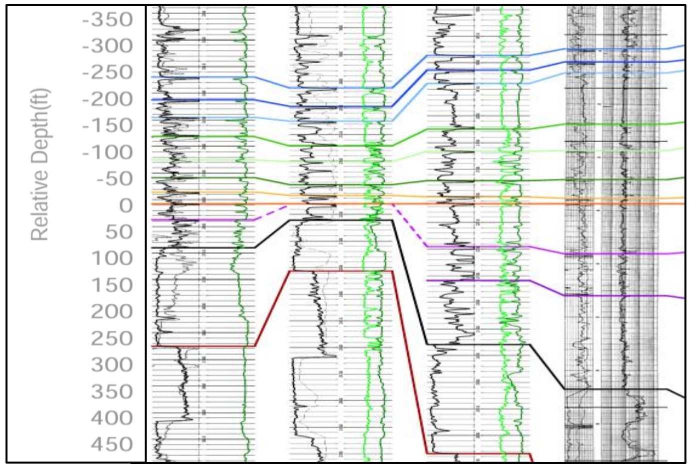

Figure 9: Representative sample from cross section WE-3 centered on the Excello Shale (orange) depicting the Base Chouteau Limestone (red) through Stark Shale Interval (top blue) as it traverses the NTZ/HFZ in Marion through Morris Counties. Full cross sections in poster format can be found in Supplementary File 2.

Cross Section	# of wells	Start County	End County
WE-1	15	Marshall, KS	Andrew, MO
WE-2	10	Riley, KS	Leavenworth, KS
WE-3	21	Marion, KS	Cass, MO
WE-4	32	Harvey, KS	Bates, MO
WE-5	27	Sedgwick, KS	Crawford, KS
WE-6	27	Sumner, KS	Labette, KS
NS-1	15	Sumner, KS	Dickinson, KS
NS-2	16	Kay, OK	Dickinson, KS
NS-3	24	Osage, OK	Marshall, KS
NS-4	44	Osage, OK	Montgomery, IA
NS-5	38	Nowata, OK	Brown, KS
NS-6	40	Nowata, OK	Fremont, IA
NS-7	34	Crawford, KS	Harrison, MO
NS-8	20	Bourbon, KS	Gentry, MO

Table 3: Statistical information for cross sections.

WE-1

The western end of cross section WE-1 begins in Marshall County, Kansas, where several Paleozoic units, including the Mississippian Carbonate and the Pennsylvanian Cherokee and Marmaton groups, are absent. Gamma-ray wireline log data in this portion of the basin are limited, requiring the use of driller's log data. Structurally, the section exhibits a general westward increase in depth to Pennsylvanian units, culminating in a broad structural high to the west of the HFZ. Crossing the HFZ between Nemaha and Brown Counties (wells 15-131-20223 and 15-013-00002), east-side-down structural juxtaposition is observed. This coincides with significant stratigraphic thickening of approximately 800 feet between the base of the Pennsylvanian Subsystem and Eudora Shale Member, including roughly 600 feet in the Krebs interval. Strata decrease in depth eastward with minor variation in unit thickness. An apparent west-side-down fault is observed in eastern Doniphan County, Kansas (wells 15-043-20011 and 15-043-20003), although the thickness of the Pennsylvanian succession remains consistent across it. From this location eastward to Andrew County, Missouri, stratigraphic thickness remains relatively uniform.

WE-2

Cross section WE-2 begins in Riley County, Kansas, where the Bronson Subgroup is observed in close depositional proximity to the Precambrian basement. All pre-Pennsylvanian Paleozoic strata are missing in well 15-161-20078, indicating significant erosion or non-deposition. The cross section traverses the HFZ in northern Wabaunsee County, where Lower and Middle Pennsylvanian strata are present. In central Jefferson County (wells 15-087-20285 and 15-087-20294), an apparent west-side-down fault (~50 feet) is observed in association with subtle eastward thinning in the Cherokee and Marmaton groups. Eastward through Leavenworth County, thicknesses of the Cherokee and Marmaton groups remain consistent.

WE-3

Cross section WE-3 begins west of the HFZ in Marion and Dickinson counties. The entire Pennsylvanian succession is observed thinning atop the NU in well 15-041-20139, most notable in the Cherokee Group. The entire Pennsylvanian increases in thickness east of the HFZ into Morris, Lyons, and Osage Counties. The Marmaton group notably thins eastward into central Franklin County and abruptly thickens into Miami County. Structurally, the section exhibits a general eastward decrease in depth to Pennsylvanian units apart from a subtle plateau at the Osage-Franklin County line (wells 15-139-00002 and 15-059-24499). Toward the east end of the cross section, in Cass County, Missouri, the Marmaton appears to thin slightly.

WE-4

The west end of WE-4 begins in Harvey County, approximately 50 miles west of the NTZ. The Mississippian Carbonate thickness varies significantly (between ~180 and 30 feet; wells 15-015-24081 through 15-015-22930) in Butler County, coinciding with a notable thinning of Cherokee and Marmaton Group strata. East of the NTZ the entire Pennsylvanian succession gradually increases in thickness into Missouri. A notable increase in Cherokee Group thickness (~200 feet) is observed in well 15-015-22115 on the down-thrown side of the NTZ. Across the next several counties into Coffey County, the Cherokee group thickens slightly then remains at a consistent thickness, while the rest of the Pennsylvanian Succession above the Excello thickens by less than 50 feet.

WE-5

Cross section WE-5 traverses the NTZ in Butler County, Kansas. In the westernmost wells, Cherokee Group strata overlie the Viola or underlying Simpson formations, supported by well records accompanying well 15-015-23826 and others. The Cherokee Group is thin (<50 ft) in wells 15-173-01014 and 15-173-20497 west of the NTZ, with only the upper Cabaniss being present, whereas east of the NTZ the entire Carboniferous succession consistently thickens eastward into Missouri, apart from significant thinning in the Pleasanton Shale at the Greenwood-Elk County line.

WE-6

WE-6 begins in Sumner County where it traverses the NTZ. Compared to cross sections WE-1 through WE-5, apparent and notable faulting is not observed in this cross section in association with the NTZ; though the Cherokee Group does thin over the inflection of what may be an anticline in Sumner County. East of Sumner County, the entire Pennsylvanian succession thickens eastward towards Missouri. Strata shallow in depth eastward in the structural profile, save for a plateau in Chautauqua County (wells 15-019-25165 and 15-019-00036).

NS-1

Traversing from south to north, NS-1 crosses historically mapped faults of the NTZ in Sumner County, Kansas, with little change in the Pennsylvanian successions' thickness apart from relatively minor thinning of the Cherokee Group and thickening of undifferentiated Kansas City and Shawnee groups (see wells 15-191-62745 and 15-191-22781). The entire Carboniferous succession thickens southward. A fault may be evident in southern Sedgwick County between wells 15-191-21600 and 15-173-01014 where the Pennsylvanian interval notably thickens over a relatively short distance of 9.4 miles (15.1 km).

NS-2

NS-2 extends from Kay County, Oklahoma, into Kansas. Northward between Kay County and Butler County, Kansas, the Pennsylvanian succession thins by approximately 600 ft. Over this distance, the Cherokee Group and Fort Scott Subgroup thin by approximately 140 and 50 ft, respectively. NTZ related faulting may be present between wells in Cowley and Butler counties. Though a distance of 17.69 miles exists between these wells (15-035-24535 and 15-015-23826) and may be attributed to regional dip, we observe that the Pennsylvanian succession thickens significantly southward. The Mississippian Carbonate is not observed to the north of the Cowley County well, whereas thick Mississippian Carbonate is observed to the south in conjunction with the rapid southward thickening of the Pennsylvanian succession. Within the structural profile of the cross section, the Heebner Shale and overlying strata remain at roughly the same depth below surface, whereas the underlying Pennsylvanian succession dips southward.

NS-3

NS-3 extends from Osage County, Oklahoma, northward into Kansas. Apart from some variation in unit thickness within the Appanoose and Holdenville Subgroups of the Marmaton Group, as well as the Bronson Subgroup of the Kansas City Group (between Chautauqua and Butler counties; between wells 15-019-23319 and 15-015-23005), strata remain relatively consistent in thickness though gradually thin northward. In southern Morris County, Kansas, the NTZ/HFZ is apparent in the structural profile, coinciding with a northward decrease in thickness of the Marmaton Group, near absence of the Cherokee Group, and complete absence of the Mississippian Carbonate (between wells 15-127-00116 and 15-127-20598). The Pennsylvanian succession generally dips southward.

NS-4

NS-4 extends from Osage County, Oklahoma, northward into Iowa. In general, the Pennsylvanian succession thickens southward, apart from the Krebs interval which increases by greater than 400 ft in the FCB portion of the basin. As with NS-3, stratigraphic complexity is observed in the Appanoose and Holdenville Subgroups of the Marmaton Group and Bronson Subgroup of the Kansas City Group along the Oklahoma-Kansas state line northward into Greenwood County, Kansas (between wells 35-113-09819 and 15-073-21754). The Mississippian Carbonate varies in thickness, abruptly thinning between northern Wabaunsee and central Nemaha Counties in Kansas, coinciding with complexity in the structural profile and apparent faulting (between wells 15-197-20200 and 15-131-20184). Faulting with approximately 250 ft of juxtaposition is also observed with the structural profile between the two wells in Montgomery County, Iowa, over relatively short distance of 4.9 miles (7.9 km).

NS-5

NS-5 extends from Nowata County, Oklahoma, northward to the Kansas-Nebraska state line. As with NS-4, the Pennsylvanian succession generally thickens southward, apart from the Krebs interval which increases by greater than 500 ft in the FCB portion of the basin. The Krebs also thickens by ~150 ft along the Oklahoma-Kansas state line within the CB. Stratigraphic complexity is observed in the Appanoose Subgroup of the Marmaton Group in Oklahoma and Montgomery County, Kansas (between wells 35-105-26973 and 15-125-31710). Similarly, internal stratigraphic variability is observed in the Bronson Subgroup of the Kansas City Group south of Woodson County, Kansas (notably between wells 15-205-28211 and 15-207-27982). The Mississippian Carbonate varies in thickness (~250-450 ft.) with notable thinning between central Osage and southern Jackson Counties in Kansas (between wells 15-139-00010 and 15-985-20044). The structural profile displays an apparent south-side down fault in Coffey County over a relatively short distance of 4.5 miles (7.2 km) between wells 15-031-20471 and 15-031-20367. Faulting may also be present between Shawnee and Jackson counties where the Krebs interval thickens by ~100 ft. However, this thickening occurs over a distance of 16.6 miles (26.7 km).

NS-6

NS-6 extends from Nowata County, Oklahoma, to Fremont County in southwest Iowa. As with NS-5 the Krebs interval thickens significantly by ~150 and 500 ft in both the CB and FCB, respectively. All Pennsylvanian strata overlying the Krebs generally thicken from north-to-south. Stratigraphic complexity of up to 150 ft is observed in both the Holdenville and Bronson Subgroups within Neosho County in southern Kansas (between wells 15-133-26132 and 15-133-26624). The structural profile shows a general northward dip. A northside-down stepwise increase in depth for the top Mississippian Carbonate, coinciding with an increase in Krebs thickness, may suggest faulting between Jefferson and Brown counties, Kansas (between wells 15-087-20294 and 15-013-19014). An approximate 250 ft of north-side-up juxtaposition may be present between Atchinson

County in Missouri. This occurs over a relative distance of 8.6 miles (13.8 km; between wells 24-005-20016 and 24-005-00030) and coincides with a notable change in Krebs thickness of ~130 ft.

NS-7

NS-7 extends from Crawford County, Kansas, to Harrison County, northwestern Missouri. As with NS-5 and -6 the Krebs interval thickens by ~60 and 250 ft in both the CB and FCB, respectively. Though comparatively subtle to other north-south cross sections, all Pennsylvanian strata overlying the Krebs generally thicken from north-to-south. This cross section reveals notable thickening of Marmaton Group strata in Miami County. The structural profile highlights apparent structural complexity in northern Crawford and Bourbon counties, Kansas, between wells 15-037-22039 and 15-011-23679, with 100 and 150 feet of alternating up/down differences in depth over a relative distance of 25.3 miles (40.7 km). Similarly, an apparent south-side up fault of ~50 ft is observed in southern Linn County (between wells 15-107-23220 and 15-107-23579), and between Johnson and Leavenworth counties (~100 ft between wells 15-091-22218 and 15-091-20939). At the Kansas-Missouri state line, between Atchinson and Buchanan counties, an apparent north-side up fault with ~100 feet of throw may be present, though these wells are 11.9 miles (19.2 km) apart and may be explained by regional dip. Additional Missouri faulting may be present in northern Andrew (~50 ft between wells 24-021-20002 and 24-003-20001) and Gentry counties coinciding with notable changes in Krebs thickness (~200 ft over 19.3 miles between wells 24-075-20005 and 24-075-20002); however, the distance between wells are 16.7 miles (26.9 km) and 19.3 miles (31.1 km), respectively, and observations may be explained by regional dip.

NS-8

NS-8 extends from Bourbon County, Kansas, to Gentry County Missouri. As with other N-S cross sections, the Krebs interval is notably thick in the FCB. This is most evident between Dekalb and Clinton counties in Missouri, where the interval increases by greater than 210 ft over 26.4 miles (42.5 km; between wells 24-049-20017 and 24-063-200001). As with cross section NS-7, strata overlying the Krebs modestly thickens southward. Potential south-side up faulting of ~50 ft is observed in the northeast corner of Bourbon County, Kansas, between Bates and Cass counties, Missouri (between wells 24-013-20369 and 24-037-20839), and potentially within Miami County, Kansas, all coinciding with notable changes in thickness within the Marmaton Group.

Interval	Lithologic Units	Base Unit	Top Unit
i8	lower Kansas City to lower Shawnee Groups	Top Hushpuckney Shale	Top Heebner Shale
i7	upper Holdenville to lower Bronson Sbgp.	Base Nuyaka Creek Shale	Top Hushpuckney Shale
i6	lower Holdenville Subgroup	Top Lake Neosho Shale	Base Nuyaka Creek Shale
i5	Appanoose Subgroup	Top Anna Shale	Top Lake Neosho Shale
i5/6	Appanoose and lower Holdenville Subgroups	Top Anna Shale	Base Nuyaka Creek Shale
i4	Fort Scott Subgroup	Top Excello Shale	Top Anna Shale
i3	upper Cabaniss Subgroup	Top Mecca Quarry Shale	Top Excello Shale
i2	lower Cabaniss Subgroup	Base Tebo Shale	Top Mecca Quarry Shale
i1	Krebs Subgroup	Top Mississippian	Base Tebo Shale
i0	Mississippian Carbonate	Base Chouteau Limestone	Top Mississippian

Table 4: Isochores generated by this study in stratigraphic order.

Isochore Maps

A total of 10 isochore maps were generated for the basin (Figures 10.0-10.8, Appendix 3). Stratigraphic details and statistical data for each isochore map are summarized in Tables 4 and 5, respectively. Isochore i5/6 was generated prior to stratigraphic delineation of the Lake Neosho Shale and differentiation of the Appanoose (i5) and lower Holdenville (i6) Subgroups;

however, i5/6 is retained here as it highlights a depositional trend in the southernmost portion of the basin that is not apparent in i5 and i6.

Stratigraphic Interval	Total Wells	Contour Index	~ Min Thickness	~ Max Thickness	Total Thickness
i8	1998	25	200	1225	1025
i7	6307	10	20	220	200
i6	5421	10	0	230	230
i5	5421	25	0	170	170
i5/6	6307	25	50	275	225
i4	6521	10	0	220	220
i3	5185	10	0	120	120
i2	3990	10	0	220	220
i1	3990	25	50	625	575
i0	1696	50	0	425	425

Table 5: Statistical data for isochores in stratigraphic order.

i0: Mississippian Carbonates (Base Chouteau Limestone to top Mississippian Subsystem)

The Mississippian Carbonate (Figure 10.0) encompasses most of the Mississippian succession within the CFCB. The interval is absent west of the HFZ, and in isolated areas to the southwest along the length of the NTZ. The west side of the fault zone gradually thickens to the south while the east side is thicker and roughly uniform – this trend dissipates as the HFZ meets the Kansas-Oklahoma border, where the interval is similar in thickness on both sides. There is also notable thinning between the known CTZ and BMTZ curving clockwise into the FCB, where the unit thins from 350 to less than

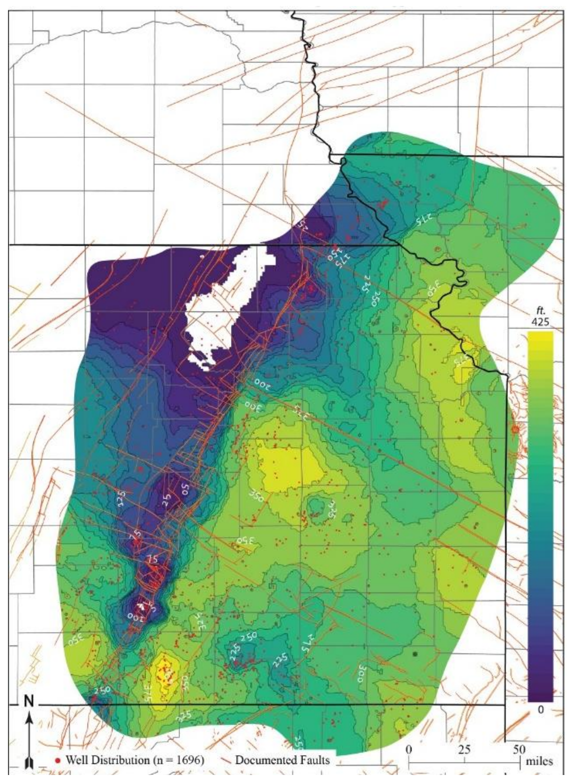

Figure 10.0: Mississippian Carbonates Isochore

100 feet from Linn to Jackson County, whereas the Mississippian is thicker to the northeast and southwest of this area. Conversely, the area between the BMTZ and FRTZ is thicker (up to 375 feet in Lyon and Osage Counties) than those to the north and south.

i1: Krebs Subgroup (Top Mississippian Subsystem to Base Tebo Shale)

This Lower Pennsylvanian interval (Figure 10.1) lacks data to the west of the HFZ, and the thickest deposits occur between Brown County, Kansas and Nodaway County, Missouri, where 575-625 feet of section is observed. From this point southward, deposition gradually thins through most of east central Kansas and then begins to thicken again near the Kansas-Oklahoma border. The area immediately east of the NTZ does not display this same pattern and remains relatively thin (<175 feet) from southern Lyon County to Cowley County, Kansas.

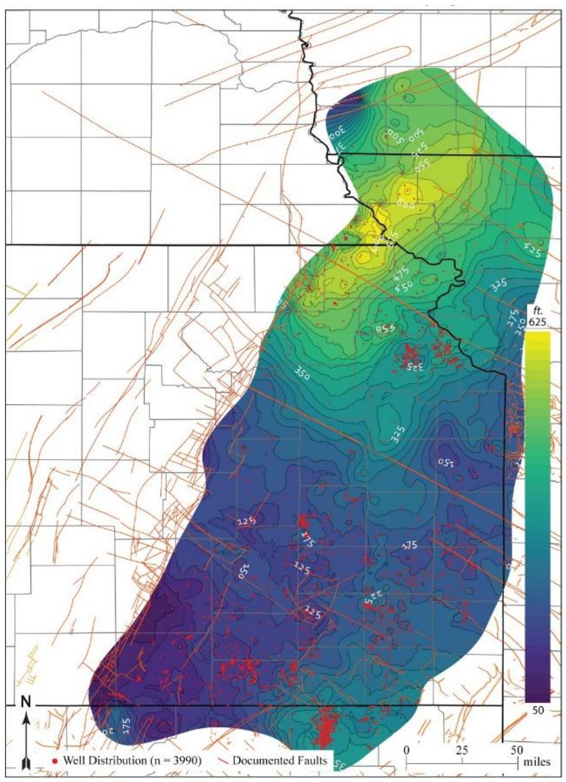

Figure 10.1: Krebs Subgroup Isochore

i2: Lower Cabaniss Subgroup: (Base Tebo Shale to Top Mecca Quarry Shale)

In the Cabaniss Subgroup (Figure 10.2), the primary site of accommodation or deposition described in the Krebs appears to have shifted southwest along the HFZ slightly, where thickness along the east flank is greater than 130 feet between Wabaunsee and Brown Counties, Kansas, and reaches 180 feet in Nemaha County. Similar to the Krebs, this unit thins to the south and thickens again toward the KS-OK border, and the thickest deposits (~200-220 feet) in this dataset occur in Nowata County, Oklahoma and may extend further southeast. The remainder of the interval in the CFCB, particularly on the eastern flank of the NTZ and in east central Kansas, averages between 70 and 90 feet in thickness.

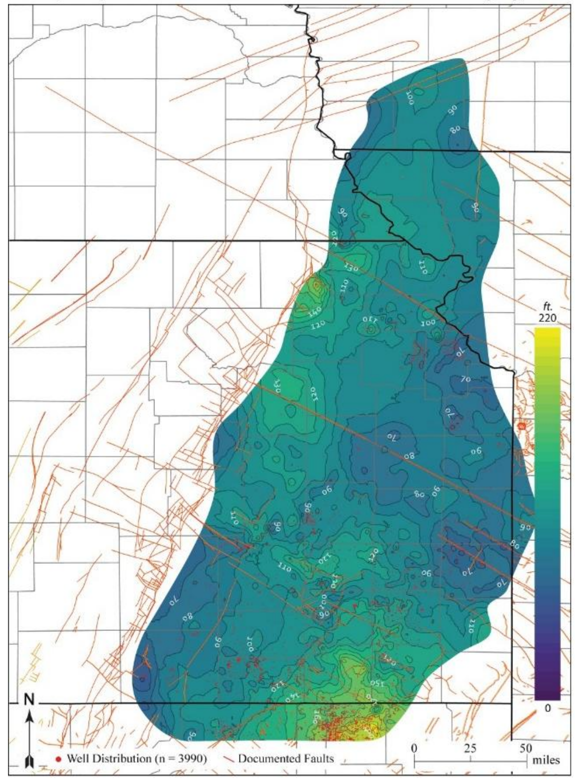

Figure 10.2: Lower Cabaniss Subgroup Isochore

i3: Upper Cabaniss Subgroup (Top Mecca Quarry Shale to Top Excello Shale)

This interval (Figure 10.3) contains upper Cherokee Group deposits that are discontinuous atop the NU, but shows a more extensive, thin (<30 feet) package west of the southern portion of the HFZ and the NTZ. Unlike the intervals

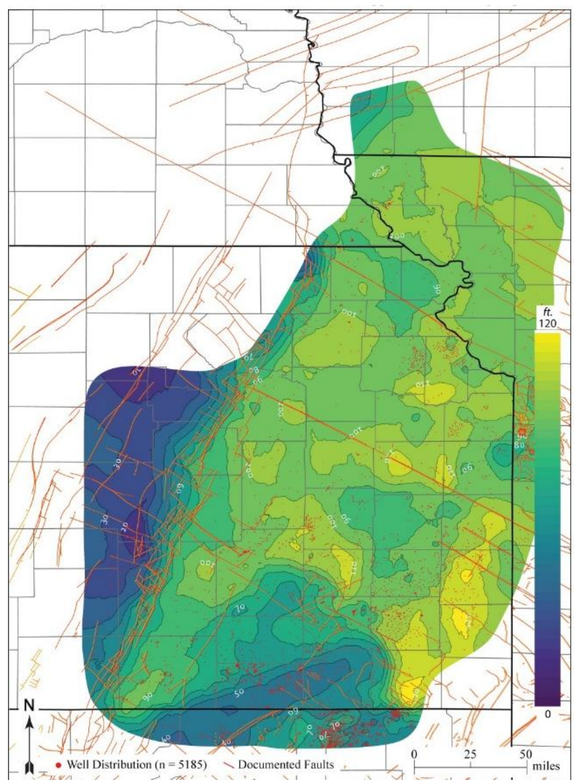

Figure 10.3: Upper Cabaniss Subgroup Isochore

described above, this isochore exhibits no major changes in thickness along the eastern trace of the HFZ and NTZ. Along the Kansas-Oklahoma border appears a WSW-ENE trending feature that terminates at the FRTZ and influenced deposition and was not present in previous isopaches. The remainder of the CFCB excluding this feature and the area east of the HFZ/NTZ has relatively uniform thickness, ranging between 90 and 120 feet, the thickest of which are found from Bourbon to Labette Counties, Kansas.

i4: Fort Scott Subgroup (Top Excello Shale to Top Anna Shale)

The Fort Scott interval (Figure 10.4) notably lacks preserved sediments atop the NU, primarily in Marshall County, Kansas. Unlike the underlying Pennsylvanian units described, this unit displays uniform thickness of 30-60 feet across the HFZ and NTZ, except for a relative thinning where the FRTZ intersects with the NTZ. The majority of the basin has a similar range of thicknesses for the Fort Scott Subgroup, but the unit sharply thickens southeastward from 70-220 feet, reaching its maximum in Nowata County, Oklahoma.

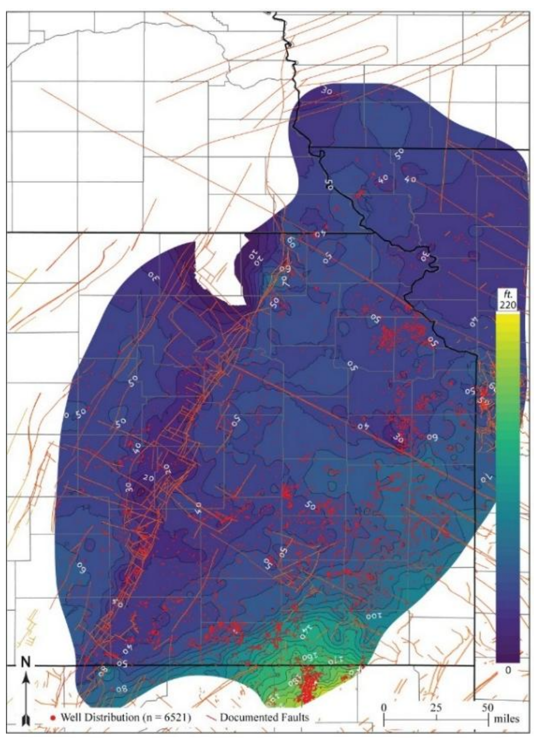

Figure 10.4: Fort Scott Subgroup Isochore

i5: Appanoose Subgroup (Top Anna Shale to Top Lake Neosho Shale)

The Appanoose Subgroup (Figure 10.5) displays thicknesses of 40-80 feet in the FCB portion of the basin, and a lack of data from non-deposition or erosion on the NU. The interval thins slightly southward from Iowa/Missouri to northeastern Kansas, and from there it gradually thickens with little complexity towards the KS-OK border east of the HFZ/NTZ, where it reaches its maximum 180 feet within the study area. Directly south, the unit thins significantly over a short distance from 180 to 40-60 feet, indicating the presence of a W-E trending feature influencing during deposition.

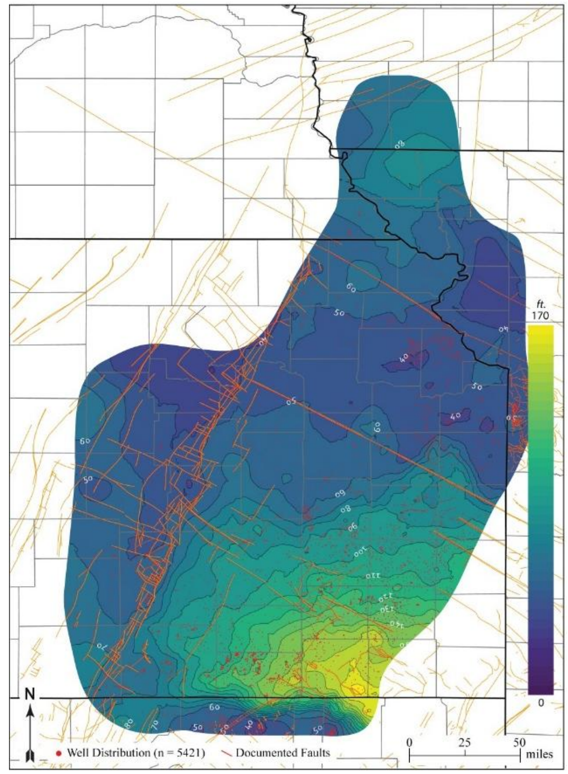

Figure 10.5: Appanoose Subgroup Isochore

i6: Lower Holdenville Subgroup (Top Lake Neosho Shale to Top Hushpuckney Shale)

In the majority of the CFCB, the Lower Holdenville Subgroup (Figure 10.6) is thin and relatively uniform in thickness, ranging between 20-40 feet, and increasing thickness from 40-100 feet is observed along the trace of the NTZ. The unit rapidly thickens across the KS-OK border (60-

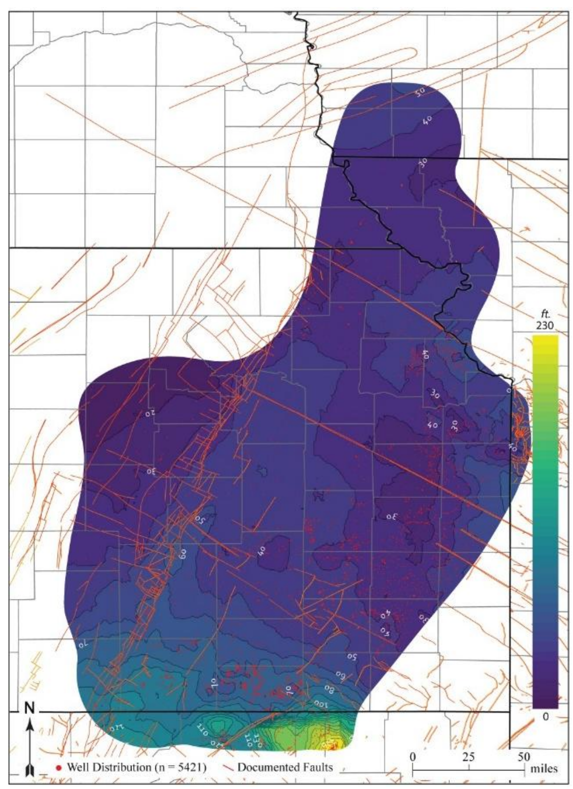

Figure 10.6: Lower Holdenville Subgroup Isochore

230 feet) and in Oklahoma, it thickens from 110-230 feet between northeastern Osage and northwestern Nowata Counties. Nowata County, Oklahoma is where the unit reaches its maximum thickness (230 feet) in this dataset.

i5/6: Undifferentiated Appanoose and Lower Holdenville subgroups (Top Anna Shale to Base Nuyaka Creek Shale

In the FCB portion of the basin, the undifferentiated Appanoose and lower Holdenville interval (Figure 10.56) thins slightly from north to south (100-75 feet) and lacks data atop the NU. Isochore i5/6 shows pattern of steady southward thickening from 75-275 feet across the CB area that is not apparent in either of the Appanoose or lower Holdenville isochores. While the unit also thickens gradually southward on the west side of the NTZ, it is thinner at any given point here than directly east of the fault zone.

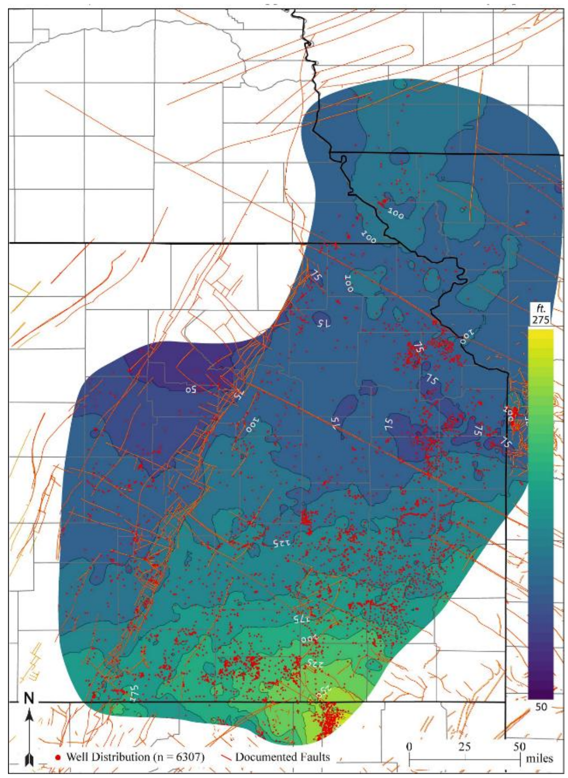

Figure 10.56: Undifferentiated Appanoose and Lower Holdenville Subgroup Isochore

i7: Upper Holdenville/Lower Bronson Subgroups (Top Nuyaka Creek Shale to Top Hushpuckney Shale)

In the Upper Holdenville and Lower Bronson Subgroups (Figure 10.7), there is no data preserved in the NU area, and east of the HFZ, the unit thickens southward with some complexity from Douglas to Linn Counties, Kansas. The interval is thickest in Allen County, Kansas (220 feet), and thins abruptly to the south across Cowley to Neosho Counties, Kansas (from 170-220 to 20-60 feet); the thinned area along the KS-OK border displays a E-W trend.

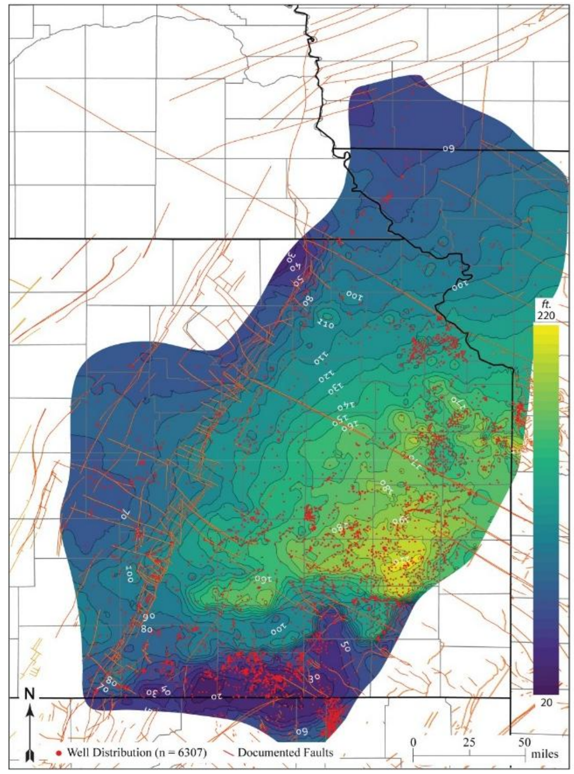

Figure 10.7: Upper Holdenville/Lower Bronson Subgroup Isochore

i8: Kansas City, Lansing, and Douglas Groups (Top Hushpuckney Shale to Top Heebner Shale)

The final isopach described in this study (Figure 10.8) covers roughly half of the Upper Pennsylvanian, ranging from ~200 feet to 1225 feet of section. This interval displays relatively smooth, southward thickening with little complexity. Unlike the previously described isochores, this interval is preserved atop the NU, and it thins gradually to the south on the west side of the HFZ and NTZ. In the southernmost NTZ area captured in this isochore, the collective Kansas City, Lansing, and Douglas interval is roughly uniform in thickness on the east and west sides of the fault zone.

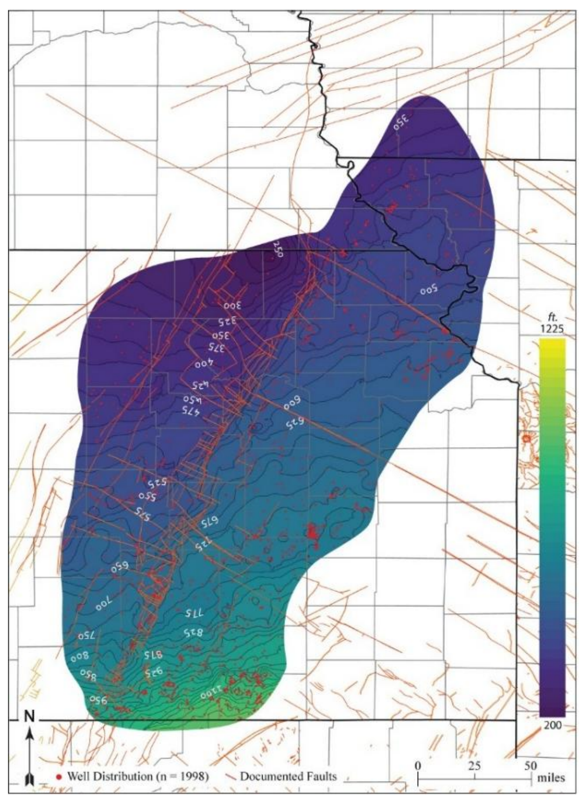

Figure 10.8: KC, Lansing, and Douglas Group Isochore

Depth Structure Surfaces

A total of 10 depth structure surfaces (Pennsylvanian surfaces on the right side of Figures 11.1-11.3; Appendix 4) were generated for the CFCB. Statistical data for each is provided in Table 6. In general, all structural surfaces display a regional west-to-northwest dip that is perpendicular to the NTZ. Each clearly shows the NU west of the HFZ, with a west-side up orientation that decreases in magnitude southward in Kansas along the length of the HFZ. Horst and graben structures are evident along the NTZ. These structures tend to decrease southward, with little to no clear presence south of Butler County, Kansas, where structural contouring for all surfaces trend NW-SE.

Surface	Total Wells	~ Min SSTVD	~ Max SSTVD
S9	1998	-1150	1200
S8	6329	-2200	1000
S7	6307	-2200	900
S6	5421	-2250	1000
S5	6521	-2350	850
S4	6565	-2550	900
S3	5185	-2300	850
S2	3990	-2200	650
S1	4674	-2800	450
S0	1696	-2750	400

Table 6: Statistical data for structure maps in stratigraphic order.

There is relatively little variation in structural geometry between the Pennsylvanian intervals evaluated in this study, apart from some notable observations in, and prior to, the Cherokee Group. In structural profile of the top Mississippian Subsystem, base Tebo Shale, and top Mecca Quarry Shale (Figure 11.1) a NE-SW trending lineament with an apparent 200-300 ft of west-side-down orientation is present in the FCB in Kansas; extending between southwestern Osage and northern Jefferson counties. The feature is not visible in the top Excello

Shale or overlying structural profiles. Similarly, within these three structural profiles, a north-trending lineament is observed in the CB, extending from Nowata County, Oklahoma, to northwest Wilson County, Kansas, with greater than 200 ft of west-side-down orientation.

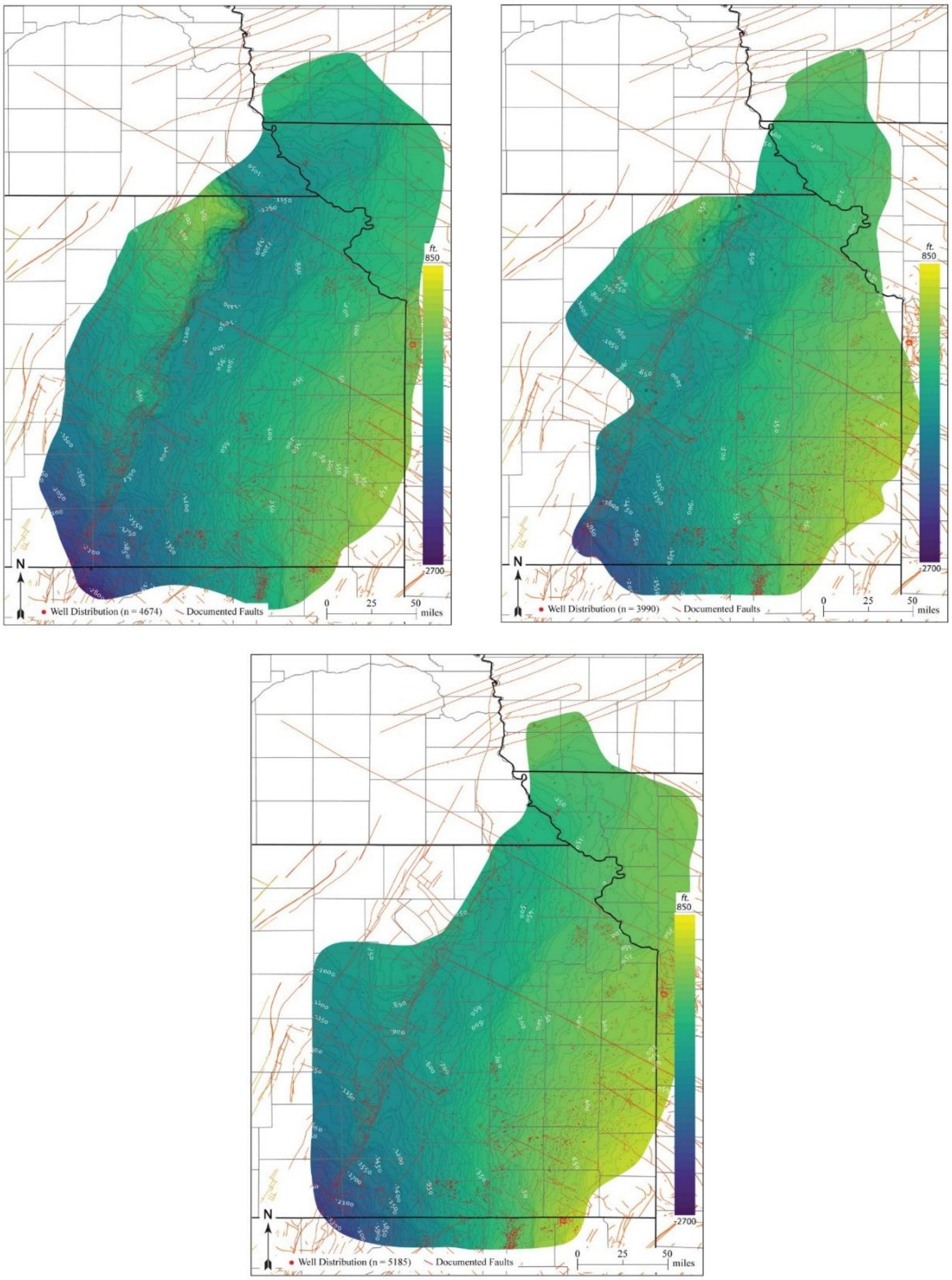

Figure 11.1: Structural surface maps for the Top Mississippian Subsystem (Left), Base Tebo Shale (Right), and Top Mecca Quarry Shale (Bottom)

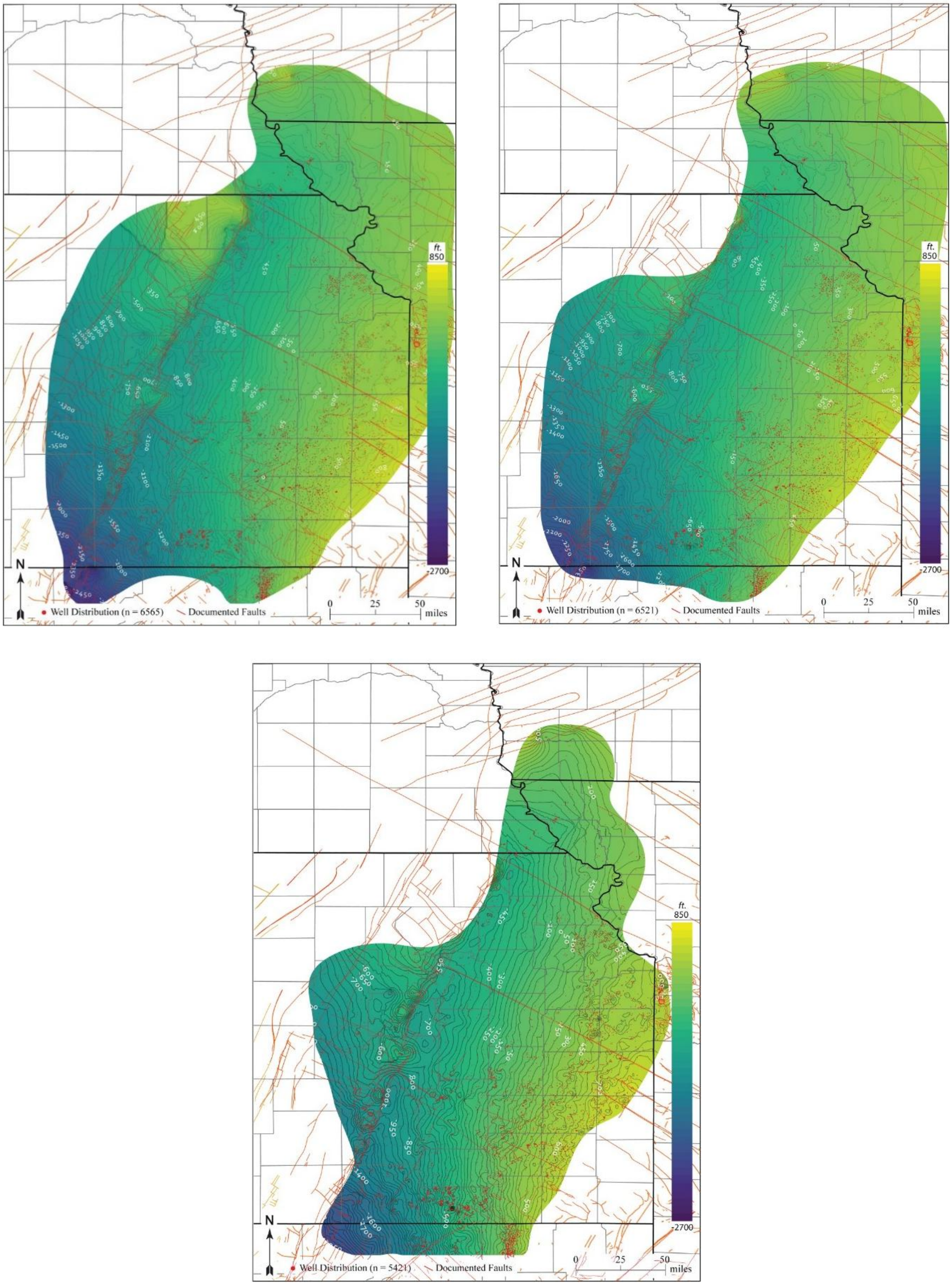

Figure 11.2: Structural surface maps for the Top Excello Shale (Left), Top Anna Shale (Right), and Top Lake Neosho Shale (Bottom)

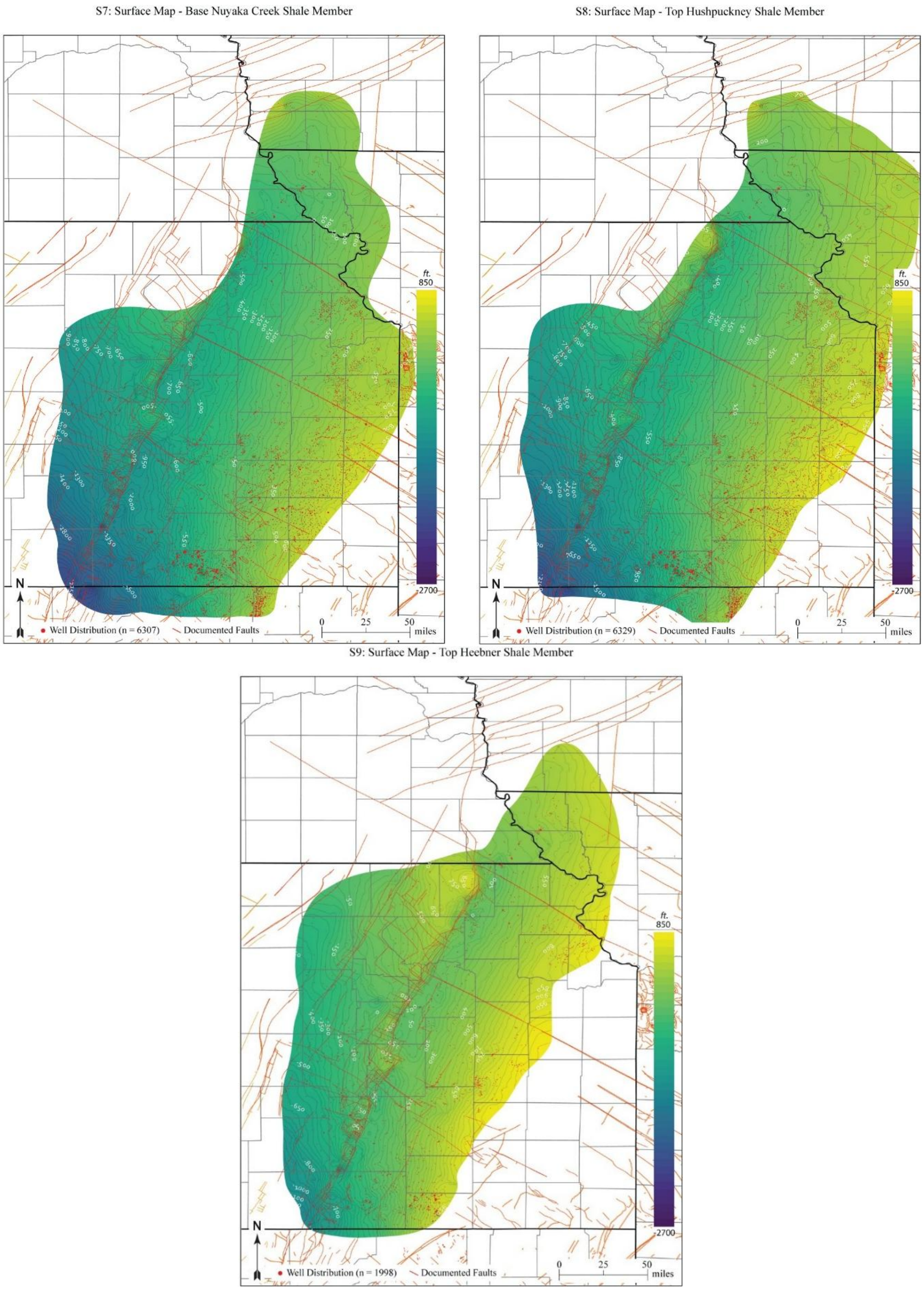

Figure 11.3: Structural surface maps for the Base Nuyaka Creek Shale (Left), Top Huskpuckney Shale (Right), and Top Heebner Shale (Bottom)

Discussion

Mississippian Stratigraphic Challenges

Due to the geographic extent of the study area, there are inevitable facies variations that, at times, create some challenge in unit correlation. Two such examples coincide with the base of the Chouteau Limestone and the top of the Mississippian Subsystem. In Kansas, the Chouteau Limestone is recognized as the basal carbonate of the Mississippian carbonate succession (Zeller, 1968). Numerous records are observed within the basin supporting the identification of the Chouteau Limestone, and in many cases the Chouteau is identified in these records as being in direct contact with the underlying Chattanooga or Kinderhookian shale, terms that have been historically interchangeable in the region (S. Oborny, personal comm., Feb. 2023), and preceding the Mississippian Northview Shale. These prior unit identifications would suggest the absence of a unit termed the Boice Shale throughout the basin, which is presently recognized by the KGS at a stratigraphic position between the Chattanooga Shale and Chouteau Limestone (Zeller, 1968). Additionally, the Boice Shale cannot be reliably distinguished from the underlying Chattanooga Shale in petrophysical logs.

Given that referring to the basal Mississippian contact as Top Chattanooga Shale would require redefinition of the Chattanooga stratigraphic unit to accommodate the inclusion of the Boice Shale (as it is presently recognized in the northern part of the basin), the horizon is instead referred to as the Base Chouteau Limestone which is sharp and may be disconformable. The Base Chouteau Limestone is assigned in some prior oil and gas well records to the Top Chattanooga, Top Kinderhookian, or Top Northview Shale. In the absence of the true Northview Shale, the Chouteau Limestone cannot be differentiated from overlying carbonates of the

Mississippian succession; however, the nature of this contact and its assignment here in defining the base of the Mississippian carbonates remains consistent throughout our area of study.

The boundary between the Mississippian and Pennsylvanian subsystems is a well-documented regional unconformity (Moore 1936; Merriam, 1963; Ebanks et al, 1979; Ellis, 1979; Thompson, 1979). Stratigraphic correlations find support for an unconformable contact at the subsystem boundary throughout the basin (see contact in all cross sections; Supplemental File 2). Despite this observation, the unconformity is frequently lithologically sharp, with carbonates/limestone below the contact and shale/fine-grained siliciclastics above. Correlation of the subsystem boundary is occasionally challenged where coarse sands at the base of the Pennsylvanian Subsystem are documented and observed in direct contact with the Mississippian carbonates. This challenge is at times further compounded by discrepancies in stratigraphic assignments between individual oil and gas well records and our own in which the sands are assigned to both Mississippian and Pennsylvanian subsystems through well correlations. One such example exists in parts of northeastern Kansas surrounding the type-well locality of the McLouth Sandstone (Lee, 1941); approximately 15 miles north of Lawrence, Kansas. The McLouth Sandstone was considered by Lee (1941) to represent the basal unit of the Pennsylvanian Subsystem in that part of the FCB. Our data is consistent with Lee's (1941) stratigraphic assignment though when correlating the sandstone away from its type area we observe the McLouth being assigned to within the Mississippian Subsystem in oil and gas well records, owing to the occurrence of an anomalous limestone directly overlying the McLouth Sandstone in some wells that was previously identified as Mississippian in age. In this particular example, we include this sandstone within the Pennsylvanian Subsystem, as was Lee's (1941) practice and note that the overlying discontinuous limestone will require further investigation.

Depositional Trends

Isochores generated in this study (Figures 10.0-10.8; Appendix 3) highlight potential changes in accommodation sites across the CFCB throughout deposition of the Pennsylvanian succession. The Krebs interval (i1) shows a SW-NE area of increased thickness of greater than 600 feet in the FCB parallelling structural strike to the east of the HFZ and extending northeastward towards Iowa. Comparatively modest thickening is observed in the same area during deposition of the lower Cabaniss (i2). Evaluation of the Cherokee Group by Brown (2003) and Grosch (2023) in northwestern Doniphan County, Kansas, in the FCB determined the entire Cherokee Group was composed of fine-to-coarse grained tidal and bar siliciclastics interbedded with coal. These lithologies typically fill accommodation and therefore indicate that the FCB acted as a primary site of fill and depocenter throughout the Cherokee Group and most notably during the Krebs. The overwhelming thickness of the Krebs in the FCB and transition toward a depocenter in the CB by lower and upper Cabaniss time is suggestive of a change in regional structural activity.

Oborny et al. (2025) postulated that the CFCB was in the backbulge setting of a foreland basin system associated with the northwest converging Arkoma Foreland Basin, accompanied by syn-depositional back thrusting along the NTZ. The observation here that the Krebs Subgroup reaches its maximum thickness parallel to structural strike of the HFZ and perpendicular to the northwest shortening direction of the Ouachita Orogeny suggests that the Krebs depocenter may have formed as a distal foredeep, which was similarly accompanied by back thrusting east of the NU (c.f. Gerhard, 2004; Oborny et al., 2025).

Throughout the lower and upper Cabaniss (i2, i3) deposition shifts to the CB portion of the CFCB (Figure 12). The upper Cabaniss Interval (i3) exhibits a northeast plunging anticline along the Kansas-Oklahoma state line (Figure 12-A) that terminates at the FRTZ as documented by Berendsen and Blair (1991). A thickened section (Figure 12-B) is observed immediately southeast of the upper Cabaniss anticline's axis in the Fort Scott (i4) Subgroup, and given the trend of thickening to the south, would be the product of sedimentation from a source to the south/southeast. These observations reflect northwestward lithospheric shortening that began at least during the lower Cabaniss and persisted into the Fort Scott Subgroup, influencing deposition throughout the interval and perhaps acting as a baffle to the southeast sedimentation source during Fort Scott Subgroup deposition.

Abrupt changes in thickness along the Oklahoma-Kansas state line (Figure 12-C) in the Appanoose (i5), and lower Holdenville (i6) intervals may be suggestive of west-east striking structural elements; alternatively, when combining the isochores i5 and i6 into i5/6 (Figure 10.56, Appendix 3), representative of a combined Appanoose and lower Holdenville Subgroups, we observe the interval thickening to the south-southeast to approximately 275 ft in Oklahoma., which implies the presence of high energy sedimentation sourced from the southeast. When the two units were separated, greater complexity is evident; the shape of an apron/fan is observed in i5/6 and is apparent in the Appanoose Subgroup (i5, Figure 12-D) but terminates south of the KS-OK border, where deposition in the lower Holdenville Subgroup is at its thickest. This pattern suggests that the CFCB was perhaps a distal deltaic environment, and that the switch from sedimentation in the area spanning between the FRTZ and KS-OK border to south of the border likely occurred soon after deposition of the Lake Neosho Shale. This abrupt change in thickness in i5 and i6 could also be representative of southward progradation into Oklahoma, an interpretation that has previously been illustrated by Cook and Bally (1975).

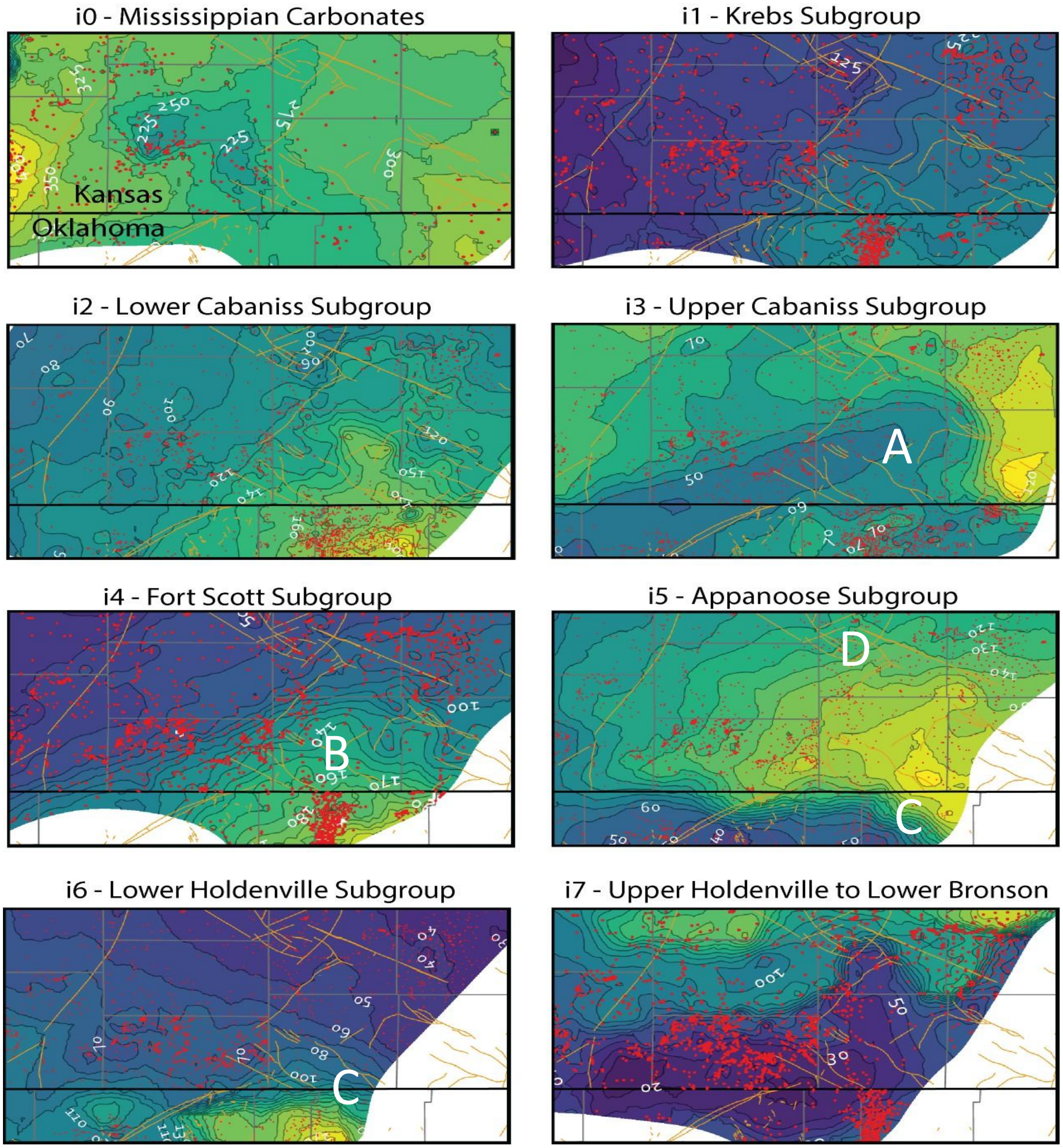

Figure 12: Collection of isochore maps spanning i0-i7 with focus on the CB portion of the CFCB. Lettering discussed in text.

When comparing the i5/6 isochore (particularly the 150 ft contour index within the CB) to the 130 ft contour interval of the overlying isochore (i7), we observe a strong similarity in thickness trend between these maps that further imply a depositional influence unrelated to broad structural activity. This is supported by prior observations by Brownfield et al. (1998) who concluded the Bandara Formation (see Figure 5 herein; within Appanoose Subgroup) had an easterly sediment source. As observed in cross section WE-6 along the Oklahoma-Kansas state line, the Bandara and overlying Nowata formations both thicken eastward. In this cross section the Montgomery County well (15-125-32103) illustrates a combined thickness of ~250 ft for the Appanoose and lower Holdenville Subgroup with ~200 ft (~80%) of the interval consisting of Bandara (~140 ft) and Nowata (~60 ft) formations, respectively. Both formations are composed chiefly of fine-to-coarse grained siliciclastics and coal (Heckel and Watney, 2002) with gamma ray signatures ranging from ~40-120 API units in cross section NS-6 (wells 35-105-0805 through 15-005-2008). These observations suggest an east-southeast sediment source for the combined i5/6 isochore and possibly a broad, lobate deltaic depositional environment. The overlying upper Holdenville through lower Bronson Subgroups (i7) distribution is subsequently thickest away from and to the north of the underlying bathymetric high generated during deposition of i5/6, indicating a compensational stacking pattern. Evaluation of depositional trends in overlying intervals within the CFCB is limited due to the outcrop belt; however, the combined isochore of the Kansas City, Lansing, Douglas, and lower Shawnee Groups (i8) show that this interval also thickens to the southeast towards the Arkoma Basin. A similar observation was made by Oborny et al. (2025).

It is notable that the Bourbon Arch region spanning from Bourbon to Chase Counties, Kansas does not restrict communication between the CB and FCB portions of the basin in any of the Mississippian and lower- to mid-Pennsylvanian isochores described in this study. Historical interpretations describe the Bourbon Arch as isolating the CB and FB prior to the Desmoinesian Stage (Lee, 1943), however this study indicates that the CB and FCB were connected and communicating during highstand shale deposition throughout the entirety of the study interval.

Inference of Structural Elements

Isochores and structure maps generated in this study support prior literature describing the HFZ/NTZ as an east-side-down fault (Figure 13-A; e.g., Cole, 1976; Berendsen and Blair, 1986; McBee, 2003). These data also support prior interpretations that the NTZ/HFZ are composed of multiple uplifted anastomosing blocks with left-lateral juxtaposition (Figure 13-A; Berendsen and Blair, 1986; McBee, 2003); however, the structural profiles indicate that these faulted blocks terminate in southern Butler County, Kansas and do not extend southward into northern Oklahoma. Isochores for the upper Cabaniss (i3) and Fort Scott (i4) Subgroups do show thinning to the west of and parallelling the NTZ in areas south of Butler County that may support the extension of the tectonic zone southward into Oklahoma as discussed by prior studies.

Away from the HFZ/NTZ, structural surface maps show relatively little variation in structural geometry between the Pennsylvanian intervals evaluated in this study, apart from the notable fault observations discussed earlier that appear in the Cherokee Group and older strata. Structural profiles of the top Mississippian Subsystem, base Tebo Shale, and top Mecca Quarry Shale all highlight two distinct lineaments (Figures 10.1-10.3; labeled on Figure 13) with ~200-300 ft of right-side up juxtaposition. The northernmost lineament (Figure 13-B) extends northeast from Osage County, Kansas, to at least Jefferson County, Kansas, and does not appear to influence interval thicknesses within isochores. The second lineament (Figure 13-C) extends northward from Nowata County, Oklahoma, to at least Wilson County, Kansas, appearing to terminate near the Rose and Silver City domes (Berendsen, 2011). Though this southern lineament does not appear to influence isochore thicknesses or unit distribution it does traverse closely to the plunging terminus of the lower Cabaniss anticline and may correspond with an area with an observed increase in subsurface geothermal temperatures (Newell and Birdie, 2021). The absence of both lineaments in structural profiles for the upper Cabaniss Subgroup or overlying strata may suggest that the lineaments were active during the lower Cabaniss; this interpretation will however require evaluation of the internal stratigraphic architecture of the lower Cabaniss.

NW-SE trending lineaments (e.g., FRTZ, CTZ, and BMTZ) that are well mapped in Missouri (e.g., Cox, 2009) are generally poorly understood in Kansas. Observations do exist, however, for at least the BMTZ in Linn County, Kansas, where horst and graben and structural deformation are documented (Padgham, 1956), and for the FRTZ (Berendsen and Blair, 1986, 1991). Multiple observations in isochores and N-S cross sections support the extension of these lineaments westward, but their projection into the basin becomes difficult due to limited subsurface data. As such, confidence in the identification of fault lineament decreases westward across the study area. Despite this observation, potential faulting identified in structural cross sections and isochores allow for some improvement.

Northwestward lithospheric shortening during the Krebs and upper Cabaniss in the FCB and CB, respectively, may be explained through variable fault activity along the FRTZ, CTZ, and BMTZ. Oborny et al. (2025) previously noted that structural and stratigraphic changes in the

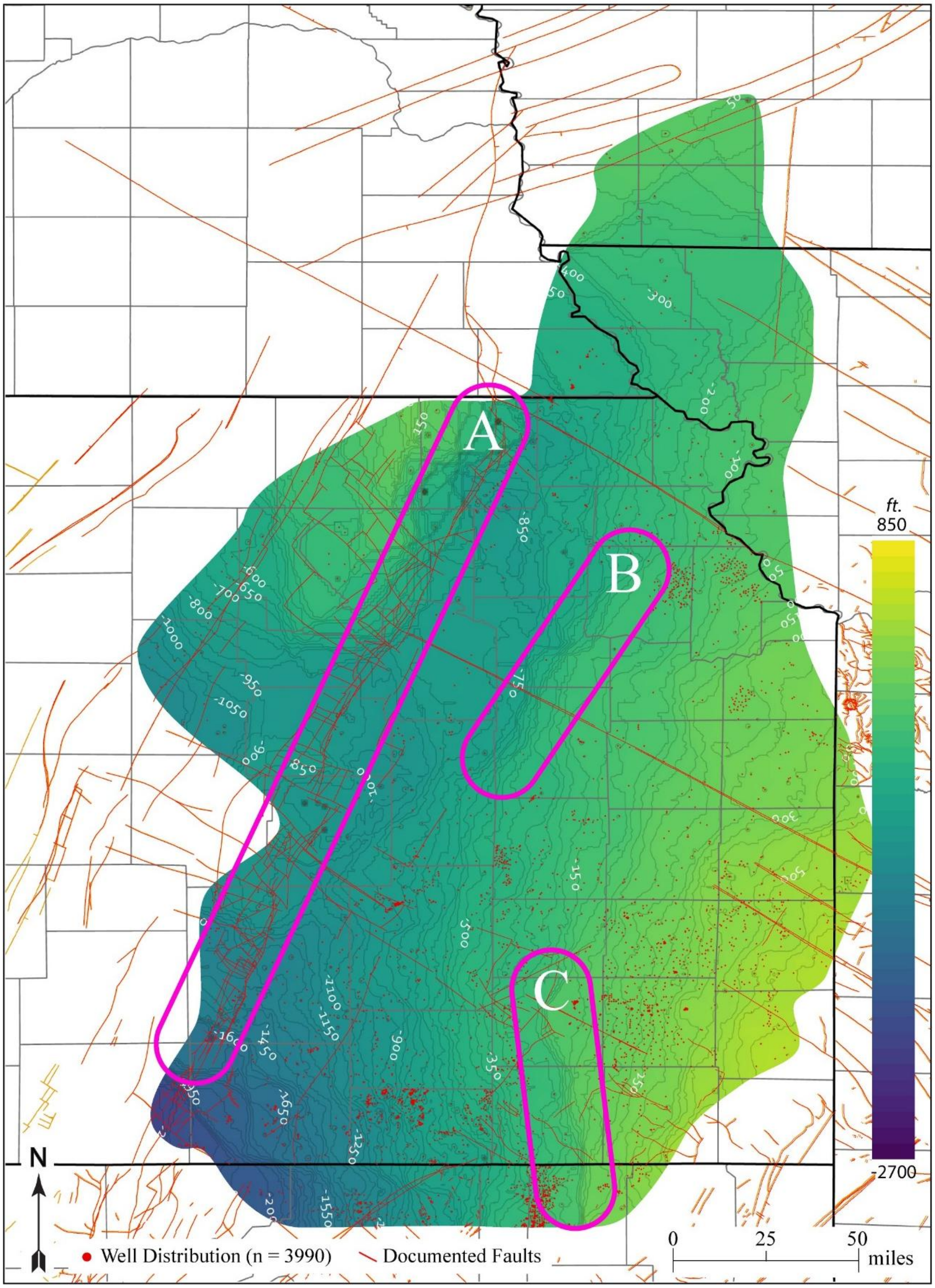

Figure 13: Structural surface map of the base Tebo Shale Member depicting the known HFZ/NTZ (A), and lineaments B/C that are described in Discussion.

upper Desmoinesian and lower Missourian stage strata coincided with both the Chesapeake and Bolivar-Mansfield tectonic zones. Their determination of northwest-southeast shortening throughout their study area and much of the basin was not observed north of the BMTZ. These authors also illustrated a west-to-north clockwise trend in both the CTZ and BMTZ, and the Mississippian Carbonate isochore (i0) generated by this study shows a similar curvature in unit thickness variation that coincides loosely with both the CTZ and BMTZ (Figure 14). As previously discussed, the Mississippian Carbonate delineations were at times difficult to correlate; however, interpretations for the FCB portion of the basin do compare well to Mississippian isochores generated by Lee (1941) and Anderson and Wells (1968). The observations of clockwise curvature are also arguably visible across combined aerogravity-magnetic data (Kruger, 1996, Sweeney and Hill, 2005) collected in eastern Kansas. A feature in Crawford County, Kansas referred to as the Pittsburg and an unnamed, NW-SE trending lineament existing between/parallel to the BMTZ and CTZ, display the same curvature seen in those fault zones. The previously unnamed feature traverses into Kansas through Linn County, and it is corroborated by the presence of Mississippi Valley Type deposits of lead and zinc (Seevers, 1969). It seems probable that the handful of major NW-SE trending fault zones are structurally connected to the large number of minor faults along the eastern side of the HFZ that are present in cross section NS-4; as such, splaying into multiple minor faults appears to occur at some point along these fault zones, but their exact geometries are obscured by the limits of subsurface data available for this study.

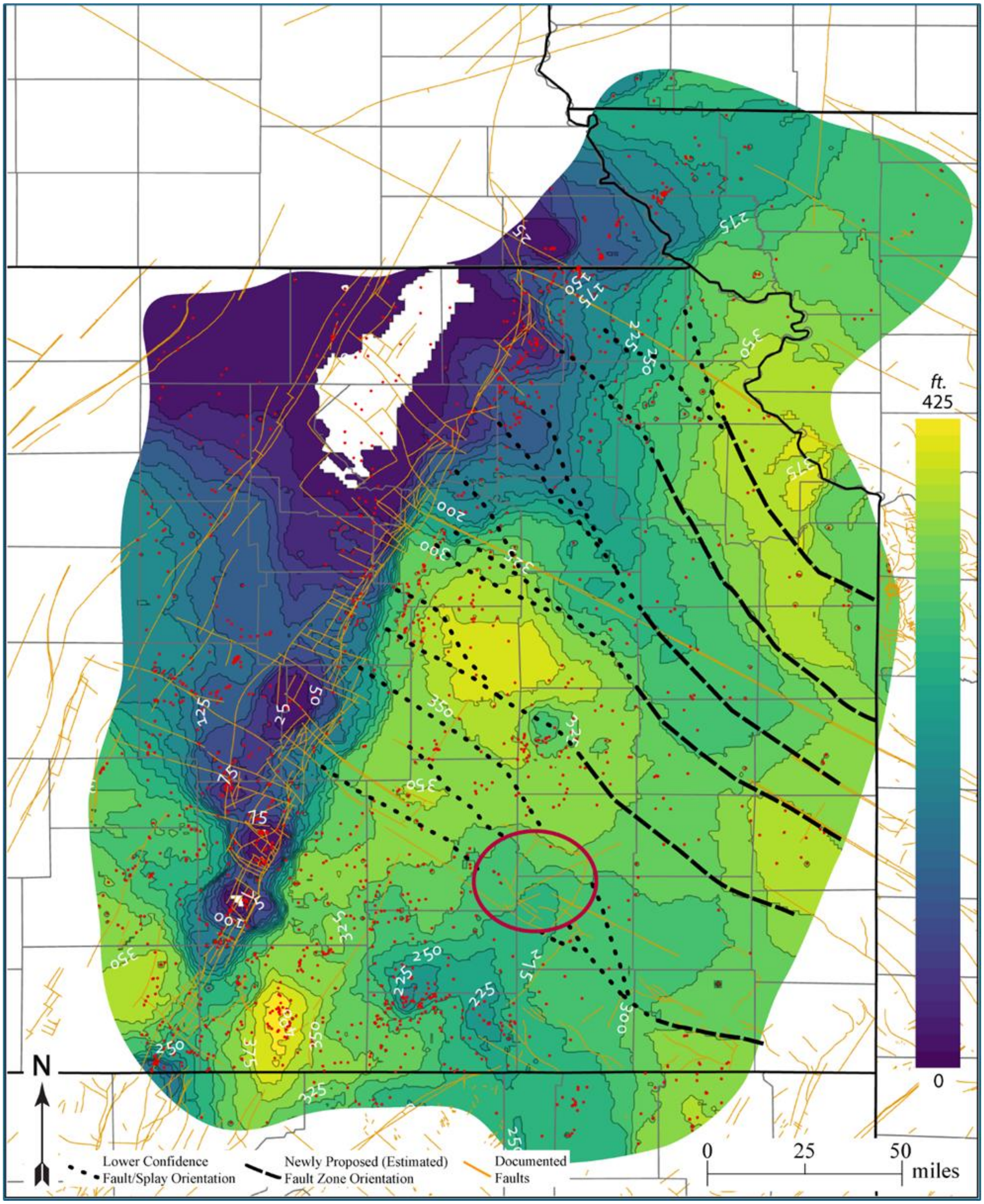

Figure 14: Interpreted NW-SE trending fault lineaments interpreted from all data; underlain by i0 isochore for the Mississippian Carbonate, accompanying isochore well distribution, and documented faults. Previously documented faults were compiled by Alan Peterson and presented in Mohammadi et al. (2022). The red circle on the FRTZ corresponds closely to the Rose and Silver City Domes and denotes an area of complexity that makes fault interpretation difficult to interpret.

Evidence exists in the CFCB that the NW-SE trending fault zones experienced strike-slip faulting during deposition of the Pennsylvanian succession (Berendsen and Blair, 1986; McBee, 2003), but from this study, slip direction is not apparent. This reduces our confidence in a simple single-direction model and supports a more complex multiphase/multidirectional strike-slip faulting hypothesis, where periods of regional relaxation may have overprinted and obscured evidence of the extent of transpression. As such, there is not enough evidence in this study to confirm or refute previous interpretations of strike-slip direction described along the NW-SE trending faults of eastern Kansas. The isochores and cross sections generated in this study did, however, highlight the complex nature of the FRTZ compared to other major fault zones in the CFCB. In the Mississippian Carbonates isochore (Figure 10.0) the FRTZ appears to be composed of multiple major lineaments compared to the single major lineaments of the CTZ and BMTZ. The well resolution in our isochores makes it somewhat difficult to determine what structures are present in the "center" of the FRTZ (Woodson and Wilson Counties), but the structural profiles of cross sections NS-6 and WE-5 indicate the presence of multiple faults. This area also corresponds closely to the previously described Silver City and Rose Domes, where documented faults display a sense of shear nearly perpendicular to the NW-SE trend of the FRTZ (Berendsen, 2011). The complexity here noted in this and prior studies may then be attributable to an associated Riedel shear fabric; a similar strike-slip regime to the CFCB with varying levels of complexity among each of its major fault lineament exists in the Tarim Basin of China (Han et al., 2017), where seismic surveys indicated that the more complex fault zones tended to have Riedel shears as well.

Conclusions

A database containing 7,785 wells, and 64,768 marker bed delineations was created for this study. These data permit cross sections, isochores, and subsurface structure maps to be generated that refine our understanding of the CFCB's shifting basin geometry throughout deposition of the Carboniferous at the Subsystem and Subgroup level. It also demonstrates that:

1. Correlation of the regionally expansive units at the subsystem and system levels in a syndepositional-tectonically active setting of the Carboniferous is possible across the CFCB; in particular, the Tebo and Mecca Quarry Shale of the Cherokee Group were yet to be differentiated and correlated across the basin and are indeed viable units for correlation. The high number of wells with petrophysical logs in the CFCB can be used to define a detailed stratigraphic framework.
2. The modern depth structure map of Mississippian Carbonates shows that the deepest part of the base Pennsylvanian succession is just east of the HFZ, and that relief across HFZ is at its maximum at the base of the Pennsylvanian (Mississippian top, 1600 ft) and diminishes through Pennsylvanian succession deposition (700 ft by the Heebner) along the eastern flank of HFZ.
3. The earliest Pennsylvanian depocenter lies in the FCB east of the HFZ during the Krebs interval. The primary site of thickened succession migrates throughout deposition of the lower and upper Cabaniss intervals, and by Fort Scott Subgroup time has fully shifted southeast to the CB. Apparent deposition of several lobate packages sourced from southeast of the study area occurs across the Appanoose to Lower Bronson Subgroups, suggesting that the basin may have accommodated sediments from a distal, high-energy deltaic environment.

4. Correlations and resulting depth structure/isochore maps are compatible with NW-SE trending strike-slip faulting in the basin, but the relative sense of strike-slip movement along these fault zones cannot be determined from the data generated in this study. The HFZ/NTZ display east-side down orientation with decreasing vertical relief to the south, and the Bourbon Arch was not restricting communication between the FCB and CB during sea level highstand deposition throughout the study interval.

Considerations for Future Research

The stratigraphic tops/bases data generated in this study will be utilized in CoreCM's efforts to characterize CM distribution in the CFCB (Oborny and Bream, 2025) and will eventually be integrated into KGS's interactive well mapping application for geologists and lay-people to use to better understand the structural complexity of the Pennsylvanian strata of eastern Kansas. Future work to further evaluate the observations and interpretations of this study should include detailed re-evaluation of the trends in facies belts on the formational and member level, as well as continued evaluation of known fault systems to identify additional stratigraphic pinch-points and areas with enhanced stratigraphic variability, which may further elucidate shear zone geometry and vergence in the region. Considering the extent of the data provided in this study, more correlation to the south/southwest would be required to further understand the complexity of the HFZ as it traverses into Oklahoma, as well as the extent of the tectonic features along the Kansas-Oklahoma border. This study also produced a valuable tool for extending Pennsylvanian correlations further into Kansas' neighboring states, thanks in great part to the nomenclature standardization efforts of partnering state surveys.

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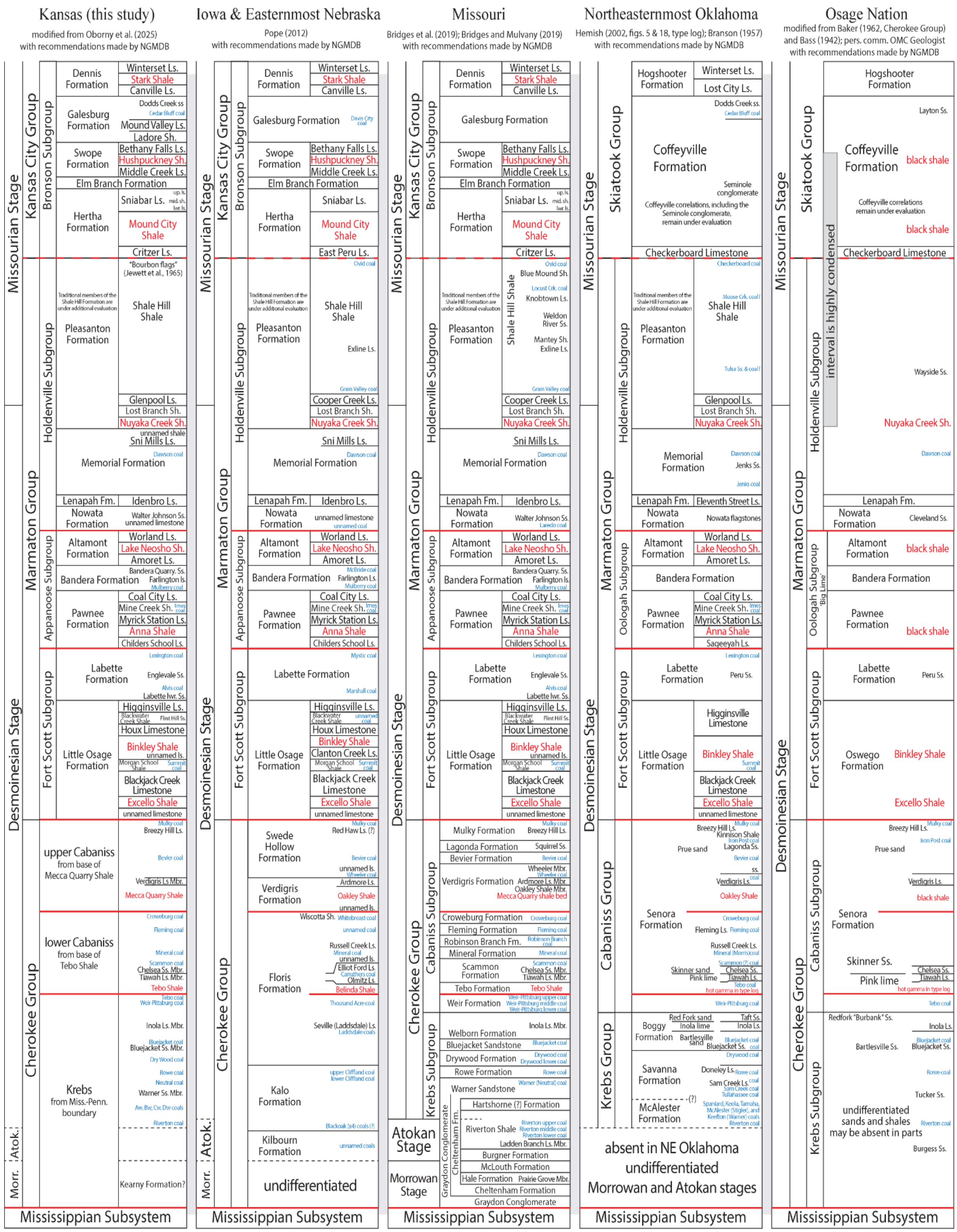
Appendix 1. CoreCM Interstate Nomenclatural Scheme

Interstate and international lithostratigraphic nomenclatural schemes for the Lower and Middle Pennsylvanian Subsystem established by various funded initiatives. Revisions to the Marmaton and Kansas City groups was completed by a working group funded by the U.S. Geological Survey National Geologic Map Database (NGMDB) focused on Pennsylvanian Nomenclatural Reconciliation (Layzell et al., 2021). Cherokee Group correlations are the product of the U.S. Department of Energy (DOE) CORE-CM Phase 1 initiative (2021-2024) focused on critical mineral potential within the CFCB succession. High-gamma signal black shales within the Cherokee interval were used by Core-CM to establish a standardized nomenclature across the study area at the subgroup level (see Kansas This Study). Figure is not representative of thickness. Blue = coal, Red = black shale. Efforts to standardize nomenclature and boundary definitions regionally within the Cherokee Group will require further work through regional collaboration. Figure provided by Dr. Stephan Oborny, CoreCM PI.


Kansas (this study)
modified from Oborny et al. (2025) with recommendations made by NGMDB
Iowa & Easternmost Nebraska
Pope (2012) with recommendations made by NGMDB
Missouri
Bridges et al. (2019); Bridges and Mulvany (2019) with recommendations made by NGMDB
Northeasternmost Oklahoma
Hemish (2002, figs. 5 & 18, type log); Branson (1957) with recommendations made by NGMDB
Osage Nation
modified from Baker (1962, Cherokee Group) and Bass (1942); pers. comm. OMC Geologist with recommendations made by NGMDB
Missourian Stage
Desmoinesian Stage
Kansas City Group
Bronson Subgroup
Skiatook Group
Marmaton Group
Holdenville Subgroup
Appanoose Subgroup
Oologah Subgroup
Fort Scott Subgroup
Cherokee Group
Cabaniss Subgroup
Krebs Subgroup
Dennis Formation
Winterset Ls.
Stark Shale
Canville Ls.
Galesburg Formation
Swope Formation
Bethany Falls Ls.
Hushpuckney Sh.
Middle Creek Ls.
Elm Branch Formation
Hertha Formation
Sniabar Ls.
Mound City Shale
Critzer Ls.
Hogshooter Formation
Lost City Ls.
Coffeyville Formation
Checkerboard Limestone
Pleasanton Formation
Shale Hill Shale
Glenpool Ls.
Lost Branch Sh.
Nuyaka Creek Sh.
Cooper Creek Ls.
Sni Mills Ls.
Memorial Formation
Lenapah Fm.
Idenbro Ls.
Nowata Formation
Altamont Formation
Worland Ls.
Lake Neosho Sh.
Amoret Ls.
Bandera Formation
Pawnee Formation
Coal City Ls.
Mine Creek Sh.
Myrick Station Ls.
Anna Shale
Childers School Ls.
Labette Formation
Little Osage Formation
Higginsville Ls.
Houx Limestone
Binkley Shale
Blackjack Creek Limestone
Excello Shale
Oswego Formation
upper Cabaniss from base of Mecca Quarry Shale
lower Cabaniss from base of Tebo Shale
Krebs from Miss.-Penn. boundary
Swede Hollow Formation
Verdigris Formation
Floris Formation
Kalo Formation
Kilbourn Formation
Senora Formation
Boggy Formation
Savanna Formation
McAlester Formation
Atokan Stage
Morrowan Stage
undifferentiated
absent in NE Oklahoma undifferentiated Morrowan and Atokan stages
undifferentiated sands and shales may be absent in parts
interval is highly condensed
Mississippian Subsystem

Appendix 2. Wireline Well Log Correlation

Gamma Ray Logs

Gamma ray (GR) logs were the most common of the wireline log data available for correlation in this study, and are a qualitative display of the natural radiation of a given formation; spectral GR can separate the signatures of major radioactive elements (U/Th/K), but the bulk of the data used in correlation used general GR logs, which display a composite of all of the natural radioactivity (Anderson and Varhaug, 2016). In the context of this study, shales/clays and coals preserve organic material that contains naturally occurring radioactive elements, resulting in a high GR signature (generally >150 API). Conversely, the carbonates and less frequently occurring siliciclastics do not preserve organic material and will have a relatively lower GR signature (Lange, 2003; Figure 1).

The GR tool is calibrated using simulated Monte Carlo modeling at the University of Houston API Calibration Facility, where nuclear activity zones of a characteristic formation are modeled and photon counting rates are calculated (Galford, 2017). Using those simulated counting rates, API unit sensitivity is calculated, and that sensitivity factor is applied to all logging tools readings to convert to the standard API unit. It is worth mentioning that there are differences in the resolution of GR logs based on the tool's vendor, but relative to this study, those effects are negligible.

Bulk Density, Neutron Porosity, and Comparative Analysis

Bulk density tools emit gamma rays that will collide with the electrons in a formation, and the resulting scattering creates a characteristic energy signature that is detected by another component of the tool (Kyi, 2019). This signature is directly proportional to the density of electrons in a formation, and thus the back-scattered gamma rays detected by the tool will be higher in a denser media.

Neutron porosity curves are the product of a tool that emits neutrons via a chemical or electronic source that slow and lose energy until they reach a thermal state as they collide with hydrogen atoms, a major constituent of water and hydrocarbons (Doveton, 1999). The rate at which the emitted neutrons reach that thermal state is proportional to the hydrogen concentration of a given formation, and this acts as a proxy for the porosity (e.g. the ability to hold fluids that contain hydrogen atoms) of that formation.

Together, bulk density and neutron porosity curves can be compared to characterize the lithology of a given formation in a compensated neutron porosity log (Doveton, 2017; Figure 2). Carbonates can display a range of apparent porosities and density as a product of how they were formed, as well as the diagenetic influence on the carbonate (i.e. dolomitization results in a denser, less porous formation). Shales and clays will have a high apparent porosity due to their propensity to absorb large volumes of fluids, but a lower bulk density signature compared to "tight" rocks as a result of the lower mass/volume ratio. Coals tend to display a low density that increases proportionally with the grade of the coal and a high apparent porosity due to the high concentration of naturally occurring micropores in the coals' structure (Ramandi et al., 2016).

Resistivity Logs

Resistivity and microresistivity logs are a quantitative measure of the electrical resistance of a formation (Anderson and Varhaug, 2016). Hydrocarbons at depth have high resistivity (non-conductive) while brines and other formation fluids generally have low resistivity (conductive). This study preferentially used GR curves for correlation because the Pennsylvanian Succession is not known for its formation fluids. Where resistivity logs were the only available data, carbonates/siliciclastics tended to display a high resistivity, as did the marker-bed shales, due to their preserved organic content reducing conductivity. Conversely, non-organic-rich shales were represented by relatively lower resistivity measurements (Doveton, 2017; Figure 3).

Correlation

Using the logs described above, correlation in this study began from a handful of logs marked with well-established horizons chosen by the Core-CM team. We used a method of selecting roughly a dozen wells in a small circular pattern in Petra where these pre-interpreted logs acted as the starting and ending wells in cross-section to ensure that the newly interpreted wells were all in agreement. This circular correlation method was employed across the study area in portions (typically counties) and cross-examined by staff at the KGS.

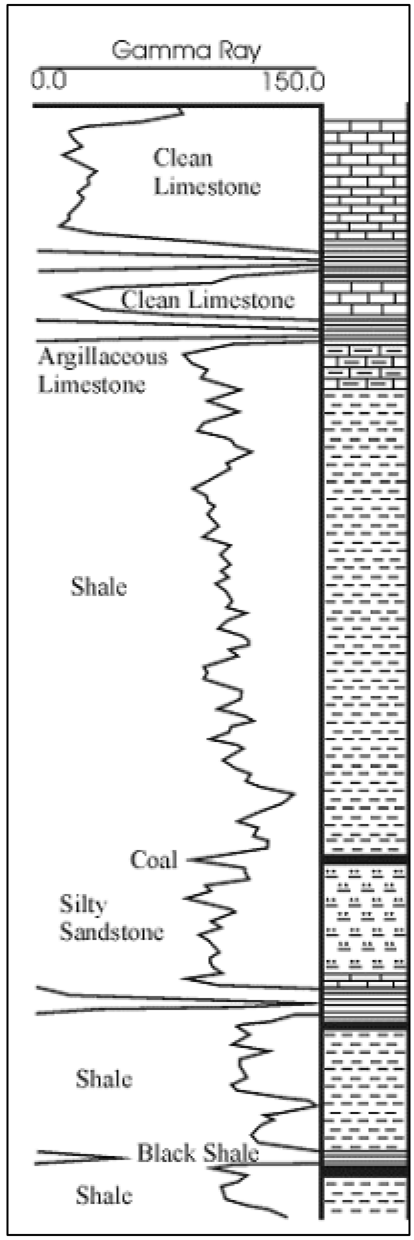


Figure 1. Gamma ray curve noting lithologies of a cyclothem section from the Hinthorn CW#1 well in Cherokee County, Kansas (Lange., 2003)

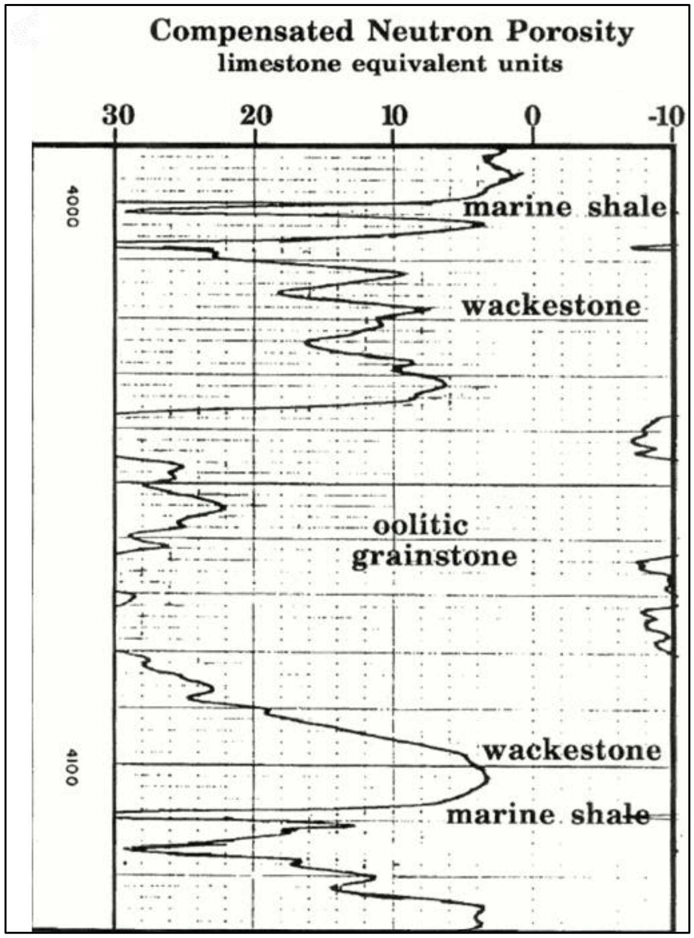


Figure 2. Neutron porosity curve noting lithology from a section of the Kansas City Group from a well in southwest Kansas (Doveton, 2017).

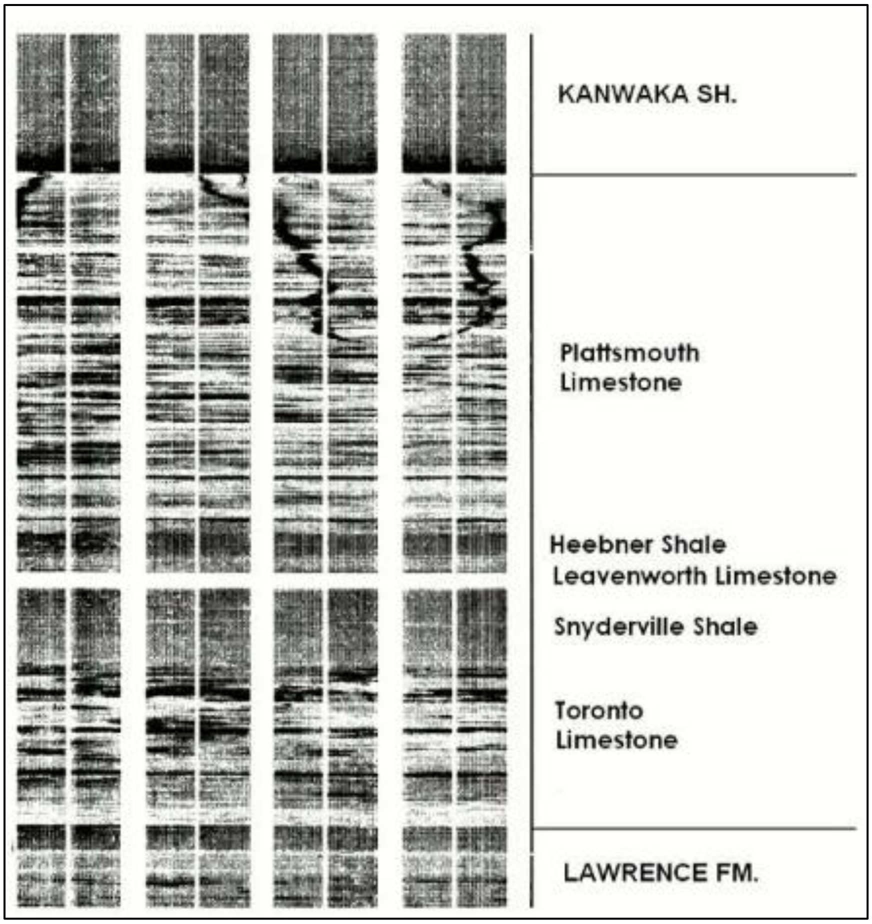


Figure 3. Micro-resistivity image of the Oread Limestone noting formations from Butler County, Kansas (Doveton, 2017).

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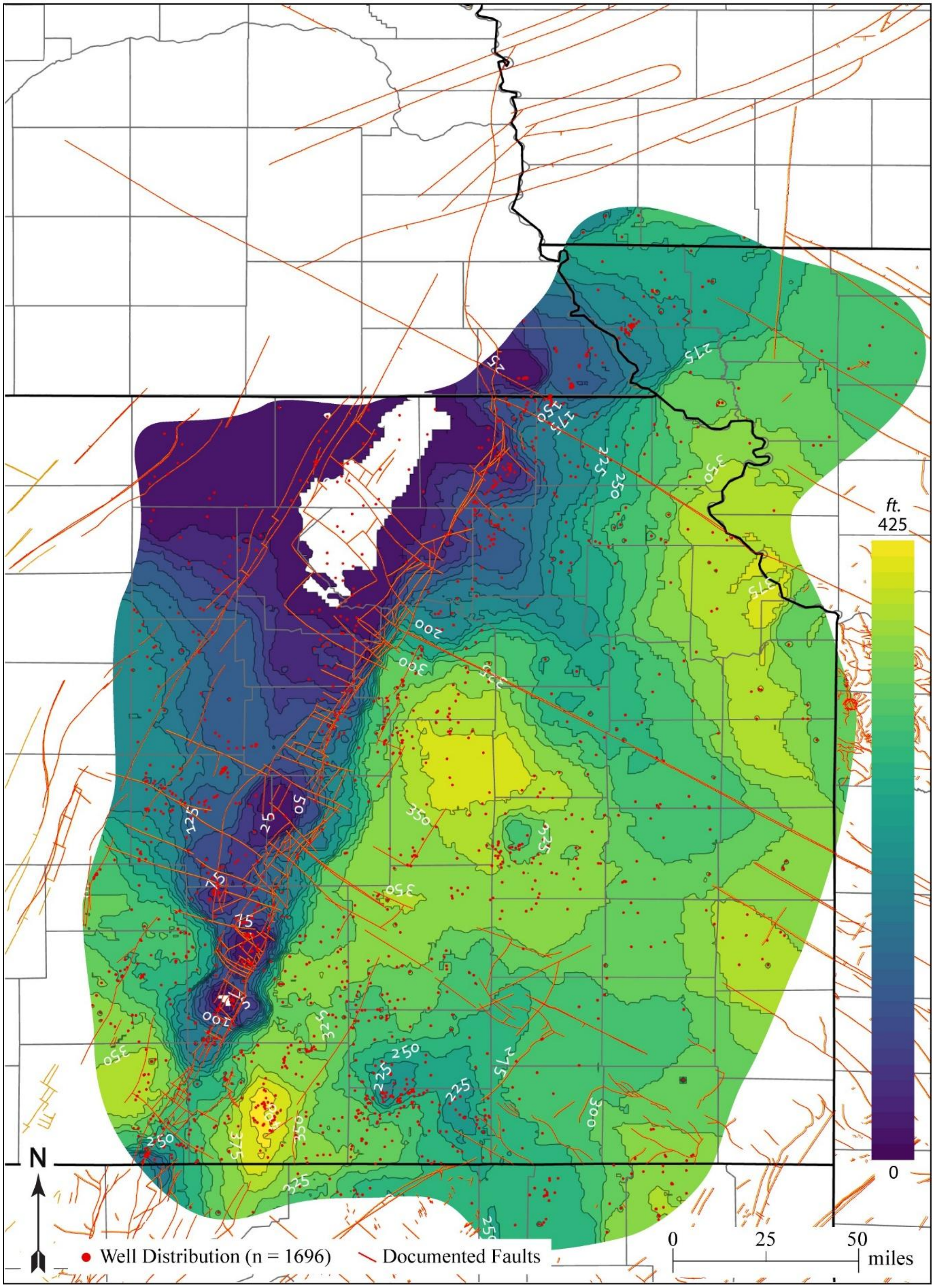
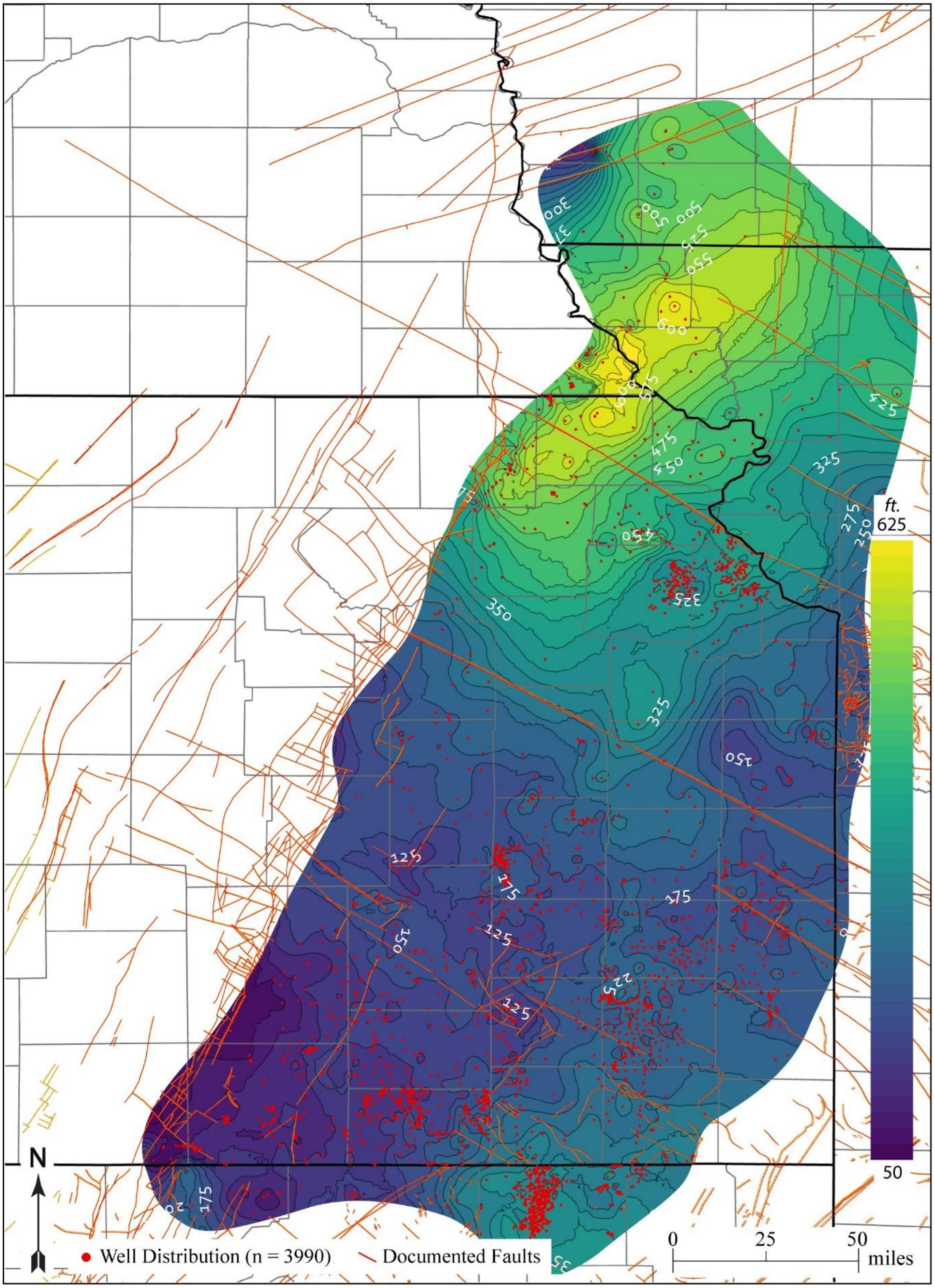
Appendix 3. Full Page Isochore Maps (i0-i8)

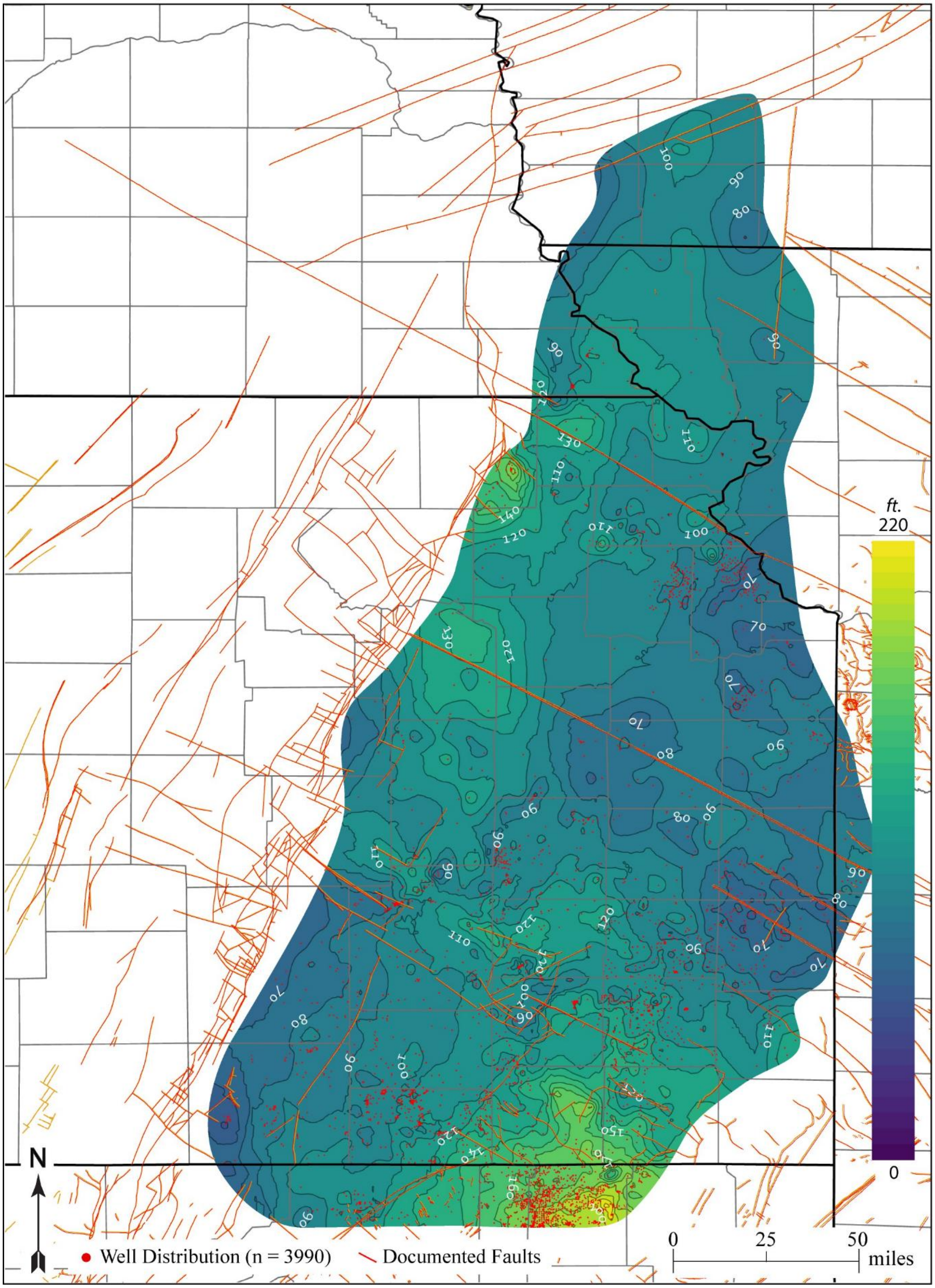
i0: Isochore Map of Mississippian Carbonates
(From base of Chouteau Limestone to top of Mississippian Subsystem)



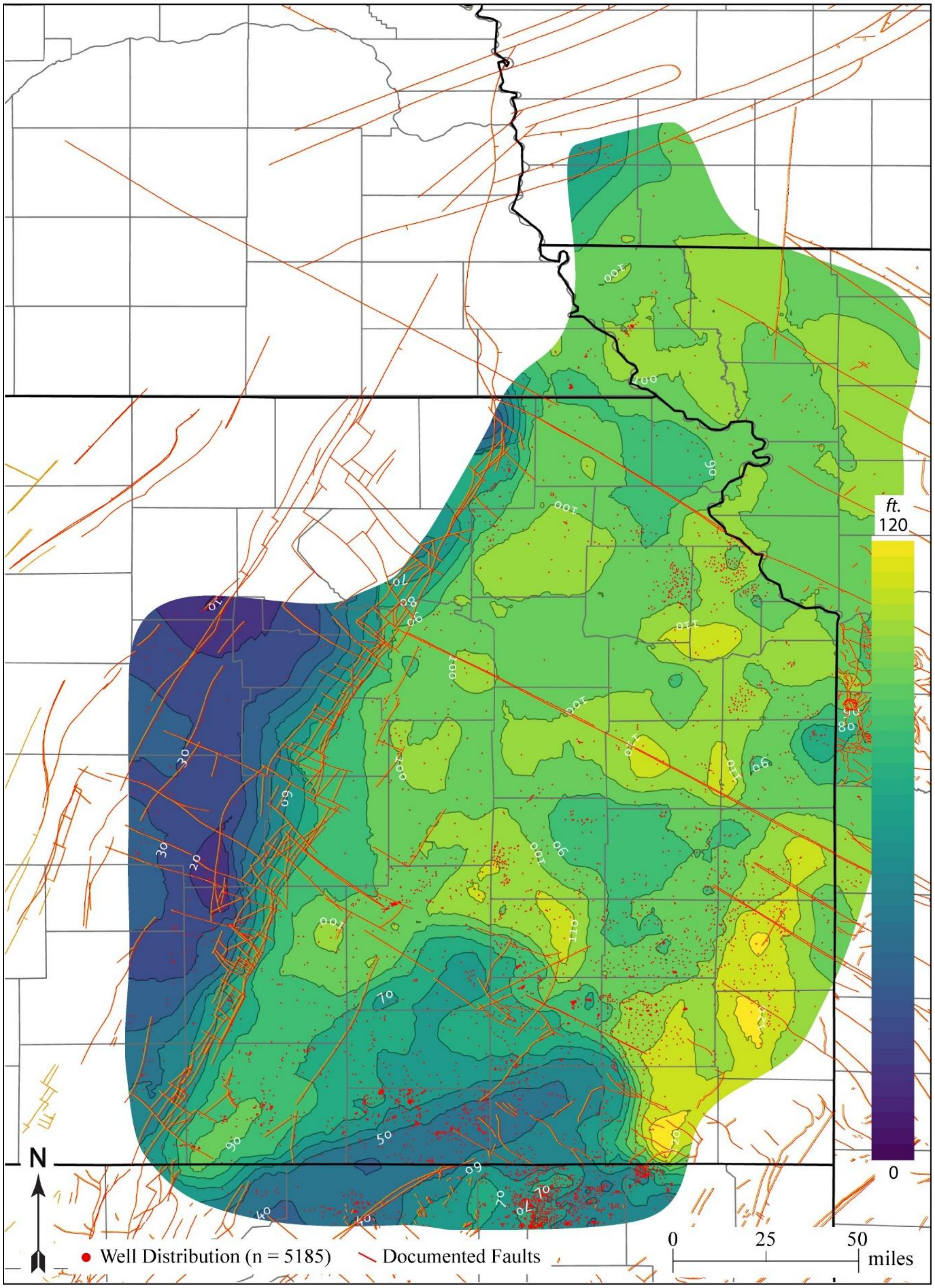
i1: Isochore Map from Top Mississippian Subsystem to Base Tebo Shale
(Correlative to CoreCM's definition of the Krebs Subgroup)



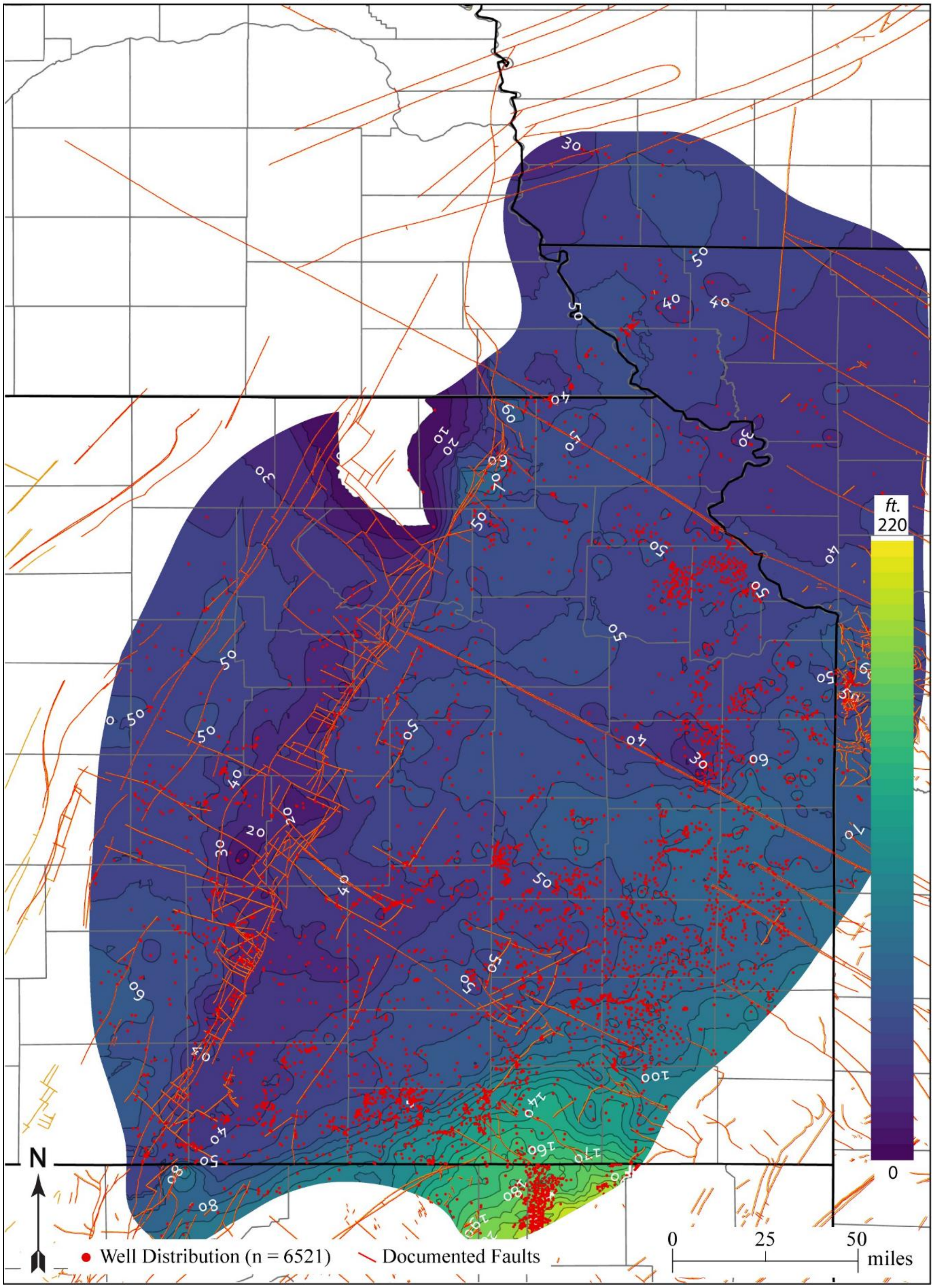
i2: Isochore Map from Base Tebo Shale to Top Mecca Quarry Shale
(Loosely correlative to CoreCM's definition of the lower Cabaniss Subgroup)



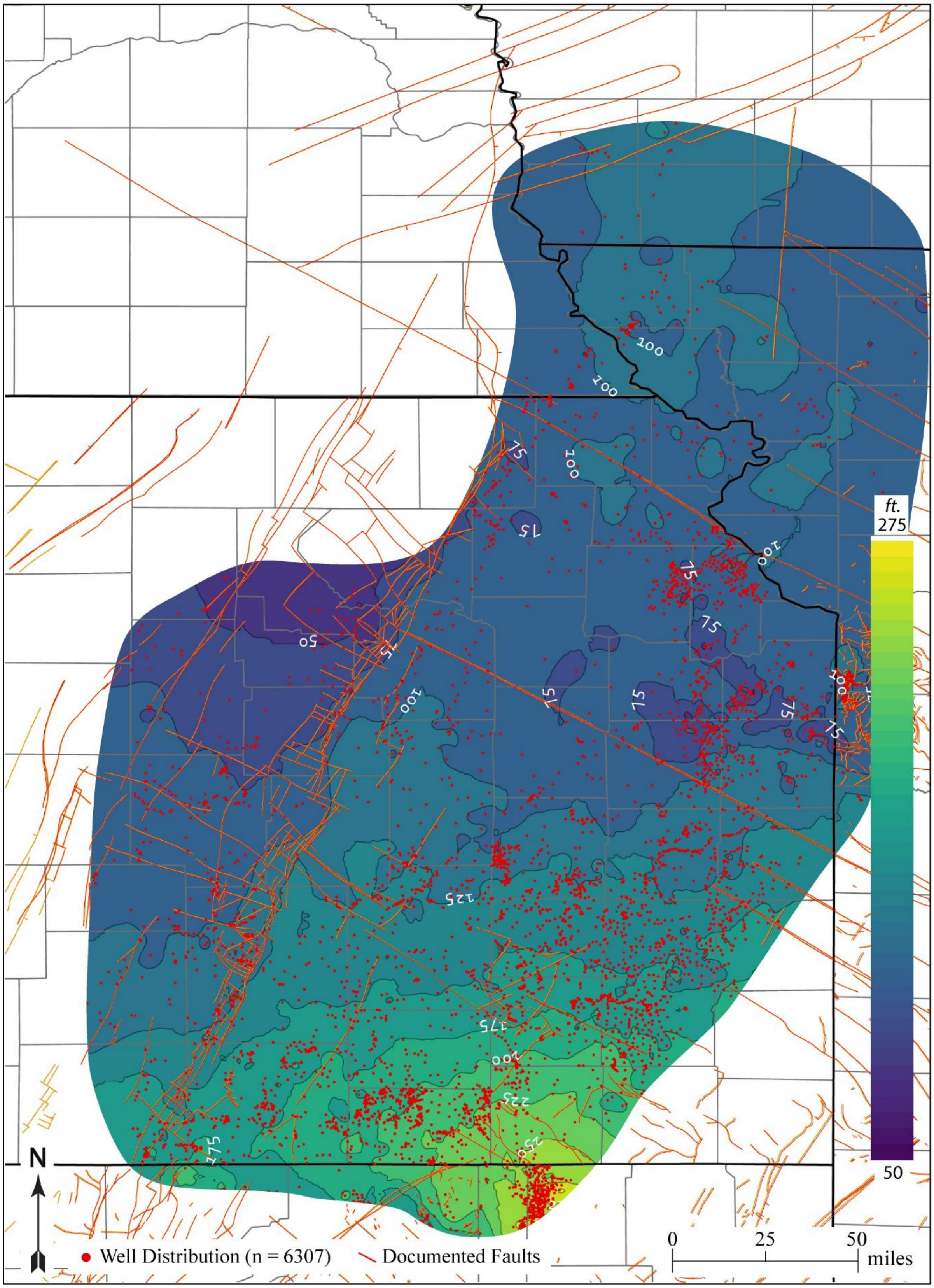
i3: Isochore Map from Top Mecca Quarry Shale to Top Excello Shale
(Loosely correlative to CoreCM's definition of the upper Cabaniss Subgroup)



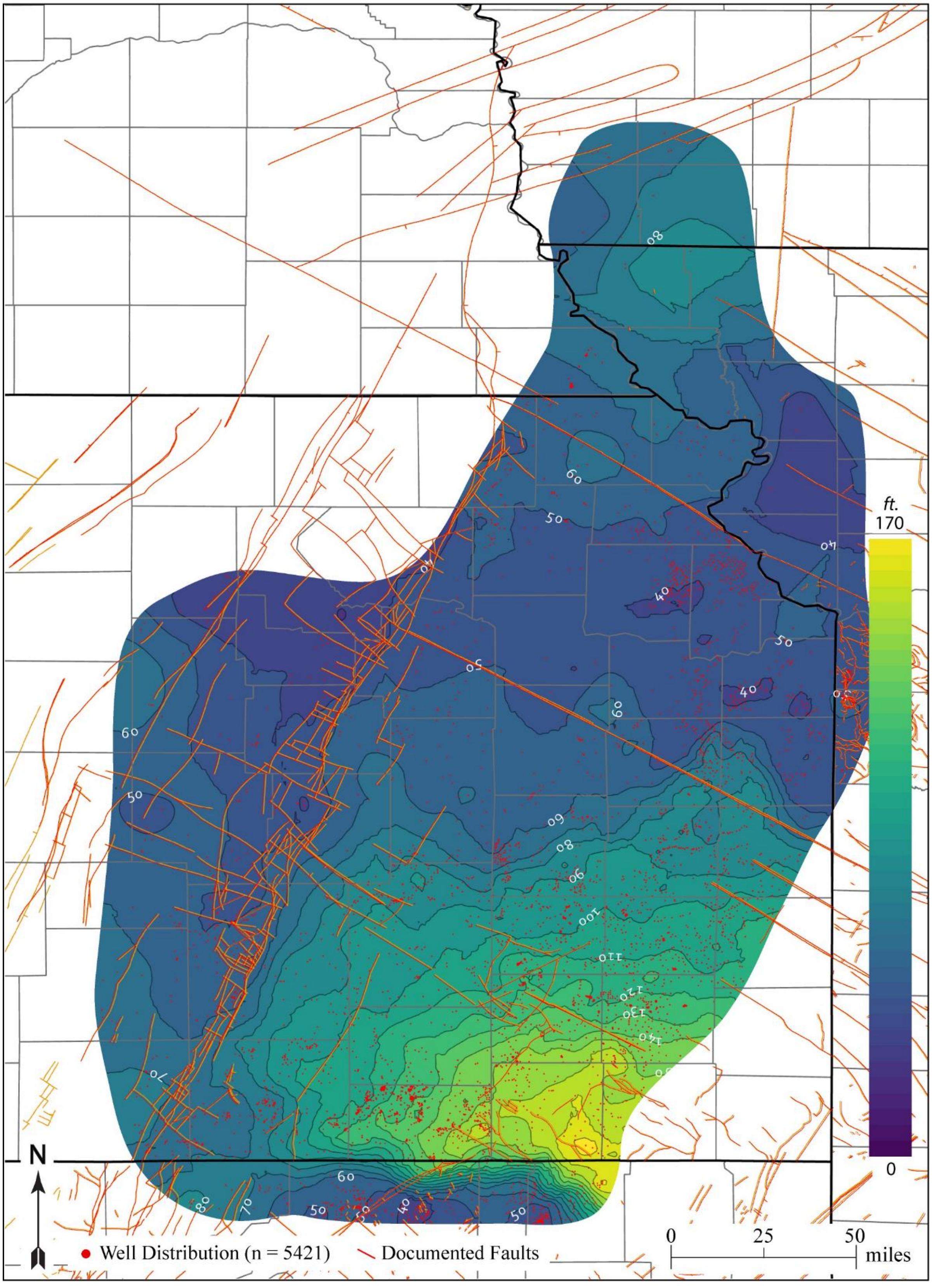
i4: Isochore Map from Top Excello Shale to Top Anna Shale
(Loosely correlative to Fort Scott Subgroup)



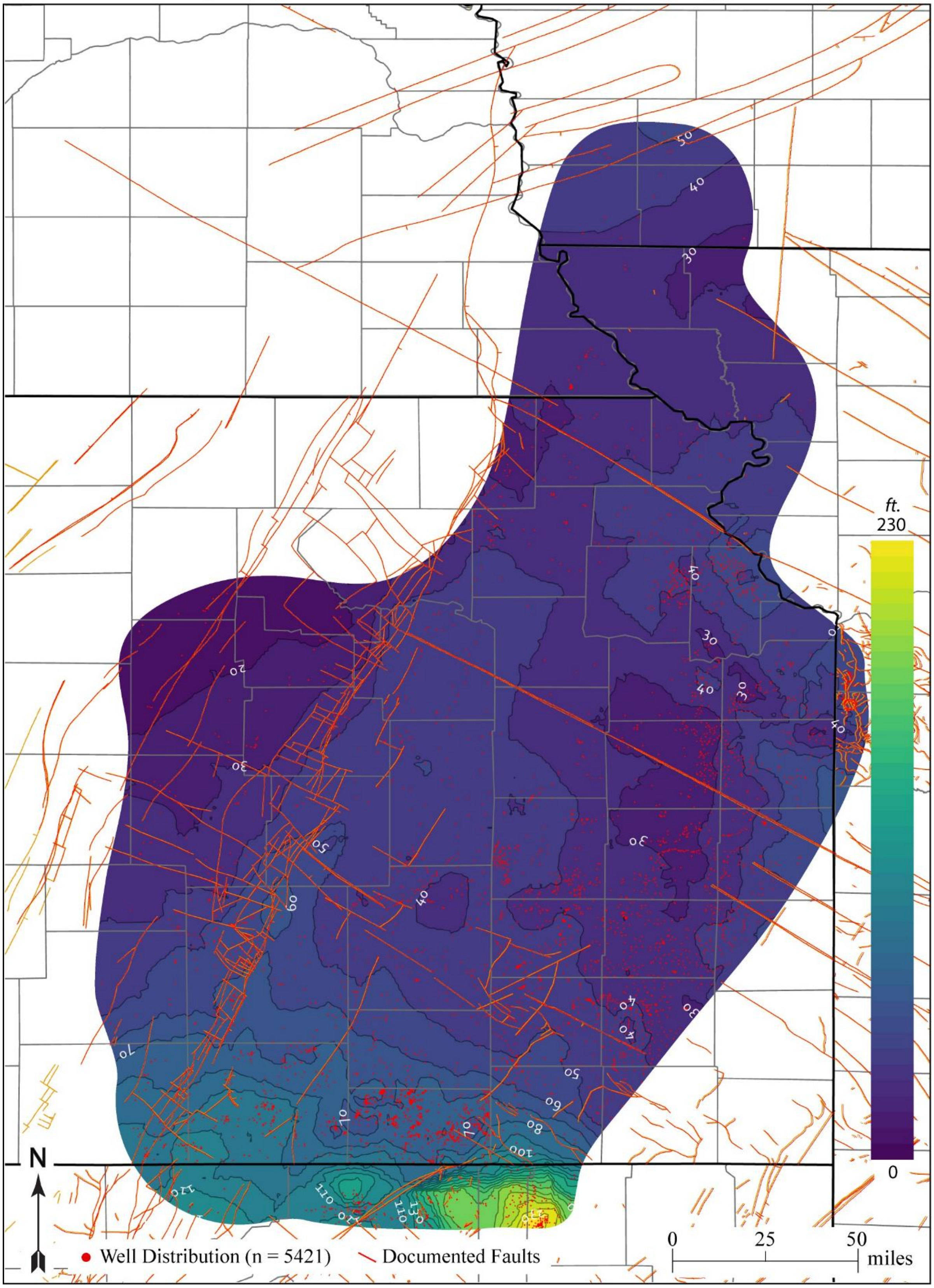
i5/6: Isochore Map from Top Anna Shale to Base Nuyaka Creek Shale
(Loosely correlative to a combined Appanoose and lower Holdenville subgroups)



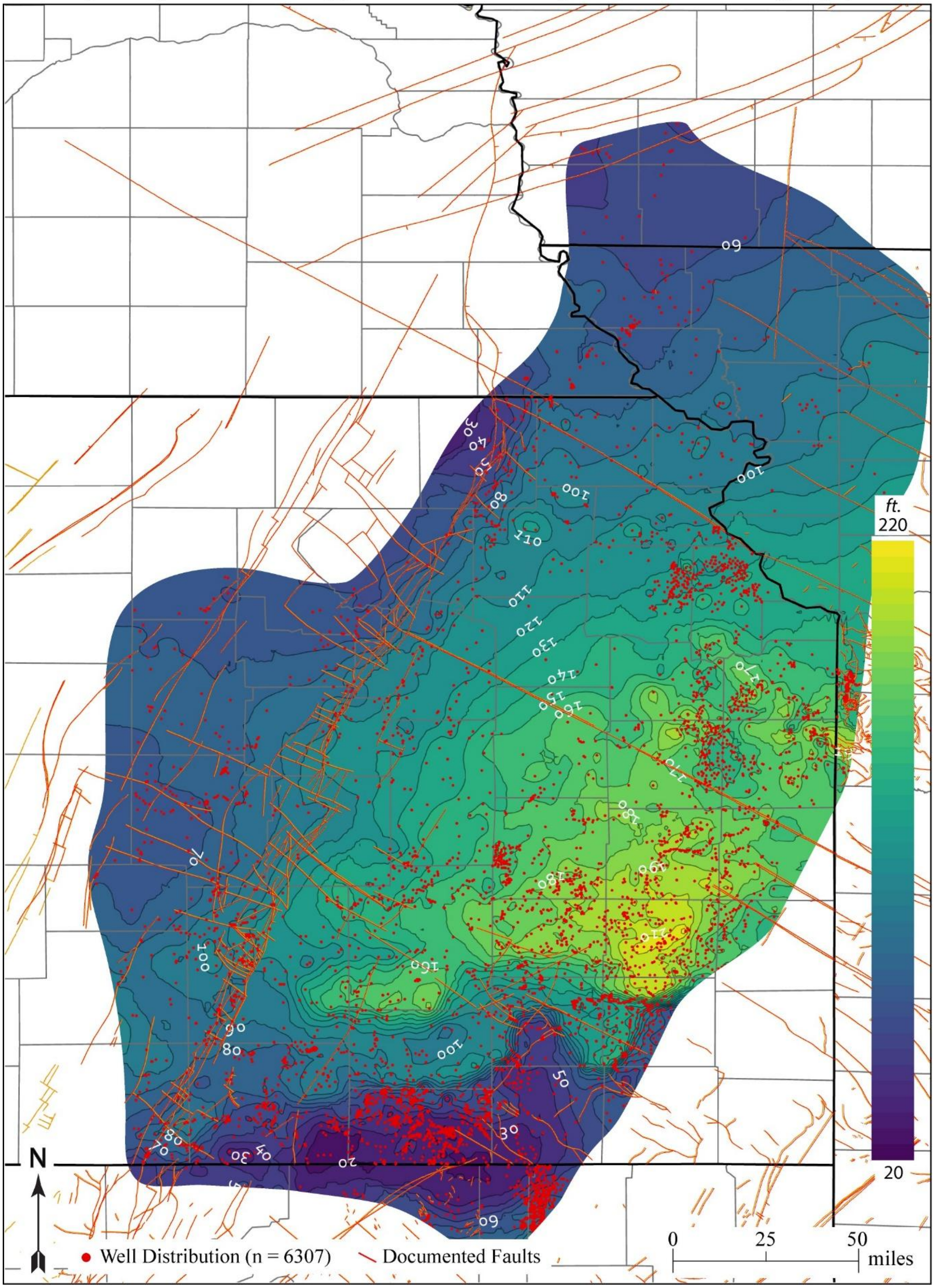
i5: Isochore Map from Top Anna Shale through Top Lake Neosho Shale
(Loosely correlative to Appanoose Subgroup)



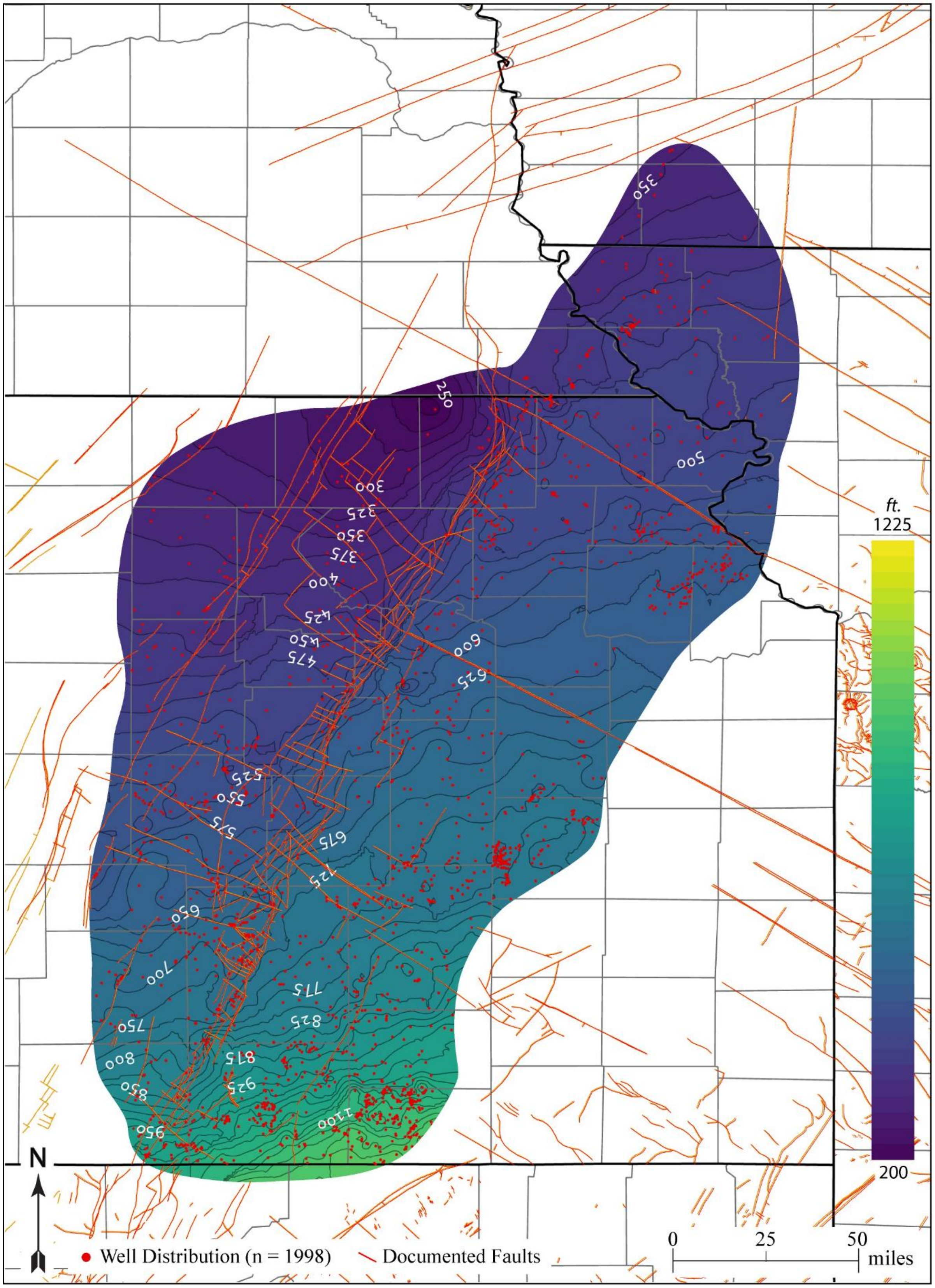
i6: Isochore Map from Top Lake Neosho Shale to Base Nuyaka Creek Shale
(Loosely correlative to lower Holdenville Subgroup)



i7: Isochore Map from Base Nuyaka Creek Shale to Top Hushpuckney Shale
(Loosely correlative to upper Holdenville through lower Bronson subgroups)

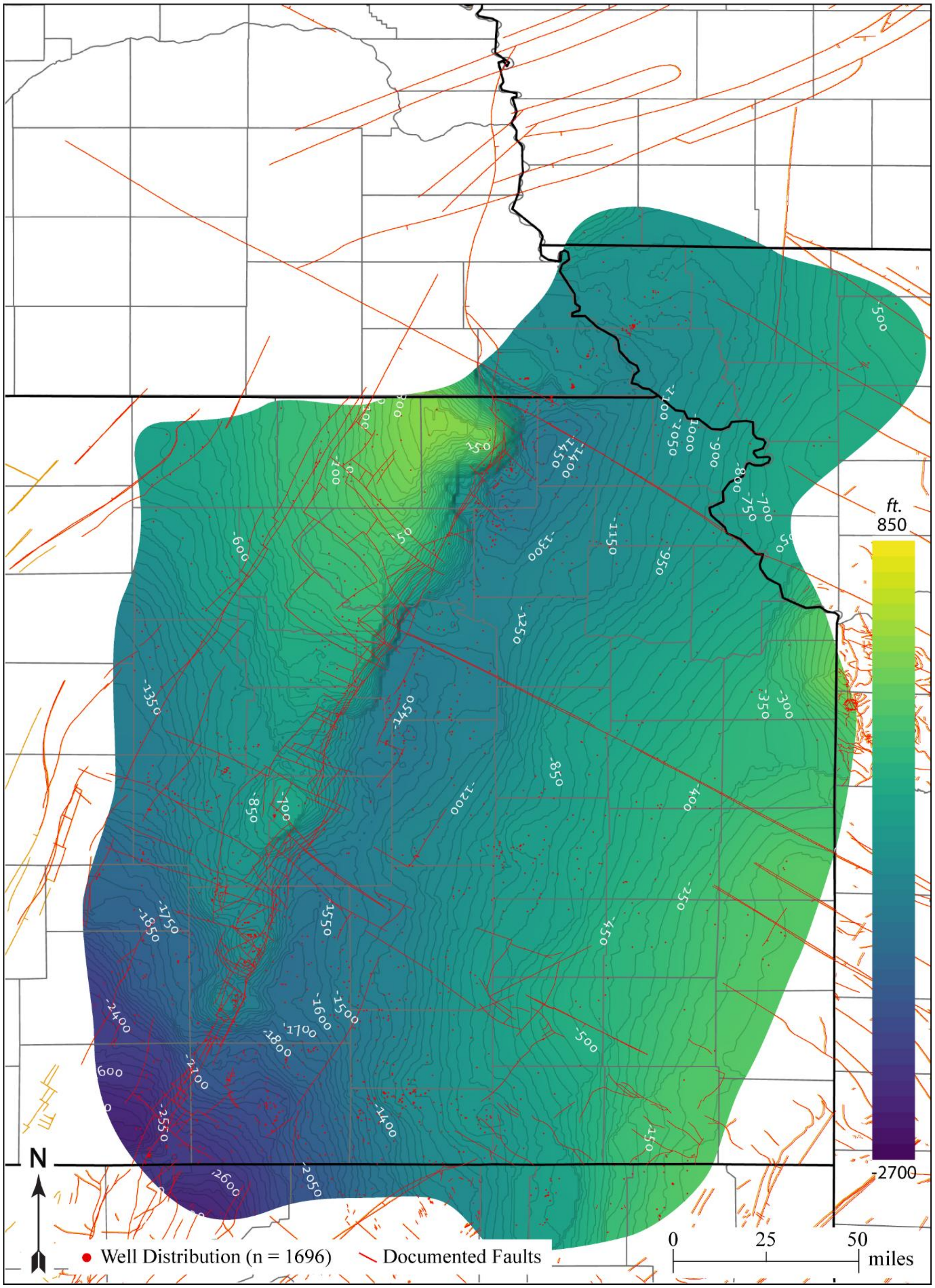


i8: Isochore Map from Top Hushpuckney Shale through Top Heebner Shale
(Loosely correlative to a combined Kansas City, Lansing, and Douglas groups)

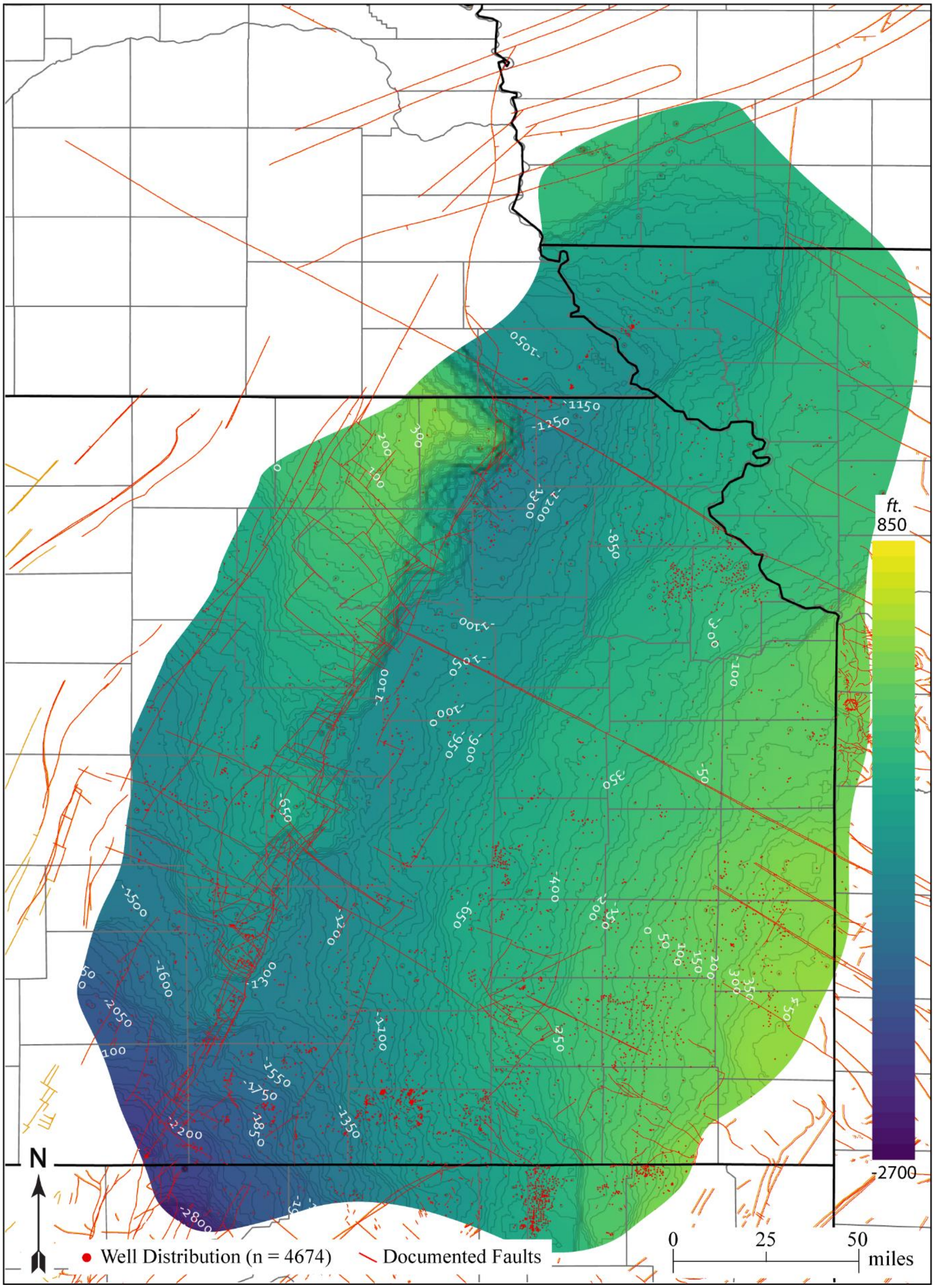


Appendix 4. Full Page Surface Maps (S0-S9)

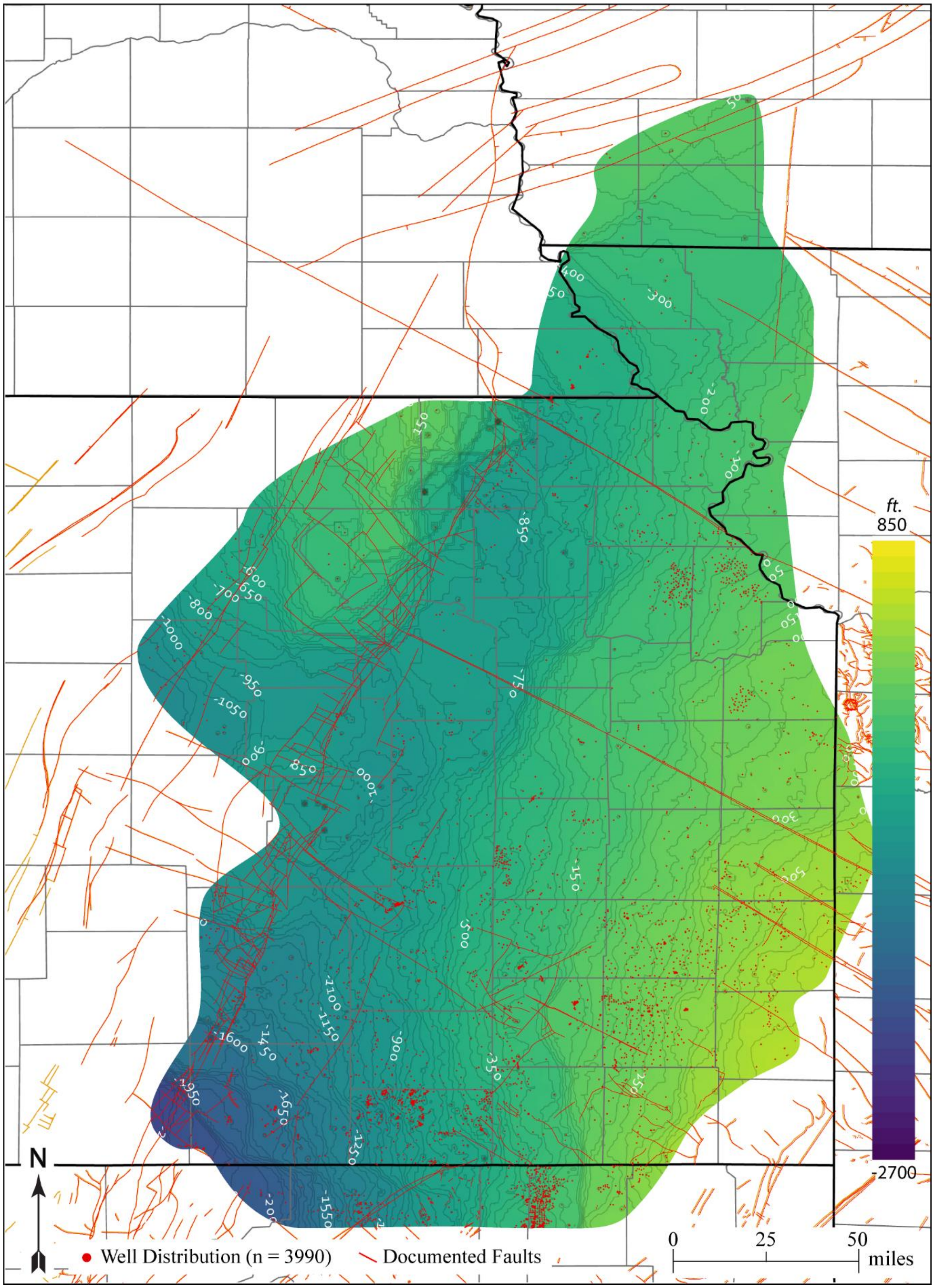
S0: Surface Map - Base Chouteau Limestone



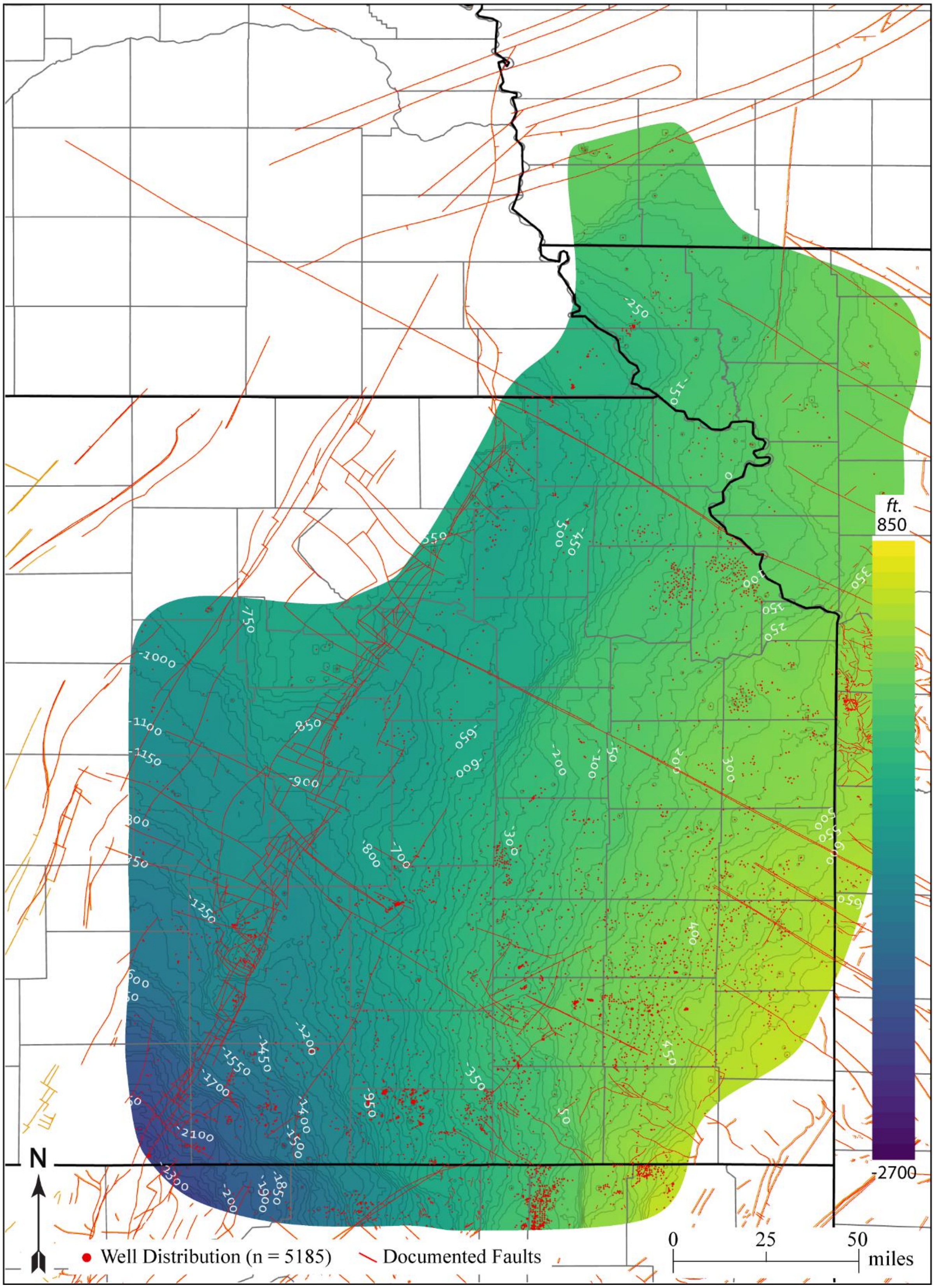
S1: Surface Map - Top Mississippian Subsystem



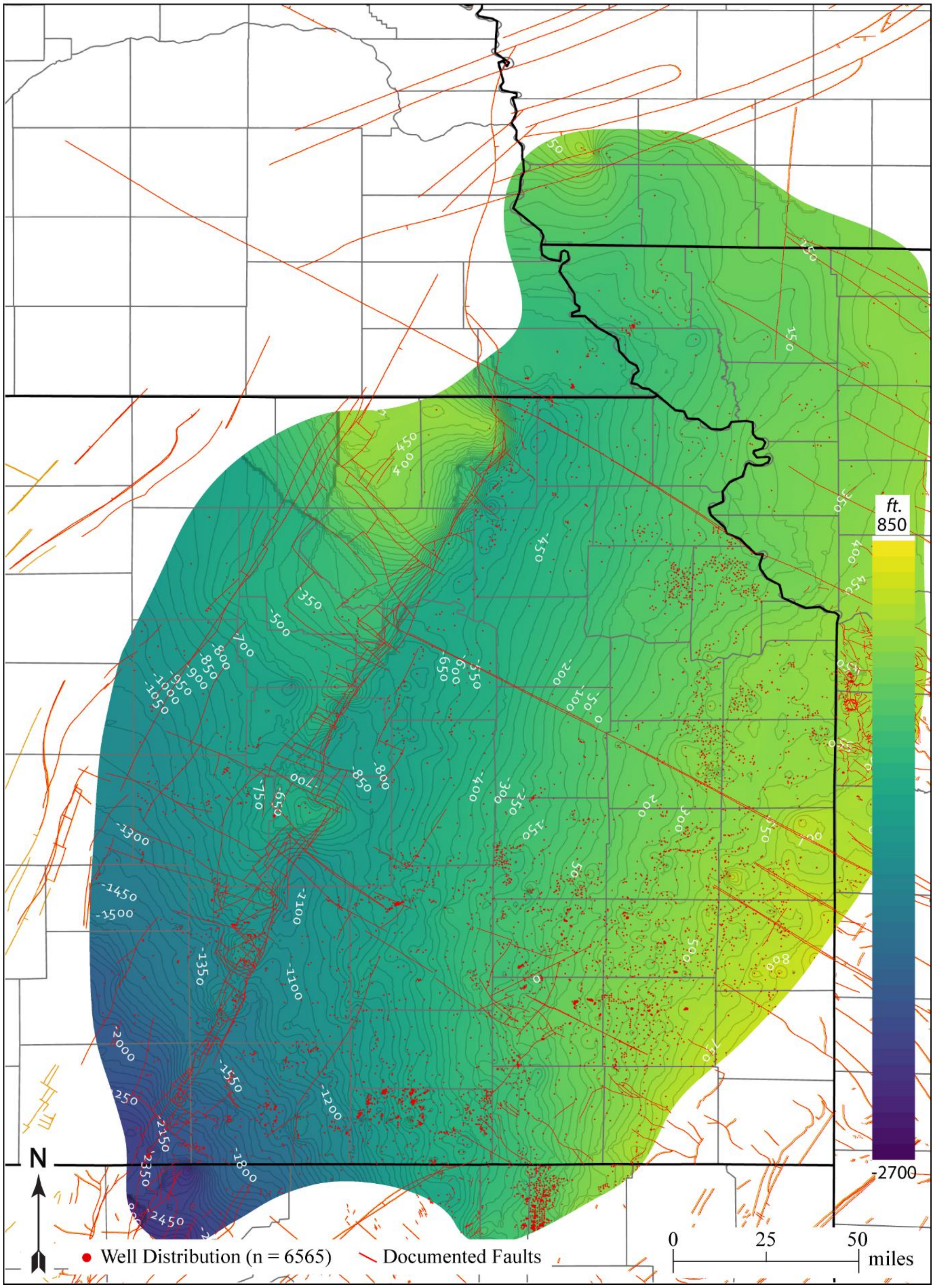
S2: Surface Map - Base Tebo Shale Member



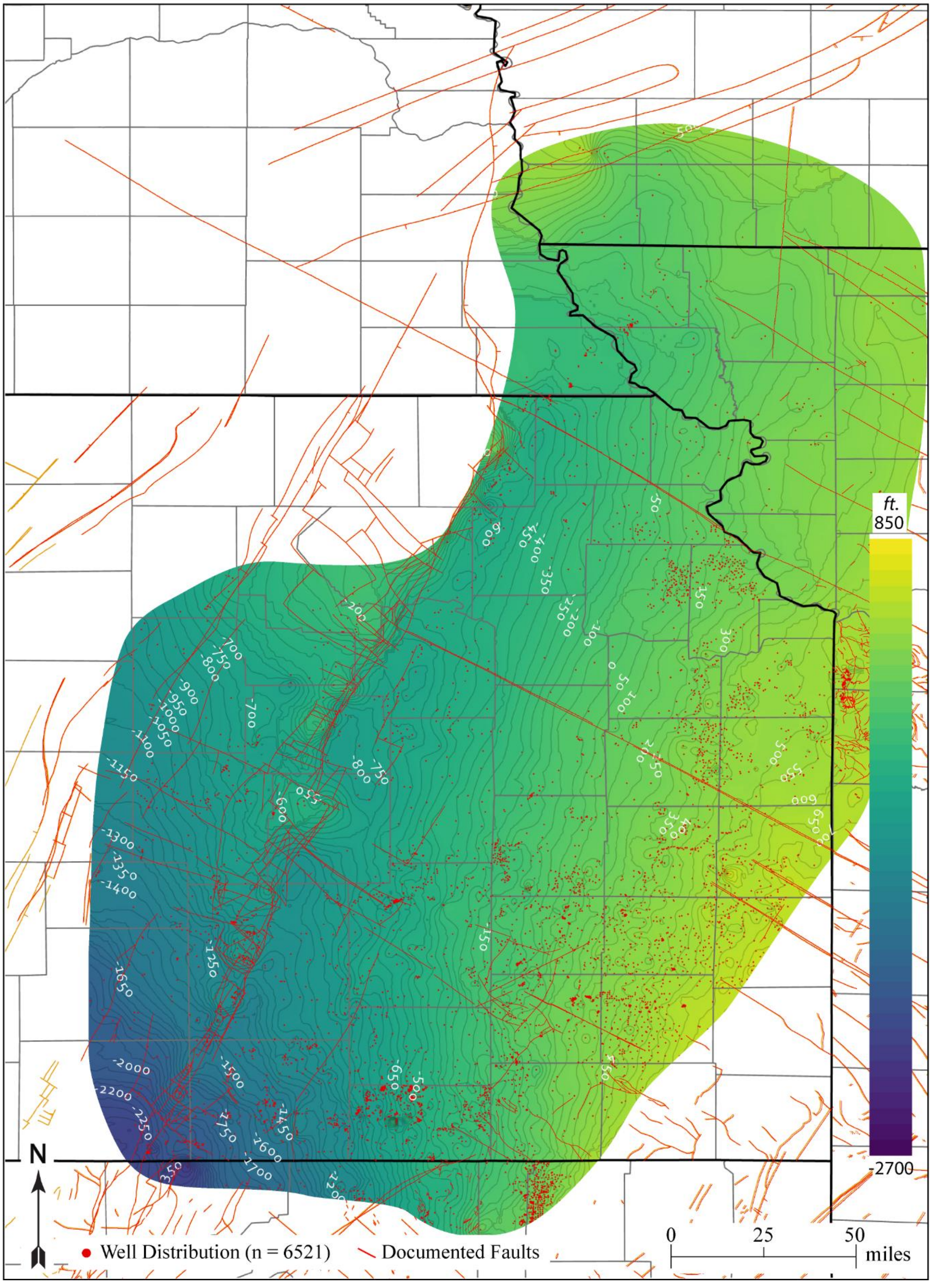
S3: Surface Map - Top Mecca Quarry Shale Member



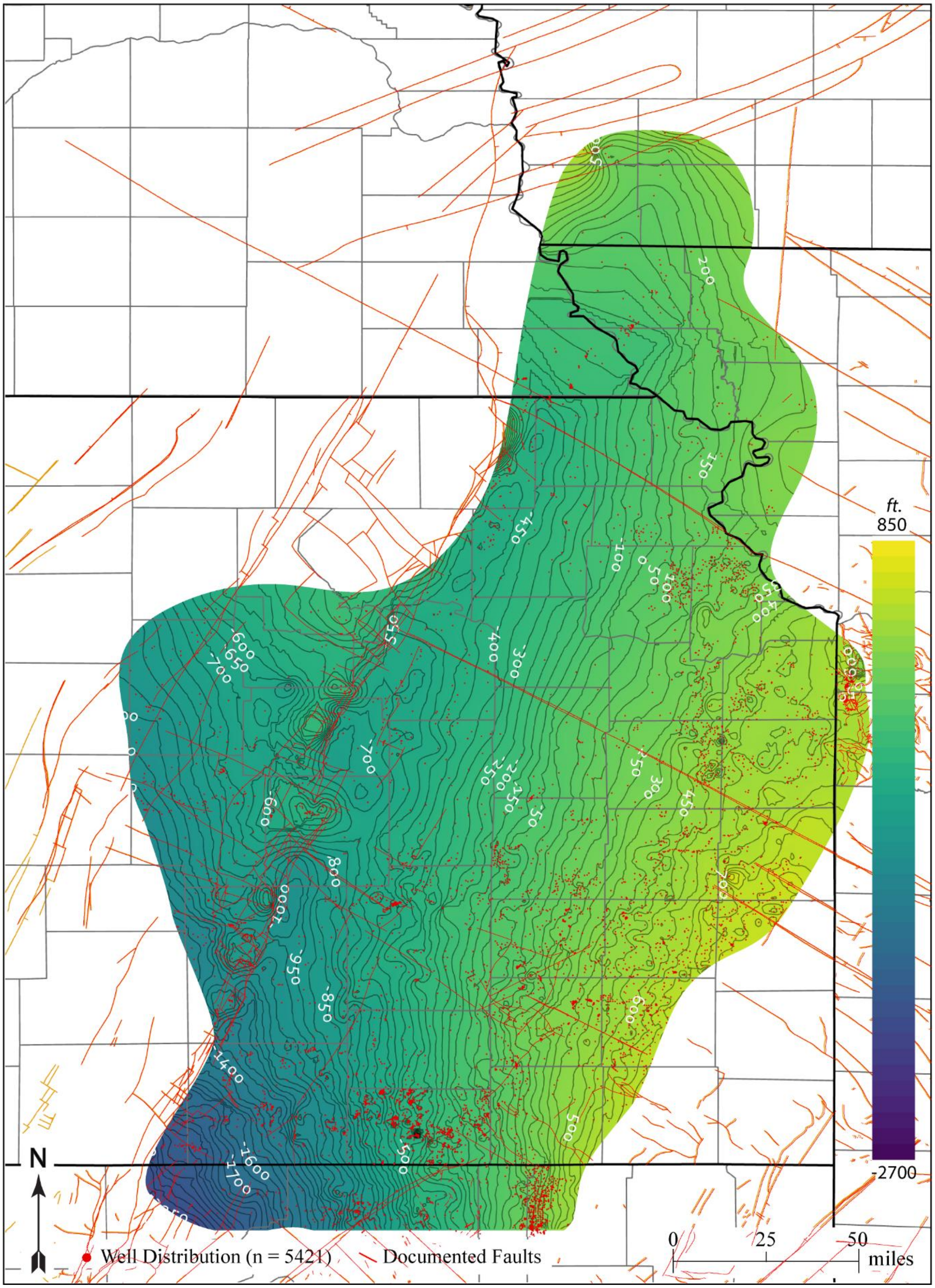
S4: Surface Map - Top Excello Shale Member



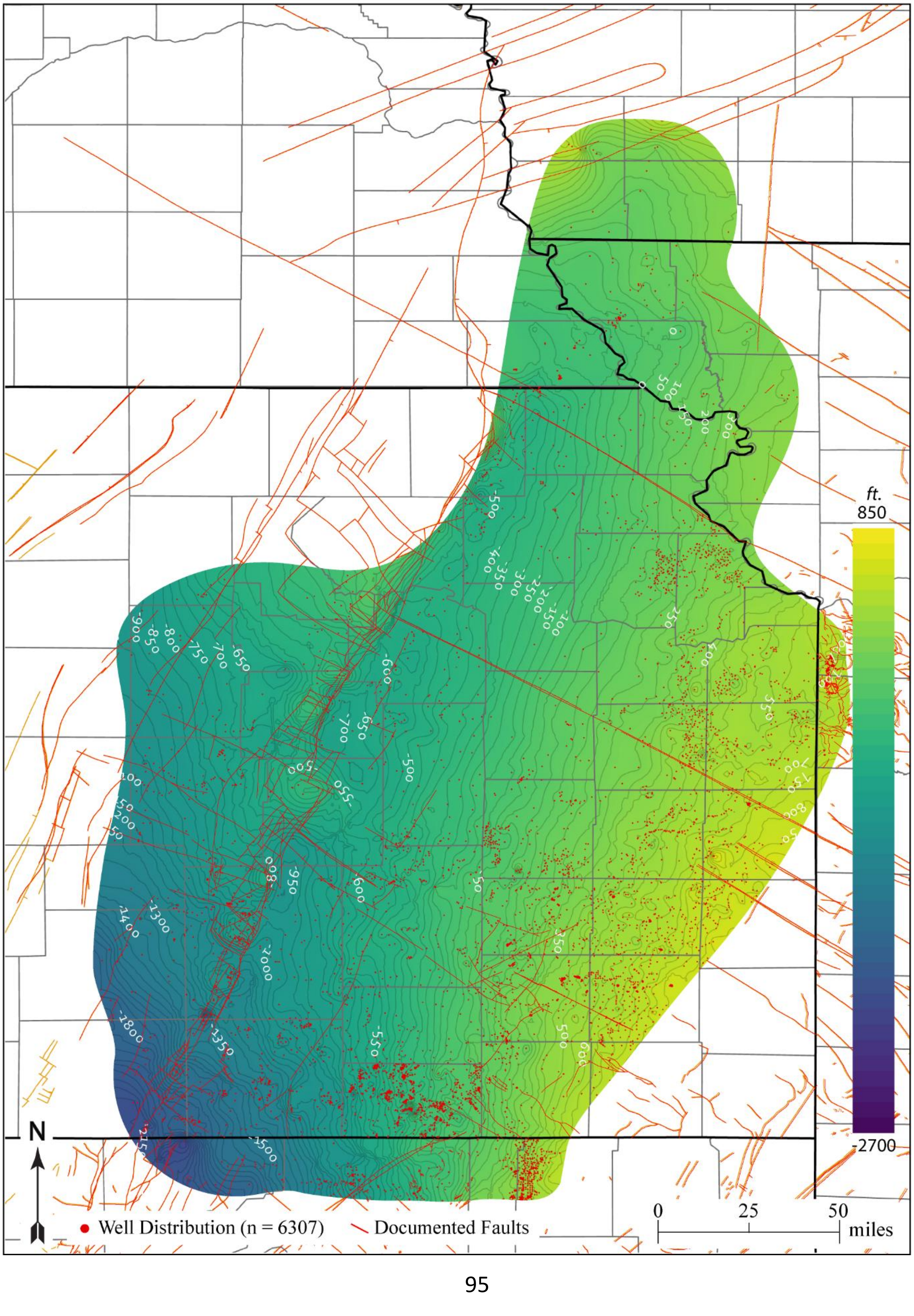
S5: Surface Map - Top Anna Shale Member



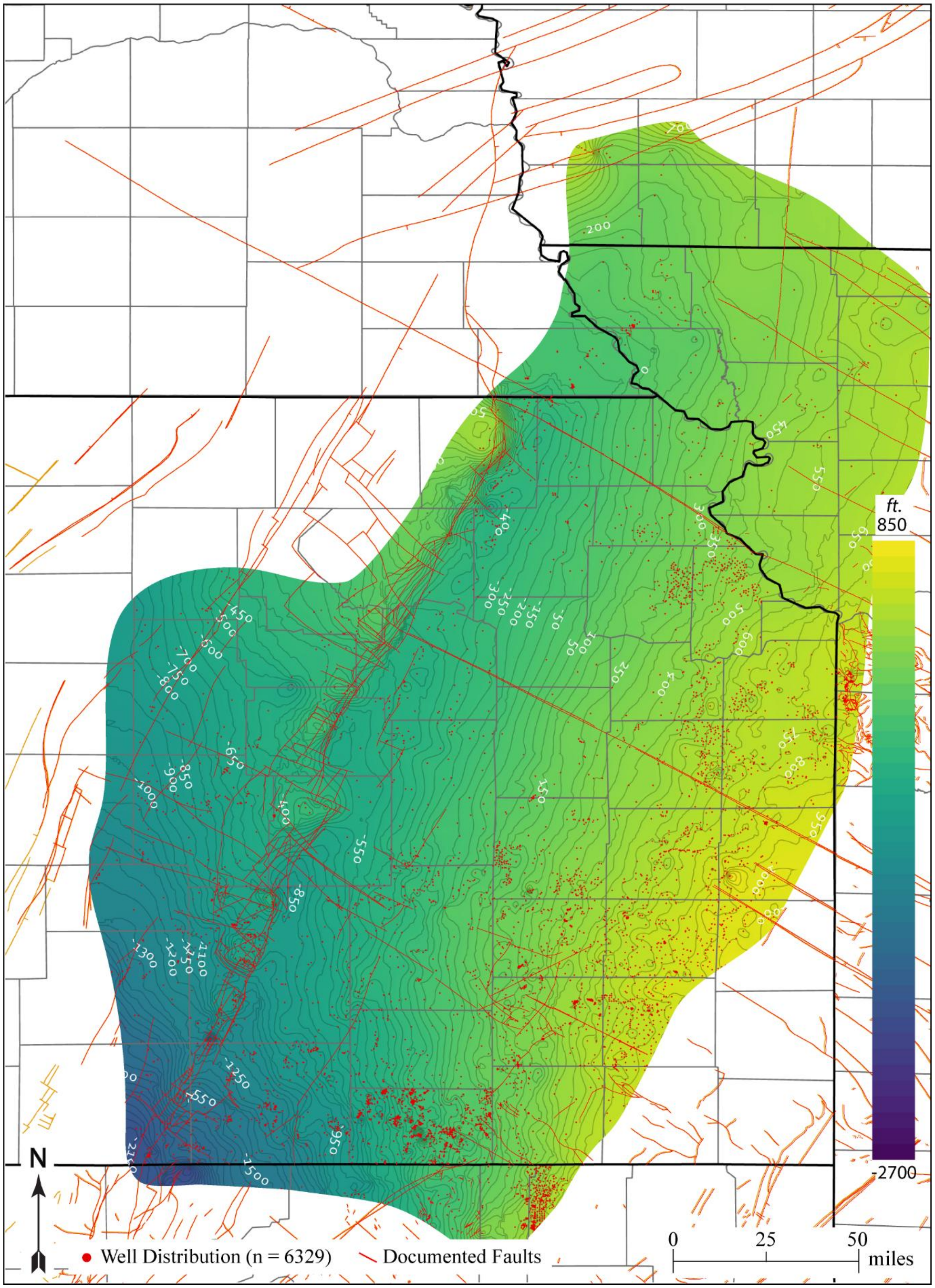
S6: Surface Map - Top Lake Neosho Shale Member



S7: Surface Map - Base Nuyaka Creek Shale Member



S8: Surface Map - Top Hushpuckney Shale Member



S9: Surface Map - Top Heebner Shale Member