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REGIONAL STRATIGRAPHY AND ORGANIC RICHNESS OF THE
MISSISSIPPIAN MERAMEC AND ASSOCIATED STRATA,
ANADARKO BASIN, CENTRAL OKLAHOMA

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REGIONAL STRATIGRAPHY AND ORGANIC RICHNESS OF THE
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This thesis is dedicated to my lovely Sarah. Thank you for your endless support, care, and love that gave me the strength to succeed. Thank you to my parents for paving my way and instilling my work ethic.

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TABLE OF CONTENTS

ACKNOWLEDGEMENTS.....	iv
LIST OF TABLES.....	vii
LIST OF FIGURES.....	viii
ABSTRACT.....	ix
INTRODUCTION.....	1
GEOLOGIC SETTING.....	5
Structural Setting.....	5
Paleoclimate and Sea Level.....	7
Stratigraphic Setting	10
METHODS.....	11
Sedimentology and Lithofacies.....	11
Stratigraphic and Structural Framework	12
Regional and STACK Petrophysical Models.....	13
RESULTS.....	17
Meramec Sedimentology and Lithofacies.....	17
Sycamore Formation Sedimentology and Lithofacies.....	22
Regional Stratigraphic Correlations and Mapping.....	27
Meramec Sequence-Stratigraphic Architecture.....	31
Regional Distribution of Vsh and TOC.....	34
Osage and Meramec Vsh, PHIT, and TOC – STACK Trend.....	44
DISCUSSION.....	51
Depositional Environments.....	51

Controls on Source-Rock Potential of Mississippian Strata.....	56
CONCLUSIONS.....	58
REFERENCES.....	61
APPENDIX A. Core Descriptions.....	68
APPENDIX B. Sycamore Outcrops.....	96
APPENDIX C. Thin Section Photomicrographs.....	109
APPENDIX D. 3-D Model Construction and Variograms.....	131
APPENDIX E. Additional Discussion Images.....	138

LIST OF TABLES

Table 1. Facies Summary	21
Table 2. TOC Calibration	42
Table 3. STACK Petrophysical Summary.....	47

LIST OF FIGURES

Figure 1. Geologic Provinces of Oklahoma	2
Figure 2. Stratigraphic Correlation Column.....	4
Figure 3. Detailed Basemap	6
Figure 4. Schematic Guide to $\Delta\log R$ Technique	16
Figure 5. Meramec Lithofacies Core Photos	18
Figure 6. Meramec Lithofacies Thin Sections	19
Figure 7. Sycamore Outcrop and Lithofacies.....	23
Figure 8. Sycamore Measured Section.....	26
Figure 9. Woodford Structure Map	28
Figure 10. Cross Section C-C'	30
Figure 11. Regional Cross Section A-A', Meramec Isopach Map, Meramec Gamma Ray < 50 API Map	32
Figure 12. Gulf Oil 1-25 Rohling and Gulf Oil 1-23 Shaffer Core Description and Sequence-Stratigraphic Interpretation.....	35
Figure 13. Meramec Sequence-Stratigraphic Architecture and Zone Isopach Maps.....	37
Figure 14. Regional Vsh and TOC Models	40
Figure 15. TOC Calibration.....	43
Figure 16. STACK Vsh Models	45
Figure 17. STACK PHIT and TOC Models	49
Figure 18. Vertical Cross Section of STACK TOC Model.....	52
Figure 19. Sycamore Formation Outcrop-Subsurface Gamma Ray Correlation.....	55

ABSTRACT

The Mississippian Meramec Series and laterally equivalent units of the Caney and Sycamore formations of central and south-central Oklahoma generally consist of a succession of interbedded quartz-rich calcareous siltstones, argillaceous siltstones, and organic-rich mudstones that form premier unconventional reservoirs. Core, well-log, and outcrop data are integrated to develop a regional stratigraphic framework, characterize the depositional environments, and map the distribution of organic-rich facies.

The Meramec can be divided into seven sequence-stratigraphic zones deposited in shallowing upward cycles that are commonly capped by marine-flooding surfaces. The Meramec is believed to represent silt deposited in lower shoreface to offshore depositional environments within or below storm wave base and reworked by a variety of processes including tides, storms, and bottom currents. The Sycamore Formation is divided into 6 zones and was deposited down-dip of the Meramec ramp facies predominately by turbidite flows. Surface to subsurface correlation demonstrates the uppermost Sycamore Formation in the Arbuckle Mountains near Springer, Oklahoma, is correlative with the lowermost Meramec in Blaine County, and the upper Meramec is correlative with the “Ahloso Member” of the lower Caney Formation.

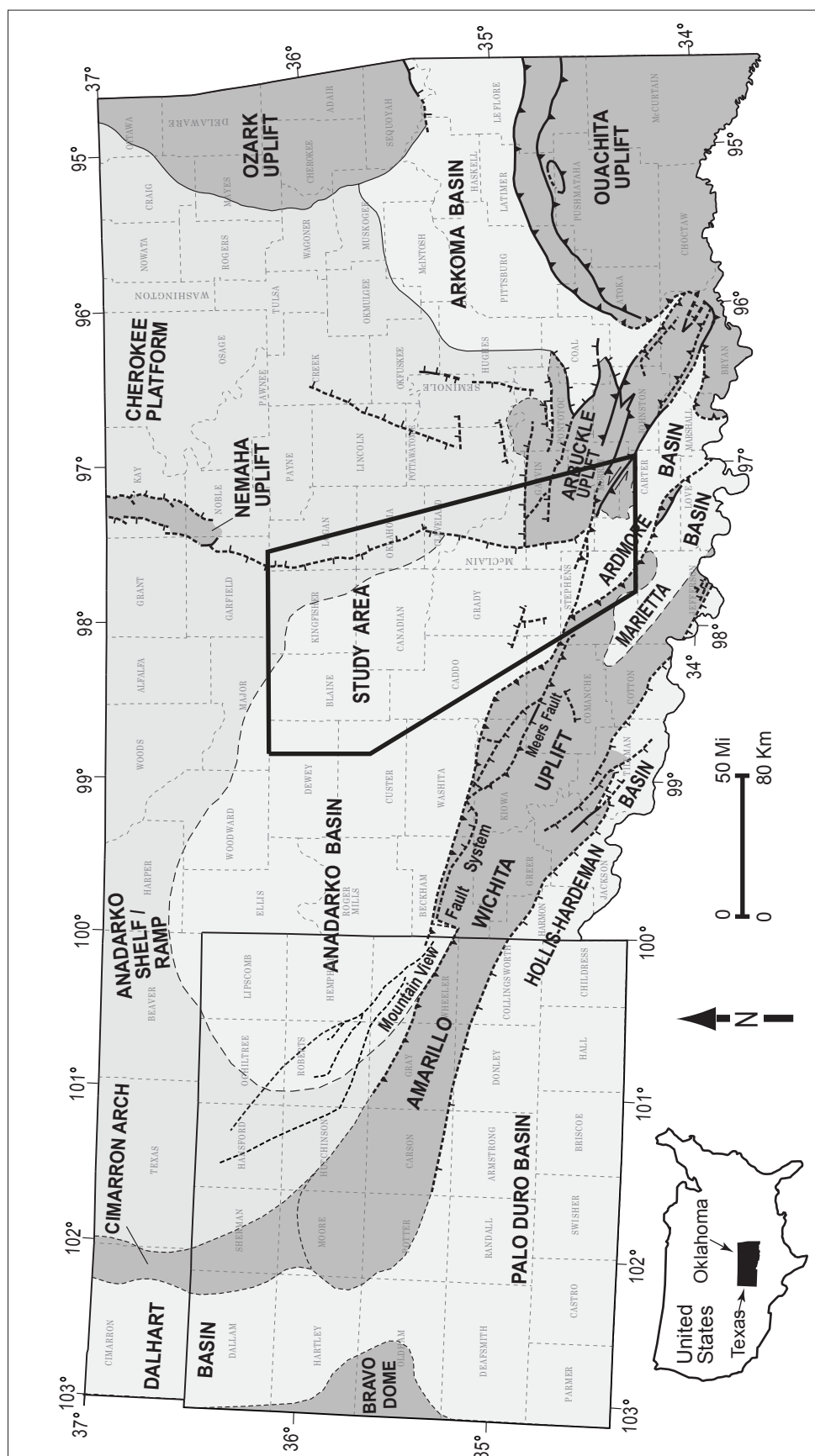
Three-dimensional shale volume and porosity models show the stratigraphic control on petrophysical properties within the Meramec. Transgressive zones are richer in shale and exhibit higher porosity than regressive zones. $\Delta \log R$ -derived estimates of total organic carbon (TOC) content (wt %) show a basinward increase in TOC to the southeast. TOC values north of the border between Canadian and Grady counties are

typically <1%. TOC values to the south range from 0 to 8% with source-rock thickness as high as 167 ft (51 m) using a >3% cutoff. Discrete source beds observed in the up-dip ramp setting correlate with flooding surfaces of the Meramec sequence-stratigraphic framework.

INTRODUCTION

The Anadarko Basin of central Oklahoma was once part of a relatively contiguous intra-continental rift basin that has subsequently been fragmented into a series of orogenic foreland-style basins in a classic example of the Wilson Cycle (Figure 1). Cambrian rifting resulted in the formation of the Southern Oklahoma Aulacogen that underwent thermal subsidence until the Devonian (Ham et al, 1965; Hoffman, 1974; Wickham, 1978; Perry, 1989). The closure of the Rheic-Iapetus oceans in the Pennsylvanian (Domeier, 2015) resulted in the conversion from the late-stage intracontinental rift basin to a foreland basin with tectonic-driven subsidence and basement involved thrusting (Ham et al, 1965; Perry, 1989). The Mississippian strata of the Anadarko Basin are of importance because they were deposited during the transition in subsidence mechanisms and potentially foreshadow coming tectonic events.

A transect through the Mississippian strata from northern to southern Oklahoma records the transition in depositional environments of age-equivalent rocks from the shallow-water “Mississippi Lime” carbonates of northern Oklahoma (Rogers., 2001; Watney et al., 2001; Mazzullo et al., 2011; Grammer et al., 2013; Pranter et al., 2016) to the deeper-water mixed carbonate-siliciclastic sediments deposited in the Anadarko and Ardmore basins (Elias, 1956; Champlin, 1959; Harris, 1975; Peace, 1994; Price et al., 2017) (Figure 2; Appendix E-1). Pennsylvanian uplift resulted in the surface exposure of the entire Paleozoic interval in the Arbuckle Mountains of southern Oklahoma, where the Mississippian rocks overlying the Devonian Woodford Shale are named the Sycamore Formation and Caney Formation. These formations loosely correlate to the informal Osage, Meramec, and Chester intervals, respectively, of the subsurface in



central Oklahoma. Intervals of the Sycamore and Caney formations are coeval with the Meramec (Schwartzapfel, 1990; Kleehammer, 1991) and potentially form the downdip, deeper-water extension of the Meramec of the “Sooner Trend (oil field), Anadarko (basin), Canadian and Kingfisher (counties)” (STACK play) in central Oklahoma. Previous studies of the stratigraphy and depositional environments of the Meramec deposits from central Oklahoma to southern Oklahoma are not fully integrated; hence, the nature of the regional transition from ramp to basin is poorly understood.

Although the Upper Devonian-to-Lower Mississippian-aged Woodford Shale is the primary hydrocarbon source for the Anadarko Basin (Cardott and Lambert, 1985; Comer, 1992; Johnson and Cardott, 1992; Wang and Philp, 1997), the Meramec of central Oklahoma also has relatively organic-rich intervals that are considered potential sources of local hydrocarbon generation (Wang and Philp, 1997). Al Atwah (2015) used pyrolysis and microscopy techniques and determined that core samples from the lower Mississippian of the Anadarko Basin have an average total organic carbon (TOC) of 2% and reached the early oil window. Al Atwah (2015) also detected biomarkers of Mississippian oils which suggests localized hydrocarbon generation in addition to longer-distance migration of Woodford-sourced oils. Welker et al. (2016) similarly distinguished locally generated fluids from migrated fluids in a study of oil samples from Mississippian wells across the Anadarko Basin. The Caney Formation to the south is also an organic-rich shale that charged some reservoirs within the Anadarko, Ardmore, and Arkoma basins (Kamaan, 2006; Andrews, 2007; Cardott, 2017).

This study focuses on the regional stratigraphy, depositional environments, and organic richness of the Meramec including its equivalent units of the Sycamore and

Outcrops across Missouri, Kansas,
and Oklahoma

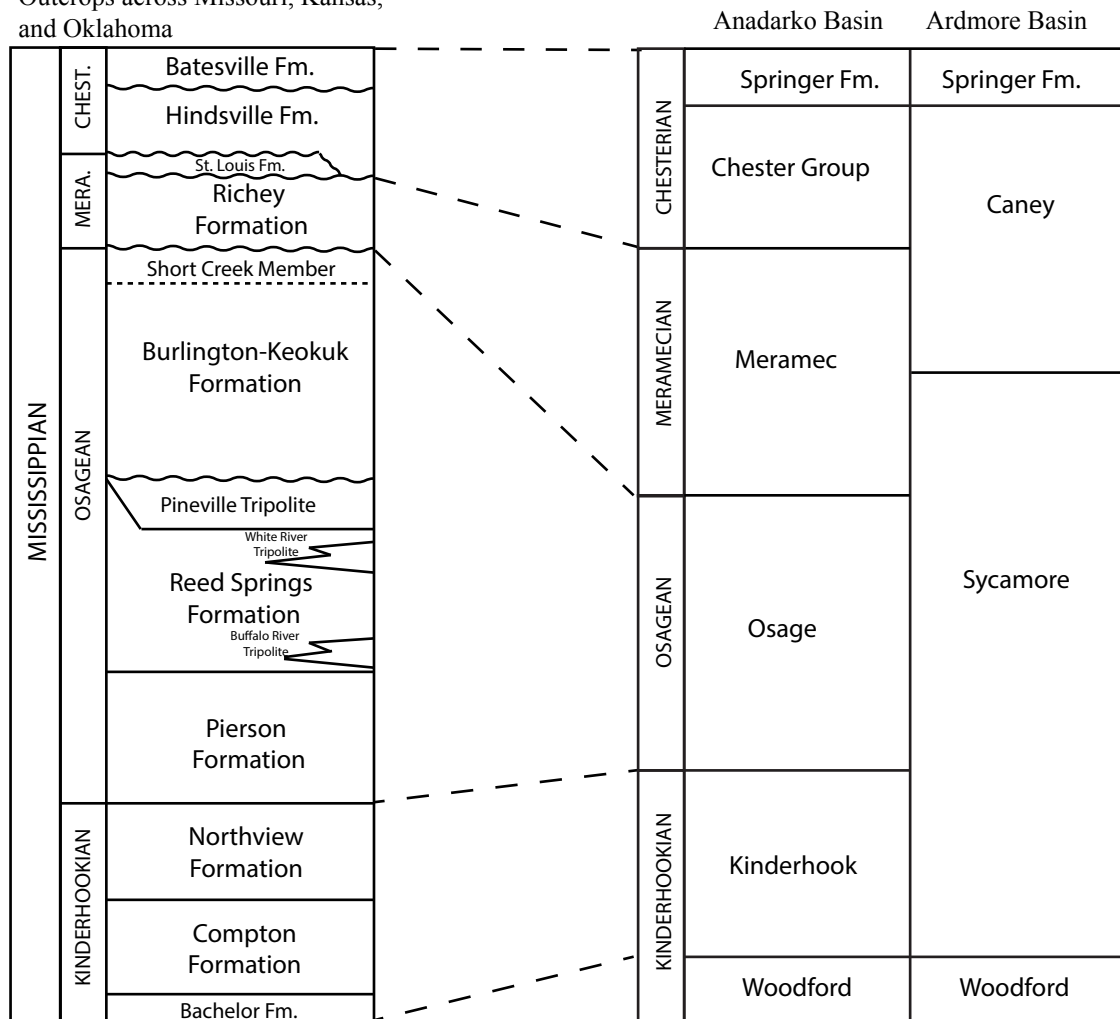


Figure 2. Generalized correlation of Mississippian rock units by location. The Mississippian becomes increasingly siliclastic from the Anadarko shelf in northern Oklahoma to the study area in the Anadarko Basin of central Oklahoma. Correlations between the Anadarko and Ardmore Basins are informal and still unresolved by biostratigraphic studies (modified from Johnson and Cardott, 1992, Boyd 2008; and Muzzulo et al., 2013).

Caney formations. Building upon previous research efforts, this study defines the stratigraphic correlations of the Meramec Series in the Anadarko Basin to equivalent units of the Sycamore and Caney formations in the Arbuckle Mountains and Anadarko and Ardmore basins. The depositional environment of Meramec and equivalent strata are characterized through the integration of core and outcrop studies with well-log data and 3-dimensional (3-D) modeling techniques. To analyze the spatial distribution and controls of organic richness, TOC is estimated using the Passey (1990) $\Delta \log R$ method and organic-rich facies are mapped across the study area. The dataset for this study includes two Meramec cores in Blaine County, two Sycamore Formation outcrops in the Arbuckle Mountains, and digital well-log data from 421 wells (Figure 3).

GEOLOGIC SETTING

Structural Setting

The Anadarko Basin is an asymmetric foreland basin covering an area of 50,000 mi² (130,000 km²) across parts of Colorado, Kansas, Oklahoma, and Texas. It contains more than 40,000 ft (12,000 m) of Paleozoic sediments. The basin is bounded by the Nemaha uplift to the east and the Arbuckle uplift and Amarillo-Wichita uplift to the south (Evans, 1979).

The formation of an aulacogen (Wickham, 1978) resulted in crustal thinning and the onset of the structural development of the Anadarko Basin during the Late Precambrian to Middle Cambrian (Hoffman et al., 1974; Perry, 1989). Following the cessation of rifting, thermal subsidence occurred as the basement rocks cooled, resulting in the formation of a passive continental boundary along the Oklahoma geosyncline

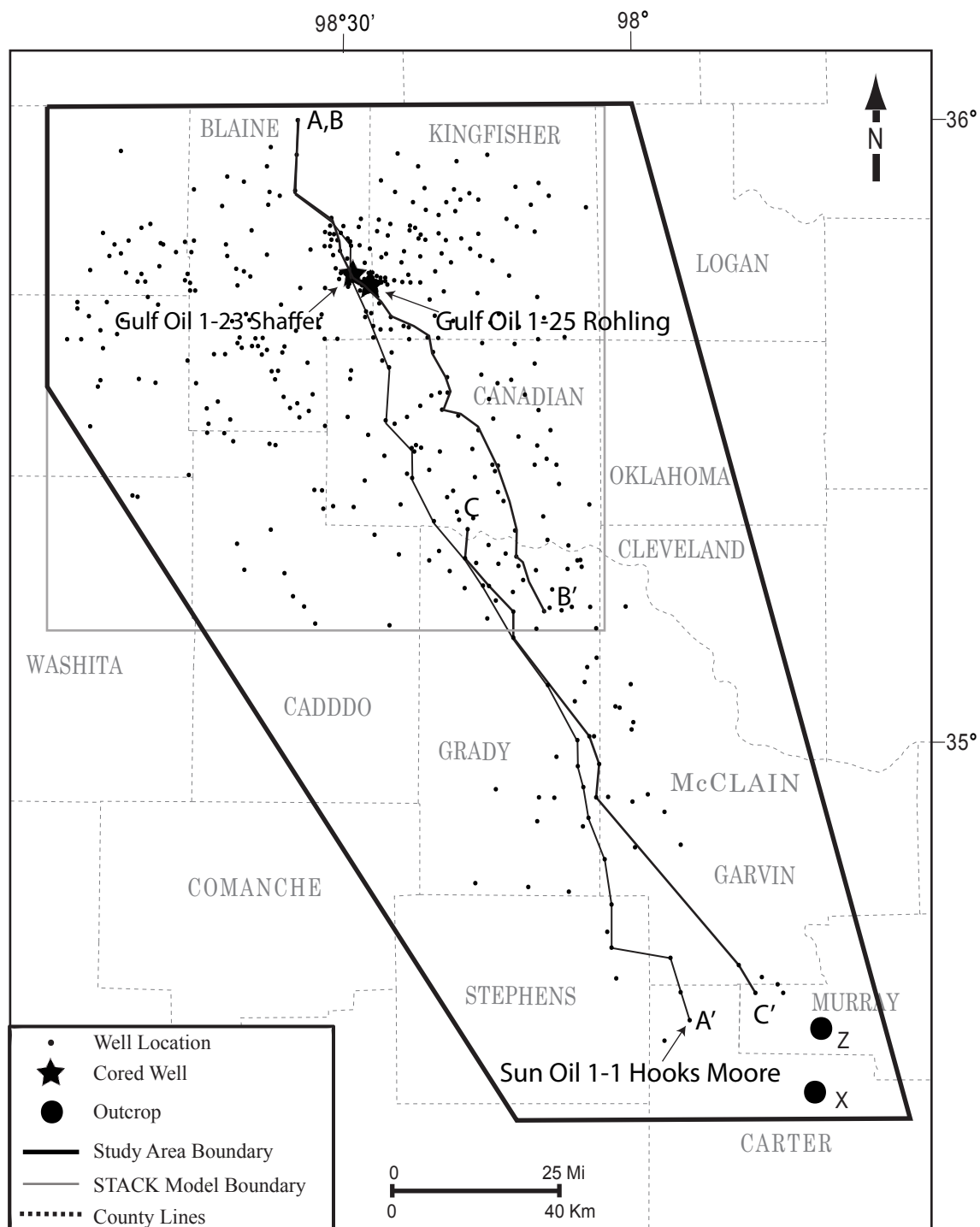


Figure 3. Detailed map of the study area. The dataset includes 421 wells with digital logs across the Anadarko Basin and northern Ardmore Basin. Detailed core analysis is performed on the Gulf Oil 1-23 Shaffer and Gulf Oil 1-25 Rohling cores. Two Sycamore Formation outcrops (X and Z) in the Arbuckle Mountains are studied.

(Perry, 1989). This regional subsidence resulted in the formation of the Anadarko-Ouachita Basin. Subsidence continued into the Middle Mississippian, when subsidence rates increased rapidly as the Rheic Ocean closed during the collision of the Laurentia and Gondwana plates (Johnson and Luza, 2008; Higley 2014).

Compressional activity from the Laurentia-Gondwana collision during the Pennsylvanian caused inversion and conversion to a foreland basin superimposed on the rift basin, fragmenting the Anadarko-Ouachita Basin into smaller basins separated by uplifted basement blocks. The Wichita Uplift occurred during the early Pennsylvanian, resulting in vertical displacements of greater than 20,000 ft (6096 m) along the Wichita Mountain Front (Evans, 1979). A second uplift event, the Arbuckle Orogeny, occurred during the Virgilian and resulted in further deformation of the southern Anadarko Basin and Ardmore Basin areas (Evans, 1979). Since the Permian, the Anadarko Basin area has remained relatively stable with minimal structural deformation (Ham et al., 1965).

Stratigraphic Setting

Studies of the Meramecian strata of central Oklahoma originated with outcrop work in the Arbuckle Mountains by Taff (1903) who first named and described the Mississippian Sycamore Formation as a blueish to yellow limestone at the type section along the Sycamore Creek in southeastern Oklahoma. This work was extended by Cooper (1926) who provided a detailed lithologic description of the Sycamore Formation but found chronostratigraphic correlation of the Sycamore difficult due to a lack of age-diagnostic fauna.

Although Sycamore Formation is the name used for Meramecian outcrops in the Arbuckle Mountains, subsurface workers commonly referred to the Meramecian interval as the Mayes Formation. Snider (1914) described the Mayes Formation as interbedded black shales and argillaceous limestones. In the aptly titled paper, *Problem of the "Mayes" in Oklahoma*, Selk (1948) delineated inconsistencies in the stratigraphic nomenclature and age correlation of Oklahoma Mississippian deposits and proposed the Sycamore Formation of the Arbuckle Mountains correlates to the subsurface Mayes Formation in the Anadarko Basin.

The Caney Formation overlies the Sycamore Formation. The Caney Formation was first described and named by Taff (1901) in the Arbuckle Mountains as interbedded shales, siltstones, and limestones. Elias (1956) subdivided the Caney Formation into three members. In ascending stratigraphic order these are: The Ahloso, Delaware Creek, and Sand Branch. The Ahloso member is composed of calcareous shales and siltstones. The Delaware Creek and Sand Branch members are richer in clay and organic material. Elias (1956) proposed that the Ahloso Member is likely Meramecian in age based on its faunal assemblage and lithologic correlations. Champlin (1959) attempted to establish a time-rock correlation of the Mississippian in the eastern Arbuckle Mountains and concurred with Elias (1956) to assign the lowermost Caney Formation to the Meramec Stage.

Difficulties surrounding the stratigraphic and chronostratigraphic relationships of Meramecian strata are abundant (Buchanan, 1927; Branson, 1959; Champlin, 1959; Braun, 1959; Peace, 1994), with the Middle Mississippian rocks referred to as the Mayes, Sycamore, Sycamore Mayes, Asa-Mayes, Welden, Meramec, and Caney. The interval is relatively devoid of fossils, making a biostratigraphic correlation difficult.

Ormiston and Lane (1976) studied conodonts in the Sycamore Formation of the Arbuckle uplift and proposed the lower Sycamore Formation is Kinderhookian to Osagean in age and the upper Sycamore and Caney formations are Meramecian in age. Schwartzapfel (1990) studied radiolaria from Sycamore outcrops, and determined the Sycamore Formation is “no older than Middle Meramecian” in age. Kleehammer (1991) concluded the Sycamore Formation is largely Meramecian and certainly no older than late Osagean based on *Gnathodus texanus* *Gnathodus girtyi* conodont assemblages.

In addition to these stratigraphic uncertainties, the depositional environments of Meramecian sediments are not thoroughly resolved. Price et al. (2017) proposed that the Meramec in the subsurface of Blaine, Canadian, and Kingfisher counties was deposited as a subaqueous delta complex with a riverine point source. Shelley et al. (2017) studied exposures of the Moorefield Formation in a quarry near Pryor Creek, Oklahoma. The Moorefield is the lateral equivalent of the Meramec in the Arkoma Basin to the east of Nemaha Uplift. Shelley et al. (2017) identified siliciclastic bar geometries and carbonate shoals likely deposited near the crest of a distally steepened ramp. Shelley et al. (2017) proposed that the Moorefield Formation as exposed near Pryor Creek was more proximal than the Meramec of the STACK given the absence of carbonate-rich facies in the STACK area. Work on the depositional environment of the Meramec in the subsurface of central Oklahoma is otherwise sparse.

In a summary of the depositional history of Oklahoma Mississippian rocks, Bennison (1956) referred to the Sycamore Formation as a clastic limestone deposited by shallow transgressive seas during the Meramecian. The shallow-water interpretation

remained the consensus (Prestridge, 1957; Curtis and Chapman, 1959; Braun, 1959; Cole, 1988) until Schwartzapfel (1990) suggested a deepwater setting on the basis of partial Bouma sequences observed in outcrops of the Sycamore Formation in the Arbuckle Mountains. Using field studies and petrographic analysis, Franklin (1997) agreed with the deep-water interpretation of Schwartzapfel (1990), but instead proposed that the Sycamore Formation was deposited in a deep-marine setting by thermohaline bottom currents. Coffey (2001) analyzed cores from the Anadarko basin and proposed the Sycamore Formation records carbonate sedimentation at moderate depths during sea-level highstands and gravity flows of autochthonous sediments during sea-level lowstands.

Paleoclimate and Sea Level

The Mississippian Period represents a time of climatic transition, with global temperatures cooling and sea level falling as the Early Paleozoic greenhouse period gave way to the Late Paleozoic icehouse (Read, 1995). Throughout the Early Mississippian, a warm, shallow, well-oxygenated sea covered the North American craton (Appendix E-2A) (Curtis and Champlin, 1959). The paleolatitude of the study area is between 20°-30° S, placing the area in a tropical to subtropical climate zone with ocean surface temperatures ranging from 65°-85°F (Buggisch et al., 2008).

The Mississippian strata of the study area were deposited during a second-order (5-50 Ma) sea-level sequence, with higher-order cyclicity prevalent throughout the interval (Sloss, 1963) (Appendix E-2B). Allogenic, Milankovich-driven eustasy is the primary control on observed higher-order cycles, but other allogenic and autogenic

controls such as climate, tectonic activity, and sedimentation rates also played a role in the development of higher frequency cyclicity (Rogers, 2001; Watney et al., 2001; Flinton, 2016).

METHODS

Sedimentology and Lithofacies

Outcrop data were integrated with subsurface core and well-log data to interpret the regional stratigraphy and depositional environments of Meramec and laterally equivalent strata. Cores from the Gulf Oil 1-23 Shaffer (242 ft [74 m]) and the Gulf Oil 1-25 Rohling (207 ft [63 m]) sample different intervals of the Meramec and were described based on lithology, texture, grain size, grain shape, allochem types, color, and sedimentary structures (Figure 3). Lithofacies were defined based on the detailed core descriptions and petrographic analysis of thin sections. Twelve unpolished thin sections were acquired from the Gulf Oil 1-23 Shaffer. The samples were stained with alizarin red S for calcite identification and injected with blue epoxy to help identify porosity. A Zeiss Axio Imager.Z1m microscope was used to observe the sections in normal-transmitted, plane-polarized, and cross-polarized light. Thin sections were analyzed for visual percentages of mineralogy, but point counts were not performed.

A stratigraphic section spanning 327 ft (100 m) of the Sycamore Formation was measured at outcrop X on the south flank of the Arbuckle Anticline (Figure 3). A gamma-ray (GR) profile was measured using a Super-Spec RS-125 scintillometer (Radiation Solutions, Inc.) with a sample increment of 1 ft (0.3 m) to relate facies stacking patterns to GR-log character and to correlate to nearby subsurface wells. The

section was described for bed thickness, lithologies, grain sizes, and sedimentary structures. Lithofacies were defined based on outcrop descriptions and petrographic analysis of thin sections. Thirteen thin sections were prepared and injected with blue epoxy and stained with alizarin red S.

Stratigraphic and Structural Framework

To establish the stratigraphic and structural framework, the Osage, Meramec, Sycamore, and Caney intervals were correlated based on their well-log signatures. Structure-contour and isopach maps were generated for each stratigraphic interval. In addition to the outcrop and cored wells, the subsurface dataset includes digital-log curves for 421 wells that have at least one of the following logs: gamma-ray (GR), neutron porosity (NPHI), density porosity (DPHI), and deep resistivity (RILD) (Figure 3).

For the STACK trend, a more detailed stratigraphic architecture was developed for the Meramec Series. The vertical succession of lithofacies observed in the Meramec cores was used to interpret stratigraphic cycles and key surfaces to divide the Meramec into mappable stratigraphic intervals (zones). The stratigraphic cycles from core were calibrated to non-cored wells of the STACK trend based on well-log response. For comparison, lithofacies cycles (zones) of the Sycamore Formation outcrops were correlated to subsurface wells using the outcrop GR log. Stratigraphic thinning and erosion limited the ability to correlate the Meramec zones of the STACK trend into the southern portion of the study area. Using the interpreted structure-contour and isopach

maps, 3-D geologic model grids were created and various petrophysical properties were mapped and analyzed.

To depict the regional and local stratigraphic and structural framework, 3-D geologic models were constructed for 1) the entire study area (regional model) and 2) the smaller STACK trend (STACK model) (Figure 3). The regional model has grid cells with aerial dimensions of 2000 by 2000 ft (609 by 609 m) and has 3 zones; each zone has 200 proportional layers with a mean layer thickness of 1.2 ft (0.4 m). The resulting 3-D grid has 46,000,000 cells. The geographically smaller STACK model was constructed to evaluate the sequence-stratigraphic controls on petrophysical properties within the Meramec interval in an expanded area of the STACK play. Grid cell aerial dimensions are 1500 by 1500 ft (457 by 457 m), and there are 8 zones with 750 proportional layers. The mean layer thickness is 1.0 ft (0.3 m) resulting in 48,000,000 model cells.

Regional and STACK Petrophysical Models

Shale volume (Vsh), total porosity (PHIT), and total organic carbon (TOC) were modeled (mapped) to evaluate their spatial distributions, aid in the interpretation of depositional environments, and help define controls on source-rock deposition of the Meramec and Caney formations. Three-dimensional petrophysical models were created using sequential-Gaussian simulation (SGS) with the following data and constraints: (1) 3-D model grids for regional and STACK areas (properties were modeled by zone for each area); (2) logs for Vsh (N=396), PHIT (N=326), and TOC (N=231); and (3) variogram parameters. Horizontal variogram ranges were estimated using empirical

evaluations of stratigraphic heterogeneity and vertical variogram ranges were calculated using experimental variograms for each zone from well data (Appendix D). SGS is a stochastic modeling technique that uses a kriging algorithm to sequentially populate grid cells in a random order based on input data distributions and variograms (Deutsch and Journel, 1998). The model results honor the well data (log curves), spatial continuity of properties defined by variograms, and the range of property values (input histograms).

Two Vsh calculations were calibrated against x-ray diffraction (XRD) measures of total clay content from the cores and used in conjunction for a robust assessment of Vsh. The first technique, considered the most common and standard Vsh calculation, is calculated from GR logs with shale and sandstone baselines, where $V_{ShGR} = (GR - GR_{Sandstone}) / (GR_{Shale} - GR_{Sandstone})$. Prior to V_{ShGR} calculation, wells were grouped into regions presumed to have relatively similar lithologic properties (approximately 30 wells per group), and the GR logs were normalized within each grouping using percentile range adjustments. The second method uses a neutron-density crossplot, where $V_{ShND} = (\phi_{Neutron} - \phi_{Density}) / (\phi_{Shale,Neutron} - \phi_{Shale,Density})$. PHIT was calculated from the root-mean-square of neutron and density porosity logs. Porosity logs were not normalized prior to calculation of V_{ShND} or PHIT. Caliper logs were used to flag intervals for poor borehole conditions prone to washout. Anomalous petrophysical estimates in poor boreholes were excluded from the models.

Analysis of the organic richness and hydrocarbon source potential of the Mississippian strata is performed using the $\Delta \log R$ technique (Passey et al., 1990) to estimate TOC content. This technique uses the separation between porosity and

resistivity log curves to identify organic-rich intervals. To calculate TOC, resistivity and porosity curves are properly scaled so that when overlain on the same track the two curves parallel each other in non-source intervals. A baseline interval is defined in a fine-grained, non-source interval where the two curves directly overlie each other. When an organic-rich or hydrocarbon-bearing interval is encountered, the two curves become non-parallel and separate owing to deflection of the porosity log (Figure 4). This separation, termed “ $\Delta \log R$ ”, occurs as the porosity log responds to the presence of kerogen, bitumen, and cracked hydrocarbons which have lower velocity and lower density. A GR cutoff is used to eliminate potential hydrocarbon reservoir intervals from the analysis, ensuring TOC is estimated only in relatively shale-rich intervals. For this study, TOC is calculated using NPHI and RILD logs as follows:

- 1) $\Delta \log R = \log_{10}(R/R_{\text{baseline}}) + 4.0 \times (\phi N - \phi N_{\text{baseline}})$
- 2) $\text{TOC} = (\Delta \log R) \times 10^{(2.297 - 0.1688 \times \text{LOM})}$

where $\Delta \log R$ is the separation between the NPHI and RILD logs measured in logarithmic resistivity cycles, R is the deep resistivity (RILD) measured in ohm-m, and ϕN is the neutron porosity (NPHI) measured in porosity units. R_{baseline} and ϕN_{baseline} correspond to the RILD and NPHI in a non-source, clay-rich rock. LOM is the level of organic maturity, typically calculated from vitrinite reflectance ($\%R_o$) data, which was unavailable in this dataset. In the absence of sample data, LOM was estimated from the $\%R_o$ maps from petroleum system models of Higley (2014).

The log-estimates of TOC were calibrated against eighteen data points of core TOC measured in the Gulf Oil 1-23 Shaffer core using LECO and Rock-Eval techniques. Potential data inaccuracies with this method arise due to differences in

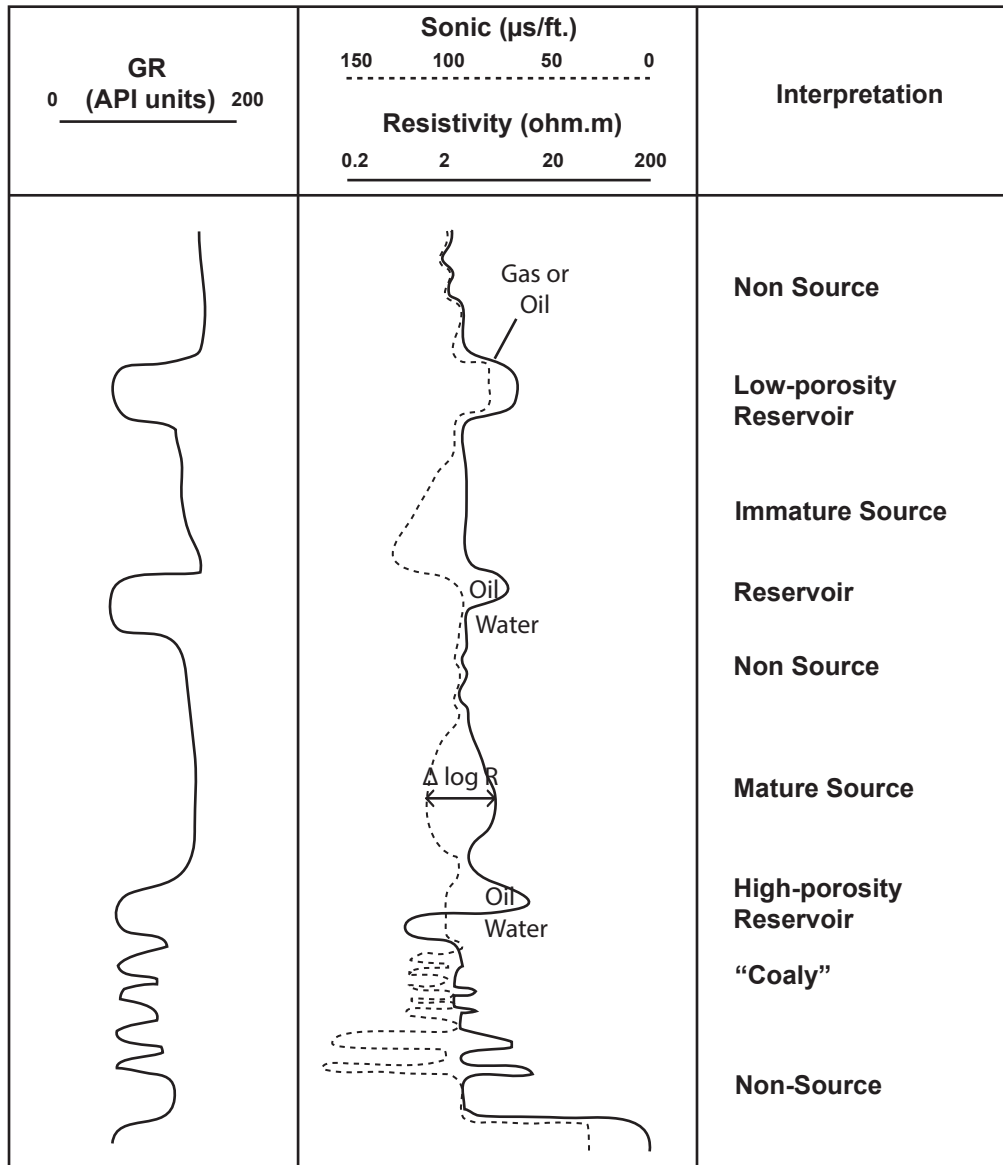


Figure 4. Schematic guide for interpreting the features of a $\Delta\log R$ overlay. From El Attar and Pranter (2016), modified from Passey et al. (1990)

resolution between core measurements and the resistivity/porosity log overlay. Core measurements can be accurate to within 1 in (2 cm), while wireline logs have a sample increment of 0.5 ft (0.15 m). An additionally complicating factor is the depth calibration of the core to the well logs. GR-scan logs of the core were used to match core depths to log depths.

RESULTS

Meramec Sedimentology and Lithofacies

The Gulf Oil 1-23 Shaffer core spans the upper part of the Meramec (-8395 to -8637 ft [-2559 to -2633 m] SSTVD). The Gulf Oil 1-25 Rohling core covers the middle of the Meramec interval (-8594 to -8800.5 ft [-2619 to -2682 m] SSTVD) (Figure 3). Based on analysis of the cored intervals, the Meramec Series consists of five lithofacies: A) calcareous fossiliferous sandstone, B) calcareous siltstone, C) argillaceous siltstone, D) bioturbated argillaceous calcareous siltstone, and E) silty mudstone (Figures 5 and 6) (Table 1).

Facies A: The calcareous fossiliferous sandstones are medium grey and contain abundant fossil fragments that include peloids (20%), crinoids (5%), brachiopods (5%), bryozoans (5%), and bivalves (2%), which commonly form discrete beds that are 1-2 in (2.5-5cm) thick. Lesser amounts of fossils are interspersed throughout some intervals. The other primary constituents are well-sorted, sub-angular silt to very-fine sand-sized quartz grains (30%) and clays (3%). Calcite, the dominant cement (30%), appears to nucleate around the calcite fossil fragments. Sedimentary structures are rare but include faint parallel and wispy mud laminations.

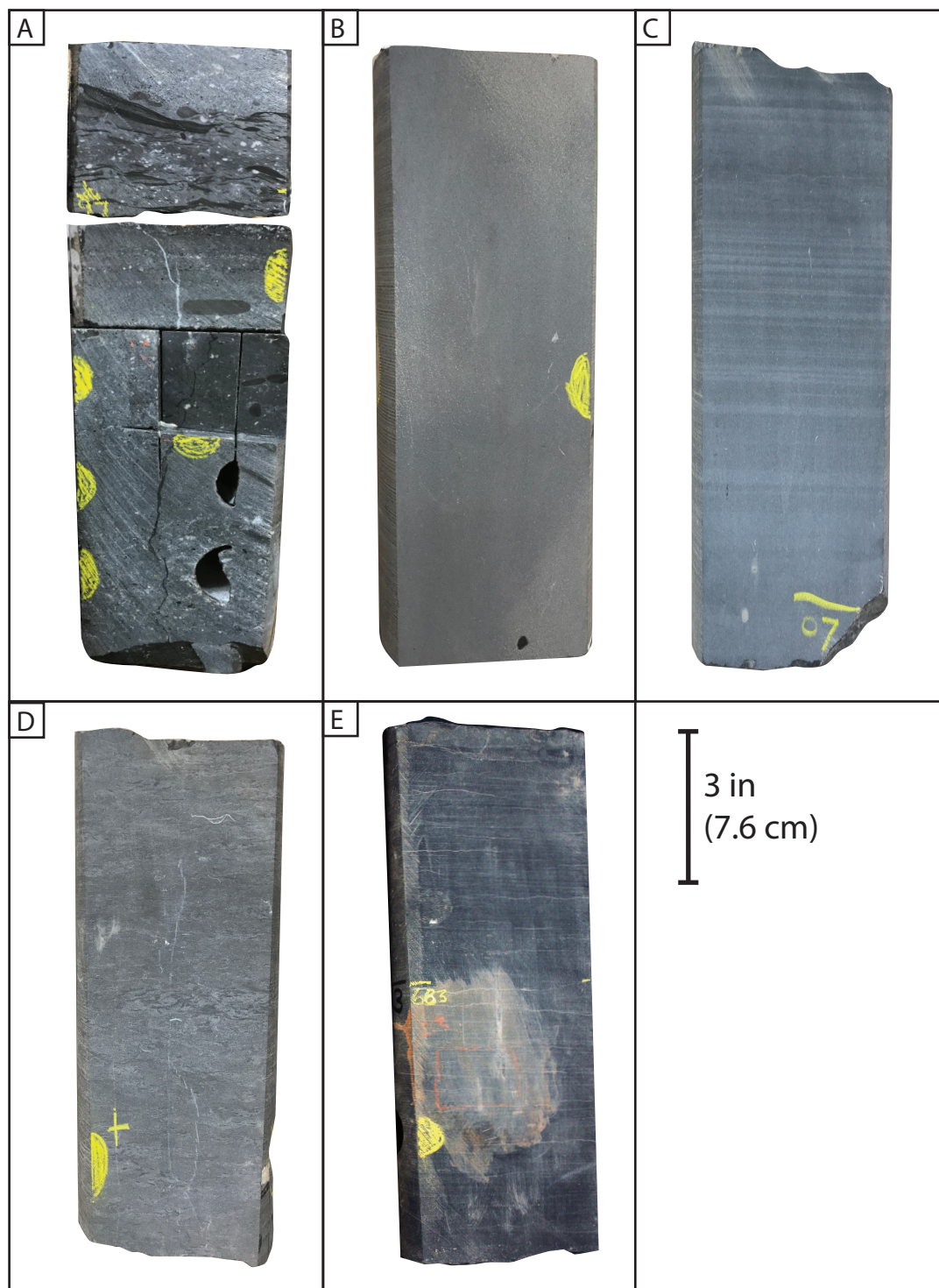


Figure 5. Representative photographs of the defined Meramec lithofacies. (A) Calcareous fossiliferous sandstone (Gulf Oil 1-23 Shaffer 9665 ft [2946 m] MD). (B) Calcareous siltstone (Gulf Oil 1-25 Rohling 9721.5 ft [2963 m] MD). (C) Argillaceous siltstone (Gulf Oil 1-25 Rohling 9906.5 ft [3019.5 m] MD). (D) Bioturbated siltstone (Gulf Oil 1-23 Shaffer 9660 ft [2944 m] MD). (E) Silty Mudstone (Gulf Oil 1-23 Shaffer 9663 ft [2945 m] MD).

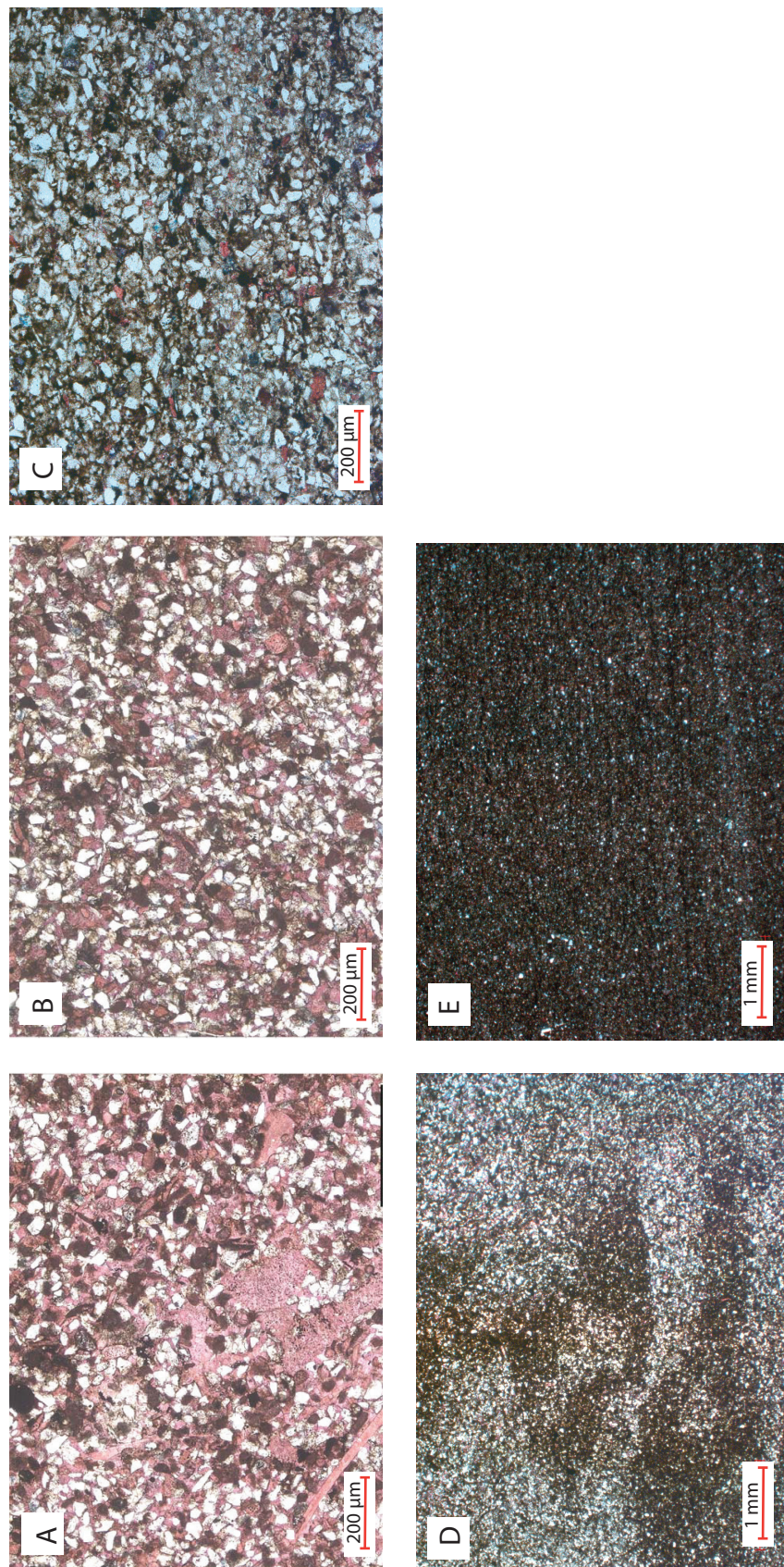


Figure 6. Representative thin section photomicrographs of the defined Meramec lithofacies. (A) Calcareous fossiliferous sandstone. Abundant fossil fragments, carbonate pellets, and silt-sized to very-fine-sand-sized quartz grains with calcite cement (Gulf Oil 1-23 Shaffer 9820 ft [2993 m] MD). (B) Calcareous siltstone. Silt-sized quartz, feldspars, and carbonate pellets cemented by calcite. (Gulf Oil 1-23 Shaffer 9887 ft [3013 m] MD). (C) Argillaceous siltstone. Predominantly silt-sized quartz grains and lesser amounts of carbonate rock fragments and pellets. Pore spaces are occluded with clay material (Gulf Oil 1-23 Shaffer 9716.5 ft [2961 m] MD) (D) Bioturbated siltstone. Cleaner, quartz-rich matrix with dark burrows infilled with mud and clay material (Gulf Oil 1-23 Shaffer 9740.5 ft [2969 m] MD). (E) Silty Mudstone. Predominantly clay minerals and lesser amounts of silt and fossil fragments. Faint horizontal laminations (Gulf Oil 1-23 Shaffer 9767 ft [2977 m] MD).

Facies B: The calcareous siltstones are medium grey and consist of well-sorted, sub-angular silt-sized quartz grains (30%), carbonate peloids (10%), clays (10%), carbonate fossil fragments (5%), feldspars (4%) and micas (1%). Micrite and finely-crystalline sparite are the primary cementing agents (40%). Sedimentary structures include hummocky cross-stratification, wavy laminations, and parallel laminations. The high percentage of calcite cement results in a hard rock that is prone to fracturing. Vertical calcite-filled fractures often span the entire length of a calcareous siltstone bed and terminate in the bedding contact with a softer argillaceous siltstone imparting a strong contrast in mechanical stratigraphy.

Facies C: The argillaceous siltstone is medium-to-dark grey and composed of predominantly well-sorted, sub-angular, silt-sized quartz grains (60 %). The facies is often structureless to slightly parallel-laminated, but may be interbedded with the calcareous siltstone facies. Thin section observations show a lack of calcite cement and carbonate fossil fragments relative to the calcareous siltstones and elevated proportions of clays (25%) that fill intergranular pores. The clay material likely coats the framework grains and limited carbonate cementation. This indicates an inverse relationship between clay and calcite material throughout the Meramec.

Facies D: The bioturbated argillaceous calcareous siltstone facies is medium to dark grey and generally lacks bedding features. These rocks are primarily composed of calcite cemented, silt-sized quartz grains, and clays. Trace fossils include skolithos, zoophycos, chondrites, phycosiphon, and undifferentiated burrows (Pemberton, 1992). The trace fossils are distinctly dark relative to the surrounding matrix due to elevated amounts of clay infilling the burrows.

Formation/ Interval	Lithofacies	Description	Interpreted Environment of Deposition
Meramec	Calcareous Fossiliferous Sandstone	Very-fine sand-sized quartz grains with abundant fossil fragments. Abundant calcite cement nucleates around the fossil fragments and occludes pore spaces.	Lower Shoreface – within fair-weather wave base (FWWB)
	Calcareous Siltstone	Abundant silt-sized quartz grains, peloids and fossil fragments cemented by micrite and sparite. Sedimentary structures include hummocky cross-stratification, wavy laminations, and parallel laminations.	Lower Shoreface – within FWWB
	Argillaceous Siltstone	Predominantly silt-sized quartz grains and clay minerals, with lesser amounts of calcite cement or fossil fragments than the calcareous siltstone.	Transitional Lower Shoreface-Offshore – within storm wave base (SWB)
	Bioturbated Siltstone	Calcite cemented, silt-sized quartz grains, and clays with abundant trace fossils. The trace fossils are distinctly dark relative to the surrounding matrix due to elevated amounts of clay infilling the burrows.	Transitional Lower Shoreface-Offshore – variably within or below SWB
	Silty Mudstone	Composed mostly of clay minerals and calcite with lesser amounts of silt-sized quartz grains, micas, and shell fragments. Predominantly structureless or faintly parallel laminated.	Offshore – predominantly below SWB
Sycamore Formation	Calcareous Siltstone	Mainly silt-sized quartz grains and rounded fossil fragments cemented by micrite and sparry calcite. Interpreted Ta-Tb-Te members of the idealized Bouma turbidite sequence and intermittent storm reworking.	Offshore – predominantly below SWB deposited by turbidite flows
	Cherty Mudstone	Predominantly siliceous chert cement that likely replaced unstable siliceous biogenic material, with lesser feldspars, clays, radiolarian, and sponge spicules	Basin Floor – below SWB
	Shale	Thinly bedded, lightly to moderately fissile, and composed of predominantly clay minerals, silt-sized quartz grains, carbonate cement, and accessory amounts of glauconite and micas	Basin Floor – below SWB

Table 1. Summary of lithofacies observed in the Meramec and Sycamore Formation.

Facies E: The silty mudstone is dark grey and predominantly structureless or faintly parallel laminated with minor to moderate amounts of bioturbation. The silty mudstones are composed mostly of clay minerals and calcite with lesser amounts of silt-sized quartz grains, micas, and shell fragments.

Sycamore Formation Sedimentology and Lithofacies

The south flank outcrop (X) is an excellent exposure of the entire Sycamore Formation (327 ft [99.7 m] true stratigraphic thickness), from its basal contact with the Woodford Shale to the overlying Caney Formation (Figure 7a; Appendix B-1). Outcrop X dips southward about 48° into the Ardmore Basin. Through analysis of the Sycamore Formation in outcrop, hand samples, and thin sections, three dominant lithofacies are: 1) calcareous siltstone, 2) cherty mudstone, 3) thinly bedded shale (Table 1). Following Fay (1989) and aided by the outcrop GR log, the Sycamore at outcrop X can be subdivided into six zones of hard, resistant calcareous siltstone benches separated by eroded shale intervals (Figure 8) (Appendix B-3).

Facies 1: The calcareous siltstones (Figure 7d) are light-to-medium grey and composed of moderately-sorted, sub-angular to angular silt-sized quartz grains and rounded fossil fragments that include sponge spicules, crinoids, and brachiopods. Also present in lesser amounts are feldspars, peloids, glauconite, and muscovite. The calcareous siltstones are cemented by micrite and finely-crystalline sparry calcite, which results in a low porosity, brittle rock that is prone to fracturing. Individual beds of the calcareous siltstone facies are generally less than 1 foot thick and have sharp basal contacts. Bed sets stack rhythmically in relatively monotonous sequence with few

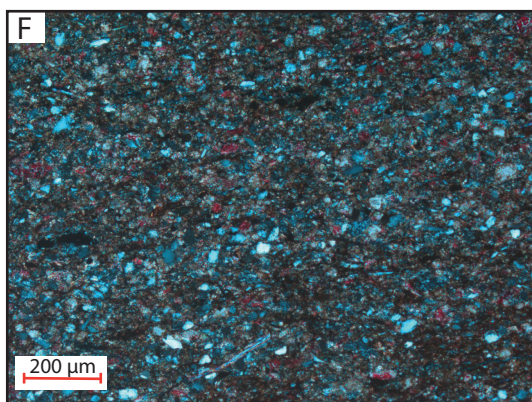
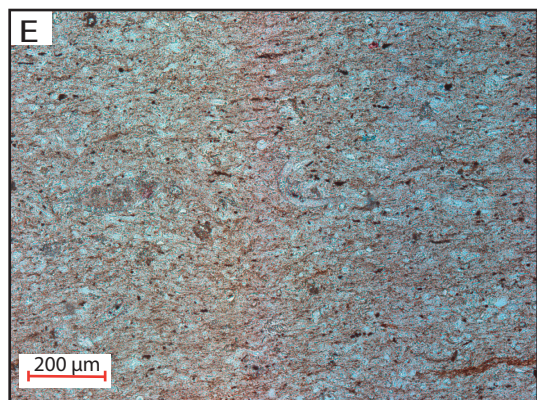
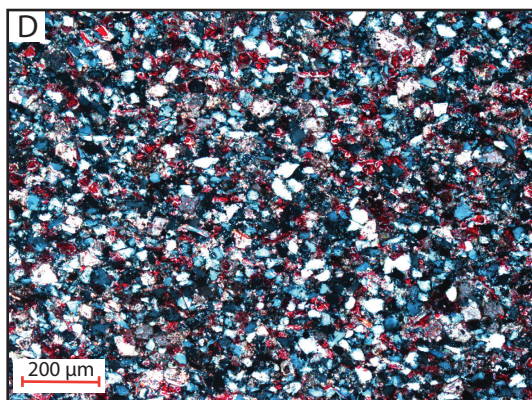
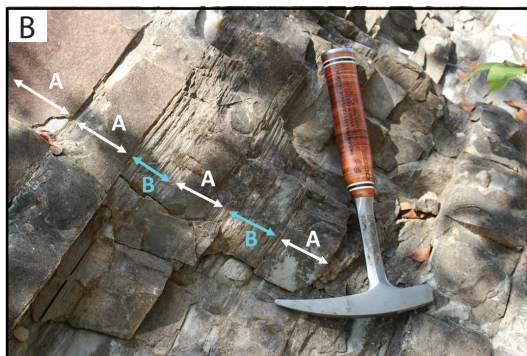
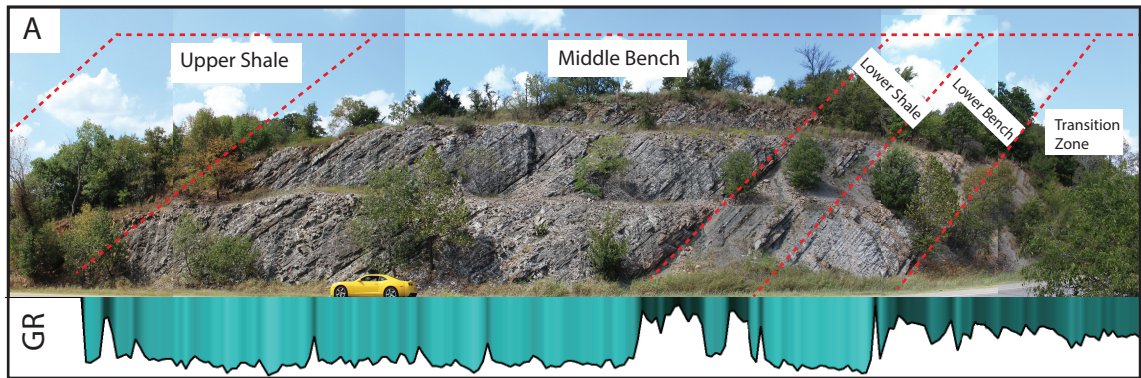
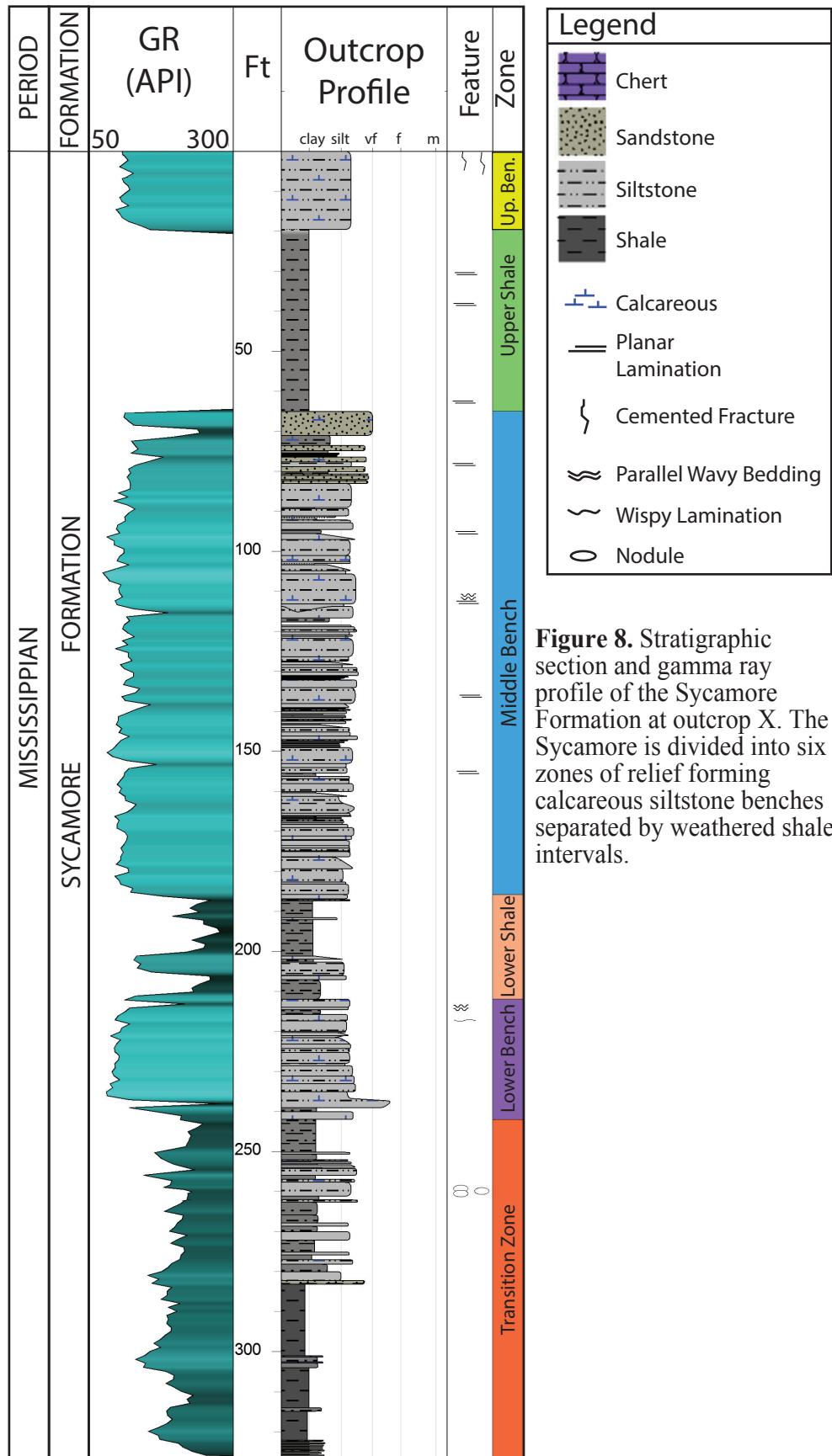


Figure 7. (A) Profile of Outcrop X on the west side of I35-S. Sycamore Formation on south limb of Arbuckle anticline dipping into the Ardmore Basin. Five of the six units discussed are highlighted. (B) Stacked massive to planar laminated calcareous siltstones interpreted as Ta to Tb members of the idealized Bouma sequence. (C) Massive calcareous siltstones with swaley bedforms and possible hummock cross stratifications interpreted as reworking within storm wave base. (D) Calcareous siltstone. Abundant siliciclastic silt that is cemented by micrite (174 ft [53 m]). (E) Cherty mudstone. Clays, fossils, and silt-sized quartz grains with a chert matrix (251 ft [77 m]). (F) Shale. Predominantly clay minerals, abundant silt-sized quartz grains, carbonate cement, and accessory amounts of glauconite and micas (77 ft [23 m]).

sedimentary structures. The most common sedimentary structures are thin (<2 in) intervals of horizontal laminations that subtly fine upward with increasing clay content and decreasing lamina thickness (Figure 7b). This succession is typically succeeded by a very thin draping shale. These packages are interpreted as Ta-Tb-Te members of the idealized Bouma turbidite sequence. The absence of complete Bouma sequences is likely due to the fine-grained, well-sorted character of the silty detritus which suppresses the expression of sedimentary structures such as ripples. Although most beds are continuous and uniform in thickness at the scale of the outcrop, close observation shows some beds are somewhat lenticular and have swaley tops with filled in troughs (Figure 7c). These hummocky beds are interpreted as reworking during intermittent storms.

Facies 2: The cherty mudstone facies forms high relief beds in the lower section of outcrop X. This facies is dark grey and composed of predominantly siliceous chert cement that likely replaced unstable siliceous biogenic material. Additional constituents are clay-sized quartz and feldspar grains, radiolarian, and sponge spicules (Figure 7e). The cherty mudstone lacks sedimentary structures or bedding features and typically occurs in beds of less than 1 foot (0.3 m) thick and interbedded with shales. The cherty mudstones have an intermediate GR signature, higher than the calcareous siltstones and lower than the shales.

Facies 3: The shales at outcrop X are dark grey and weather to either light grey or tan. The shales are thinly bedded, lightly to moderately fissile, and composed of predominantly clay minerals, silt-sized quartz grains, carbonate cement, and accessory



amounts of glauconite and micas (Figure 7f). The shales have the highest GR signatures, with values approaching 280 API.

Regional Stratigraphic Correlations and Mapping

The Mississippian System has a general northwest-southeast structural strike and dips primarily to the southwest (Figure 9). In the southern portion of the study area, the Mississippian rocks are deformed by a series of faults and folds associated with the Pennsylvanian orogenesis that exhumed the Mississippian outcrops along Interstate 35. The structural uplift in the eastern portion of the study is related to the Nemaha ridge and the Central Oklahoma Fault Zone.

The Osage is a succession of carbonates and mudstones overlying the Woodford Shale. It has low GR and RILD >100 ohm-m. The Osage thins to the southeast until it pinches out in northern Caddo and Grady counties (Figure 10). The Sycamore Formation unconformably overlies the Woodford Shale to the south of the Osage pinch out, as evidenced by abundant phosphatic nodules at outcrop X indicative of a depositional hiatus. Correlation of the Sycamore Formation of outcrop X to the subsurface to the north demonstrates the stratigraphic succession of the Sycamore Formation lithostratigraphically correlates to the Lower Meramec (Figure 10). This is supported by the increased silt abundance up-section in outcrop X and comparison of thin sections from the upper Sycamore bench to the Meramec of the Gulf Oil 1-23 Shaffer core (Appendix E-4). This lithostratigraphic correlation is an approximate chronostratigraphic correlation between the Sycamore of southern Oklahoma and the

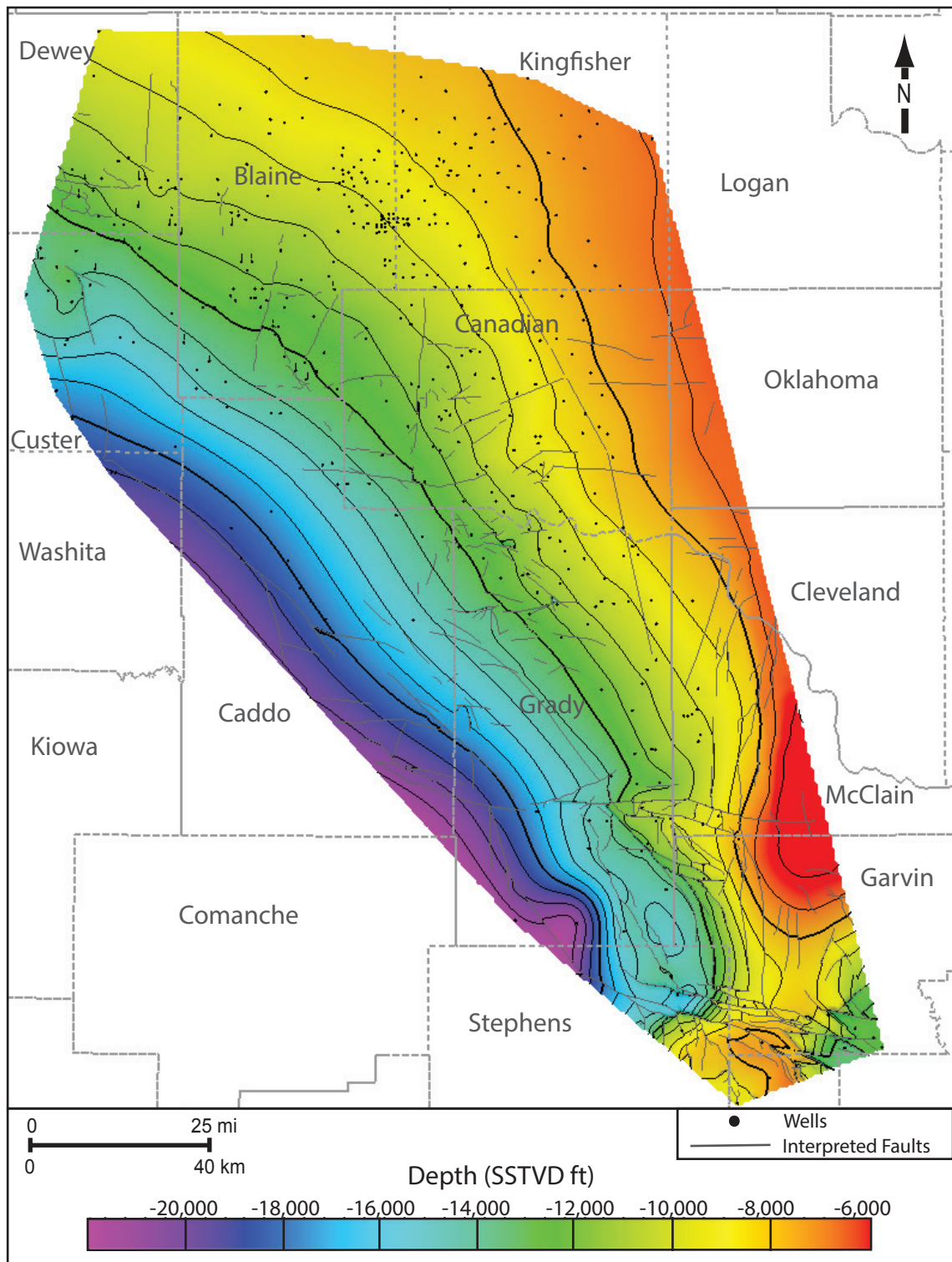


Figure 9. Structure depth map of the top of the Woodford Shale (base Mississippian) for the study area. Structural dip is generally to the southwest, but the southern extent of the study is folded and faulted by Paleozoic uplifts. Interpreted faults lines from Marsh and Holland (2016).

Meramec of central Oklahoma. Further biostratigraphic and chemostratigraphic work would be useful in refining the correlations between these units.

The top of the Meramec on well logs is interpreted at the inflection point of a resistivity increase corresponding to increased siltstone content (Figure 15). The same high-resistivity signature of the Meramec correlates to the high-resistivity, silty Ahlso member of the lower Caney Formation throughout the southern Anadarko Basin. This correlation is in accordance with Elias (1956) and Champlin (1959) and is observed in the Arkoma Basin on the eastern side of the Nemaha Ridge, where the “Mayes” (Meramec) siltstones correlate with silty, organic-rich shales in the lower Caney Formation in outcrops and the subsurface (Kamaan, 2006).

The top of the Caney Formation is correlative to the Lower Chester in the Anadarko Basin as a high GR interval overlain by a thick, carbonate-rich bench. The contact between the high GR shale interval and overlying carbonate bench is likely unconformable. The Lower Chester-Caney correlation represents a downdip facies change from interbedded limestones and shales of the lower Chester to the organic-rich, fissile Caney Formation in the southern Anadarko and Ardmore Basins (Ball et al., 1991).

Figure 11a shows the regional stratigraphic correlations in the dip direction. The stratigraphic section is flattened on the top of the Woodford Shale. The Meramec was deposited on the gently-dipping Osage ramp and the coeval Sycamore and Caney formations were deposited deeper in the basin. Following deposition of the Sycamore Formation, the basinal portion of the system becomes increasingly rich in shale, as defined by “hotter” GR logs. The Meramec interval has a maximum observed thickness

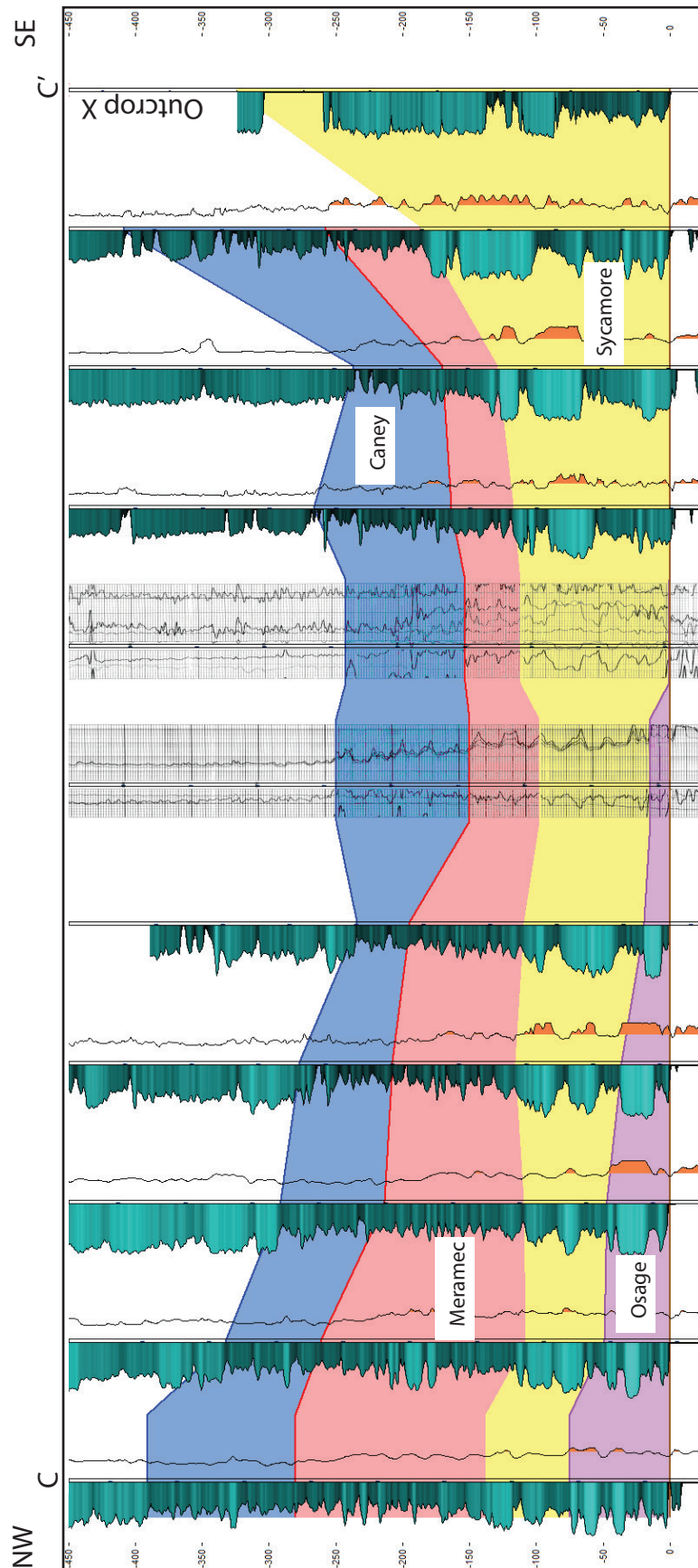


Figure 10. Surface-subsurface correlation from C to C' (Outcrop X) in the Arbuckle mountains into the southern Anadarko Basin. The Osage thins from north to south and pinches out. The Sycamore Formation thins to the north and lithostratigraphically correlates with the lower Meramec.

of 763 ft (233 m) in the study area with a strike-elongate thickness trend that runs NE-SW (Figure 11b). A net isopach map for the interval from the top of the Meramec to the top of the Woodford Shale that exhibits GR <50 API helps define the inferred NE-SW trending shelf edge through the northwest side of the study area and a thinning of low GR units basinward (Figure 11c).

Meramec Sequence-Stratigraphic Architecture

Numerous upward-shallowing depositional cycles are interpreted for the Meramec interval based on the vertical succession of lithofacies as observed in core and interpreted based on well-log responses. An idealized upward-shallowing stacking pattern is defined as (from base to top) silty mudstone, bioturbated argillaceous calcareous siltstone, argillaceous siltstone, calcareous siltstone, and calcareous fossiliferous sandstone. Such cycles are often incomplete or irregular and typically consist of only three of the five lithofacies. The upward-shallowing and coarsening cycles are often manifested in well-log signatures as an upward-decreasing GR-log motif punctuated by a sharp increase in GR at the top of each cycle. Each upward-shallowing cycle is interpreted to be a parasequence.

Based on lithofacies stacking patterns observed in core and calibrated to wireline logs (e.g., GR-log motifs), the Meramec is divided into seven parasequences (Figure 12; Figure 13). Each parasequence is defined as an upward-shallowing lithofacies succession capped by a marine-flooding surface. The parasequences (depositional cycles) exhibit deposits that reflect an initial transgressive phase followed by a regressive phase (Figure 12) as opposed to being completely asymmetric upward-

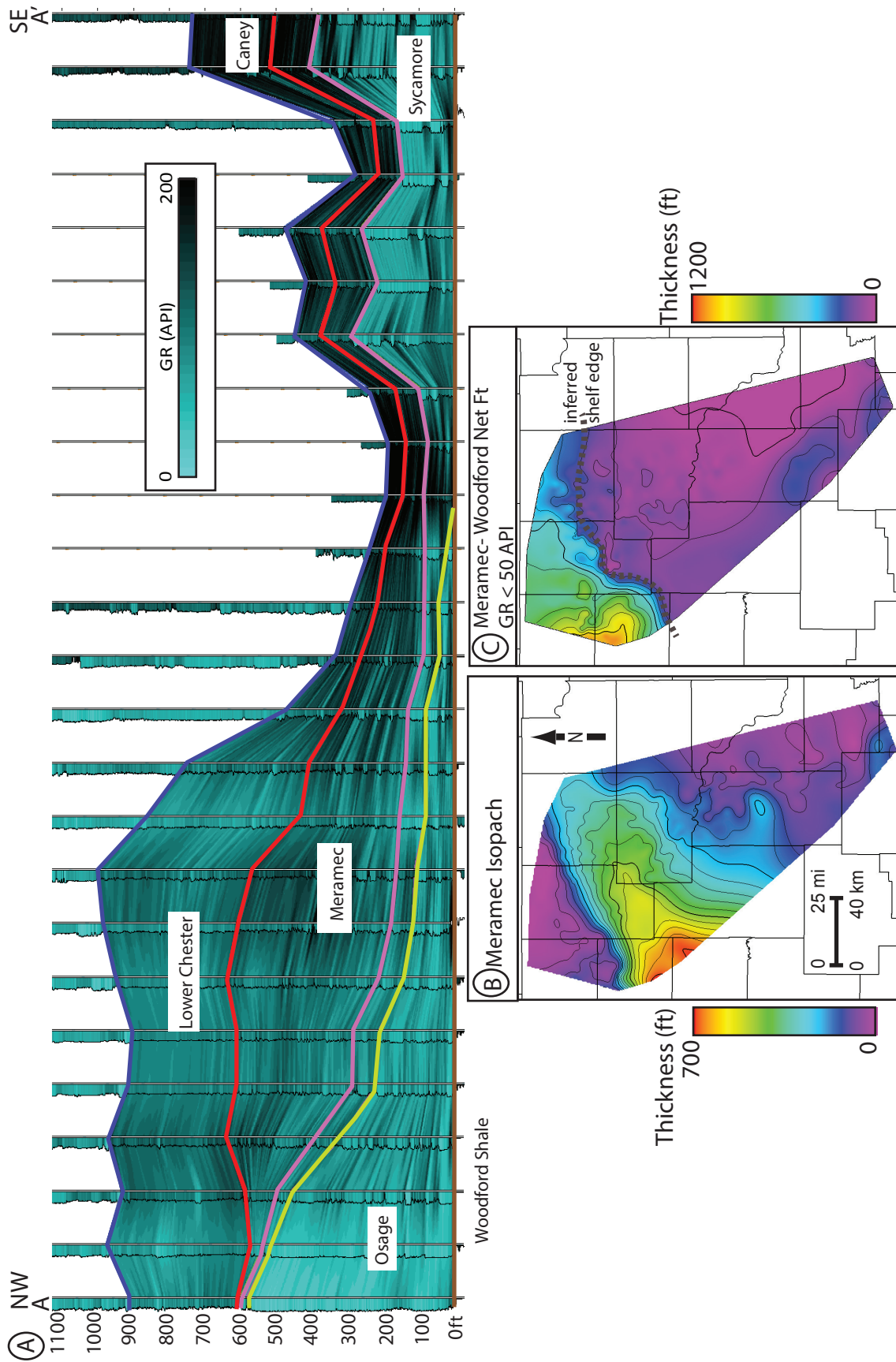


Figure 11. (A) Regional correlations (A-A') between the Meramec of central Oklahoma and the Sycamore and Caney formations of southern Oklahoma. The Osage carbonates pinch out in Northern Grady county. The Sycamore Formation lithostratigraphically correlates to the lower Meramec, and the Ahloso Member of the Caney Formation correlates to the upper Meramec. (B) Isopach map of the Meramec interval. The Mississippian generally thins basinward to the south but there is a thickened interval of Sycamore Formation siltstones in the southern extent of the study area. (C) Isopach map of net feet with GR > 50 API for the Meramec-Woodford. Low gamma ray units thin basinward over a short lateral distance. This thickness change is interpreted as the shelf edge.

shoaling cycles with only a regressive phase. Individual parasequences increase in bed thickness, grain size, and energy of sedimentary structures up-section. The marine-flooding surfaces that bound each parasequence typically occur at the interface between a silty mudstone overlying a more proximal calcareous siltstone. These are interpreted as abrupt increases in water depth.

Correlation and mapping of the parasequences demonstrates that the Meramec parasequences were deposited as a series of strike-elongate clinoforms (Figure 13a). Calculated inclinations of the topset and foreset angles are consistently less than 0.2° . Parasequences 1-3 are retrogradational, indicated by an overall upward-fining vertical succession and onlapping geometries with relatively static depocenters in the lateral direction (Figure 13b). The clinoform geometries of parasequences 4-7 are progradational, as shown by an upward-coarsening vertical succession in core and well logs; progradation is to the southeast. The parasequence stacking patterns suggest that parasequences 1-3 form a retrogradational parasequence set, and parasequences 4-7 form a progradational parasequence set. The boundary between the retrogradational and progradational parasequence sets is interpreted as the maximum flooding surface for the interval (Figure 12). This maximum flooding surface is possibly the boundary between the transgressive-systems tract and the highstand-systems tract of a lower order depositional sequence. Based on this interpretation, the unconformities that bound the sequence are stratigraphically below and above the Meramec interval of this study.

Regional distribution of Vsh and TOC

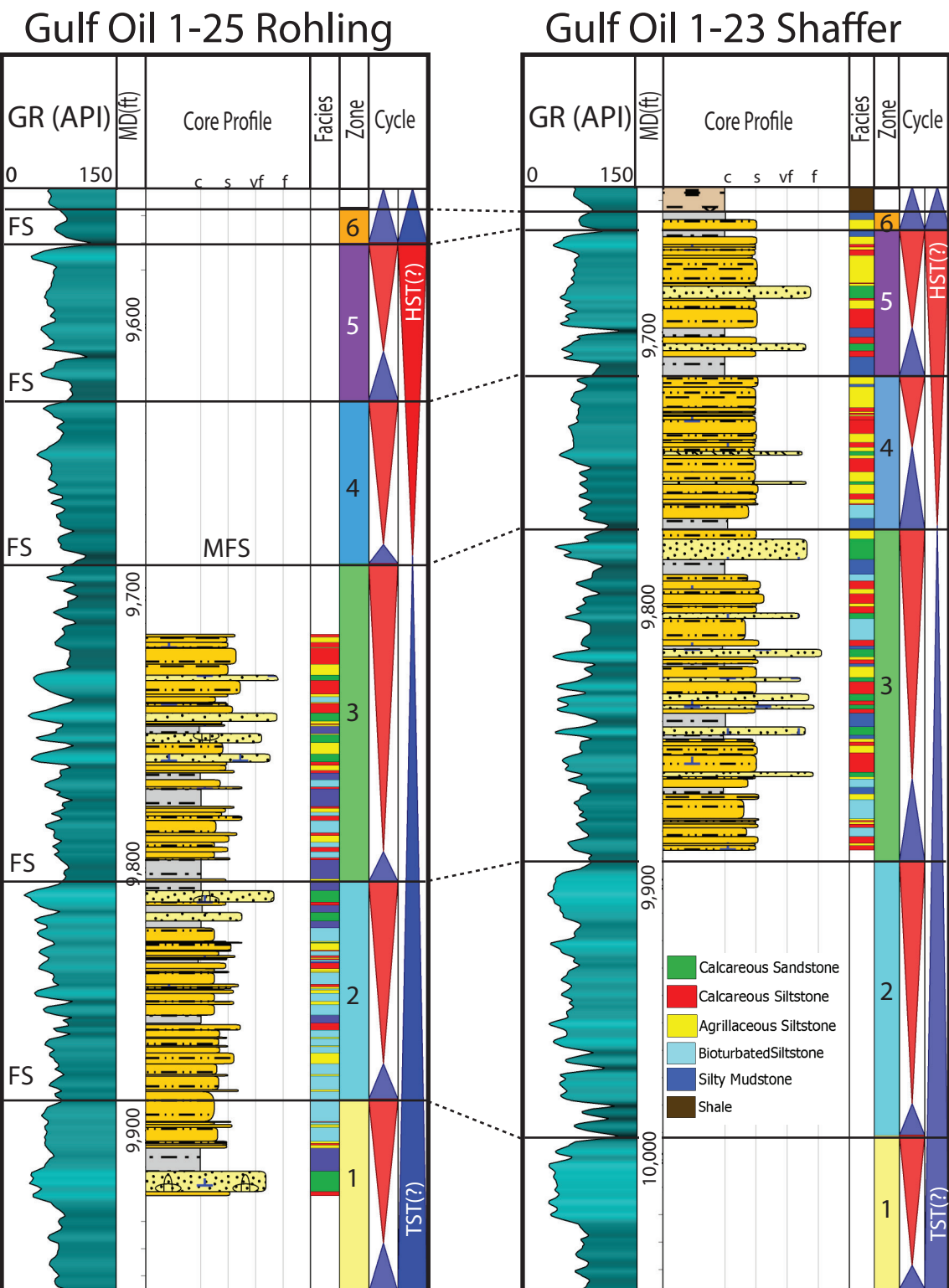


Figure 12. Comparison of core descriptions to wireline log responses for the Gulf Oil 1-25 Rohling and Gulf Oil 1-23 Shaffer cores. The Gulf Oil 1-25 Rohling covers the lower to middle Meramec and the Gulf Oil 1-23 Shaffer covers the middle to upper Meramec. The Meramec was described for dominant lithology and lithofacies. The Meramec is subdivided into seven sequence-stratigraphic zones capped by marine flooding surfaces (FS). The FS between the retrogradational and progradational parasequence sets is interpreted as the maximum flooding surface (MFS).

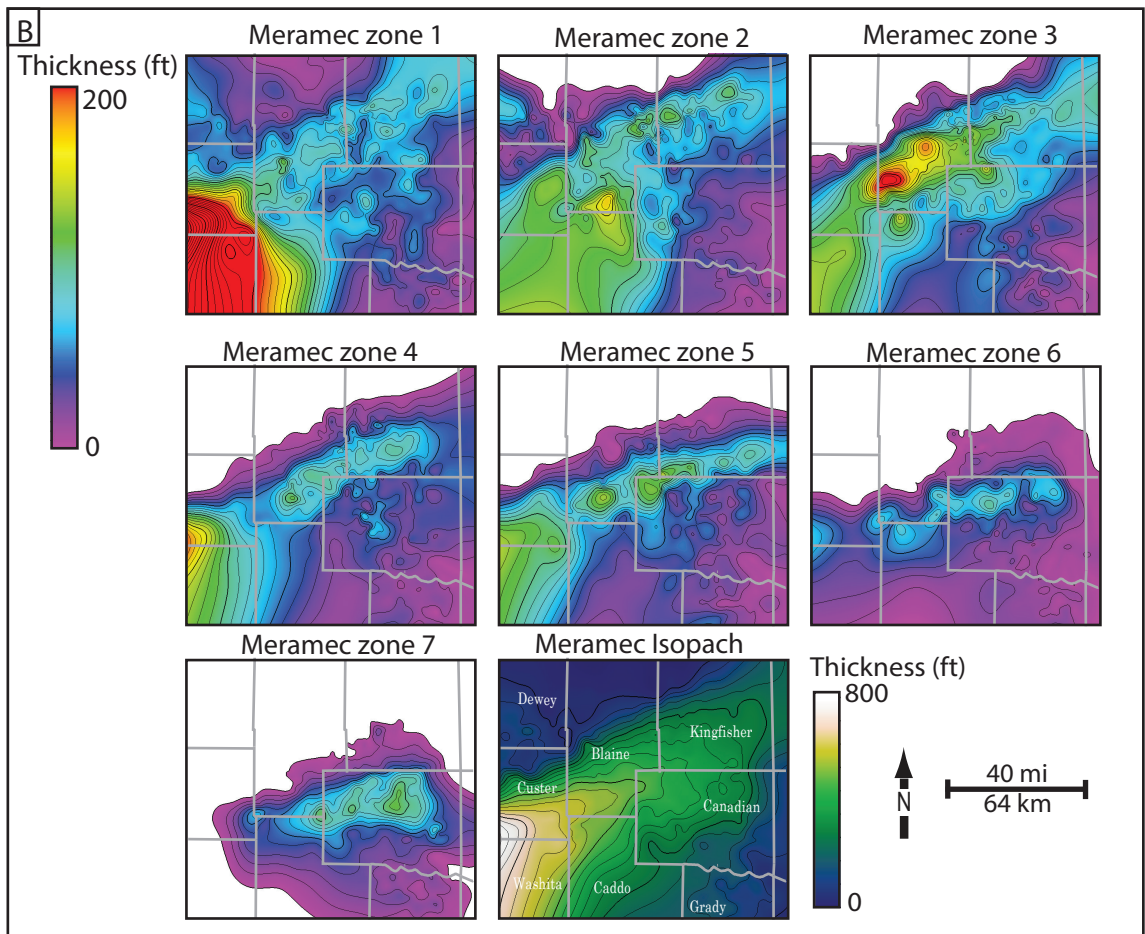
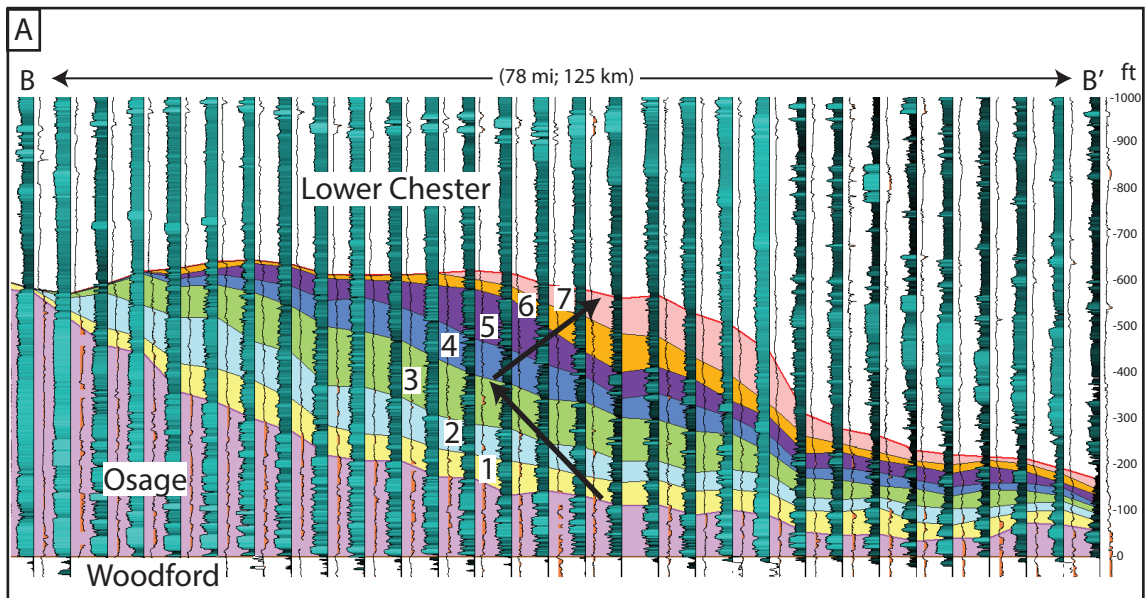


Figure 13. (A) Subsurface correlation of the Meramec zones along dip-oriented cross section B-B'. Meramec parasequences 1-3 are retrogradational and form a retrogradational parasequence set. Parasequences 4-7 are progradational and form a progradational parasequence set. (B) Isopach maps of each of the Meramec zones and the entire Meramec interval in Blaine, Kingfisher, and Canadian counties and parts of Dewey, Custer, Caddo, and Grady counties. The Meramec zones are elongate in the NE-SW direction and overall step to the southeast as the clinoforms prograde along the Anadarko ramp. All of the Meramec zones are scaled equally, while the total Meramec isopach is scaled differently, indicated by the changing color bars.

The regional model of the Mississippian consists of three stratigraphic zones. From oldest to youngest these are: 1) Sycamore and Osage, (2) Meramec, and (3) Caney. The Sycamore Formation and Osage are treated as a single zone because the precise location of the interpreted Osage pinch out is uncertain, and both the Sycamore Formation and Osage are lithologically similar but more carbonate-rich than the overlying Meramec. A spherical variogram was used with horizontal ranges set at 70,000 ft (21,336 m) in both the major and minor direction, and variograms were computed in the vertical orientation (Appendix D).

Regional Model V_{sh}

V_{SHGR} shows an increase in shale content up-section, increasing from an average of 23% in the Sycamore, 41% in the Meramec, to 46% in the Caney (Figure 14a). V_{SHGR} increases in the southeasterly downdip direction for all three intervals. In the Meramec, mean V_{SHGR} values increase from a minimum of 11% along the Osage carbonate ramp margin to as high as 82% in the distal portion of the Anadarko Basin. This is indicative of a facies change stratigraphically downdip from the inferred shelf edge (Figure 11c) for each stratigraphic interval, with clay content increasing at the expense of carbonate content. This facies change is gradual to the southeast across the 140-mi- (225 km) long orientation of the regional model.

Regional Model TOC

Core TOC measurements range from 0–1.5% in the Meramec of the Gulf Oil 1-23 Shaffer, making it a poor to fair source rock. Log estimates of TOC calibrate well

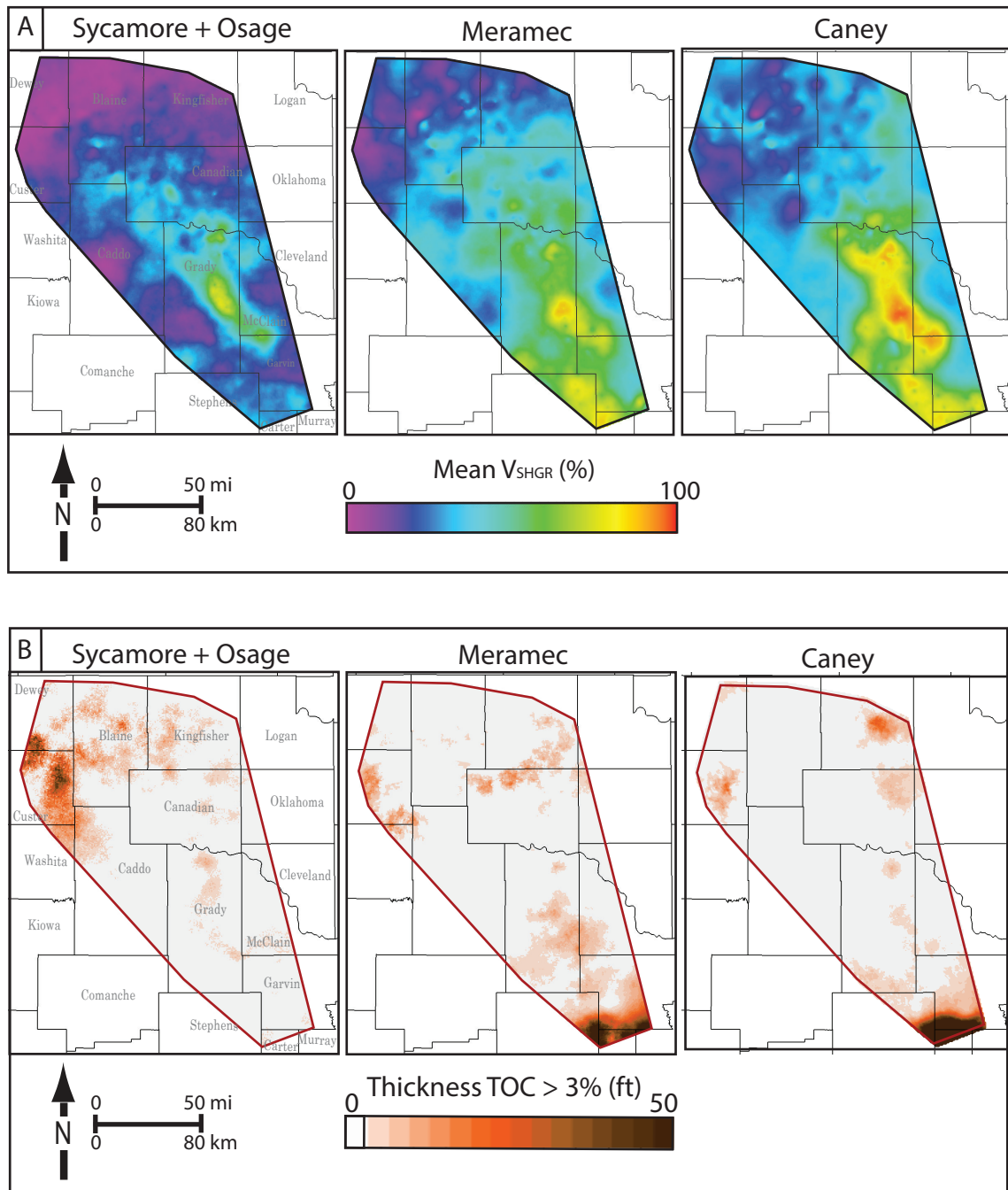


Figure 14. (A) Mean V_{SHGR} per zone for the regional model. V_{SHGR} increases up section and is highest in the Caney model zone. In all three zones, V_{SHGR} increases basinward to the south and reaches a maximum in the far southern portion of the study area. This lateral trend pertains to a decrease in depositional energy from ramp to basin. (B) Isochore thickness of source rock (TOC > 3%) per zone for the regional model. The Sycamore + Osage zone is relatively lean in TOC content in the basin. Increased thickness on the ramp is attributed to the Kinderhook Shale that lies between the Woodford and Osage but subcrops to the south. Source rock thickness increases basinward to the south in the Meramec and Caney intervals, suggesting anoxic conditions in the deeper basin.

with the core measurements (Table 2). The mean absolute error (measured in wt.%) between the Gulf Oil 1-23 Shaffer core TOC measurements and $\Delta\log R$ estimates is 0.264% with a standard deviation of 0.271%. This calibration indicates that the Passey (1990) $\Delta\log R$ is a qualitatively representative measure of TOC in the Meramec interval, at least at these relatively low TOC values. While no direct TOC measurements were available for the Caney Formation in this study, Kamaan (2006) measured TOC values ranging from <1-9.79% in Caney Formation outcrops along the eastern flank of the Arbuckle Mountains. A comparison of the Gulf Oil 1-23 Shaffer and the Sun Oil 1-1 Hooks-Moore 1-1, located downdip in Carter County near the study area of Kamaan (2006), shows this downdip increase in TOC in the Meramec and Caney intervals, and empirically corroborates the accuracy of the $\Delta\log R$ estimates of TOC (Figure 15). Because no wells of this study have core TOC measurements in the Caney Formation, the confidence in this calibration must be regarded as relatively weak; however, this calibration does support ranking intervals for source potential on a relative basis.

Calculated TOC is typically less than 1% north of the border between Canadian and Grady counties, but TOC values to the south range from 0 to 8%. Intervals with TOC > 3% are likely source rocks that are more capable of producing and expelling hydrocarbons. Mapping of these source rock intervals demonstrates a maximum source-rock isochore of 167 ft (51 m) at the southern end of the study area (Figure 14b). Source rock intervals to the north in the Sycamore-Osage zone pertain to Kinderhookian-aged shales overlying the Woodford Shale. These shales were not mapped as part of this study but are presumed to pinch out to the south. Source-rock thickness increases to the south for the Meramec and Caney zones, and there is a thick, laterally expansive source

Depth (MD) ft	TOC Core (wt%)	TOC Δ LogR (wt%)	% Change	Absolute Diff (%)
9654.5	1.46	1.46	-0.22	0.003
9663.2	0.229	0.00	-100.00	0.229
9665.5	0.201	0.00	-100.00	0.201
9676	0.295	0.10	-66.10	0.195
9678	0.471	0.10	-78.77	0.371
9704.5	0.476	0.73	52.73	0.251
9716.5	0.777	0.64	-17.63	0.137
9717.2	1.11	0.63	-43.12	0.479
9722	0.615	0.61	-1.22	0.008
9742	0.315	0.63	99.05	0.312
9769.9	0.818	0.80	-2.02	0.017
9771	0.498	0.34	-31.73	0.158
9807.85	0.859	0.28	-67.59	0.581
9827	0.204	1.34	558.16	1.137
9851	0.481	0.03	-92.91	0.447
9863.3	1.33	1.35	1.28	0.020
9874	0.345	0.53	54.46	0.189
9878	1.62	1.61	-0.81	0.013

Table 2. Statistical summary of the of Δ log R estimates of TOC to the core-measurements of TOC. Core TOC measurements range from 0.20% to 1.62%. Δ log R TOC estimates range from 0% to 1.61%. The maximum error is 1.14%, with a mean absolute error of 0.26% and a standard deviation of 0.271%.

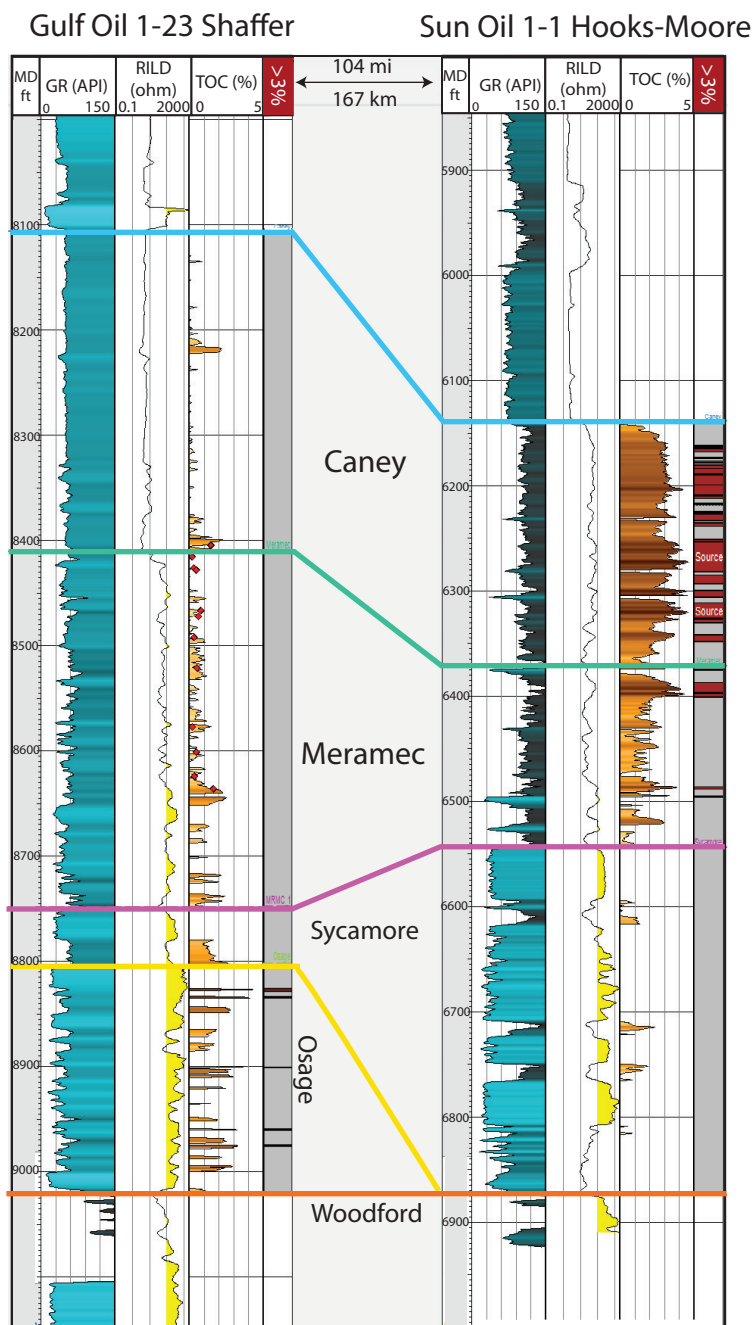


Figure 15. Comparison of $\Delta \log R$ estimates of TOC in the Gulf Oil 1-23 Shaffer well in Blaine county and the downdip Hooks-Moore 1-1 well in Carter County. Red diamonds on the Gulf Oil 1-23 Shaffer TOC track are TOC core measurements. The distance between the wells represents a transition from the ramp to basin depositional settings. Equivalent units of the Meramec and Caney intervals are typically less than 1% in the ramp setting but are elevated to 2-5% in the basin.

interval across Stephens, Carter, Murray, and Garvin counties. In the Meramec, there is an east-west trend of source rocks in southern Kingfisher and northern Canadian counties that averages 12 ft (3.5 m) thick (~2% source/non-source net-to-gross thickness).

Osage and Meramec Vsh, PHIT, and TOC – STACK trend

The STACK model is composed of 8 zones: a basal zone from the top of the Woodford to the top of the Osage, and the seven sequence-stratigraphic Meramec zones. The STACK model zones are constructed with truncational upper boundaries to represent the Meramec clinoform geometry (Appendix D-1). A spherical variogram was oriented with a major direction of 70°, the observed strike-orientation of the Meramec deposits. The horizontal variogram was set at 30,000 ft (9,144m) in the major direction and 20,000 ft (6,096 m) in the minor direction to impose the observed strike-elongate nature of the Meramec zones. Experimental variograms were computed in the vertical orientation for each zone (Appendix D).

STACK Model Vsh

Vsh increases stratigraphically upward throughout the Meramec (Figure 16; Table 3). Vsh is lowest in the Osage and increases substantially into the Meramec as the sedimentary system transitions from carbonate-dominated to siliciclastic-dominated. V_{SHGR} is relatively low in Meramec zones 1 (18%) and 2 (18%) and increases into zones 3 (26%) and 4 (30%). V_{SHGR} is lower in zone 5 (24%), and higher values of mean Vsh occur in zones 6 (28%) and 7 (34%). V_{SHGR} shows a notable increase in shale

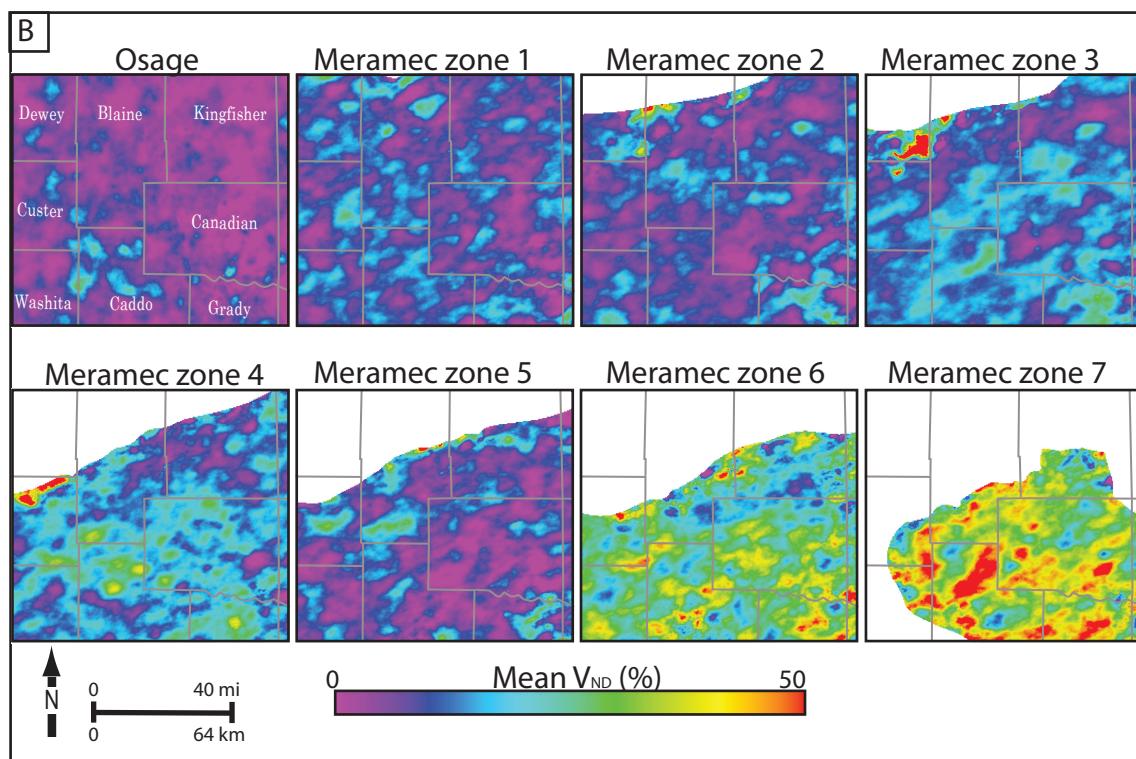
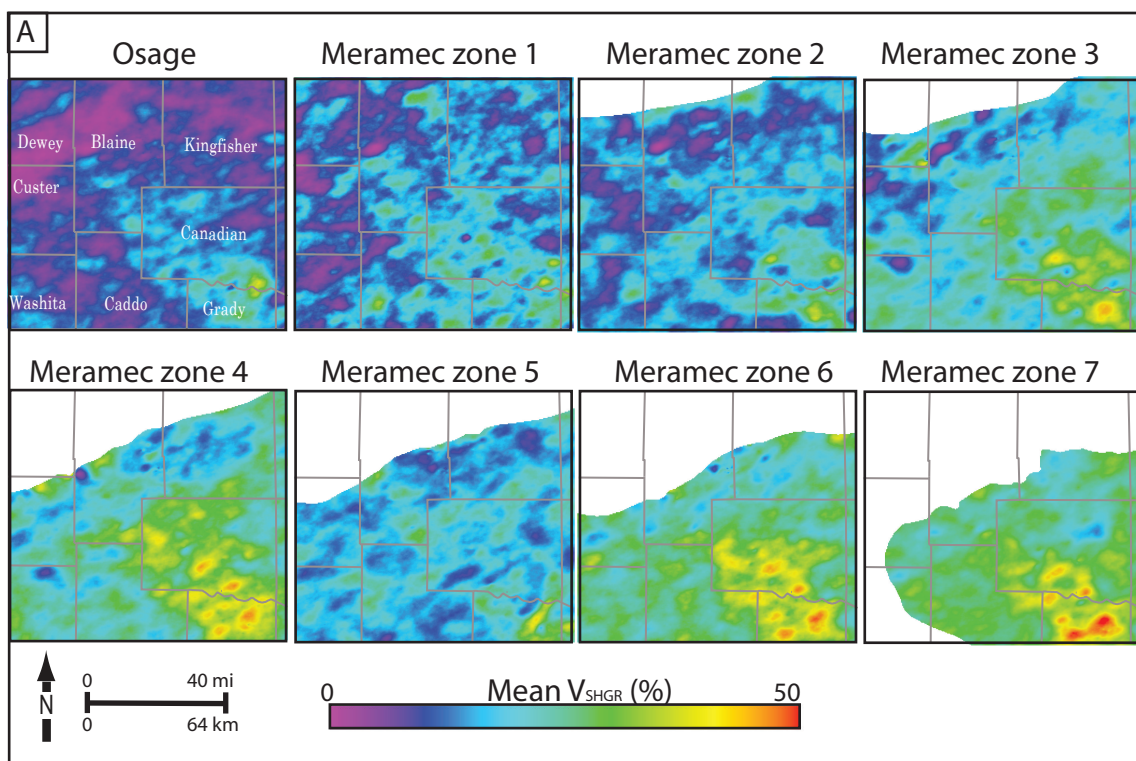


Figure 16. (A) Mean V_{SHGR} per zone in the STACK model. V_{SHGR} is highest in zones 3, 4, 6, and 7 and lower in the zones 1, 2, and 5. V_{SHGR} is lowest in the northwest and highest in the southeast, indicating a facies change from clinoform topset to foreset. (B) Mean V_{SHND} per zone. V_{SHND} is highest in zones 3, 4, 6, and 7. V_{SHND} does not have consistent, discernible lateral trends.

Zone	Mean VSHGR (%)	Mean VSHND (%)	Mean PHIT (%)	Mean TOC (%)
Osage	12	7	4.5	0.26
MRMC zone 1	18	12	4.9	0.25
MRMC zone 2	18	12	5.7	0.17
MRMC zone 3	26	16	6.9	0.29
MRMC zone 4	30	12	8.7	0.43
MRMC zone 5	24	18	6.3	0.17
MRMC zone 6	28	33	11.1	0.32
MRMC zone 7	34	36	14.6	0.25

Table 3. Statistical summary of petrophysical properties by zone for the STACK model. V_{SHGR} , V_{SHND} , and PHIT are highest in zones 4, 6, and 7.

content in the southeast dip direction that is consistent for each model zone. The distribution of V_{SHND} lacks discernible spatial trends within each zone. The V_{SHGR} and V_{SHND} models are broadly comparable with similar vertical trends. Zone 6 (33%) and zone 7 (36%) have higher V_{SHND} than V_{SHGR} . This is likely due to the baseline definitions of shale in the corresponding log types. Confidence in these zones is weaker because zone 6 is only partially present in the Gulf Oil 1-23 Shaffer core, and zone 7 is not sampled by either core.

STACK Model PHIT

PHIT follows a similar vertical trend to V_{sh} , with an overall increase stratigraphically upward throughout the Osage and Meramec (Figure 17a; Table 3). Mean PHIT increases from 4.5% in the Osage, to 4.9% and 5.7% in zones 1 and 2. Zones 3 and 4 have relatively high PHIT at 6.9% and 8.7%, respectively. PHIT decreases in zone 5, followed by mean PHIT >10% in zones 6 and 7. Each zone has a demonstrable increase in PHIT in the southeast-dip direction.

Measurements of PHIT likely overestimate effective porosity (not occupied by clay-bound waters or representing isolated pores), which is especially apparent in the more shale-rich zones 6 and 7. The relationship between PHIT and V_{sh} indicates PHIT is a useful proxy for shale content and therefore depositional energy within a stratigraphic zone. Corrections to convert total porosity to effective porosity are uncertain. Core measurements of porosity in Blaine county are insufficient to apply to the larger study area, and core measurements of PHIE in the shale-rich zones 6 and 7 were not available. However, thin section analysis shows the calcareous siltstones have

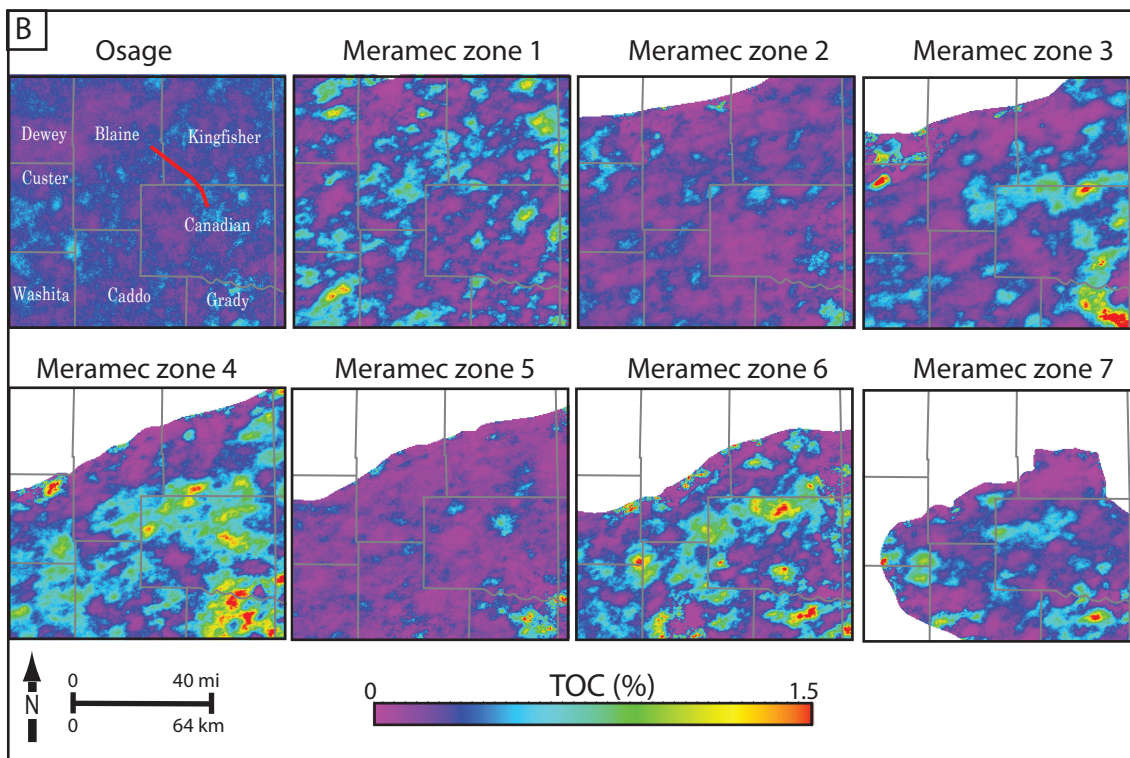
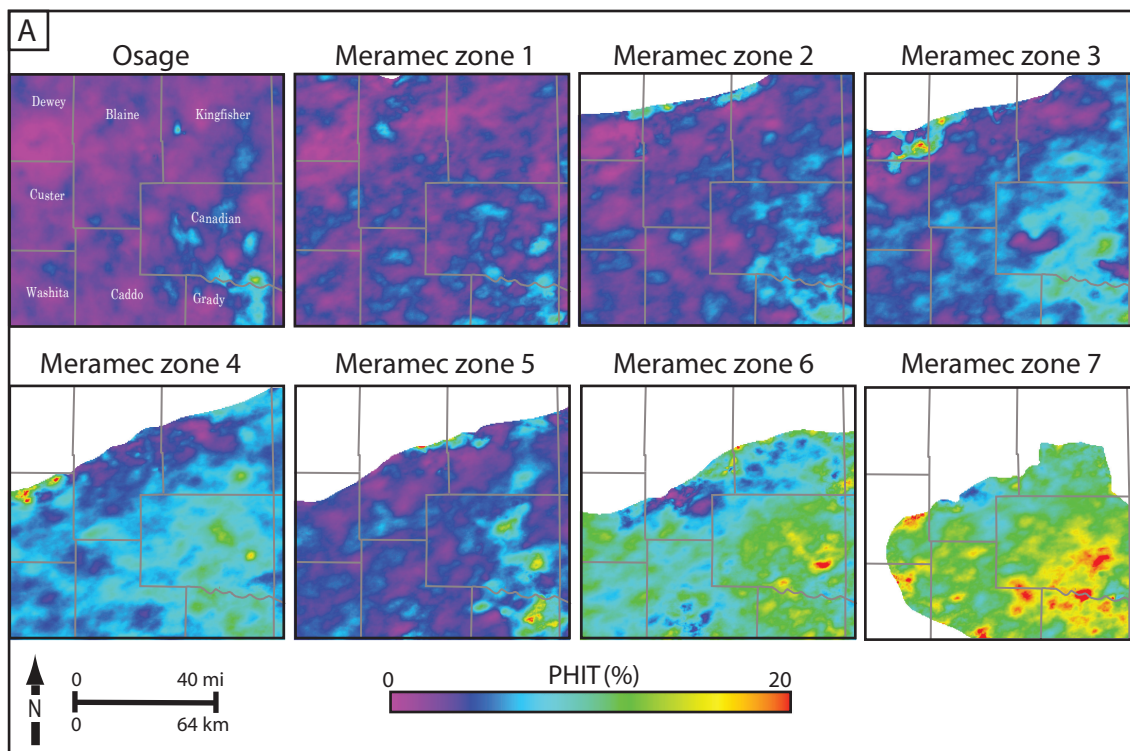


Figure 17. (A) Mean total porosity (PHIT) of the Meramec zones in the STACK model. PHIT increases up section and is at a maximum in zone 7. PHIT is typically highest in zones 3, 4, 6, and 7, indicating a proportional relationship between Vsh and PHIT. PHIT is highest in the southeast, downdip extent of the model, likely corresponding to an increase in shale content at the toe of the Meramec clinoforms. (B) Mean TOC per zone in the STACK model. Mean TOC is typically < 1% in the ramp setting, but areas of mean TOC > 1% are observed.

lower porosity (~2% visual estimate) than the more argillaceous siltstones (~4%). This indicates an inverse relationship between calcite content and porosity where the calcite cement is responsible for occluding pore spaces and suggest that clay coatings may inhibit nucleation of calcite cement (Price et al., 2017).

STACK Model TOC

Figure 17b shows mean TOC by zone for the STACK area. TOC is typically low (<1%) throughout the STACK model. The basal Osage zone has a mean TOC of 0.26%. Meramec zone 1 has a mean TOC of 0.25%. Zone 2 has negligible TOC values (0.17%), followed by an increase in TOC into zones 3 (0.29%) and 4 (43%). Zone 4 demonstrates an overall increase in TOC downdip to the southeast. Zone 5 has minimal TOC development (0.17%). Mean TOC is relatively high in zone 6 (0.32%), and zone 7 (0.25%). The most organic-rich accumulations are loosely linked to the depocenters of the Meramec. This is especially apparent for zone 6 (Appendix E-3). Figure 18 demonstrates the vertical distribution and lateral continuity of TOC. Organic-rich (TOC >1%) intervals are typically dispersed and discontinuous. The laterally continuous organic-rich intervals correlate with the marine flooding surfaces of the Meramec sequence-stratigraphic framework.

DISCUSSION

Depositional environments

The Meramec of the STACK area possess a range of lithofacies and sedimentary structures that indicates the depositional environment varied considerably throughout

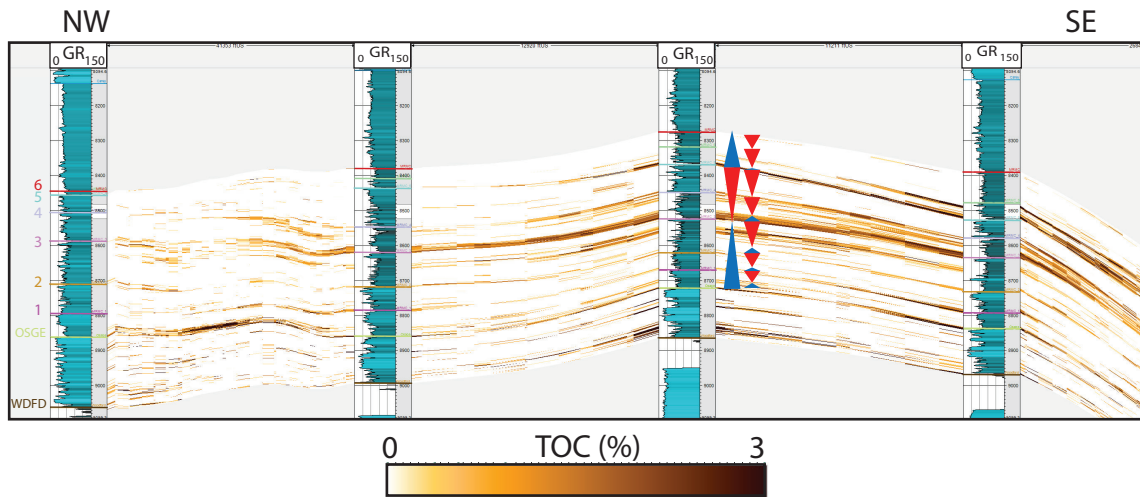


Figure 18. Cross section through the 3-D TOC model along the cross section shown by the red line in Figure 17b. TOC is typically low (<1%) throughout the STACK model. Continuous beds with TOC > 1% correspond to the marine flooding surfaces separating model zones.

the Middle Mississippian (Table 1). Ripple laminations and cross-stratification in fossiliferous sandstone and calcareous siltstone facies are likely created by tidal and storm wave motion and indicative of periodic deposition within or near fair-weather wave base. The rocks are interpreted as lower shoreface deposits with traction as the dominant depositional mechanism. The concurrent increase in clay content and lower energy sedimentary structures of argillaceous and bioturbated siltstones represent deposition in a deeper, calmer setting interpreted as a transitional shoreface-offshore to deeper offshore environment. Churned beds within these deposits indicate episodic deposition above storm-wave base, and the system was likely near storm-wave base throughout the Middle Mississippian (Meramec deposition). Silty mudstones represent the deepest environment of deposition and were likely deposited near or below storm-wave base in the offshore setting. There are several facies successions consisting of, from base to top, structureless calcareous siltstones, parallel-laminated siltstones, wavy-laminated-argillaceous siltstones, and faintly laminated mudstones with an overall increase in clay content and decrease in carbonate content from base to top. Such intervals may represent partial Bouma sequences, indicating deposition by turbidity flows in the offshore setting (Appendix E-6).

The low relief ($< 1^\circ$) of the Anadarko ramp likely resulted in similar depositional energy across the ramp. The gradual downdip increase of V_{SHGR} and PHIT indicates a minor facies change between the clinoform topset, foreset, and bottomset, with the topsets being more calcareous and the bottomsets being more argillaceous. The strike-elongate isopach trends and lateral continuity of petrophysical properties of the Meramec indicate shoreline-parallel bottom currents potentially reworked the

transported siliciclastic silt along the Anadarko ramp. The increase in Vsh and PHIT in southern Canadian County and northern Grady County observed in every zone in the STACK continues to the south in the regional model. This is interpreted as the transition between the ramp and basinal depositional settings.

Meramec petrophysical properties correlate to the sequence-stratigraphic framework and indicate changes in relative sea level exhibit control on the depositional environments of the Meramec in the ramp setting. Overall sea-level deepening in the Meramec results in an overall increase in Vsh and PHIT up-section, but higher-order cyclicity is present. Meramec zone 4 contains the maximum flooding surface that separates the retrogradational and progradational parasequence sets and has the highest Vsh and PHIT.

Farther south, the Sycamore Formation, represents the downdip, basin-floor extension of the ramp deposits. Partial Bouma sequences indicate the Sycamore Formation was likely deposited by turbidite flows of autochthonous silt and carbonate material. The occurrence of storm beds at outcrop Z indicate paleo-water depths were sometimes shallow enough to be above storm-wave base. On the north flank of the Arbuckle anticline, the Sycamore Formation is slightly coarser grained and has a higher quartz silt-to-carbonate peloid ratio (Franklin, 2002), indicative of a more proximal setting. The Sycamore Formation thickens to the south indicating increased accommodation space. If turbidity flows came off the shelf and travelled down-dip, coarser grains would progressively be deposited and produce the thicker and coarser silty beds on the more proximal north flank. The thickening to the south continues into the subsurface in the nearby Springer Field (Figure 19). Considering the horizontal

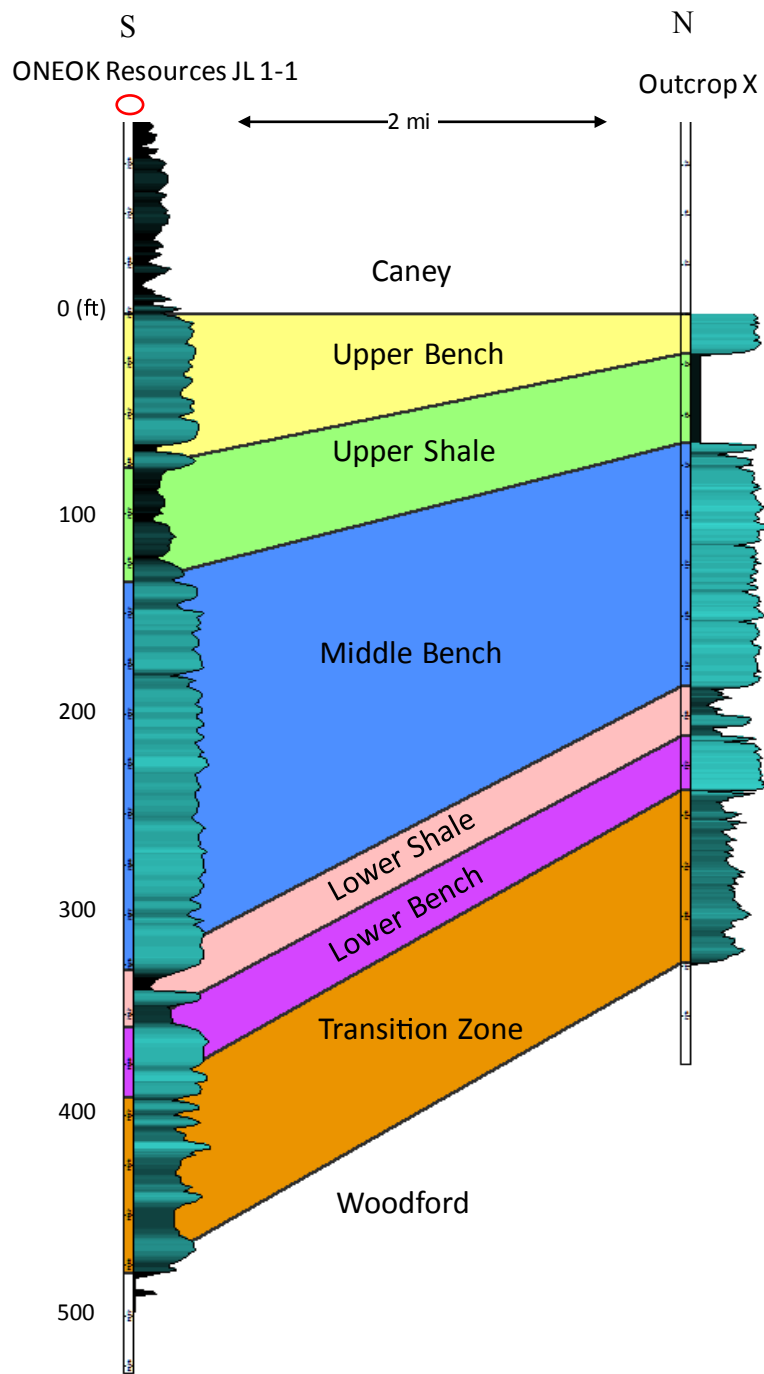


Figure 19. Correlation of lithologic zones in outcrop X to the nearby Springer Field using gamma ray logs show an overall thickening of the middle and upper benches to the south, with intrazonal thickening of individual calcareous siltstone (low GR) and shale (high GR) beds.

distance and inferred paleowater depths, a very low depositional gradient can be inferred. Such a low gradient implies a very long distance for gravity-driven flows from the Meramec-Osage shelf edge (Figure 11c). A southern source of the sediment should not be rejected.

The transition from the siltstones of the upper Sycamore Formation into the silty mudrocks and shales of the Meramecian Ahloso Member of the Lower Caney Formation records a basinward shift in depositional environment. This deepening continues into the overlying Delaware Creek and Sand Branch Members of the Caney Formation that are primarily organic-rich fissile shales with more clay and less silt and calcite than the Ahloso Member (Andrews, 2007). The presence of clay minerals and preserved organic matter are indicative of very slow sedimentation rates in anoxic waters that were well below storm-wave base (Kamaan, 2006).

Controls on source-rock potential of Mississippian strata

To produce a source rock capable of generating hydrocarbons during thermal maturation, the necessary conditions must exist to both deposit and preserve substantial amounts of organic matter. Biologic primary productivity, mainly in the form of pelagic settling of phytoplankton, is responsible for supplying organic matter (Huc et al., 2005). In oxygenated waters, over 90% of organic material that settles on the ocean floor is decomposed by aerobic metabolizing organisms (Emerson and Hedges, 1988). Organic-matter preservation relies on an under-supply of oxygen in the water column, referred to as anoxia, causing a cessation of aerobic biologic activity. Such conditions commonly develop in very deep waters below the oxygen minimum, in restricted waters of silled

basins, or in areas where deep, oxygen-depleted water upwells toward the surface (Demaison and Moore, 1980).

Kamaan (2006) noted the presence of preserved organic matter of both marine and terrestrial origin and intervals with no observed bioturbation in the Caney Formation in the southeastern flank of the Arbuckle Mountains, and suggested the Caney Formation was deposited in periodically anoxic bottom waters. Kamaan (2006) also observed apatite minerals and phosphate nodules throughout the Caney Formation and hypothesized they were deposited in phosphorous-rich waters, a vital nutrient for photosynthetic processes that would result in high primary productivity. Low amounts of stable nitrogen isotopes indicate that the Caney Formation, in a more proximal position east of the Nemaha uplift, underwent incomplete denitrification during deposition and was likely deposited in suboxic waters (Quan et al., 2013).

Modeled TOC is at a maximum in the Meramec and Caney Formation in the distal portion of the study area. The increase in TOC is concurrent with a sharp increase in shale volume at the top of the Sycamore Formation, corresponding to a basinward shift in depositional environment. Such elevated levels of TOC indicate deposition in an anoxic environment in the southern extent of the study area during the Middle to Late Mississippian.

Average TOC values also notably increase in the Meramec in the more proximal ramp environments. While upwelling is typically associated with continental margins against open oceans, upwelling events are observed in gently dipping carbonate ramp settings (Lowery and Rankey, 2017) and can occur on shallow ramps under the proper conditions. Upwelling events are common during transgressive phases in epeiric seas at

low latitudes (Arthur and Sageman, 2004). Upwelling currents in a tropical setting are driven by divergence of wind patterns at an equatorial zone with low atmospheric pressure. The Anadarko Basin was located at 20°-30° S, placing the area in a tropical to subtropical climate zone (Gutschick and Sandberg, 1983). Global circulation models of the Mississippian by Parrish (1982) place the locus of equatorial wind divergence over the Anadarko Basin.

Although organic matter is dispersed throughout most of the Meramec (Appendix E-4), discrete source beds are associated with the marine flooding surfaces (and the maximum flooding surface) that separate zones 3 and 4 and zones 5 and 6 (Figure 18). Bioturbation present throughout much of the Meramec in the lower shoreface to offshore environments indicates a well-oxygenated water column; however, the silty mudstones that form the flooding surfaces are laminated with little-to-no bioturbation. The proper paleogeographic conditions existed to potentially produce vigorous upwelling currents. These increases in preservation of organic matter are possibly the result of upwelling of the oxygen-poor, nutrient-rich waters from deeper in the basin during transgressive periods. Elemental geochemistry as a proxy for paleo-redox conditions would be useful in determining the depositional conditions on the Anadarko ramp.

CONCLUSIONS

The Mississippian Meramec deposits of central and southern Oklahoma consist of a stratigraphically complex succession of siliciclastic strata influenced by changing relative sea levels. Two cores and one outcrop were described in detail and integrated

with 3-D modeling techniques to evaluate the stratigraphic correlations, depositional environment, and organic richness of Meramecian strata. The key conclusions are as follows:

1. Surface to subsurface correlation demonstrates the upper Sycamore Formation is lithostratigraphically correlative to the lower Meramec, and the upper Meramec correlates to the lower Caney Formation.
2. Five lithofacies are assigned in the Meramec in Blaine County. The Meramec is divided into seven parasequences that are capped by marine flooding surfaces. Correlation and mapping of these zones demonstrates the Meramec was deposited as a series of retrogradational to prograding parasequence sets forming clinoforms that are elongate in the northeast-southwest orientation and ultimately step basinward to the southeast.
3. The Meramec of the STACK area was deposited on a gentle ramp that extended from lower shoreface (above FWB) to offshore (below SWB) depositional environments. A variety of processes including tides, storms, and currents reworked these ramp deposits.
4. The Sycamore Formation is divided into six zones of relief-forming calcareous siltstone benches separated by weathered shale intervals. The Sycamore was deposited down-dip of the Meramec by turbidite flows.
5. 3-D petrophysical models from this study demonstrate a regional increase in shale volume (V_{sh}) to the southeast with increasing distance from the presumed shelf edge.

6. In the STACK area, the distribution of petrophysical properties corresponds to the sequence-stratigraphic framework. Zones 3 and 4 are bound by the maximum flooding surface and have higher Vsh and PHIT. Zones 6 and 7 also have higher Vsh and PHIT due to the overall deepening during the Meramec.
7. TOC values estimated using the Passey (1990) $\Delta\log R$ technique are elevated in the basinal systems of the Meramec and Caney Formation. Intervals with TOC>3% reach a maximum thickness of 167 ft (51 m), and TOC values as high as 8% are observed in the southern portion of the study area. High TOC occurrences in the up-dip ramp setting of the Meramec correlate to the marine flooding surfaces of each parasequence.

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APPENDIX A: Core descriptions

Operator Gulf Oil Corporation		EasyCore The EasyCopy Company
Top 9645 ft	Bottom 10266 ft	
Country United States	Well Name & No. Shaffer 1-23	
Location Blaine County, OK	Date Aug 30, 1980	
Basin Anadarko	UWI No. 35011215220000	
Field Omega West	KB 1250 ft	
Latitude -98.2355156	Longitude 35.8428394	

Lithologies

 Claystone	 Mudstone	 Sandstone
 Siltstone		

Accessories

 Cemented Fractures

Fossils

 Bivalves	 Brachiopods	 Crinoids
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Sedimentary Structures

 Faint Lamination	 HCS	 Herringbone Cross-bedding
 Planar Lamination		

Trace Fossils

 Bioturbation (undifferentiated)	 Chondrites	 Helminthopsis
 Skolithos		

Facies

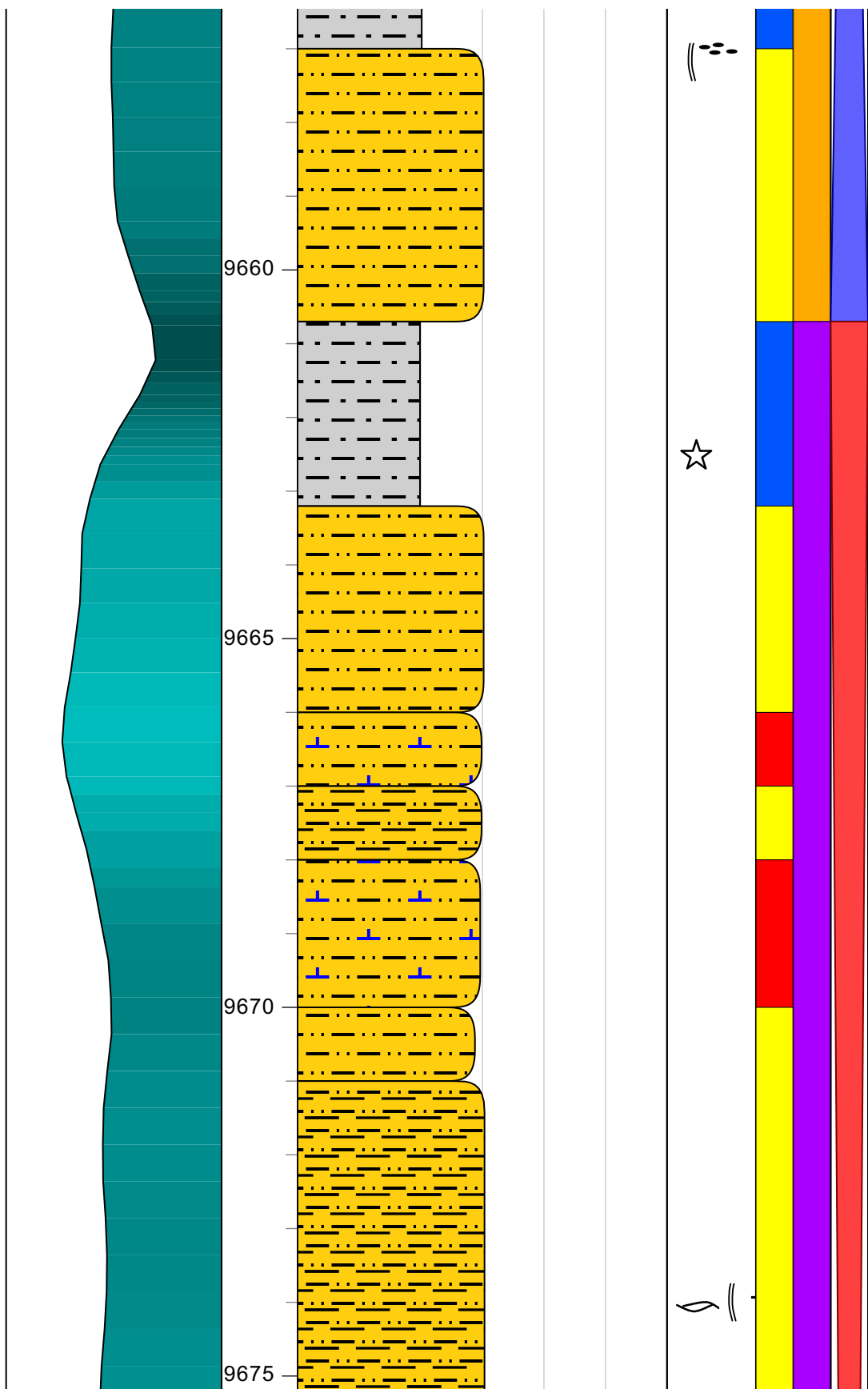
 Agrillaceous Siltstone	 Bioturbated siltstone	 Calcareous Sandstone
 Calcareous Siltstone	 Shale	 Silty Mudstone

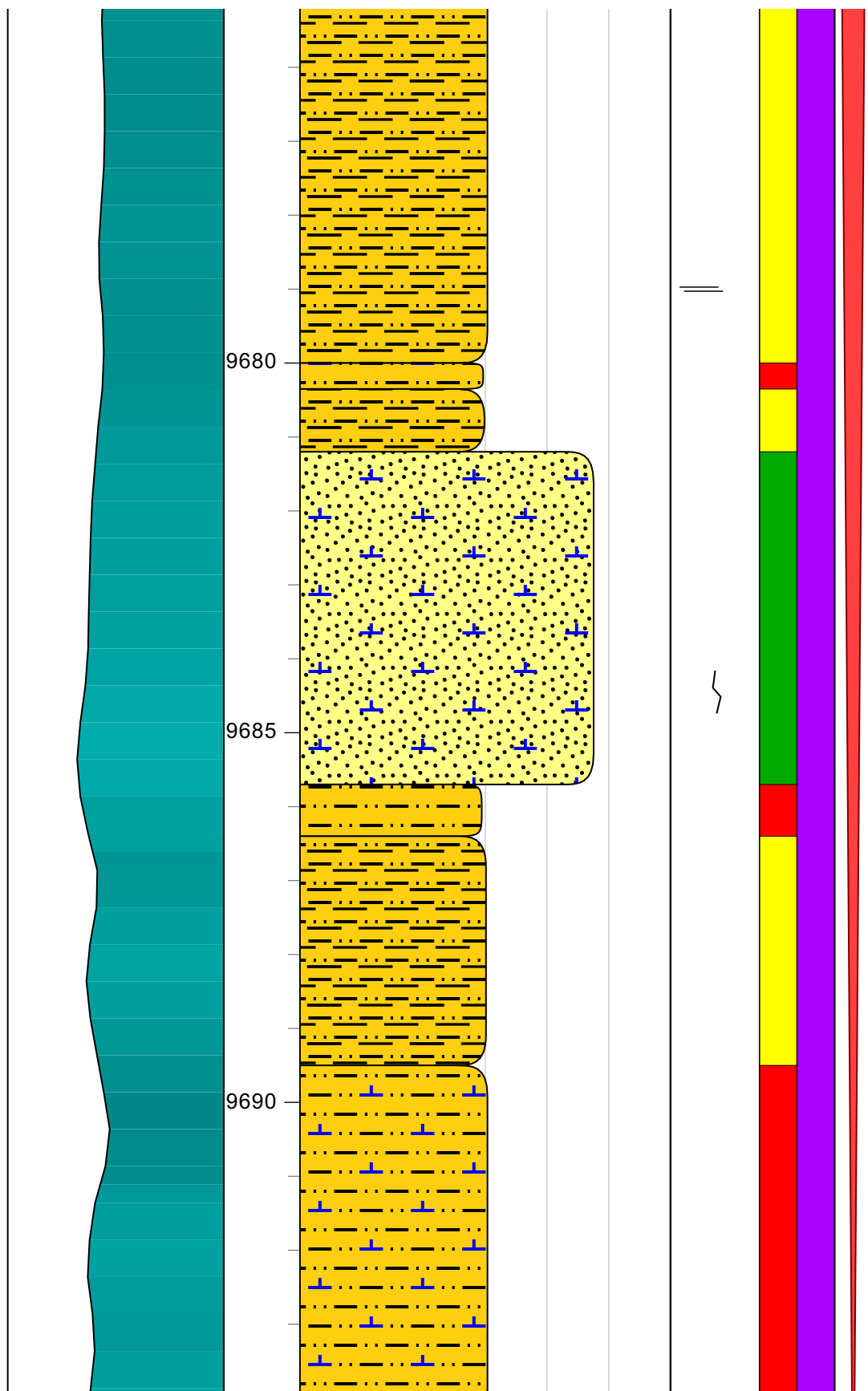
Zones

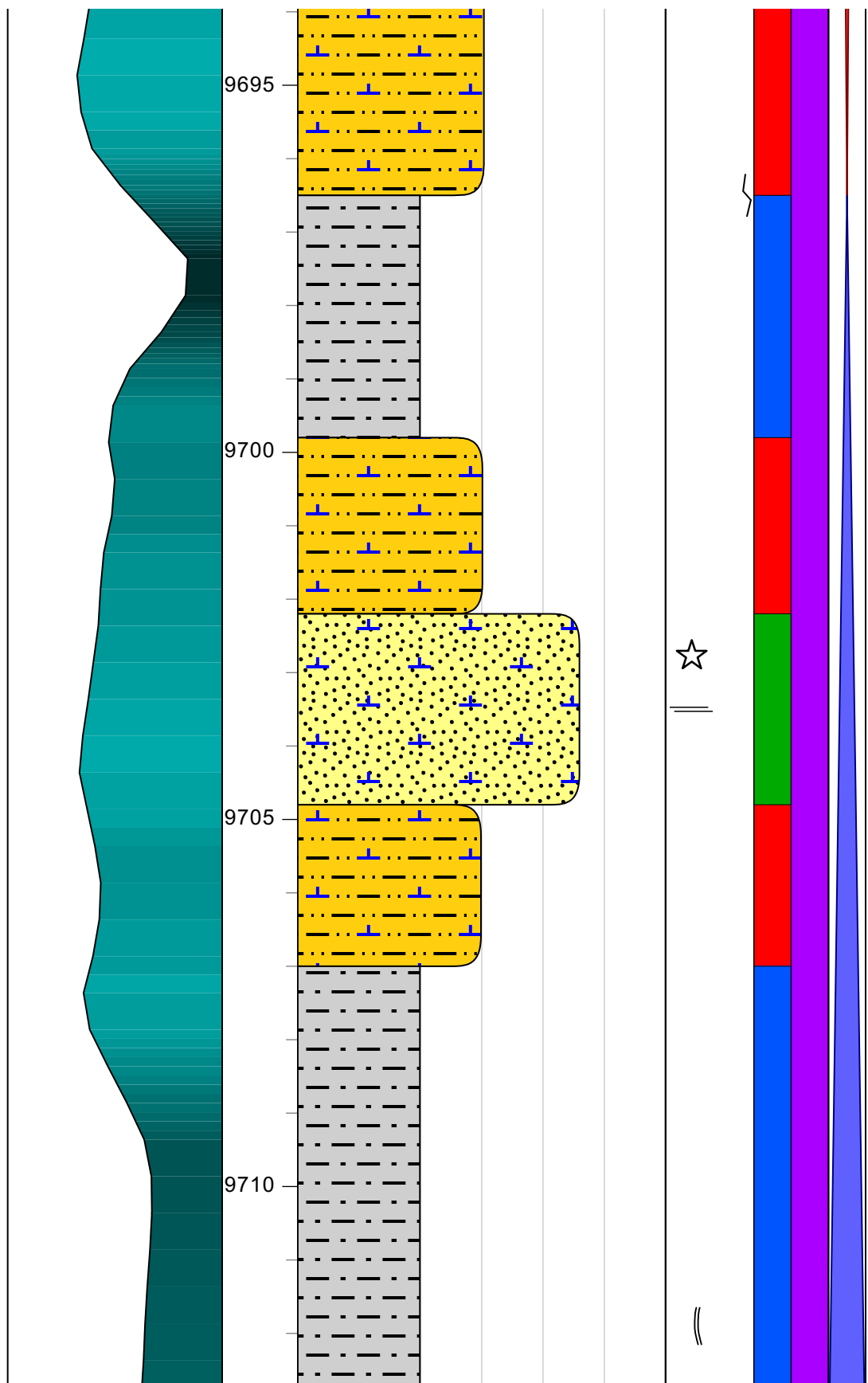
 Meramec zone 1	 Meramec zone 2	 Meramec zone 3
 Meramec zone 4	 Meramec zone 5	 Meramec zone 6

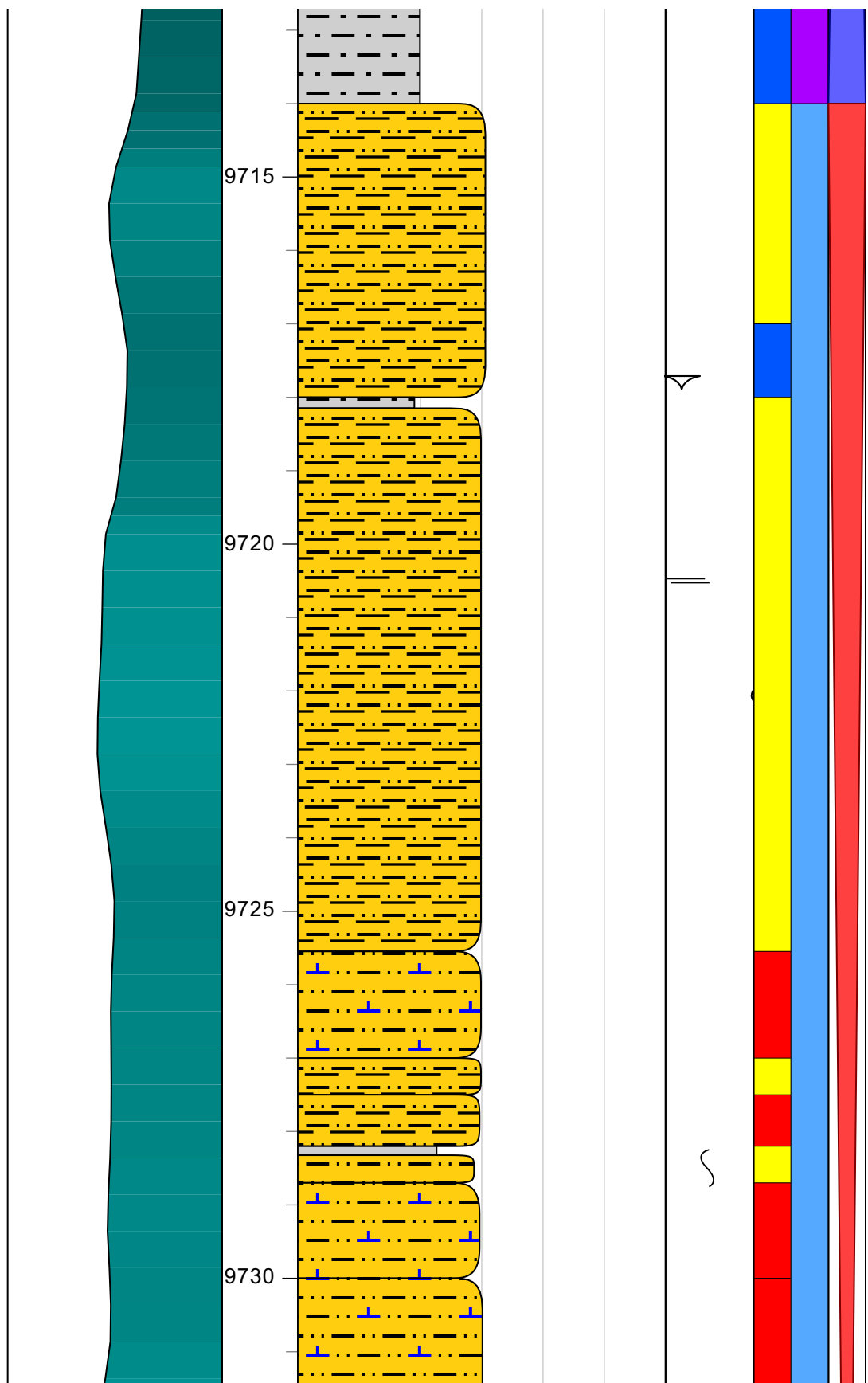
Seq Stratigraphy

 Shallowing	 Deepening
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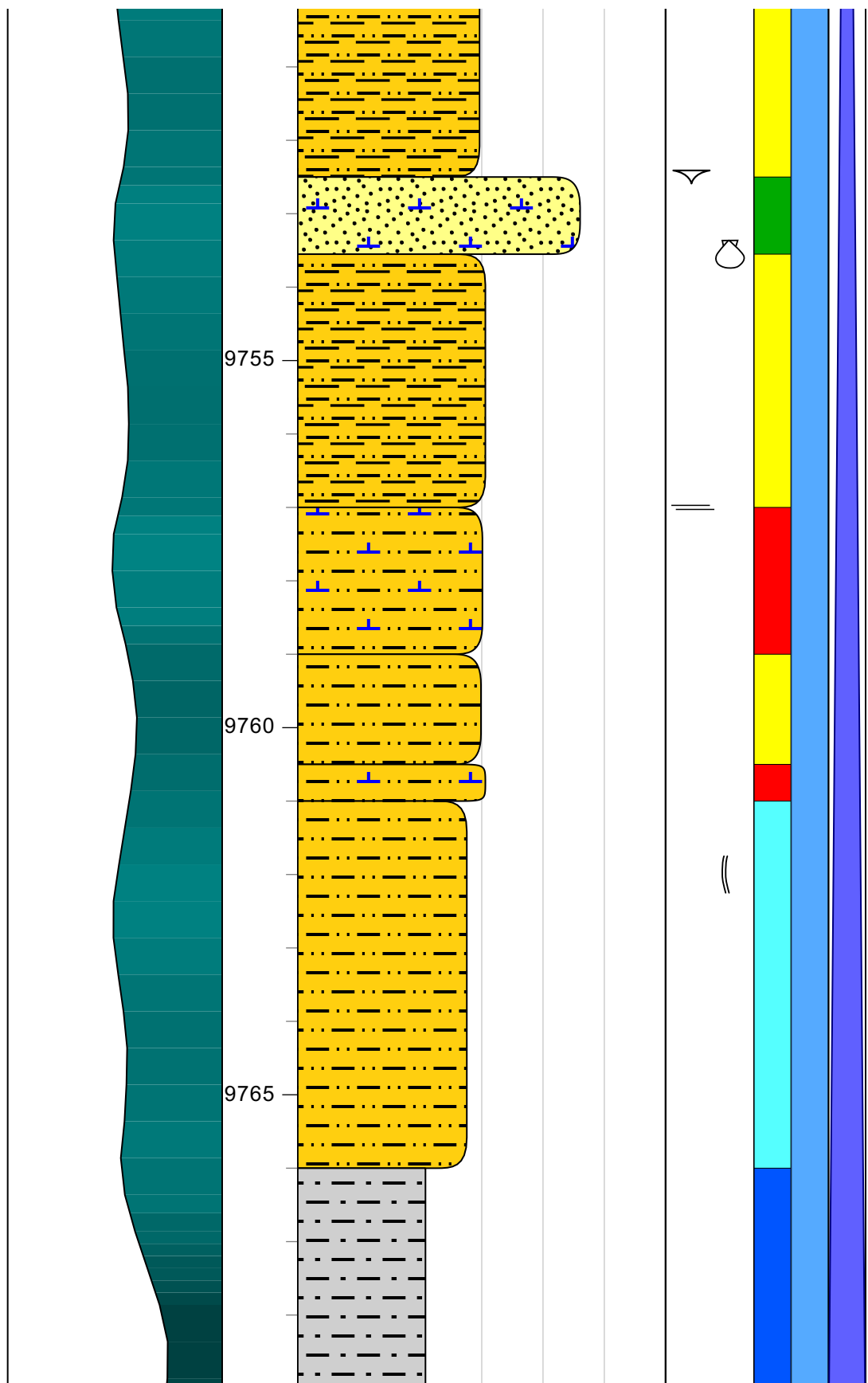


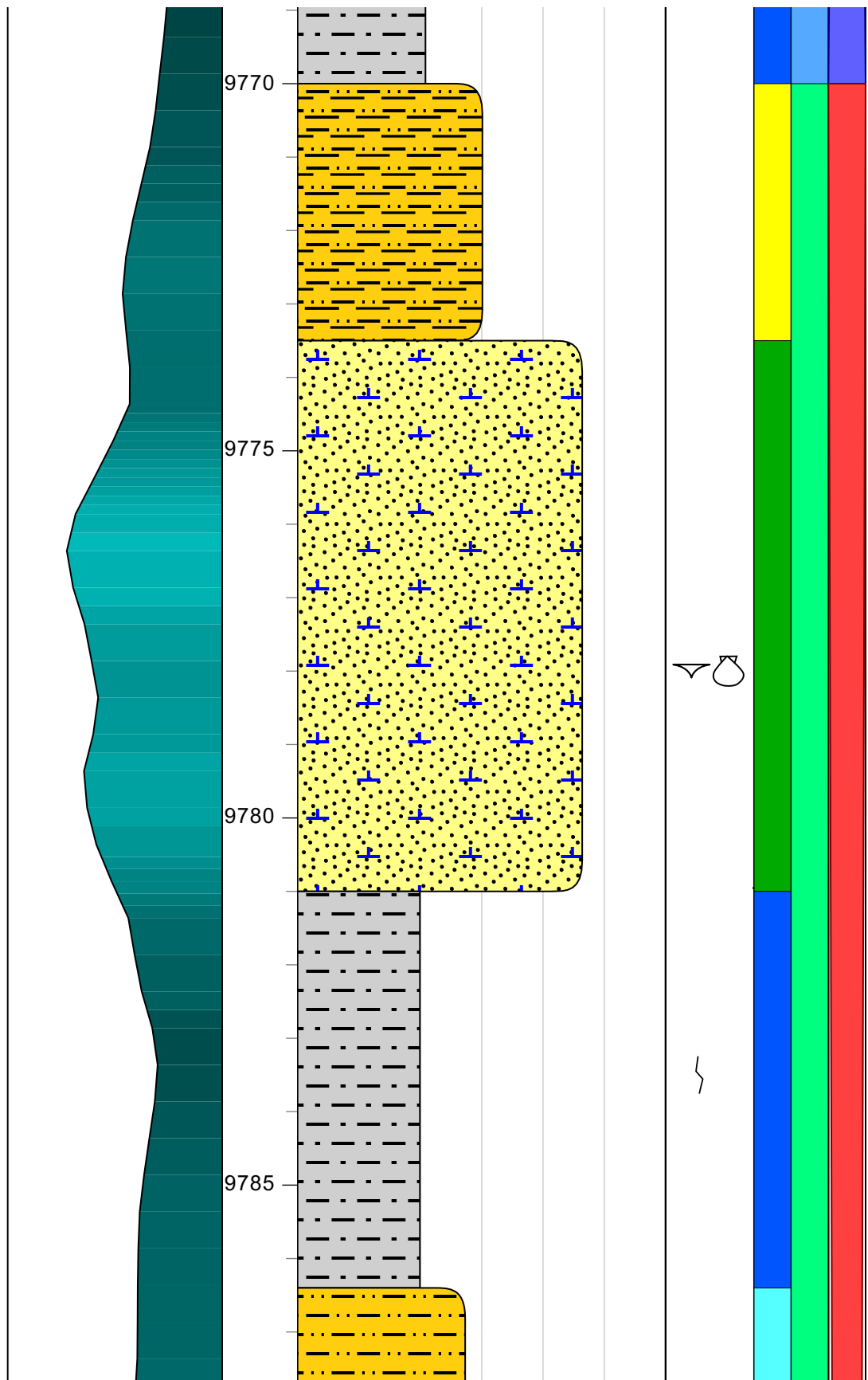


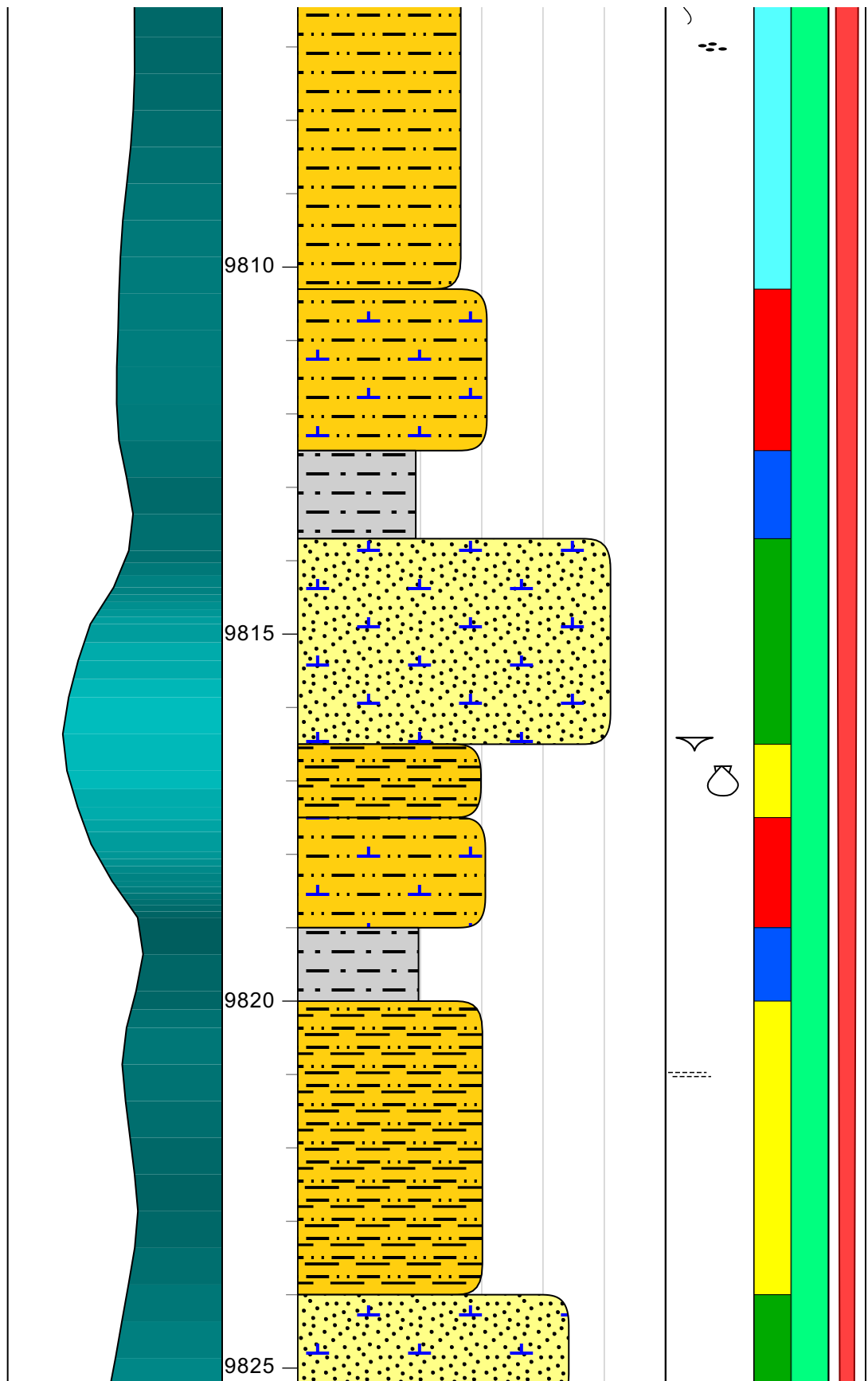


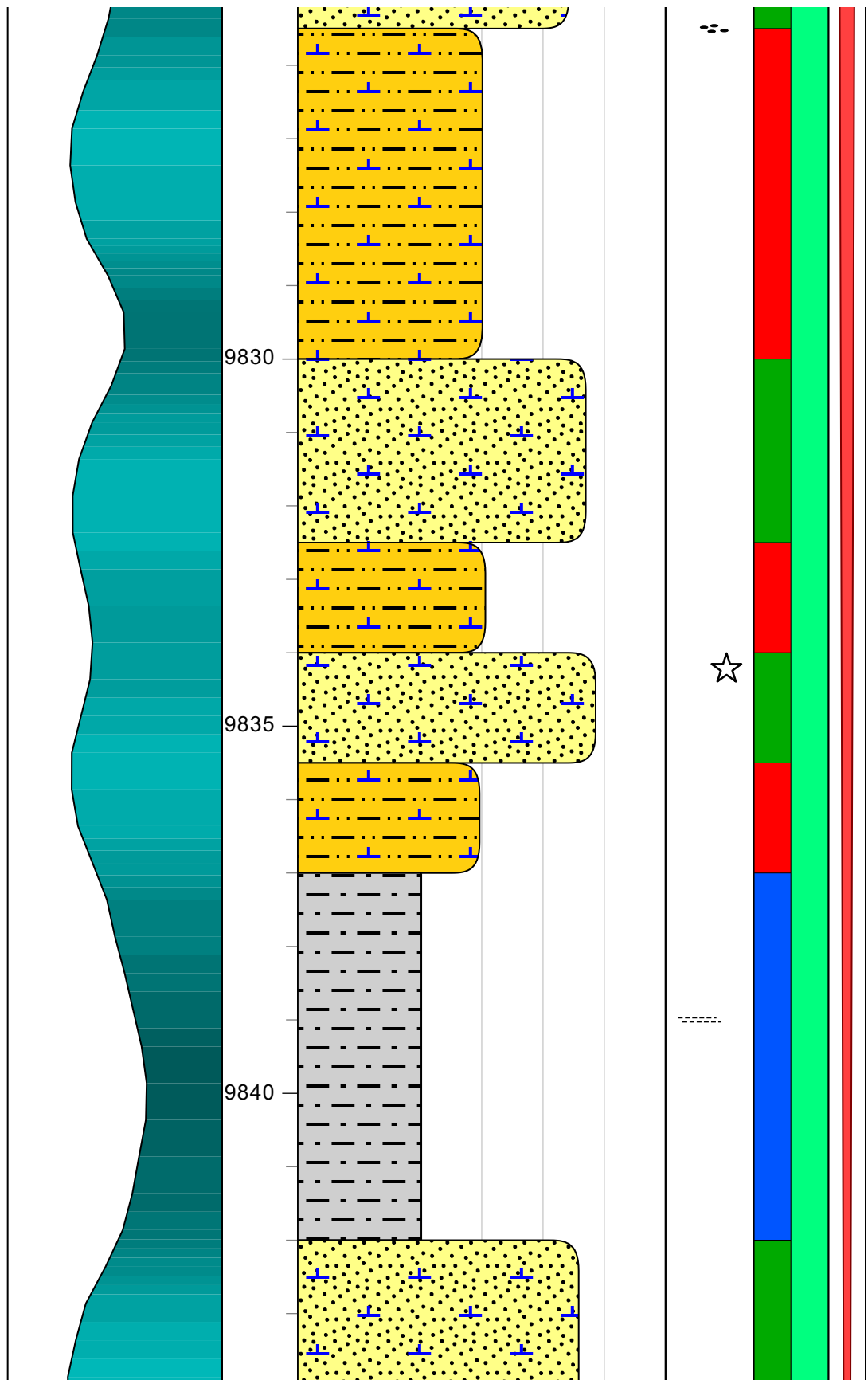


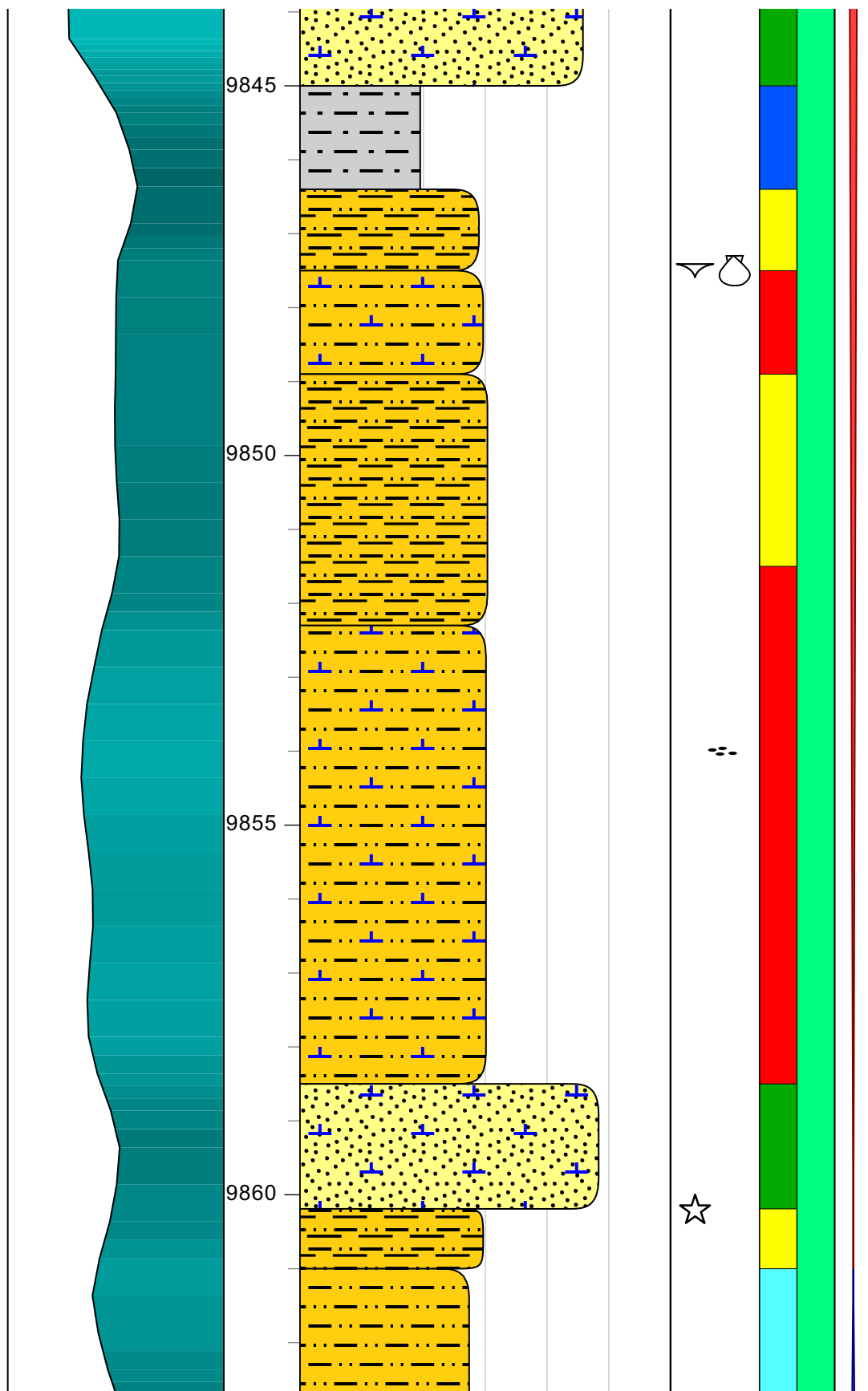




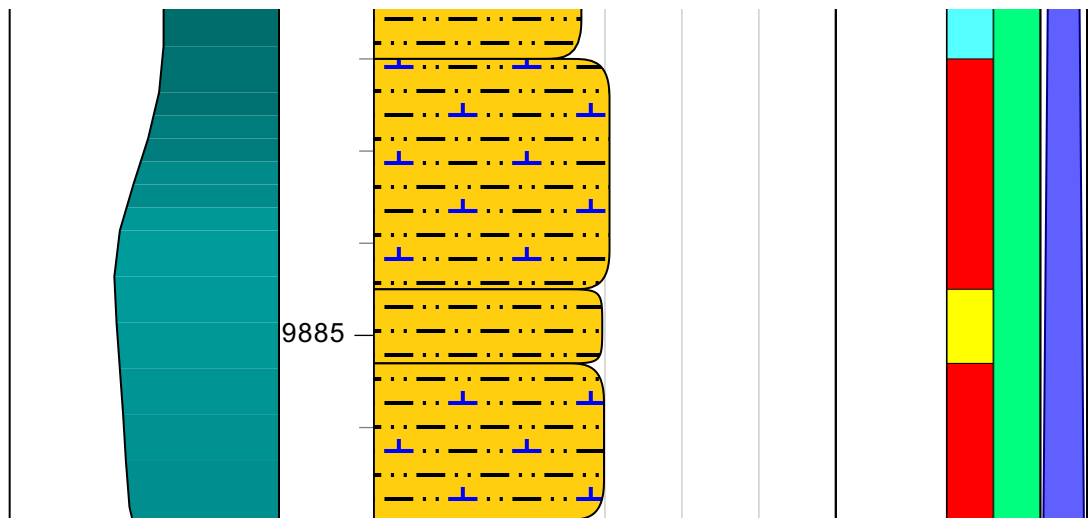












Operator Gulf Oil Corp	
Top 9714 ft	Bottom 9920.5 ft
Country United States	Well Name & No. Rohling 1-25
Location Blaine County, OK	Date Sat Feb 25 2017
Basin Anadarko	UWI No. 35011215690000
Field Omega South	KB 1220 ft
Latitude 35.8383013	Longitude -98.2211144

Lithologies

 Mudstone
  Sandstone
  Siltstone

Admixture

 Calcareous

Structure

 Bioturbated
  Planar Laminated

Contacts

 Straight

Accessories

 Shale Clasts

Fossils

 Brachiopods
  Bryozoans
  Crinoids

Sedimentary Structures

 Planar Lamination
  Trough Cross Lamination
  Wispy Lamination

Trace Fossils

 Bioturbation (undifferentiated)
  Skolithos
  Zoophycos

Facies

 Agrillaceous Siltstone
  Bioturbated siltstone
  Calcareous Sandstone

 Calcareous Siltstone
  Silty Mudstone

Zones

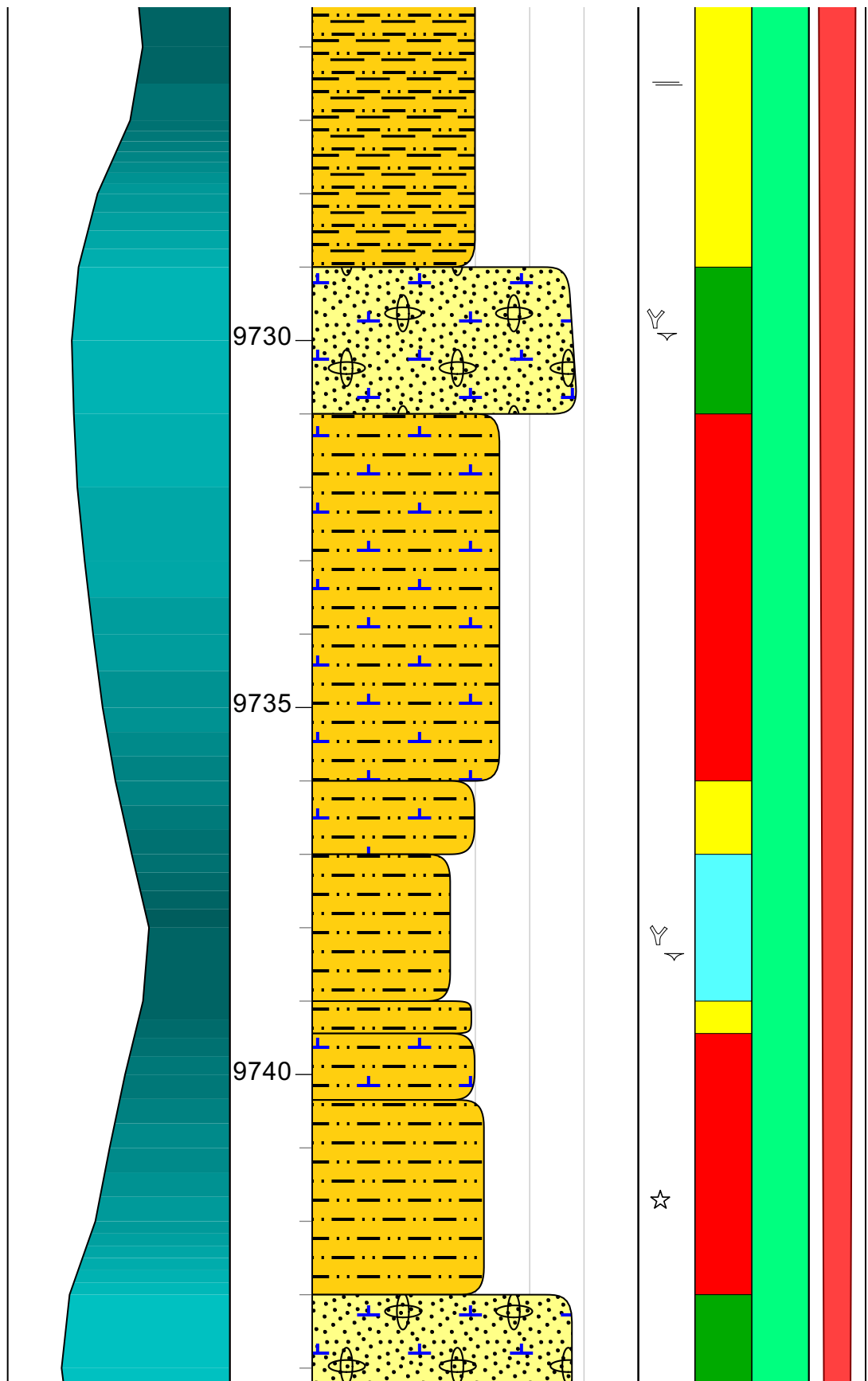
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  Meramec zone 2
  Meramec zone 3

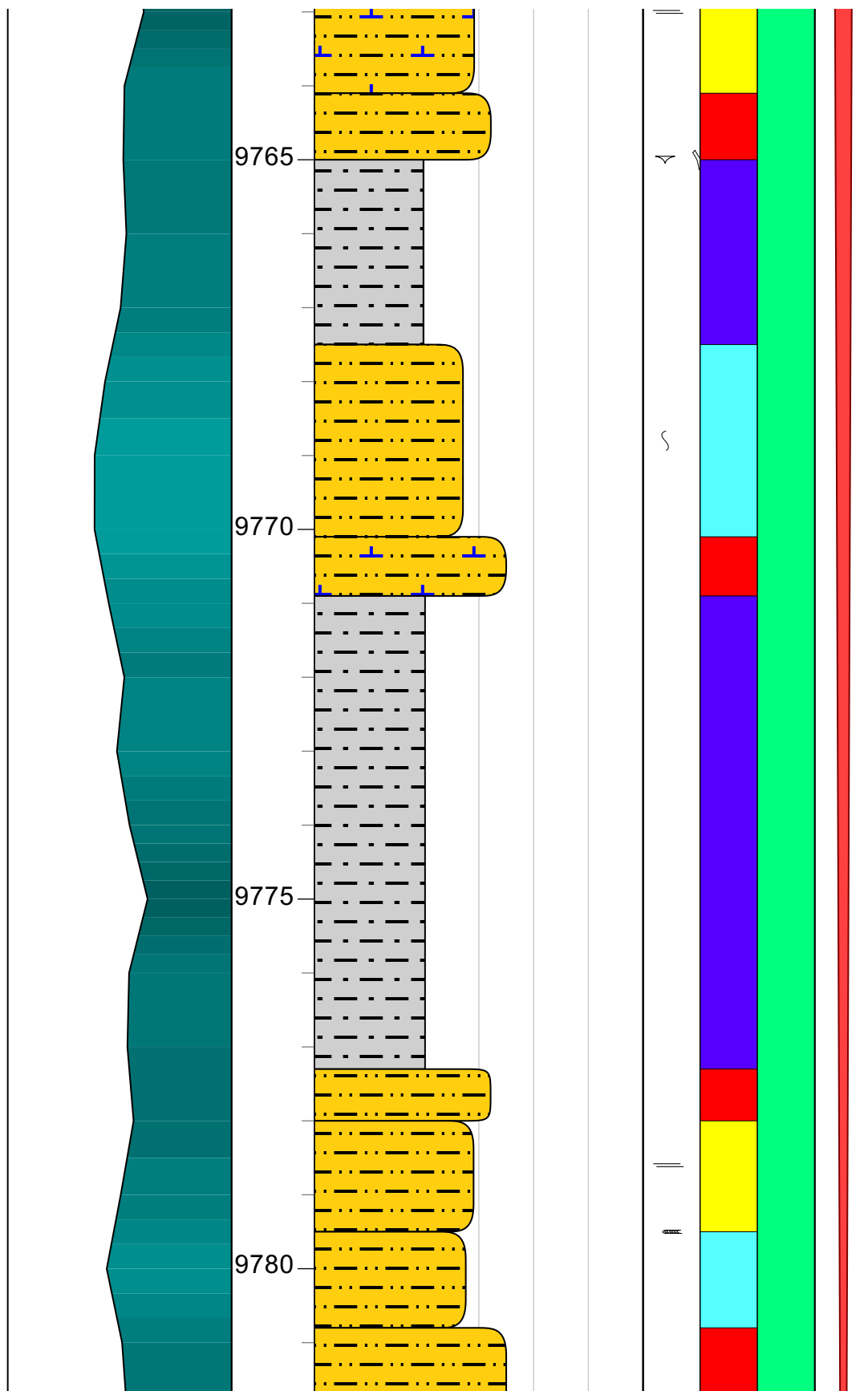
 Meramec zone 4
  Meramec zone 5
  Meramec zone 6

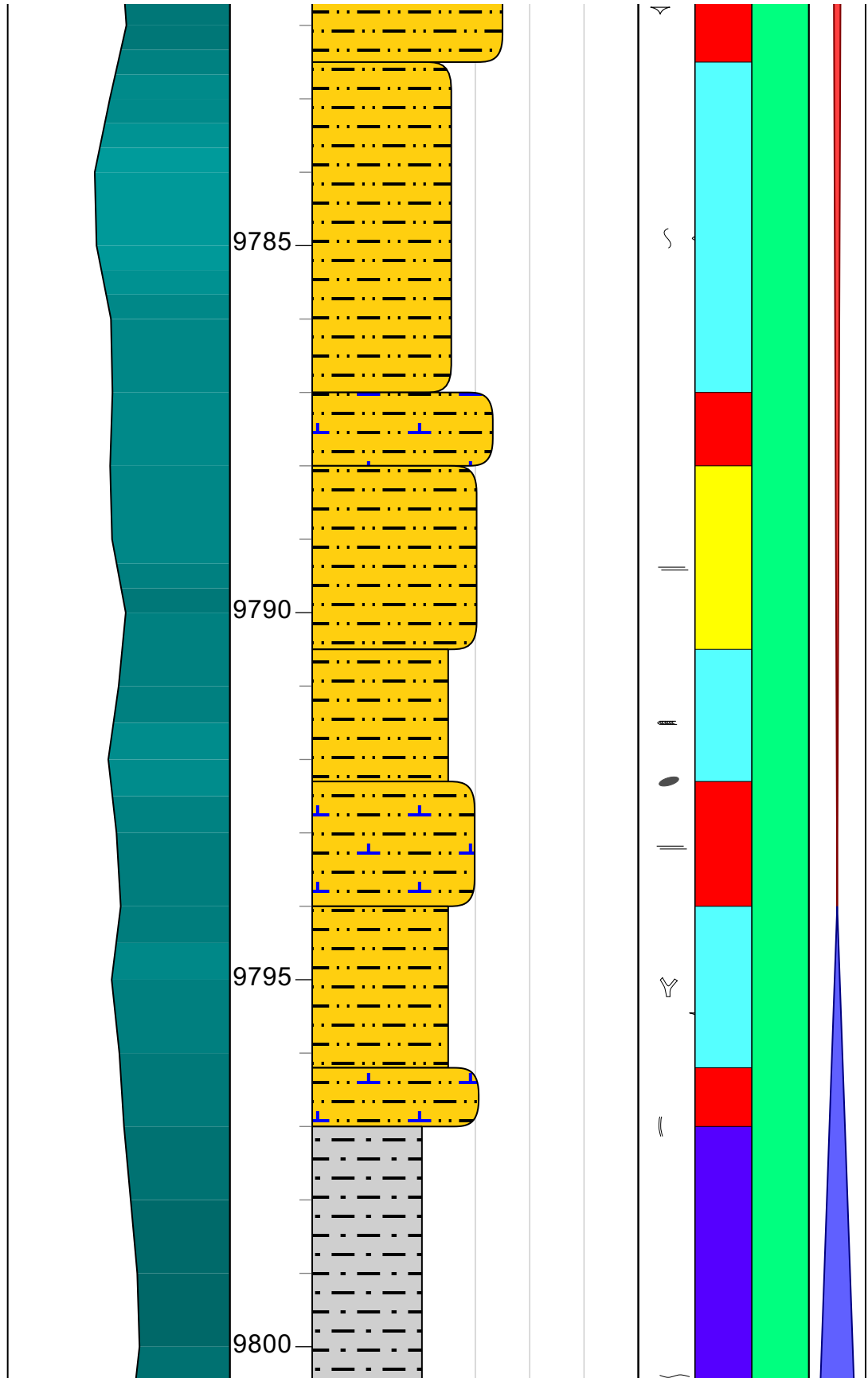
 Osage

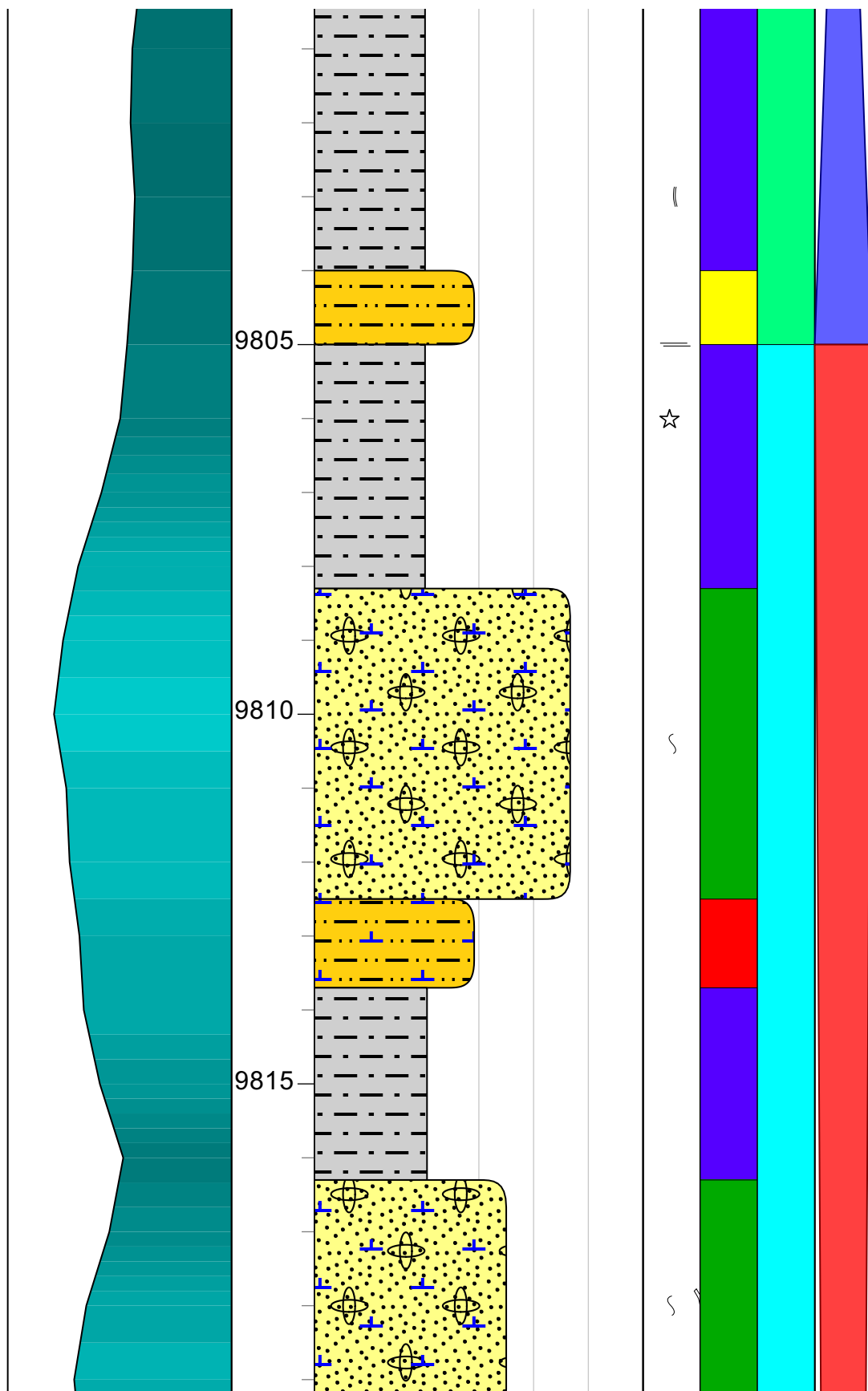
Sequence

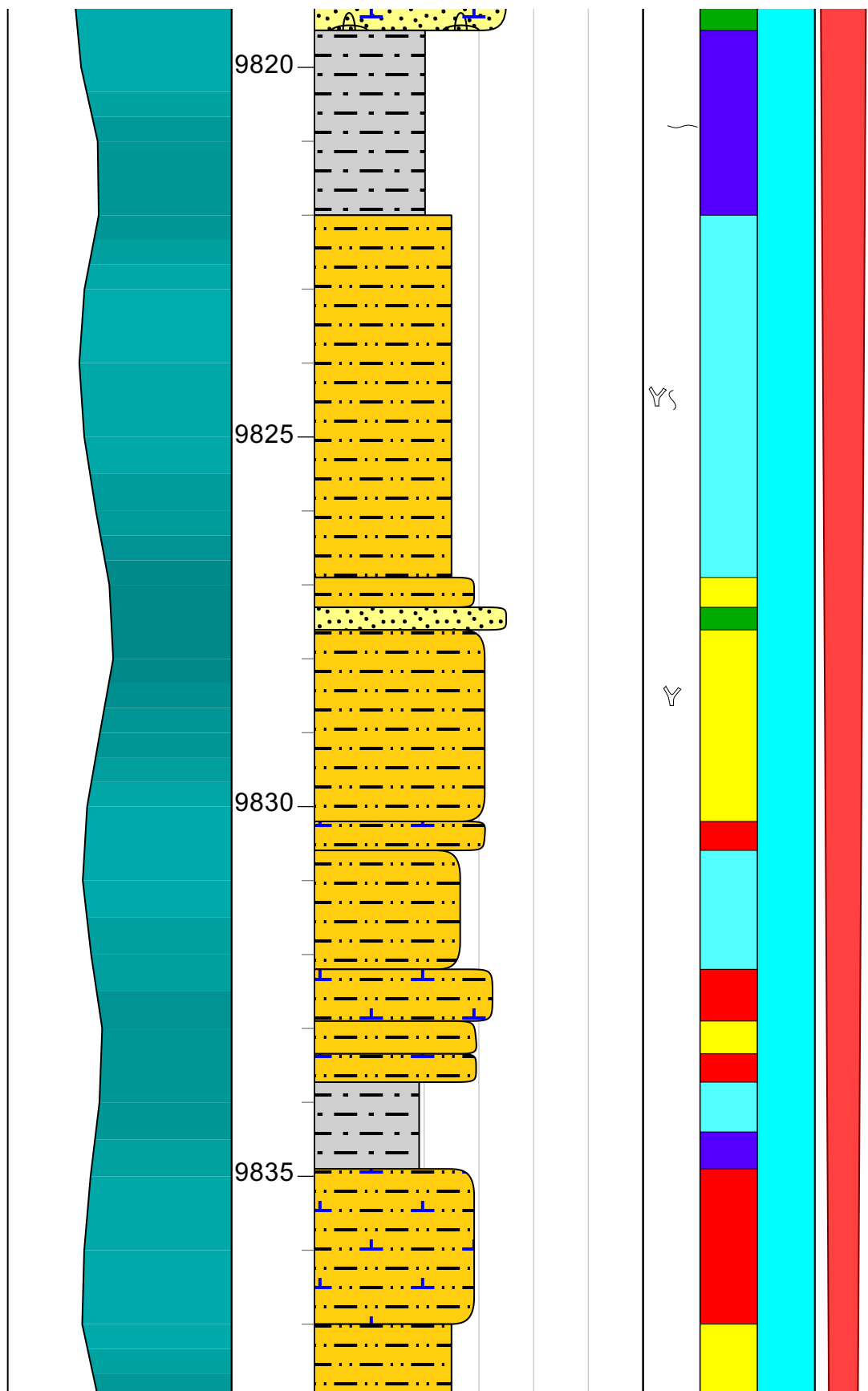
 Shallowing
  Deepening

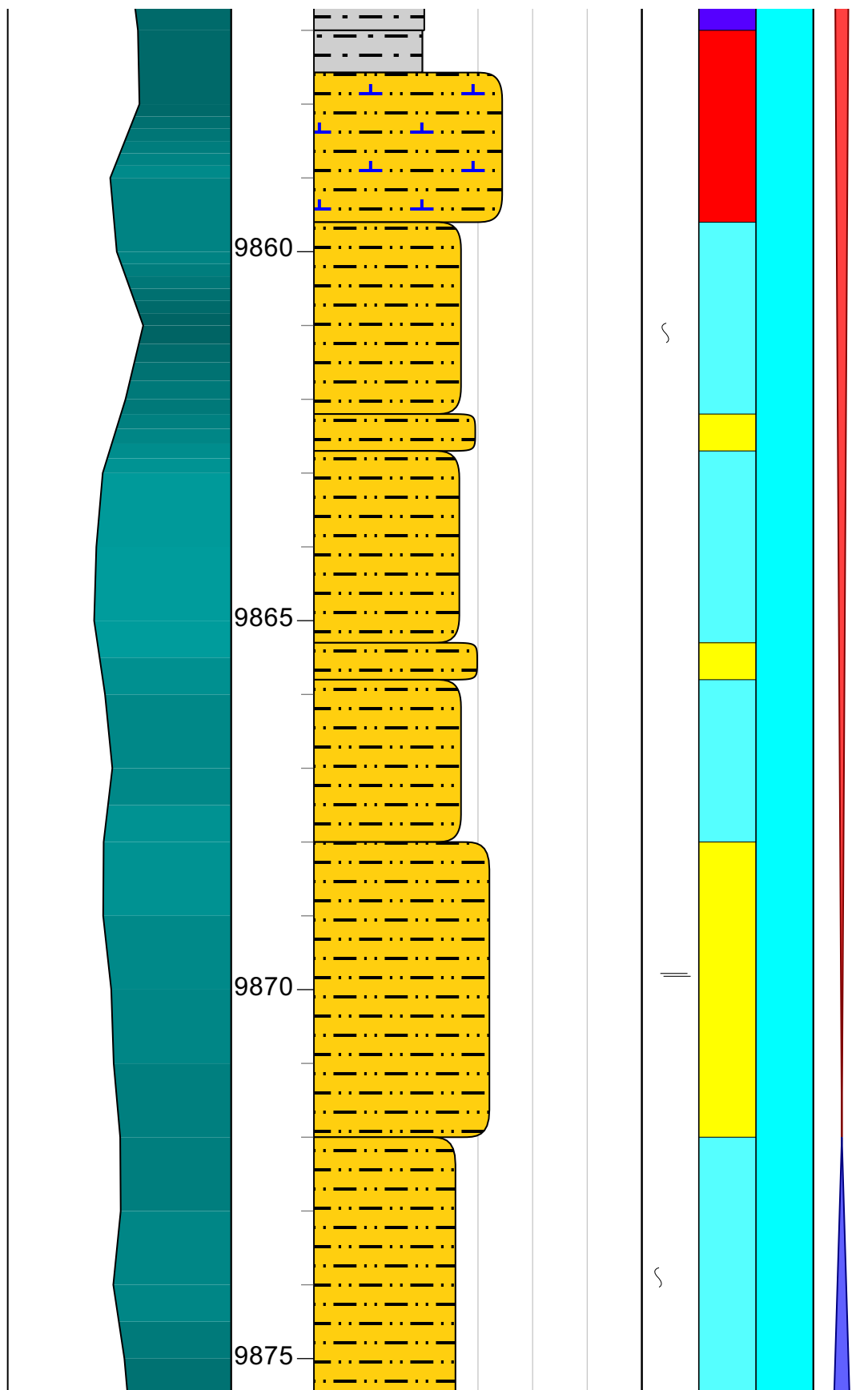


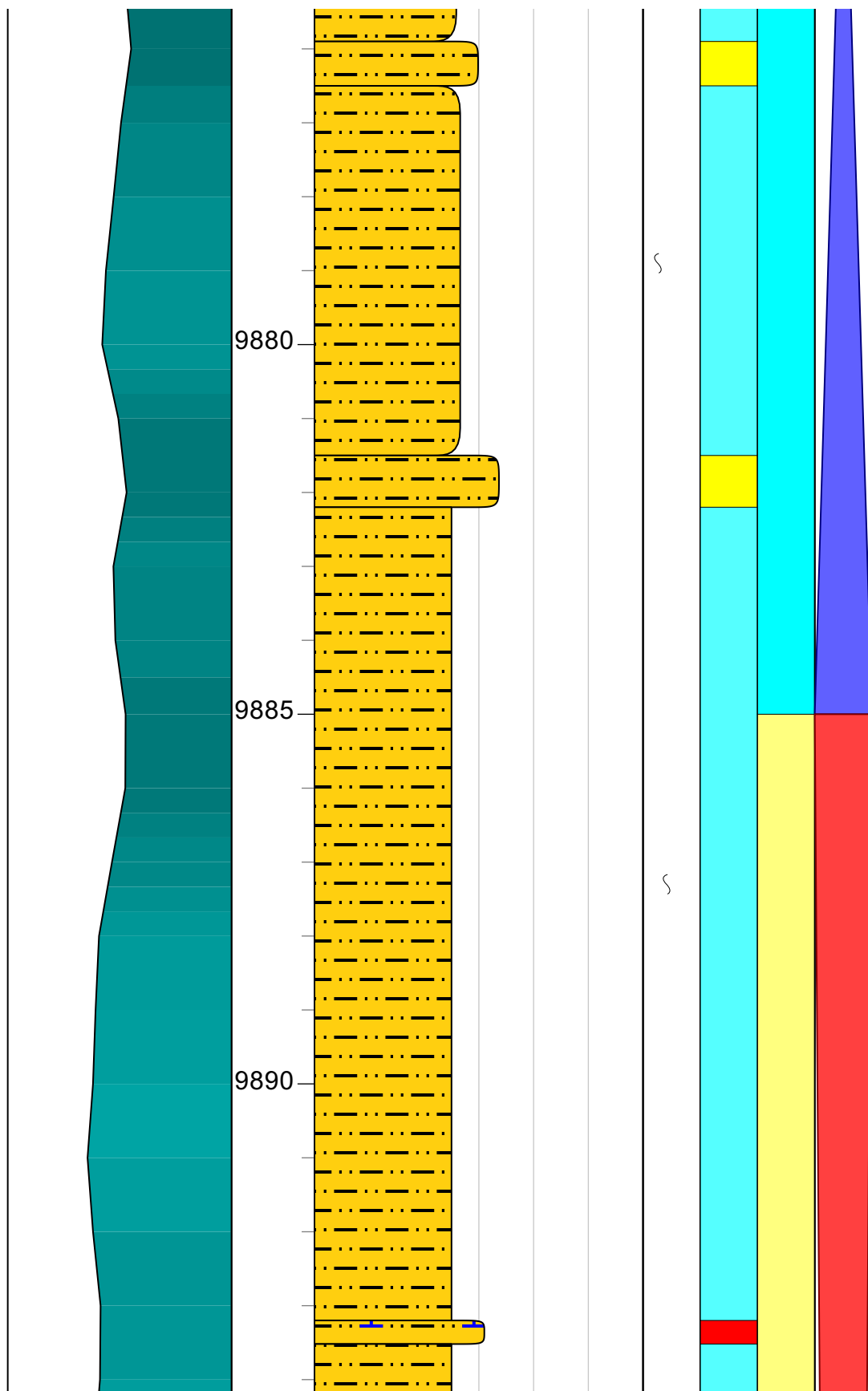


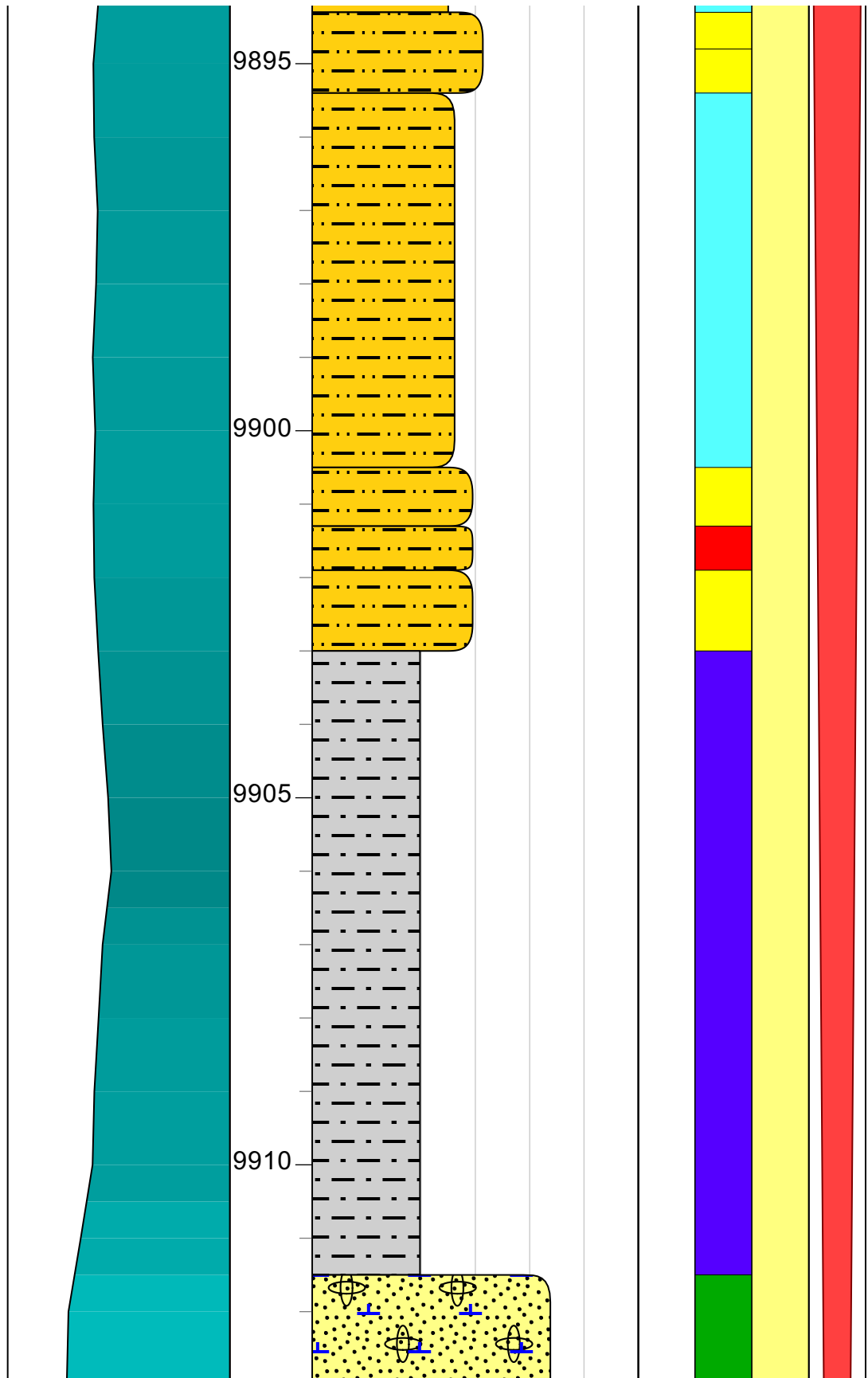


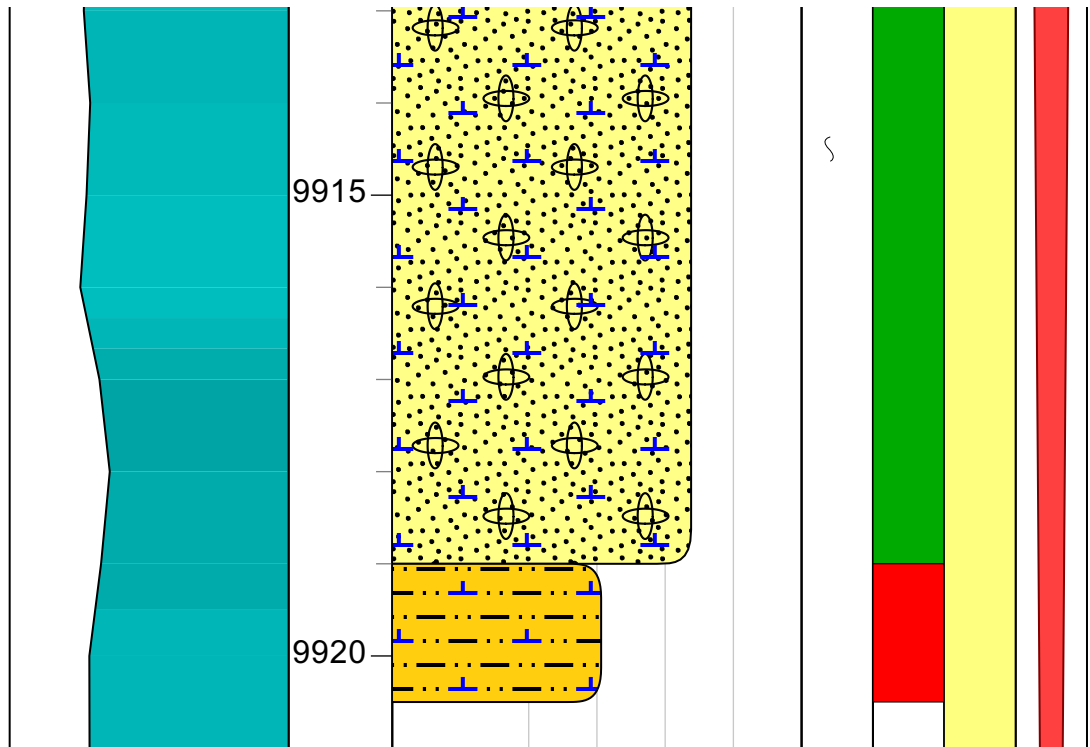




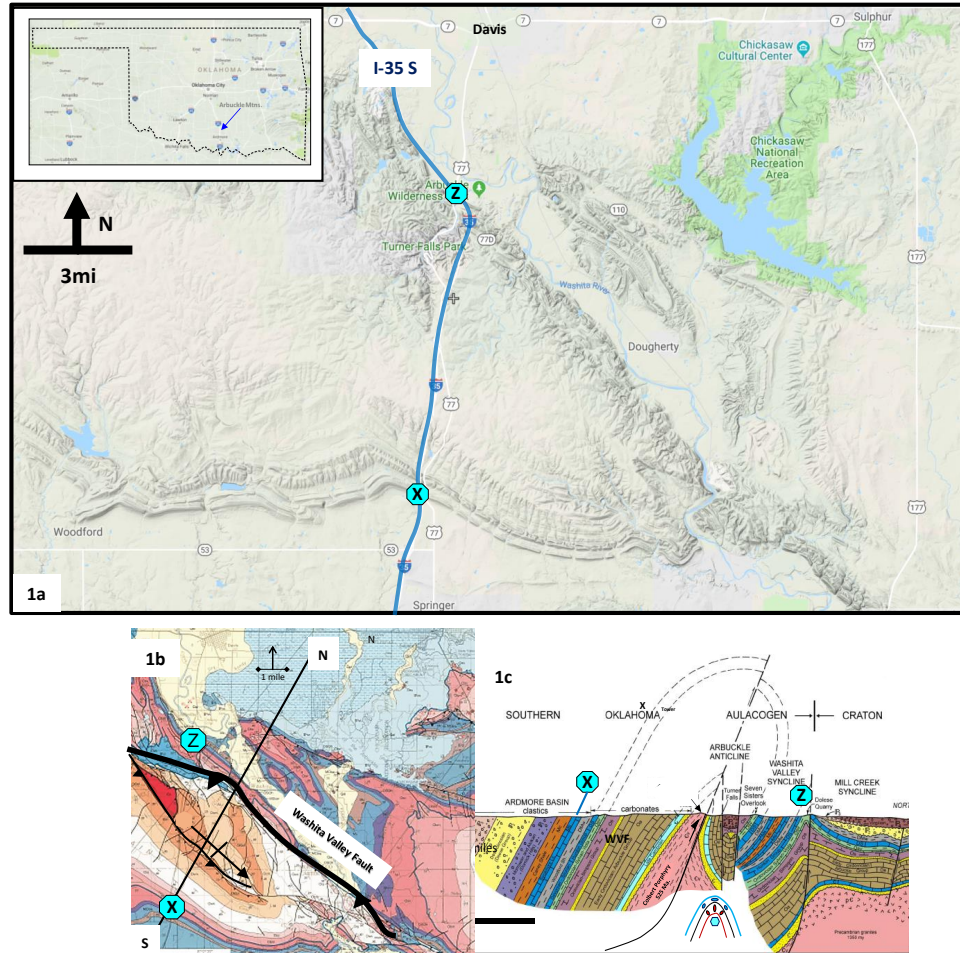




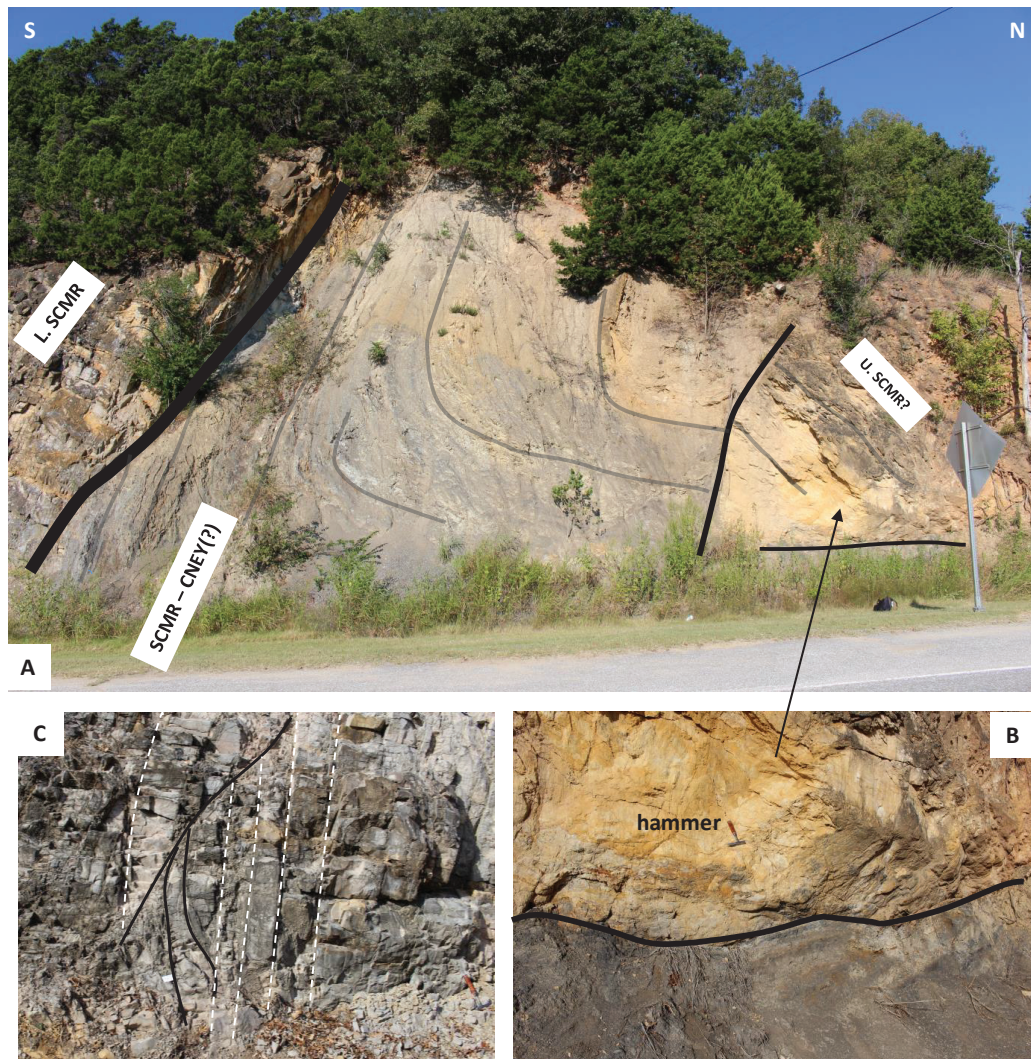




APPENDIX B: Sycamore Outcrops



Appendix B-1. a) Location map. X marks main outcrop Sycamore on I-35 South at the last ridge on south limb of Arbuckle Anticline b) Geological map of Arbuckle Mountains (Ham et al., 1954, revised by Johnson, K., 1990) c) Cross section through across Arbuckle Anticline (Ham et al., 1954, revised by Johnson, K., 1990)



Appendix B-2. (A) Arbuckle Fried Pies Outcrop (Z) west side of Highway 77: Overturned Sycamore beds with bedding plane fault contact within the Sycamore (possibly with the Caney). Bedding planes are in light gray, faults in black lines.

Appendix B-3. Stratigraphy of the Sycamore.

The common lithologic moniker of the Sycamore Formation as the Sycamore Limestone is somewhat misleading because the limestone beds are markedly silt-rich. Petrographic analysis shows the Sycamore Formation is better treated as a mixed siliciclastic-carbonate system with some samples being predominantly composed of silt-sized quartz grains and others being predominantly micritic calcite and carbonate shell fragments. The distinction between silty limestone and calcareous siltstones is not discernible in hand sample and thin section sampling was too sparse to distinguish each bed, so it is simply referred to as a calcareous siltstone herein.

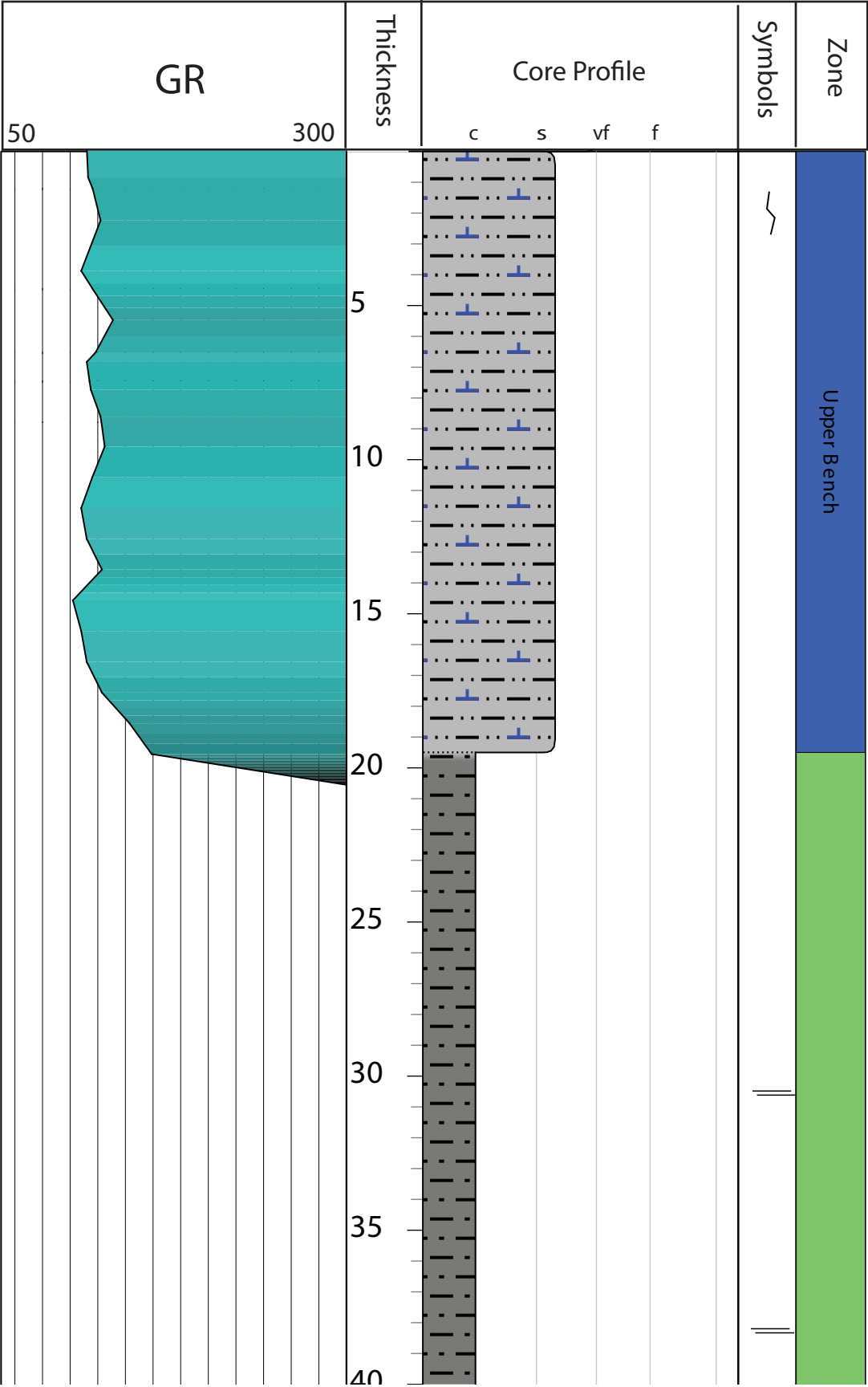
The basal transition zone (85 ft [26 m]) unconformably overlies the Woodford Shale and weathers into a slope and composed of mostly interbedded fissile shales with some high-relief calcareous siltstones and cherty mudstones. The lower bench (30 ft [9 m]) is composed of thick-bedded calcareous siltstones often separated by thin shale interbeds, and some of the calcareous siltstone beds display horizontal and wavy laminations at their tops. The lower shale (26 ft [8 m]) is mostly covered, composed of weathered fissile shales and several thick calcareous siltstone beds.

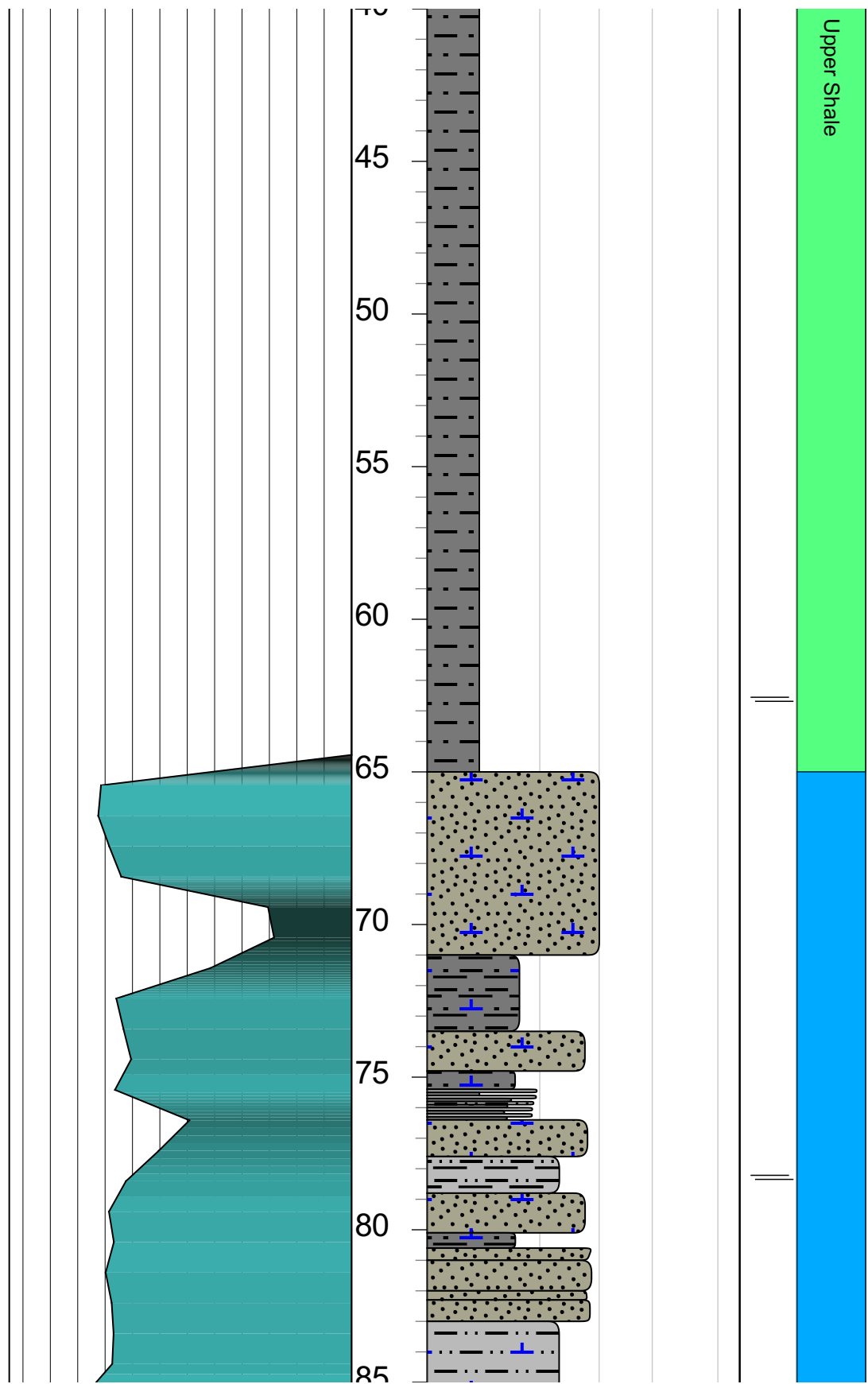
The middle bench is the thickest zone (121 ft [37 m]), creating the prominent relief along the Sycamore ridge. It is composed of alternatively thick and thin-bedded calcareous siltstones that are separated by thin shale laminations. The uppermost beds possess more abundant silt-sized quartz grains, representing an overall coarsening-upwards sequence throughout this zone. Many of the beds possess the fining-upwards Bouma Ta to Te sequence. The upper shale zone (45.5 ft [13.7 m]) is composed of medium grey fissile shales and is mostly covered. The upper bench (19.5 ft [6 m]) is a

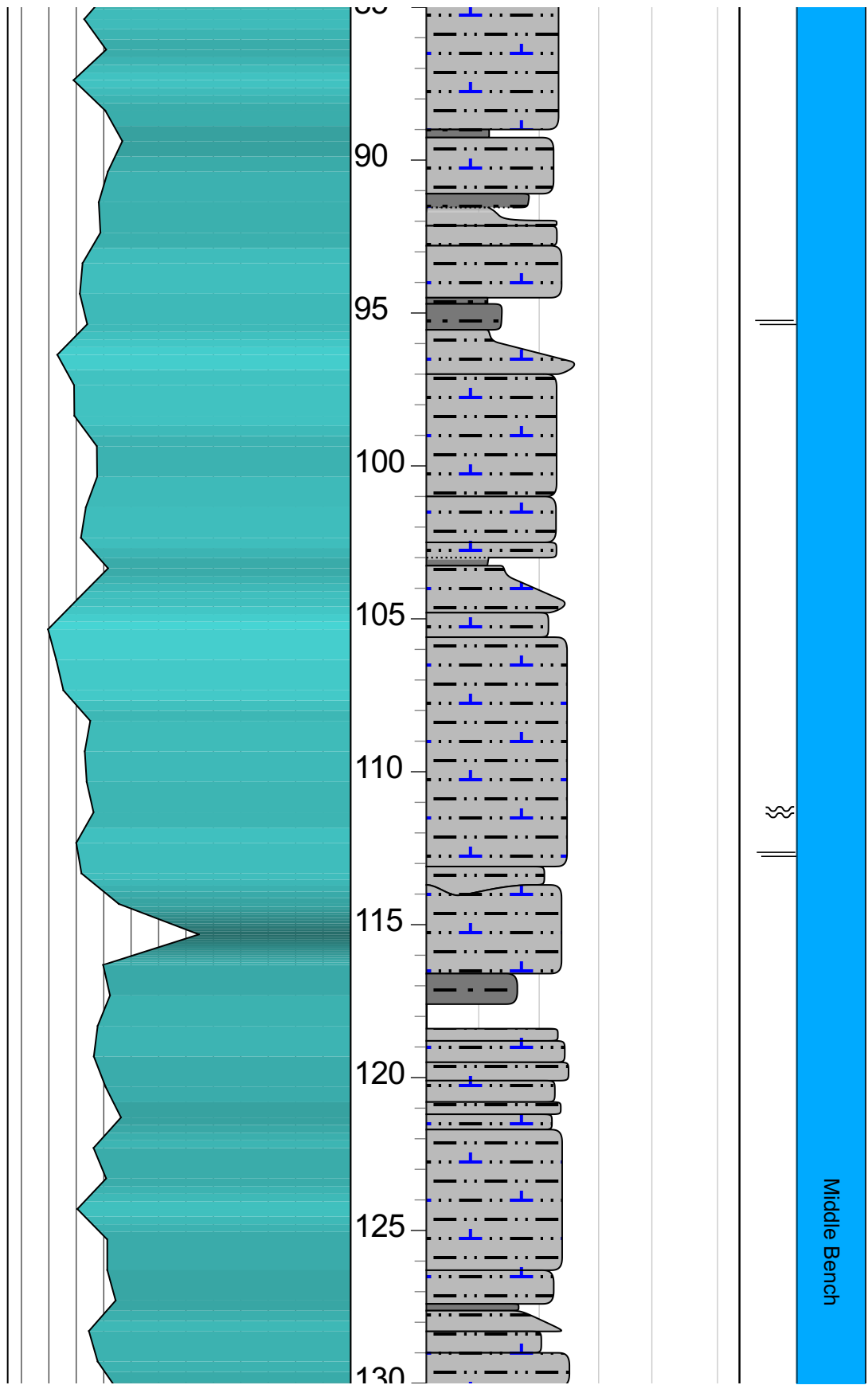
large block of poorly bedded, monolithic, calcareous siltstone. Thin sections show this interval is richer in silt and leaner in carbonate than the siltstones of the lower and middle benches (Appendix C). In addition to silt-sized quartz grains and carbonate cement are accessory microcline, sodic plagioclase ($An < 30$ from Michel-Levy extinction), muscovite, and rare zircon.

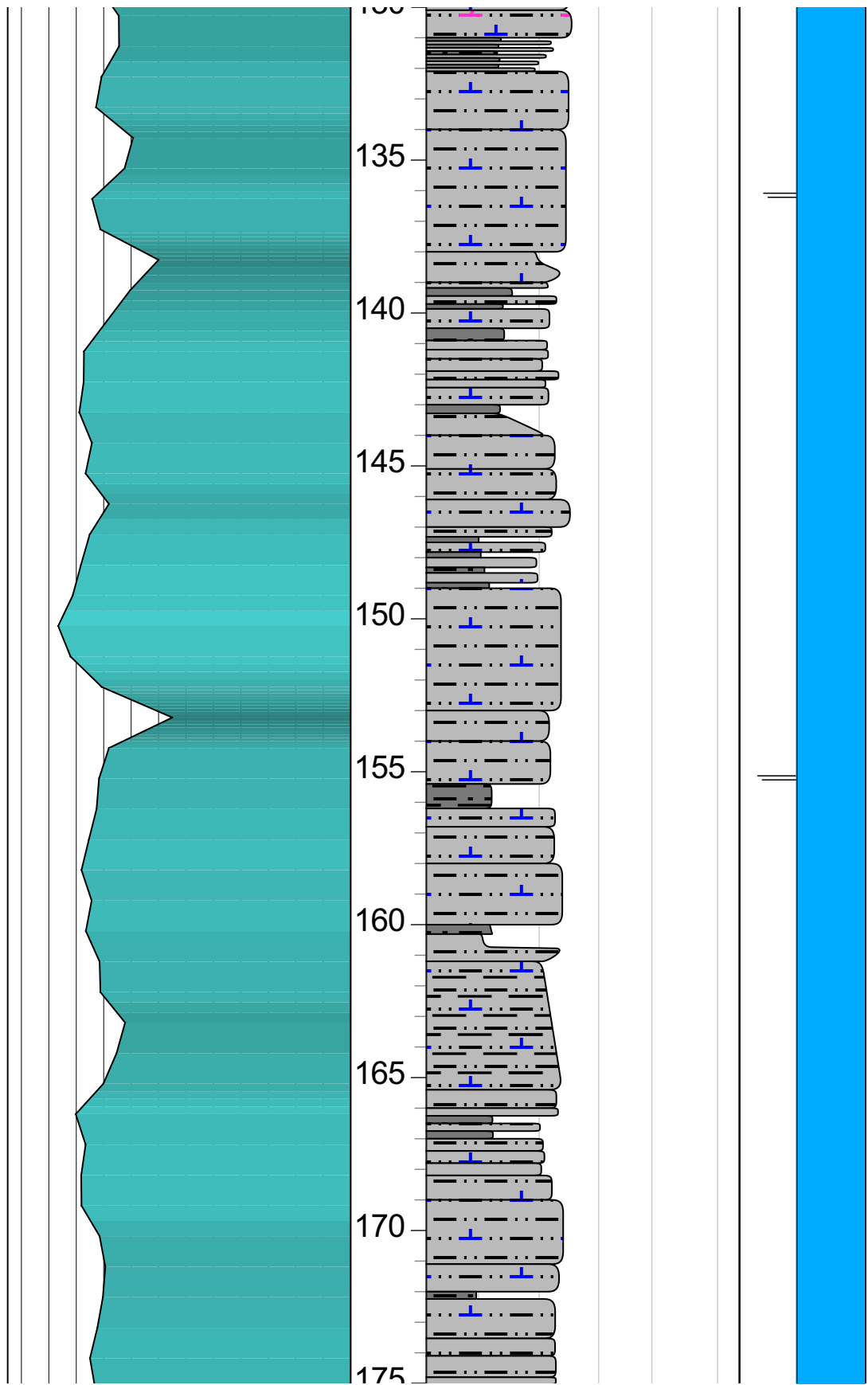
Outcrop Z is located on the overturned front limb of the Arbuckle Anticline. At this outcrop, regional dip is approximately 75° to the south (Appendix B-1). Local structural complications, expressed as rotated blocks and several minor faults (Appendix B-2), limit the usefulness of this outcrop in stratigraphic studies. There is no published literature on this outcrop. The shale interval below the main Sycamore Formation exposure is interpreted as the upper shale unit as defined on the ridge to the east of I-35 (Fay, 1989), and the large “floating” block of calcareous siltstone (Appendix B-2) on the northern limit of this outcrop is interpreted as the upper Sycamore unit. There is substantial intra-bed deformation and bed-parallel shortening in the Sycamore at this outcrop. Thus, outcrop Z appears to record an episode of strong low-angle-to-bedding parallel deformation that predates folding of the Arbuckle anticline.

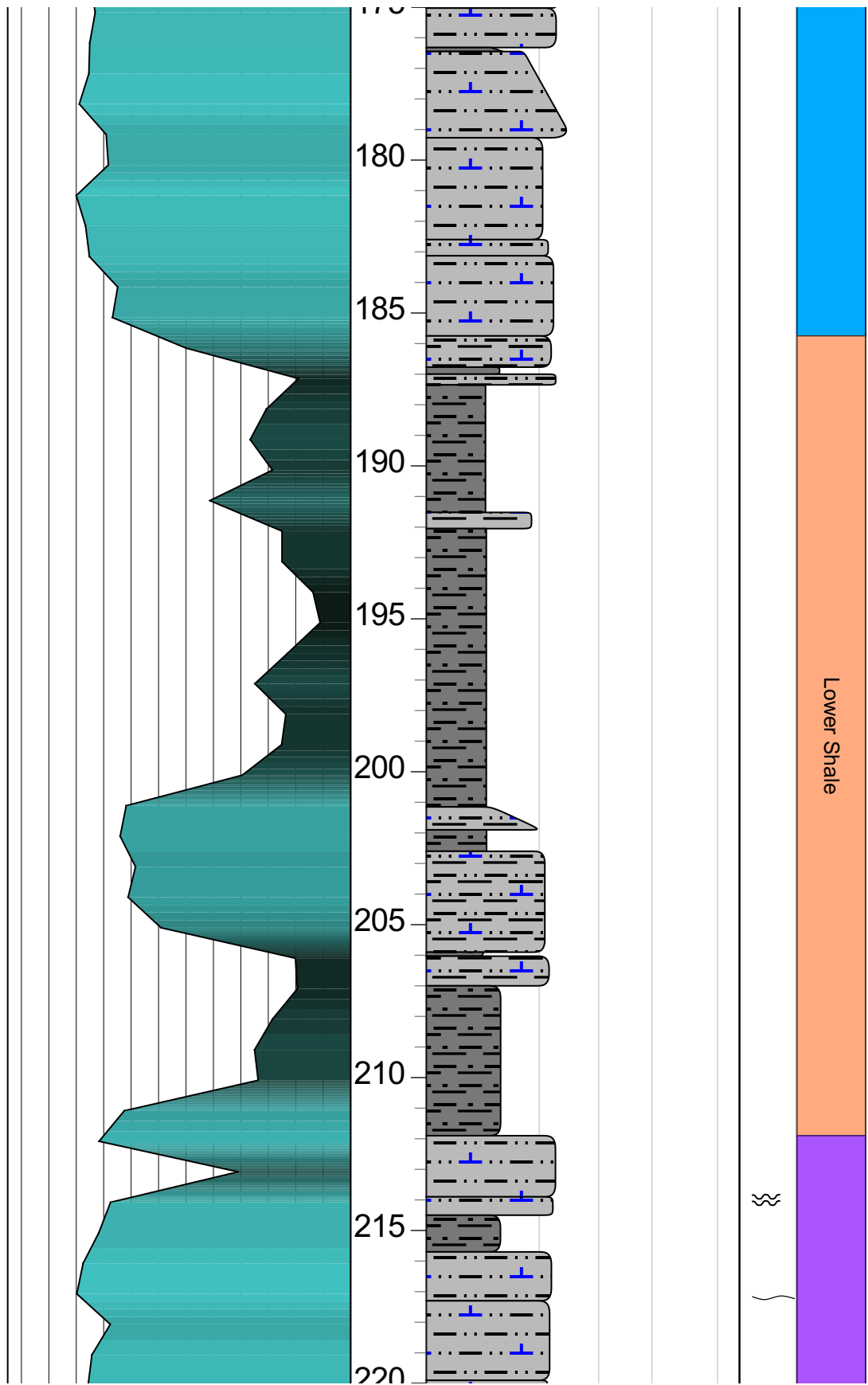
Top 0 ft	Bottom 327 ft
Country United States	Well Name & No. Outcrop X
Location Carter County, OK	Date Sun Nov 19 2017
Elevation 1000 ft	Latitude 34.3519433
Longitude -97.1488799	
<u>Lithologies</u>  Chert  Claystone  Mudstone  Sandstone  Siltstone <u>Admixture</u>  Calcareous  Dolomitic <u>Structure</u>  Faintly Laminated  Planar Laminated <u>Contacts</u>  Straight  Scoured  Gradational <u>Accessories</u>  Cemented Fractures  Nodules <u>Sedimentary Structures</u>  Parallel Wavy Bedding  Planar Lamination  Wispy Lamination <u>Zones</u>  Lower Bench  Lower Shale  Middle Bench  Transition Zone  Upper Bench  Upper Shale	

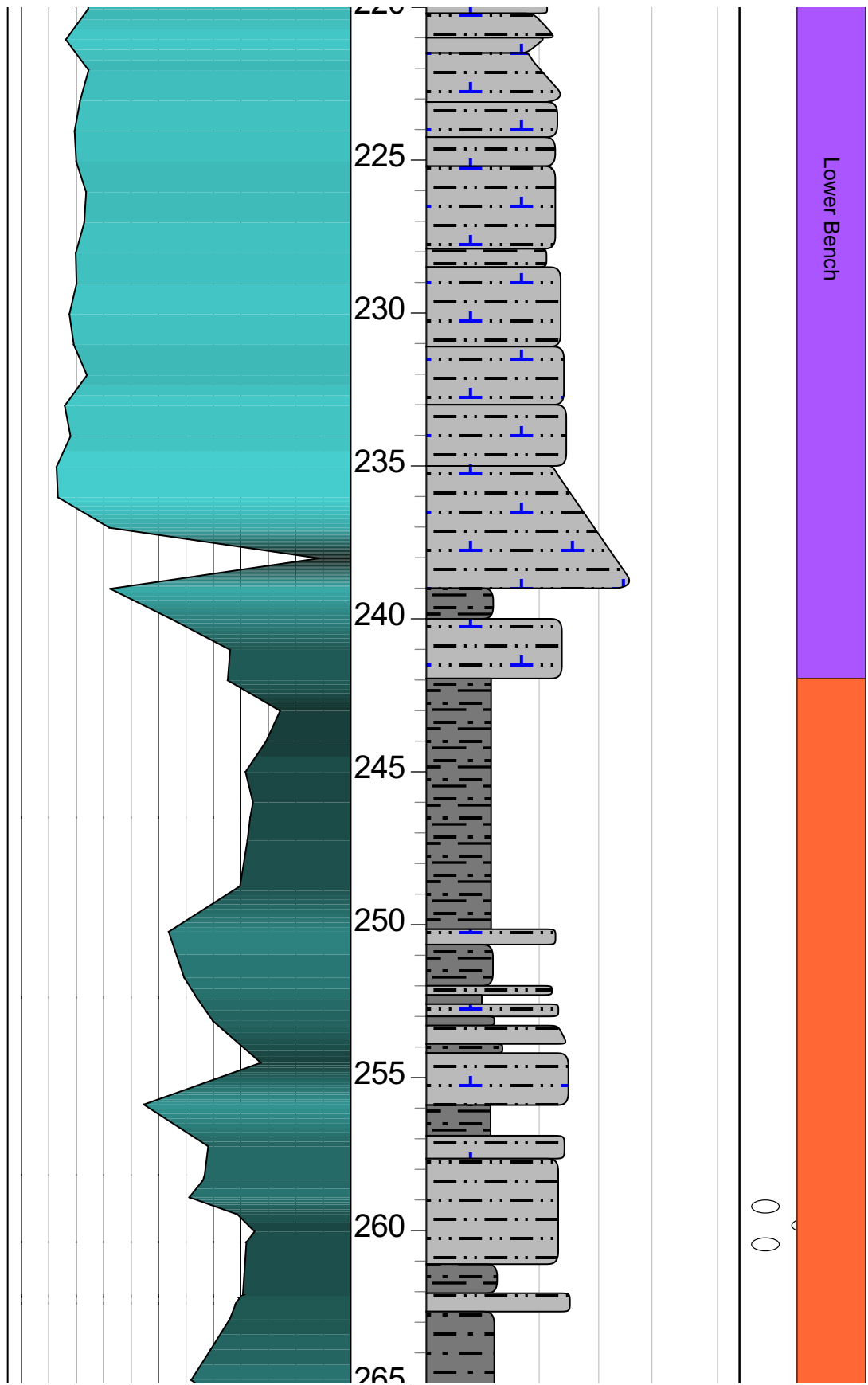


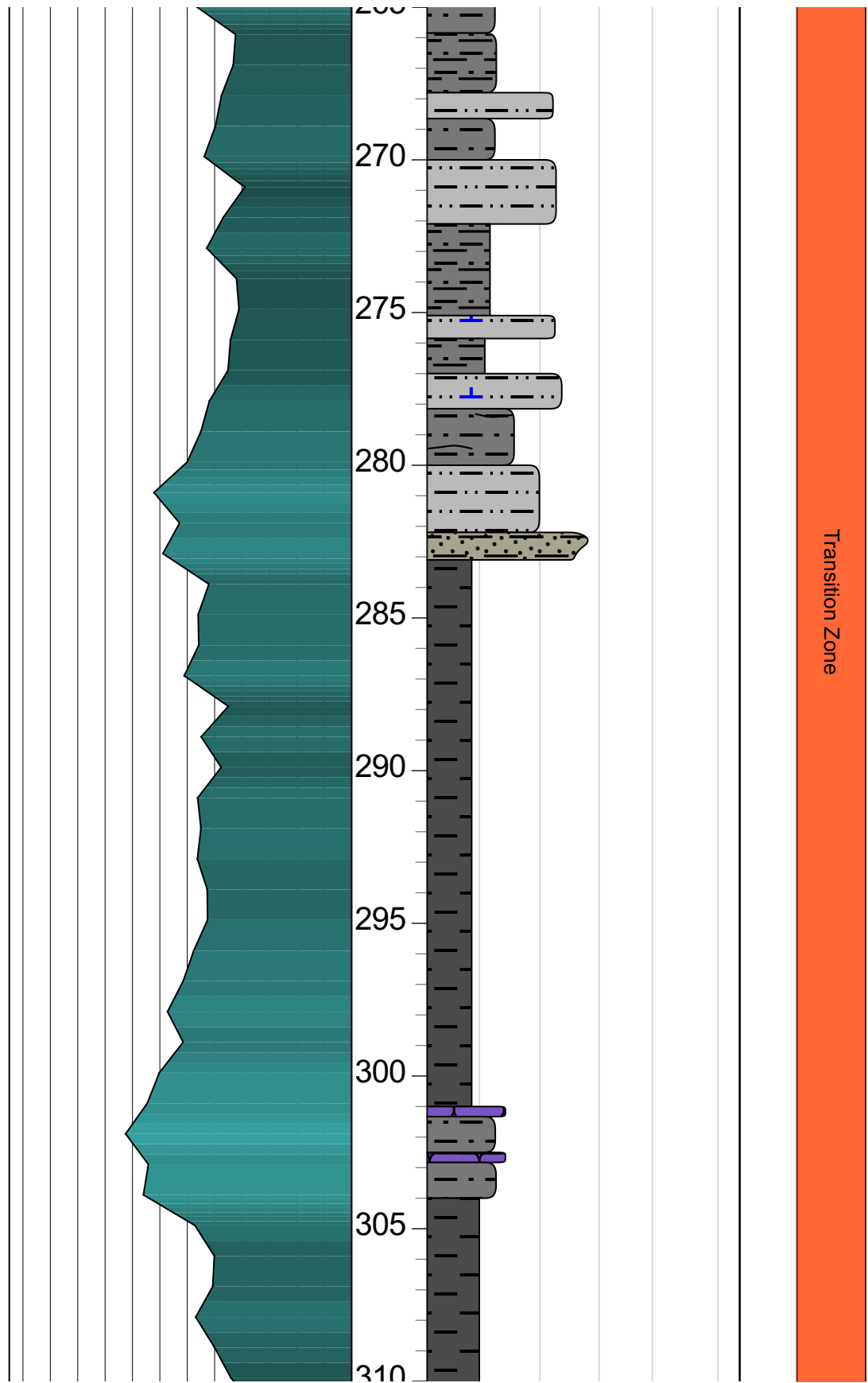


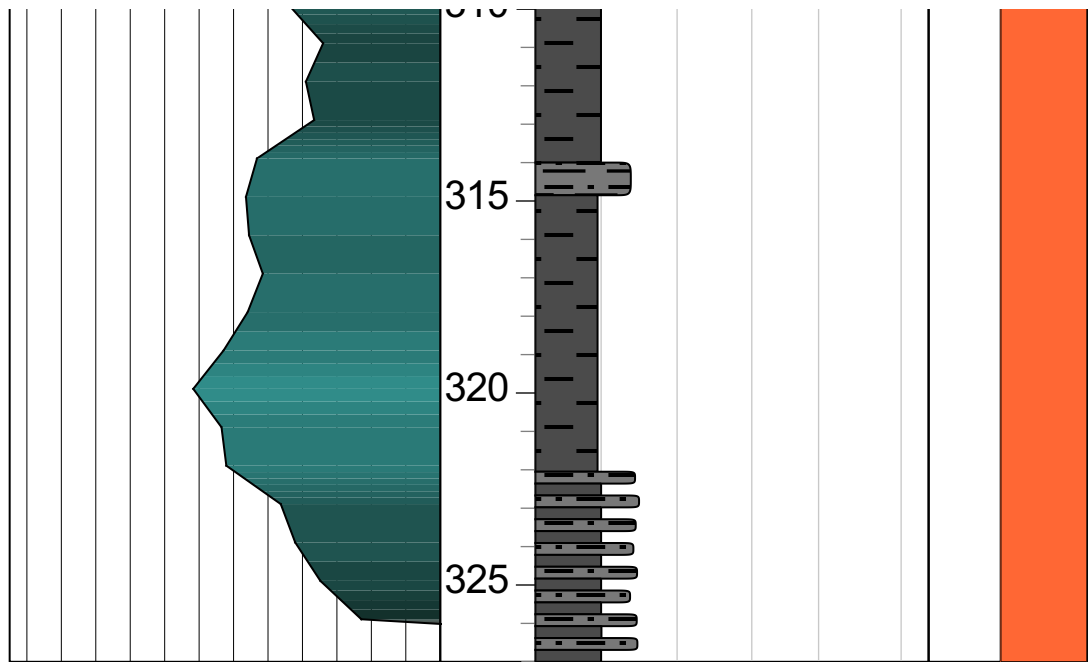








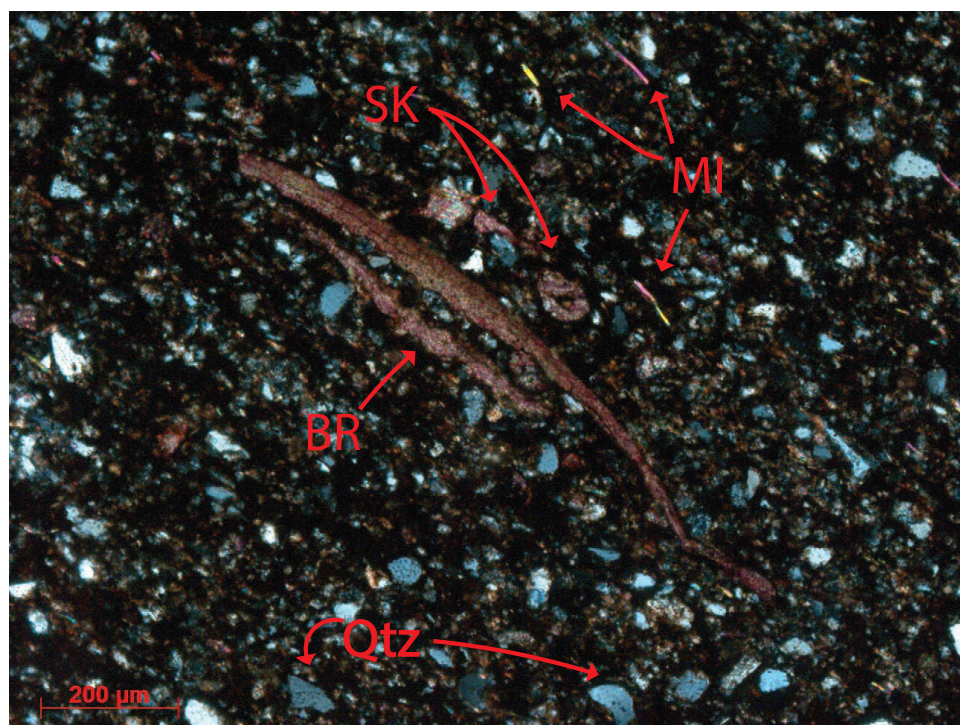
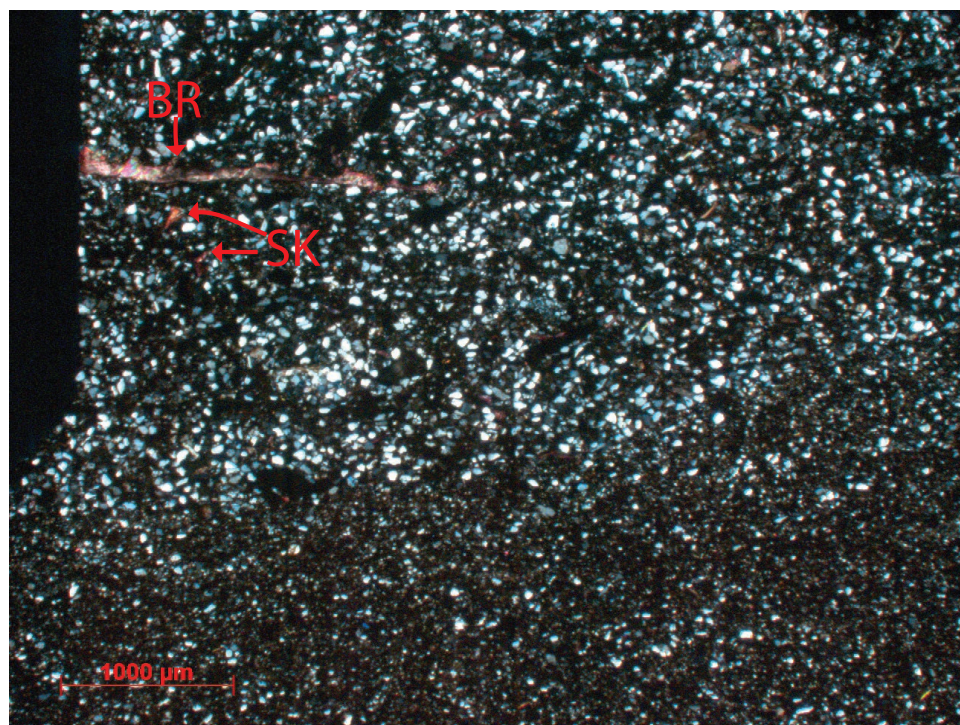




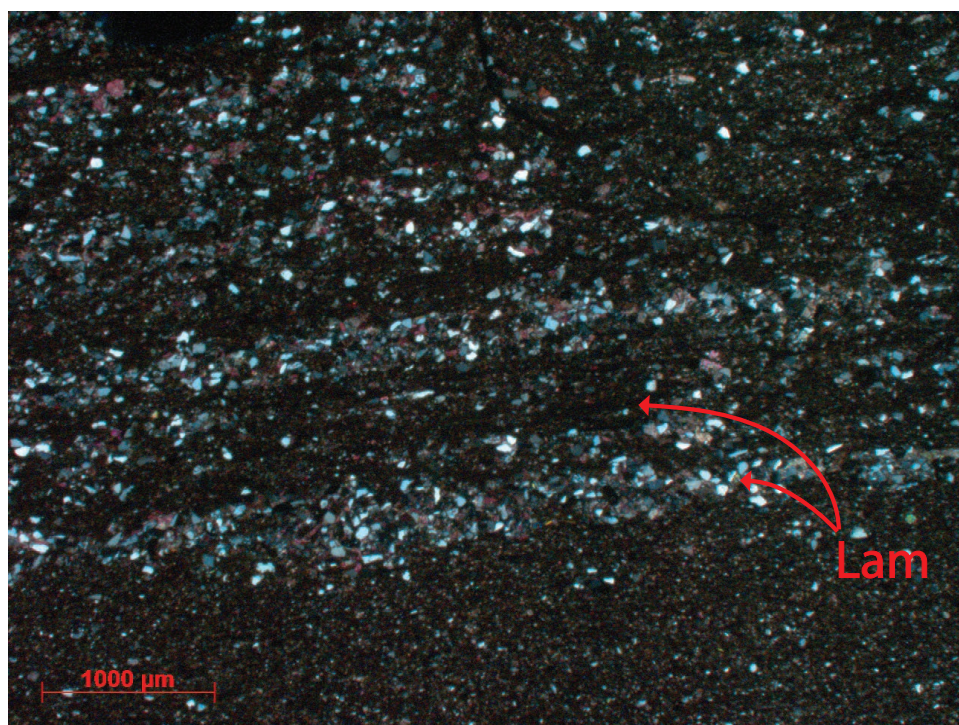
APPENDIX C: Thin Section Photomicrographs

Thin Section Key			
Br	Brachiopod	Fs	Feldspar
Bu	Burrow	Gl	Glauconite
Ca	Calcite	Lam	Lamination
Ch	Chert	Mi	Mica
Cr	Crinoid	Pel	Peloid
Dol	Dolomite	Qtz	Quartz
Dz	Detrital Zircon	Ra	Radiolaria
Fo	Fusulinid	Sp	Sponge Spicule
Fr	Fracture	Sk	Skeletal Fragment

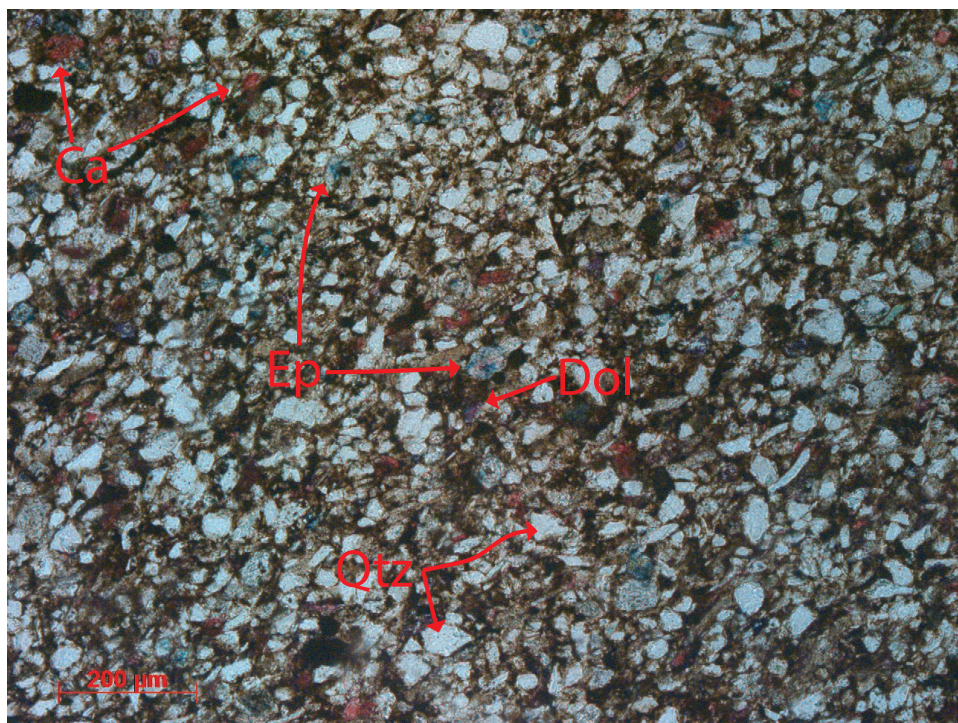
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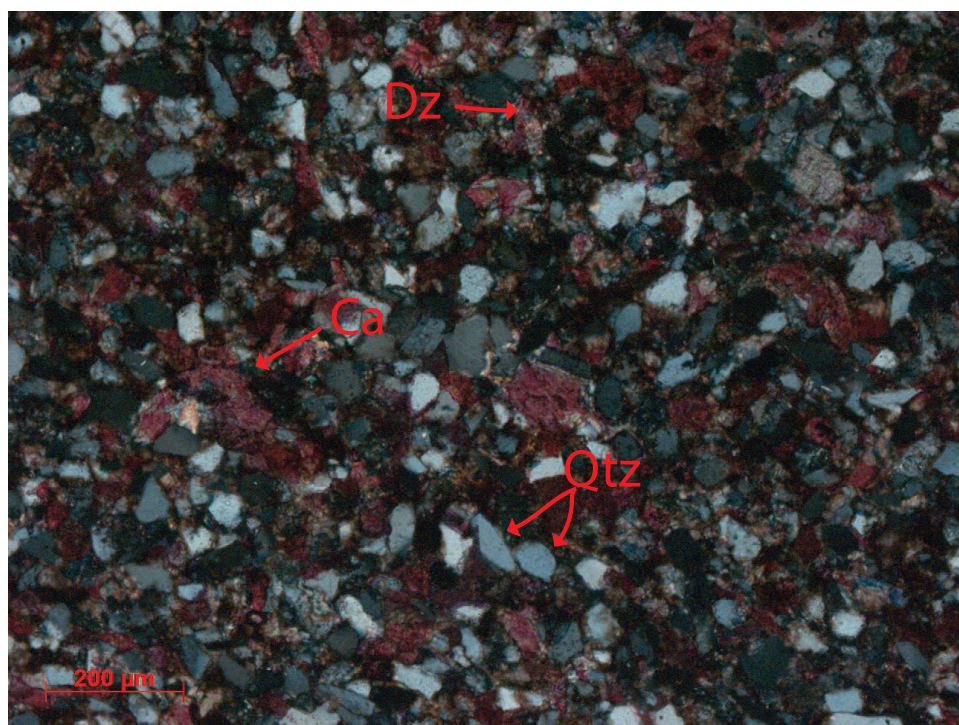
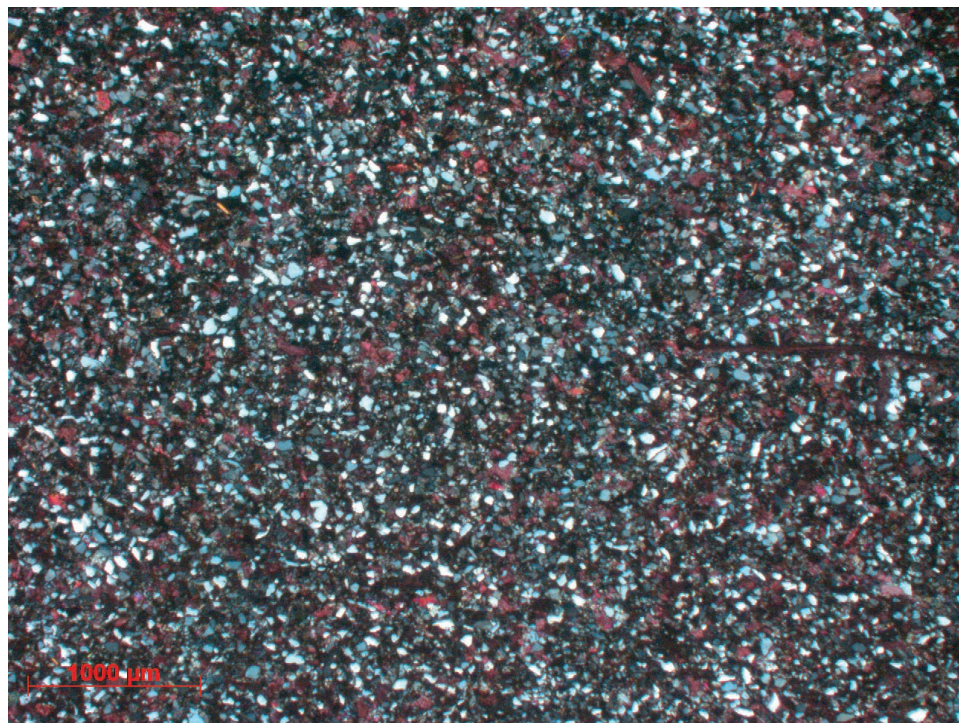
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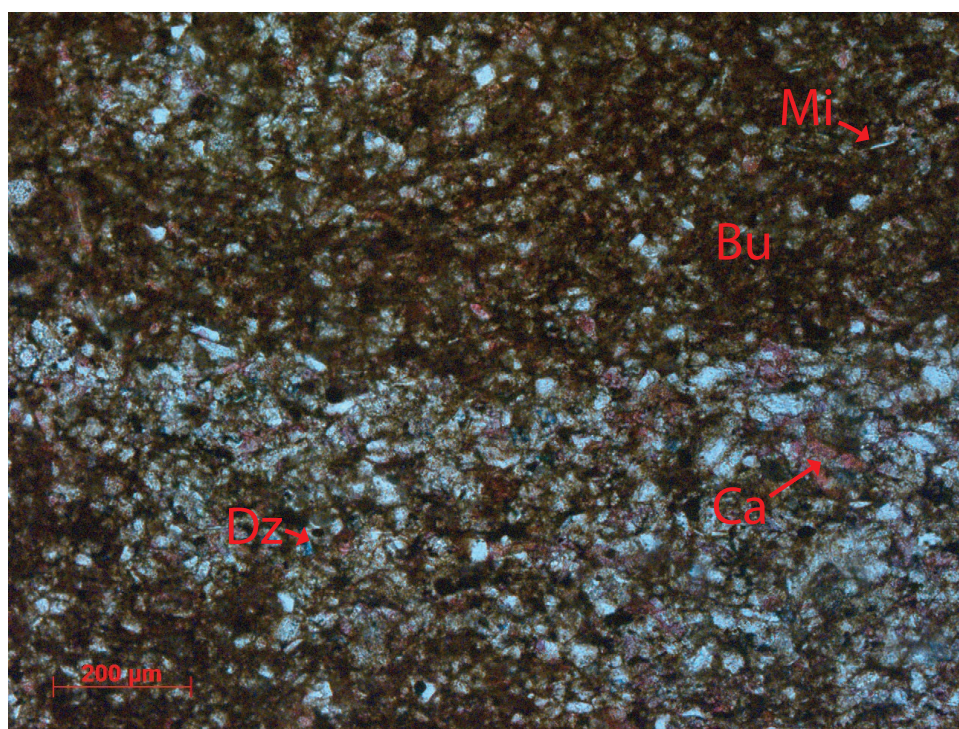
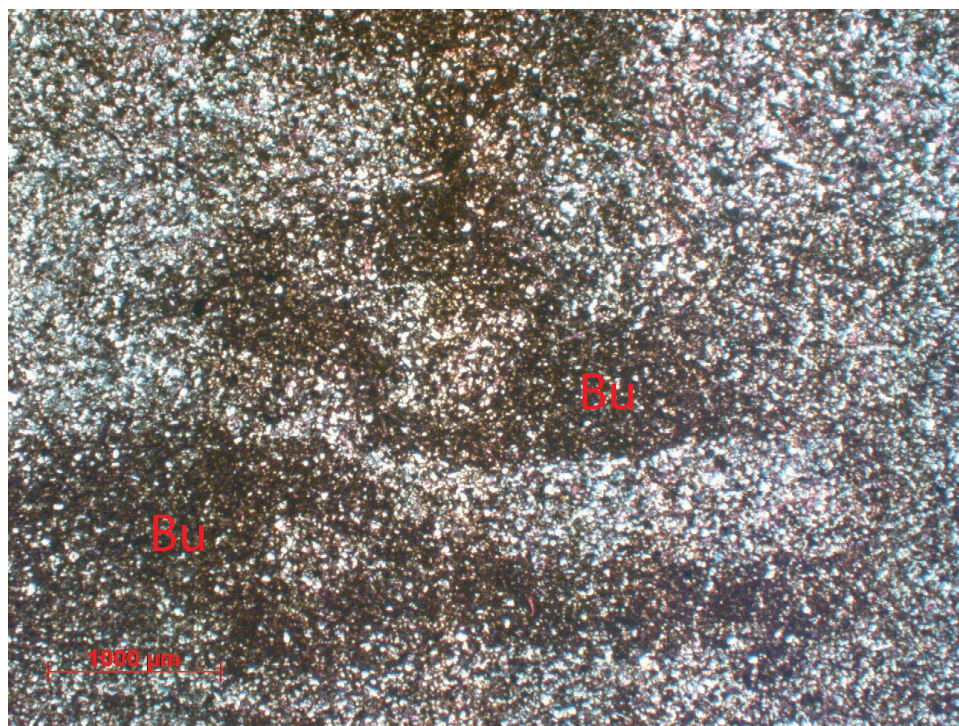
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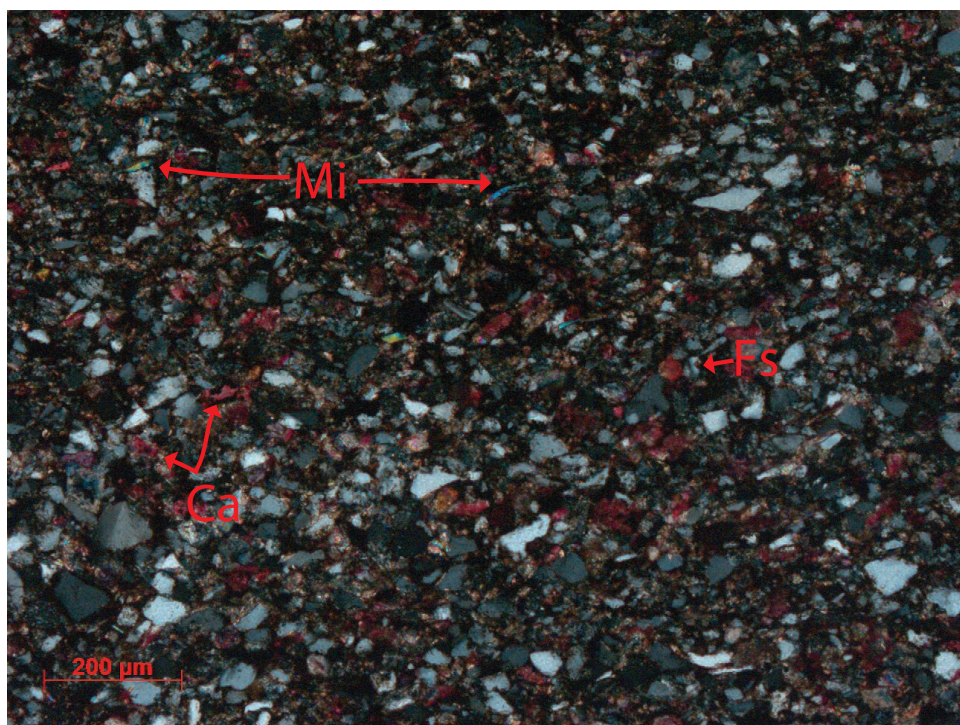
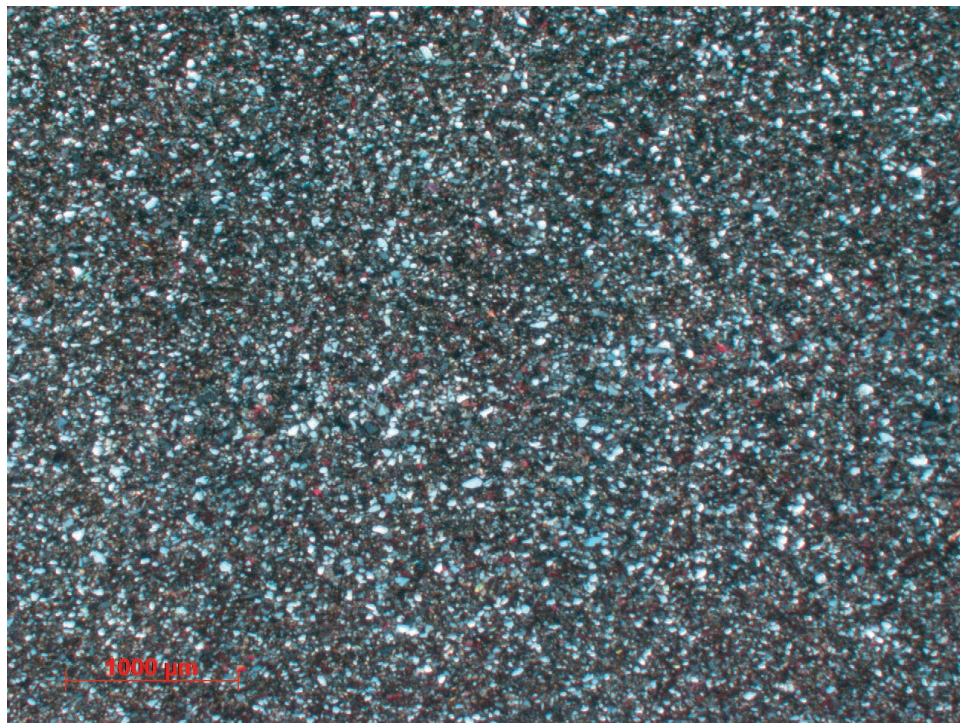
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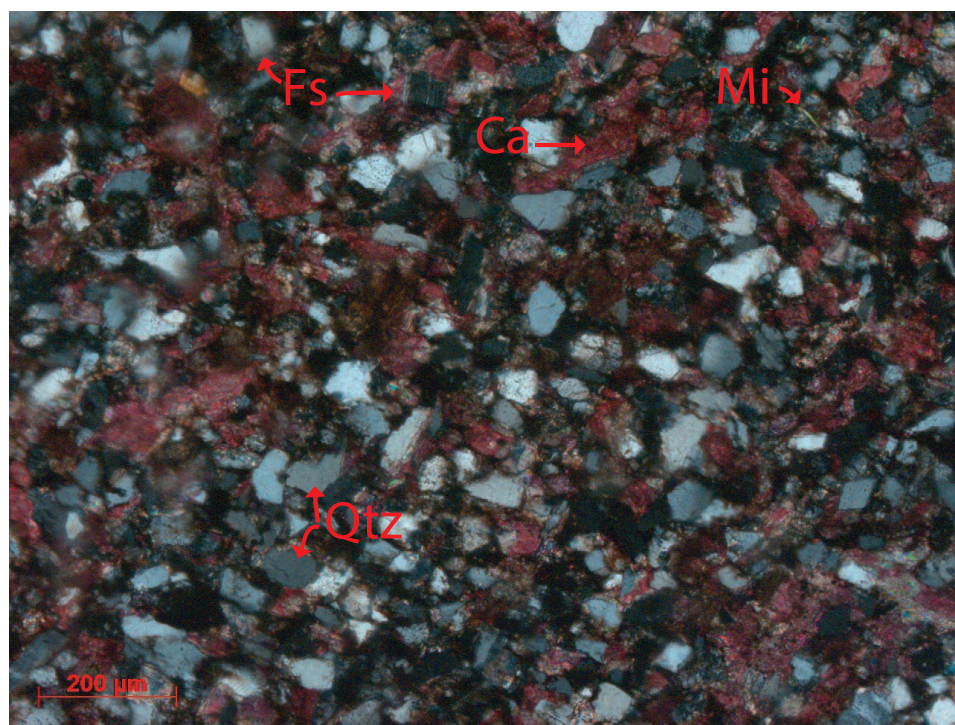
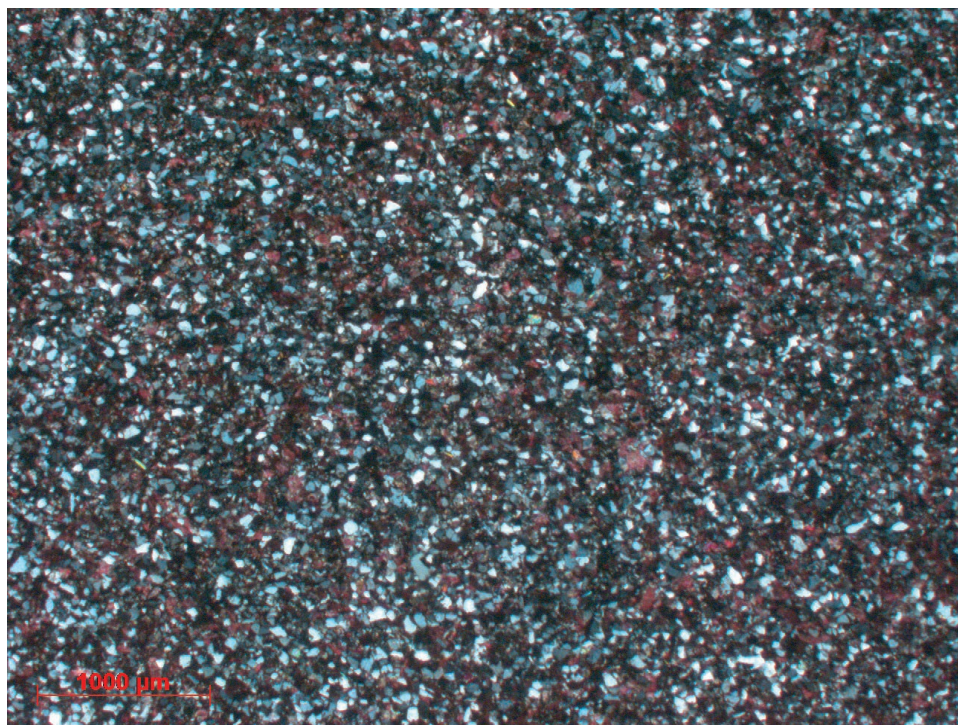
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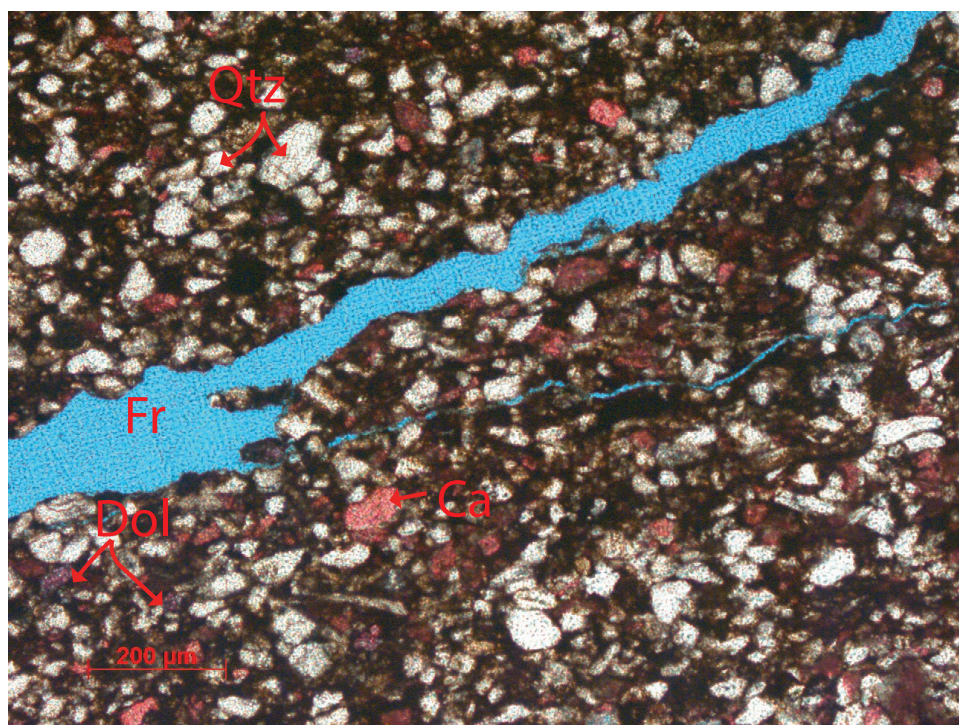
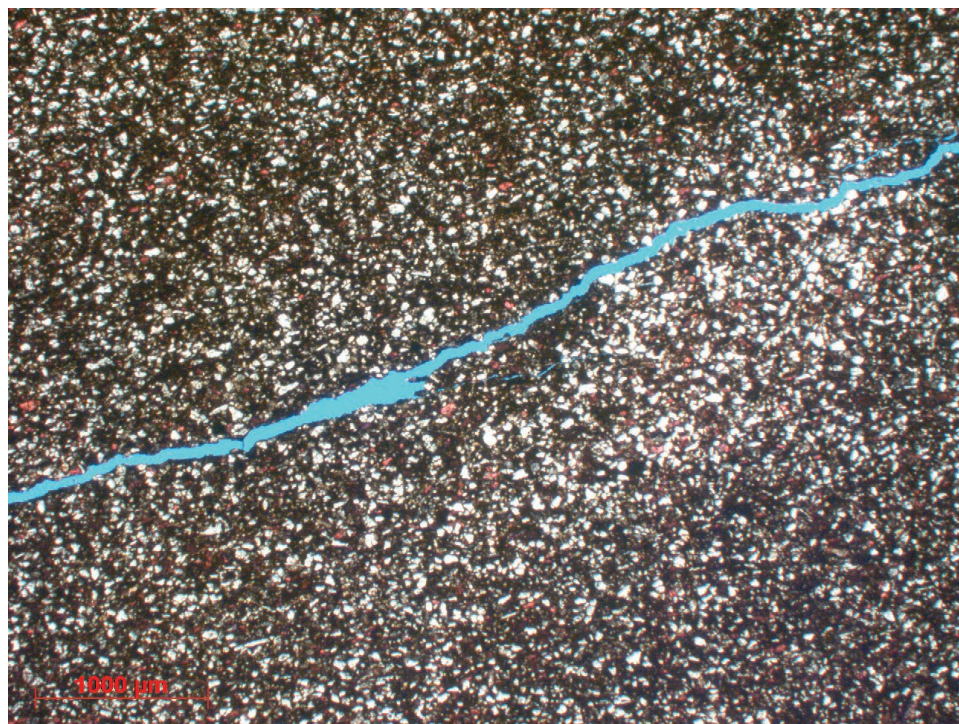
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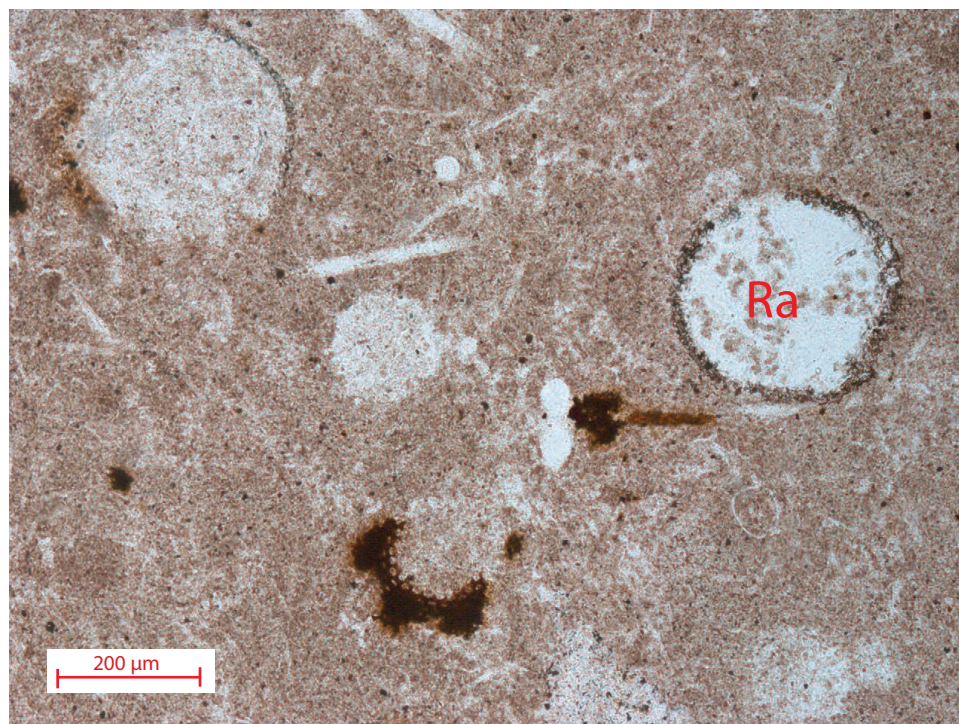
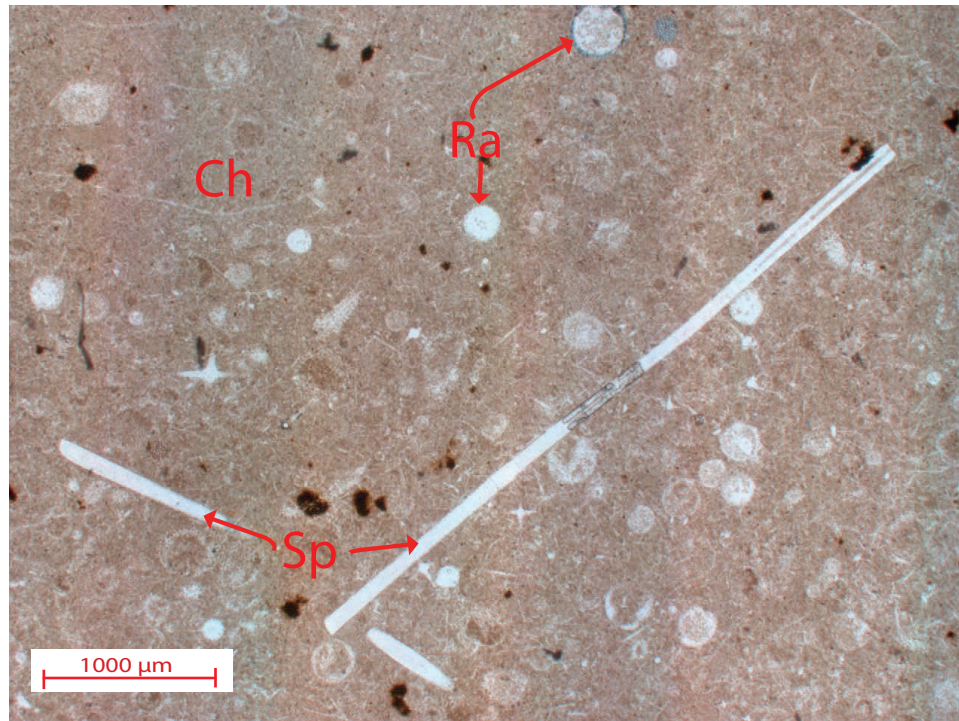
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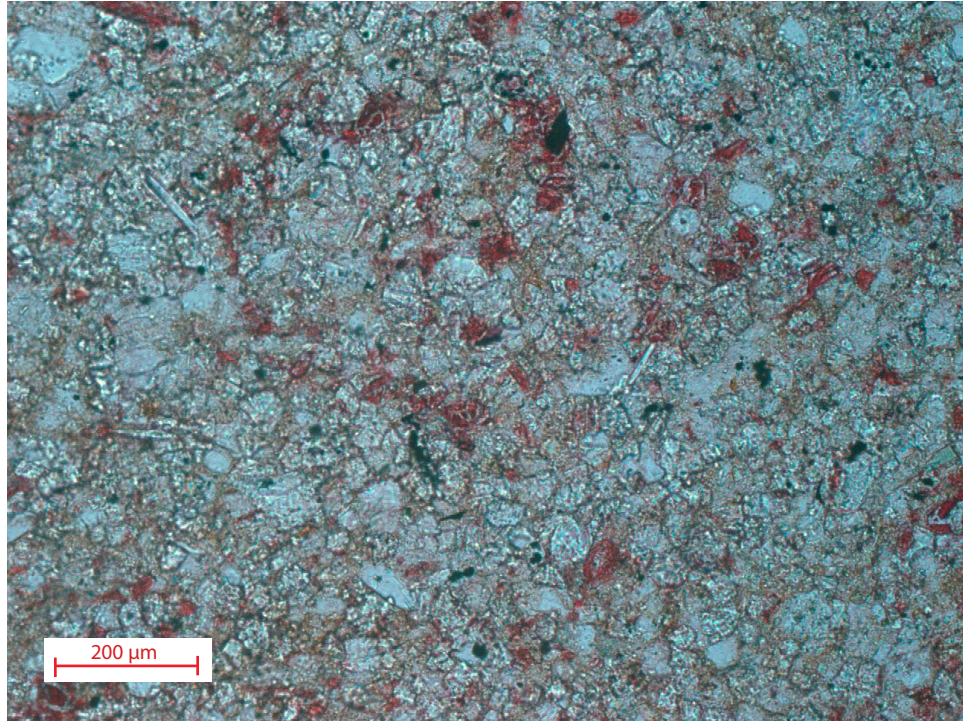
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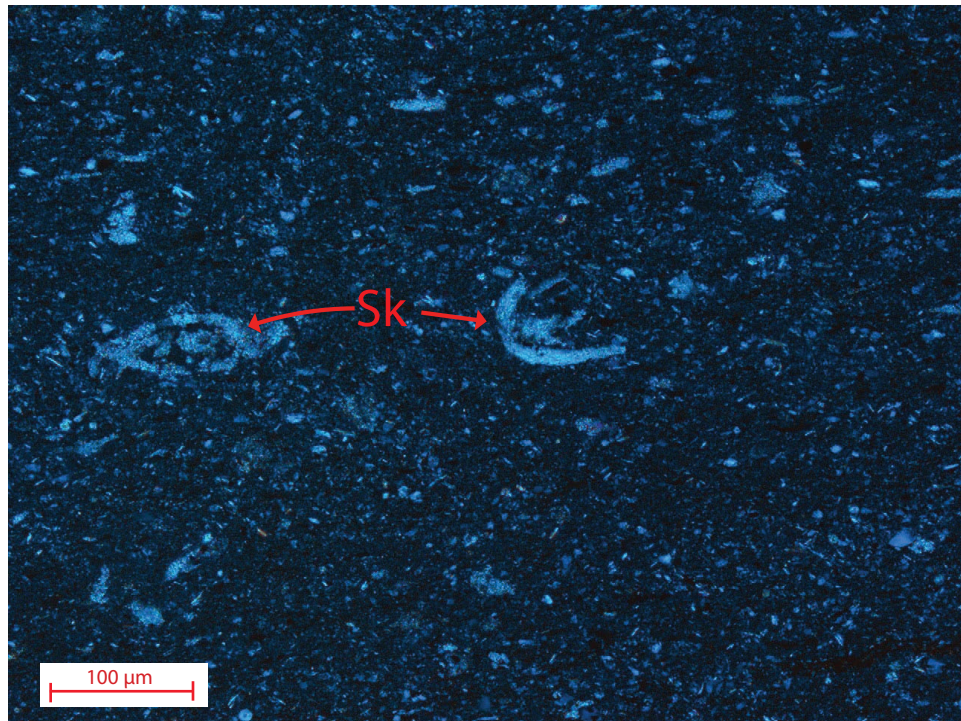
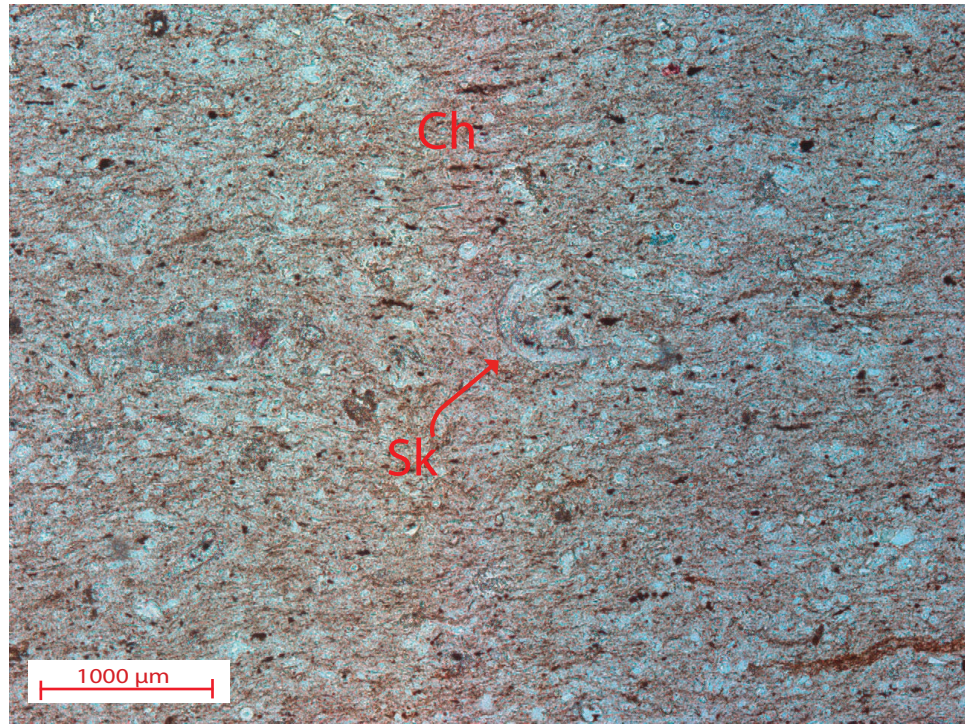
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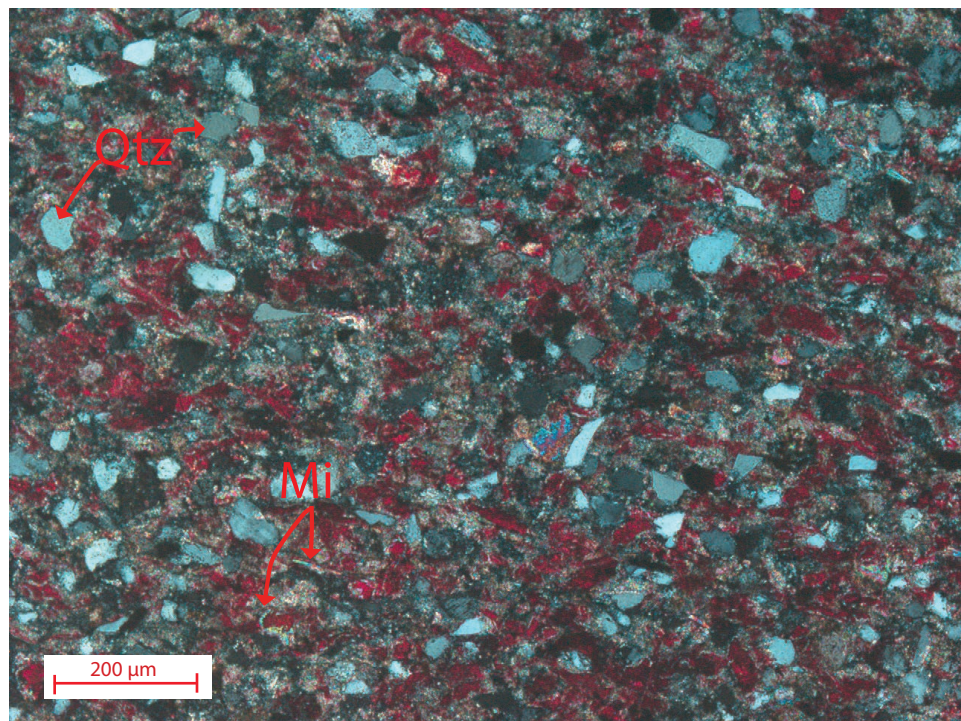
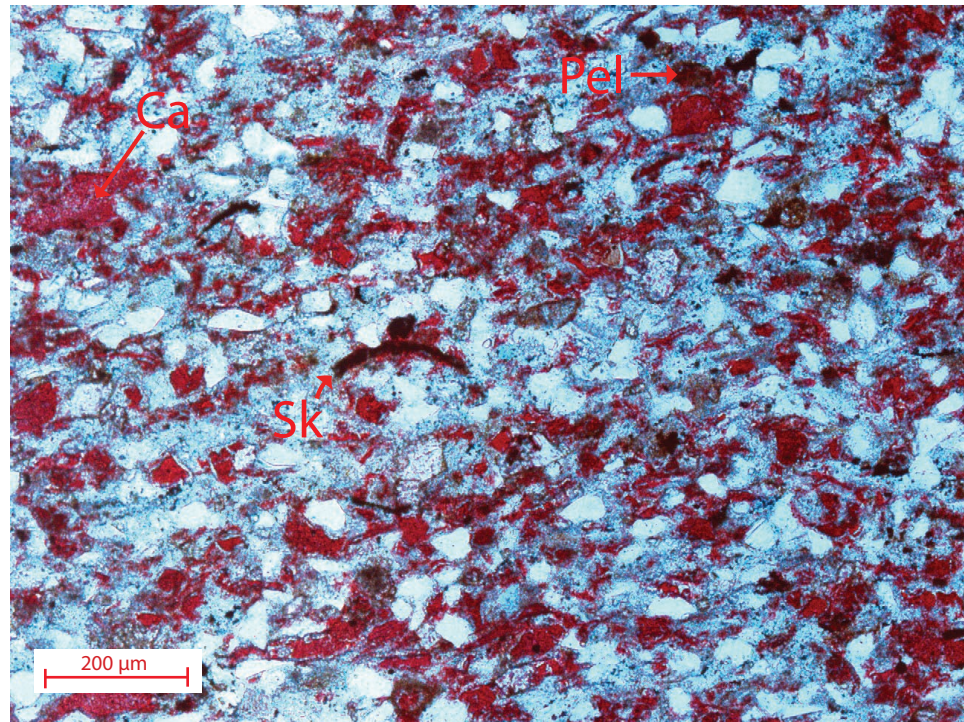
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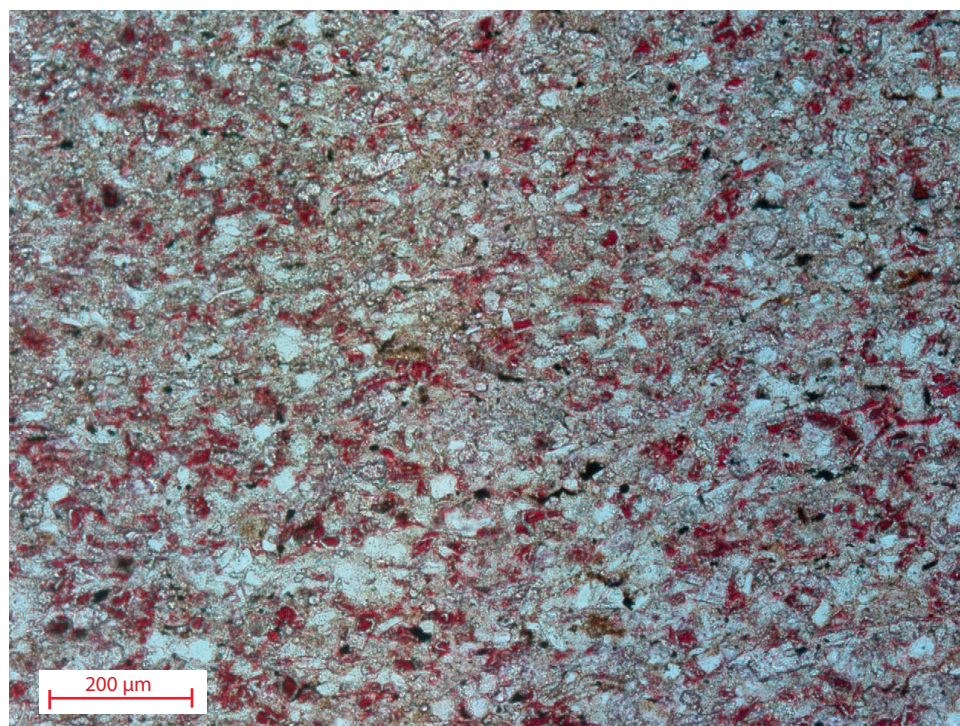
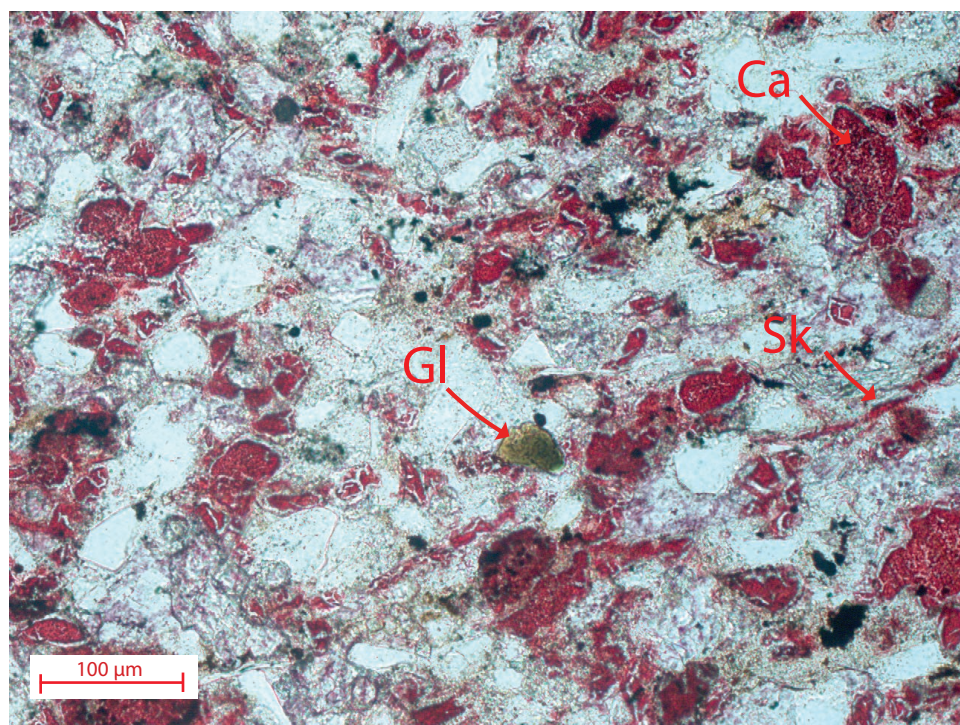
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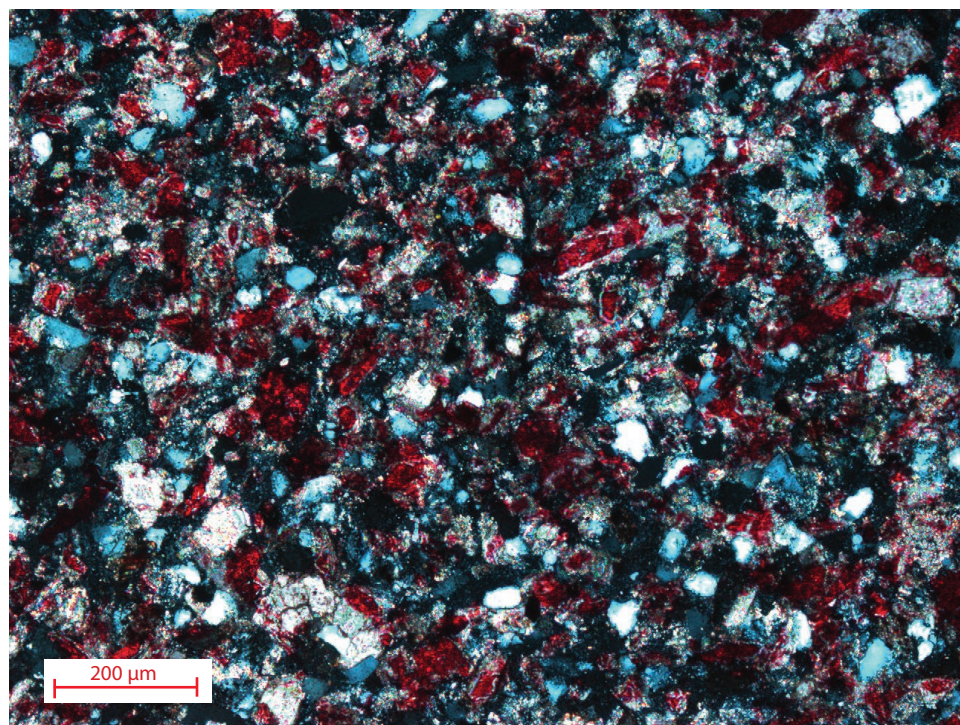
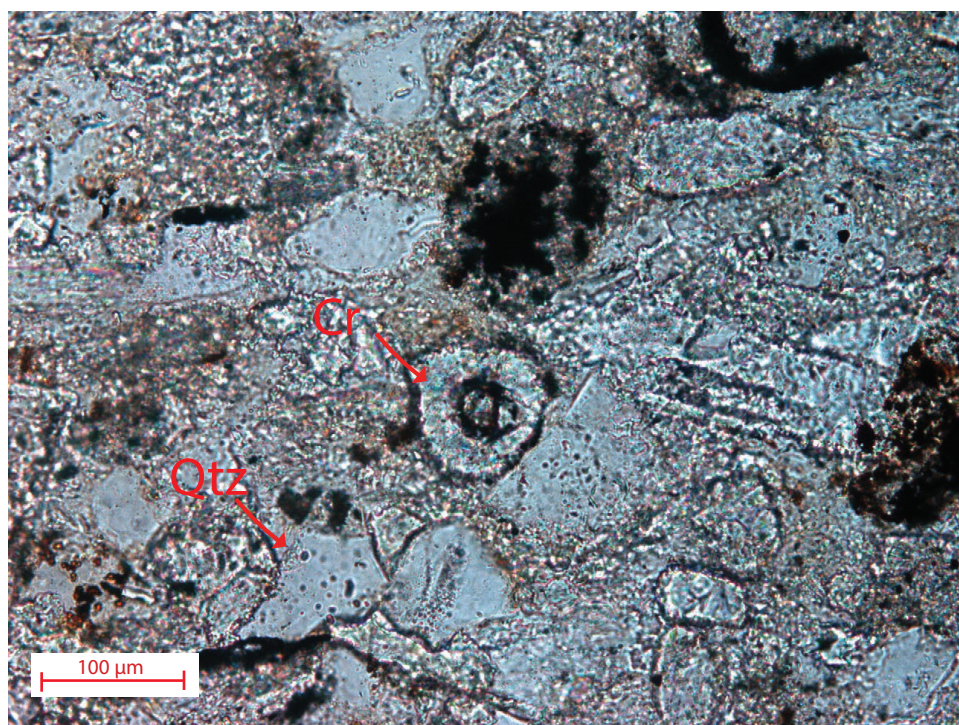
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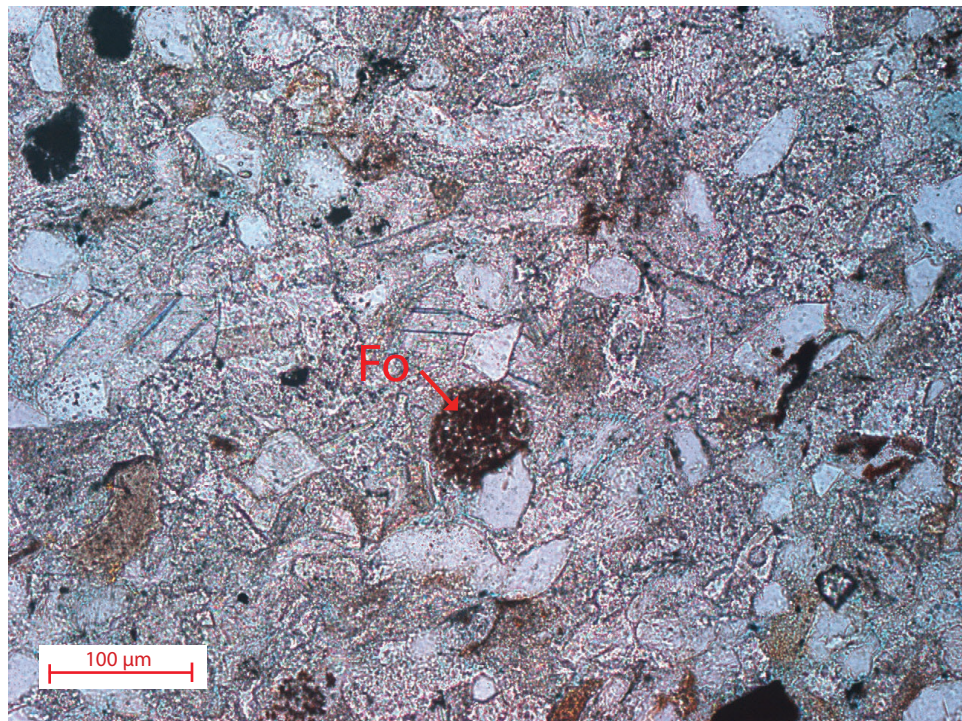
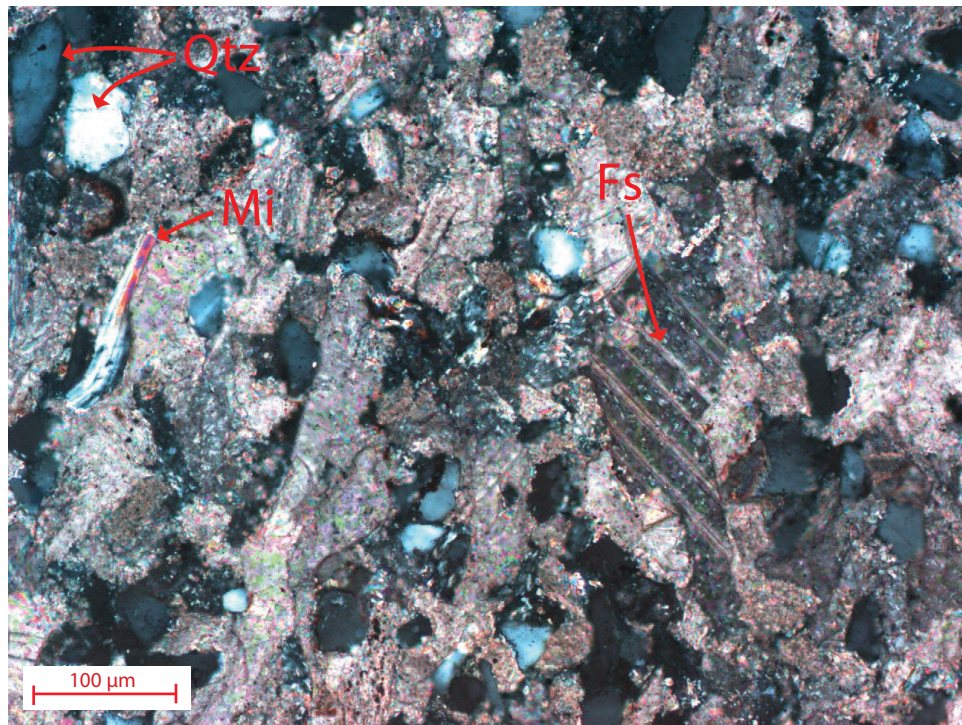
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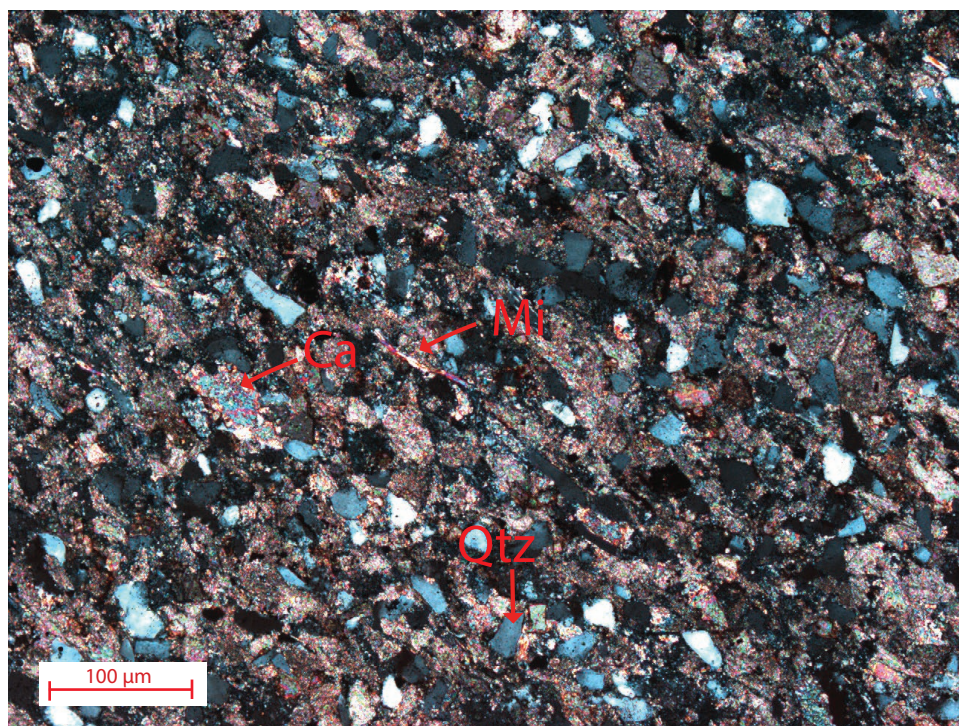
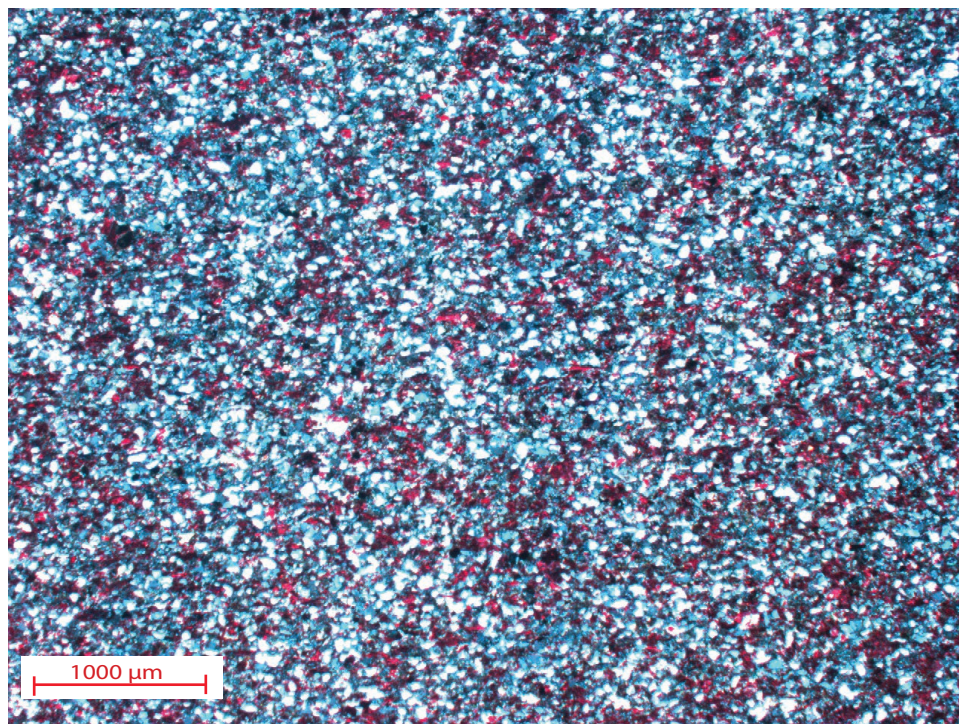
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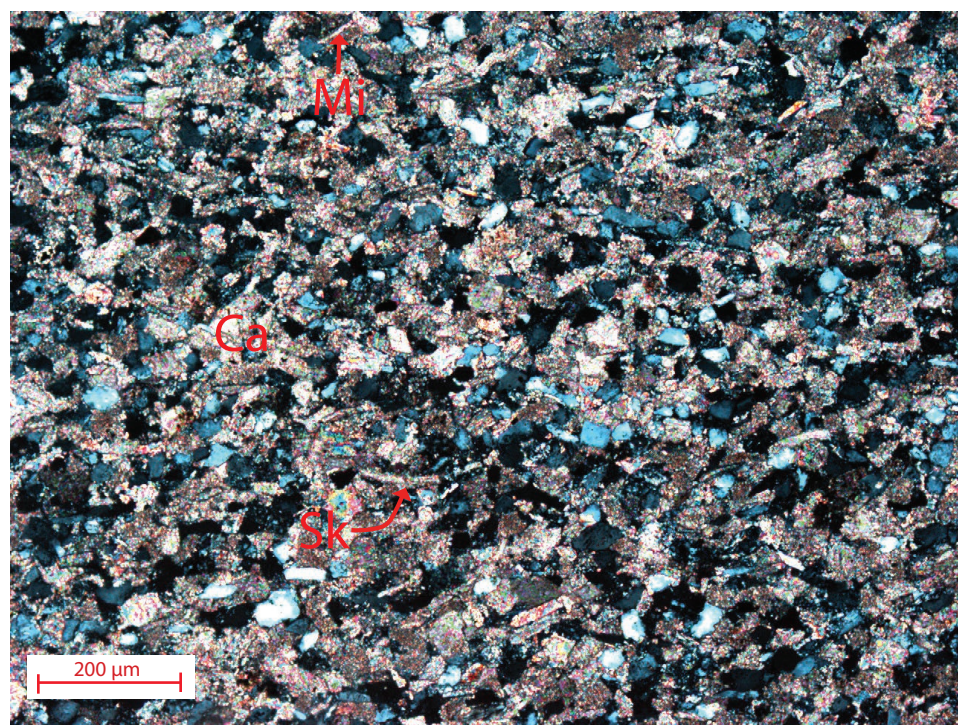
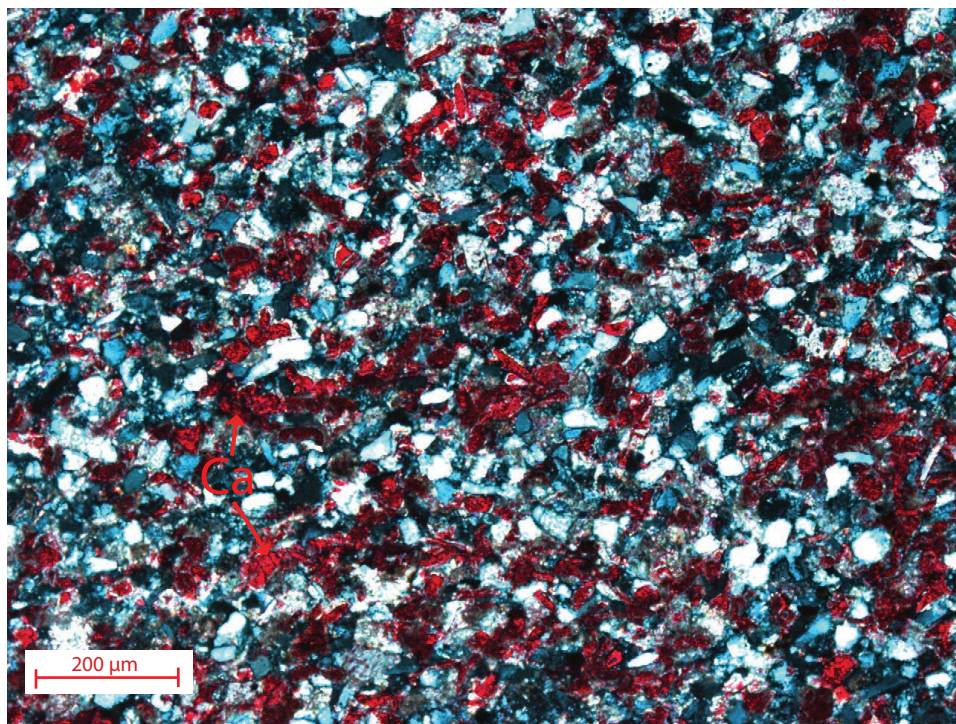
Outcrop X
115 ft



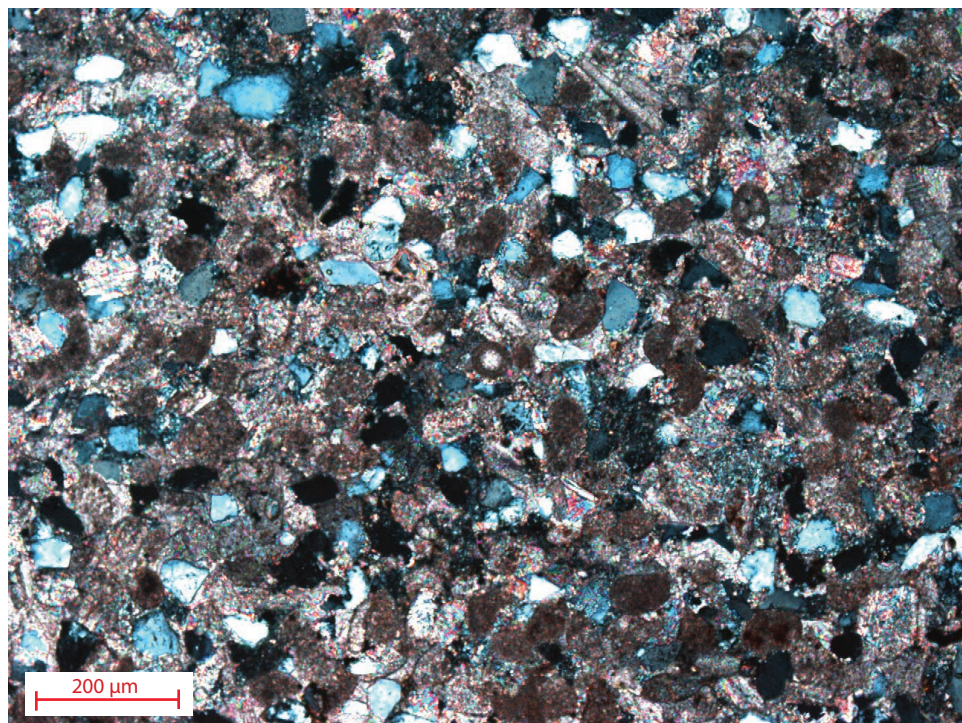
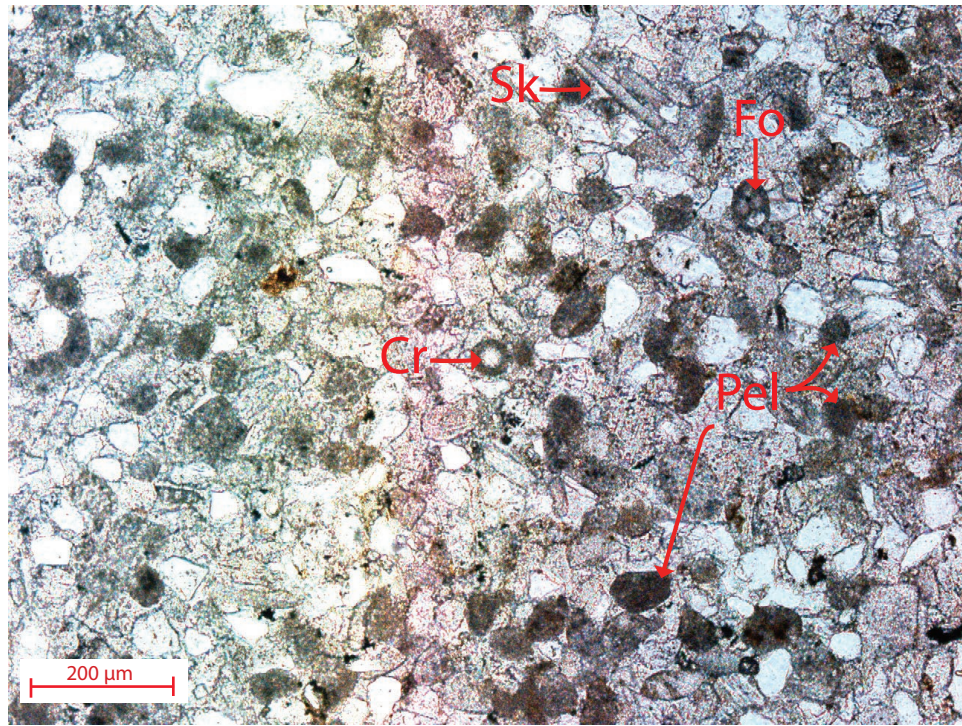
Outcrop X
102 ft



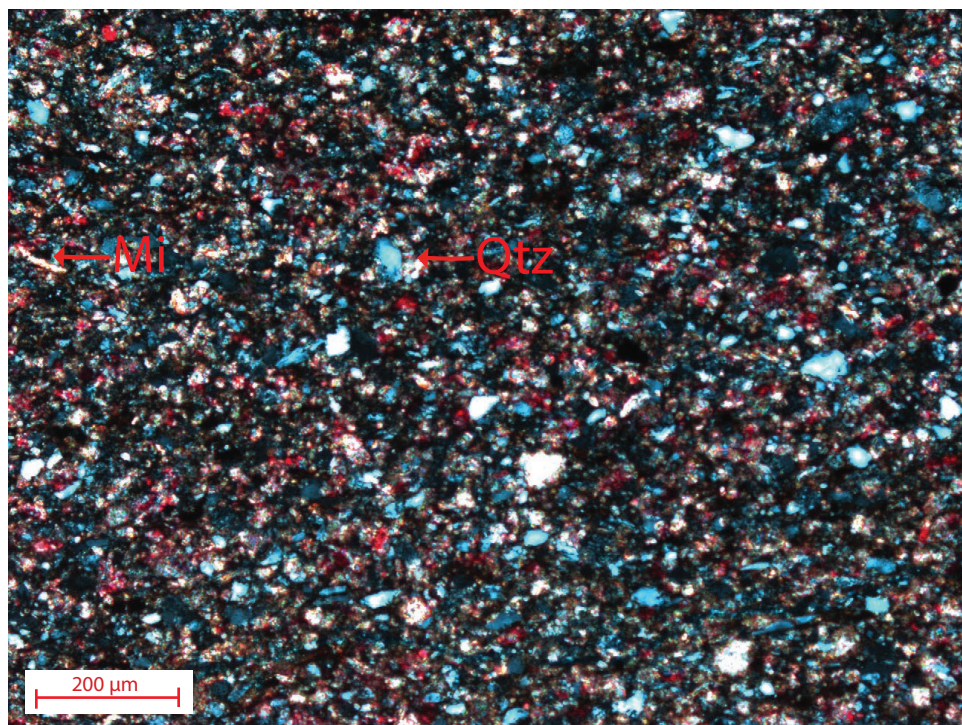
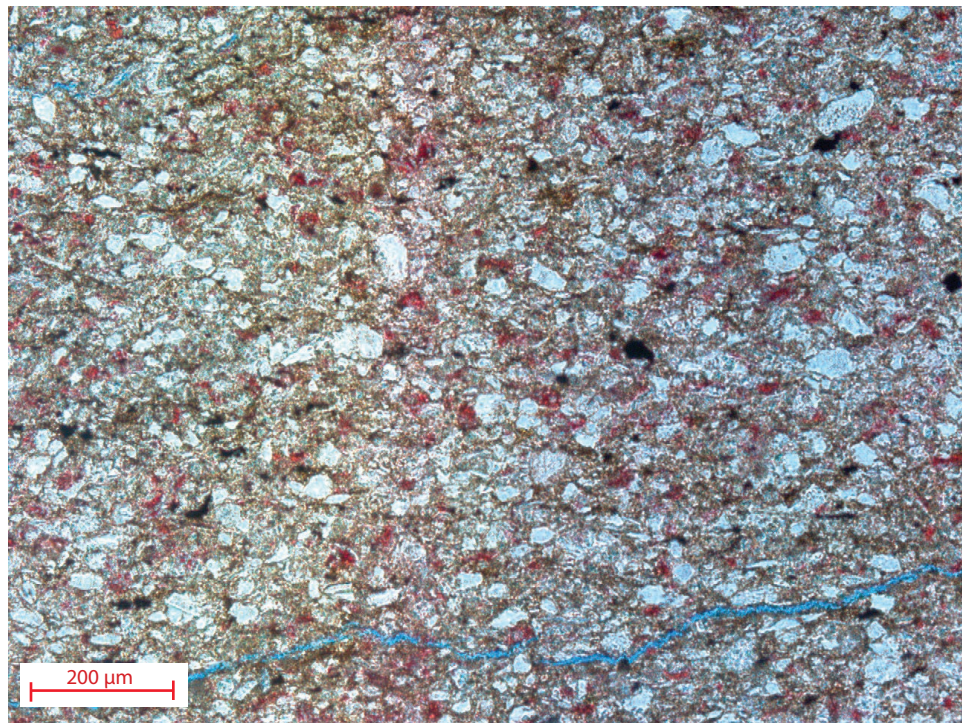
Outcrop X
79 ft



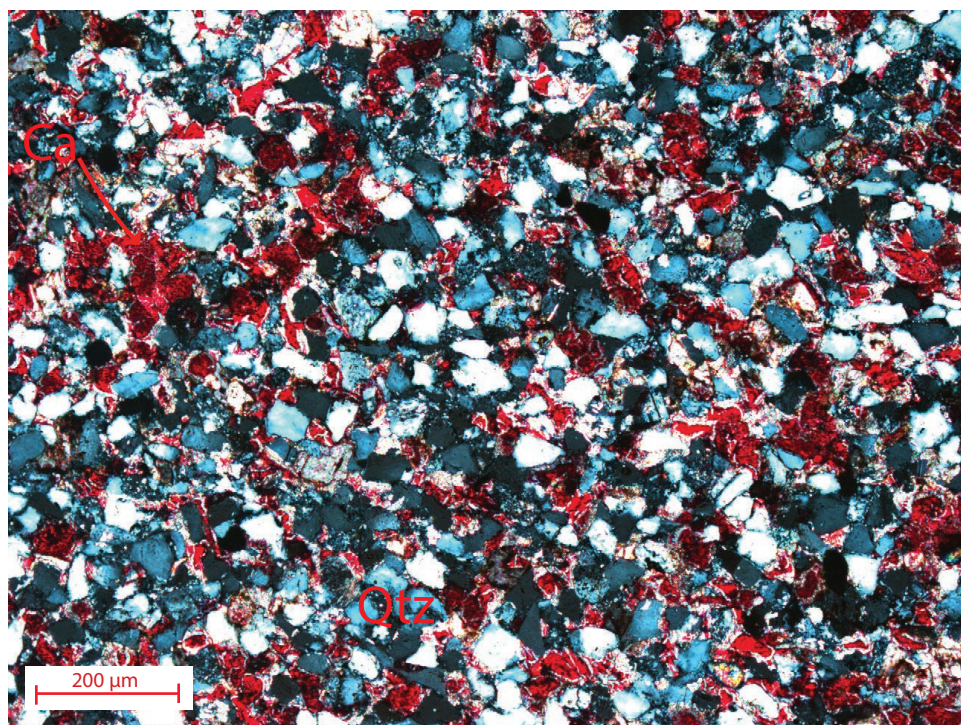
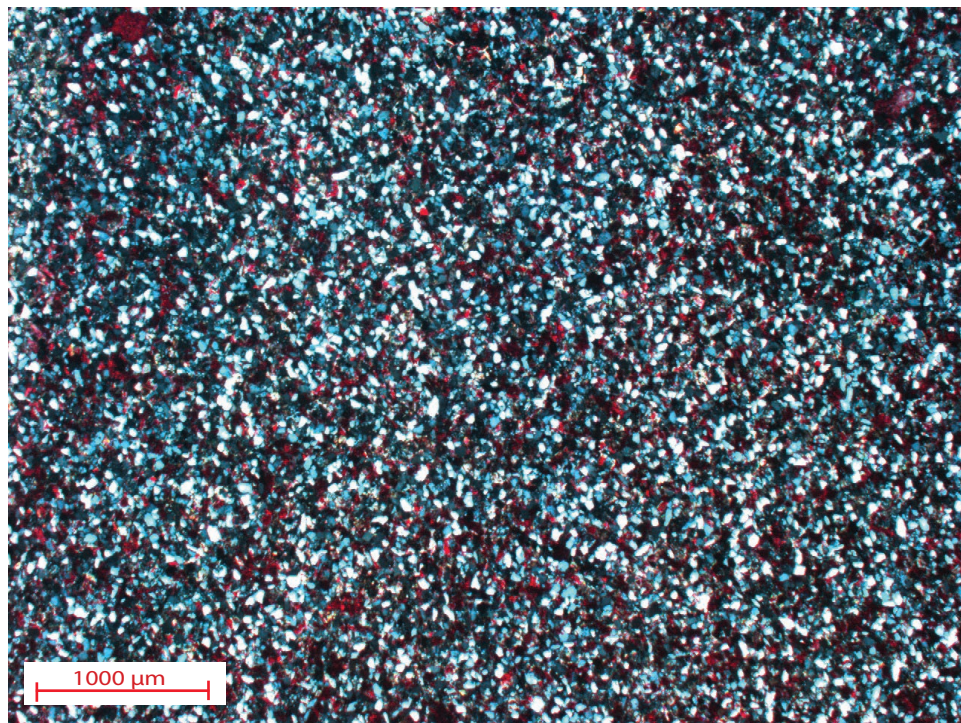
Outcrop X
70 ft



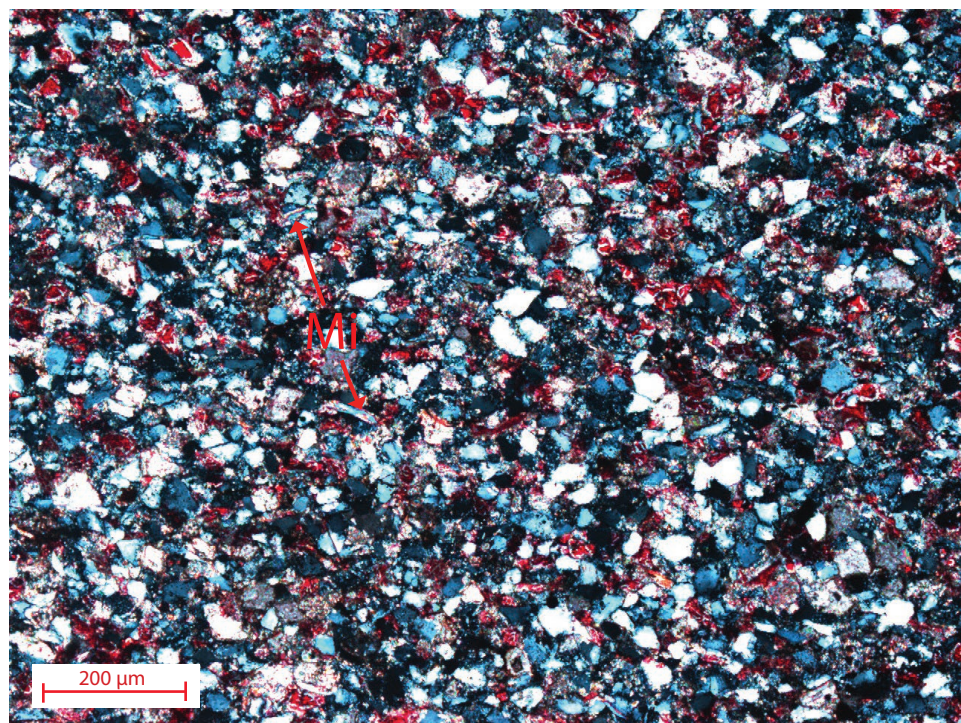
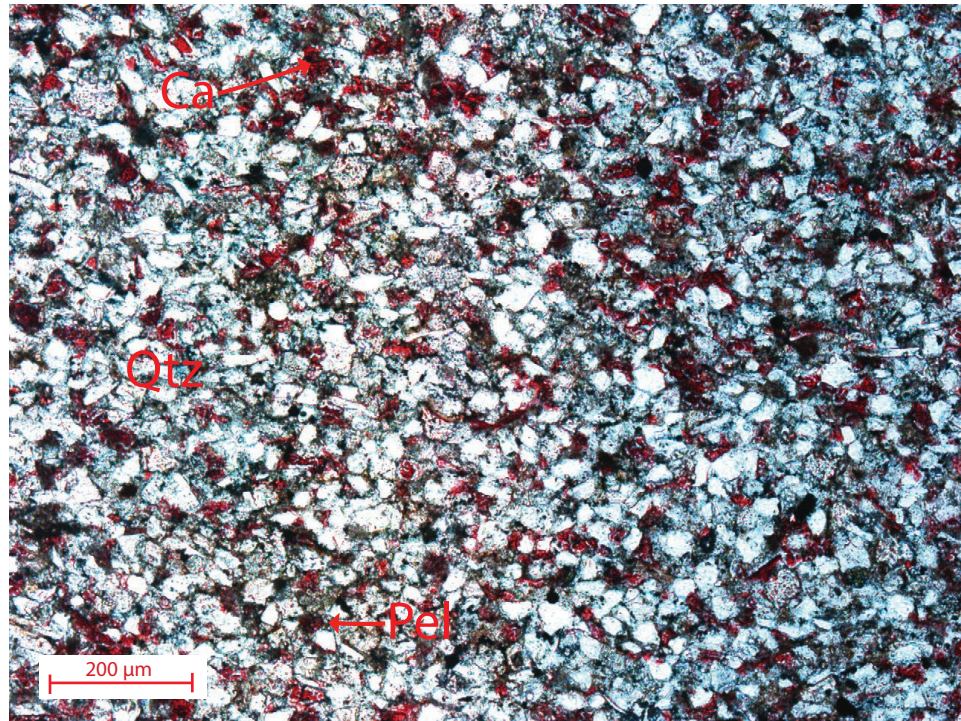
Outcrop X
77 ft



Outcrop X
15 ft

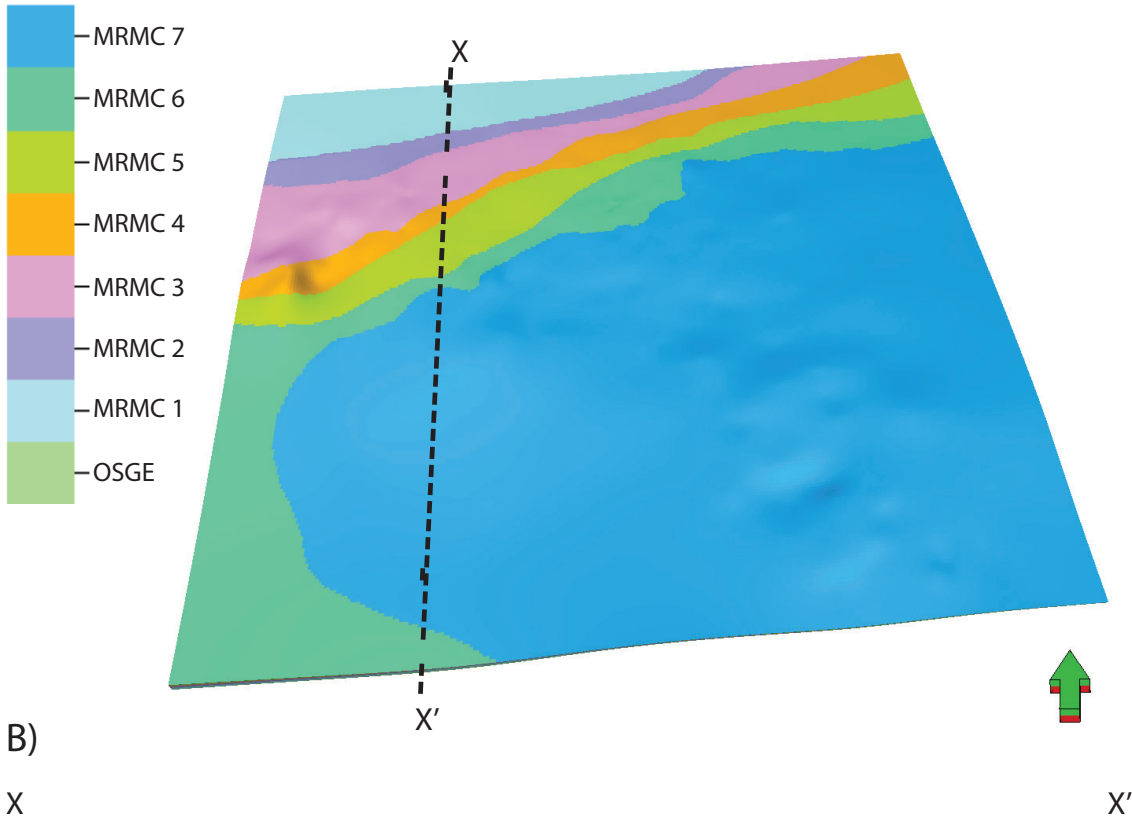


Outcrop X
5 ft

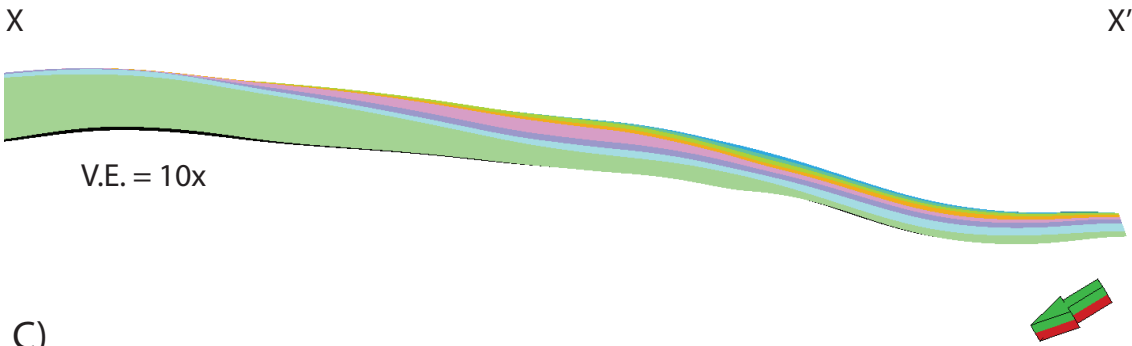


APPENDIX D: 3-D Model Construction and Variograms

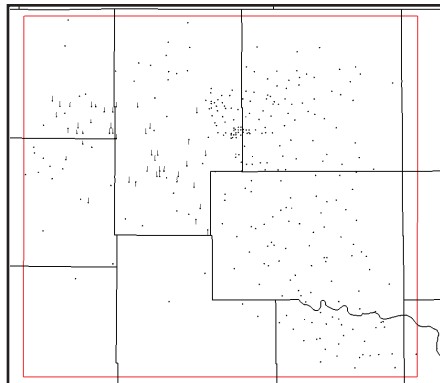
A)



B)

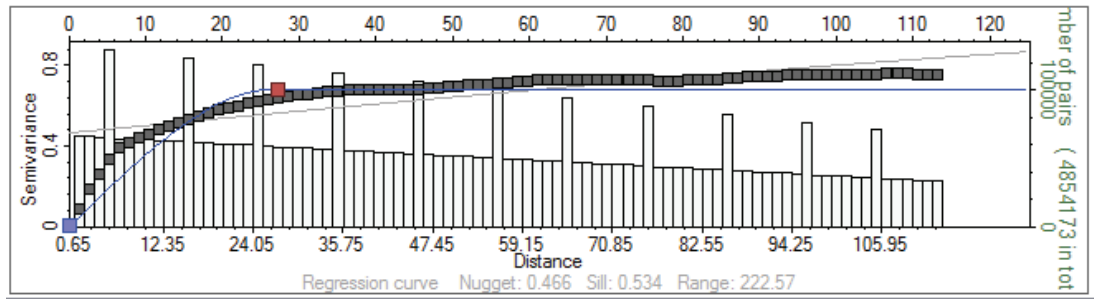


C)

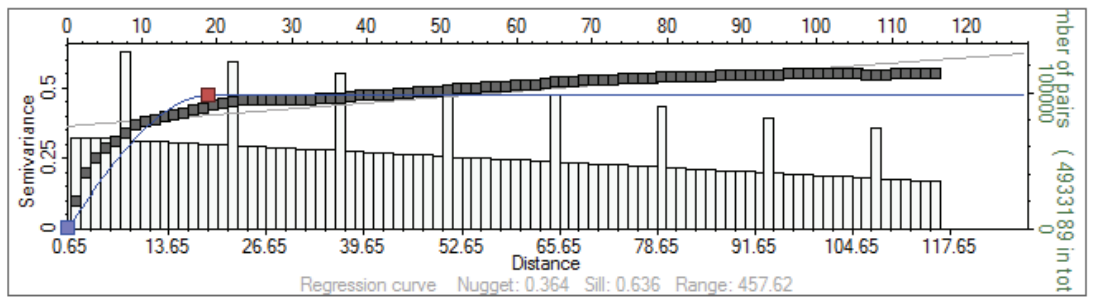


Appendix D-1. (A) 3-D view of the STACK model. (B) Stratal geometries of the Meramec zones. (C) Boundary of the STACK model outlined in red.

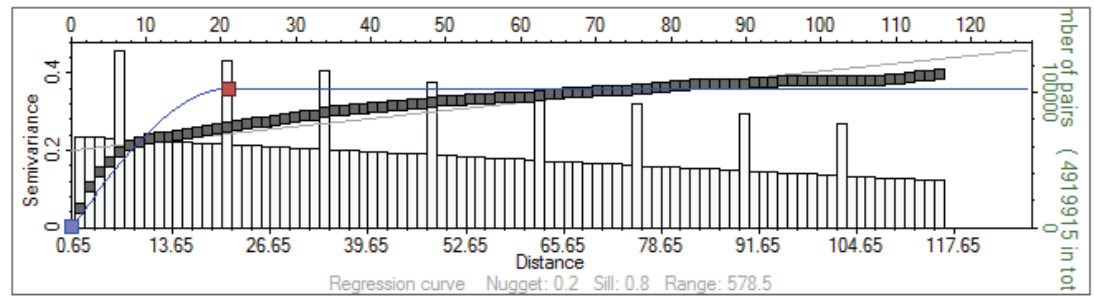
Sycamore + Osage



Meramec

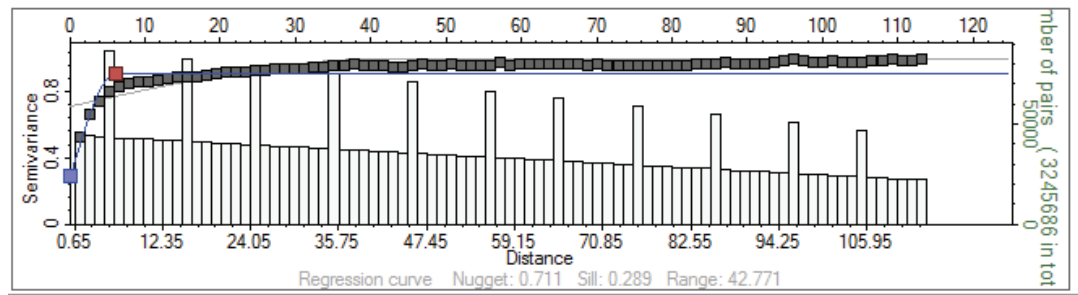


Caney

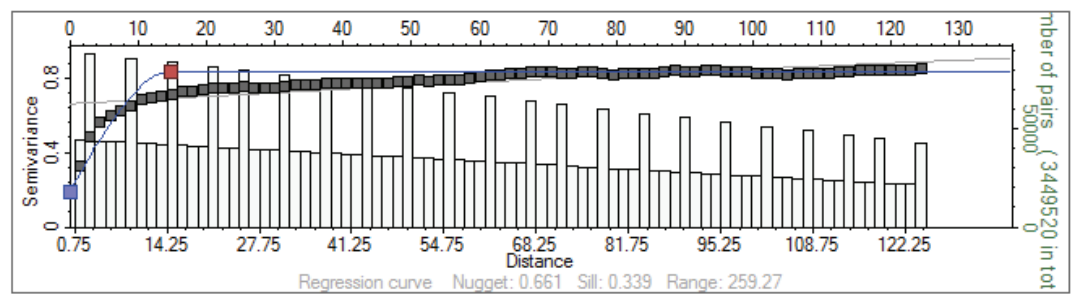


Vertical variograms for VSHGR for the zones of the regional model.

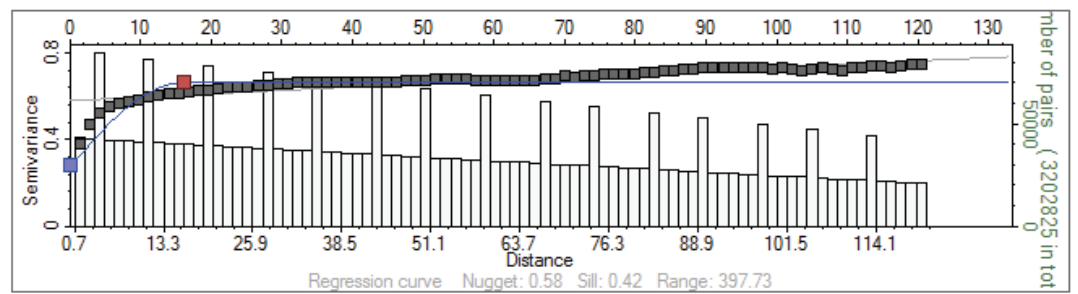
Sycamore + Osage



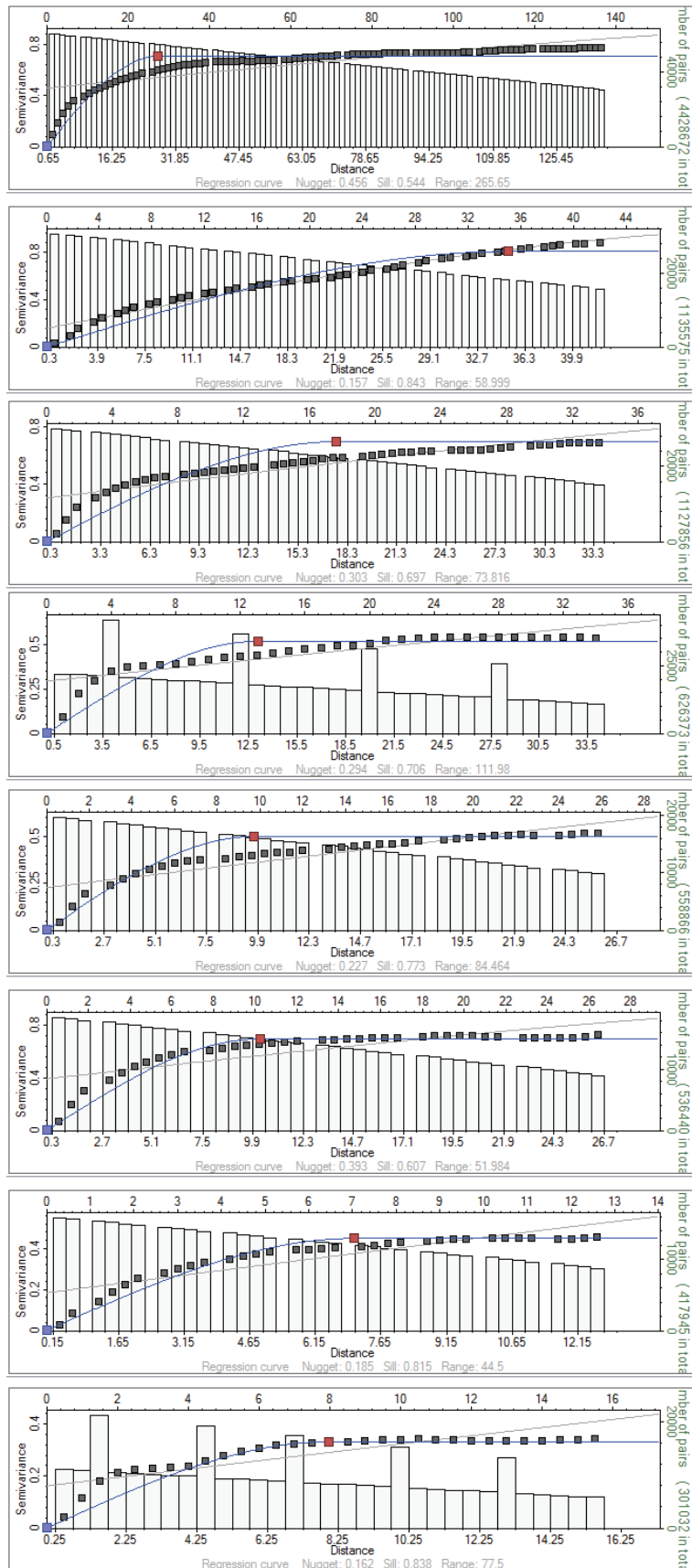
Meramec



Caney



Vertical variograms for TOC for the zones of the regional model.



Osage

MRM C 1

MRM C 2

MRM C 3

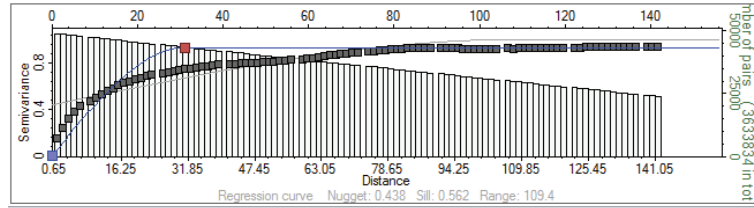
MRM C 4

MRM C 5

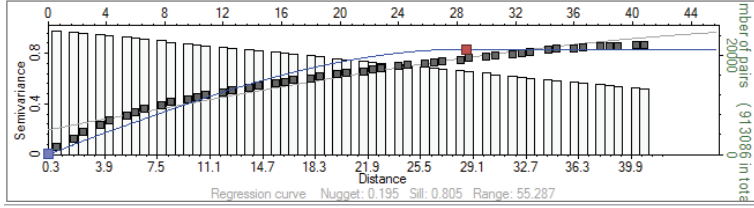
MRM C 6

MRM C 7

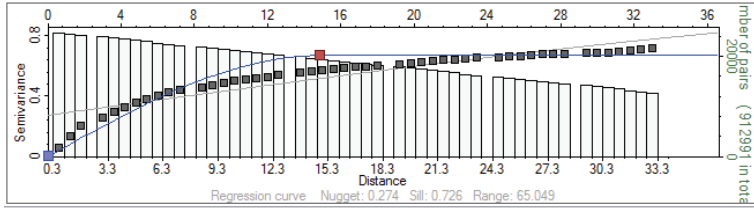
Vertical variograms for V_{SHGR} for the zones of the STACK model.



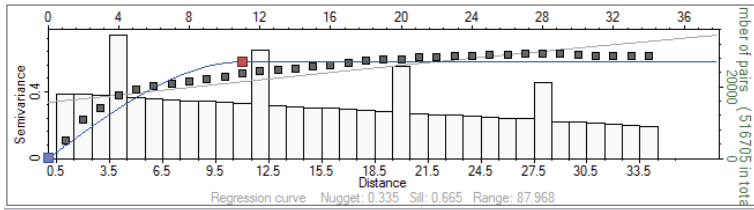
Osage



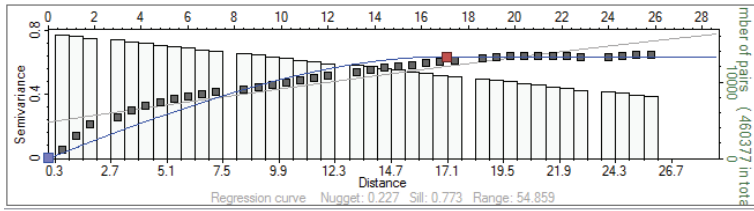
MRMC 1



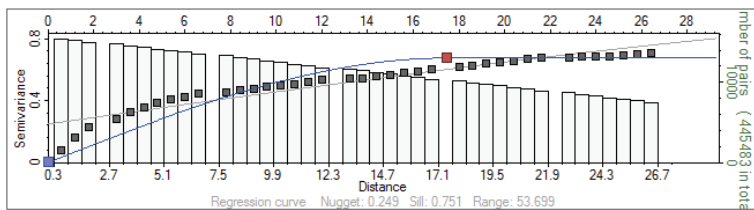
MRMC 2



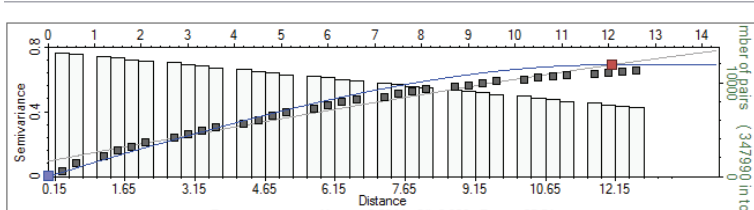
MRMC 3



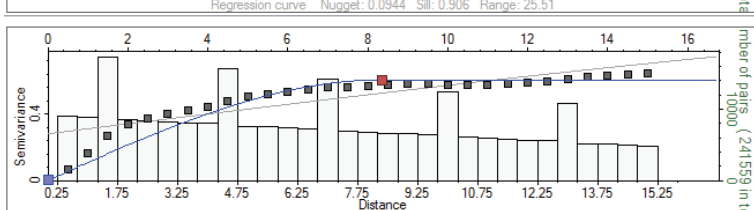
MRMC 4



MRMC 5

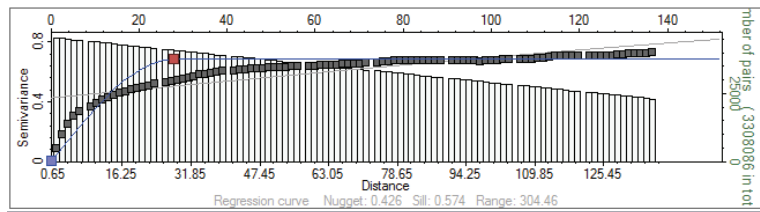


MRMC 6

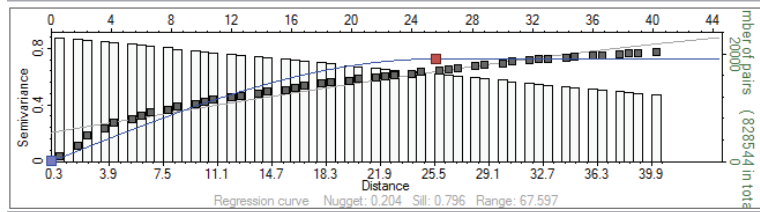


MRMC 7

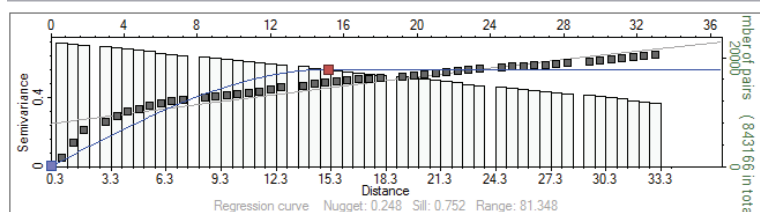
Vertical variograms for V_{SHND} for the zones of the STACK model.



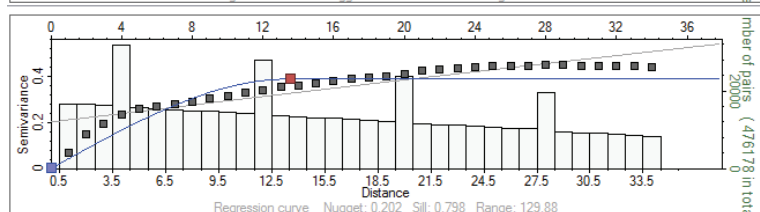
Osage



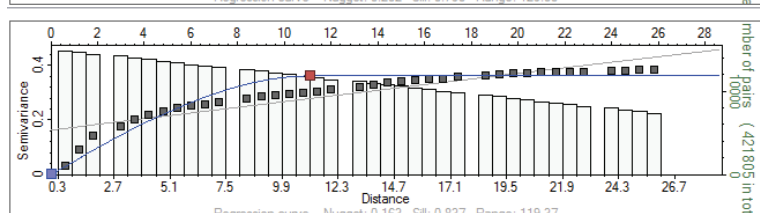
MRMC 1



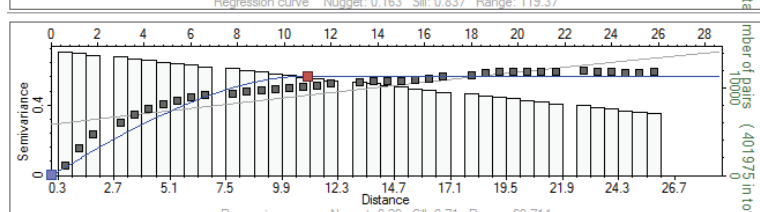
MRMC 2



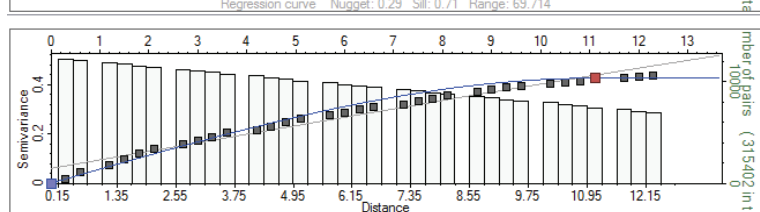
MRMC 3



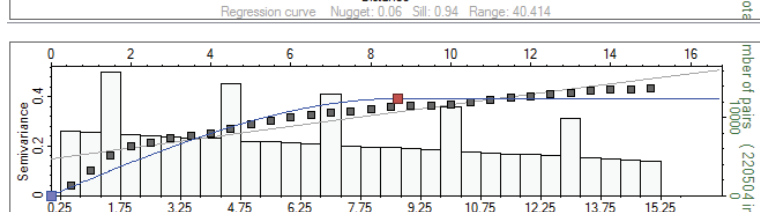
MRMC 4



MRMC 5

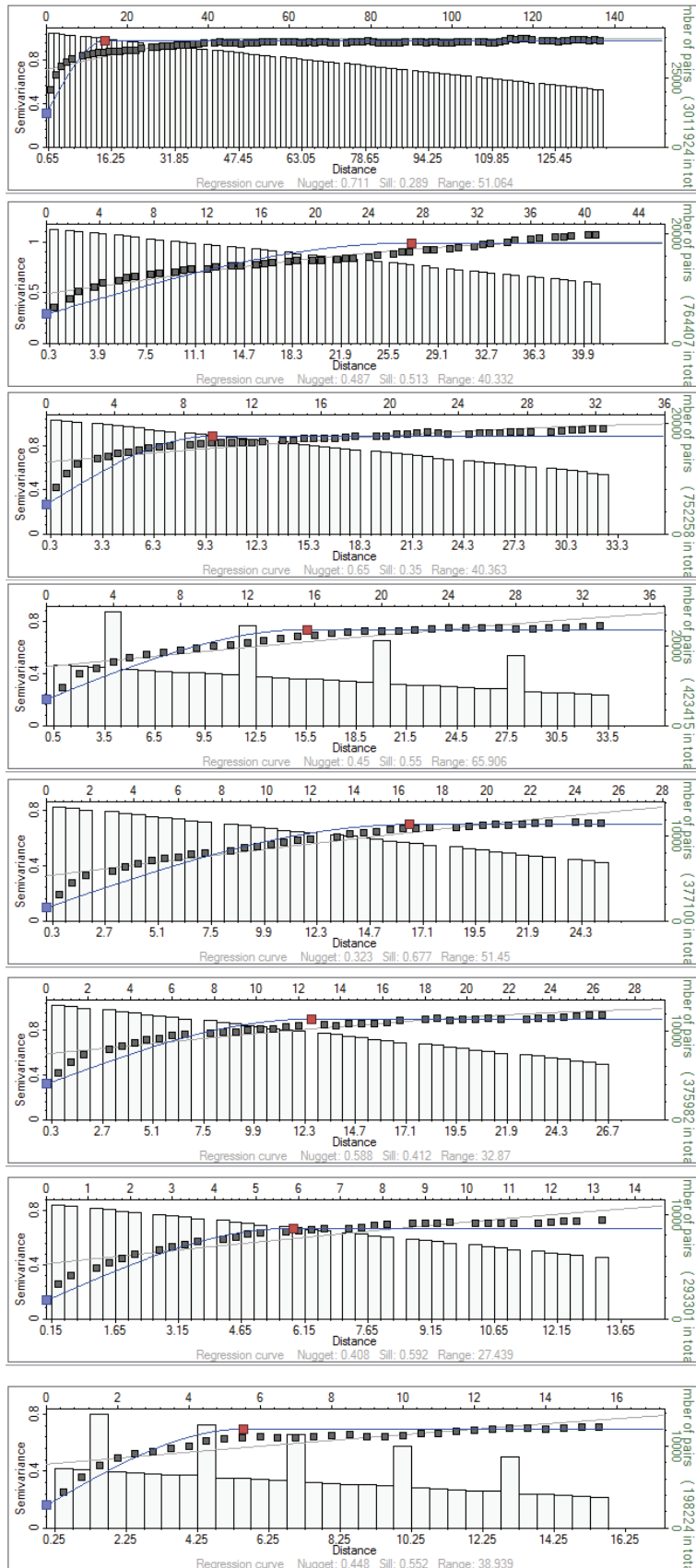


MRMC 6

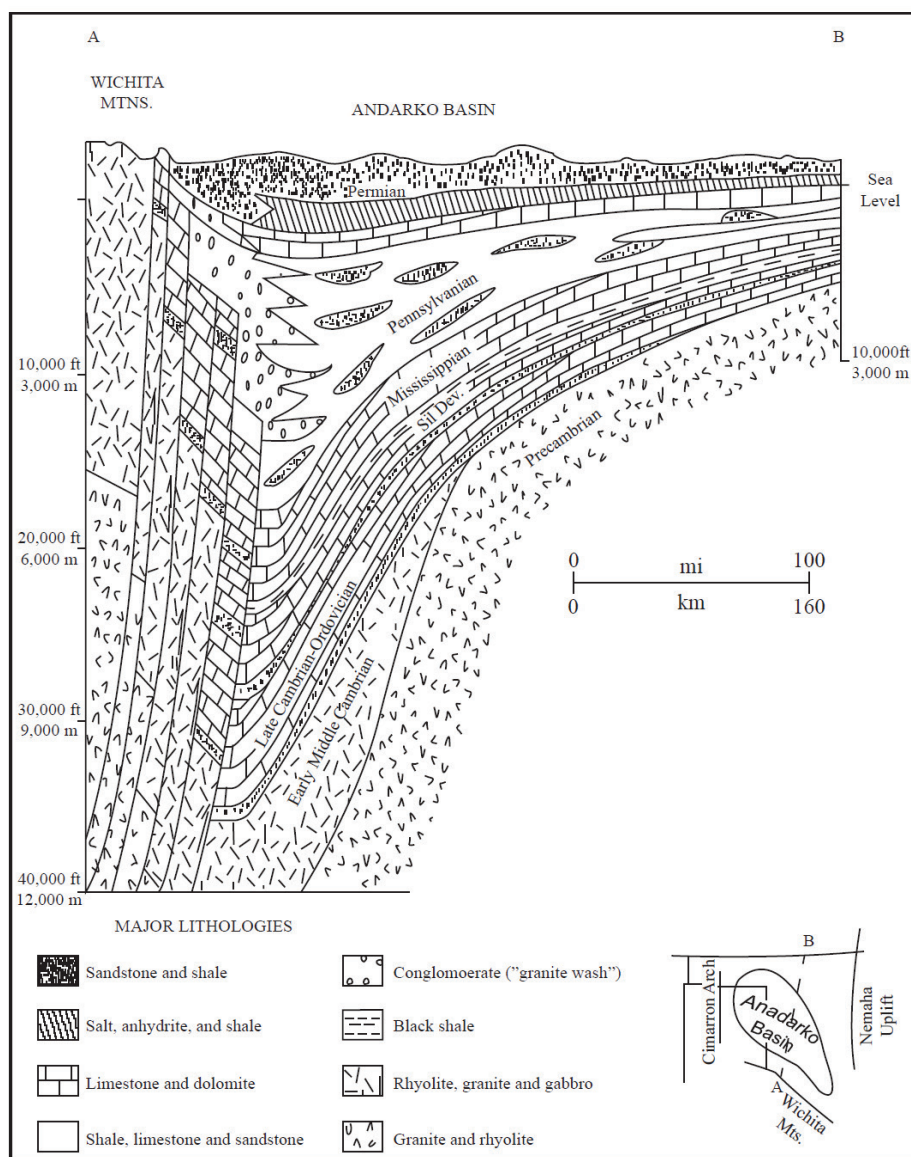


MRMC 7

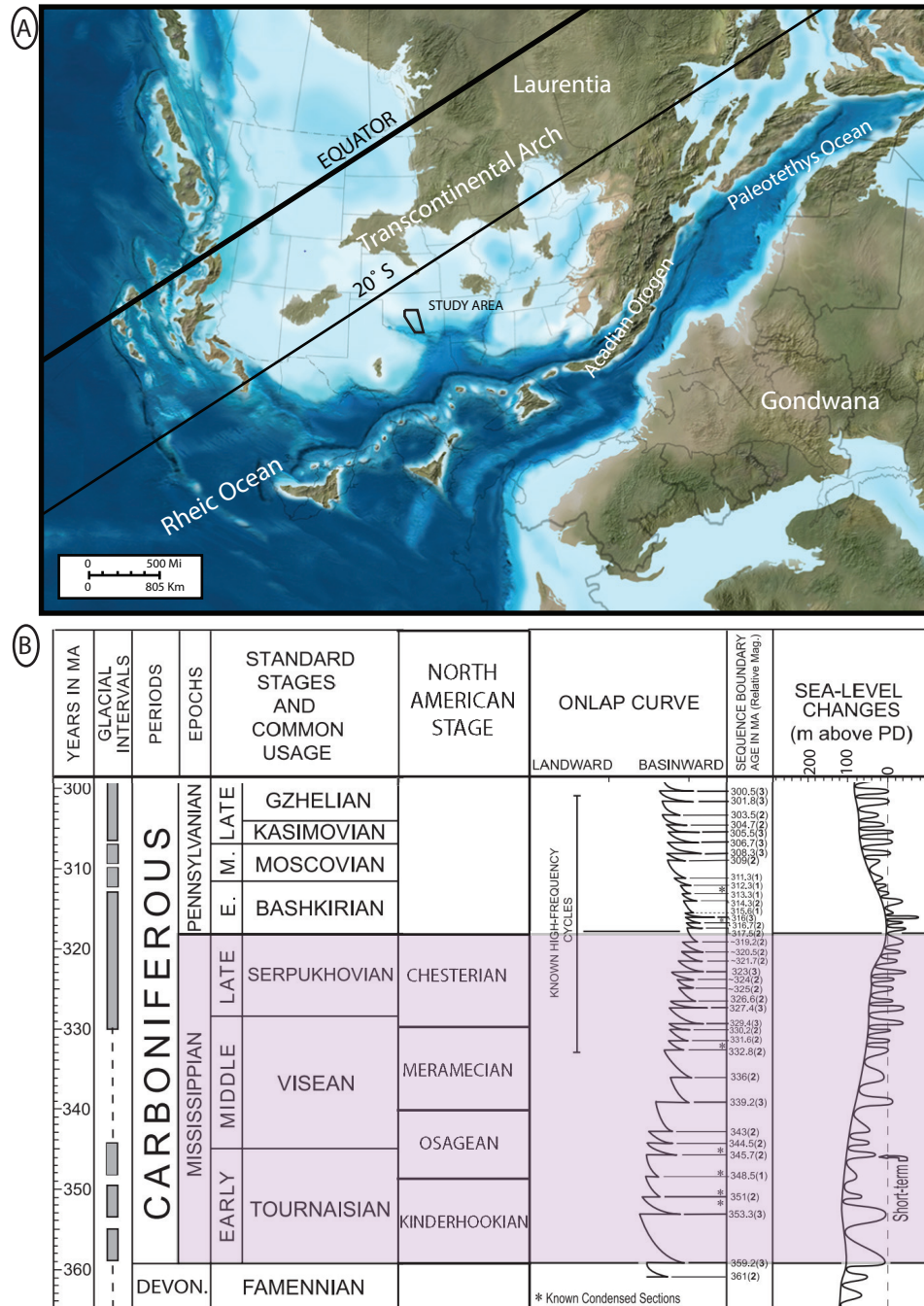
Vertical variograms for PHIT for the zones of the STACK model.



APPENDIX E: Additional Discussion Images



Appendix E-1. SW to NE structural cross section through the Anadarko Basin showing generalized lithology throughout the Paleozoic. The Mississippian was deposited during the transitional subsidence regime between the Cambrian rift basin and Pennsylvanian foreland-style basin. The Mississippian generally becomes more siliclastic in the dip direction from B to A. From Johnson, 1989.



Appendix E2. (A) Early Mississippian paleogeography. The study area is located is located between 20-30° S. Blue shading indicates water depth, with light blue being relatively shallow water and dark blue being deep water. The study sits along the margin between the Anadarko shelf and basin, represented by the change in water depth to the south (modified from Blakey, 2014). (B) Sea level curve during the Carboniferous Period. Purple shading indicates the Mississippian Epoch. The studied interval was deposited during a global 2nd-order sea-level fall with higher-order cyclicity present throughout (modified from Haq and Schutter, 2008).

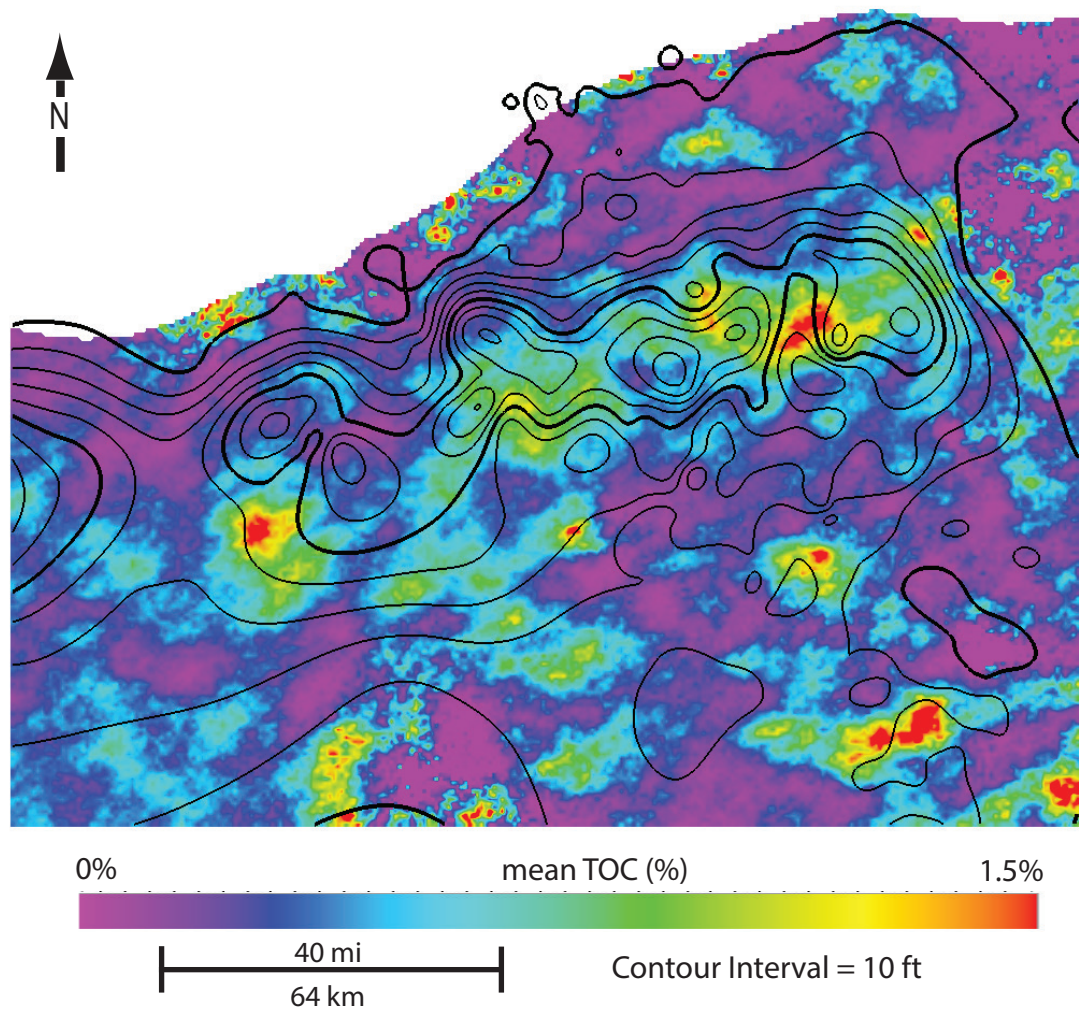


Figure E-3. Average model TOC of Meramec Zone 6, with contours representing isopach thickness of Meramec Zone 6. TOC is highest in the depocentre of this Meramec sequence.

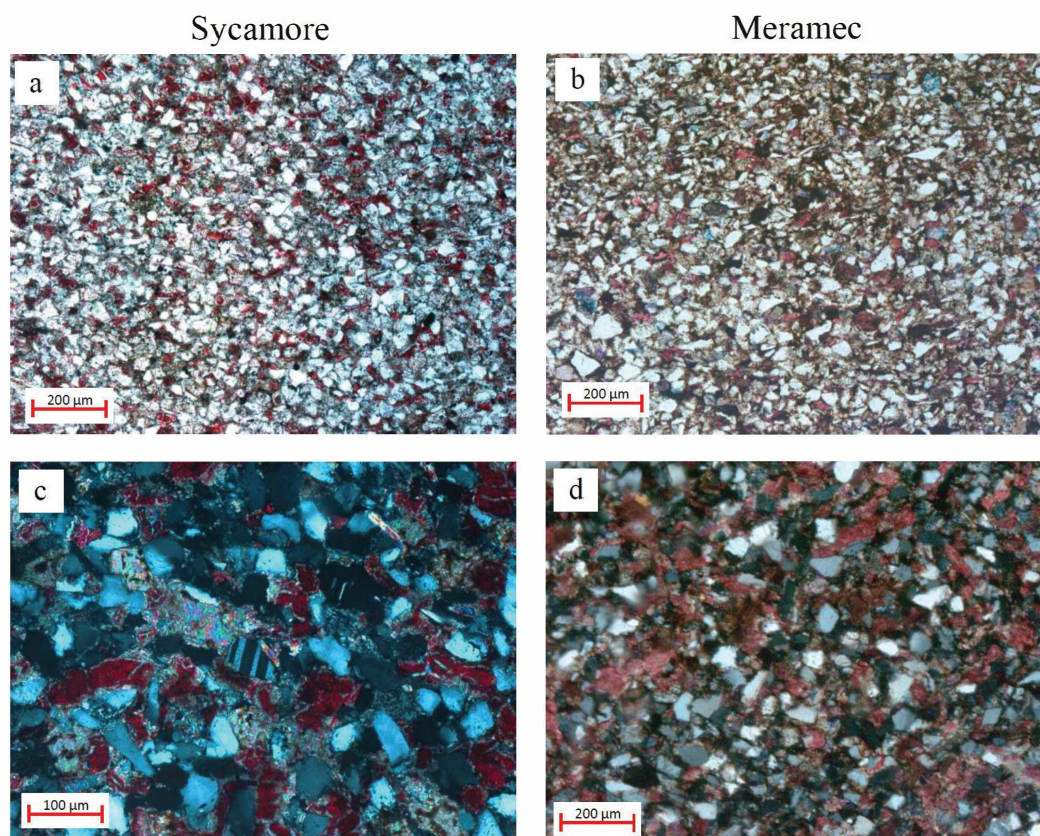


Figure E-4. (A&B) Comparison of silt abundance in upper bench of the Sycamore formation at outcrop X and the Meramec in Blaine County. Images are in plane-polarized light at 10x magnification, with calcite stained pink and blue epoxy. (C&D) Comparison of silt character in Sycamore and Meramec. Both possess sub-angular quartz grains with additional feldspars and micas, and carbonate cement occluding pore spaces. Images are in cross-polarized light.

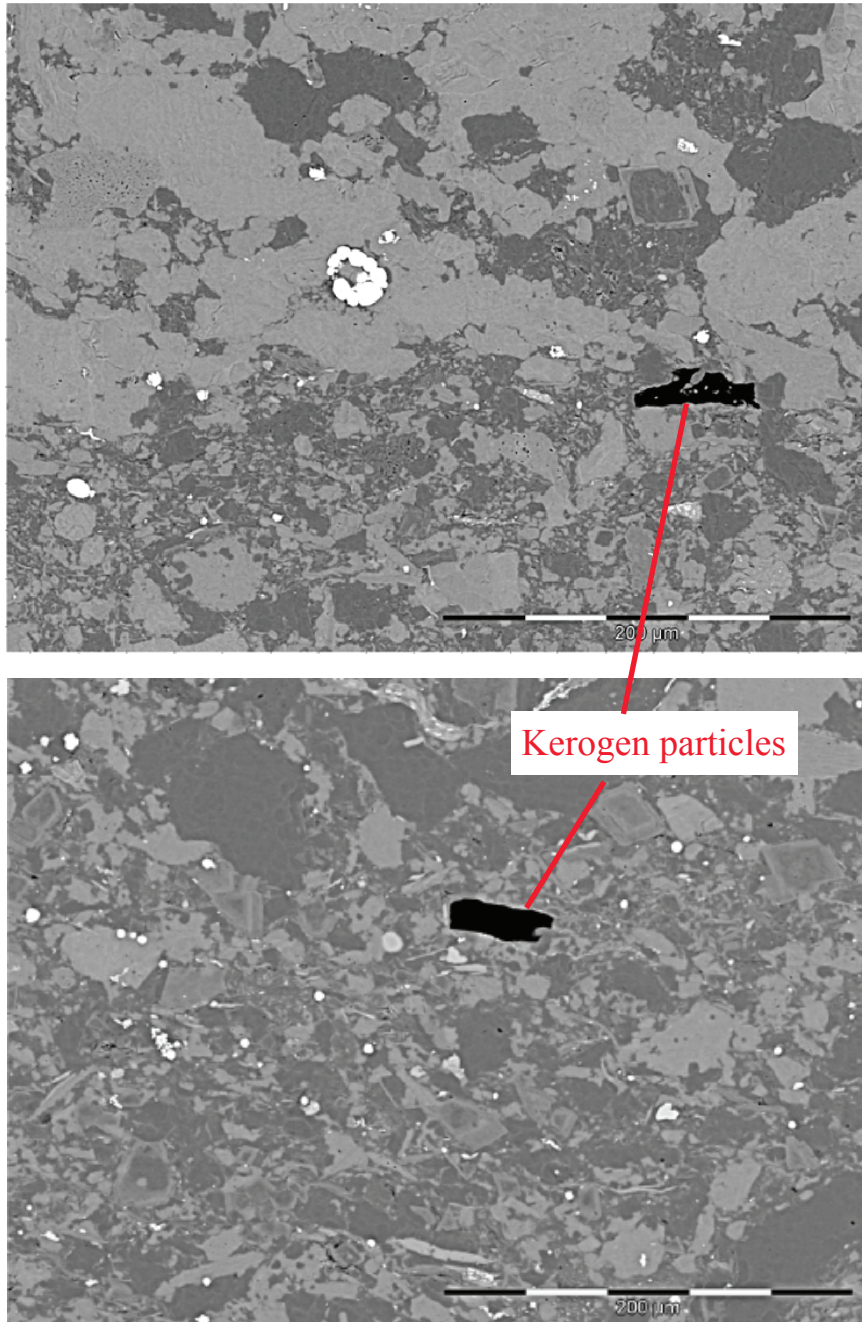


Figure E-5. Backscattered Electron Photomicrograph (300x) of two Shaffer 1-23 thin sections. Note the prescence of kerogen particles.



Figure E-6. Possible Bouma sequence in Shaffer 1-23 consisting of, from base to top, structureless calcareous siltstones (Ta), parallel-laminated siltstones (Tb), wavy laminated argillaceous siltstones (Tc), and faintly-laminated mudstones (Td). These fining-upwards sequences increase in clay content and decrease in carbonate content from base to top.