SEQUENCE STRATIGRAPHIC FRAMEWORK AND RESERVOIR QUALITY OF THE RED FORK SANDSTONE, CLINTON-WEATHERFORD CHANNEL, ANADARKO BASIN, OKLAHOMA: EVALUATING HORIZONTAL EXPLORATION POTENTIAL IN FORMER CONVENTIONAL PLAYS

By

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SEQUENCE STRATIGRAPHIC FRAMEWORK AND RESERVOIR QUALITY OF THE RED FORK SANDSTONE, CLINTON-WEATHERFORD CHANNEL, ANADARKO BASIN, OKLAHOMA: EVALUATING HORIZONTAL EXPLORATION POTENTIAL IN FORMER CONVENTIONAL PLAYS

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Major Field: GEOLOGY

Abstract: The Pennsylvanian Red Fork Sandstone has a long history of conventional oil and gas production in western Oklahoma, particularly in an elongate trend called the Clinton-Weatherford channel. This study focuses on this trend in four counties, Blaine, Caddo, Custer, and Washita to establish a depositional framework based on a sequence stratigraphic interpretation of the Red Fork Sandstone interval. The Red Fork Sandstone is becoming a target for horizontal completion in the western Anadarko basin and understanding the Red Fork Sandstone and determining its position in the sediment dispersal system within a sequence stratigraphic framework is essential to locating reservoirs suitable for horizontal development. In this study area, the Red Fork Sandstone is subdivided into upper and lower subunits, which are separated by a shale marker bed that is recognized with consistence on wireline logs. Within the study area, the Red Fork Sandstone interval thickens from the northeast to southwest. The east-west trending Clinton-Weatherford channel has been interpreted as a shelf fluvial channel and submarine slope channel that supplied sediment to basin floor fans to the west. By reinterpreting and examining the key stratigraphic surfaces in core and core calibrated wireline logs, depositional sequences were established that allow delineation of thickness trends and facies distribution patterns, facilitating an overall interpretation of the sediment fill within this channel and the surrounding areas. This improves our ability to predict bypassed reservoir distribution within and outside channel-fills and as a result, contribute to exploration success. The results of this study could impact interpretation of other Pennsylvanian sandstone reservoirs in the western Anadarko basin including the Upper Skinner Sandstone, which displays a similar east-west trending elongate channel morphology.

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INTRODUCTION

The Red Fork Sandstone is a Middle Pennsylvanian (Desmoinesian) subsurface formation within the Cherokee Group. The term Cherokee was originally used in 1894 by Haworth and Kirk (1894) to classify a shale interval between the Fort Scott Limestone (also known as the Oswego Limestone) and the Mississippian carbonate in Cherokee County, Kansas. In 1954, the Oklahoma Geological Survey advocated to utilize the terms "Krebs" and "Cabaniss" to replace the Cherokee Group; however, the term Cherokee is still commonly used today with respect to the Pennsylvanian stratigraphy in Oklahoma (Withrow, 1967). In western Oklahoma, the Red Fork Sandstone has been conventionally and consistently drilled for hydrocarbons since the early 1960s, but other than a few isolated wells, the Red Fork Sandstone has yet to be produced from horizontal wells. Since discovery, many fields, trends, and districts producing primarily from the Red Fork Sandstone have been developed. For example, in 1982, the South Thomas oil and gas field in Custer county, had produced an estimated 2.9 million barrels of oil and 81.8 billion cubic feet of gas from wells that were completed in the Red Fork Sandstone (Johnson, 1984). Important reservoirs occur as channel-fills, and recognizing the complexity within these depositional environments is essential to understanding the depositional history, the shelf-to-basin transition, and the impact that different frequencies and magnitudes of relative sea level change had on valley erosion and filling. Recognizing incised valley-fill systems is essential for characterizing and predicting reservoir quality, improving reservoir development strategies by better predicting distribution, and recognizing unconventional or bypassed petroleum exploration opportunities in tight and/or compartmentalized sandstone accumulations. The principal purpose of this study is to understand the overall facies distribution and reservoir character of the Red Fork Sandstone within a sequence stratigraphic framework. Multiple interpretations of depositional settings and environments during Red Fork deposition have been suggested for different areas within the Anadarko basin; however, a complete sequence stratigraphic framework has yet to be formed. Defining whether the sediment accumulated in the channel during falling sea level or backfilled during a subsequent transgression could significantly impact lithofacies distribution, facies geometries, and the overall reservoir quality, parameters necessary to determine if the Red Fork channel or non-channel sandstone bodies are candidate reservoirs for horizontal drilling to produce low porosity/permeability sandstone or bypassed reserves in compartmentalized reservoirs.

ERA	PERIOD	SUB-PERIOD	SERIES	STAGE	GROUP	SUBSURFACE NOMENCLATURE
Paleozoic	Carboniferous	Pennsylvanian	Upper	Virgillian	Wabunsee	Wabaunsee SS
					Shawnee	Heebner SH
						Lovell LS
					Douglas	Tonkawa SS
				Missourian	Ochelata	Avant LS
						Cottage Grove SS
					Skiatook	Hogshooter LS
						Lower Layton SS (Marchand)
						Checkerboard LS
						Cleveland SS
			Middle	Desmoinesian	Marmaton	Big Lime
						Oswego LS
						Prue SS
					Cherokee	Verdigris LS
						Skinner SS
						Pink Lime
						Red Fork SS
						Inola LS

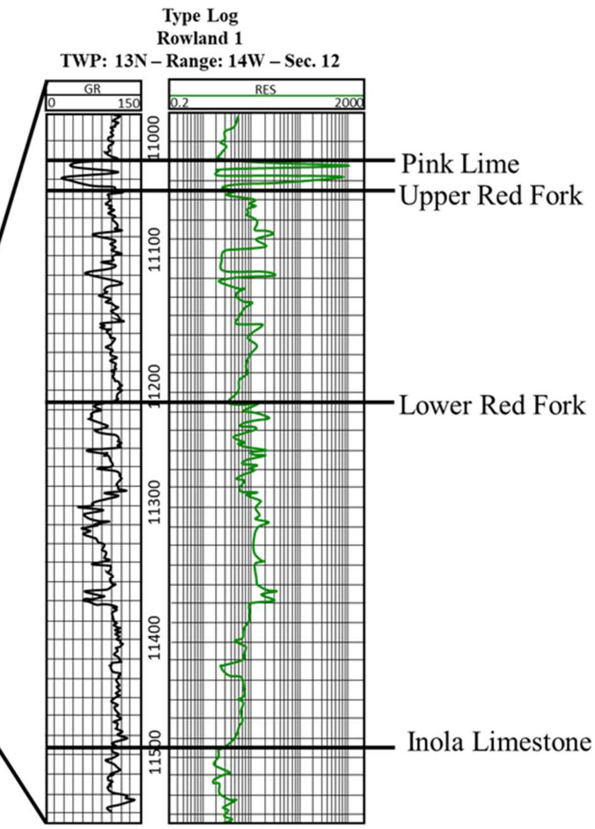

Figure 1: Stratigraphic nomenclature and type log for the interval of interest during the Pennsylvanian Subperiod, Carboniferous Period. Black lines indicate the interval of interest in this study. The Pink Limestone is positioned above the Red Fork Sandstone and the Inola Limestone is placed below. The Rowland 1 type log presents the common gamma-ray and resistivity signatures associated with the formation tops throughout this study (modified after Clement, 1991).

Location of Study

This study is located within the Anadarko basin, Oklahoma. The Anadarko basin is an asymmetrical depositional and structural basin with a relatively thick section of Pennsylvanian and Permian sedimentary rock (Hawthorne, 1985). The Anadarko basin is surrounded by the Anadarko shelf to the north, the Nemaha ridge to the east, and the Amarillo-Wichita Uplift to the south. Precisely, the location of this study consists of twelve (12) townships that include portions of four different counties: Blaine, Caddo, Custer, and Washita. Within these counties, well data were utilized from an area including townships 12 to 13 north and ranges 14 to 19 west. Specific attention was given to the stratigraphic relationships evident within and associated with the elongate trend known as the Clinton-Weatherford channel. This trend extends from township 12 north, range 13 west to township 12 north, range 19 west. The Clinton-Weatherford channel trend was the leading site of conventional exploration during the 1980s (Clement, 1991). The subsurface interval of interest within this study area is the Red Fork Sandstone, but the context of the Red Fork interval with the overlying Pink Limestone along with the underlying Inola Limestone was considered in establishing the sequence stratigraphic framework.

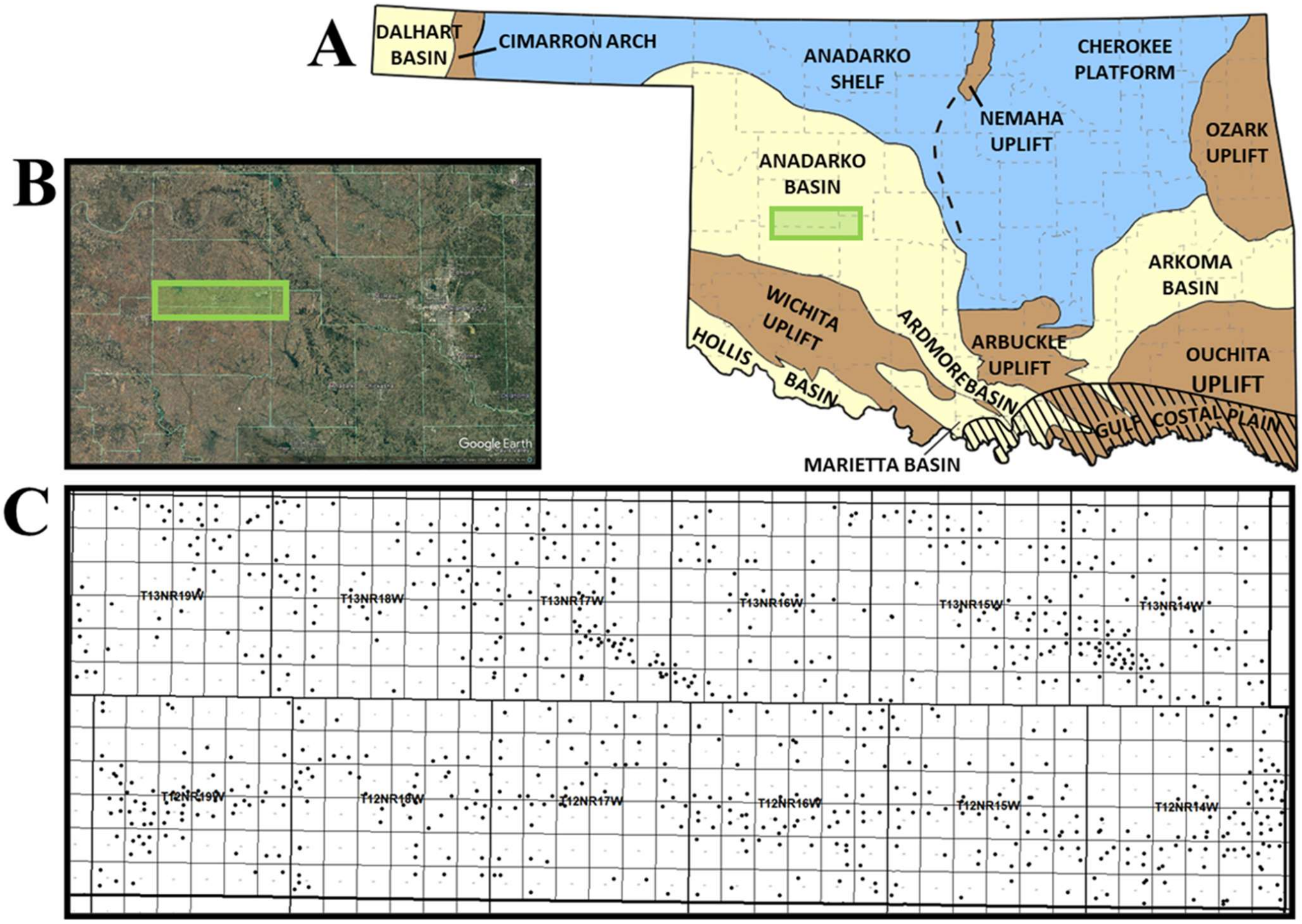

Figure 2: A) Map of Oklahoma with tectonic provinces. Green box indicates approximate location of counties located in study area (modified after Northcutt and Campbell, 1995). B) Google Earth insert of county outlines. Green box indicates location of well data (Google Earth). C) Location of well data represented by solid black circles from T.12N-13N and 14W-19W. "T." and "R." are abbreviated for Township and Range designations in the U.S. land grid (generated from GeoGraphix, wells provided by MJ Systems).

Discovery of the Clinton-Weatherford trend was the result of conventional exploration on anticlinal features. A shallow structural feature along the shelf to the north identified as the Corn-Eakly (or Fort Cobb) anticline became a central component in the development of the Clinton-Weatherford Red Fork trend (Clement, 1991). Six wells drilled along this anticlinal trend played a large role in the development of the East Clinton Field, which in the 1980s, quickly became one of the most actively explored oil and gas fields within the Anadarko basin (Clement, 1991). Twenty five wells within the East Clinton Field, producing the Upper Red Fork Sandstone cumulated approximately 220.8 billion cubic feet of gas (bcf) and 4.5 million barrels of condensate, or 46% of the total recoverable gas and 43% of the recoverable condensate produced in the first decade (Clement, 1991).

Objectives and Premise

The primary objectives of this study were to: A) identify sequence boundaries, probable systems tracts, and sediment distribution patterns for the Red Fork Sandstone, B) determine a depositional model for the Red Fork Sandstone within the Clinton-Weatherford channel trend, and C) evaluate reservoir quality and estimate the potential for successful horizontal drilling and completions. Understanding the depositional environment, thickness trends, reservoir geometries, and how diagenetic processes degrade or enhance porosity provide the basis for performing an evidence-based assessment of the potential for successful horizontal completions in the Red Fork Sandstone.

Basic topics addressed by this study include: Red Fork lithofacies and distribution of sandstone bodies, comparison of Red Fork distribution to the distribution of similar channel-fill and non-channel fill environments, depositional environment(s) that formed the Red Fork Sandstone, and the processes that controlled channel erosion and filling. This information produced was used to suggest parameters (or constraints) of sandstone body thickness and width that are necessary for horizontal completion within channel-fill environments and better exploration and production strategies to further develop the Red Fork Sandstone, as well as similar channel-fills.

Based upon previous investigations and interpretations regarding the depositional history of the Red Fork Sandstone, the Red Fork Sandstone was formed in two separate depositional environments. Accounting for the scarcity of well data for the Lower Red Fork within the study area, the depositional characteristics for the Lower Red Fork align with the suggestion that it was deposited within a submarine setting (Johnson, 1984). More specifically, within the study area the Lower Red Fork reveals steady gamma-ray curves (aggradational), with occasional submarine slope channel sandstones or fan deposits. The depositional setting was linked to submarine fan and pro deltaic settings that Johnson (1984) established. As a result of the scarcity of data, the principal focus of this study was the Upper Red Fork stratigraphic interval. A hinge line proposed by Anderson (1992) was determined to be present within the boundaries of this study, and supported his premise that the Upper Red Fork was likely deposited as a fluvial-deltaic complex on the shelf immediately landward of the shelf-slope break and transitioned into a slope setting. In the Anderson (1992) model, a channel eroded during a drop in sea level became the major conduit of sediment deposited as basin floor fans. This study proposes that the majority of Red Fork sediment accumulated during a highstand, but was eroded during the falling stage systems tract to form an incised valley known as the Clinton-Weatherford trend, which subsequently filled with sediment during the lowstand and transgressive systems tracts. To test this hypothesis and answer some of the fundamental topics outlined above, sequence boundaries, probable system tracts, and sediment distribution patterns were identified and explored. Understanding the processes that formed Red Fork sandstone reservoirs, depositional environments, thickness trends, reservoir geometries, and diagenetic processes is necessary to assess the potential of drilling successful horizontal wells within the Red Fork Sandstone, as well as similar channel fills and associated environments.

CHAPTER II

LITERATURE EVALUATION

Geologic History and Tectonic Framework

The Anadarko basin and its precursor the Oklahoma basin were determined to overlie basement rocks whose distribution indicate aulacogen characteristics and the premise that a failed rift arm developed in southern Oklahoma during the early Paleozoic (Burke and Dewey, 1973). The Middle Cambrian revealed early rifting, slow subsidence, and extensional faulting throughout the Late Cambrian to the Acadian orogeny during Late Devonian time (Clement, 1991). The subsiding basin remained relatively calm through the Mississippian and Early Pennsylvanian and became active with the beginning of deformation of the Wichita orogeny during Morrowan and Atokan time (Clement, 1991).

Major tectonic activity associated with the Pennsylvanian orogeny affected Early Desmoinesian Cherokee Group deposition in Oklahoma. Additionally, cyclical transgressive and regressive sedimentation occurred throughout the Pennsylvanian (Hawthorne, 1985). These cyclical patterns affected the Red Fork Sandstone and its sediment packages by increasing and decreasing accommodation, forcing transgression and regression, and resulting in deposition, erosion and patterns of sediment distribution influenced by these processes. Heckel (1996) determined that widespread transgression, regression, and progradation associated with Mid-Continent Pennsylvanian cyclothems were driven mostly by glacial eustasy, whereas Hawthorne (1985) acknowledged that relative sea level fluctuations were influenced by uplift of the craton.

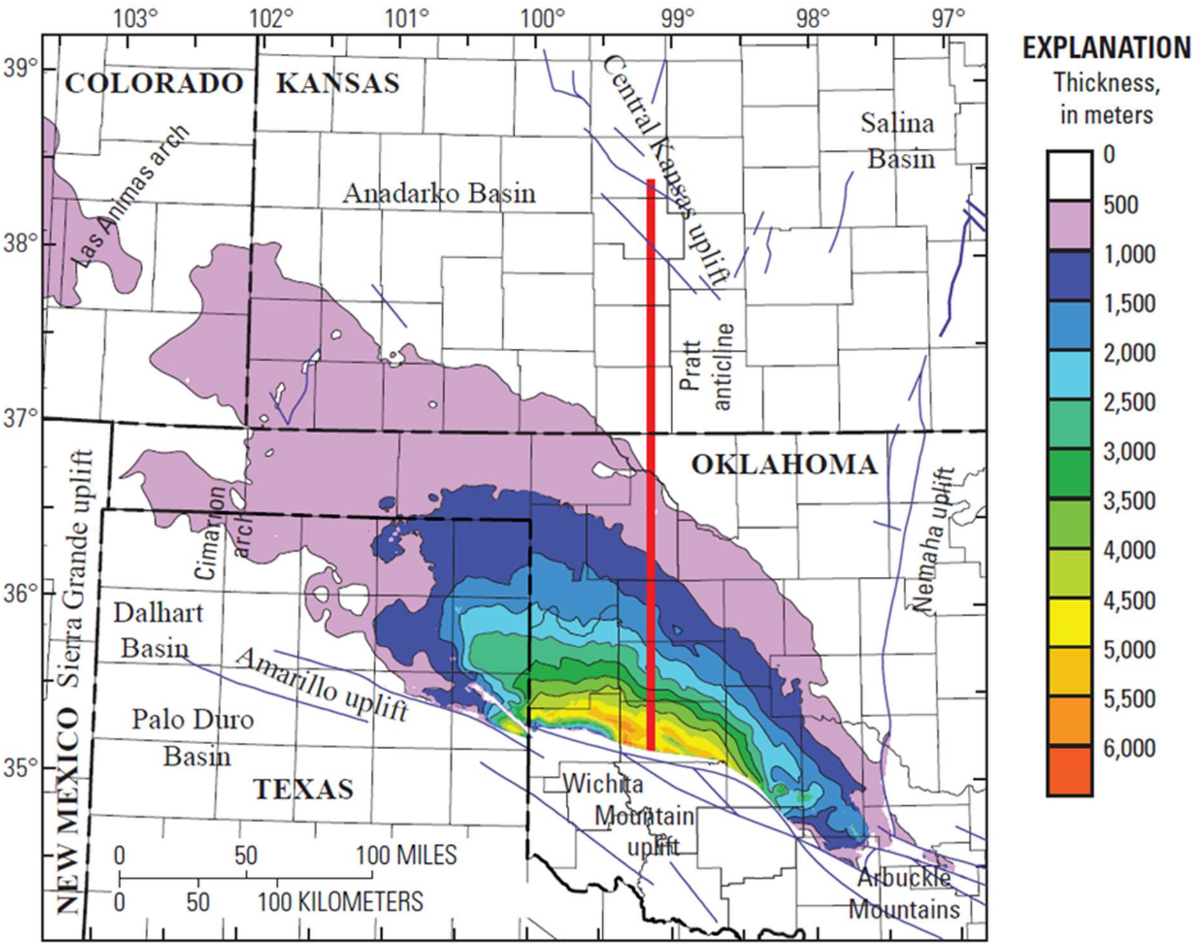

Figure 3: Geologic map of the Anadarko basin. Map illustrates thickness from the Hunton to the Desmoinesian. The Anadarko basin covers a large area and is approximately 360 miles long where it extends from the Arbuckle Mountains, into parts of Texas and Kansas (Higley, 2014).

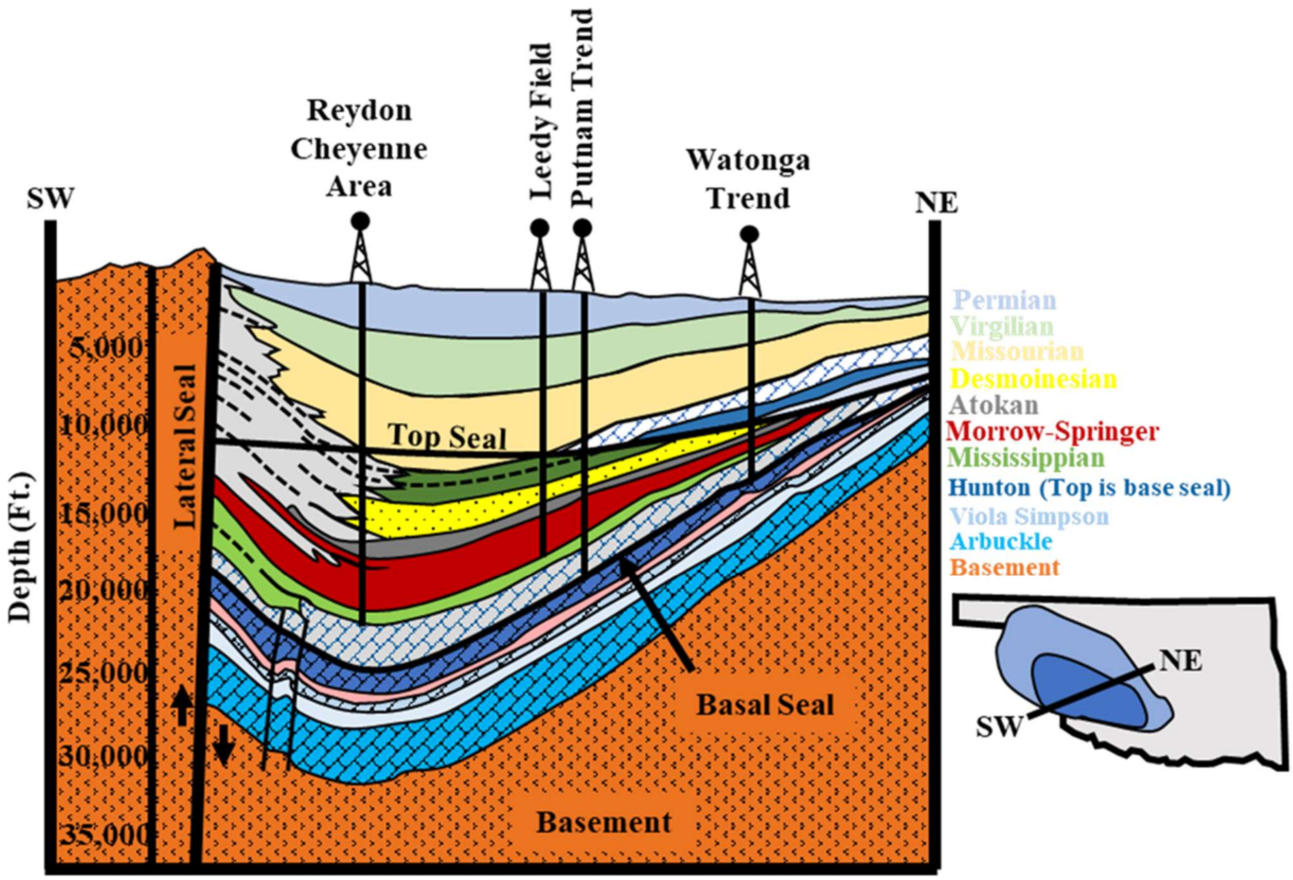

Figure 4: Cross-sectional view across the Anadarko basin showing relationships, common lithologies, and geometry of different stratigraphic units and trends. Arrows indicate generalized fault movement (modified after Lambert, 2006 and Al-Shaieb, 1992).

Previous Investigations

The Red Fork Sandstone was first described in 1911 by Hutchinson and is the subsurface stratigraphic equivalent of the Taft Sandstone that outcrops in eastern Oklahoma (Hawthorne, 1985). Consistently correlatable in this study area, the Red Fork Sandstone is subdivided into upper and lower subunits, which are separated by a radioactive shale marker. Lithostratigraphically, the Red Fork interval is overlain by the Pink Limestone and positioned above the Inola Limestone. A stratigraphic nomenclature chart and schematic diagram illustrating the erosive nature of major valley forming sandstone units can be seen in Figure 5. In the Anadarko basin, the Red Fork Sandstone produces from a variety of environments including higher-permeability channel fills and marine bars, and low permeability sandstones that are associated with submarine fans (Anderson, 1992). The Red Fork Sandstone interval thickens across the Anadarko shelf and into the basin from the northeast to the southwest in conjunction with northeast to southwest sediment transportation direction (Clement, 1991; Al-Shaieb et al., 1995; Puckette et al., 2000; Fritz et al., 2003; Tunin, 2020). A variety of depositional environments have been proposed for the Red Fork Sandstone. Whiting (1984) suggested deep-water channelized turbidity currents as the mechanism of deposition, Hawthorne (1985) described the Red Fork as a fluvial dominated deltaic complex (particularly within the South Thomas field), and Johnson (1984) characterized the Red Fork as a submarine channel-fill and fan environment. Johnson (1984) also recognized a hinge line for the Lower Red Fork that stretched northwest and southeast subparallel to paleostrike. Anderson (1992) identified a basin-floor submarine fan complex. Al-Shaieb et al. (1995), Puckette et al. (2000), and Fritz et al. (2003) presented regional interpretations of Red Fork Sandstone distribution patterns and identified fluvial-deltaic and marginal marine environments, shelf edge marine bars, and basin-floor fans. Toth (2018) recognized deep incision of the Cherokee Platform during Red Fork time and indication of eustacy driven changes in sea level.

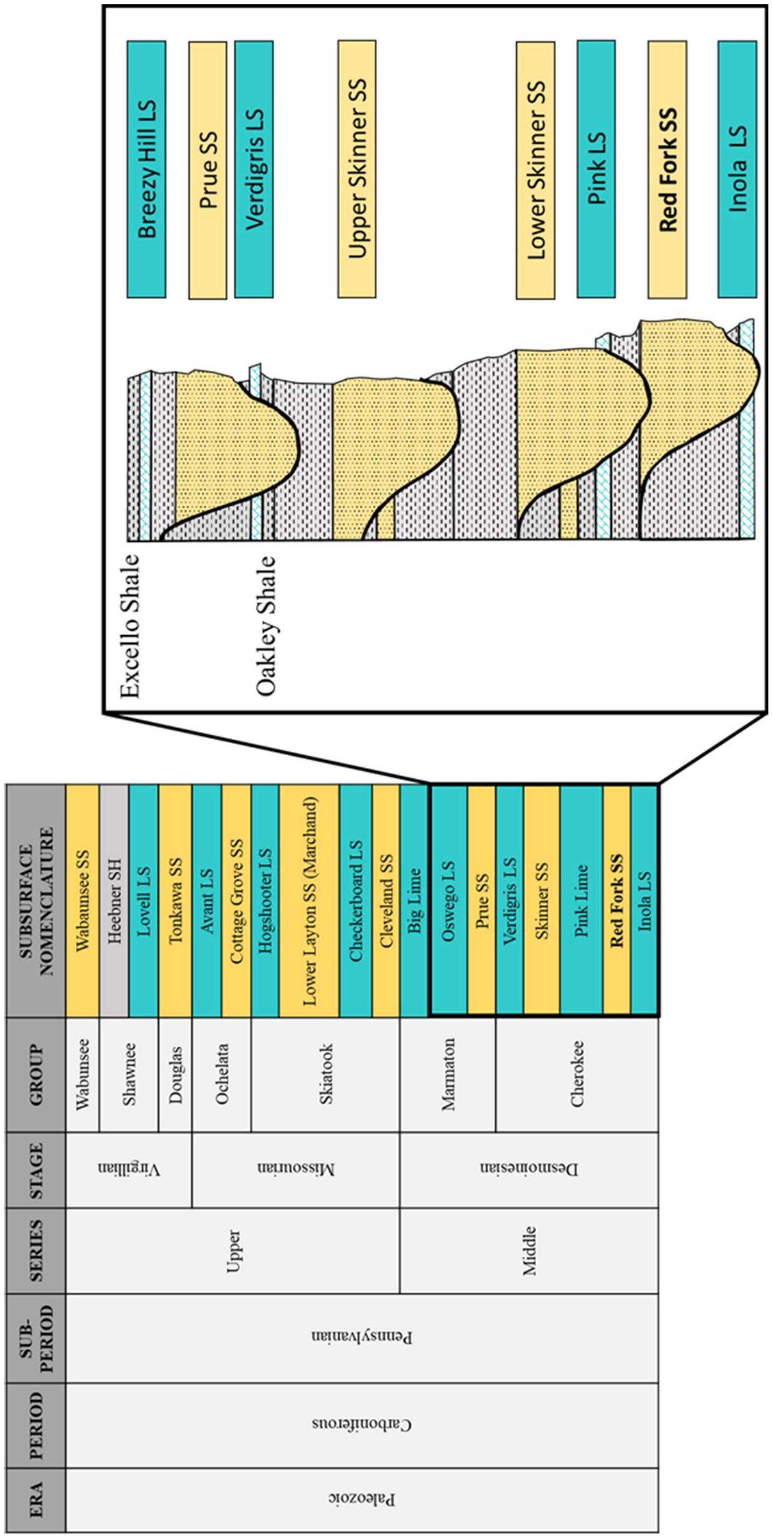

Figure 5: Chart showing stratigraphic organization, subsurface nomenclature, and the position of the Red Fork Sandstone and other important reservoirs that help define lithostratigraphy within the Middle Pennsylvanian (modified after Andrews, 2003 and Boardman, Marshall, & Lambert, 2002).

The Clinton-Weatherford Red Fork channel exemplifies a complex valley history that developed through a minimum of three separate phases of valley erosion and filling described in a study of the East Clinton field by Clement (1991). The valley development model proposed by Clement (1991) was used to further explain the channel trends within this study and consists of three different stages of valley development: I, II, and III. Stage I is the original incision and erosion of the valley during early Upper Red Fork time, stage II describes adjustment to a new base level and the development of an incised valley sequence with a range of depositional environments, and stage III signifies a second drop in base level with valley rejuvenation, downcutting and erosion, with subsequent backfilling of the valley during transgression (Figure 6) (Clement, 1991). Stage I deposition, if preserved, consists of intervals with wireline log characteristics that suggest fining-upwards and occasionally contain a sharp base. This stage predictably contains poorly-sorted very-fine to medium-grained quartz-rich sandstone (Clement, 1991). The intravalley heterogeneity and separation of stage II and stage III sandstone was supported in the completion results and production data (Clement, 1991). Stage II reservoirs were thicker, more resistive (up to 10 ohm-meters), fine- to very-fine grained fairly-sorted sandstone that is more widely distributed than stage III sandstone. These differences reflect stages of valley erosion and filling that result from changes in base level.

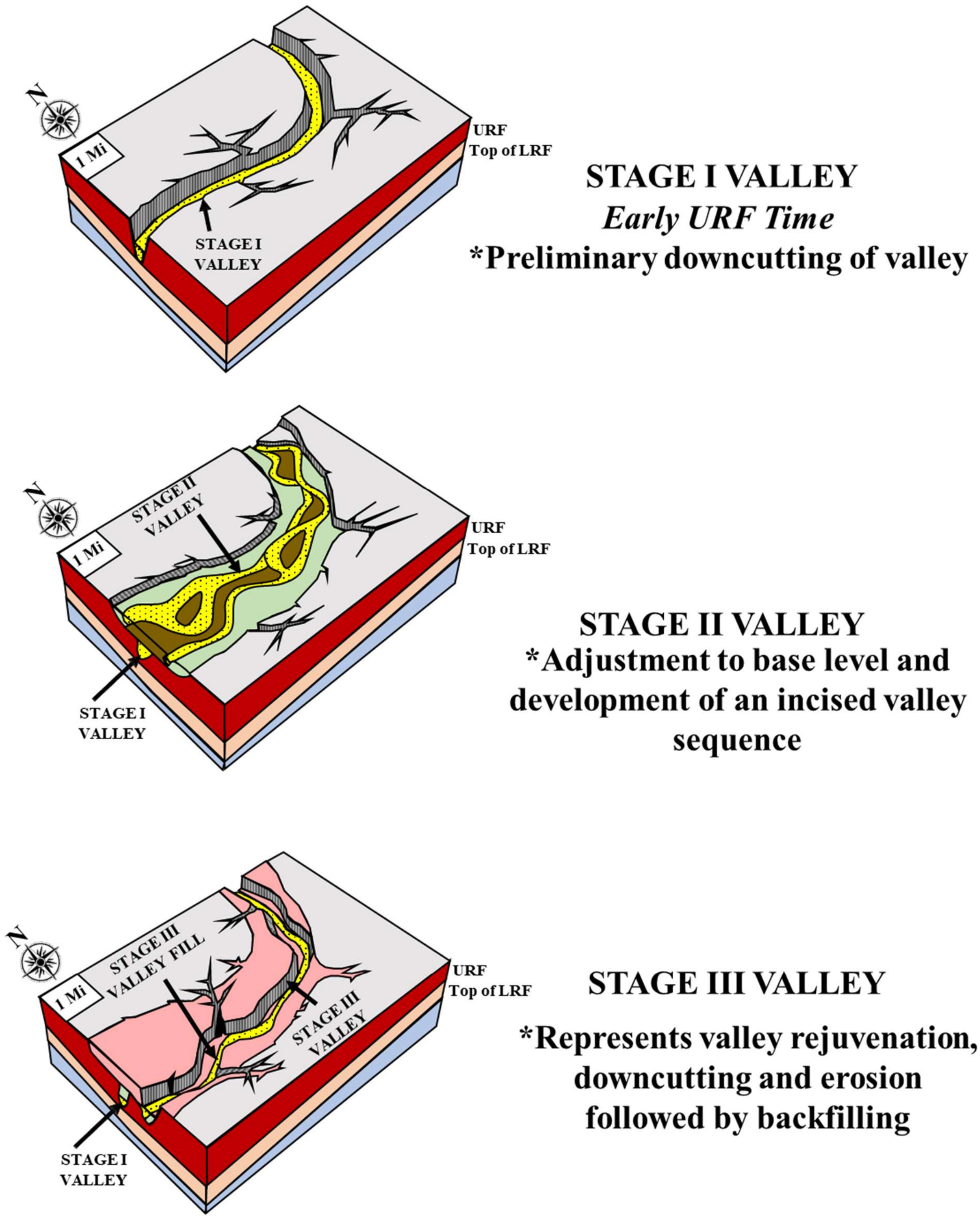

Figure 6: Models demonstrating the evolution of the East Clinton stretch of the Clinton-Weatherford trend. Stage I is preliminary incision. Stage II shows adjustment to base level resulting in heterogeneity of the valley fill with clay-rich estuarine muds (brown). Stage III shows rejuvenation after a drop in base level, that was subsequently filled during transgression(modified after Clement, 1991).

CHAPTER III

GEOLOGIC SETTING

Regional Stratigraphy

The Red Fork Sandstone is distributed across the Cherokee platform, Anadarko shelf, and within the Anadarko basin. It is part of the Cherokee Group, Desmoinesian Series, Pennsylvanian Subsystem, Carboniferous System, within the Paleozoic Era. The Anadarko basin is a mixed carbonate-siliciclastic system. Active tectonics and the expansion/-subsidence of the Anadarko basin during the Pennsylvanian, combined with fluctuations in relative sea level and changes in siliciclastic sediment supply, created cyclic patterns of sedimentation throughout the Mid-Continent region (Clement, 1991). This cyclicity continued into the Late Pennsylvanian and is represented stratigraphically by a wide variety of depositional settings and environments (Chenoweth, 1979). Lithostratigraphically, the Red Fork Sandstone interval is above the Inola Limestone and is in turn, overlain by the Pink Limestone. When carbonate is present in sufficient amounts, the Pink Limestone is characterized by a distinct gamma-ray and resistivity signature that is easily correlated across the study area. Puckette (1990) mapped this interval and produced a map that delineated the transition from limestone to a biomicritic shale. The change from carbonate to calcareous shale in the Pink Limestone interval was interpreted as a transition from shallower to deeper water on the shelf (Puckette, 1990). The transition shown on the map constructed by Puckette (1990) overlaps the study area in T.13N., R.16W. and T.13N., R.17W., and can be inferred to continue to the east and southeast similar to the shelf edge trend identified by Johnson (1984) for the Lower Red Fork interval.

The Red Fork is divided into upper and lower units. Lithostratigraphically, the Upper Red Fork interval extends from a shale marker bed that has an increased gamma-ray signature of about 105 to 120 API units over the immediately underlying section, to the base of the Pink Limestone described above. The more-radiogenic shale that marks the top of the Lower Red Fork interval is widely recognized in the Anadarko basin (Babb, 2020; Anderson, 1992; Udayashankar, 1985; Johnson, 1984). Occasionally, other studies noted a middle Red Fork; however, in this area the single division of the Red Fork interval into upper and lower division was applied. Within the study area, the Lower Red Fork displayed less complex stratigraphy and extends from the Inola Limestone, which is distinguished by a gamma-ray signature of 45 to 75 API units and a corresponding decrease in resistivity (Rt of < 4 ohm). When developed, the Inola displayed carbonate that was lower than the actual marker bed (Johnson, 1984). To the west and southwest, the Inola Limestone became more difficult to pick using wireline logs. The Atokan interval (13 Finger Limestone) was recognized on wireline logs of deeper wells because of its distinct interbedded radiogenic shale (> 150 API units) and carbonate.

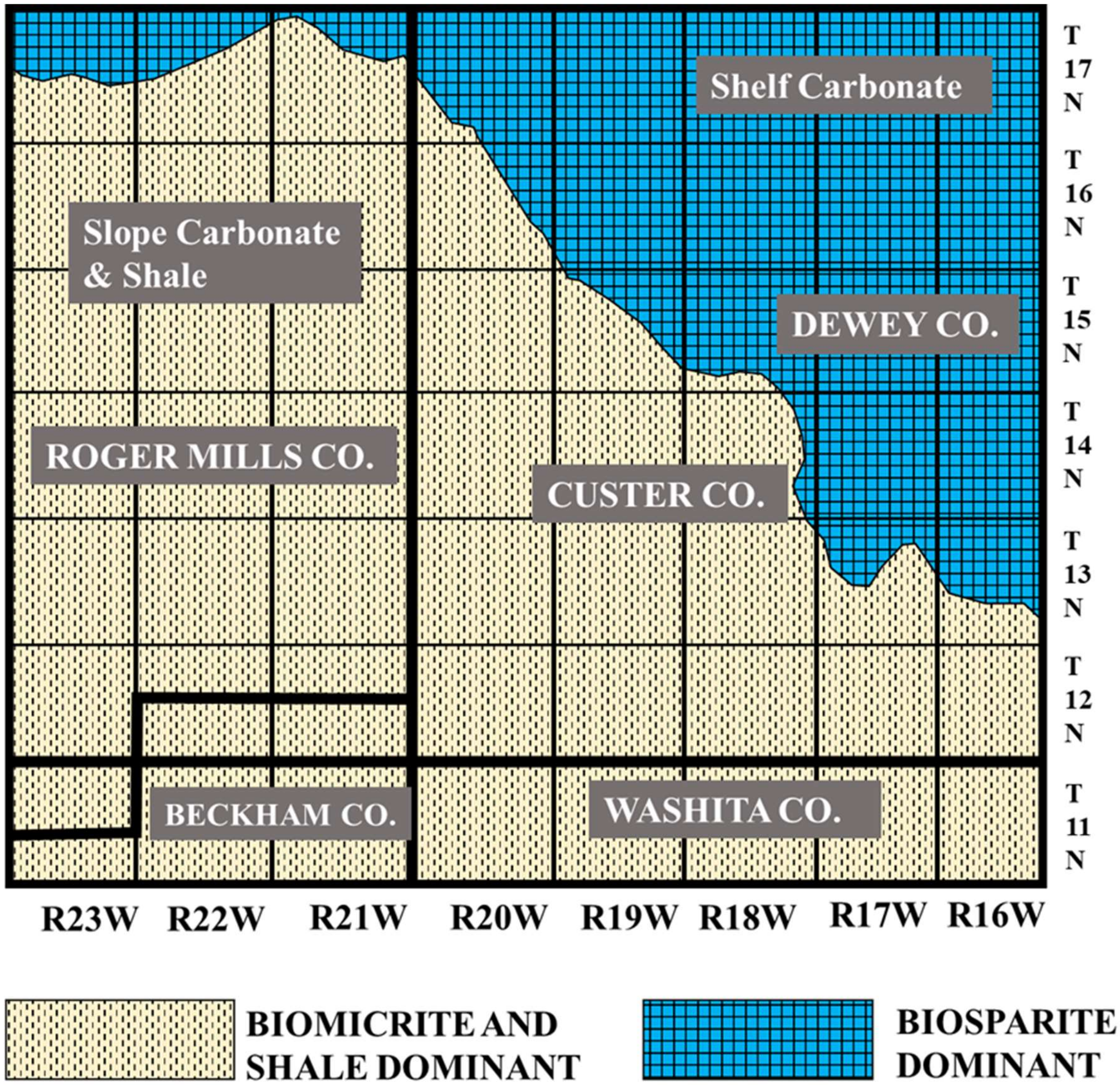

Figure 7: Pink Limestone transition from limestone to biomicritic shale. Transition line can be inferred to follow the trend of the hinge identified by Johnson (1984) for the Lower Red Fork (modified after Puckette, 1990).

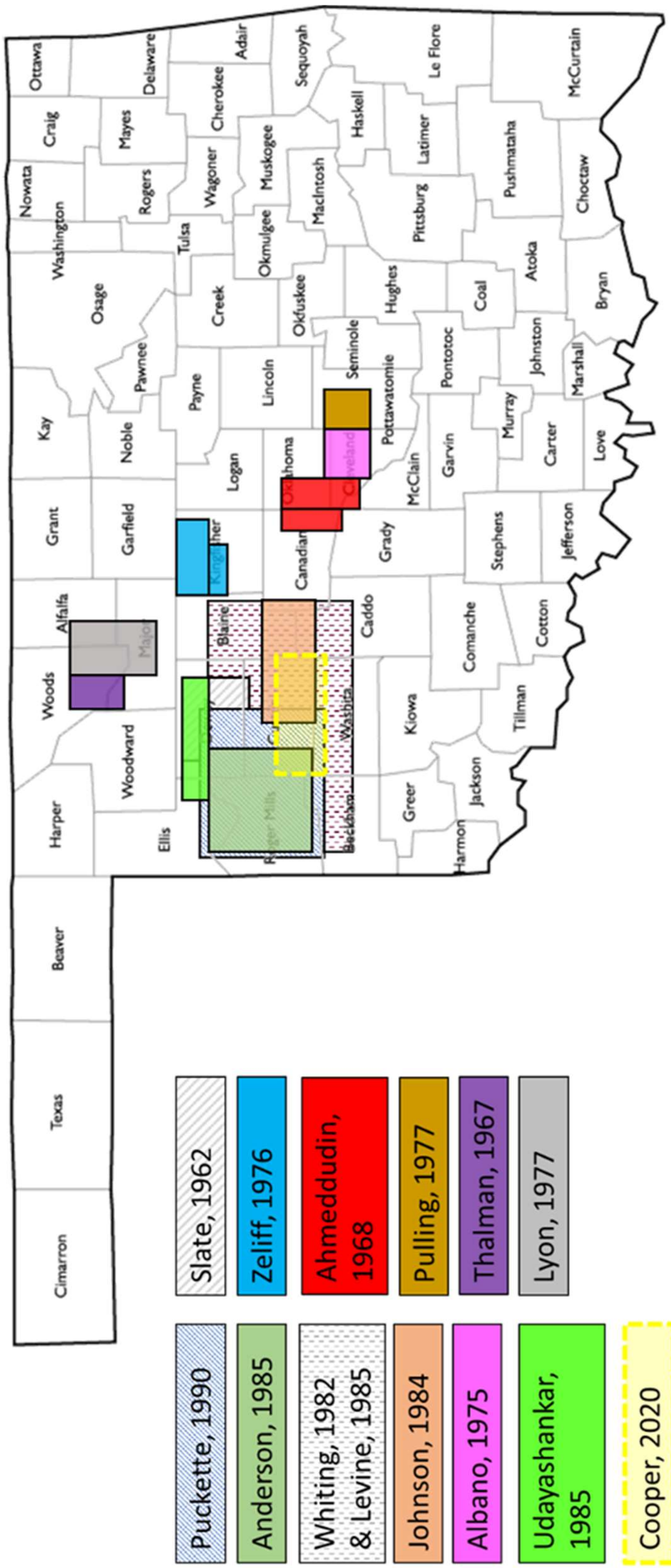

Figure 8: Oklahoma map showing county outlines and approximate locations of previous investigations of the Red Fork Sandstone (modified after Anderson, 1992).

Depositional Setting of the Mid-Continent

The regional depositional setting of the Red Fork Sandstone was influenced by the tectonic and eustatic processes that affected the Mid-continent from Iowa to Kansas, Missouri, Nebraska, and Oklahoma. During the Pennsylvanian, a shallow inland sea covered the North American Mid-continent. This sea was subject to repetitive cycles of rising and falling base level as Gondwanan ice sheets waxed and waned. These cyclic eustatic sea level changes generated a somewhat repetitive succession of lithofacies (Heckel et al., 1994; Heckel, 2008; Wanless and Shepard, 1936). These cyclic patterns were termed cyclothems (Wanless and Weller, 1932). Three categories of cycles affected periods of deposition through the Mid-continent that coincide with transgressive-regressive (T-R) sequences: (1) major cycles, (2) intermediate cycles, and (3) minor cycles (Heckel, 1994). Commonly, transgressive limestones overlie mudstone paleosols, terrestrial, or deltaic sandstone and shales that represent highstand or lowstand deposits, comparable to the transgressive Pink Limestone and the underlying Red Fork Sandstone (Heckel, 1994). Tectonism also influenced deposition and Brown Jr. (1979) described tectonic and sedimentary features in Pennsylvanian paleogeography within the Mid-continent that greatly influenced deposition: faulted and uplifted mountains, stable cratonic shelves and platforms, less stable subsiding shelves, deep-basin centers that are found beyond the shelf-platform edge during maximum subsidence of intracratonic basins, and the Granite Wash that was deposited proximal to the uplift.

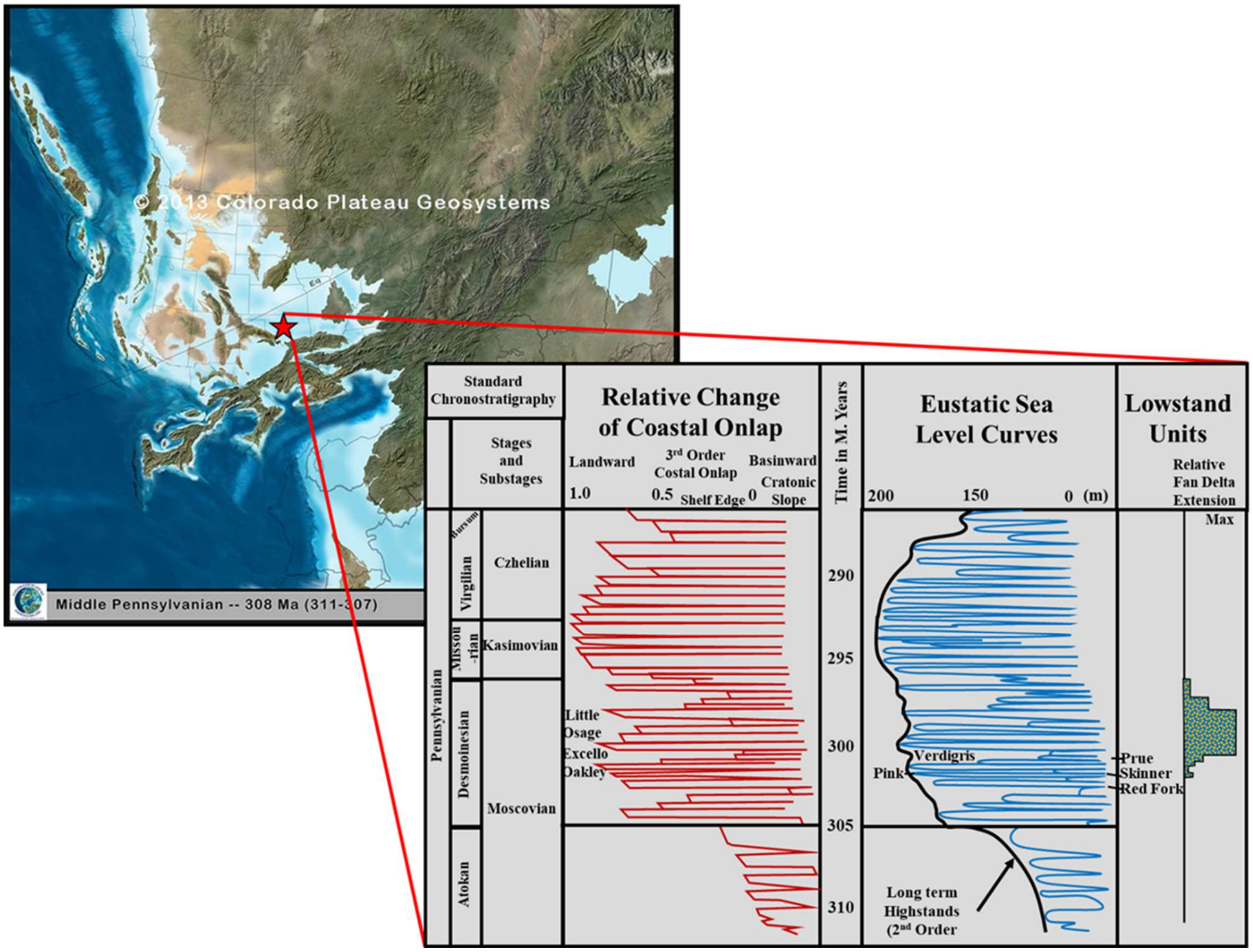

Figure 9: Middle Pennsylvanian (~ 308 Ma) paleo landform map from Blakey (2020) displaying shallow inland seas (left) and the position of the equator immediately north of the study area (red start). Mid-continent stratigraphic names for some radiogenic shales, sandstones, and lithostratigraphic interval-defining limestone marker beds, as well as relative extension of fan deltas from the Wichita-Amarillo uplift, superimposed on Pennsylvanian eustatic sea level curve and relative coastal onlap curve (right) (modified after Ross and Ross, 1987).

Fundamentals of Sequence Stratigraphy

Sequence stratigraphy has been defined as the study of rock relationships within a chronostratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or nondeposition, or their correlative conformities (Van Wagoner et al., 1987). The basic components of a sequence include sequence boundaries, systems tracts, condensed sections, flooding surfaces, and maximum flooding surfaces, all relative to the rise and fall of the sea level. The different system tracts include, among others, the lowstand, transgressive, and highstand systems tract. Posamentier and Vail (1988) recognized two different types of sequences for clastic deposition such as a type-I or type-II sequence, dependent on the unconformity that rests at the base (Wright and Marriot, 1993). A type-I sequence boundary (or unconformity) occurs when the eustatic fall of sea level is greater than the subsidence rate while the type-II sequence boundary occurs when the eustatic drop in sea level equals the rate of subsidence. A type-I bounded sequence often includes incision of a valley(s), as seen in Figure 10, revealing an erosional surface.

Sequence stratigraphic interpretation can vary, however, the typical log signatures with respect to the sequence stratigraphy concepts are commonly understood and accepted. As Posamentier and Vail (1988) stated, a type-I sequence is bounded by the unconformity at the base. In this context, a sequence boundary is a widespread surface that separates the rocks above from those below and is marked by truncation in a type-I sequence (Van Wagoner et al., 1990). This sequence boundary signifies a drop in sea level that caused incision and is often represented by a distinct change in lithology or sharp basal contact between an interval of low gamma-ray readings on a wireline log and subjacent mudrocks. Often, the erosional sequence boundary at the base of a channel is associated with a lowstand systems tract (LST), as seen in Figure 12. This erosional surface is often correlated to a surface known as the correlative conformity. The correlative conformity is defined as a stratigraphic surface that indicates the shift in stratal stacking patterns from highstand normal regression to forced regression or from forced regression to lowstand normal regression (Catuneanu et al., 2009; Van Wagoner et al., 1990). The lowstand systems tract is typically well-preserved in the siliciclastic sequences, and its main geologic feature is the incised valley (or channel) (Van Wagoner et al., 1990). The lowstand systems tract is linked to a sea level retreat (or the lowest point before the sea begins to rise again). It is frequently characterized by lower gamma-ray readings on a wireline log coupled with sand infill and oftentimes exhibits a “rectangular” or “blocky” shaped gamma-ray curve. This curve eventually shows upward increasing gamma-ray values that reflect a transition upwards until it merges with shale that represents a transgressive surface (Wright and Marriott, 1993). The valley eroded during the falling stage and lowstand systems tracts is clearly identifiable by its distribution pattern of elongate and thick sandstone bodies, blocky gamma-ray log signatures, and erosional relationships with local stratigraphic marker beds and underlying mudrock. Subsequently, the transgressive systems tract (TST) begins as the first flooding event after the lowstand regression and represents rising sea level (Wright and Marriott, 1993). Deposition during the transgressive systems tract is characterized by a fining-upwards profile that can be either drastic and short or prolonged and subtle. The maximum flooding surface (MFS) denotes the highest point of the transgressive systems tract and often involves a condensed section (or CS) (Van Wagoner et al., 1990). The maximum flooding surface marks the boundary between the transgressive systems tract and the highstand systems tract, is characterized by a sudden rise in the water depth, and indicates the flooding surface that extends the furthest inland (Van Wagoner et al., 1988). The MFS usually is associated with the largest short-duration increase in the gamma-ray values on the wireline log and is caused by a buildup of clay minerals and specifically organic matter. Conditions such as stratification of the water column favor the preservation of organic matter and the deposition of uranium (U) in sediment. The condensed section is made up of marine sediments that were deposited at very slow rates, a factor that favors U accumulation. Condensed sections can be difficult to identify using wireline logs alone, owing to their thin nature and the homogenizing effect on wireline logs, as well as the significant time span that these sections represent (Van Wagoner et al., 1990). The highstand systems tract (HST) is positioned at the top of a sea level rise and fall sequence. The HST is represented by the later stages of a eustatic sea level rise, a eustatic stillstand (high-level water depths), and the early stages of eustatic fall. The HST commonly supports prograding clinoform geometries (Van Wagoner et al., 1998). This systems tract displays a coarsening-upwards gamma-ray profile bounded at the top by a distinct change in gamma-ray values associated with the upper sequence boundary.

Wireline well logs within the Red Fork Sandstone interval often portray characteristics that align with those of a channel fill. It is essential to understand that an incised valley originates when a fluvial stream erodes and cuts through the sediment (Schumm et al., 1994). Incised valleys are deeply rooted fluvial systems that extend their channels basinward while eroding into underlying, older strata (Van Wagoner et al., 1990). The incision and subsequent filling of a valley system occurs in two separate stages encompassing a drop in relative sea level (also known as the falling stage systems tract or FSST) and the later rise. When sea level rises during the LST and TST, these valleys and channels therein predominantly fill with sand by a backstepping depositional process whereby rising base level reduces energy in the valley, forcing deposition. Flooding culminates with a valley-flooding surface, typically a marine mudstone or shale. Andrews (2003) stated the Red Fork Sandstone interval has channel sandstones, which consistently display incised valley characteristics such as the sharp basal contact with a blocky to fining-upwards textural shape. Thicker Red Fork Sandstone bodies on the shelf are associated with incision of the underlying highstand prograding deltaic deposits (Toth, 2020).

These two categories of incised valley-fill systems and their accompanying sediment fill: those eroded in response to a sea level fall and those linked to other factors such as tectonic uplift or climatic fluctuations (Dalrymple et al., 1994). Sediments that fill these incised valley systems generally form elongated belts of sandstone that can be reservoirs for oil and gas (Kindinger et al., 1994). Wells in the Red Fork Sandstone within the Clinton-Weatherford channel trend produce from low permeability sandstone contained by stratigraphic traps (Clement, 1991). An incised valley deposit is characterized by many different sedimentary features (rip-up clasts, massive sandstone bedding, chaotic bedding, etc.) and factors (rate of sea level rise, sediment supply source, architectural geometry of the valley (depth, slope, and width), etc.) that impact the incision and its subsequent sediment infill (Weimer et al., 1993). Other common sedimentary features observed in channel-filling sandstone include bedforms such as cross-bedding or ripples (Andrews, 2003).

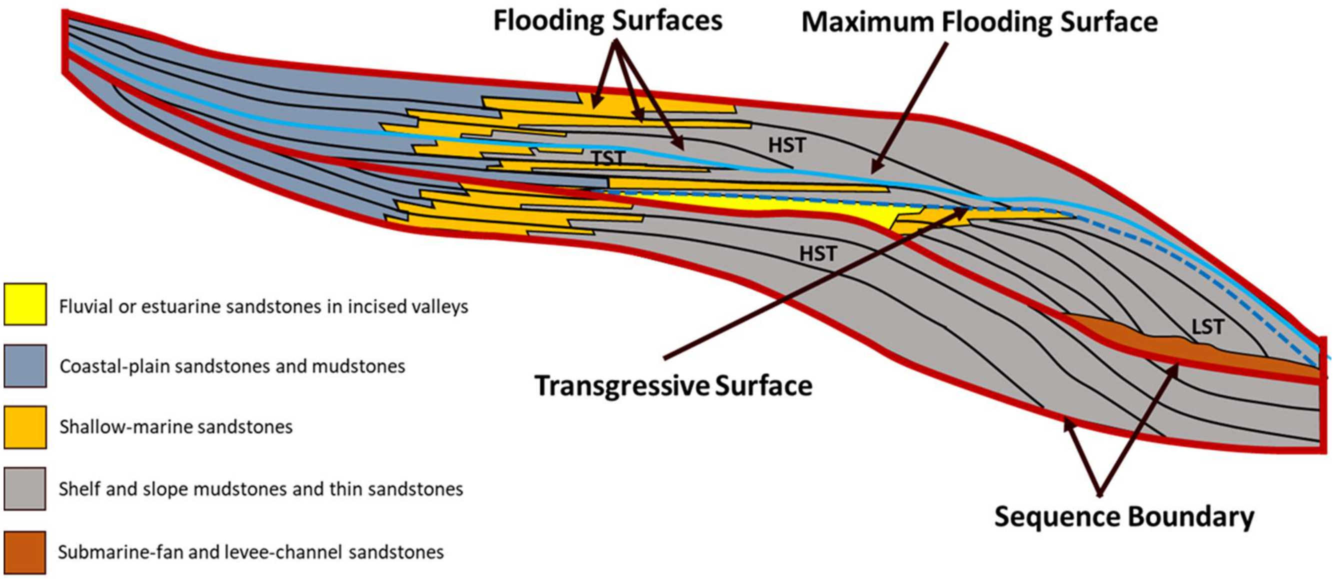

Figure 10: A type-1 sequence established on a shelf margin. The bright yellow color fill represents fluvial or estuarine sandstones that filled in a valley. The sequence boundary is shown by the dark red bolder line (modified after Van Wagoner et al. 1990).

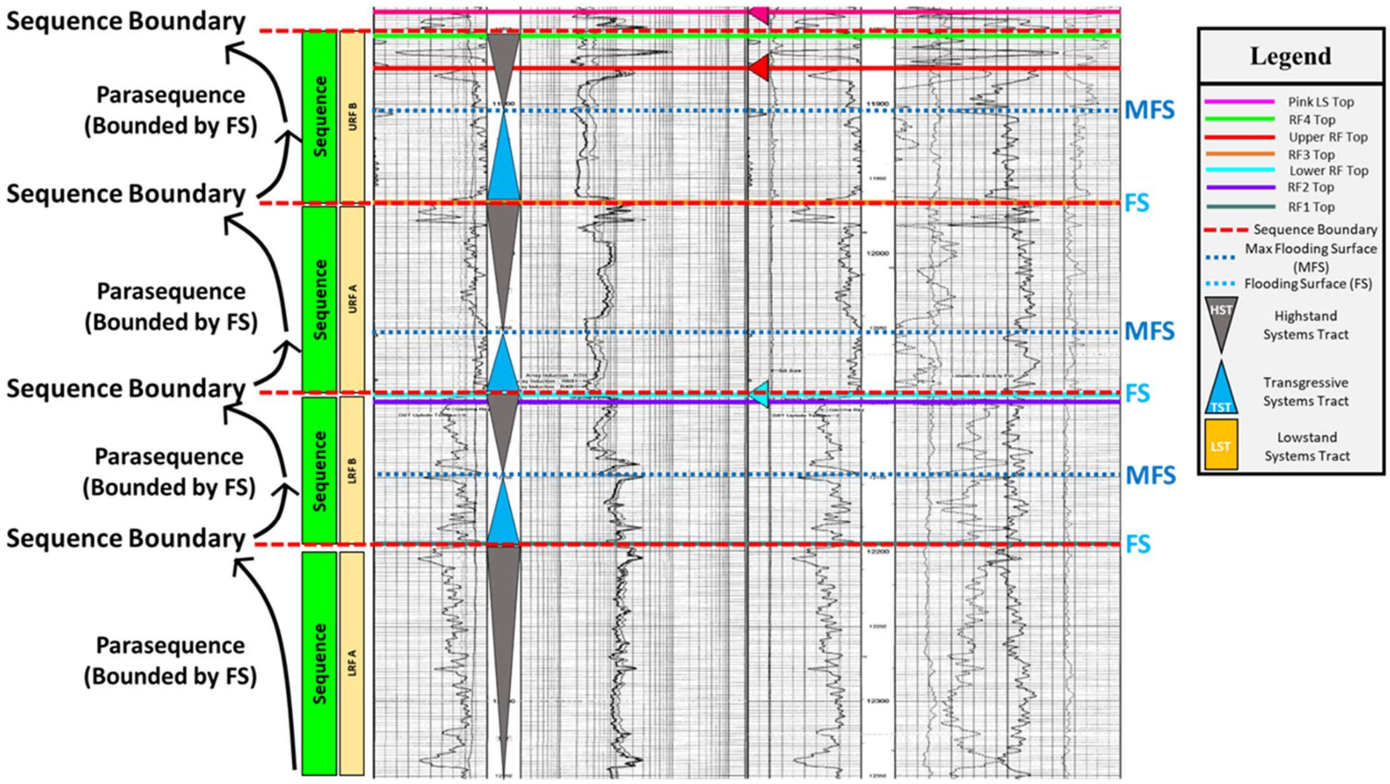

Figure 11: Example of the Red Fork sequence stratigraphy. Four parasequences within this well are bounded by flooding surfaces. URF: Upper Red Fork; LRF: Lower Red Fork. Inola Limestone not shown in this wireline log.

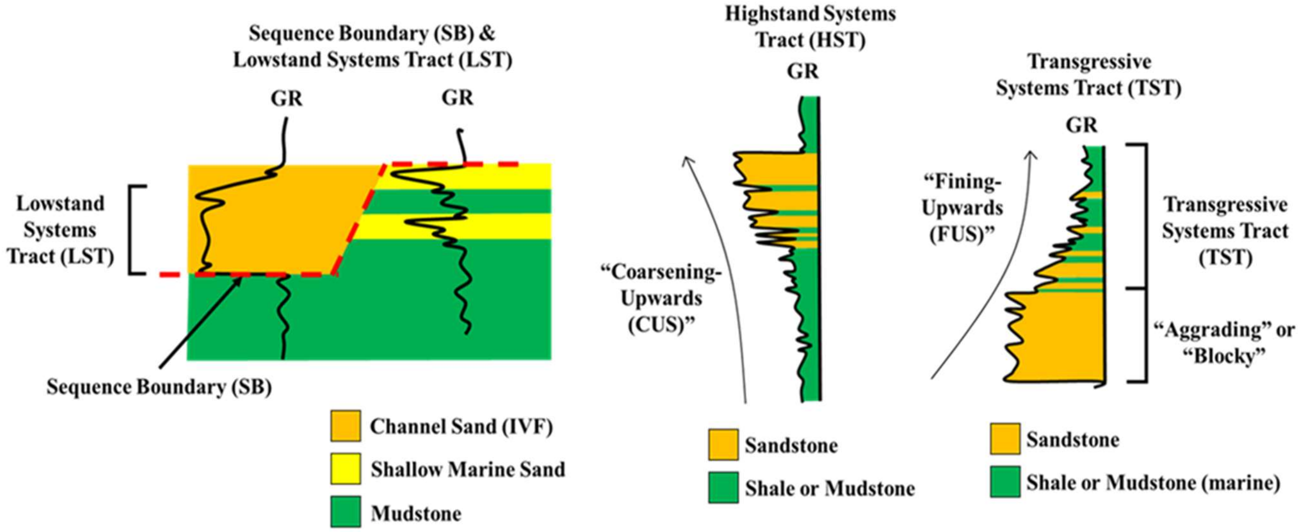

Figure 12: Common examples of log signatures with respect to sequence stratigraphy (modified after Van Wagoner et al., 1990).

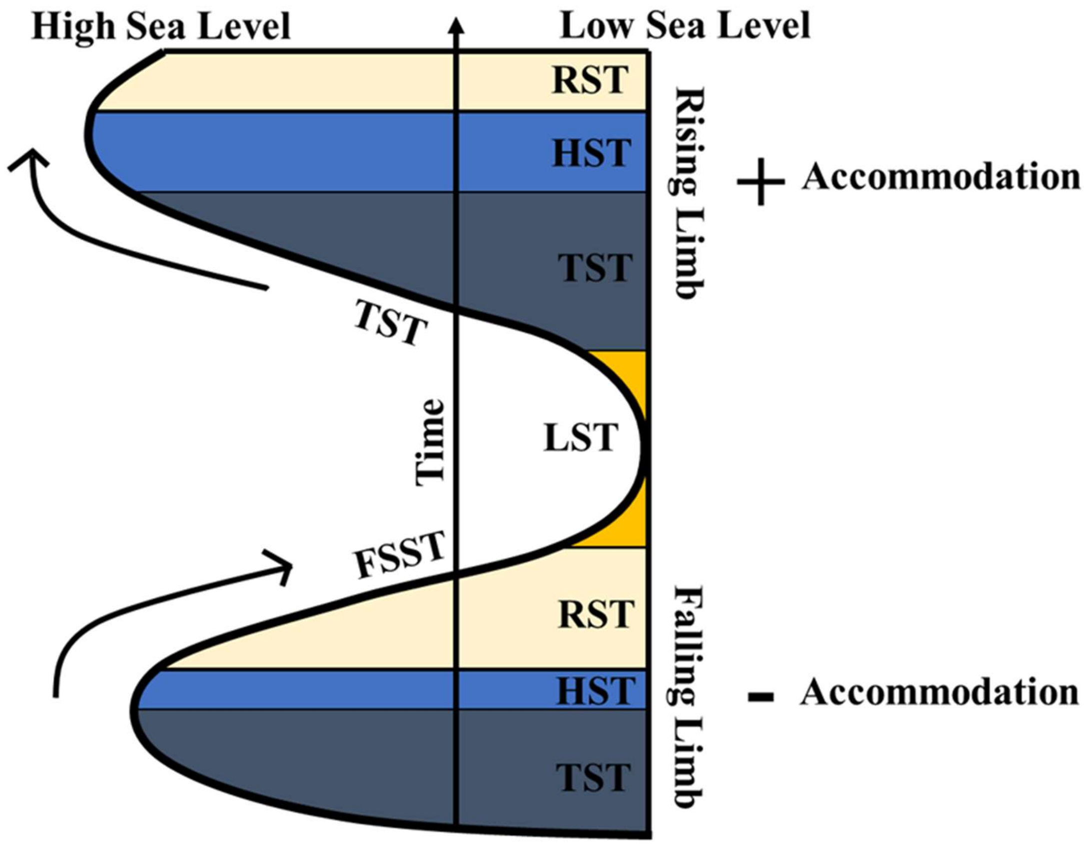

Figure 13: Sine curve model representing a relative sea level cycle and standard sequence stratigraphic surfaces and systems tracts with respect to the sea level curve. RST: Regressive Systems Tract; HST: Highstand Systems Tract; TST: Transgressive Systems Tract; LST: Lowstand Systems Tract; FSST: Falling Stage Systems Tract. Increasing vertical accommodation during the rising limb and decreasing accommodation space during the falling limb (modified after Pigott and Bradley, 2014).

CHAPTER IV

METHODOLOGY

Establishing if the fill within a channel represents a backfilling during transgression or accumulation by aggradation during regression is important to deciphering potential compartmentalization and determining if the fill is a candidate for horizontal drilling to produce bypassed pay. In addition, the impact of depositional processes operating within a valley during periods of stable base level could impact depositional style, reservoir, and seal evolution. The following methods and procedures were used to interpret the evolution of Red Fork Sandstone bodies within the area of interest: literature review, mapping and cross sections, examining sedimentary and biogenic features, and review of completion and production data. An initial review of published literature and unpublished investigations of the Red Fork Sandstone was completed to understand the overall basin analysis, geological history of the basin and formation of interest, as well as a regional analysis of Red Fork Sandstone petrology and diagenesis. The two nearest studies were MS theses completed at Oklahoma State University by Johnson (1984) and Anderson (1992).

Well data were obtained from MJ Systems and used to evaluate the subsurface including thickness, attitude and distribution of the Red Fork Sandstone within the area of interest. Well data were obtained in townships 12 to 13 north and ranges 14 to 19 west. Once all well data were obtained, a mass import was made into GeoGraphix software to assist in the development of subsurface maps, regional cross-sections, and reservoir analysis for the Red Fork Sandstone. First, four key formation tops were identified and recorded in the available well data: Pink Limestone, Upper Red Fork, Lower Red Fork, and Inola Limestone. These tops were picked using their common signatures developed in nearby studies, oil and gas well record forms (1002A) from the Oklahoma Corporation Commission (OCC), and well logging field experience. Wireline well log cross-sections were created to correlate four main stratigraphic intervals within the area of interest: Pink Limestone, Upper Red Fork, Lower Red Fork, and Inola Limestone. Numerous cross-sections were constructed in order to estimate and interpret the accommodation during Red Fork time and expected trends of channelized and non-channelized sandstone deposits. This was achieved by the determination of sub-interval stratigraphic surfaces within the Red Fork interval which included: Red Fork 1 (RDFK1), Red Fork 2 (RDFK 2), Red Fork 3 (RDFK 3), and Red Fork 4 (RDFK 4). These cross-sections included some that were oriented subparallel to expected depositional strike and others that were oriented at a high oblique angle to depositional strike in order to identify sediment thickness patterns. Approximately 1,500 wire-line well logs were acquired from MJ Systems and reviewed during the construction of these cross-sections. As a result of missing raster images, several wells were unaccounted for, which reduced well control. An effort to locate missing well data from other sources when raster images from MJ Systems were absent included contacting sources such as Enverus (also known as Drilling Info) and the Oklahoma Geological Survey database. After reviewing available data, it was decided meaningful interpretation of the Lower Red Fork was not likely due to a scarceness of well logs across the interval. As a result, the study was restricted to the Upper Red Fork interval and it became the section of interest.

Depositional facies and stratigraphic boundaries were identified in a single core provided by the Oklahoma Petroleum Information Center (or OPIC). Due to the core facility being closed for over nine months, the core analysis had to be completed virtually from photographs. This core was correlated and calibrated to its wireline well log to establish any identifiable sequence boundaries or unconformities, identify probable systems tracts, and extract thicknesses necessary to map sediment distribution patterns. This core was located just outside of the Clinton-Weatherford channel in the NE Sec. 23, T.12N., R.15W., and was drilled by Amoco (now BP America Production Co.). Core analysis allows for observation of sedimentary and biogenic structures present within the Red Fork Sandstone along with textures and lithologies associated with depositional facies. Since core observation was completed virtually and from a single core, core analysis also relied on information obtained from previous studies by Johnson (1984) and Anderson (1992). Color core photographs from a single core within Johnson's area were acquired and presented within this study as a reference for the Lower Red Fork. This core is the Blakemore 1-27 and is located in Sec. 27, T.12N., R.20W., which is immediately outside (west) of the study area. Core plug photos, mineralogic weight percentages, and porosity records for the Blakemore 1-27 well were offered by OPIC to support this investigation.

Thickness patterns were determined and combined with lithofacies distributions to assess erosion and filling of the Clinton-Weatherford channel. Stratigraphic relationships as expressed by wireline-log curves were evaluated and compared to establish the relationships between erosion and filling with the context of the falling stage, lowstand, or transgressive systems tracts. Red Fork interval and sub-interval thickness maps, structural maps, and a gross sandstone map were generated, and as necessary, contours were manually corrected to give more realistic patterns. All data were integrated to improve the understanding of the basin configuration, accommodation, and depositional settings during deposition through Red Fork time. These maps were constructed using data collected for four key formations as well as four sub-intervals and helped interpret the geometry of the Anadarko basin from the Inola marker (or equivalent) to the Red Fork marker during Red Fork deposition. A wireline-log electrofacies map was also constructed in order to help interpret depositional processes for the Upper Red Fork.

Reservoir characterization was explored for horizontal potential using production data provided by Enverus, production data recorded in previous investigations, as well as thin section petrography collected from studies by Johnson (1984), Anderson (1992), and Udayashankar (1985). Petrology from thin sections was used to determine the general detrital and authigenic constituents, infer sediment provenance and transport direction, and to estimate porosity for the overall horizontal potential. Porosity was also estimated from wireline well logs. A simple petrophysical analysis was done by hand to compare sandstone bodies formed in channelized and non-channelized depositional environments. Production data for specific wells of interest were limited. A determination of detrital grain composition using thin section petrography was completed on thin sections from a cored well in the South Thomas field to identify the general mineralogical constituents of the Red Fork Sandstone and determine principal sediment sources. The results as determined by point counting were normalized for quartz (Q), lithics (R), and feldspar (F) and plotted on a ternary diagram following the methodology of Folk (1968). These results were compared to the findings of nearby studies (Johnson, 1984; Udayashankar, 1985; and Anderson, 1992).

A sequence stratigraphic framework for the Red Fork Sandstone was established using log characteristics and signatures, which assisted in the interpretation of relative changes in base level and the timing of erosion and deposition of the Red Fork sediments. This sequence-stratigraphy-based interpretation relied heavily on changes in wireline log curves and the placement of the sub-interval formation tops within the Red Fork interval. Major coarsening-upward (progradational) and fining-upward (aggradational) log signatures, flooding surfaces (transgressions), maximum flooding surfaces, systems tracts, and sequence boundaries were interpreted and correlated between wells.

CHAPTER V

RESULTS

Core Analysis and Sedimentary Structures

Color core photographs were provided for three cores located close to or within the study area. These images were examined and described to identify lithology, depositional facies, sedimentary and biogenic structures, and interpret stratigraphic surfaces and boundaries within the Upper Red Fork Sandstone. One of these cores that contained color photographs described by Johnson (1984). The primary core of interest that was examined virtually and given specific attention was the Walter Sauer 1 drilled by Amoco Production Co. This core is from a well located immediately northeast of the main channel trend. This core was examined, but due to the circumstances of having to be analyzed virtually, the confidence in the results is not as strong as it might be under other circumstances where visual inspection and description tends to yield significant and consistent results. The lack of cores located within the study area made it difficult to interpret major depositional environments for the Red Fork Sandstone. Only seven cores of the Red Fork Sandstone were available in the general area through the OPIC facility and of those seven, three were acquired, including the one described by Johnson (1984). The cored interval of the Walter Sauer 1 was from 12,397 to 12,620 feet within the Upper Red Fork interval. Other core descriptions from Johnson (1984) and Anderson (1992) were used if the wells were located within the study. Table 1 lists wells with core photographs. These wells are shown on the corresponding well-location map (Figure 14).

API	Operator	Well Name	Location	Formation	Cored Interval (Depth)	Photos
35039204660000	Amoco (BP America Production Co.)	Walter Sauer 1	TWP: 12N Range: 15W Sec. 23 NE	Red Fork (Upper)	12,397'-12,620'	Yes
35039203370000	Davis Oil Co.	Herring No. 1	TWP: 14N Range: 14W Sec. 17 C SW/4	Red Fork (Lower)	10,857'-10,917'	Yes
35039218270000	Presidio Petroleum Co.	Blakemore 1-27	TWP: 12N Range: 20W Sec. 27	Red Fork (Upper)	13,692' – 13,736'	Yes
35039204080000	Conoco	Meachum 1	TWP: 12N Range: 16W Sec. 14	Red Fork (Upper)	12,300' – 12,354'	No
35039202800000	Conoco	Snider No. 1-A	TWP: 12N Range: 16W Sec. 22 C S/2 NE	Red Fork (Upper)	12,370' – 12,430'	No
35039203440000	Conoco	Hoffman 1	TWP: 12N Range: 16W Sec. 15	Red Fork (Upper)	12,350' – 12,450'	No

Table 1: List of wells referenced in the study from Johnson (1984) and cores provided by OPIC.

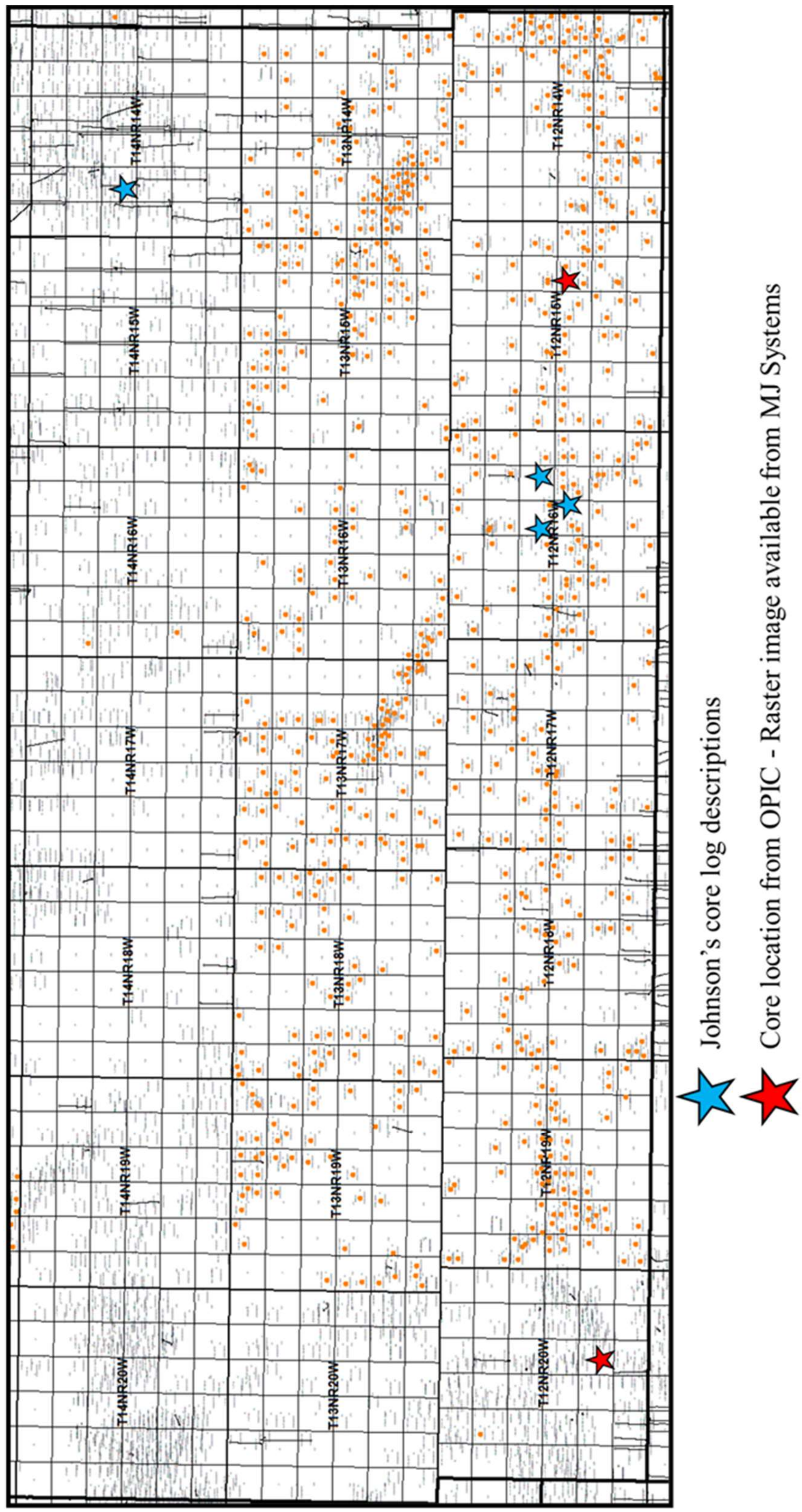

Figure 14: Location of cores from Table 1. Orange circles represent wells that penetrate the Red Fork interval and contain useful data.

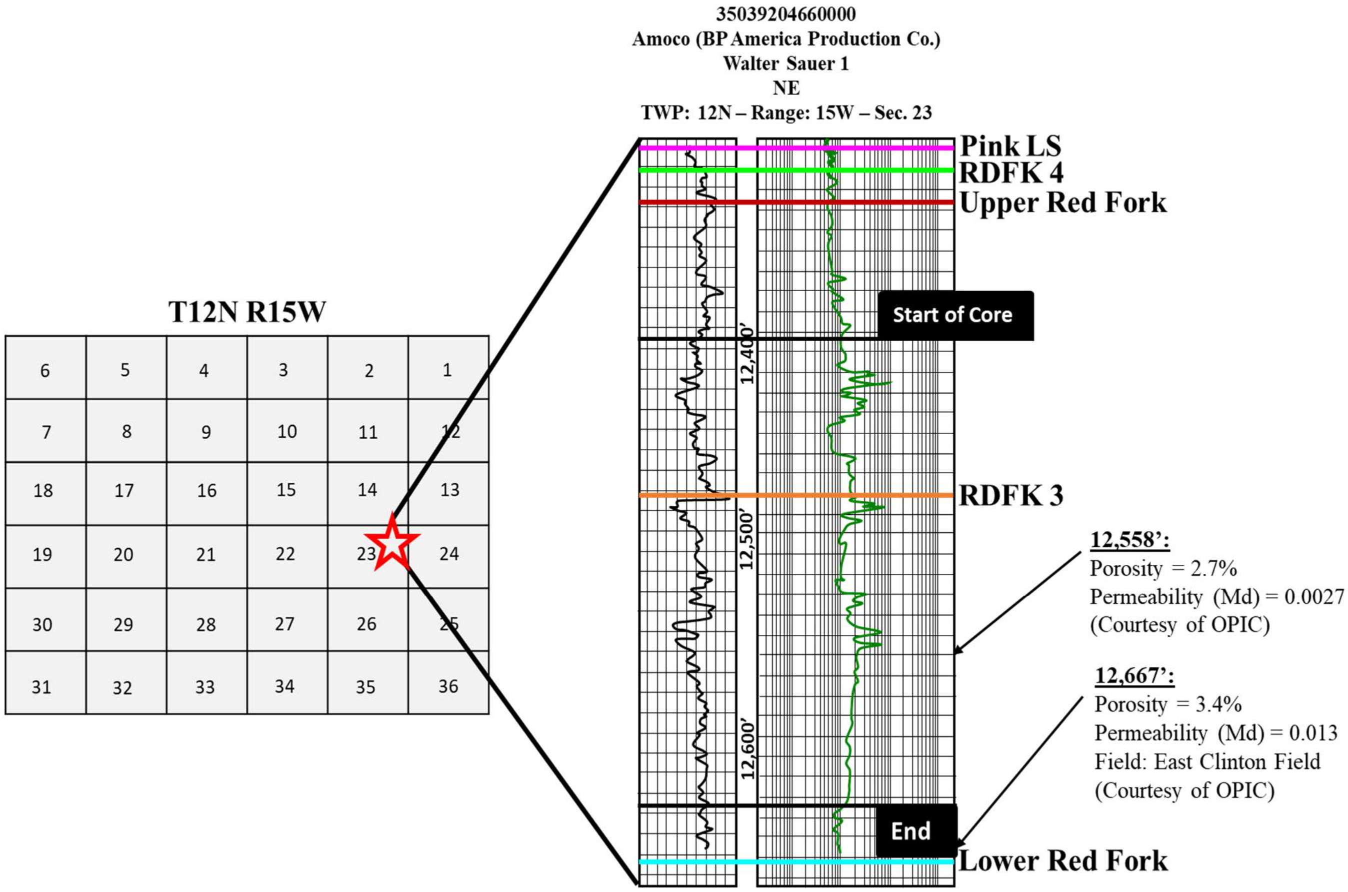

Figure 15: Well location and well log associated with the Walter Sauer 1 core drilled by Amoco Production Co. in Section 23, T.12N., R.15W. This well was perforated and produced from the Skinner Sandstone. Pink line: Pink Limestone, Green line: RDFK4 sub-interval, Maroon line: Upper Red Fork, Orange line: RDFK 3 sub-interval, Turquoise line: Lower Red Fork.

A variety of sedimentary features and structures were observed and recorded during the virtual assessment of the Walter Sauer 1 core. Some of the more common structures and features included: massive bedding, wavy bedding, planar bedding, flaser bedding, lenticular bedding, marine fossils, bioturbation, burrows, sharp contacts, small scale cross-bedding, siderite nodules, mud clasts or nodules, zones of chaotic bedding, possible calcite filled fractures, zones of oxidation, occasional soft sediment deformation, and mud drapes.

Massive Bedding:

Several sections of the Walter Sauer 1 core lacked bedding features and classified as massively bedded. Massive bedding appears as uniform sections without bedding planes, disturbances resulting from biogenic activity or soft-sediment deformation, primary sedimentary structures (bedforms) or loading features (Figure 16). Intervals that display this uniform "massive" bedding are in ascending (as deposited) order: 12,609, 12,603, 12,579, 12,545, 12,470, and 12,406 feet. Massively bedded sandstone sections are thin (<1 ft.) and the massively bedded mudrock sections are larger (1-5 ft.).

Wavy Bedding:

Small sections of wavy bedding are present throughout the core. The best examples of the wavy bedding are located at 12,532, 12,520, and 12,519 feet (Figure 17). These thin (1 to 2 feet) sections of wavy bedding occur in both sandy and shaly intervals that exhibit low-energy (laminar) flow characteristics.

Planar Bedding:

Large sections of this core exhibit low-flow regime planar laminated bedding (Figure 18). These sections contain horizontal laminations that vary in composition with changing abundances of sand, silt, and clay that form relatively consistent patterns. Depths within the Walter Sauer 1 core that display planar bedding are: 12,564 feet, 12, 559 – 12,558 feet, 12,501 – 12,490 feet, 12,438 – 12,427 feet, and 12,422 – 12,419 feet. Only a few zones display very dark laminated shale. Zones of planar bedding are often disrupted by burrowing (Figure 19) and occur within a few feet of zones of soft-sediment deformation (Figure 19).

Flaser Bedding:

Flaser bedding is interpreted as alternating rippled sand and discontinuous mud layers formed by the deposition of mud on previously existing sand ripples (Martin, 2000). Only a few small sections of this core display flaser bedding and these are located at approximately 12, 533, 12, 419, and 12,405 feet.

Lenticular Bedding:

Lenticular bedding is similar to flaser bedding, but contains "lenses" of sandstone contained in shale, and exhibits a wavy appearance (Schieber et al., 2010). Some examples of lenticular bedding are found at: 12,536, 12,530, and 12,529 feet (Figure 17).

Massive bedding

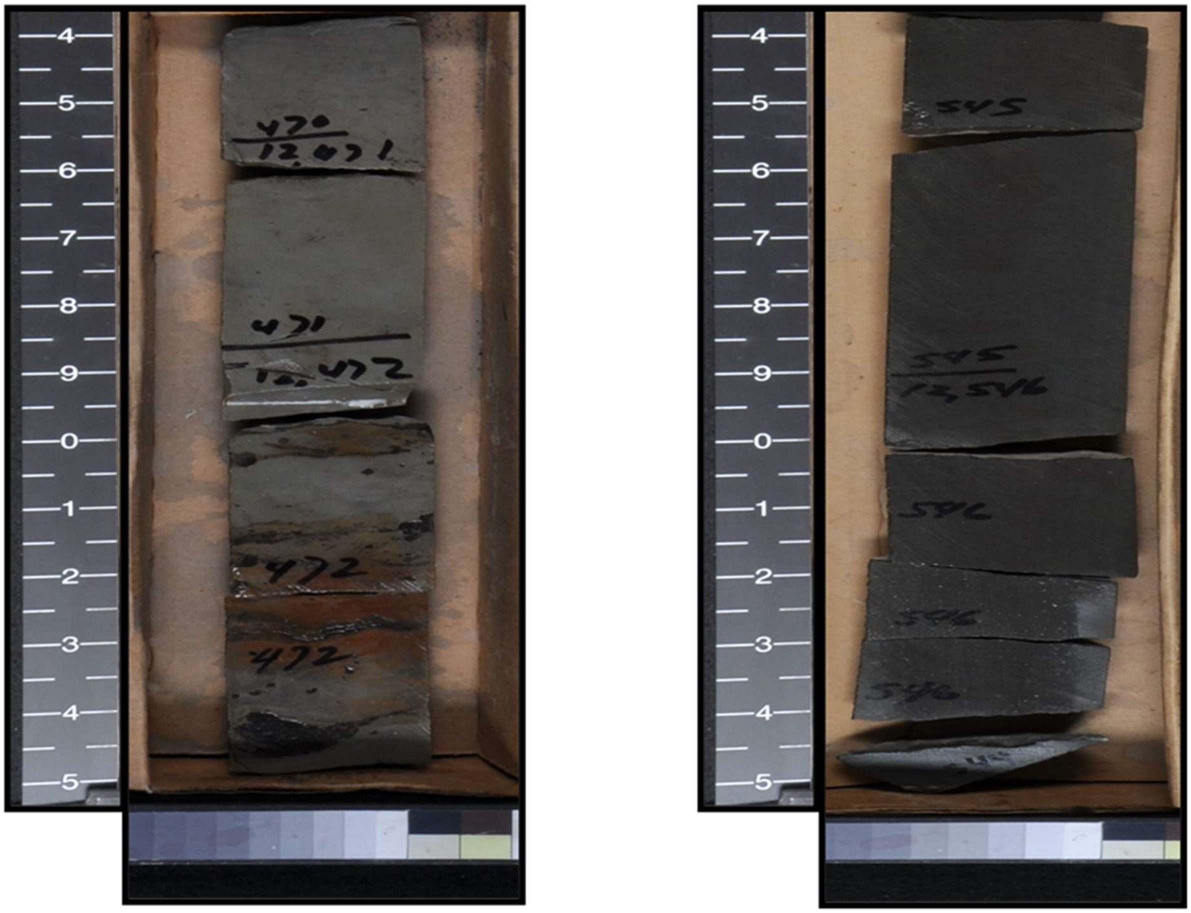

Figure 16: Examples of massive (featureless) bedding at depths 12,470 feet (left) in sandstone and 12,545 feet in mudrock (shale). Both examples are from the Amoco Production Co., Walter Sauer 1 core.

Figure 17: Examples of wavy bedding (left) with relatively uniform amounts of sandstone and shale, depth 12,519 feet; and lenticular bedding (right) with thin lenses of sandstone within shale from 12,520 feet. Both are from the Amoco, Walter Sauer 1 core.

Planar bedding

Figure 18: Three examples of planar laminations within burrowed sandstone with lesser amounts of shale (left), dark shale dominated section (middle), and slightly burrowed near-equal amounts of dark shale and sandstone (right) in the Walter Sauer 1 core, 12,420, 12,446, and 12,559 feet, respectively. Brown band at 12,419.8 feet is siderite.

Bioturbated Sandstone & Soft-Sediment Deformation

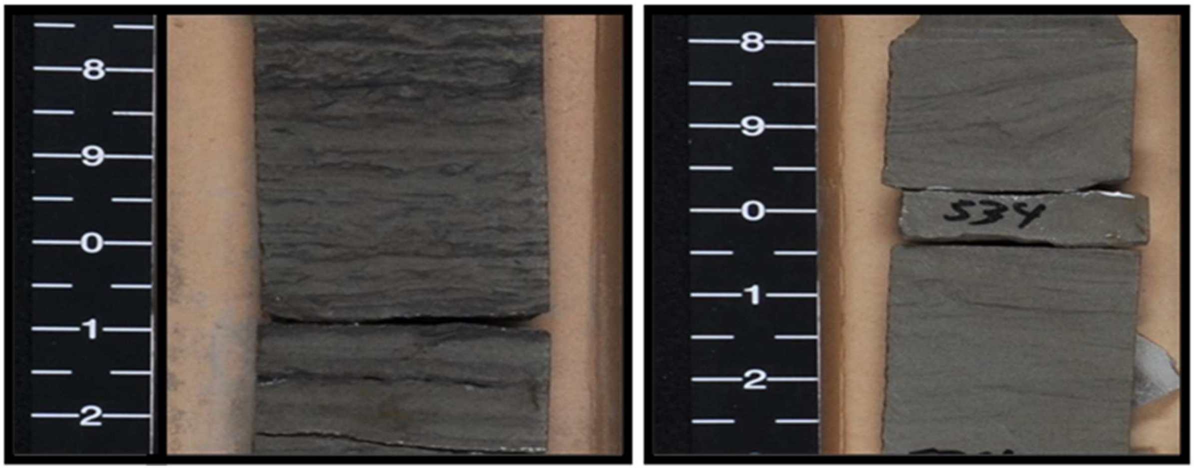

Figure 19: Bioturbated sandstone at depth 12,419 (left) and soft-sediment deformation at depth 12,534 feet (right) in the Walter Sauer 1 core.

Fossil Zone:

A zone at approximately 12,504 feet contains shell fragments of unspecified fossils (Figure 20). These shell fragments are consistent with the brachiopod fossils seen within the Upper Red Fork interval from Johnson (1984) in the Southport No. 2 Switzer well in T.14N., R.13W. and the Conoco Hoffman No. 1 in T.12N., R.16W.

Bioturbation:

Bioturbation appears at many different depths within the Walter Sauer 1 core. Specific trace fossils that caused the bioturbation were not identified. Some examples of this can be found at depths: 12,417, 12,415, 12,408 – 12407, 12,400, and 12,399 feet (Figures 19 and 21).

Burrows:

Burrows in the Walter Sauer 1 core occur at depths: 12,519, 12,424, 12,421, 12,411, 12,407, 12,403 feet (Figure 22). Occasional burrows are located at the depths where the bioturbation is easily seen. Specific fossils were not identified. A few larger burrows were present, and the evidence of burrows lessened with depth. Johnson (1984) indicated the burrowing and shell fossils suggest a deltaic front environment.

Sharp Contacts:

Sharp contacts can be seen throughout the Walter Sauer 1 core. These contacts show abrupt changes from a dark shale to a sandy interval. Example depths that exhibit sharp contacts are 12,535, 12,524, and 12,412 feet (Figure 23).

Cross-bedding:

An example of planar cross-bedding can be found at depth 12,407 feet (Figure 24). No other indications of cross-bedding were noticed.

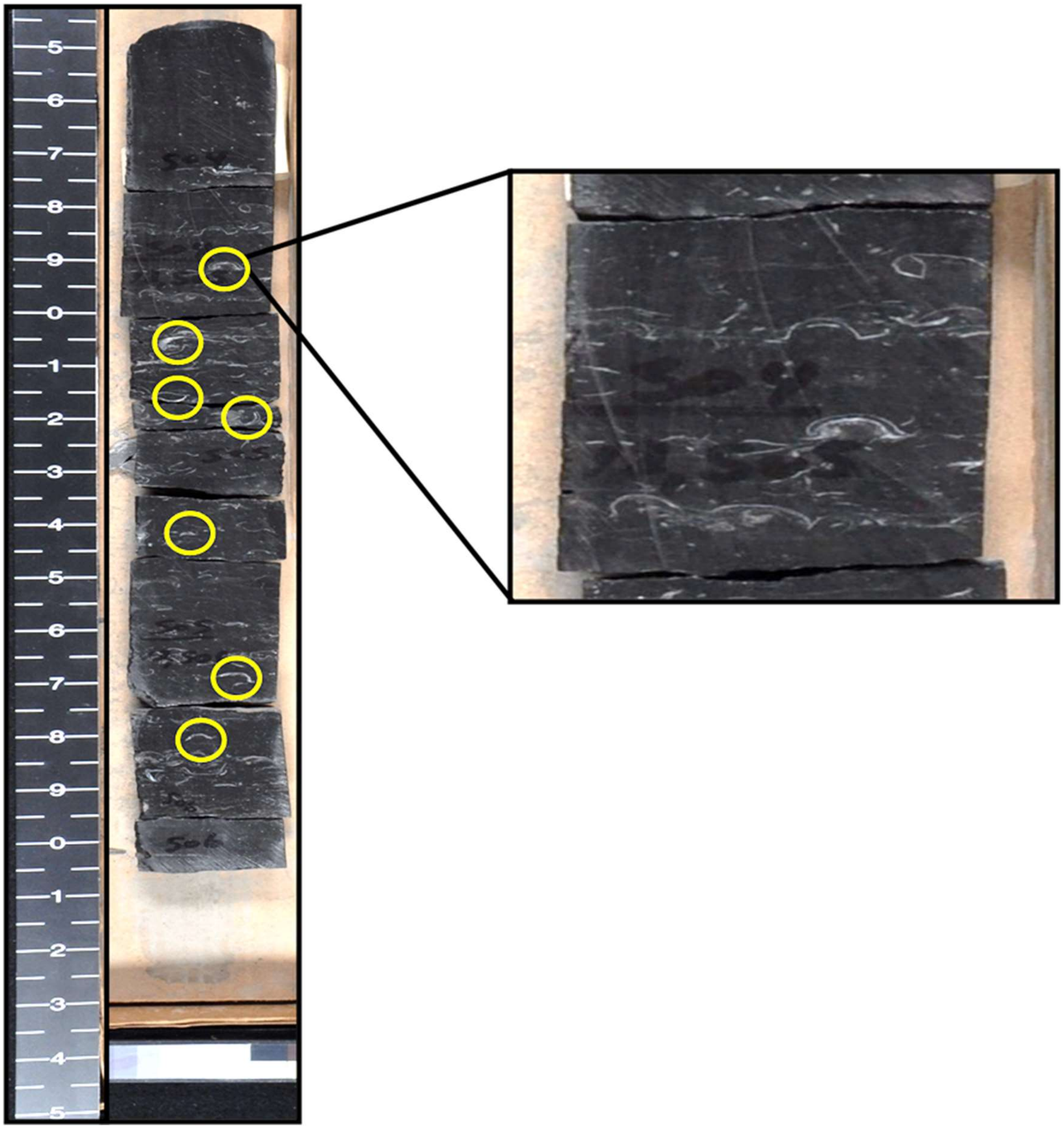

Figure 20: Example of a zone containing shell fragments interpreted as brachiopods: depth 12,504 feet. Amoco, Walter Sauer 1 core.

Bioturbation

Figure 21: Examples of bioturbation at depths: 12,399 – 12,400 feet (left), 12,415, and 12,417 feet, upper and lower right, respectively. Amoco, Walter Sauer 1 core.

Burrows

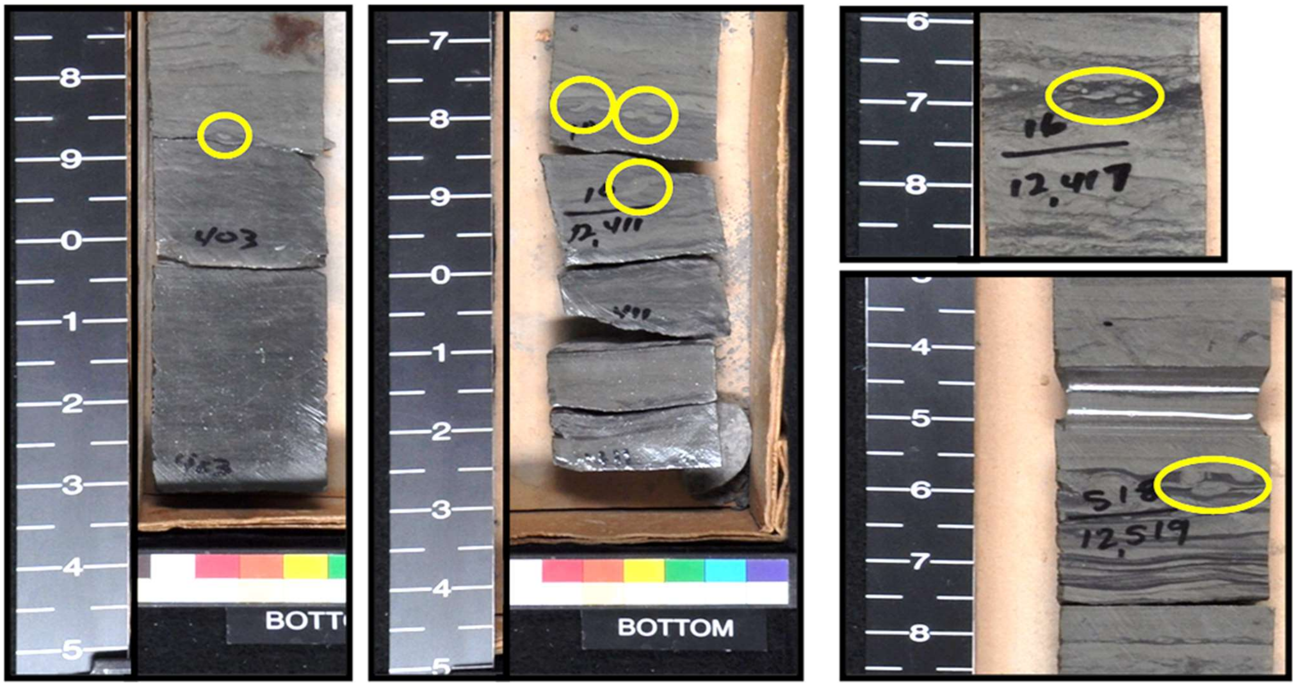

Figure 22: Examples of burrows highlighted in yellow, Walter Sauer 1 core. Depths: 12,403 feet (left), 12,411 feet (middle), 12,417 feet (upper right) and 12,519 feet (lower right). Amoco, Walter Sauer 1 core.

Sharp contacts

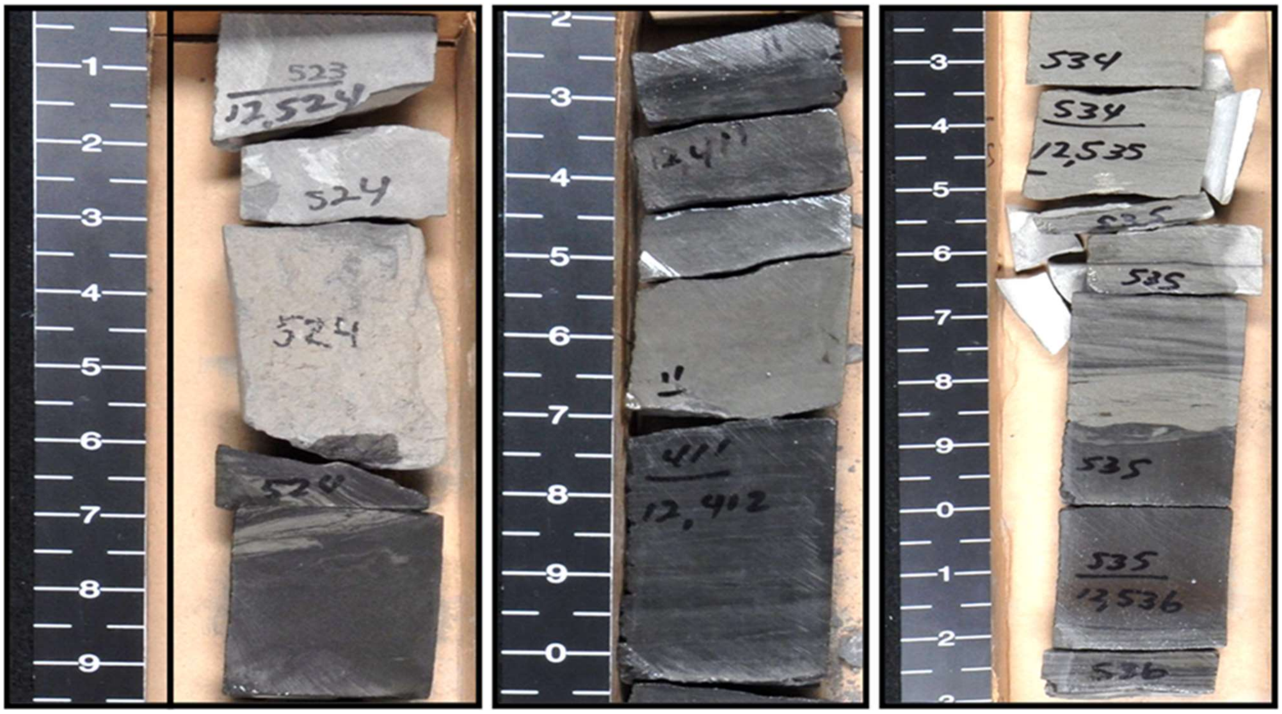

Figure 23: Examples of sharp contacts between underlying shale and overlying sandstone/sandy siltstone. Depths: 12,424 feet (left), 12,411 (middle) and 12,535 feet (right). Amoco, Walter Sauer 1 core.

Cross-bedding

Figure 24: Example of apparent low-angle, planar cross-bedding at depth 12,407 feet. Amoco, Walter Sauer 1 core.

Siderite clasts and Zones of Oxidation:

Siderite and zones of oxidation, possibly after siderite, occur across the core. Siderite appears as laminae and clasts (Figures 18 and 25). Zones of oxidation occur as irregular patches, bands, or discrete areas (Figure 25). Siderite is a common iron carbonate mineral in sedimentary rocks (Dunlop and Ozdemir, 2015) and is commonly authigenic in pore spaces or replaces clay clasts. Numerous zones of the core display red-brown oxidation of iron, possibly siderite.

Mud clasts:

Mud clasts or nodules occur in several sections of the Walter Sauer 1 core (Figure 26). The composition of mud clasts appears to be very similar to shale beds in the core allowing the inference that these clasts are locally sourced.

Zones of Chaotic Bedding:

Chaotic bedding is observed at several depths in the Walter Sauer 1 core. The largest zone of chaotic bedding occurs at 12,465 feet (Figure 27), just above the RDFK 3 sub-interval top.

Soft-Sediment Deformation:

Soft-sediment deformation is common in the Walter Sauer 1 core. Examples shown in Figure 28 come from depths 12, 540, 12,538, 12,537, and 12,533 feet. Soft-sediment deformation structures are influenced by liquefaction and fluidization processes (Alencar et al., 2021) giving deformed zones unique patterns.

Mud Drapes:

An example of a mud or clay drape is shown in Figure 29. This drape formed over an apparent buildup of sand, but the feature cannot be described with confidence because of soft-sediment deformation and burrowing.

Siderite and Oxidized zones

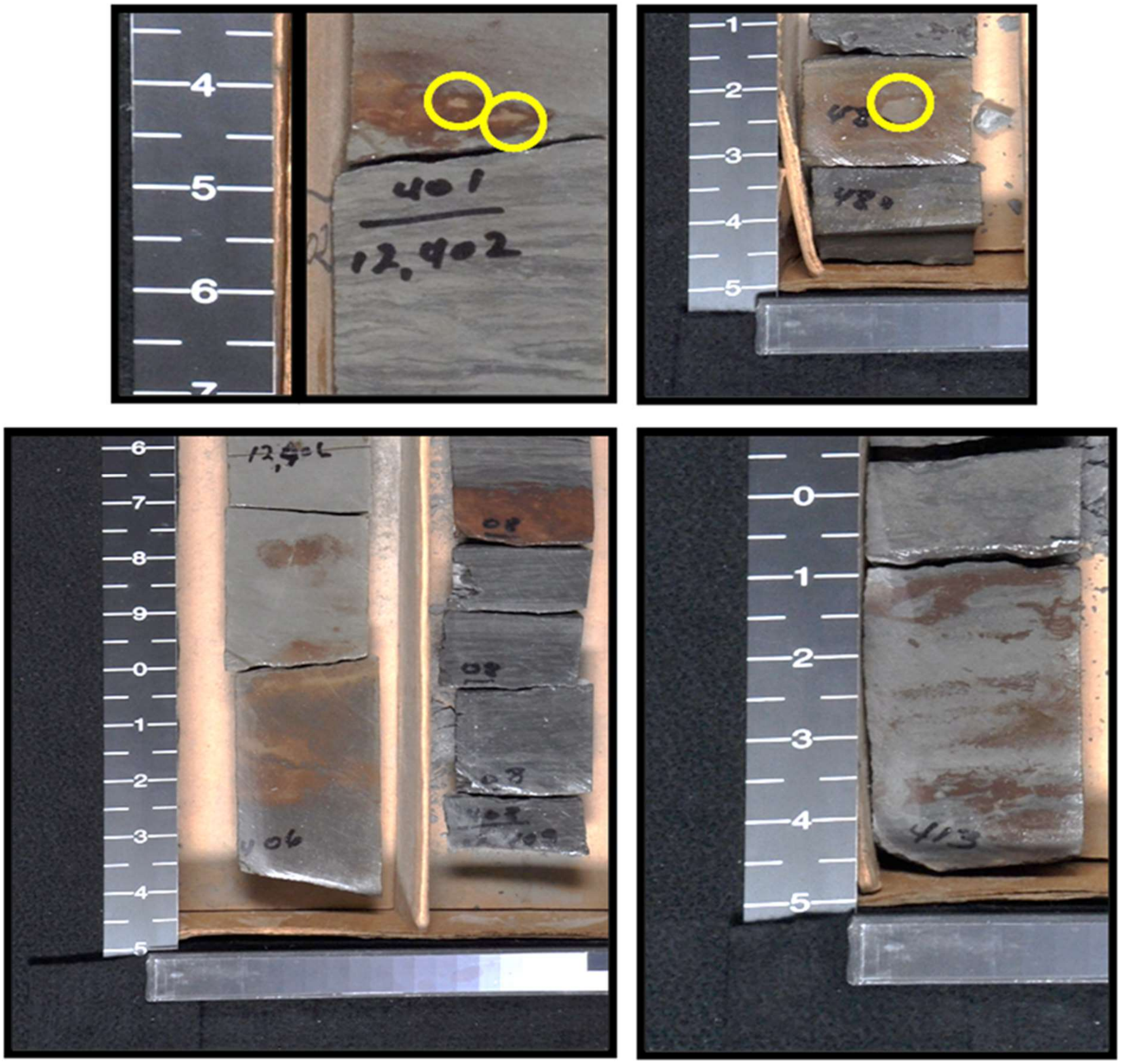

Figure 25: Siderite clasts and zones of oxidation likely after siderite in the Walter Sauer 1 core.

Mud Clasts

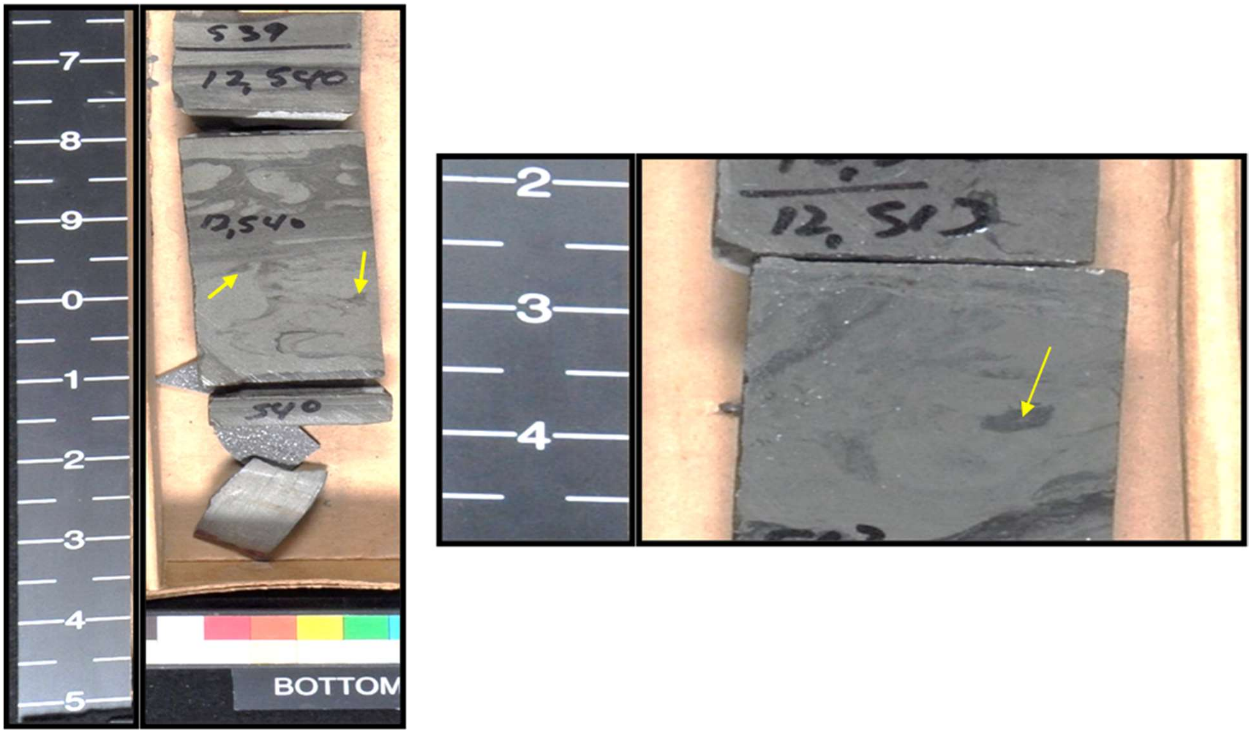

Figure 26: Example of mud clasts that were entrained in sand. Both are in zones of soft-sediment deformation and likely represent breakup of nearby shale beds. Left: depth 12,540 feet. Right: depth 12,513 feet. Amoco, Walter Sauer 1 core.

Chaotic Bedding

Figure 27: Largest zone of chaotic bedding in the Amoco, Walter Sauer 1 core, depth 12,465 – 12,466 feet.

Figure 28: Soft sediment deformation of liquefied sediment, Walter Sauer 1 core. Depths 12,534 to 12,537 feet. Amoco, Walter Sauer 1 core.

Mud Drape

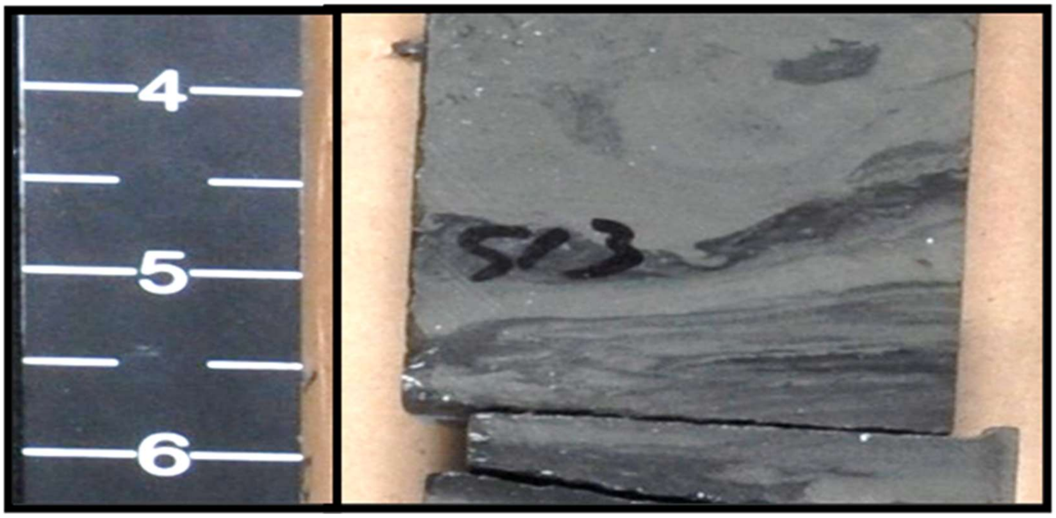

Figure 29: Mud or clay drape at depth 12,513 feet that appears to be deformed by burrowing and soft-sediment deformation. Amoco, Walter Sauer 1 core.

Johnson (1984) examined and described several cores within the study area. One of these, the Conoco, Meachum No. 1 was located in the SE/4 Section 14, T.12N., R.16W. The core of the Upper Red Fork Sandstone from this well was described in detail, providing useful information for this study. The Upper Red Fork extends from 12,303 to 12,355 feet and the sandstone reservoir was perforated from 12,310 to 12,346 feet to initially flow 27,000 mcf (thousand cubic feet) of gas per day from untreated perforations. The flow rate is indicative of a higher-permeability reservoir and the well had produced more than 4.8 bcf (billion cubic feet) the first thirteen months on production.

Beginning at the base of the channel, Johnson (1984) notes a smaller shale bed with small scale cross-bedding and convolute bedding, and suggested this to be a part of a delta-front deposit. The active channel-fill was primarily sublitharenite sandstone with approximately 12% secondary porosity (Johnson, 1984). This channel-fill sandstone is approximately 40 ft. thick and contains small-scale cross-bedding, an erosional surface, rip-up clasts, and wavy bedding. Johnson (1984) interpreted the sandstone as a distributary channel mouth bar.

Johnson (1984) also described three other cores from wells located in the same area. These cores are referenced and summarized for the reason of a limited core analysis within this study. Johnson (1984) observed that the Conoco, Snider No. 1-A located in Section 22, T.12 N., R.16 W., was sublitharenite sandstone and shale, which was interpreted to be adjacent to a deltaic complex. Another well described by Johnson (1984) was the Conoco, Hoffman 1 in Section 15, T.12N., R.16W. This core contains a paleosol and was interpreted as a levee deposit within a deltaic complex. Just south of the channel complex, the Conoco, Fransen No. 1 well located in Section 27, T.12N.,R.16W., was mostly shale and this well was completed as a dry hole.

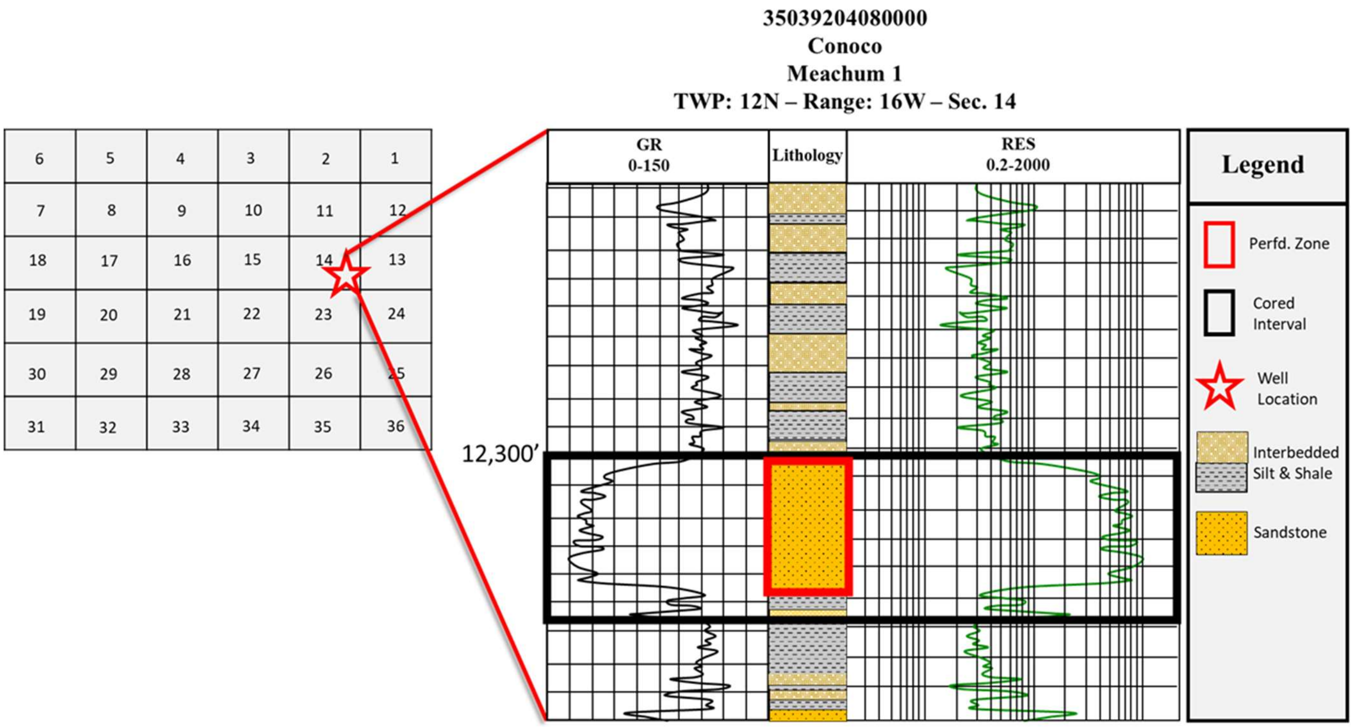

Figure 30: Wireline well log associated with core description from Johnson (1984) located in Section 14, T.12N., R.16W. Note that the core depths are approximately four (4) feet shallow to open-hole wireline log depths.

Thin Section Analysis

Thin sections from a well located outside of the study area were examined to define the generalized mineralogical composition of the Red Fork Sandstone, infer sediment provenance and transport direction, and to estimate porosity and overall potential as a horizontal drilling target. These thin sections were from the Southport Exploration, Switzer No. 2 well in Section 18, T.14N., R.13W. in the South Thomas field.

These thin sections were from the Lower Red Fork interval, but are believed to be a representative sample of Red Fork interval detrital composition. These thin sections are critical in defining the provenance of the Red Fork Sandstone and their analysis builds on the recent zircon geochronology completed by Tunin (2020), which suggests sand was transported from the northern Appalachians to the subsiding Anadarko basin during Red Fork time. Detrital composition from thin section petrography will help confirm that the sediment and channel features reflect flow from east-northeast to west-southwest toward the basin axis.

Thin sections from five (5) different depths were analyzed to establish detrital composition. The Red Fork Sandstone in the Southport Switzer No. 2 is very fine grained sublitharenite to litharenite. Most thin sections plotted as litharenites with monocrystalline quartz, metamorphic rock fragments, pseudomatrix, and mud fragments. The Folk (1968) ternary diagram for each thin section can be found in the appendices. At depth 10,433 feet, the normalized detrital composition plotted as a litharenite with approximately 62% quartz, 30% rock fragments, and 8% feldspars. Other diagenetic features include silica cement in the form of syntaxial quartz overgrowths, calcite cement, pseudomatrix, and secondary porosity developed from the dissolution of detrital mud fragments and feldspar. Aligned muscovite grains in very fine grained sandstone indicate low energy flow. Two (2) thin sections plotted as a sublitharenite. A paragenetic sequence was created for both the Upper and Lower Red Fork by Johnson (1984). For both the Upper and Lower Red Fork, Johnson (1984) concluded that chlorite, quartz overgrowths and feldspar overgrowths formed early as Red Fork sediments compacted and grain to grain contact liberate silica. Authigenic clays such as kaolinite and illite formed later along with calcite cement, and secondary porosity evolved along with the precipitation of authigenic clay minerals (Johnson, 1984). An example of Johnson's (1984) paragenetic sequence can be seen in the Appendices. Folk ternary diagrams completed by Johnson (1984) for the Upper Red Fork and Lower Red Fork will be shown as a reference in the appendix, as well as plots completed by Anderson (1992) for the Upper Red Fork and Udayashankar (1985) for both the Upper and Lower Red Fork sandstones.

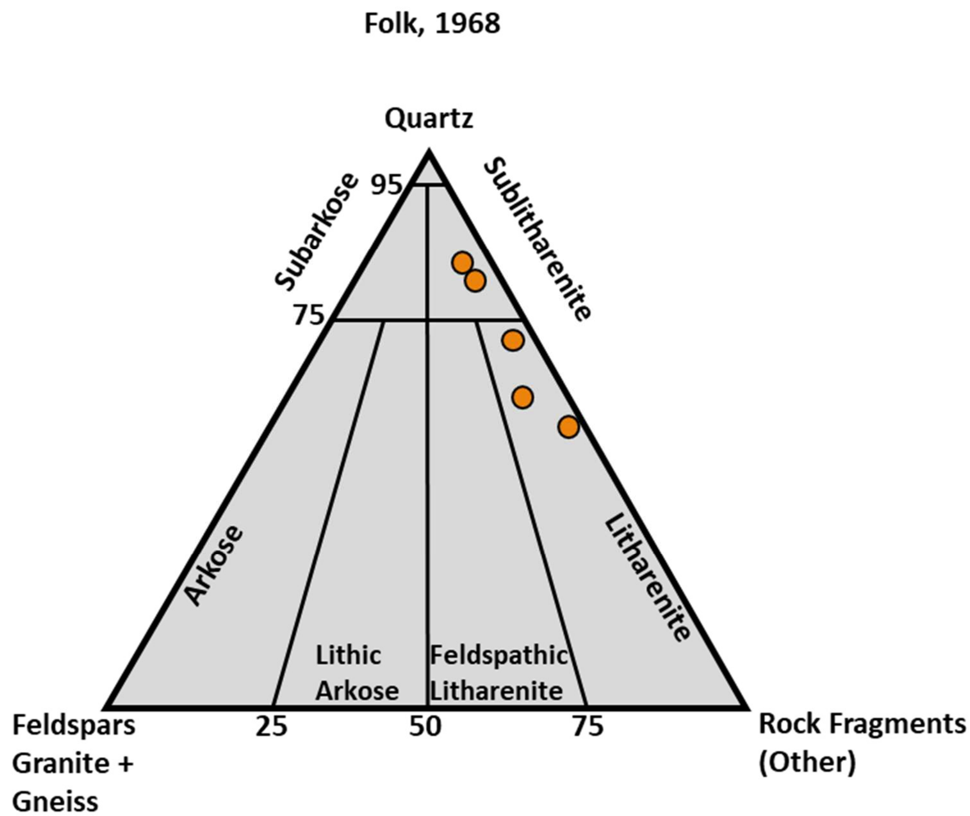

Figure 31: Folk ternary diagram with the five thin sections plotted for the Southport Exploration Switzer No. 2 well.

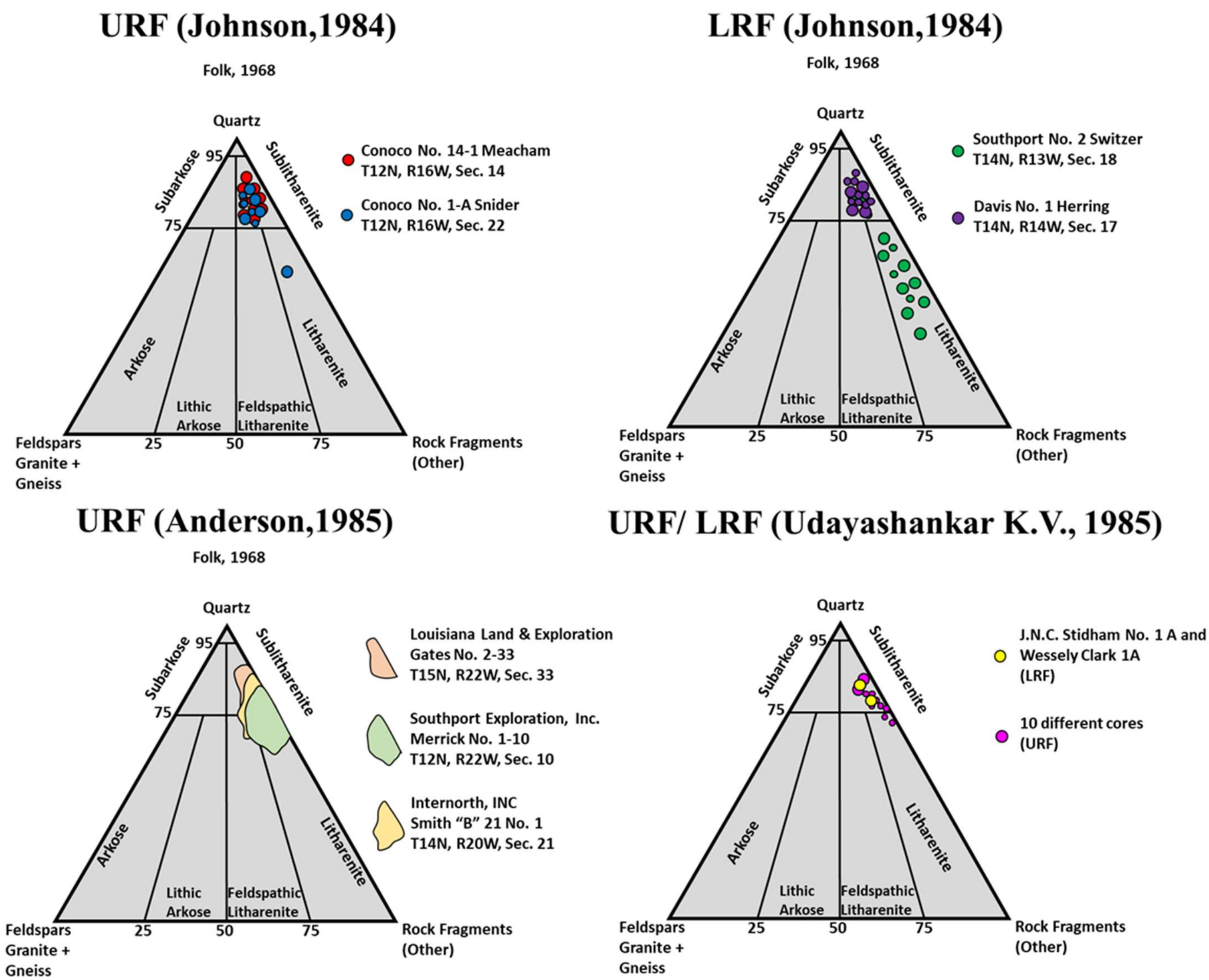

Figure 32: Folk ternary diagrams from Johnson (1984), Anderson (1992), and Udayashankar (1985). Both Upper and Lower Red Fork plotted as sublitharenite to litharenite.

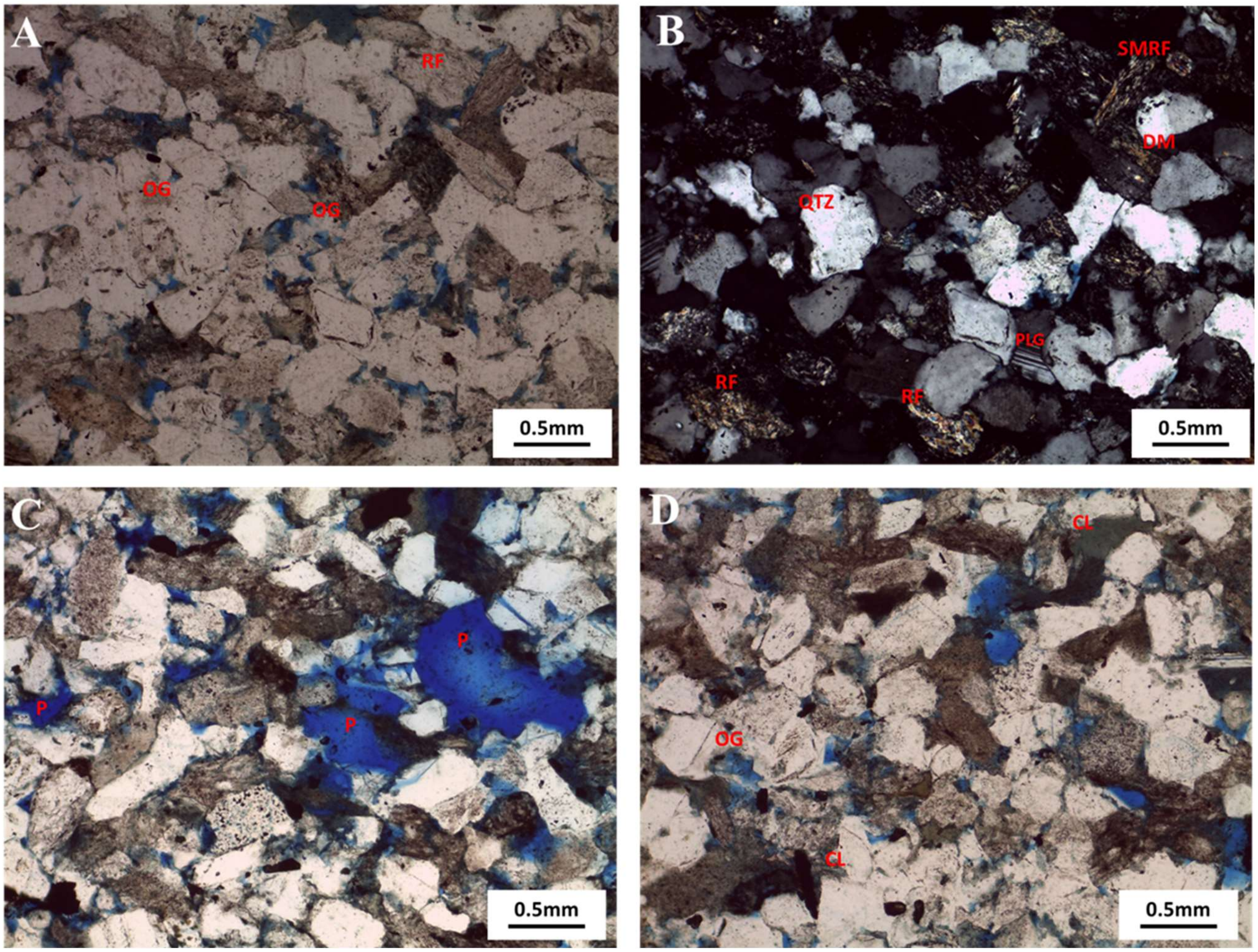

Figure 33: Thin section photo-micrographs showing characteristics of monocrystalline quartz, metamorphic rock fragments, pseudomatrix, quartz overgrowth, and secondary porosity at depth 10,433 feet from the Switzer No. 2 in PPL (A), CPL (B), porosity in PPL (C), and chlorite in PPL (D). All images 10x. OG: Overgrowth, RF: Rock fragment, QTZ: Quartz, PLG: Plagioclase Feldspar, DM: Detrital mud, MRF: Metamorphic rock fragment, S: Schistose, P: Porosity, and CL: Chlorite.

Structure Maps

Structural contour maps were generated to illustrate the current structural attitude of the Anadarko basin following the Pennsylvanian orogeny, subsequent deposition, and uplift. Each structure map reflects dip to the south-southwest along with two main structural features: the south plunging nose of the Roden-Nickel structure and the northwest Corn-Eakly, Ft. Cobb anticline which behaved as a tectonic barrier to the south (Clement, 1991). The Clinton-Weatherford Upper Red Fork trend developed in a structural depression (or subbasin) north of the Corn-Eakly, Ft. Cobb anticline (Clement, 1991). No major faults are interpreted from changes in contour gradient or direction on these structural contour maps. Structural maps were computer generated, but manually hand contoured to reflect more realistic patterns. Well locations were also added to these maps.

The Pink Limestone (map D) presents a northwest-southeast strike of the beds with a 0.7º - 0.8º dip to the southwest. The south plunging Roden-Nickel nose existed during the deposition of the Pink Limestone as well as the deeper formations, and can be seen by a thinning over the nose in T.12N. to T.13N., R.16W.

Map C shows the Upper Red Fork and also establishes a northwest-southeast strike of the beds with a slightly greater dip of 1.0º to the southwest. Dip is observed to be slightly greater in areas near the inferred shelf-slope hinge line in T.12N., R.15W.

Map B displays the Lower Red Fork structure and the same northwest-southeast strike with a dip of approximately 1.1º to the southwest. Greater depth and dips can be inferred from contours in the southwestern portion of maps A and B.

Map A displays the structural attitude of the Inola Limestone (or equivalent) and shows a slightly steeper gradient (or local topographic high) that is evident in the southwestern area of the map in T.12N., R.19W. The approximate dip of the Inola Limestone is equivalent to that of the Lower Red Fork of 1.1º.

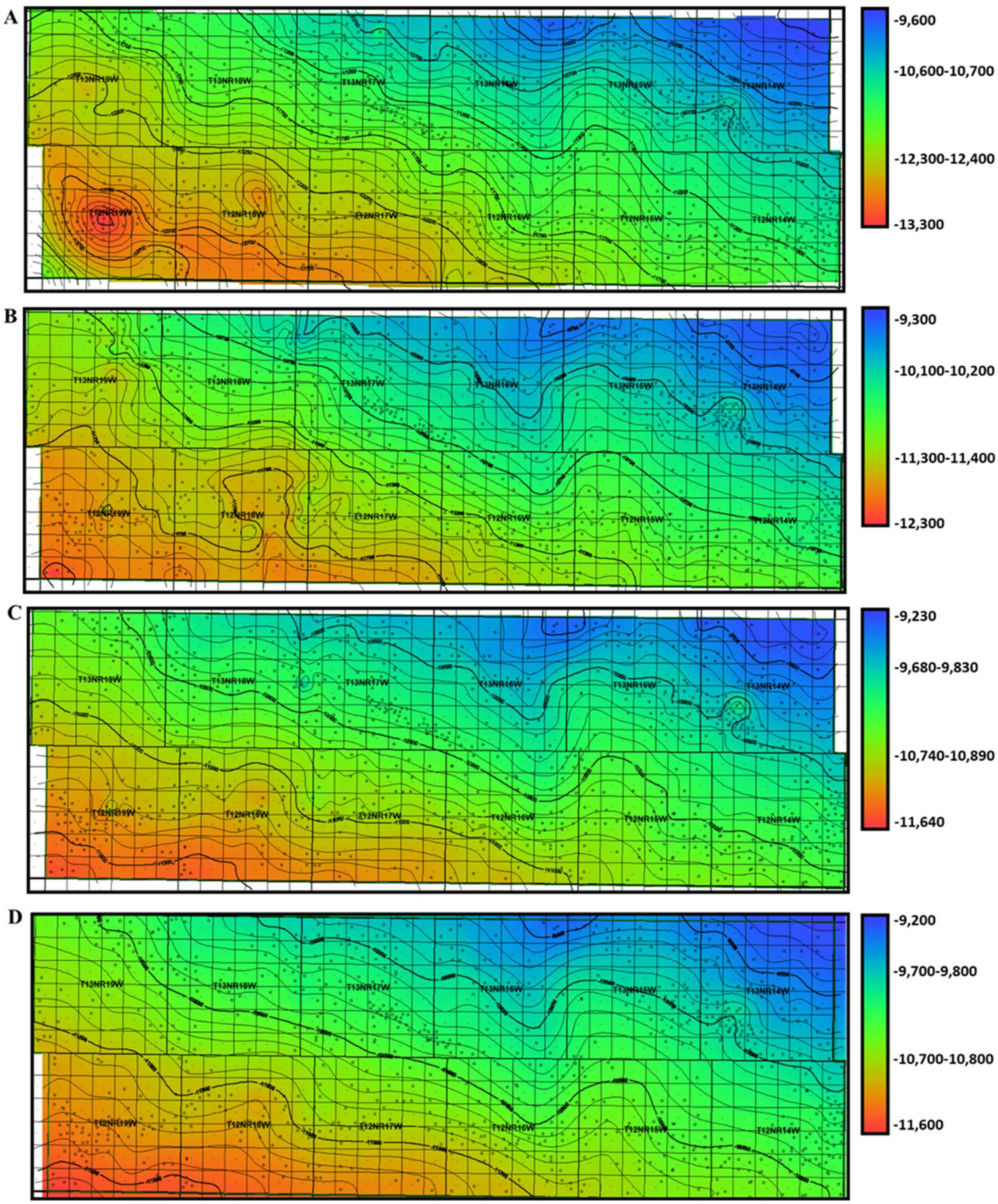

Figure 34: Structural attitude of four key stratigraphic tops moving from oldest to youngest. A: Inola Limestone, B: Lower Red Fork, C: Upper Red Fork, and D: Pink Limestone. Contour interval is 100 feet and datum is sea level.

Isopach Maps

Sub-Interval Thickness Maps

Inola Limestone (or equivalent) to Red Fork 1 (RDFK1):

Map A refers to the interval from the Inola Limestone (or equivalent) to the Red Fork 1 sub-interval (RDFK 1). This interval, which is in the Lower Red Fork, thickens from northeast to west-southwest. The gamma-ray curve for this interval commonly hovers near the shale baseline and generally displays aggradation with thin intervals that display coarsening or fining – upward gamma-ray signatures.

Red Fork 1 (RDFK 1) to Red Fork 2 (RDFK 2):

Map B refers to the RDFK 1 to RDFK 2 interval that is immediately above the Inola to the Red Fork 1 interval. This interval displays thickening toward the south-central part of the area. This interval remains relatively consistent thickness. This interval is directly below the top of the Lower Red Fork interval.

Red Fork 2 (RDFK 2) to Red Fork 3 (RDFK 3):

Map C refers to the interval Red Fork 2 to Red Fork 3. This interval is within the Upper Red Fork interval and commonly displays a coarsening-upwards (progradational) gamma-ray profile. This interval also thickens to the southwest and develops a pronounced thickness trend along northwest-southeast line near the center of the mapping area.

Red Fork 3 (RDFK 3) to Red Fork 4 (RDFK4):

Map D shows the thickness of the Red Fork 3 to Red Fork 4 interval. This interval thickens in a similar fashion as Map C except for an anomalous west-east thinning across the southern portion of the map.

Red Fork 4 (RDFK 4) to Pink Limestone:

Map E was generated to demonstrate the thickness of the interval between the base of the thicker Upper Red Fork sandstone and the Pink Limestone. In essence, this is a sandstone thickness map. This map shows thickening of the sandstone along the same trend as the thinning of the RDFK 3 to RDFK 4 interval implying that the sandstone is thicker at the expanse of the underlying unit.

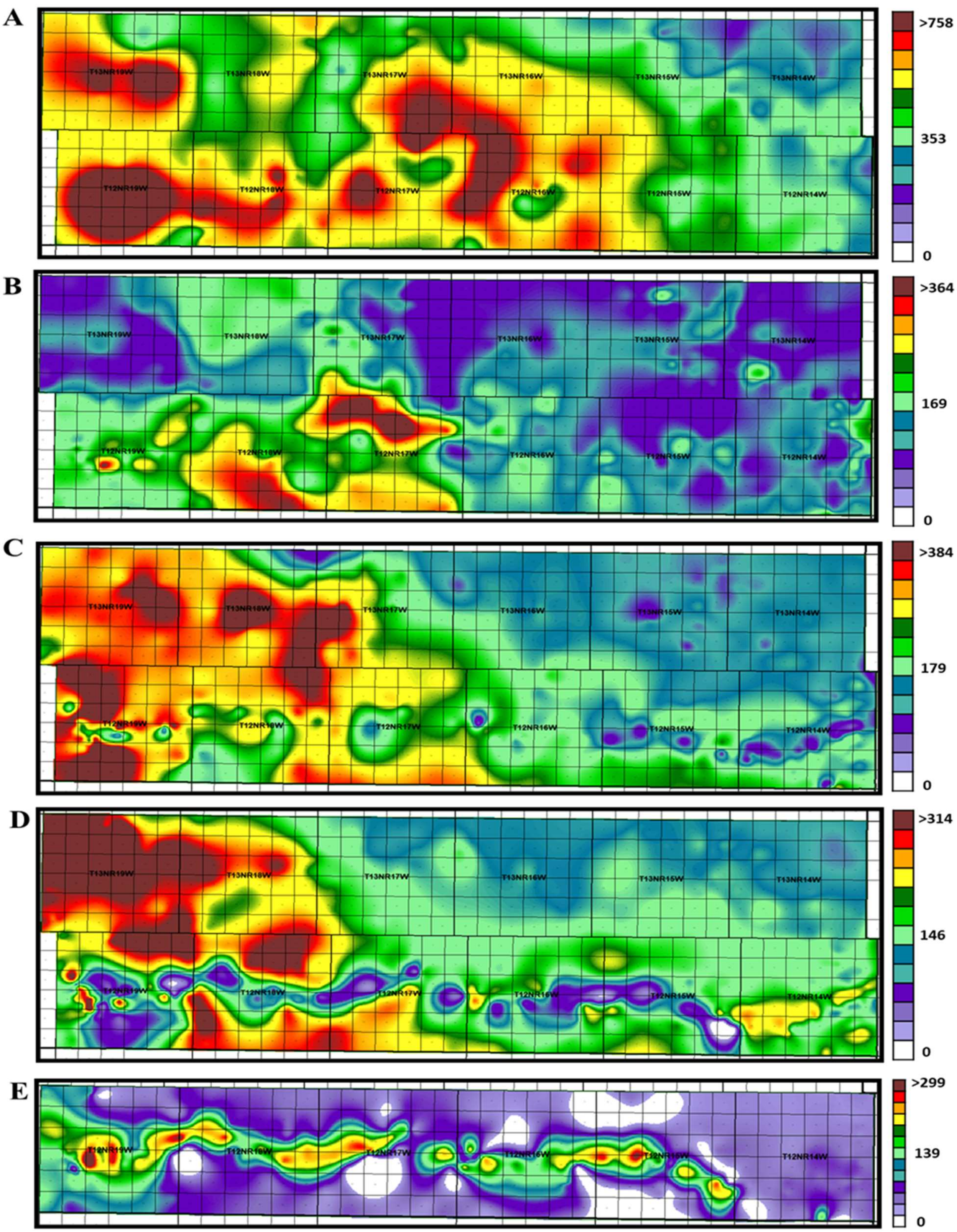

Figure 35: Colored thickness maps indicating thickness of the five sub-intervals in the Upper Red Fork. Moving from oldest to youngest: A: Inola Limestone – RDFK1, B: RDFK 1 – RDFK 2, C: RDFK 2 – RDFK3, D: RDFK 3 – RDFK4, and E: RDFK 4 - Pink Limestone.

Upper Red Fork Thickness

Within the Johnson (1984) study, the Upper Red Fork lacked significant thickening, which he attributed to the absence of a hinge line. However, Anderson (1992) observed possible thickening in a cross-section presented by Johnson (Johnson, 1984; Anderson, 1992) that is within the boundary of this study. In T.12N., R.16W. from the thickness map for the Upper Red Fork, southwest-westward thickening basinward can be observed. The approximate location of an Upper Red Fork thickening is indicated by the dashed yellow line in Figure 37. The dashed red line in Figure 37 represents another possible location of the thickening. Uncertainty in the trend of the thickening in this area is attributed to scarceness of well data. In the northeastern portion of the area of research, thickness of the Upper Red Fork is relatively constant. Change in thickness occurs more quickly in the northwestern part of the study area and the shift from potential stable shelf (purple and blue colors) to unstable shelf or slope (blue to green or dark green to yellow) could be placed on either boundary. It is imperative to note that the Upper Red Fork interval increases in sandstone percentages southwest of the thickening, which can be seen within the Upper Red Fork sandstone map (Figure 38).

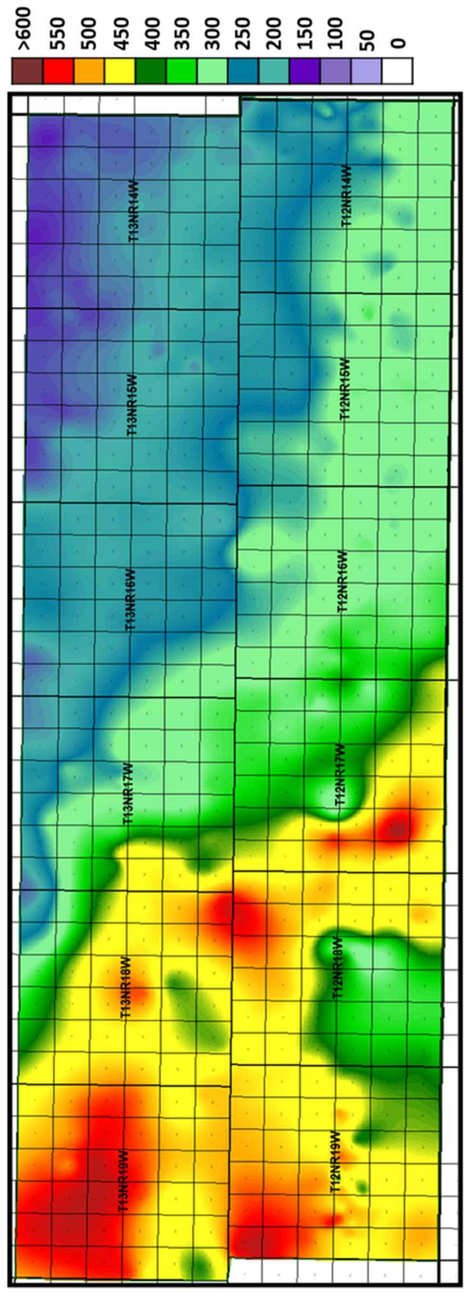

Figure 36: Upper Red Fork thickness map. Hotter colors indicate thicker intervals. Apparent increase in the rate of thickening occurs along light blue to light green transition or dark green to yellow transition. Contour interval is 50 feet, and all values were derived from wireline logs.

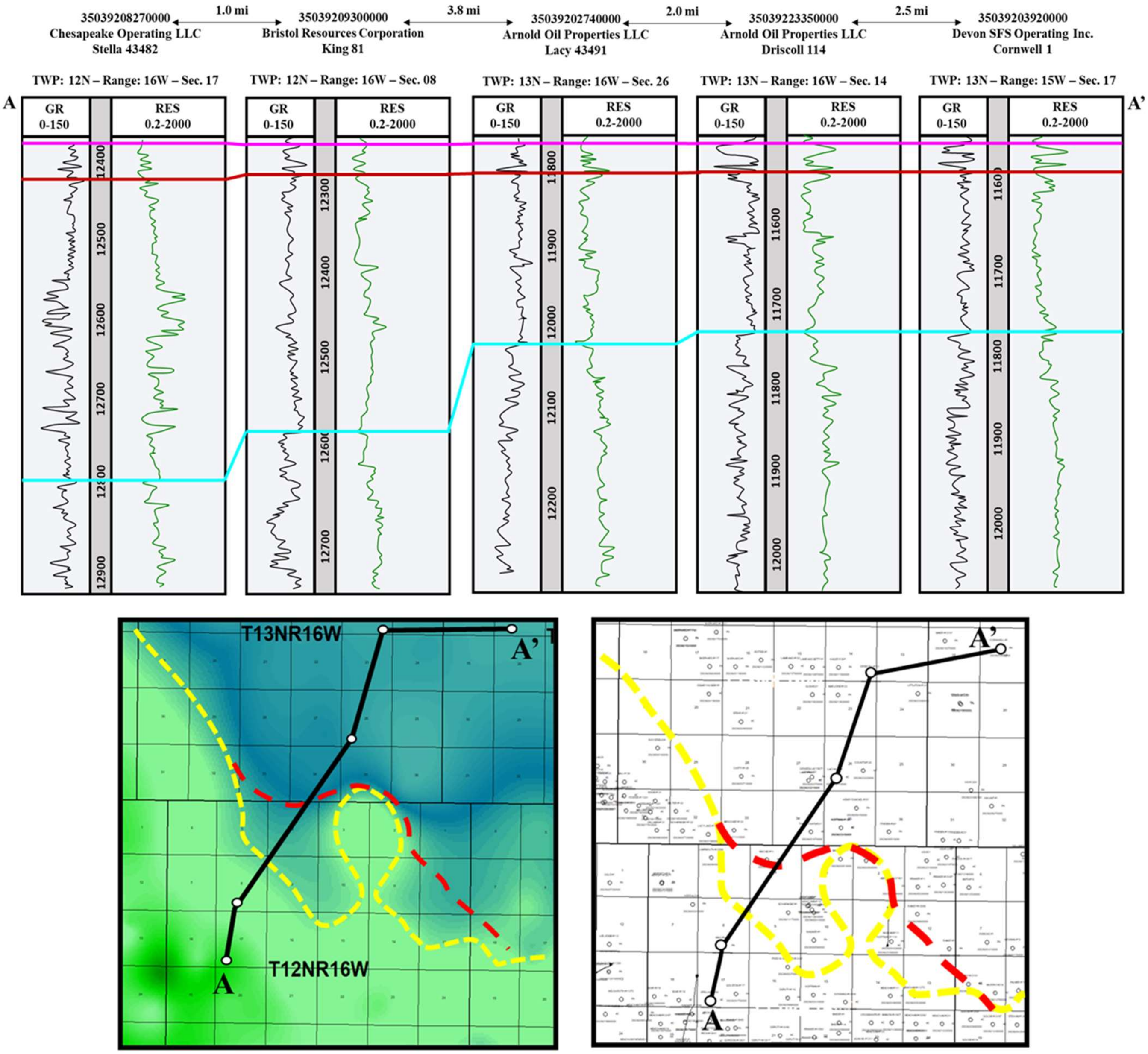

Figure 37: Dip oriented cross-section A-A' across the apparent rapid increase in thickness shown in the Upper Red Fork thickness map (Figure 36). Notice increased thickening towards A. Datum = Pink Limestone. Pink line = Pink Limestone, Red line = Upper Red Fork, Turquoise line = Lower Red Fork. Dashed yellow line represents the trend of the rapid thickening. Color map (left) shows thickness and map (right) shows well locations. Red dashed line represents another possible position of the rapid thickening. Inadequate well data hinders exact placement of trend of thickening.

Lower Red Fork Thickness

The Lower Red Fork displayed constant widespread thickness that began farther to the northeast, and outside of the study area. Johnson (1984) assigned a hinge line for the Lower Red Fork that is northeast of the boundary of this study. Because of a lack of control less attention was applied to the Lower Red Fork interval.

Total Sandstone Thickness

Isopach maps were constructed to determine sandstone distribution and thickness within the Upper and Lower Red Fork intervals. Sandstone thicknesses were determined from the gamma-ray curve with a baseline of 65 A.P.I. units or less. Johnson (1984) applied a baseline of 75 A.P.I. units; however, in order to better illustrate cleaner sandstone content, a lesser baseline cutoff was utilized. The total Upper Red Fork sandstone map displays the sandstone content between the Upper Red Fork marker to the top of the Lower Red Fork marker. The Upper Red Fork sandstone map was manually contoured to give a more representative thickness distribution.

The Upper Red Fork sandstone thickness map identifies a narrow and elongate or channel-like distribution trending east to west from T.12N., R.14W. to T.12N., R.19W. (Figure 38). The typical gamma-ray signatures within this thick sandstone trend display constant blocky profiles. Within the channel-like trend, the bulk sandstone packages account for approximately 40 – 60% of sand of the entire Upper Red Fork interval. The Lower Red Fork sandstone is less definitive and as a result of a lack of data, was not included. Attempts to map the Lower Red Fork resulted in wide ranges in sandstone percentages without well log data required to refine distribution.

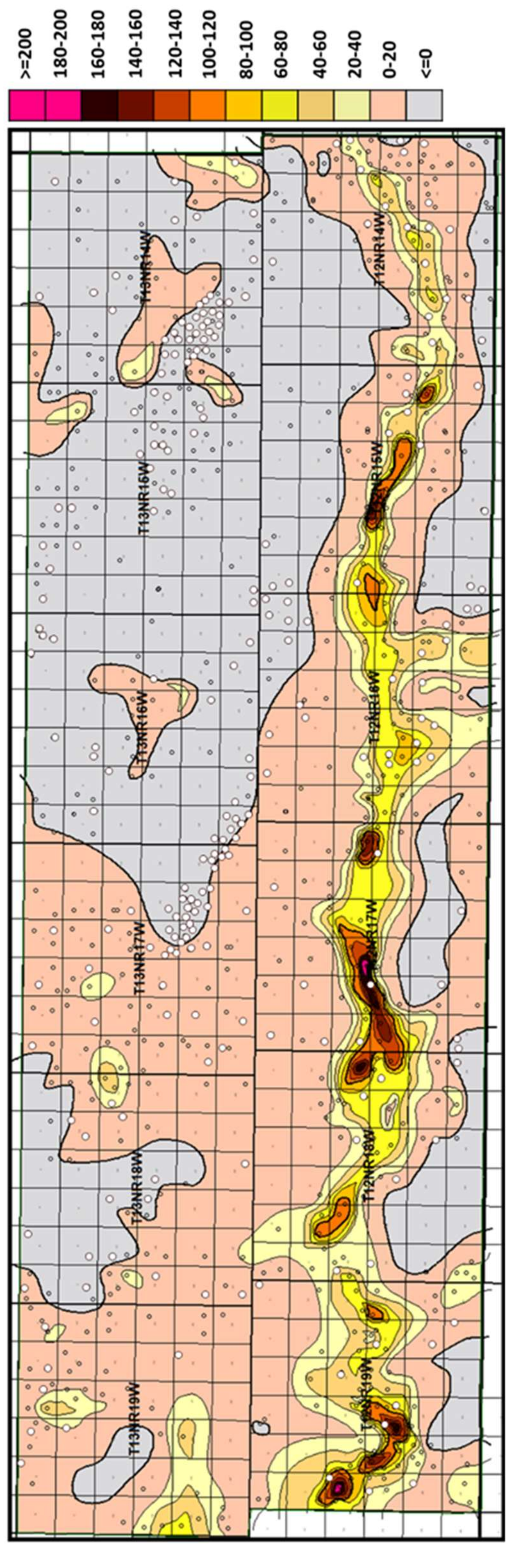

Figure 38: Total Upper Red Fork sandstone thickness map. Net sandstone thicknesses were determined from the gamma-ray curve using a cutoff value of 65 A.P.I. units or less to define clean sandstone intervals. This Upper Red Fork sandstone map defines a narrow trend associated with a channel. The white filled circles represent wells that did not penetrate the Red Fork interval and logs or well data of no value to this study.

CHAPTER VI

DISUCSSION AND INTERPRETATION

Stratigraphic Analysis

Several cross-sections were created to support correlations, build the overall sequence stratigraphic framework, and to aid in the construct of an accurate depositional model based off of gamma-ray electrofacies characteristics for the Red Fork Sandstone. Full length cross-sections can be found in the appendices. These cross-sections include some that are oriented subparallel to expected depositional strike and others that are oriented at a high oblique angle to depositional strike. A log facies map also helped simplify the interpretation of the depositional system. The Upper Red Fork was the main interval of focus because the Lower Red Fork was less definitive owing to a lack of control; the interval is difficult to characterize without core and sufficient well logs. Gamma-ray log signatures were studied to define the stratigraphy of the Red Fork Sandstone. Common characteristics included blocky, cleaning/coarsening-upward (C.U.), fining-upward (F.U.), or irregular (aggrading) log shapes. Sharp contacts that were observed throughout the Walter Sauer 1 core show abrupt changes from a dark shale to a sandy interval. Due to the location of the well, this could be indicative of a crevasse splay where the sediment supply exceeds the capacity of the channel and spills over top of the deltaic shale. Chaotic bedding was also observed at several depths in the Walter Sauer 1.

The chaotic bedding could represent a gravity driven slump in prodelta deposits that accumulate on an unstable shelf or a gentle slope setting. Another hypothesis is the chaotic beds represent a transgressive surface of erosion with clasts originating in the underlying beds. The wavy bedding observed can be indicative of a tidally dominated environment or low-energy (below tidal bore energy) deposits while lenticular bedding are common in high energy environments. Within the channel-like environments, blocky, well-defined, and clean sandstone intervals dictated the log signatures. These blocky sandstone units contained a sharp base which exemplified a sequence boundary along the base of the incised valley. In the thicker zones of the blocky sandstone units, sandstone proportions extended up to 150 feet. The Nelda Ruth 41275 well operated by Chesapeake Operating LLC in T.12N, R.17W. has approximately 170 feet of clean sandstone. This suggests that a minimum of 170 feet of sea level occurred to carve this valley, in addition to the ocean depths that the sea level was at during the Lower Red Fork. The next most common characteristic to help define the stratigraphy, were the coarsening-upward log shapes. These signatures were common within the Upper Red Fork and were in place prior to the incision of the valley. Coarsening-upward signatures were associated with a prograding delta and prograding sediment. Fining-upward signatures observed flanking the main channel are interpreted as deltaic distributaries or less defined channels. Within the Upper Red Fork interval, a vast majority of the well locations in the northeastern portion of the study displayed irregular gamma-ray associated with a deltaic or fluvial flood plain. This was the common characteristic found northeast of a proposed hinge line that coincides with the thickening shown in Figures 36 and 37.

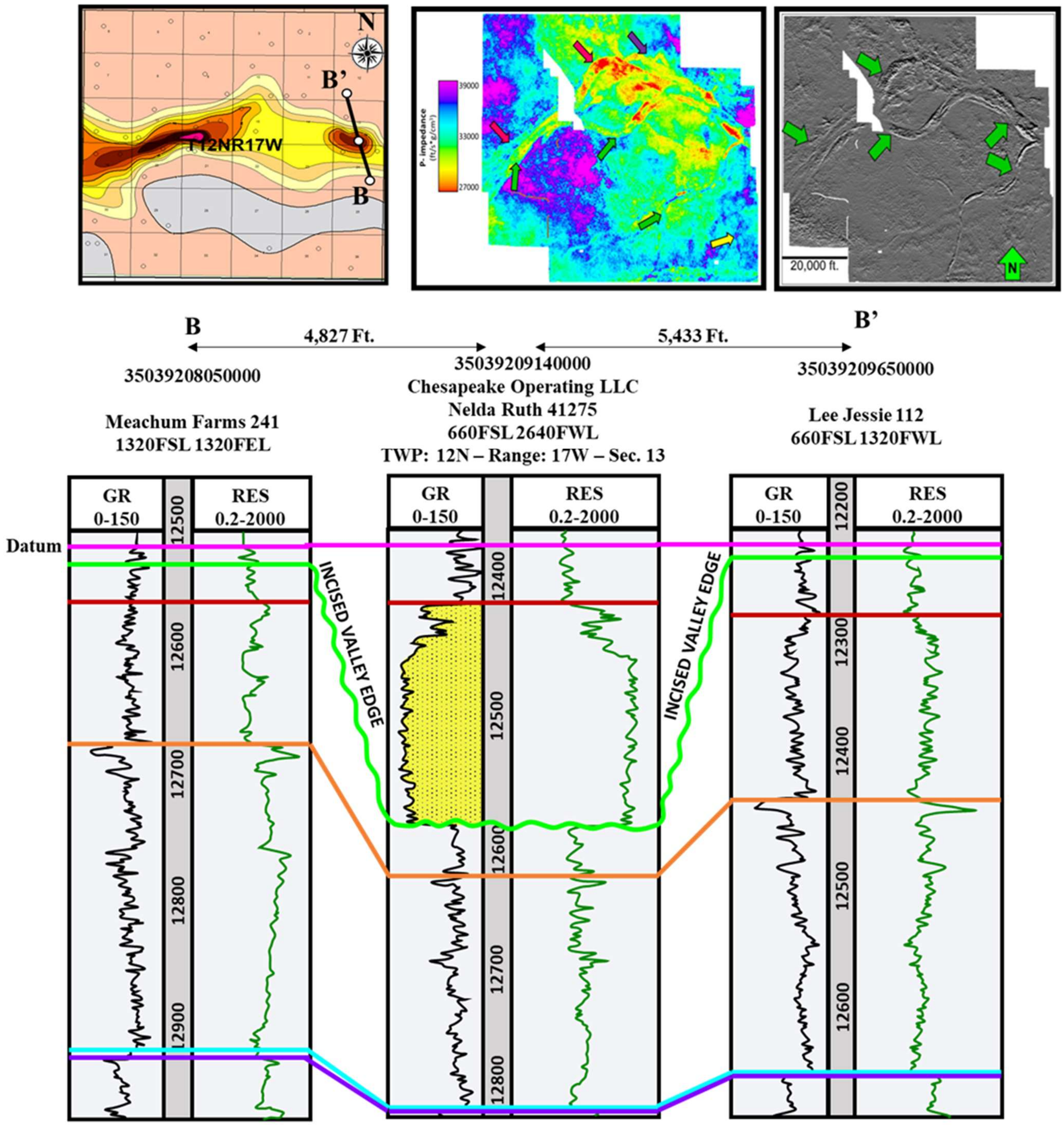

Figure 39: Interpreted incised valley-fill stratigraphy of the Nelda Ruth 41275 well within the Upper Red Fork. Sandstone map (left) signifies sand percentages and the location of the cross-section flattened on the Pink Limestone. Two seismic analog examples obtained from Del Moro (2012) and Peyton et al., (1998). Colored map (middle): Horizon slice displaying incised channels. Different colored arrows represent different stages of valley erosion and filling. Grey map (right): Horizon slice below the Pink Limestone with green arrows signifying incised channels. Cross-section located in Appendices.

Regional Depositional Setting

Two former studies that were utilized as a reference for the regional depositional setting were those by Johnson (1984) and Anderson (1992) due to their close proximity to the study area. Johnson (1984) characterized the Red Fork as a submarine channel and fan environment. His focus was of the Lower Red Fork. Wide ranges in sandstone percentages suggests areas of sandstone thicknesses that could be related to fan lobes or basin-plain depositional environments with interbedded sand and shale units, which can be linked to the slope setting suggested by Johnson (1984). The cleaner intervals of the Lower Red Fork could represent pulses of sand-rich sediment coming down slope to form muddy submarine fans characterized by serrate gamma-ray curves. Sandstone percentages within these possible lobe environments are interbedded and account for 40-60%. Poor well data and missing raster images are common in T.12N. to T.13 N., R.16W. to R.17W., and the southwestern portion of T.13N., R.14W., which accounted for wide variation sandstone percentages. As a result of this scarcity of data, this study focused on the Upper Red Fork interval. Anderson (1992) examined the Upper Red Fork, focused on an area to the west, and suggested a basin-floor submarine fan complex as the depositional model for the Red Fork Sandstone. Al-Shaieb et al. (1995), Puckette et al. (2000), and Fritz et al. (2003) introduced regional interpretations of the Red Fork Sandstone and identified fluvial-deltaic and marginal marine environments along the shelf edge, as well as basin-floor fans. Toth (2018) recognized deep incision of the Cherokee Platform during Red Fork time. Recent work by Tunin (2020) reinforced regional channel traits which allowed for the evidence that these channels were flowing and prograding from the east to the west and southwest. It is important to acknowledge that this channel formed in many different stages of erosion and filling and that these depositional settings led to the development of several structural, stratigraphic, paleo-topographic, and combinational traps (Clement, 1991).

Depositional Model

Several depositional systems can be associated with the Red Fork Sandstone. Although the Lower Red Fork was not the focus of this study, electrofacies characteristics helped verify the Johnson (1984) interpretation of a submarine channel and fan environment in the northeastern portion of the study area. Common gamma-ray characteristics observed for the Lower Red Fork were small blocky distributive channels, with overlapping fans that displayed a serrate gamma-ray log signature.

The Upper Red Fork depositional system was that of a shelf-to-slope environment near the East Clinton field, a fluvial-deltaic complex with multiple stages of channel erosion and filling, and various channel complexes as the channel trends west down slope. Generally speaking, an incised valley dominated the region. Within the interval between Red Fork 3 and Red Fork 4, an anomalous west-east thinning occurs as a result of the shallower Red Fork 4 interval incising into the lower Red Fork 3 interval. A thick channelized trend can be assumed within the interval between the Red Fork 4 and Pink Limestone and could be linked to stage II-III filling. A simplified model near the East Clinton field was formed off of correlations of well log signatures and a log facies map, studies nearby from Johnson (1984) and Anderson (1992), and sedimentary biogenic structures observed within the Walter Sauer 1 core and reported in earlier studies. During Upper Red Fork time, relative sea level dropped far enough to cause incision of a main valley, and in some instances, this valley reached thicknesses upwards of 40-50 meters (~ 170 ft.). Backfilling of this valley occurred during transgression causing the channel to be submerged and become a submarine channel. Due to the gentle dip of the slope (1 - 2º), deltaic and delta-front coarsening-upward log signatures and evidence of fossils/ burrowing suggests that the Upper Red Fork was deposited within a deltaic to marginal marine environment near the East Clinton field. The Upper Red Fork began with pro-deltaic marine shale, followed by prograding deltaic (delta-front) environments with fluvial influence from the northeast. This deltaic complex was incised during a drop in sea level to form the large valley trend that became the Clinton-Weatherford channel.

A variety of channel settings could occur along the main channel including incised valleys on the shelf to slope channels south and west of the hinge line that defines the shelf to slope break. Sprague et al. (2005) outlined several channel hierarchies and architectures found in shelf-slope environments, which could be applied to the Upper Red Fork. Moving down slope and to the west of the study area, these different settings include feeder/ submarine channel/ or canyon with higher net-to-gross (NTG), bypass/ leveed channels with lower NTG, confined settings with moderate to high NTG, distributary/ deltaic lobes/ or splays with very high NTG, weakly confined settings with higher NTG and are generally laterally offset, and distributive/ submarine channel fans with moderate to high NTG. Examples of wireline log signatures taken from a cross-section on the western half of the channel trend, along with a model illustrating these channel complexes can be seen in Figure 42.

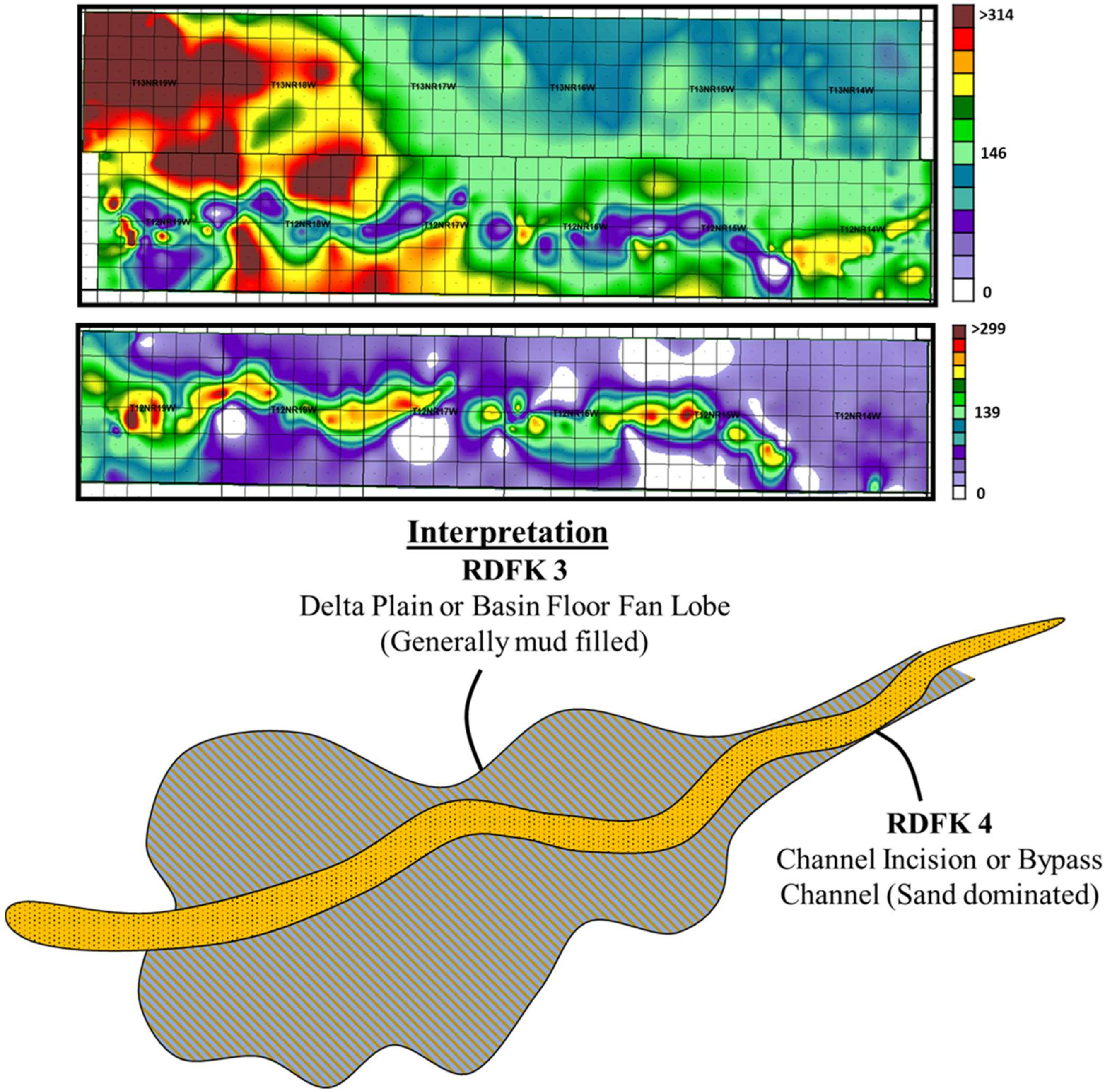

Figure 40: Red Fork 4 (RDFK 4) appears to thicken at the expense of the underlying Red Fork 3 (RDFK 3). Red Fork 4 (RDFK 4) appears to be a linear channel-like feature that is sand dominated. The thin area in Map D that corresponds to the thicker trend in Map E is likely due to missing and or thinner section resulting from erosion.

Gamma Ray Electrofacies Characteristics				
Color	Electrofacies (Gamma-Ray)	Description	Depositional Environment Interpretation	Sediment Supply
		No signature	Fluvial flood plain, delta plain, or deep marine	Aggrading
		Coarsening upward SS or Sh (or thin CUS)	Delta Fringe or Delta Boarder	Slight CUS
		Coarsening Upward Signature (CUS)	Delta front (Slope Setting)	Prograding; Sharp CU
		Coarsening Upward Signature (CUS)	Delta Front	CUS; Sharp Top
		Cylindrical (Blocky)	Channelized SS; Incised Valley	Lowstand; Backfilled

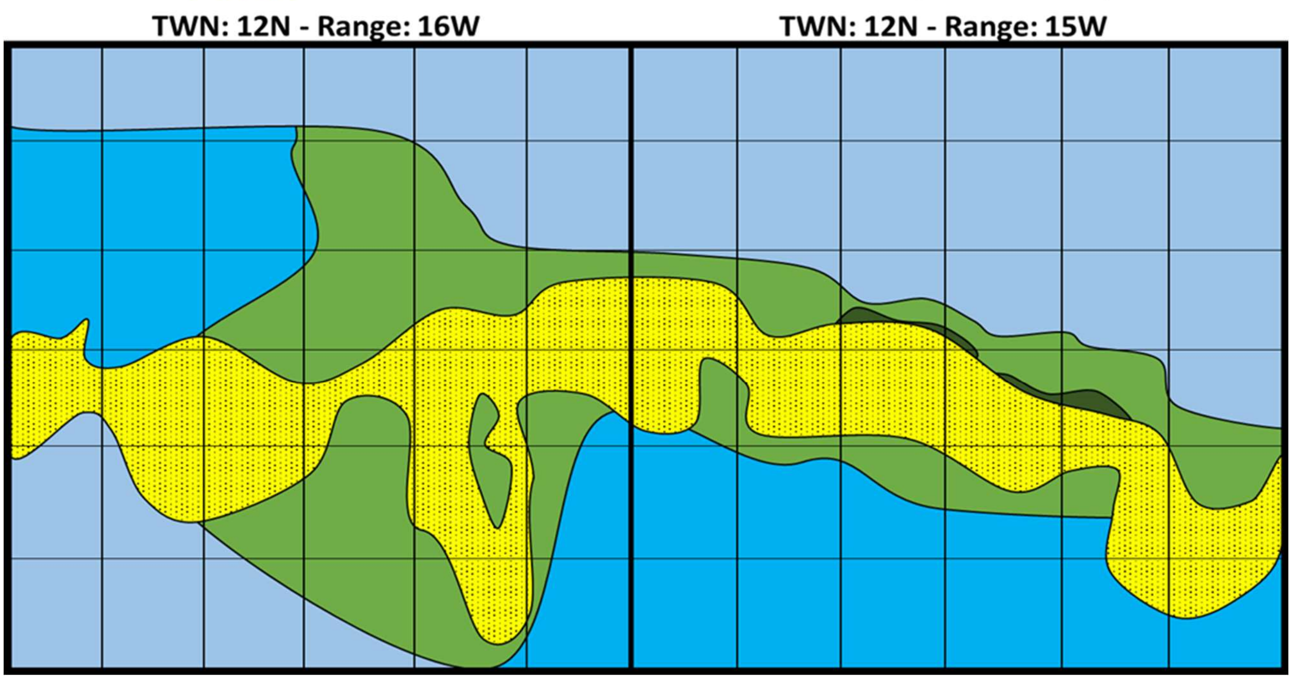

Figure 41: Total Upper Red Fork electrofacies distribution (East Clinton Field). This distribution is interpreted as a fluvial-deltaic complex and an incised valley. Lowstand and transgressive deposits are shown in yellow. Green and blue represent progradational deposits, whereas gray are mudrock-rich aggradational deposits.

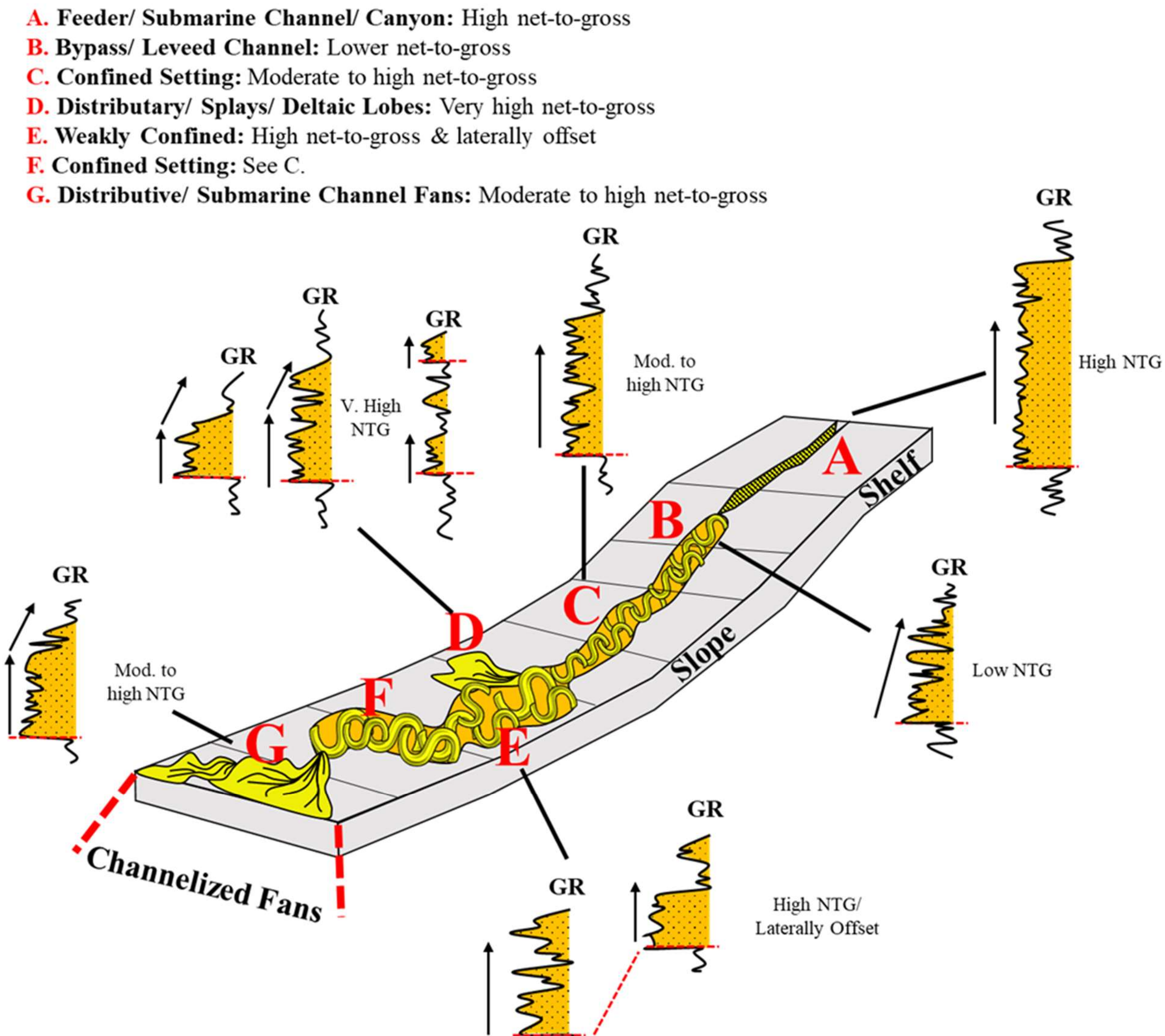

Figure 42: Schematic model with wireline log signatures found within the channel trend, representing the various reservoir architectures found within shelf-slope settings (modified after Sprague et al., 2005).

Sequence Stratigraphic Framework

Better insight into the timing of valley incision and its subsequent sediment fill, reservoir facies within these incised valleys, and required conditions for trapping of hydrocarbons will result in an improved exploration strategy and future field development (Bowen and Weimer, 1997). The processes operating during deposition of Pennsylvanian age Red Fork sediment are linked to the Mid-continent cyclothems, which have been the topic of many studies including (Heckel, 1977; Klein, 1996; and Jensen, 2016). Cyclothems are high-frequency depositional cycles that contain marine and non-marine strata and originate from eustatic sea level change fueled by glaciation, fluctuating climates, and basin subsidence (Jensen, 2016; Wanless et al., 1963). These cyclothems represent stratigraphic sequences which give us clues about the depositional settings in which they were formed. Heckel (1977), Klein (1996), and Pashin (2004) acknowledged that sea level fluctuated within the Mid-continent, and that valley incision reflects a lowering of base level. Eustacy driven decline in sea level forced regression and depth of incision was controlled by the magnitude of the lowering of base level (Jensen, 2016). To determine the frequency and inferred magnitude of sea-level change, numerous cross-sections were constructed to identify and correlate stratigraphic surfaces and generate a sequence stratigraphic framework for the Red Fork Sandstone. A simplified sequence stratigraphic model, its related sea level curve, and a wireline log displaying the common features can be seen in Figures 43 and 44.

For this study, four separate sub-interval stratigraphic surfaces (Red Fork 1 – 4) were identified and utilized to develop an accurate sequence stratigraphic representation of the upper and lower units of the Red Fork. The first sub-interval within the Lower Red Fork (RDFK 1 or LRF A) includes a type-II sequence boundary at the base, a transgressive systems tract (TST 1), and a highstand systems tract (HST 1). The second sub-interval (RDFK 2 or LRF B) also includes a type-II sequence boundary at the base and the top, a transgressive systems tract (TST 2), and a highstand systems tract (HST 2). The third sub-interval (RDFK 3 or RDFK A), within the Upper Red Fork, contains a type-II sequence boundary at the base, a transgressive systems tract (TST 3), and a highstand systems tract (HST 3). Occasionally, the highstand interval is incised by the overlying channel that trends east-west. The fourth sub-interval (RDFK 4 or URF B) begins with a type-I sequence boundary at the base of the incision, followed by a lowstand systems tract (LST 4) which occurs southwest of the Upper Red Fork shelf break, followed by a transgressive systems tract (TST 4), and a highstand systems tract (HST 4). The sequence boundary near the top is an erosional surface within the Pink Limestone interval. Each sequence can be further sub divided into parasequences that can be defined as genetically related beds that reflect an increase in water depths (Jensen, 2016; Van Wagoner et al., 1987). These parasequences often overlap with sequence boundaries (Van Wagoner et al., 1988). Within the study area, the Red Fork Sandstone interval represents a 3rd order depositional sequence with a higher order internal stratigraphy. The Upper Red Fork interval comprises a fourth-order sequence boundary with two, fifth order parasequences. Each sequence contains a transgressive systems tract, a maximum flooding surface, and a highstand systems tract with a lowstand systems tract in areas where valley incision occurred. A two well cross-section (Figure 46) was constructed across the Upper Red Fork shelf-slope break (or hinge line). The well located landward (to the northeast) drilled by Ward Petroleum Corporation shows a highstand interval (HST 3) that is not present basinward (to the southwest) past the shelf break. The well located towards the basin penetrated a channel that incised the prograding highstand systems tract (or HST 3) seen in the well located landward.

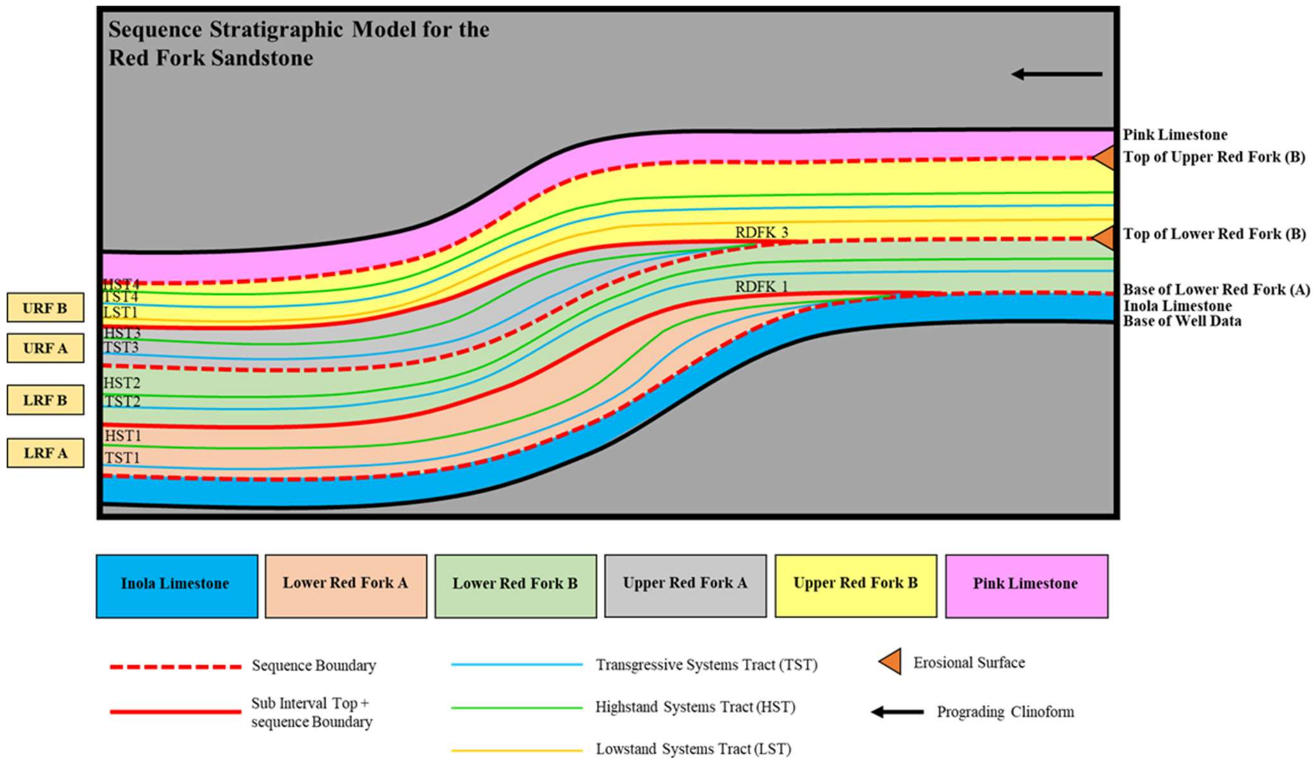

Figure 43: Prograding clinoform illustration of the sequence stratigraphic framework for the Red Fork Sandstone.

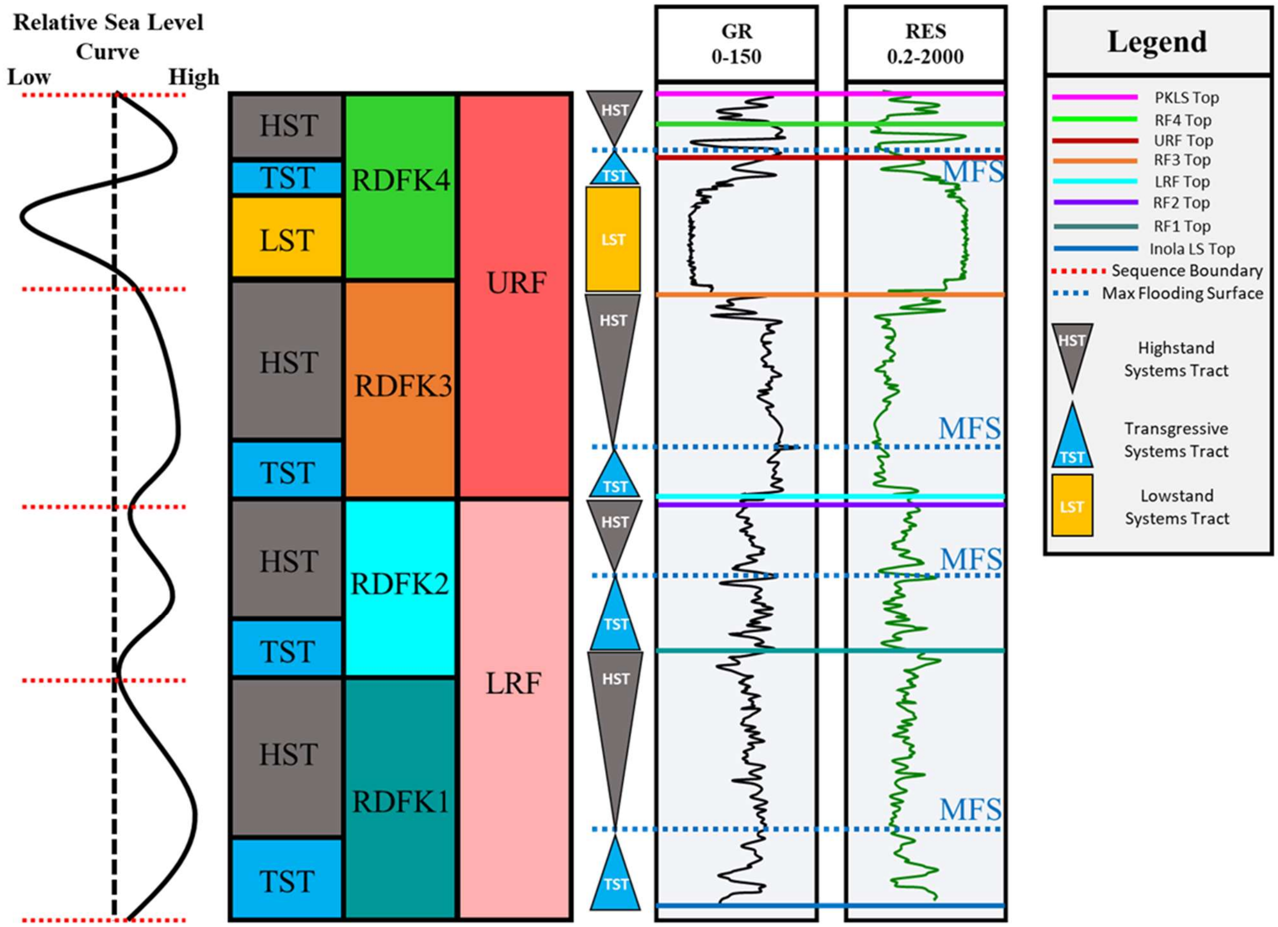

Figure 44: Relative sea level curve and associated wireline log displaying the interpreted sequence stratigraphic framework of the Red Fork Sandstone (modified after Lang et al., 2001).

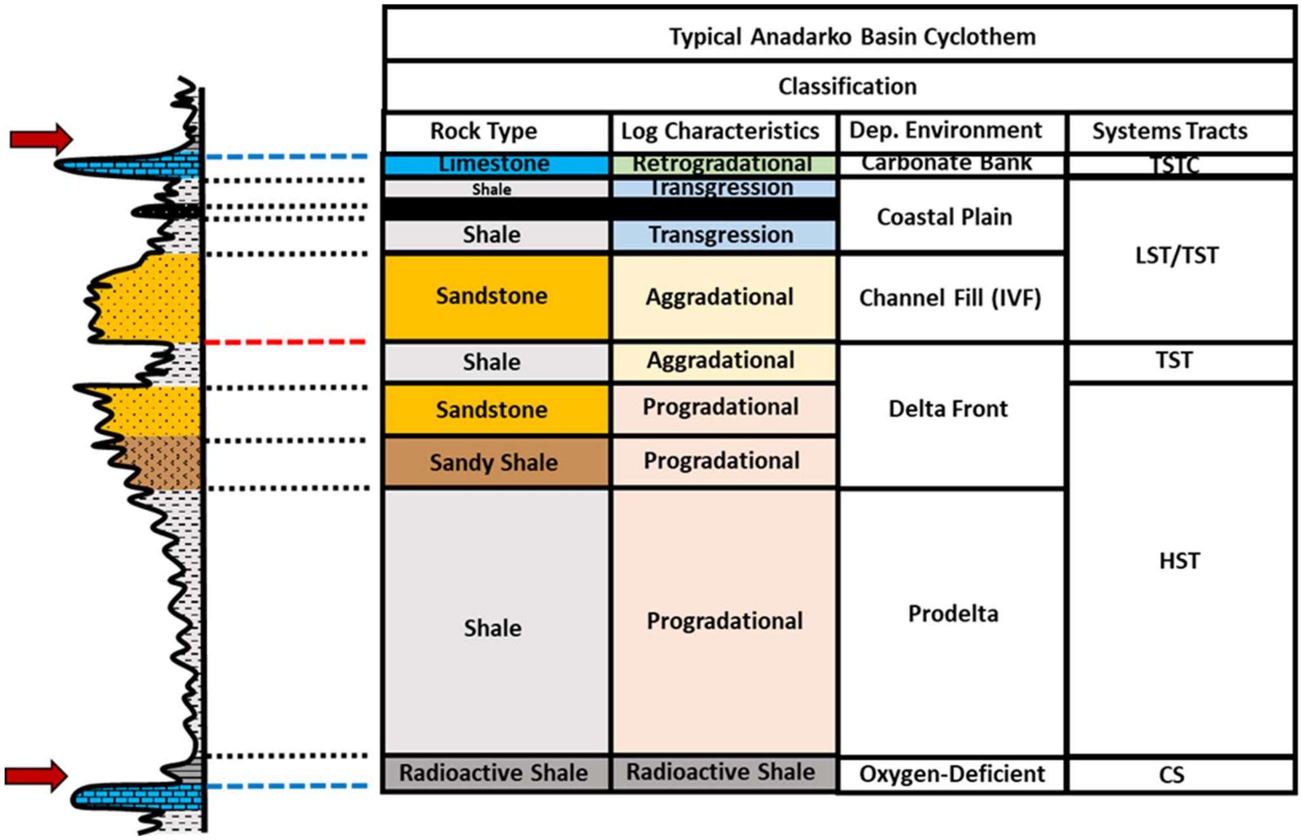

Figure 45: Gamma-ray and lithology characteristics associated with typical Pennsylvanian cyclothems for the Anadarko basin, which reflect the general succession of the Upper Red Fork Sandstone. General log characteristics (left) with red arrows representing the cycle boundaries, blue dashed lines represent general flooding surfaces, and red line representing a type I sequence boundary (modified after Jensen, 2016).

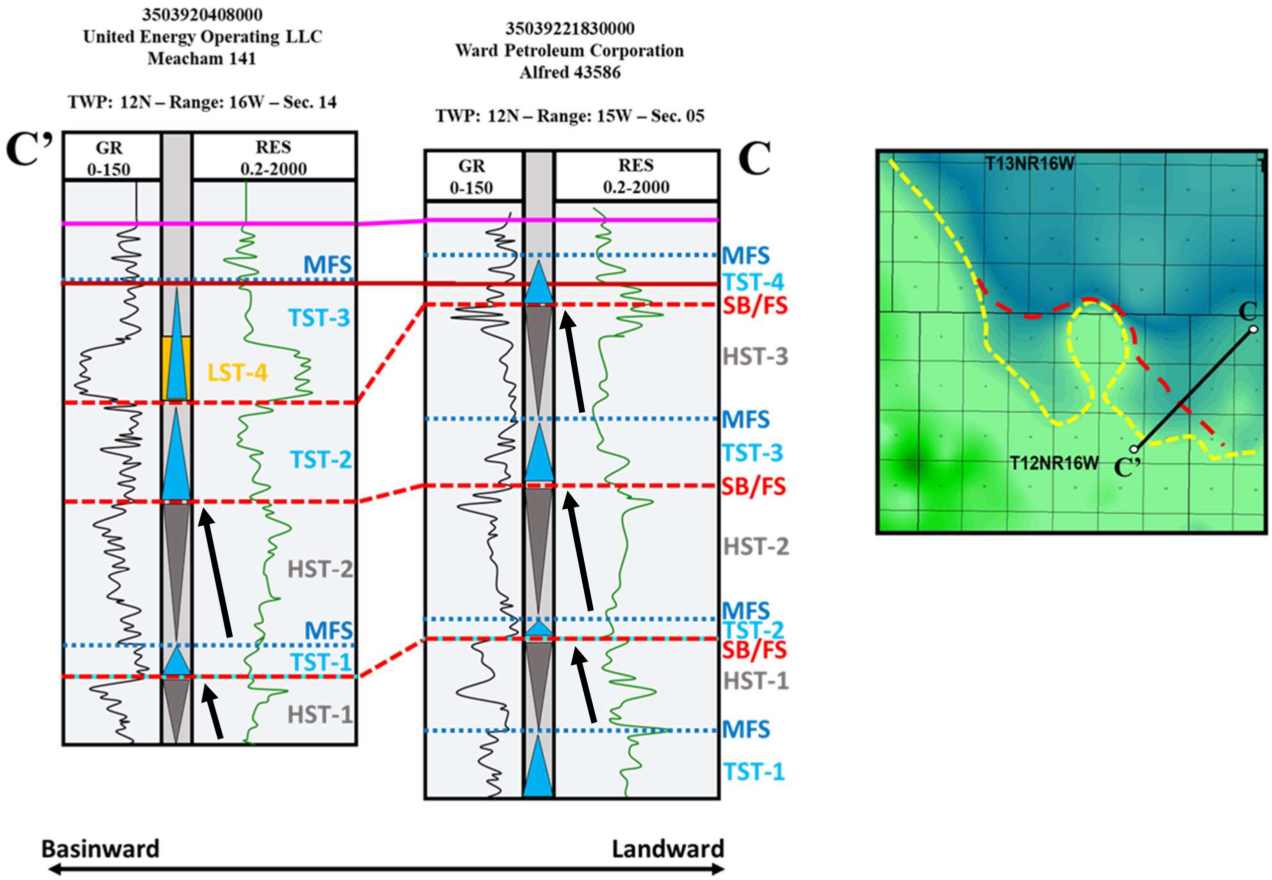

Figure 46: Schematic cross-section displaying Upper Red Fork sequence stratigraphy with respect to the Upper Red Fork shelf-slope break (hinge line). The uppermost prograding highstand systems tract (black arrows) is not evident in the more basinward (southwest) well.

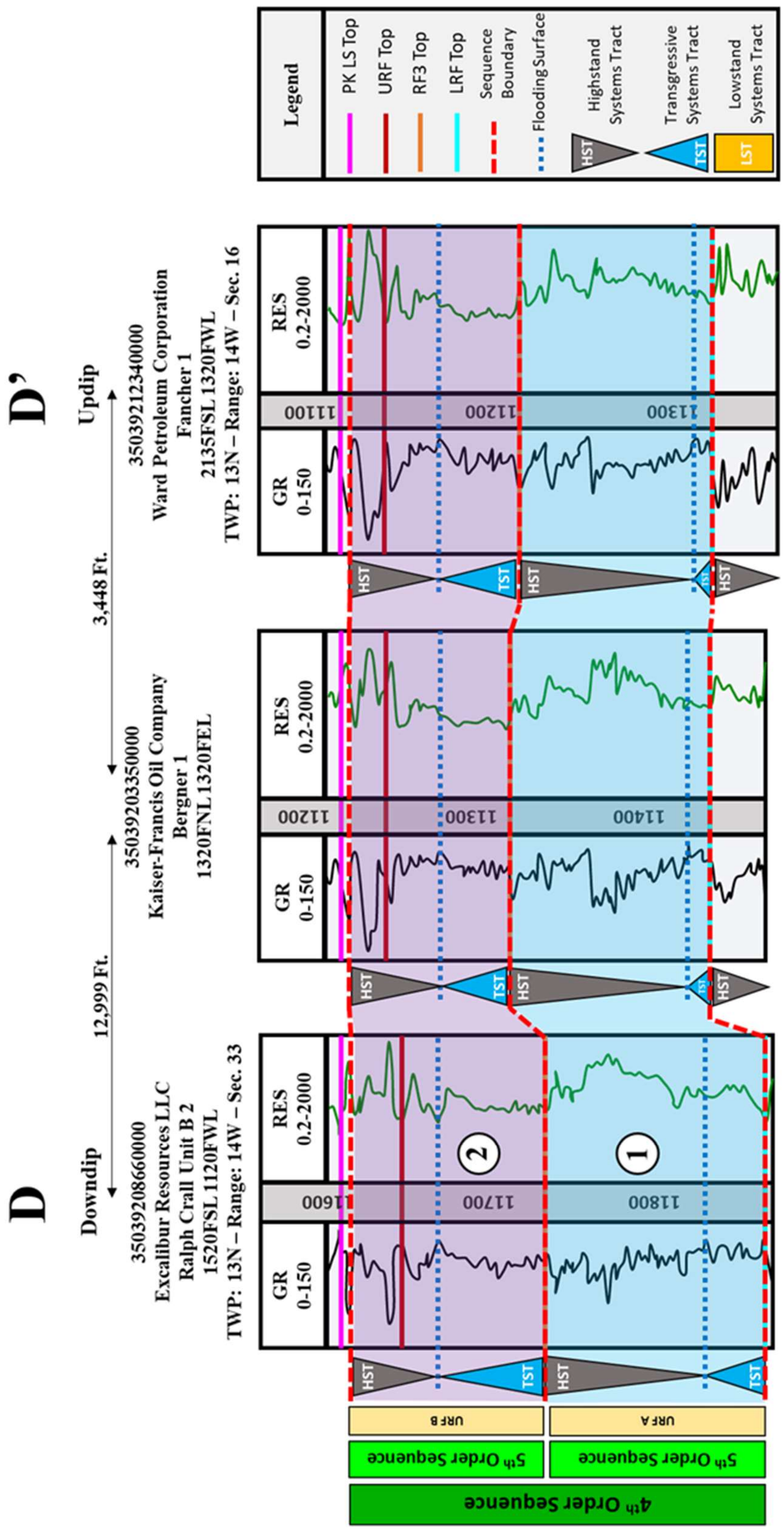

Figure 47: Schematic cross-section displaying Upper Red Fork cycles with 4th and 5th order cycles. CRX was located in T.13N., R.14W. up-dip of the main channel trend.

Production and Horizontal Reservoir Potential

The Pennsylvanian Red Fork Sandstone has a long history of conventional oil and gas production in western Oklahoma, particularly in the elongated trend known as the Clinton-Weatherford channel and within the East Clinton field. The success in this area and other parts of the Anadarko basin and elsewhere in Oklahoma has resulted in the development of a number of fields and plays including: Oakdale field, South Thomas field, southwest Leedey, the Strong City District, Naval Reserve, Burbank field, Tecumseh field, southwest Wakita field, Cherokita and Wakita trends, Cheyenne Valley field, Carmen N field, Otoe City S field, Long Branch, N.W. Stafford field, N.W. Foss field, N. Stafford field, Weatherford field, S. Hydro field, S.W. Geary trend, the N.E. Eakly trend, and of course the East Clinton field (Withrow, 1968; Campbell et al., 1998; Andrews, 2003; Clement, 1991). The East Clinton field alone contained recoverable reserves up to 480 billion cubic feet (bcf) of gas and 10.5 million barrels of condensate within the Upper Red Fork (Clement, 1991). Puckette and Al-Shaieb (2001) described generalized facies that occur in incised valley fill deposits and their importance as reservoirs. Reservoir traits are similar for incised valley fills, though the Morrow incised valley fills are generally coarser grained than their Red Fork counterparts. Some of these generalities are finer-grained sandstone that is burrowed is prevalent in the upper part of valley fills, whereas coarser-grained sandstone within the fluvial influenced part of the valley fill typically has higher porosity and permeability. Lateral deposition associated with stable base level can provide excellent reservoir facies in point bars. Similarly, higher energy braided streams of mid to lower channel-fills in fluvial settings often form higher porosity and permeability reservoirs. Bowen and Weimer (2003) worked on Upper Morrow incised valleys and reported that medium- to coarse-grained fluvial sandstones deliver the greatest production and cumulative production opportunities. Comparable formations such as the Skinner Sandstone and Red Fork Sandstone provide the same opportunities, though the greater depth of burial in the Anadarko basin increases the reliance on secondary dissolution porosity for reservoir facies (Johnson, 1984; Puckette, 1990; and Anderson, 1992). Pennsylvanian Morrowan incised valley-fill reservoirs within the Sorrento field in portions of Colorado and Kansas have produced high-volumes of oil and gas with cumulative oil production of 107 million barrels of oil (Bowen and Weimer, 1997).

Of the Red Fork exploration and development wells drilled in the Clinton-Weatherford trend, 26% were dry holes and 74% producers. Of the original producing wells, 49% are now plugged and abandoned. 13.36% are labeled "inactive." The cumulative production graph of the Red Fork Sandstone within the Clinton-Weatherford channel trend indicates the Red Fork production peaked at approximately 12 million barrels of oil equivalent (BOE) in 1987. Those numbers have declined in the last few decades due to depletion. Based on the style of deposition with multiple sandstone bodies within a larger valley, the potential for horizontal production to locate bypassed pay in compartmentalized reservoirs should be high. The low permeabilities in these more deeply buried and finer-grained sandstones, help generate lithologic and diagenetic flow barriers that are lacking in the Morrowan shelf analogues described by Puckette and Al-Shaieb (1990) and Bowen and Weimer (2003). Besides a propensity for compartmentalization, the higher gas to oil ratios of these deeper reservoirs should energize and facilitate recovery when the Red Fork reservoirs are drilled horizontally and hydraulically fractured. Steering horizontal wells in thinner more compartmentalized reservoirs will require logging while drilling and close attention to the gamma-ray curve to maintain position within the reservoir. Other important factors include hydrocarbon indications on wireline log curves including neutron-density cross-over and low water saturations. Joshi (2003) outlined the disadvantages and benefits related to horizontal drilling. Some of those disadvantages that Joshi (2003) summarized included higher costs (1.5 to 2.5x), only a 65% commercial success rate, and the ability to only produce one zone. Some of the benefits involved higher production rates and reserves, finding (or developing) costs were less than the cost of buying producing reservoirs, and the volume of production accomplished by one horizontal well opposed to several vertical wells, which offers better outcomes in reduced needs for pipelines, locations, and surface facilities (Joshi, 2003). The objective of horizontal drilling within these incised valley-fill deposits is to unlock more surface area within the reservoir and target thin channel bodies that have yet to be effectively produced, resulting in higher reserves and better return on investment. The cross-section in Figure 52 illustrates valley incision, sequence boundaries, and sandstone reservoir facies within the valley. Near the valley edges, the reservoir is absent. Lengthwise across the approximate valley axis displays the incised valley-fill reservoir facies with fair to good sandstone continuity along the valley.

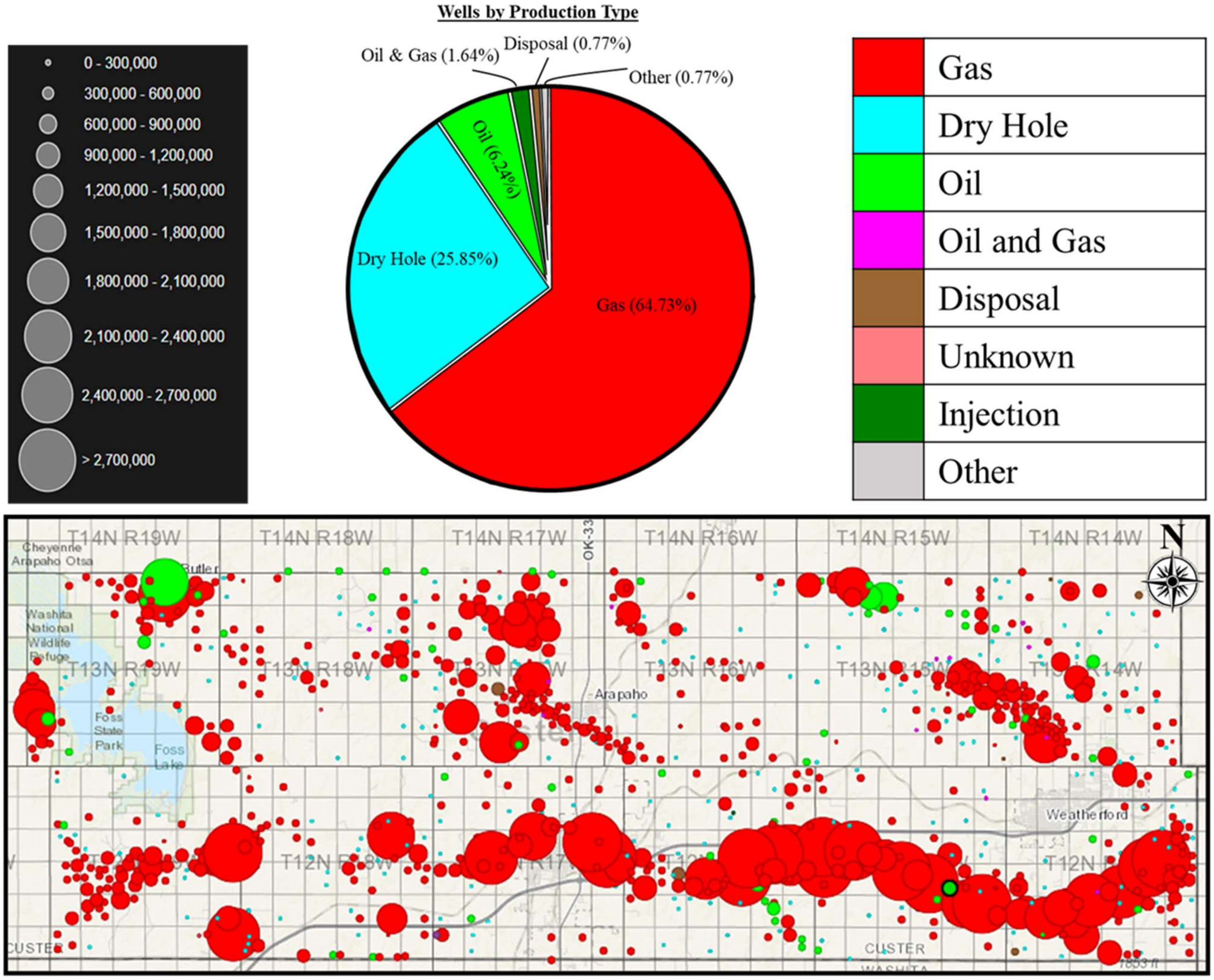

Figure 48: Cumulative barrels of oil equivalent (BOE) production map for the Red Fork Sandstone across the study area. A barrel of oil equivalent is the amount of energy that is equivalent to the amount of energy found in a barrel of crude oil, usually a 1:6 ratio (one barrel of oil to 6,000 cubic feet of natural gas) (Chen, 2020). Pie chart displays production types identified in the map (acquired and modified from Enverus (Drilling Info)).

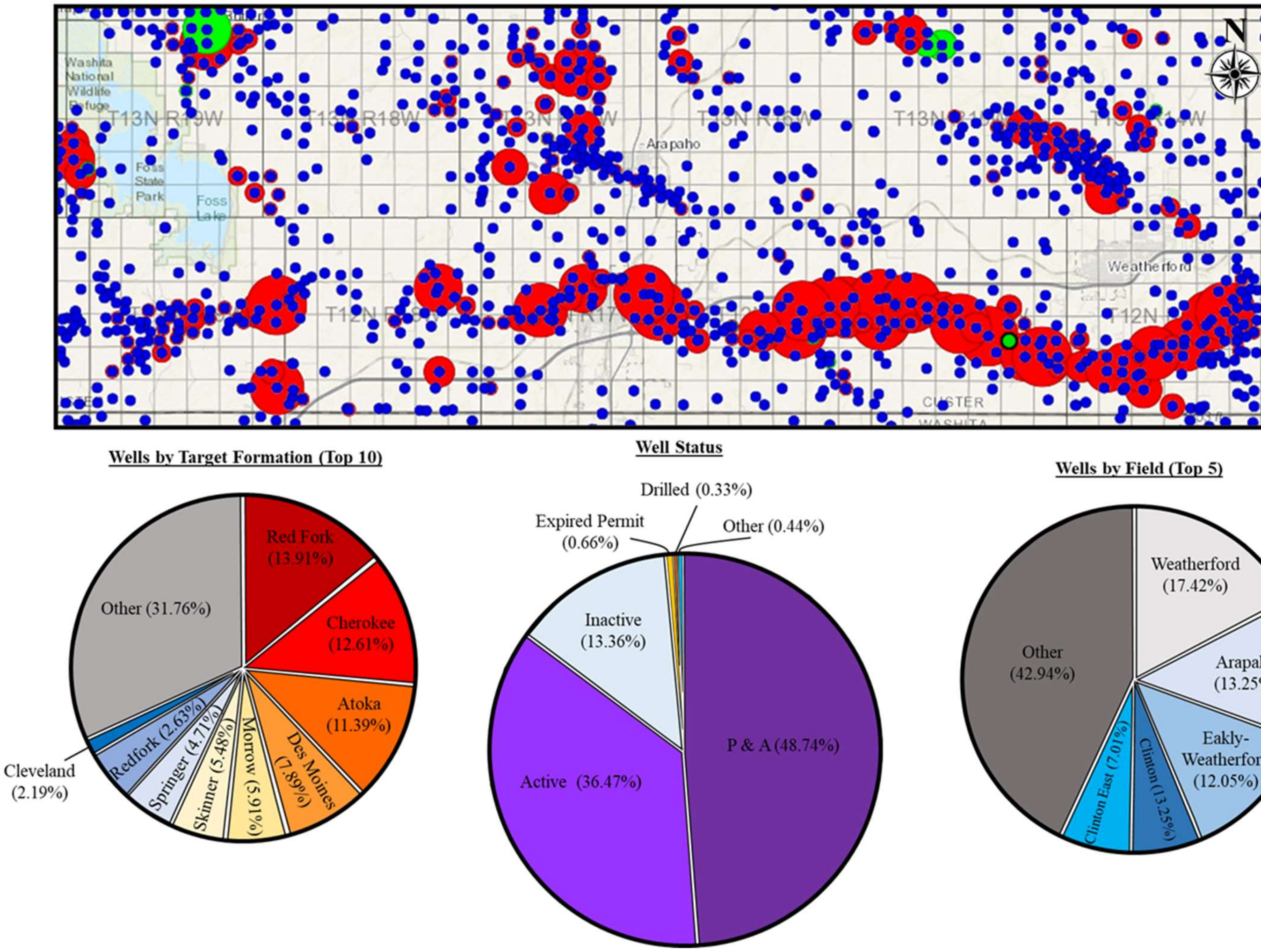

Figure 49: Cumulative barrels of oil equivalent (BOE) production map for the Red Fork Sandstone with a well location overlay within this study (blue dots). Pie charts display wells by target formation (left) (Desmoinesian, Red Fork, and Cherokee are undifferentiated), well status (middle), and wells by field (acquired and modified from Enverus).

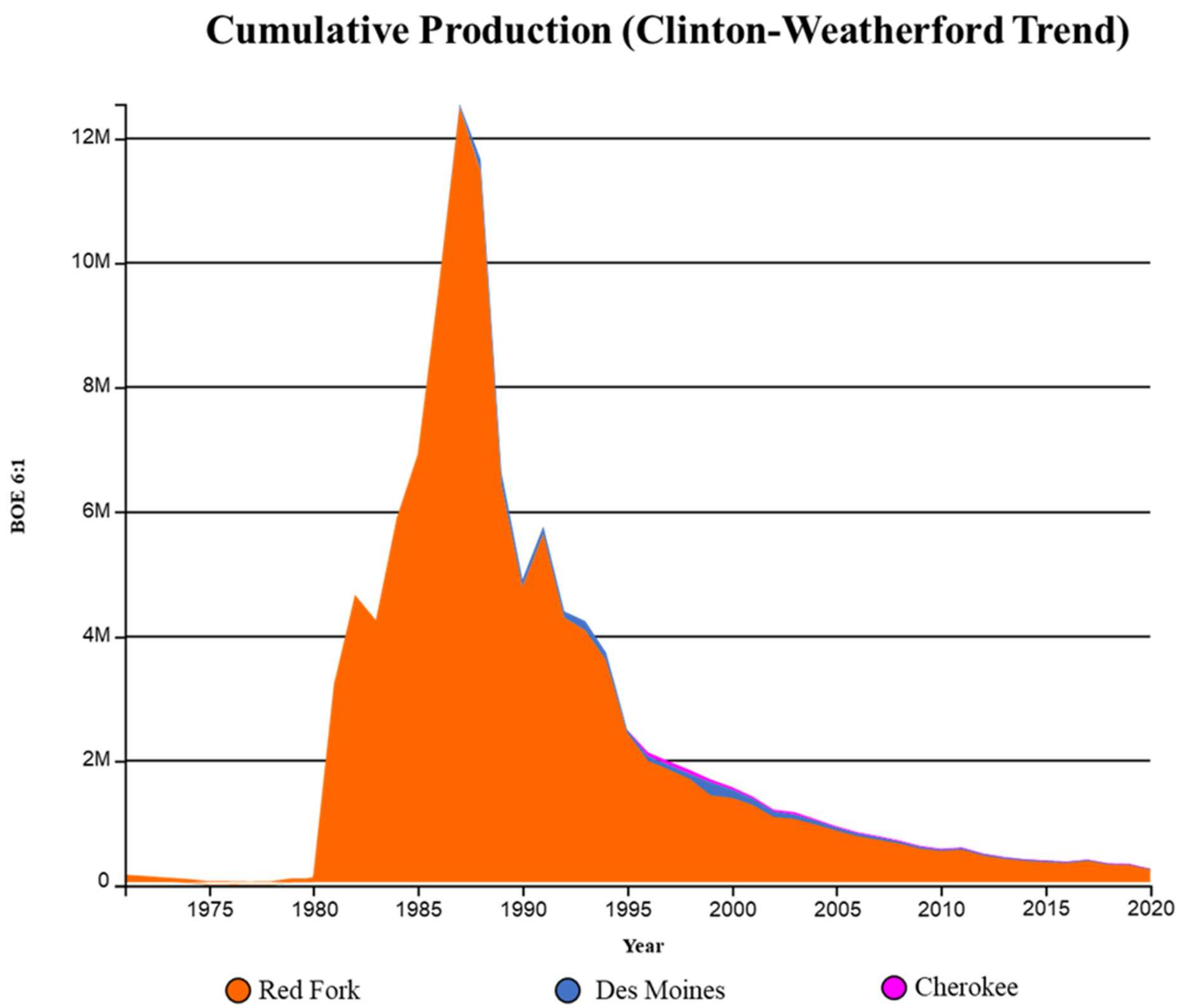

Figure 50: Cumulative production per year for the Red Fork Sandstone within the Clinton-Weatherford trend. Red Fork production peaked over 12 M (million) BOE (barrels of oil equivalent) in 1987 from approximately 65 wells. Production has declined in the recent decades. Des Moines and Cherokee are undifferentiated (acquired and modified from Enverus).

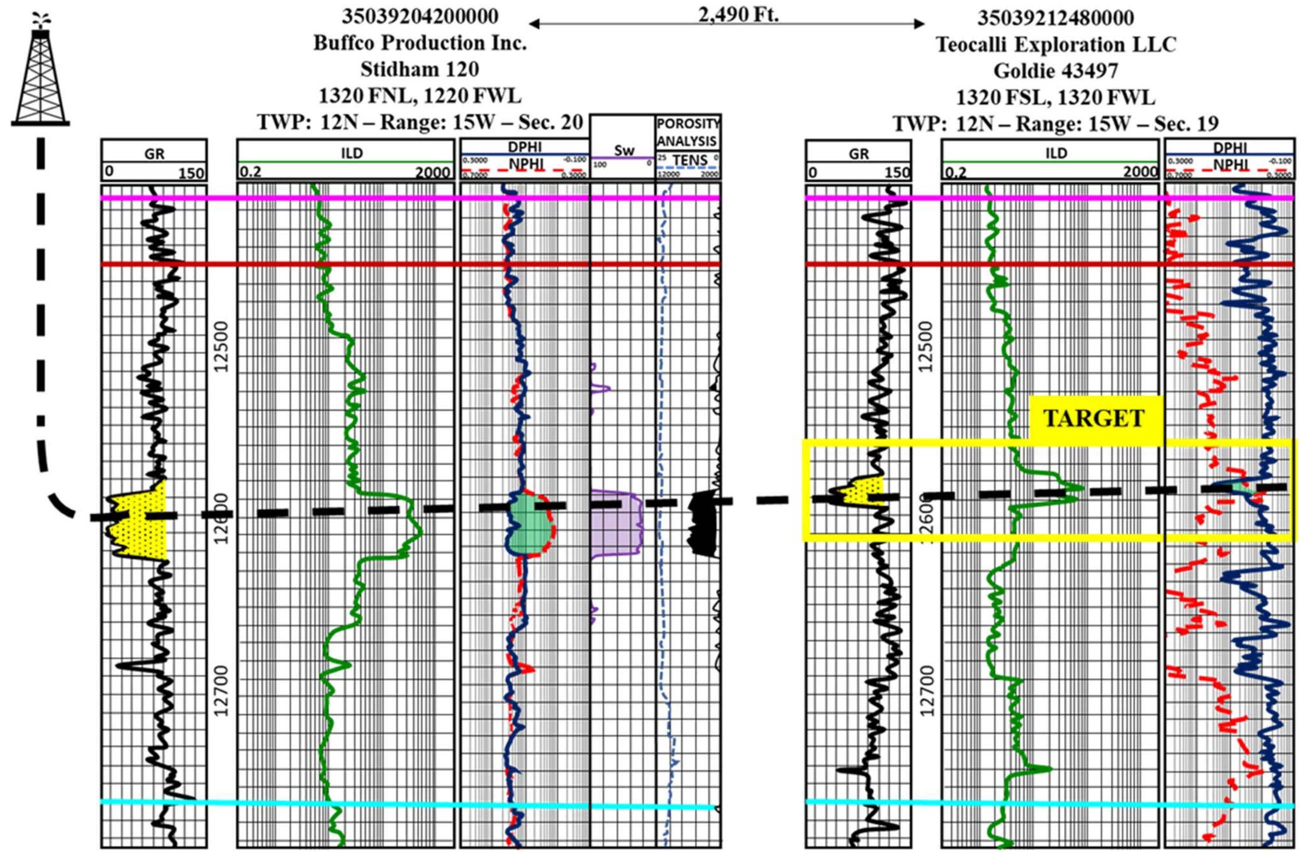

Figure 51: Example of the horizontal potential within the Upper Red Fork Sandstone. Target reservoir resembles 10-12 ft. of potential within the Upper Red Fork Sandstone.

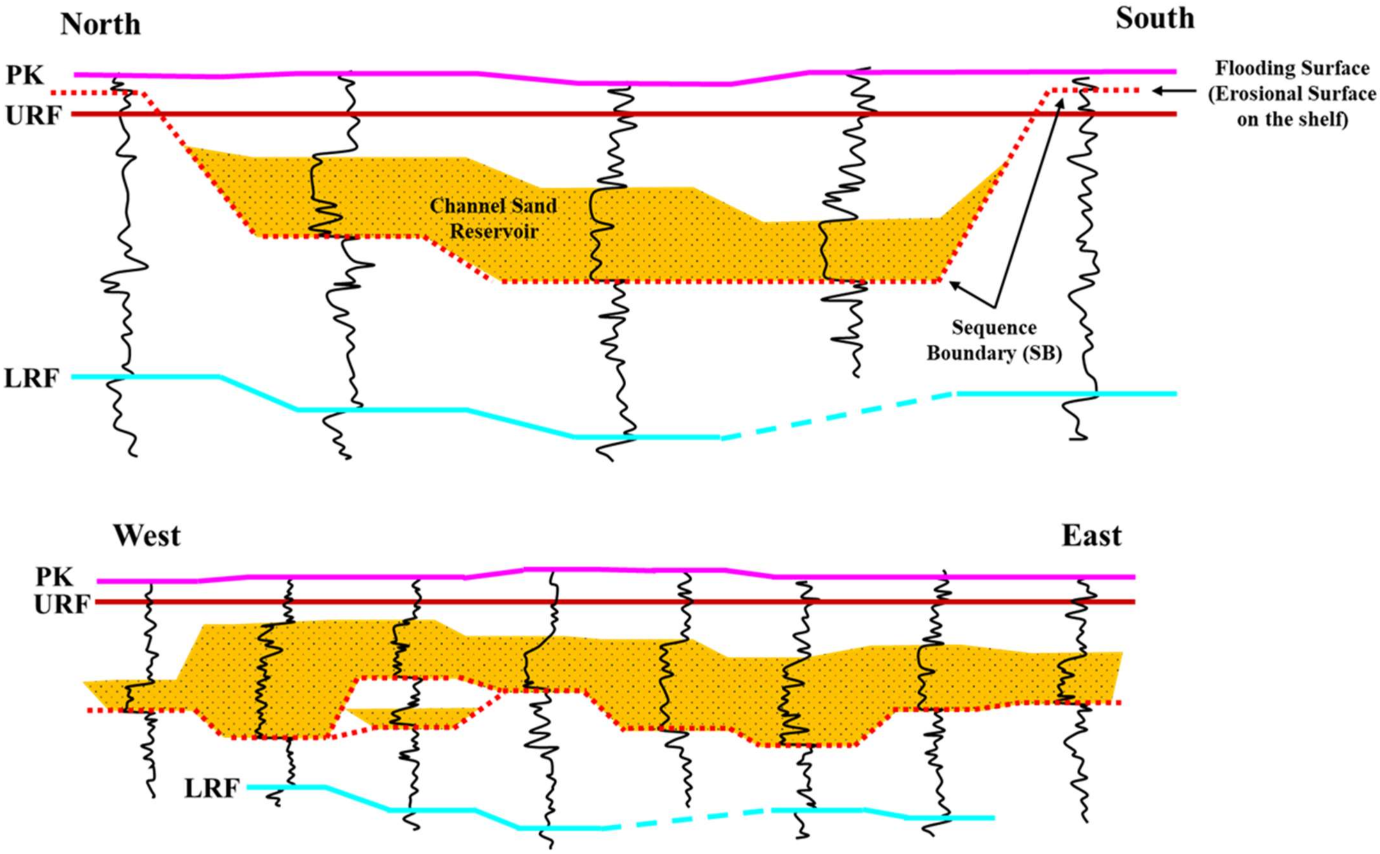

Figure 52: Representative cross-sections demonstrating incised valley-fill reservoir characteristics (top) and abundant sandstone continuity along the approximate channel axis (bottom). Datum: Upper Red Fork Sandstone (URF).

Analog Models

Slope channel environments that include a mix between fluvial, deltaic, and submarine depositional settings are common around the world. Some examples that show similarity to the Red Fork Sandstone include, but are not limited to, the Nile delta off the coast of Egypt or the Cook Sandstone on the Eastern Shelf of the Midland basin.

The offshore Nile delta, Egypt, is dominated by slope channel systems that contain heterogeneous successions of sandstones with upward-fining gamma-ray signatures (Cross et al., 2009). The sandstone bodies in this region occur as laterally amalgamated and sinuous channel-fills. Above the basal incision, the reservoir is sandstone dominated and occurs within different types of channels (Cross et al., 2009). Within these slope channel systems, the general sequence stratigraphic context includes a sequence boundary associated with incision, a lowstand systems tract with well-established channel sand bodies, a transgressive systems tract, a maximum flooding surface, a highstand systems tract signifying prograding slope deposits, and multiple stages of erosion and filling. This multi-stage channel erosion and filling can be comparable to the Red Fork Clinton-Weatherford channel, with initial incision and erosion (stage I), laterally amalgamated channel formation (stage II) with more stable base level, aggrading sinuous channels (stage III), and eventually reaching abandonment and maximum flooding (stage IV and V) (Cross et al., 2009).

The Cook Sandstone is located on the Eastern Shelf of the Midland basin, Texas and contains Upper Pennsylvanian to Lower Permian reservoirs that consist of fluvial sandstones, deltaic environments with meandering belts, and submarine canyons and fans that trend to the west - southwest (Bloomer, 1991). The average dip of the Cook Sandstone is approximately 0.5º to 3º, similar to the dip of the Red Fork Sandstone. The Lower Cook Sandstone demonstrates deltaic-front sandstones incised by a channel and then filled with sand (Bloomer, 1991). The

Cook Sandstone resembles a feeder channel with deltaic deposits on the shelf and slope channels that supplied submarine fans to the west. The Red Fork Sandstone shows comparable characteristics of fluvial-deltaic environments preceding a shelf-slope break, and a submarine feeder channel supplying fans to the west. The oil pools on the Eastern Shelf of the Midland basin produce from both shelf and slope facies of the channel trends (Bloomer, 1991).

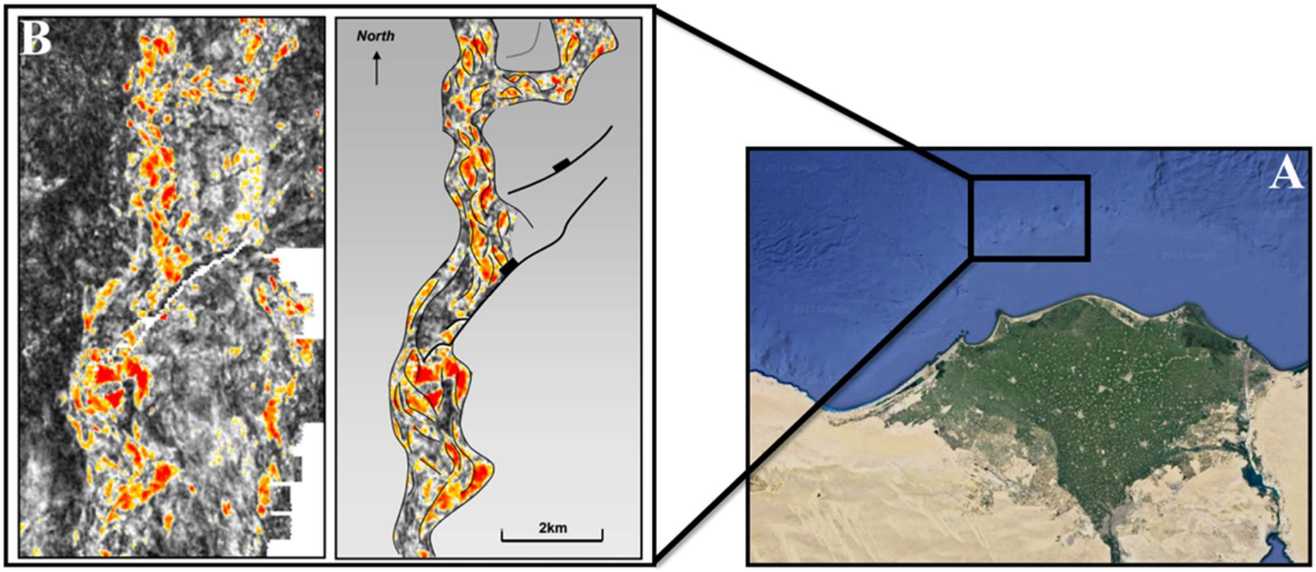

Figure 53: Example from the Nile delta basal part of the slope-channel dominated by stacked channels. Seismic slice displaying channel belt and channels approximately 30 meters thick (B) and a Google Earth image indicating approximate location (A) (from Cross et al., 2009).

CHAPTER VII

CONCLUSIONS

Based on review of wireline well logs, core photographs, thin sections, and completion and production data, it was possible to construct a sequence stratigraphic framework for the Red Fork Sandstone in the study area within the Anadarko basin. The research effort focused on the Upper Red Fork intervals where data were more plentiful. Though the study was hindered by a lack of rock data resulting from closings and travel restrictions during the pandemic, a number of useful conclusions are proposed.

1) The Upper Red Fork interval is marked by a rapid thickening that is interpreted to represent a hinge line that separates shelf deposits to the north from slope deposits to the south-southwest.

2) Thickening of the RF4 interval coincides with thinning of the underlying RF3 interval, suggesting that the thinning is the result of erosion/incision of the underlying RF3 unit and filling of the valley by RF4 sediments.

3) The isopach map of the Upper Red Fork net sandstone delineates a narrow and elongate east to west trend that coincides with the thicker trend of the RF4 interval.

4) Caliche reported in the Upper Red Fork by Johnson (1984) in a well outside the thicker sandstone trend confirms a shelf setting and probable deltaic depositional environment in the East Clinton Field. Other common sedimentary structures and biogenic features

within the Upper Red Fork sandstone outside the elongate thicker sandstone trend included thin (<1 ft.) massive bedding, wavy/ planar/ flaser, and lenticular bedding, marine fossils, bioturbation, burrows, sharp contacts between sandstone and underlying shale, low angle planar cross-bedding, mud clasts, chaotic bedding, and soft-sediment deformation.

5) Structural contours of the Upper Red Fork reflect an average dip of approximately 1.0º to the southwest, with slightly greater dip observed near the inferred shelf-slope hinge line.

6) Based on thin sections from the Lower Red Fork and petrographic analysis of the Upper Red Fork from Johnson (1984), Udayashankar (1985), and Anderson (1992), the Red Fork Sandstone is primarily very fine-grained sublitharenite to litharenite with detrital composition of mostly monocrystalline quartz, metamorphic rock fragments, plagioclase feldspar, and mudrock fragments.

7) The Upper Red Fork comprises a 4th order sequence with two parasequences (or 5th order sequences) that contains a transgressive systems tract, a maximum flooding surface, and a highstand systems tract. A lowstand systems tract is evident in the upper parasequence and is associated with valley incision.

8) The Upper Red Fork depositional system consisted of prograding deltaic complexes that formed on the shelf and along the shelf-slope hinge line. A drop in base level resulted in deep incision and continuation of the channel downslope where it became a feeder for basin floor fans described by Anderson (1992).

9) Incised valley-fill is heterogeneous as a result of multiple stages of channel erosion and filling that tend to generate isolated reservoirs that could be potential targets for horizontal drilling.

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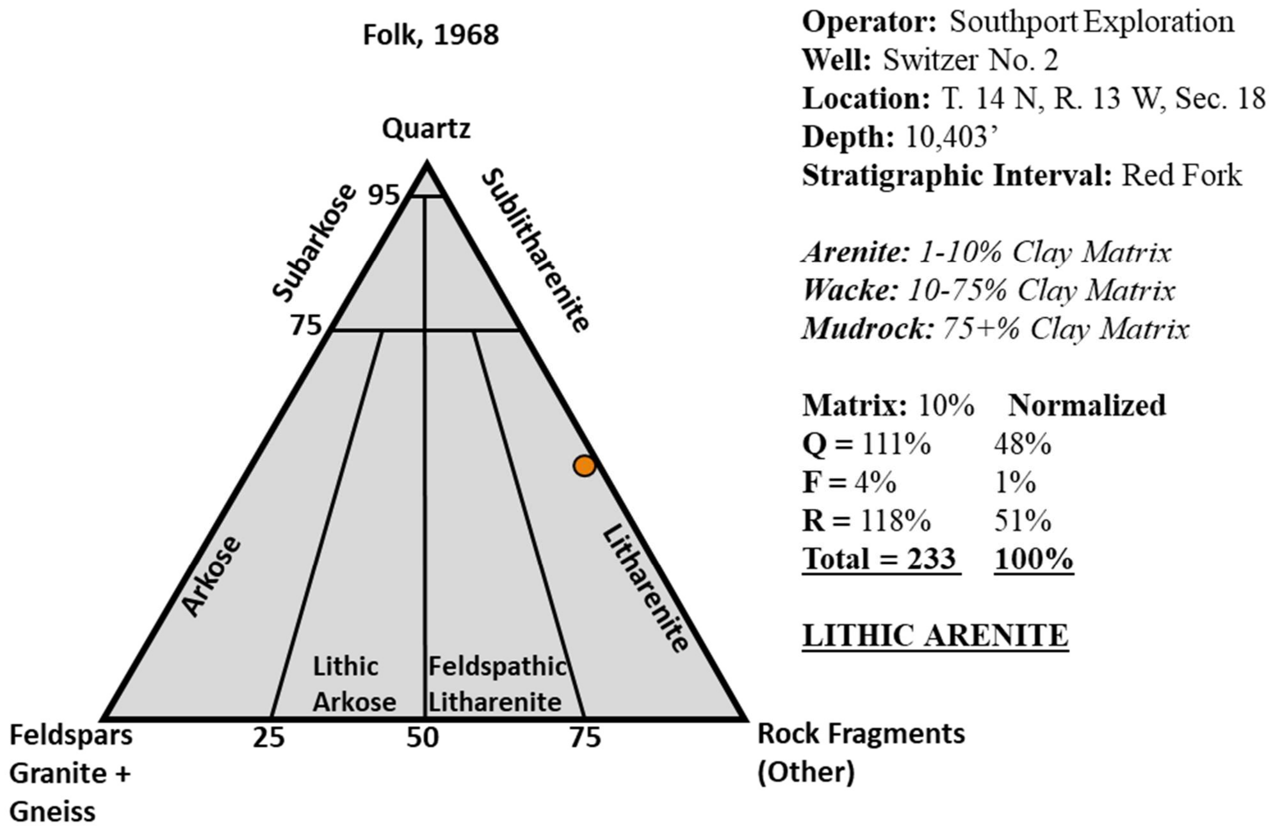
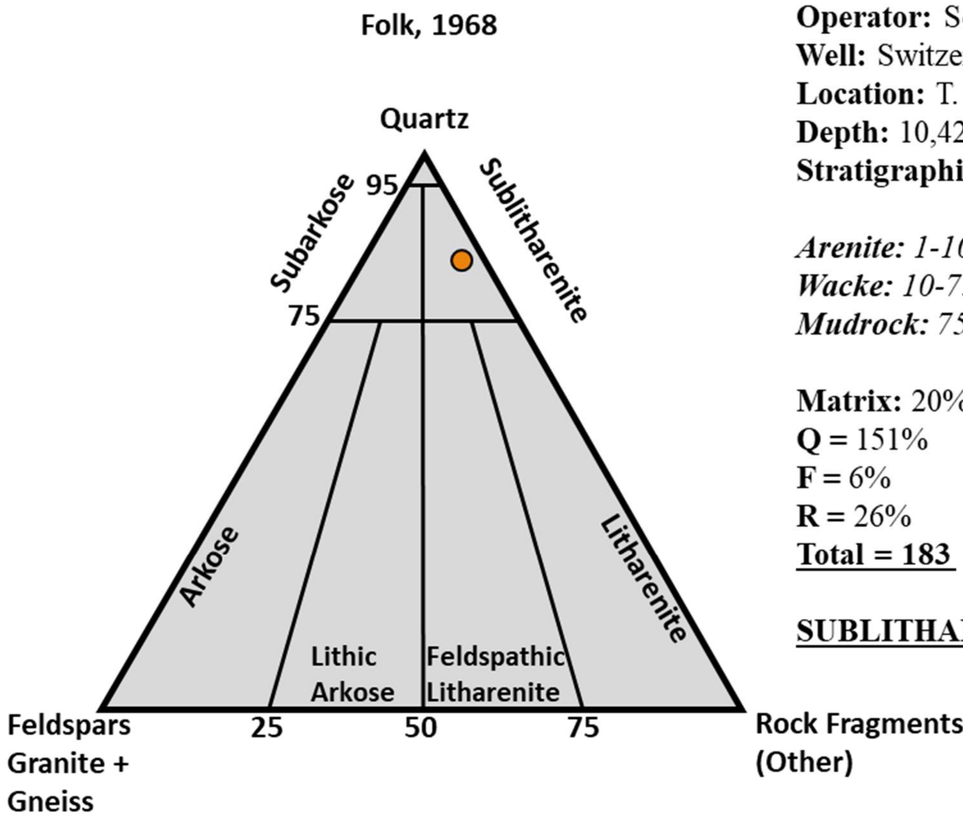
APPENDICES



Folk ternary diagram for Southport Exploration Switzer No. 2 at depth 10,403 feet. Q: quartz, F: feldspar, R: rock fragments.



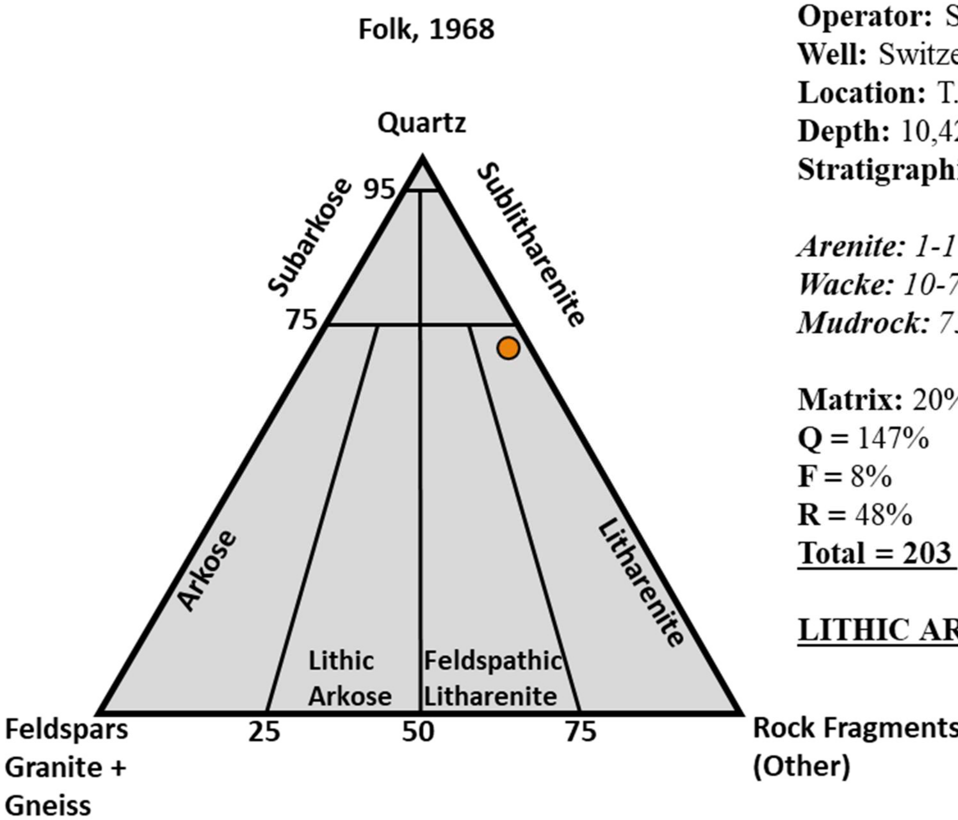
Operator: Southport Exploration
Well: Switzer No. 2
Location: T. 14 N, R. 13 W, Sec. 18
Depth: 10,420'
Stratigraphic Interval: Red Fork

Arenite: *1-10% Clay Matrix*
Wacke: *10-75% Clay Matrix*
Mudrock: *75+% Clay Matrix*

Matrix: 20%	**Normalized**
Q = 151%	82%
F = 6%	3%
R = 26%	15%
Total = 183	**100%**

SUBLITHARENITE

Folk ternary diagram for Southport Exploration Switzer No. 2 at depth 10,420 feet. Q: quartz, F: feldspar, R: rock fragments.



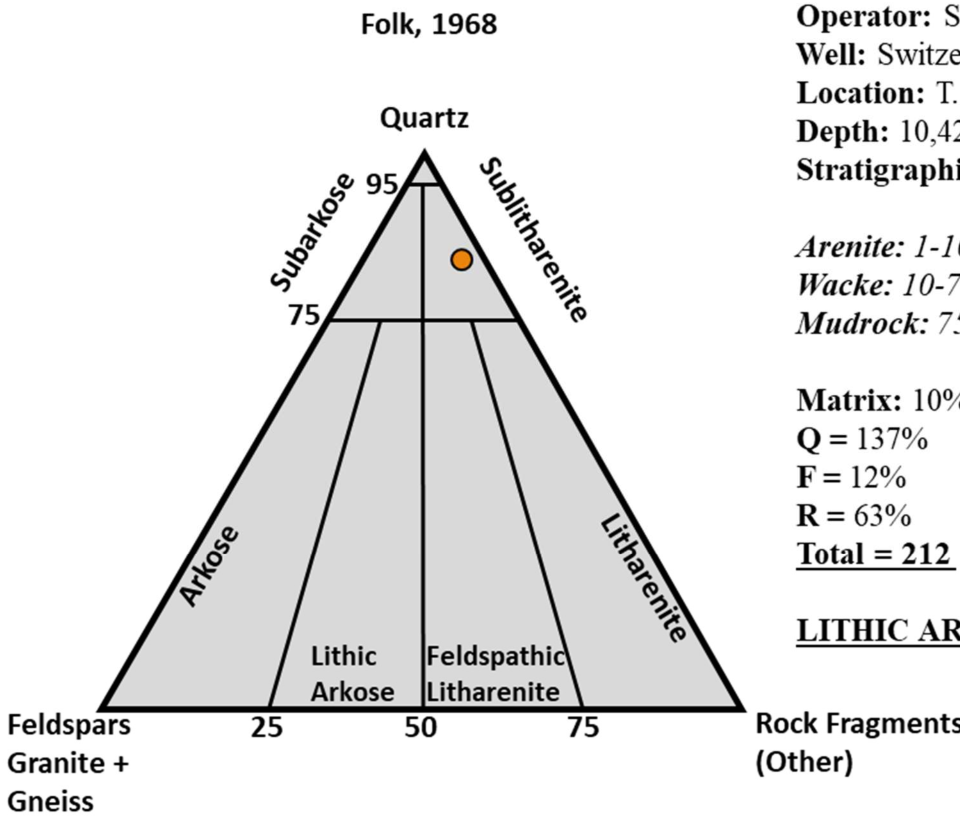
Operator: Southport Exploration
Well: Switzer No. 2
Location: T. 14 N, R. 13 W, Sec. 18
Depth: 10,424'
Stratigraphic Interval: Red Fork

Arenite: *1-10% Clay Matrix*
Wacke: *10-75% Clay Matrix*
Mudrock: *75+% Clay Matrix*

Matrix: 20%	**Normalized**
Q = 147%	72%
F = 8%	4%
R = 48%	24%
Total = 203	**100%**

LITHIC ARENITE

Folk ternary diagram for Southport Exploration Switzer No. 2 at depth 10,424 feet. Q: quartz, F: feldspar, R: rock fragments.



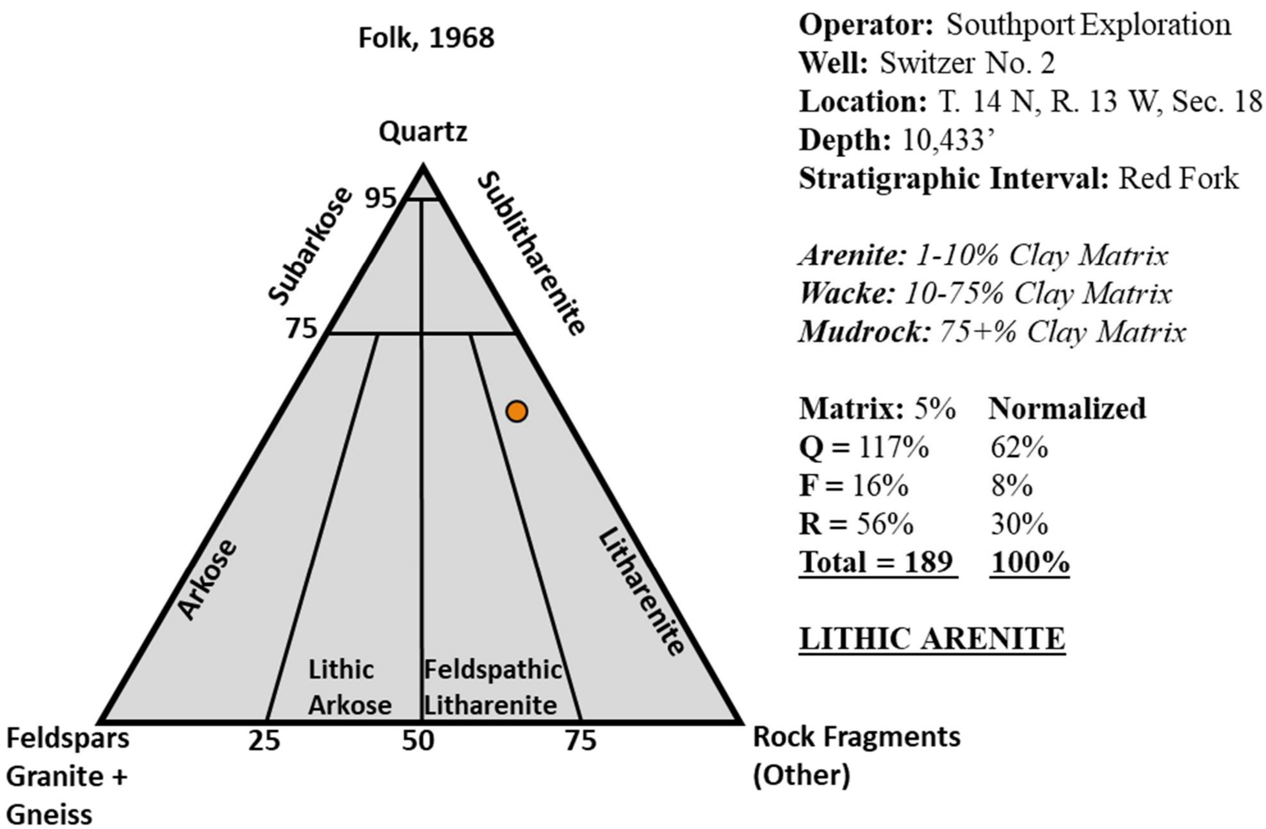
Operator: Southport Exploration
Well: Switzer No. 2
Location: T. 14 N, R. 13 W, Sec. 18
Depth: 10,428'
Stratigraphic Interval: Red Fork

Arenite: *1-10% Clay Matrix*
Wacke: *10-75% Clay Matrix*
Mudrock: *75+% Clay Matrix*

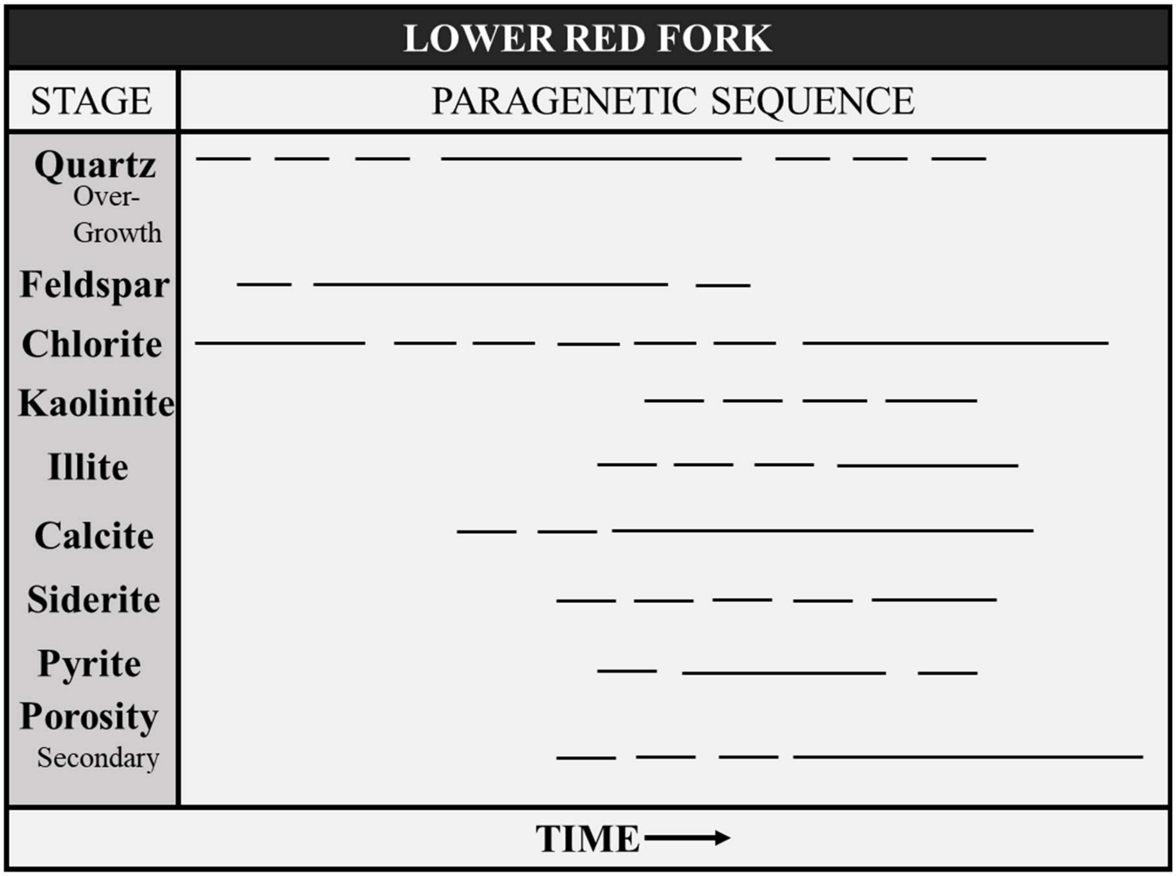
Matrix: 10%	**Normalized**
Q = 137%	65%
F = 12%	5%
R = 63%	30%
Total = 212	**100%**

LITHIC ARENITE

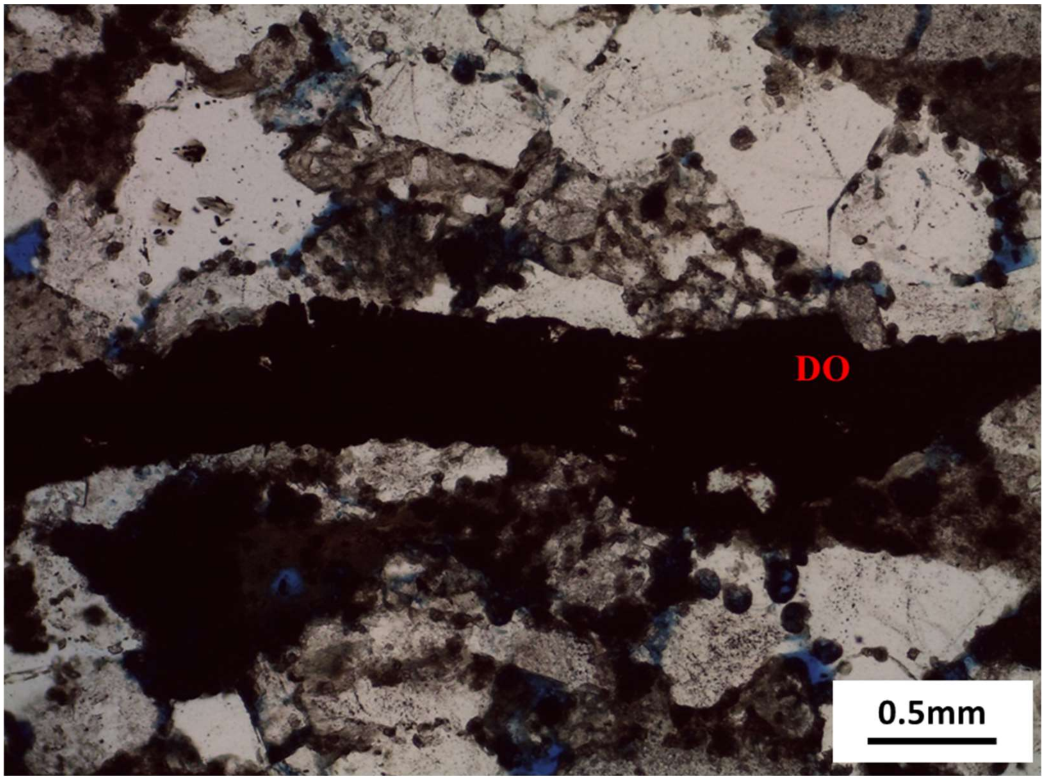
Folk ternary diagram for Southport Exploration Switzer No. 2 at depth 10,428 feet. Q: quartz, F: feldspar, R: rock fragments.



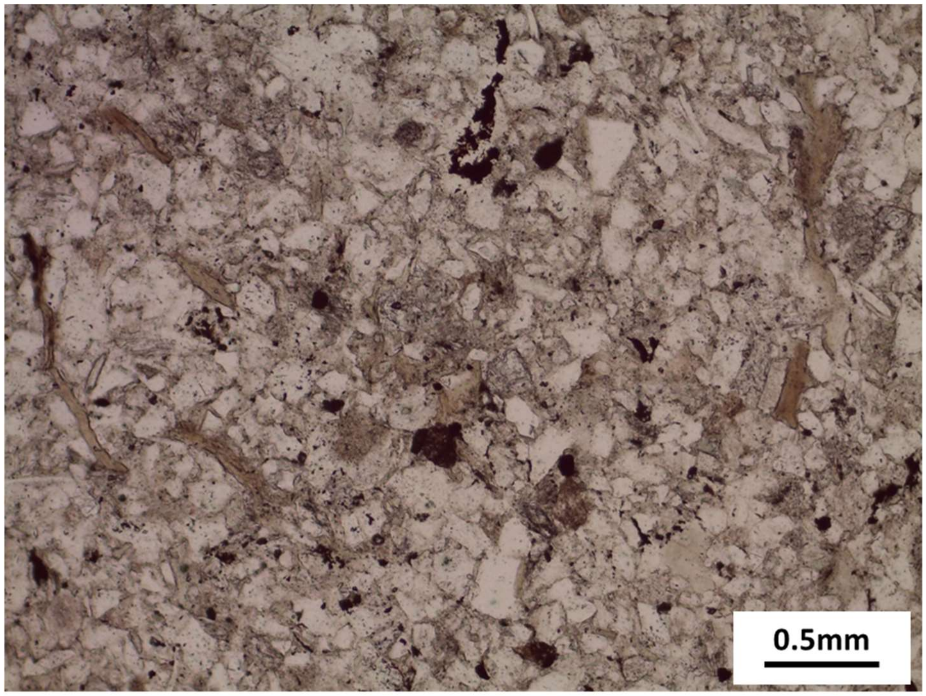
Folk ternary diagram for Southport Exploration Switzer No. 2 at depth 10,433 feet. Q: quartz, F: feldspar, R: rock fragments.

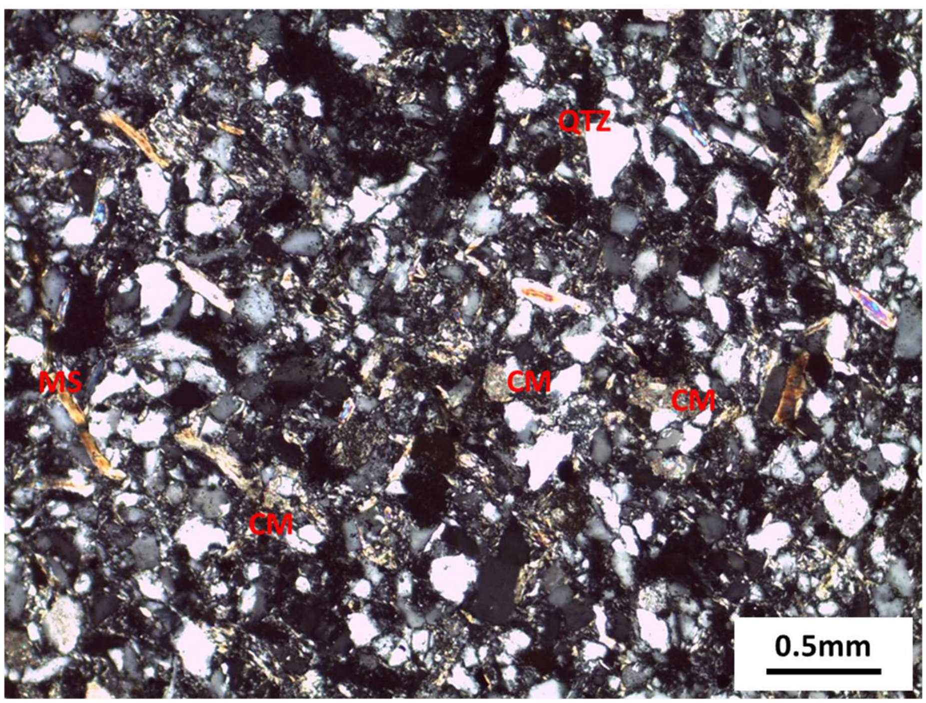


Digitized paragenetic sequence established by Johnson (1984) for the Lower Red Fork interval.

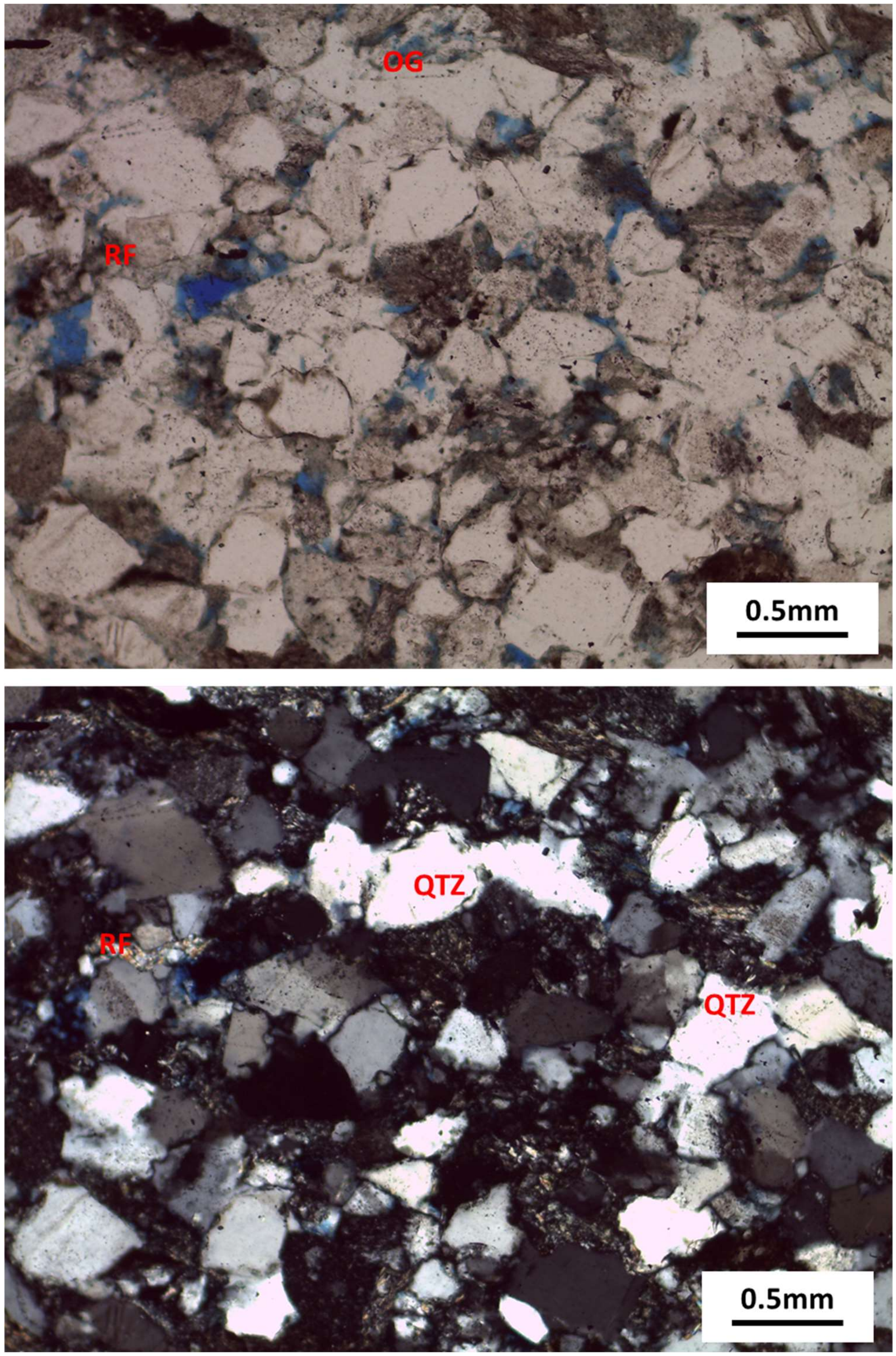


Thin section photo-micrograph showing characteristics of dead oil (DO) at depth 10,440 feet in plane polarized light (PPL) 10x. Southport Switzer No. 2.

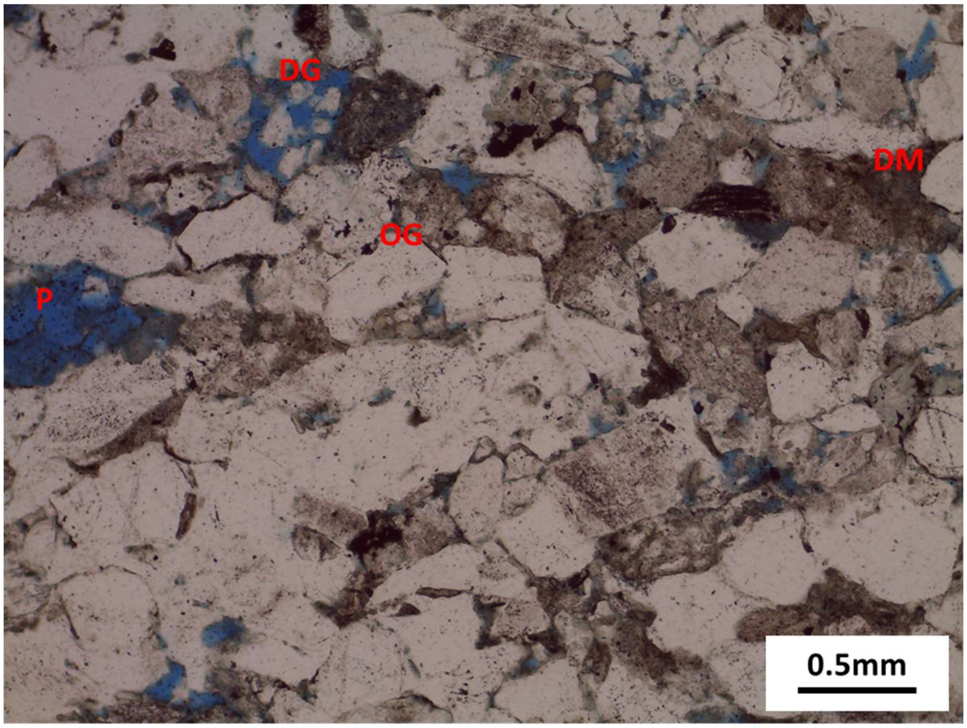


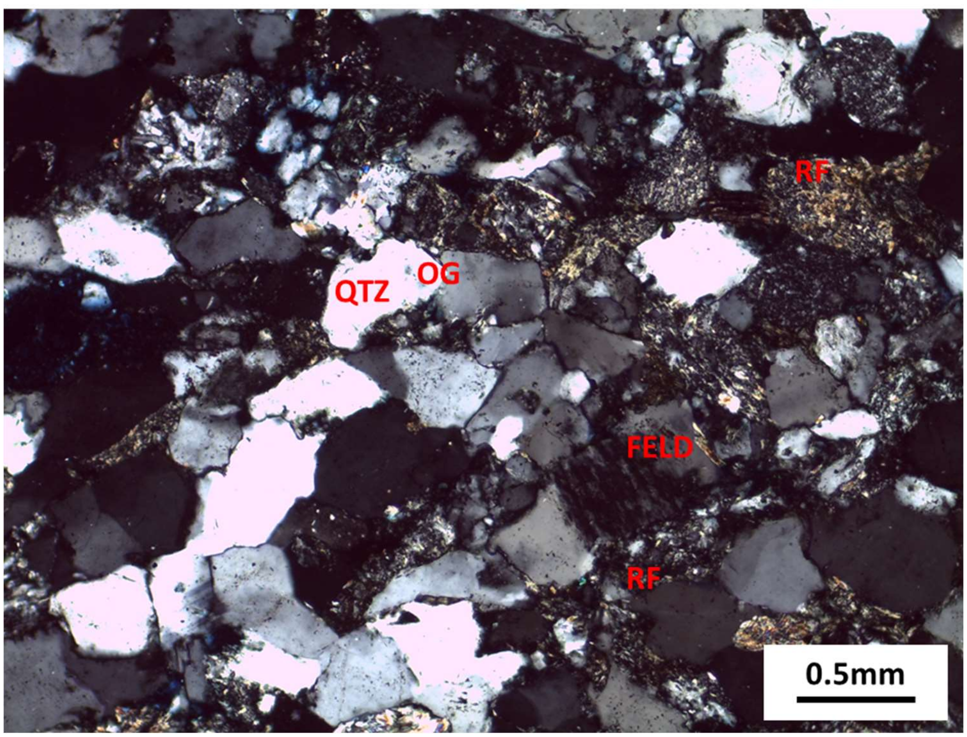


Thin section photo-micrograph showing characteristics of a very fine-grained litharenite containing 48% monocrystalline quartz (QTZ), 1% plagioclase feldspar, and 51% metamorphic rock fragments, along with calcite carbonate cement (CM), muscovite (MS), and pseudomatrix at depth 10,403 feet in plane-polarized light (top) and cross-polarized light (bottom) 10x. Southport Switzer No. 2.

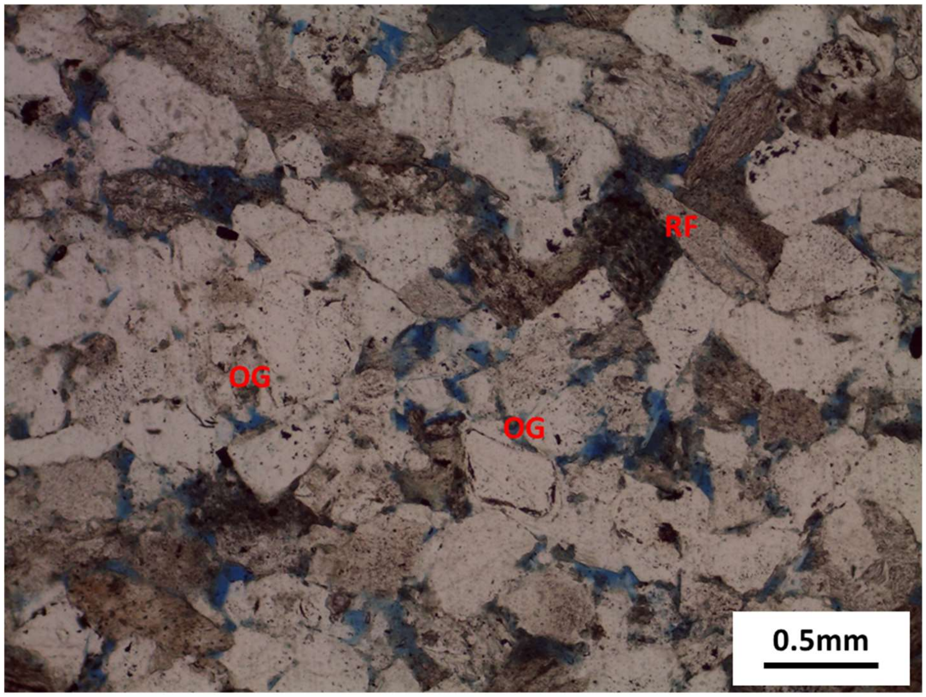


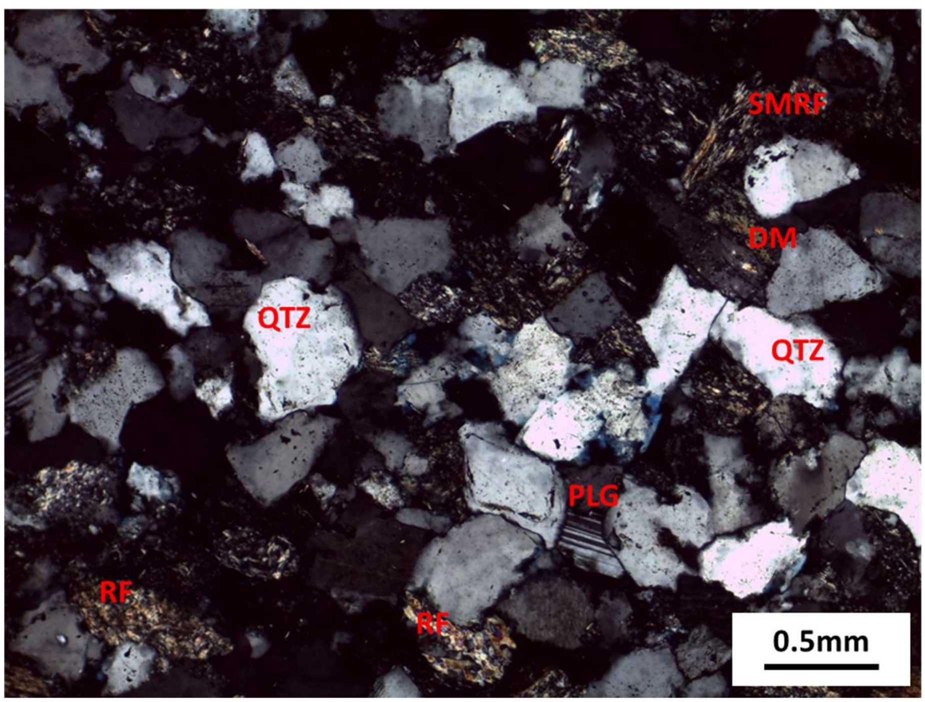
Thin section photo-micrograph showing characteristics of a sublitharenite to litharenite at depth 10,424 feet in plane-polarized light (top) and cross-polarized light (bottom) 10x. Southport Switzer No. 2. QTZ: quartz, RF: rock fragments, OG: overgrowth.



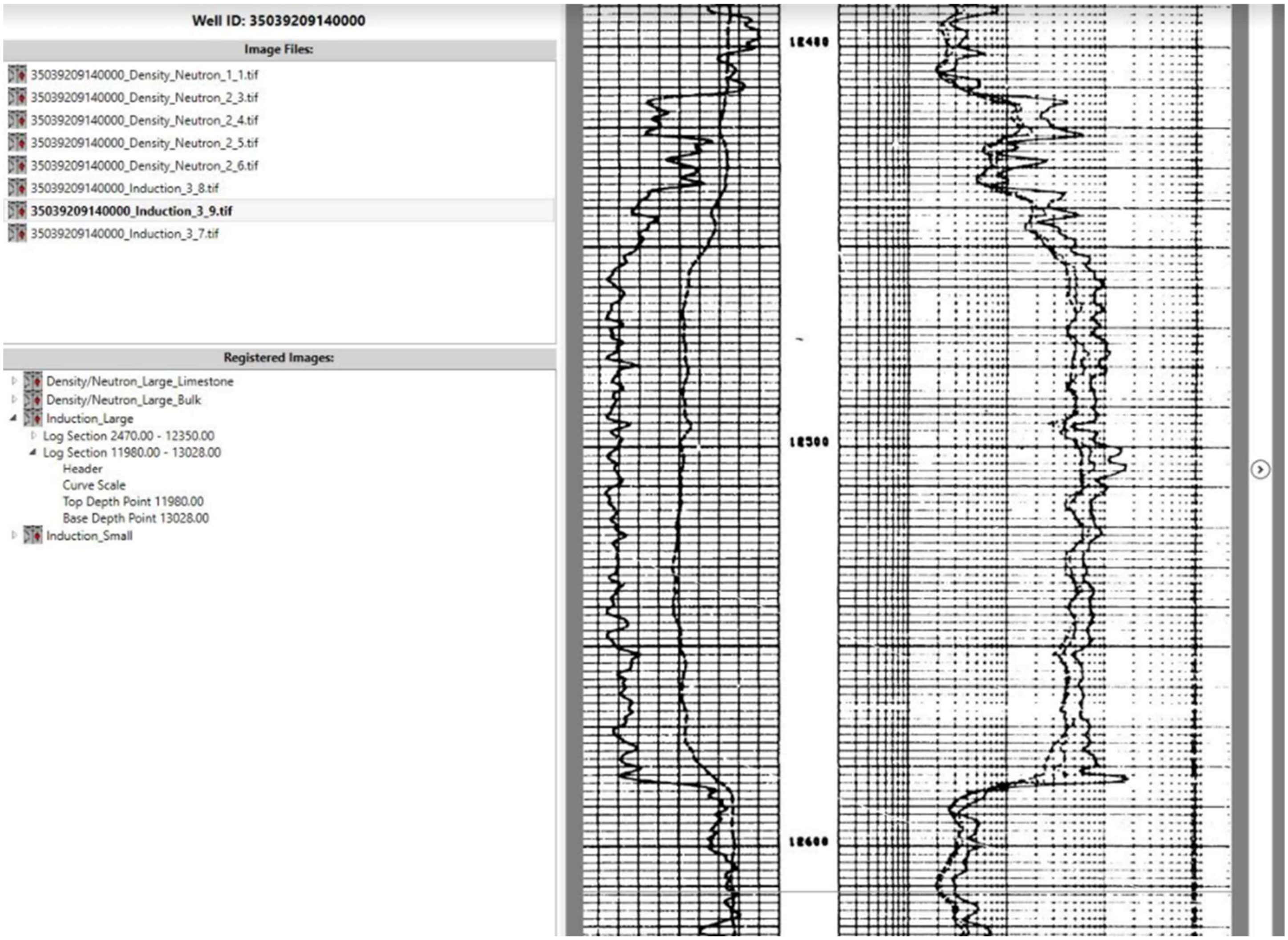


Thin section photo-micrograph showing characteristics of a litharenite at depth 10,428 feet in plane polarized light (top) and cross-polarized light (bottom) 10x. Southport Switzer No. 2. QTZ: quartz, FELD: feldspar, RF: rock fragments, OG: overgrowth, DM: detrital mud, P: porosity.





Thin section photo-micrograph showing characteristics of a litharenite at depth 10,433 feet. 42% monocrystalline quartz, 22% polycrystalline quartz, 8% plagioclase feldspar, and 30% metamorphic rock fragments in plane-polarized light (top) and cross-polarized light (bottom) 10x. Southport Switzer No. 2. QTZ: quartz, FELD: feldspar, RF: rock fragments, OG: overgrowth, DM: detrital mud, P: porosity.

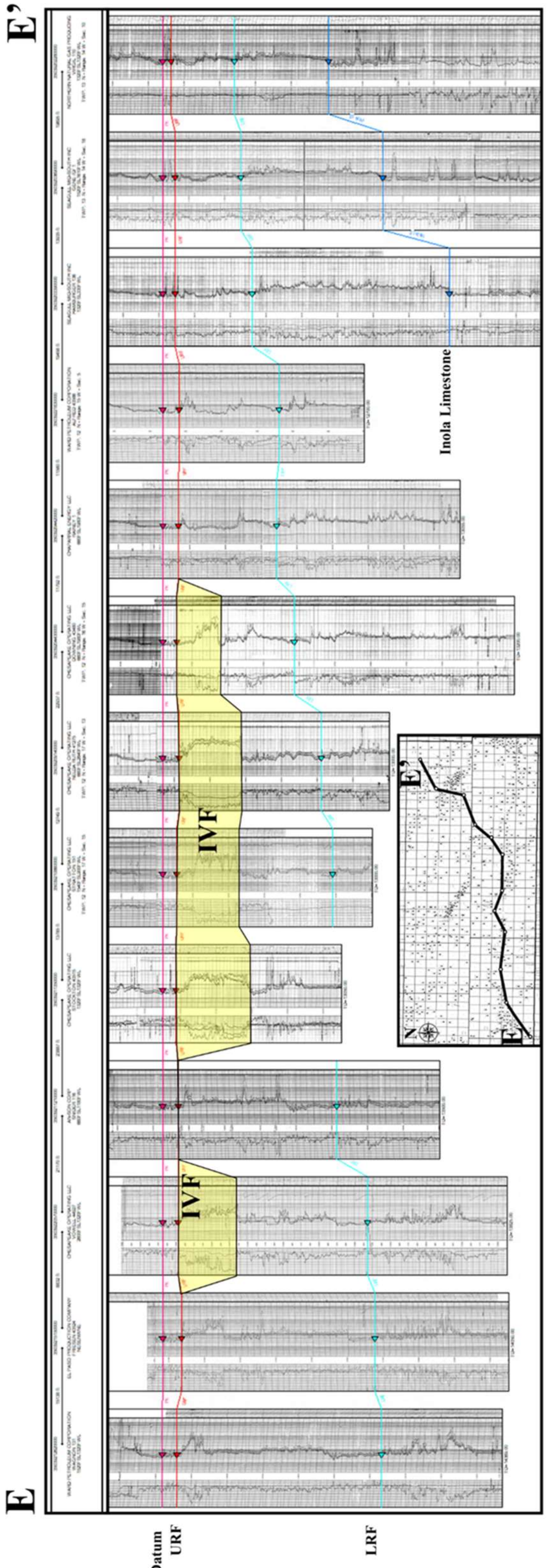


Raw induction log for the Chesapeake Nelda Ruth wireline log. Obtained from depth registration within GeoGraphix software. 5" per 100'. Raw image from MJ Systems with no vertical exaggeration to show thick channel sandstone body. Depth: 12,500 feet.

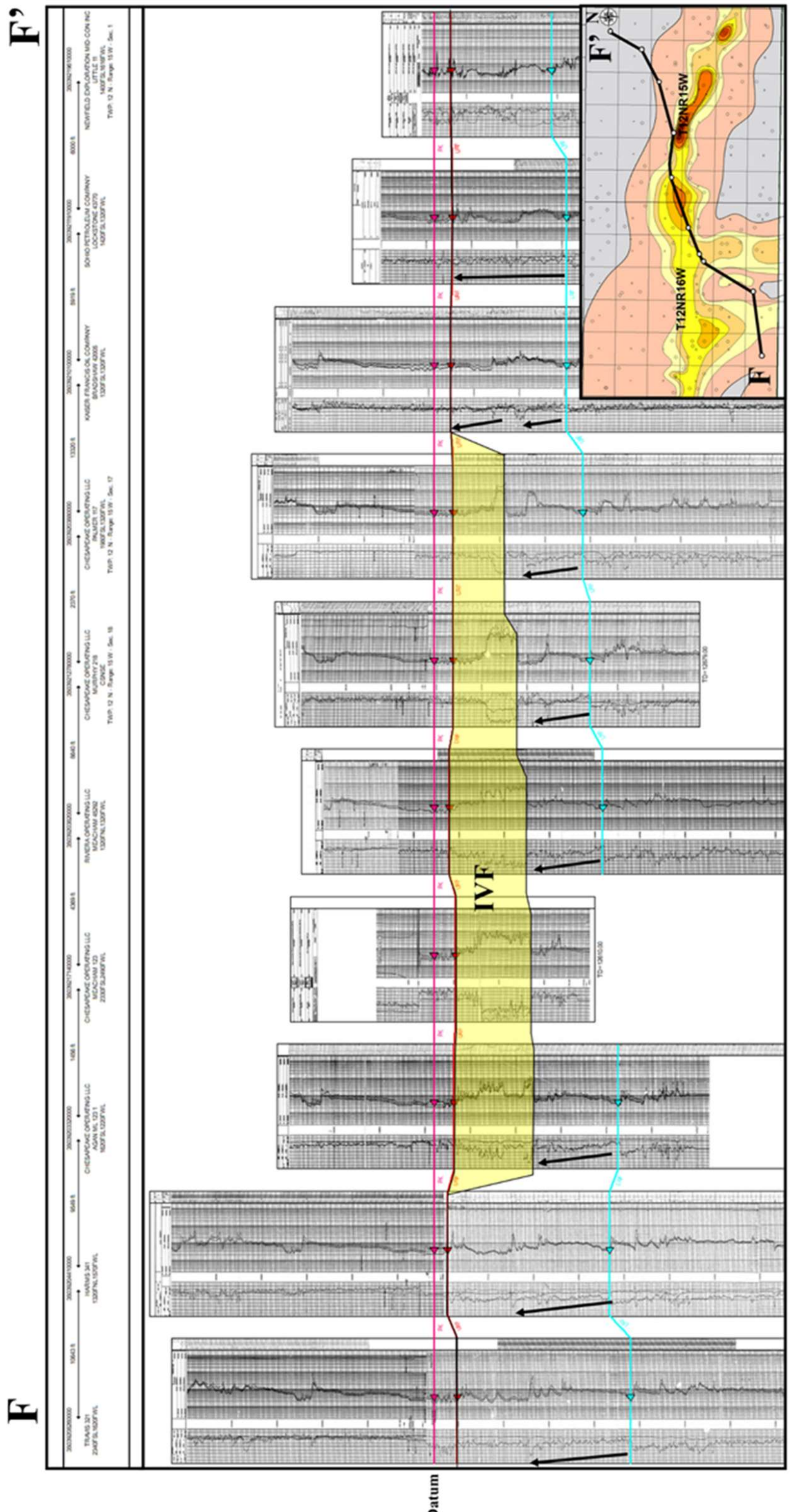
Core images for the Amoco, Walter Sauer 1 core. Depths: 12,397 to 12,466 feet. Core photos lightened to 20% brightness. Images courtesy of Oklahoma Geological Survey Oklahoma Petroleum Information Center (OPIC).

Core images for the Amoco, Walter Sauer 1 core. Depths: 12,478 to 12,551 feet. Core photos lightened to 20% brightness. Images courtesy of Oklahoma Geological Survey Oklahoma Petroleum Information Center (OPIC).

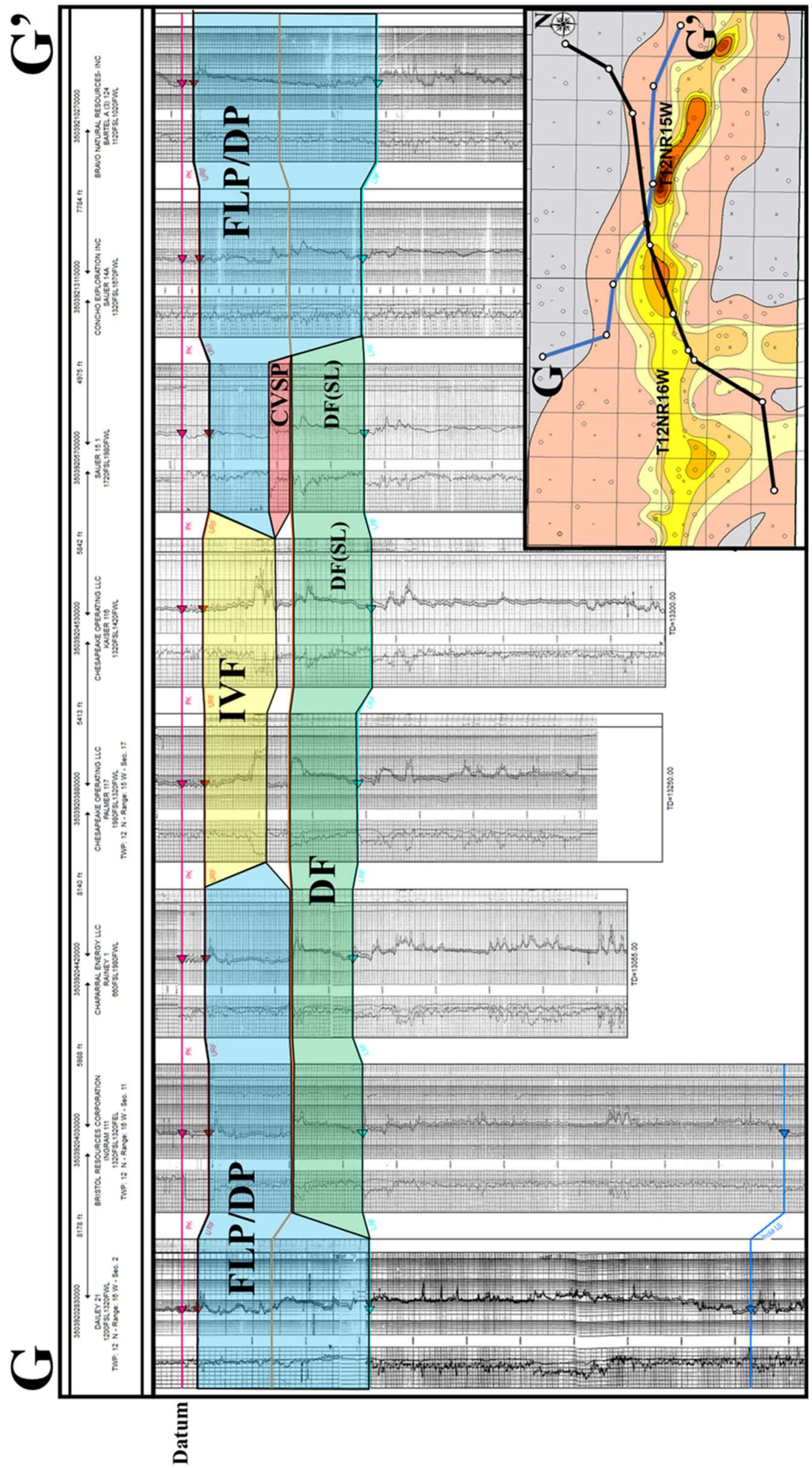
Core images for the Amoco, Walter Sauer 1 core. Depths: 12,557 to 12,620 feet. Core photos lightened to 20% brightness. Images courtesy of Oklahoma Geological Survey Oklahoma Petroleum Information Center (OPIC).



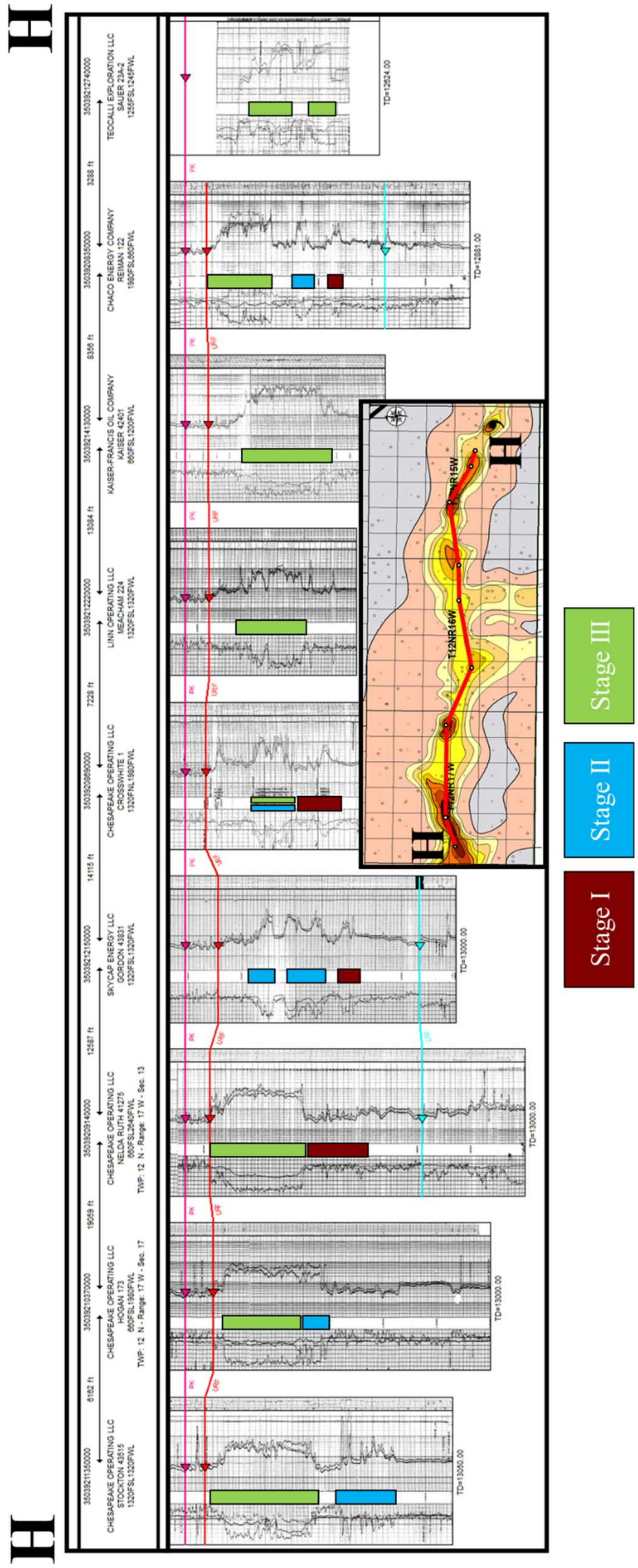
Dip-oriented regional cross-section (E-E') displaying incised valley fill (IVF) characteristics and log signatures. URF: Upper Red Fork, LRF: Lower Red Fork.



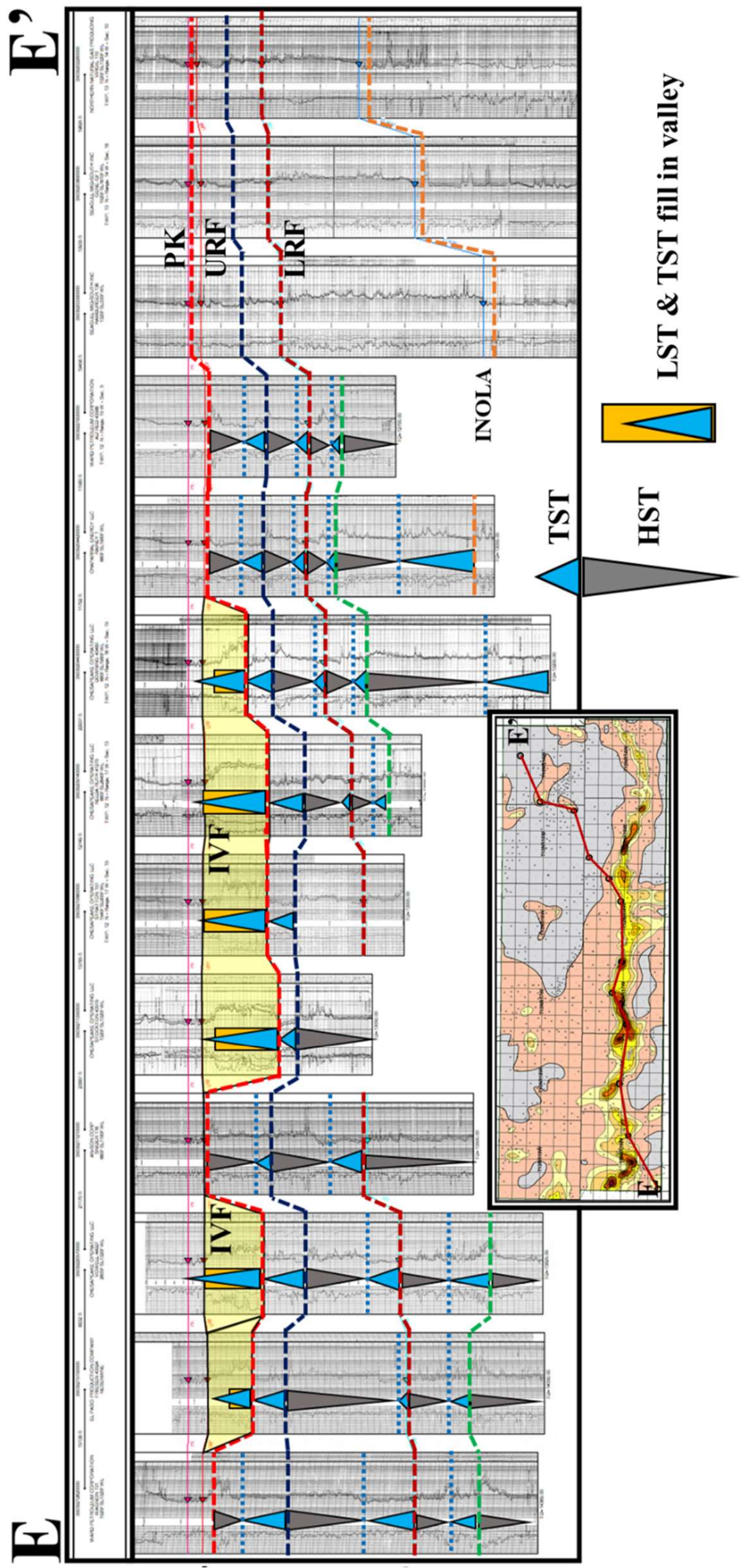
Dip-oriented cross-section (F-F') displaying incised valley fill (IVF) characteristics, log signatures, and progradation (arrows).



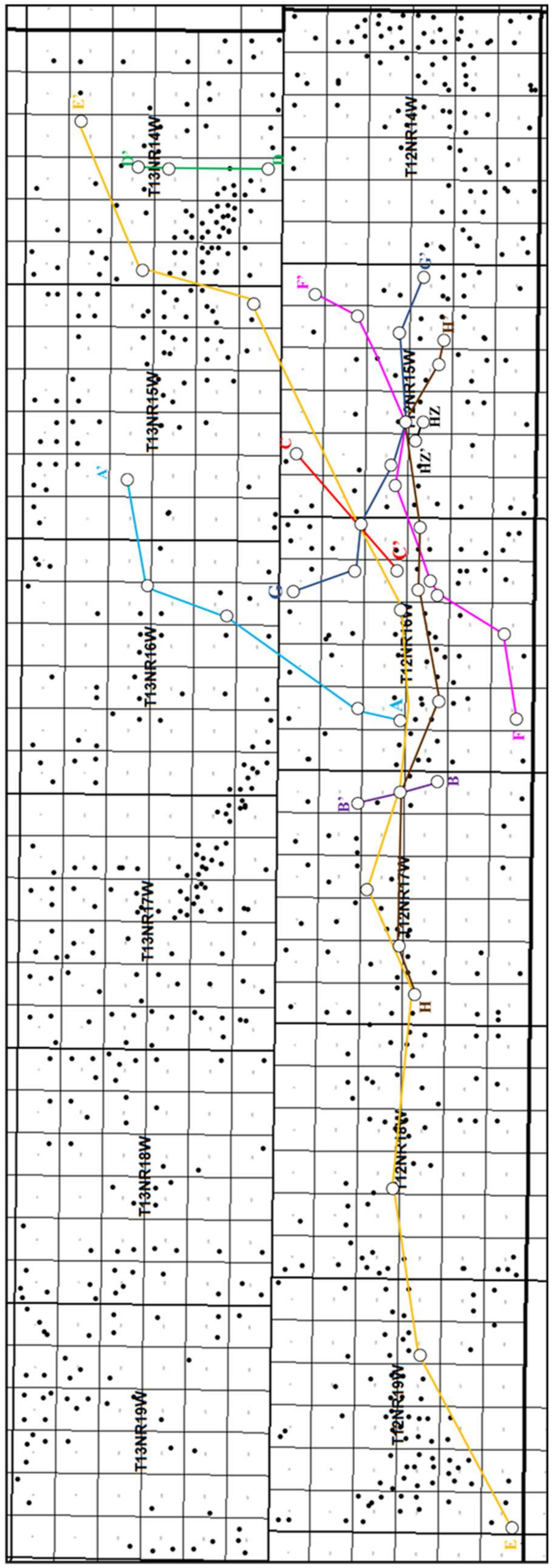
Strike-oriented cross-section (G-G') displaying interpreted incised valley fill (IVF) characteristics, fluvial flood and delta plain (FLP/DP), delta front (DF), crevasse splay (CVSP), and delta front slope setting (DF(SL)) within the Upper Red Fork interval.



Cross-section (H-H') displaying interpreted valley evolution near the East Clinton field. Different stages represented by different colors. Stage I: Red, Stage II: Blue, Stage III: Green.



Dip-oriented regional cross-section (E-E') displaying interpreted sequence stratigraphy, incised valley fill (IVF) characteristics, and systems tracts. Dashed lines: sequence boundaries, TST: transgressive systems tract, LST: lowstand systems tract, and HST: highstand systems tract.



Map across study area illustrating different cross-sections (A through H)

VITA

Dalton Jett Cooper

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Master of Science

Thesis: SEQUENCE STRATIGRAPHIC FRAMEWORK AND RESERVOIR QUALITY OF THE RED FORK SANDSTONE, CLINTON-WEATHERFORD CHANNEL, ANADARKO BASIN, OKLAHOMA: EVALUATING HORIZONTAL EXPLORATION POTENTIAL IN FORMER CONVENTIONAL PLAYS

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