PS Stratigraphic Controls on Mississippian Limestone Reservoir Quality through Integrated Electrofacies Classification and Seismic Constrained Spatial Statistics, Barber County, Kansas*

Niles W. Wethington[1] and Matthew J. Pranter[1]

Search and Discovery Article #41924 (2016)**
Posted October 31, 2016

*Adapted from poster presentation given at AAPG 2016 Annual Convention and Exhibition, Calgary, Alberta, Canada, June 19-22, 2016

[1]University of Oklahoma, Norman, Oklahoma, United States (nwethington@ou.edu)

Abstract

Generation of accurate electrofacies estimations is in many ways essential for effective reservoir characterization. Classifying electrofacies, especially those constrained to core observations, can elucidate key relationships between depositional environments and reservoir properties. In addition, these relationships require an appropriate understanding of both the vertical and lateral heterogeneity of the deposits of interest. Typical subsurface data, particularly from vertical wells, lacks sufficient spatial constraints on lateral variability. Thus, this study uses 3-D seismic attributes of key reservoir lithologies to establish estimates of horizontal lithological variability. The integrated electrofacies classifications and seismic-based spatial statistics are used to analyze the stratigraphic controls on reservoir quality within the Mississippian Limestone. The Mississippian Limestone formed through complex structural, stratigraphic, and diagenetic processes involving subsidence, tectonic uplift leading to periodic subaerial exposure, changes in ocean chemistry, variability inherent with carbonate cyclicity, as well as post-depositional alteration. These geologic complexities have led to significant heterogeneity and compartmentalization within Mississippian mid-continent reservoirs. In the Hardtner field area, the Mississippian Limestone is approximately 350 ft (107 m) thick and is divided into 4 to 5 stacked shoaling-upward cycles. Historically, the most productive interval within this play has been the highly porous, diagenetically altered tripolitic chert. As is evidenced by characteristically low resistivity and high porosity, the tripolite facies (which is frequently associated with the sub-Pennsylvanian unconformity) occurs dominantly near the top of the formation. Stratigraphically lower tripolite intervals are often associated with small-scale high-frequency cycles. Through an integration of several electrofacies classification techniques, including an artificial neural network (ANN) and geostatistical clustering analysis, a "lithofacies log" is produced that predicts lithology and facies based only on the combined signatures of open-hole digital well logs in non-cored wells. Predictive lithology logs and seismic constrained spatial statistics are used to generate 3-D reservoir models that illustrate the stratigraphic control of high-frequency cycles on porosity development.

References Cited

Lindzey, K., 2015 Geologically constrained seismic characterization and 3-D reservoir modeling of Mississippian reservoirs, north-central Anadarko shelf, Oklahoma: Master's Thesis, University of Oklahoma.

Mazzullo, S., B.W. Wilhite, and I.W. Woosley, 2009, Petroleum reservoirs within a spiculite-dominated depositional sequence: Cowley Formation (Mississippian: Lower Carboniferous), south-central Kansas: AAPG Bulletin, v. 93/12, p. 1649-1689.

Rogers, S. M., 2001, Deposition and diagenesis of Mississippian chat reservoirs, north-central Oklahoma: AAPG Bulletin, v. 85/1, p. 115-129.

Watney, W.L., W.J. Guy, and A.P. Byrnes, 2001, Characterization of the Mississippian chat in south-central Kansas: AAPG Bulletin, v. 85/1, p. 85-113.

The UNIVERSITY of OKLAHOMA
Mewbourne College of Earth and Energy
ConocoPhillips School of Geology and Geophysics
ConocoPhillips

STRATIGRAPHIC CONTROLS ON MISSISSIPPIAN LIMESTONE RESERVOIR QUALITY THROUGH INTEGRATED ELECTROFACIES CLASSIFICATION AND SEISMIC CONSTRAINED SPATIAL STATISTICS, BARBER COUNTY, KANSAS

Niles W. Wethington and Matthew J. Pranter

ConocoPhillips School of Geology and Geophysics, University of Oklahoma, Norman, Oklahoma

RCML
Reservoir Characterization and Modeling Laboratory
The University of Oklahoma

Abstract

Generation of accurate electrofacies estimations is in many ways essential for effective reservoir characterization. Classifying electrofacies, especially those constrained to core observations, can elucidate key relationships between depositional environments and reservoir properties. In addition, these relationships require an appropriate understanding of both the vertical and lateral heterogeneity of the deposits of interest. Typically subsurface data, particularly from vertical wells, lacks sufficient spatial constraints on lateral variability. Thus this study uses 3-D seismic attributes of key reservoir lithologies to establish estimates of horizontal lithological variability. Integrated electrofacies classifications and seismic-based spatial statistics are used to analyze the stratigraphic controls on reservoir quality within the Mississippian Limestone.

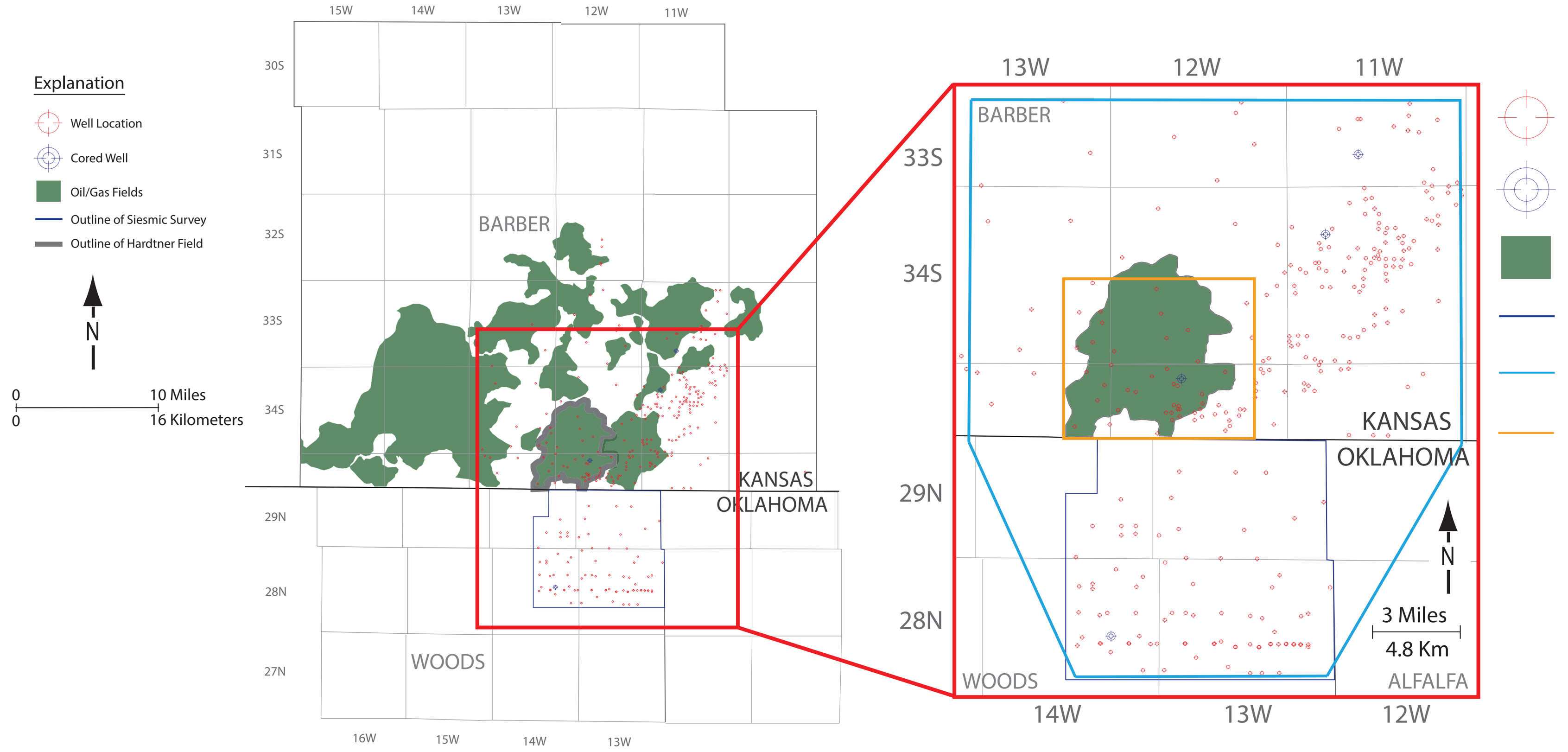
The Mississippian Limestone formed through complex structural, stratigraphic, and diagenetic processes involving subsidence, tectonic uplift leading to periodic subaerial exposure, changes in ocean chemistry, variability inherent with carbonate cyclicity, as well as post-depositional alteration. These geologic complexities have led to significant heterogeneity and compartmentalization within Mississippian mid-continent reservoirs. In the Hardtner field area, the Mississippian Limestone is approximately 350 ft (107 m) thick and is divided into 4 stacked shoaling-upward cycles. Historically, the most productive interval within this play has been the highly porous, diagenetically altered tripolitic chert. As is evidenced by characteristically low resistivity and high porosity, the chert rich facies (which is frequently associated with the sub-Pennsylvanian unconformity) occurs dominantly near the top of the formation. Stratigraphically lower tripolite intervals are often associated with small-scale high-frequency cycles. Through an integration of several electrofacies classification techniques, including an artificial neural network (ANN) and geostatistical clustering analysis, a "lithofacies log" will be produced that predicts lithology and facies based only on the combined signatures of open-hole digital well logs in non-cored wells. Predictive lithology logs and seismic constrained spatial statistics are used to generate 3-D reservoir models that illustrate the stratigraphic control of high-frequency cycles on porosity development.

Research Objectives

This study expands upon previous work in the Anadarko ramp to resolve some of the stratigraphic complexity that has perplexed academic and industry professionals alike. For the Mississippian limestone and silica rich reservoirs in the Hardtner Field area, this study aims to better define (1) the dominant lithologies, lithofacies, rock fabrics, and pore types, (2) the stratigraphic patterns present and how they are associated with carbonate cycles, (3) how key lithofacies and petrophysical reservoir properties are distributed laterally and vertically, and (4) how the spatial distribution of reservoir properties links to production in the area.

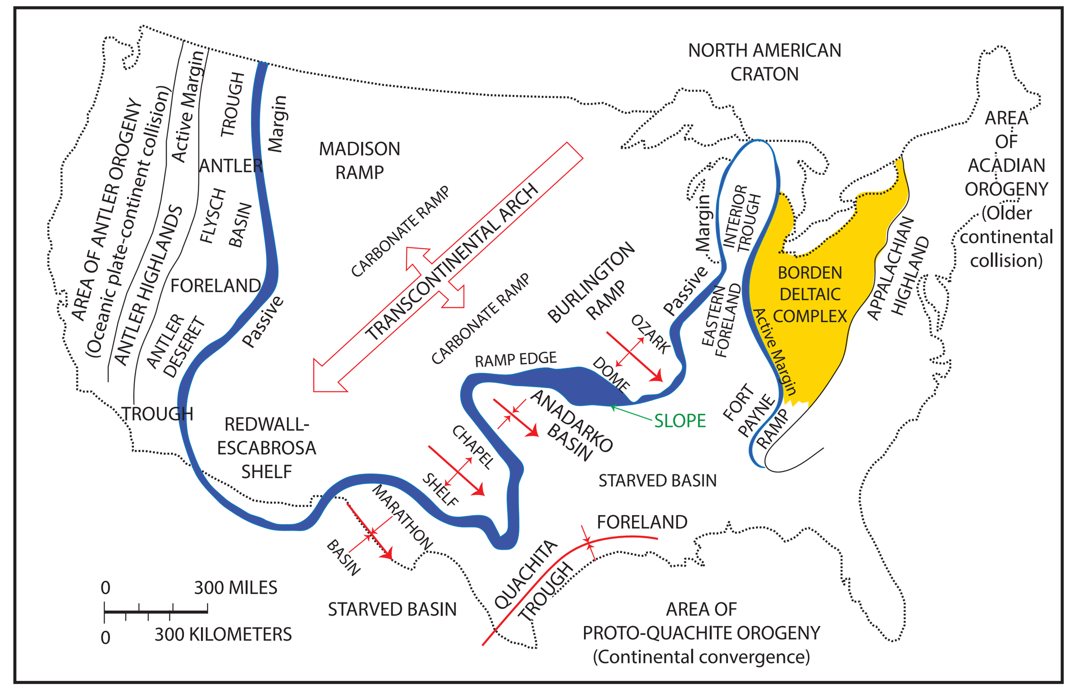
Study Area

Regional map showing tectonic provinces of Kansas, Oklahoma, and the Texas panhandle. Study area is highlighted in red. (Modified from Johnson and Luza, 2008 and Northcutt and Campbell, 1995)

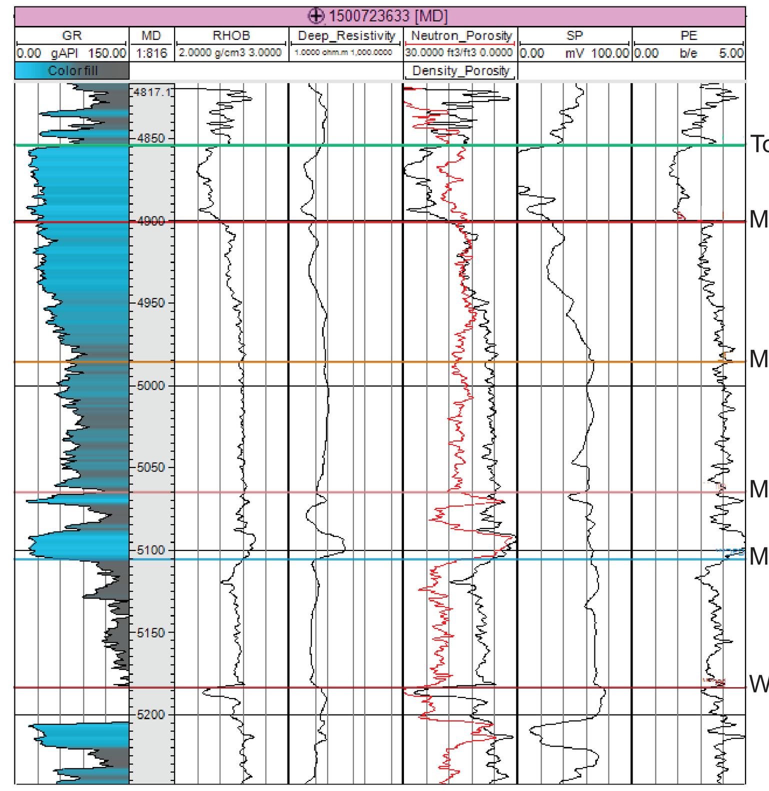


Detailed maps of study area including location of major oil and gas fields in Barber County and model boundaries. Data includes 298 wells with logs, four cored wells, a 3D seismic survey, scaled production data, and thin sections.

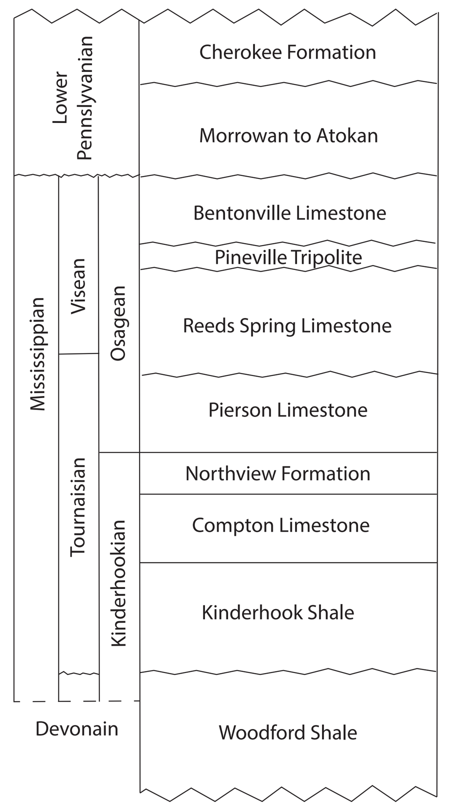
Geologic Setting



North American paleogeography during the Mississippian showing position of the Anadarko Basin and relevant structural features. (Modified from Gutschick and Sandberg, 1983)

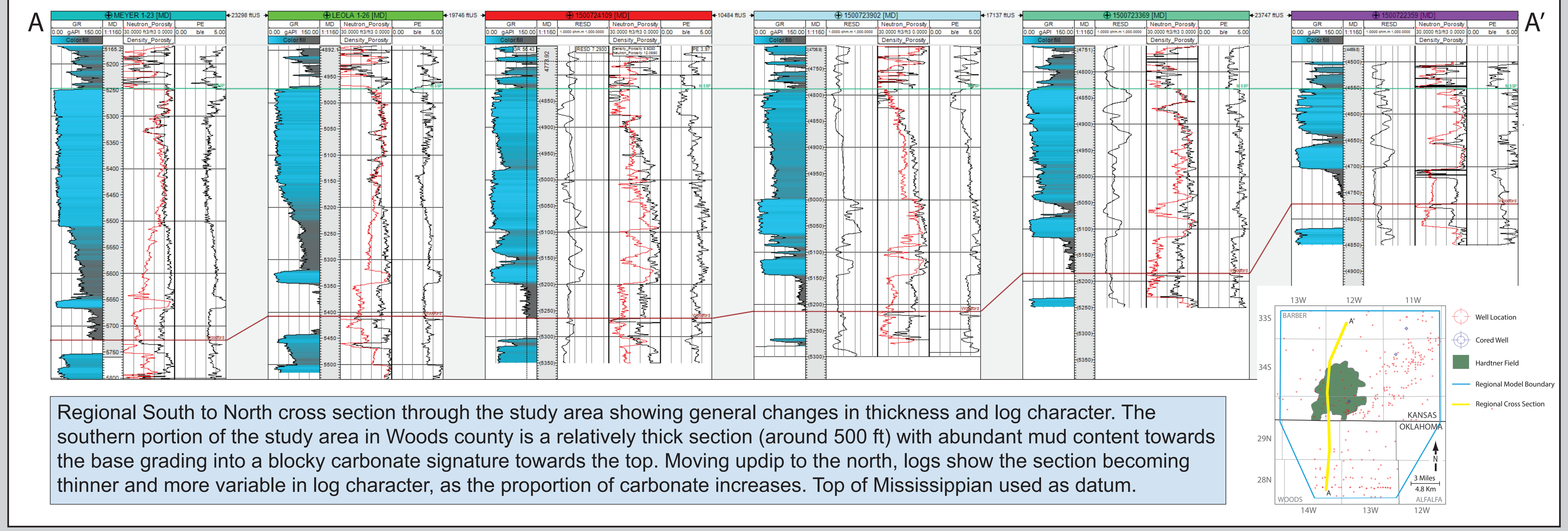


Type log for the Mississippian section in the Hardtner Field area. Well top picks shown represent changes in log signature consistently observed throughout the study area



Idealized stratigraphic column for south-central Kansas. (Modified from Mazzullo and Wilhite, 2009 and 2016)

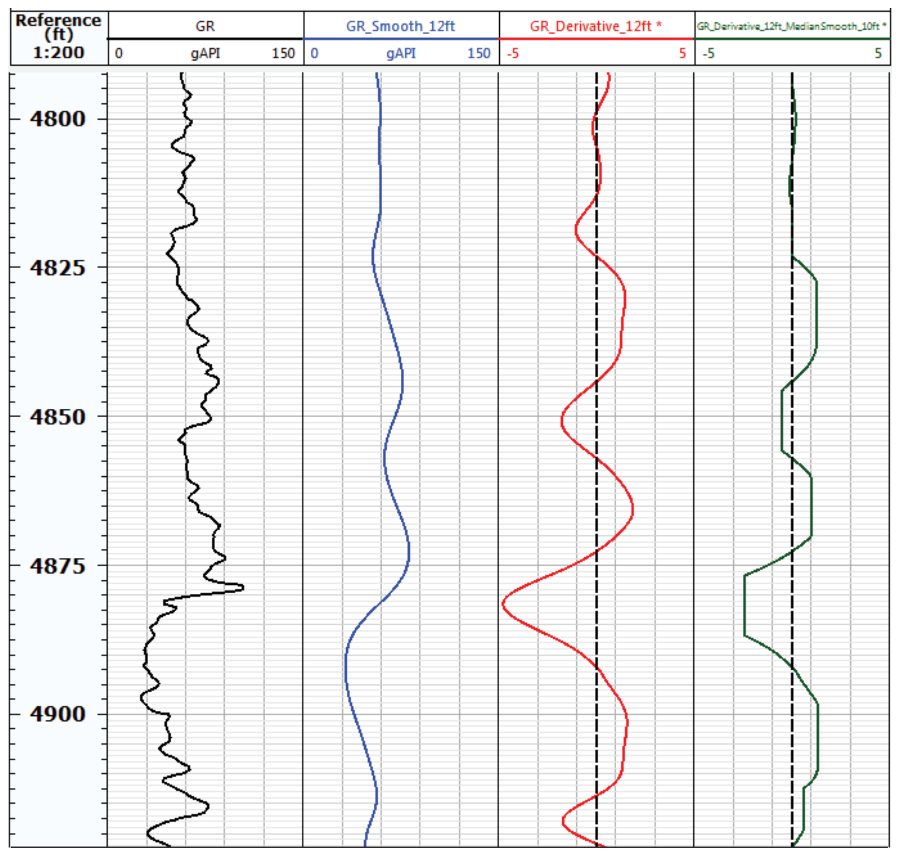
Regional Stratigraphy



Regional South to North cross section through the study area showing general changes in thickness and log character. The southern portion of the study area in Woods county is a relatively thick section (around 500 ft) with abundant mud content towards the base grading into a blocky carbonate signature towards the top. Moving updip to the north, logs show the section becoming thinner and more variable in log character, as the proportion of carbonate increases. Top of Mississippian used as datum.

Gamma Ray Derivative Trend Modeling

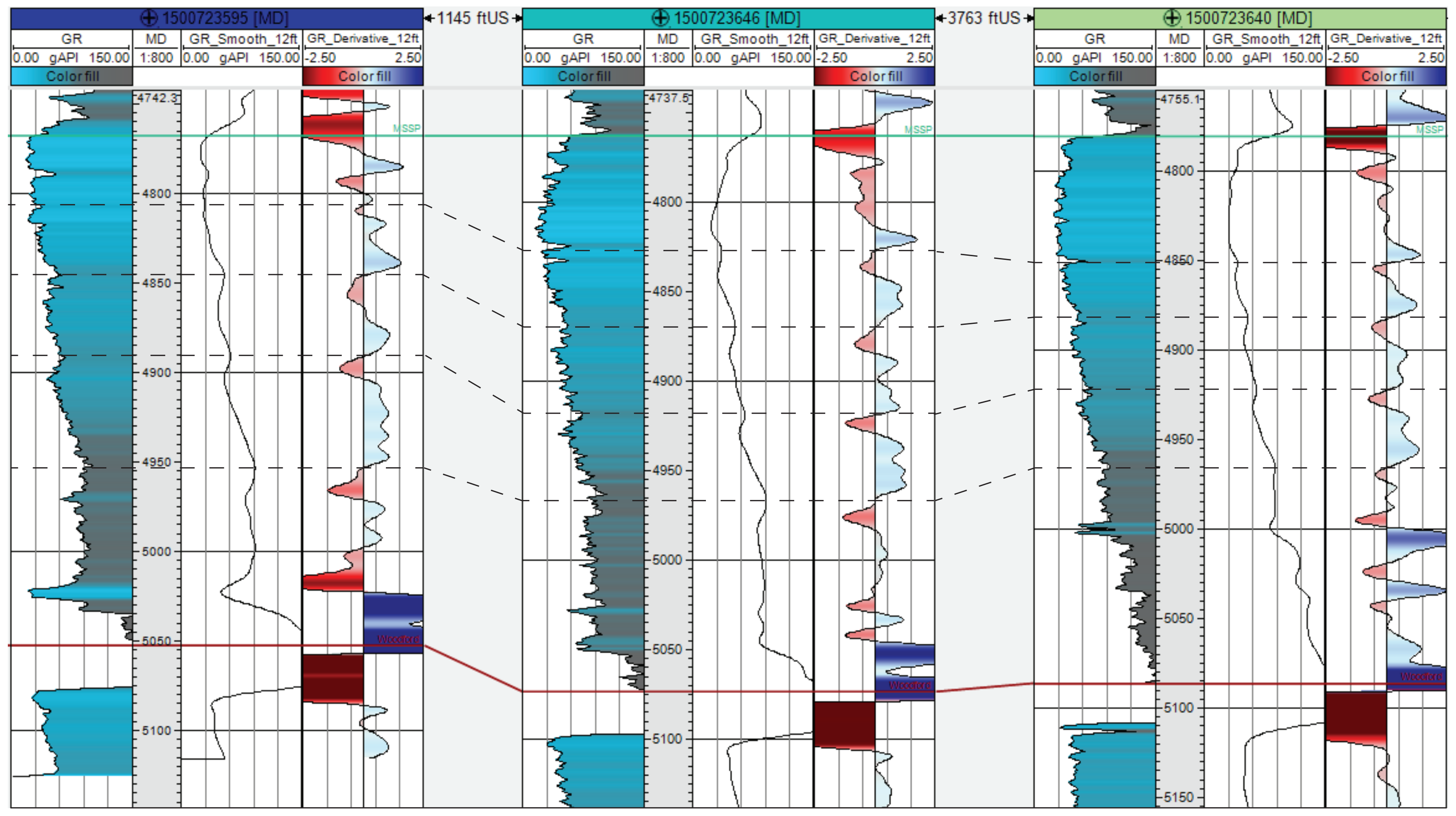
Well 1500723359



Vertical gamma ray trends can often indicate "coarsening" or "fining" upward sequences, which can be related to cyclicity in both clastics and carbonates. In order to identify, visualize, and correlate specific vertical gamma ray trends, a derivative curve was created. Gamma ray curves were first smoothed using a Gaussian function to reduce high frequency or small scale fluctuations, while preserving low frequency or long-term trends. Various smoothing windows were computed and compared using Techlog software. Ultimately a 12 ft (3.6m) smoothing window was used for analysis. The 1st derivative is approximated using the central difference method according to the following general formula:

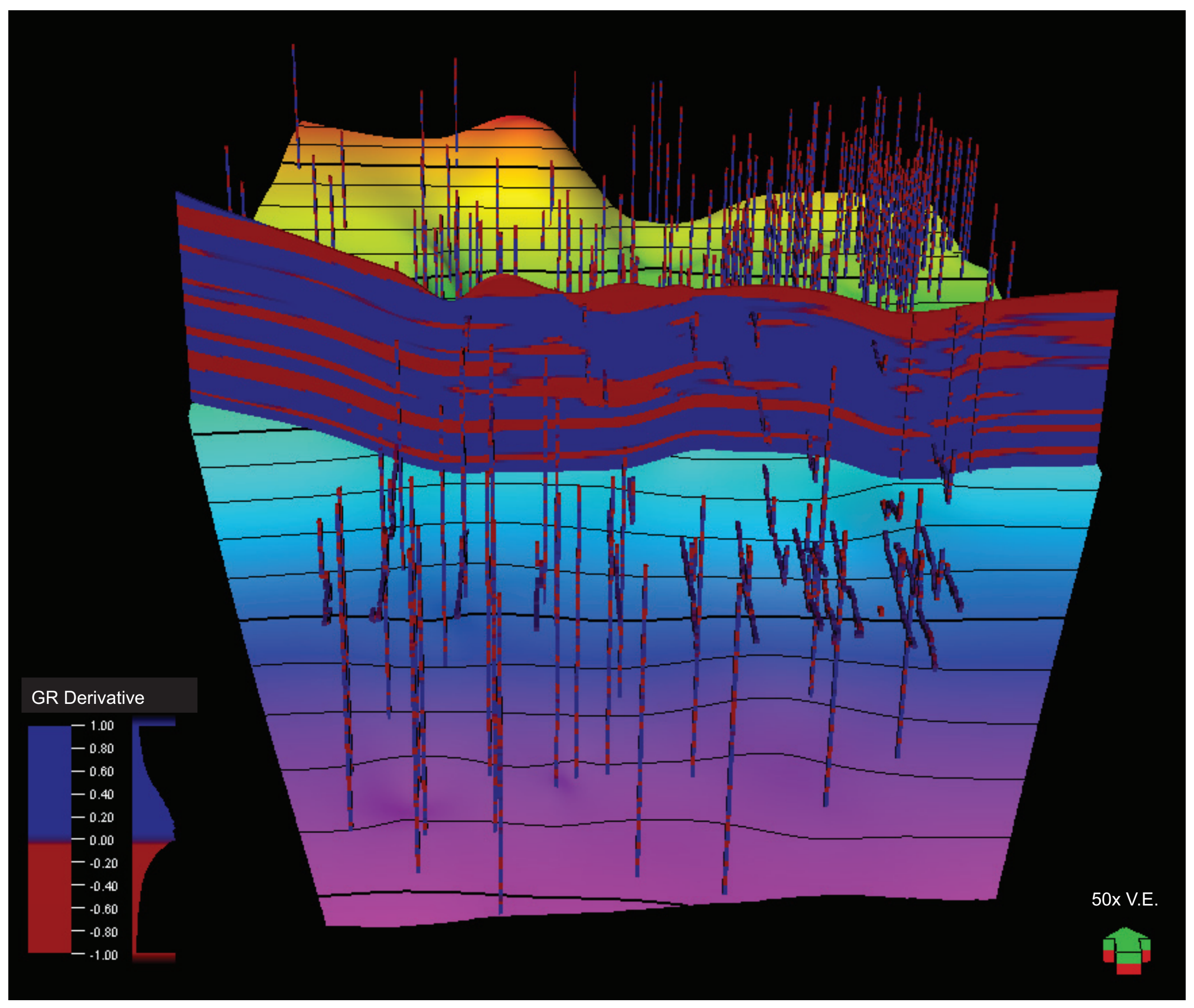
Value(i) = (Value(i +1) - Value(i -1)) / (Depth(i+1) - (Depth(i-1))

For portions of the curve that display a "coarsening" upward trend, the derivative curve will have positive values, and for portions of the cuve that display a "fining" upward trend, the derivative curve will have negative values. The derivative curve is then discretized or upscaled in order to generalize and correlate cycles.



Cross section showing original GR curves, smoothed GR curves, and GR derivative curves (red fill represents negative derivative values or cycle breaks, and blue fill represents positive values or coarsening upward cycles). "Coarsening" upward cycles appear to correlate. In general we can distinguish 4 stacked cycles, which agrees with the core based interpretation proposed by Watney, 2001.

Regional and Local smoothed gamma ray derivative models were computed in an attempt to visualize how carbonate cycles are correlated in 3 dimensions. This East West slice of the regional model shows that blue "coarsening" upward cycles tend to correlate locally, however the model struggles to break out individual cycles regionally, particularly towards the east of the Hardtner Field area. The model displayed was computed using Petrel's functional method using an inverse distance squared algorithm.Structure map of the top of the Woodford (base of Mississippian section) shown beneath model for reference.

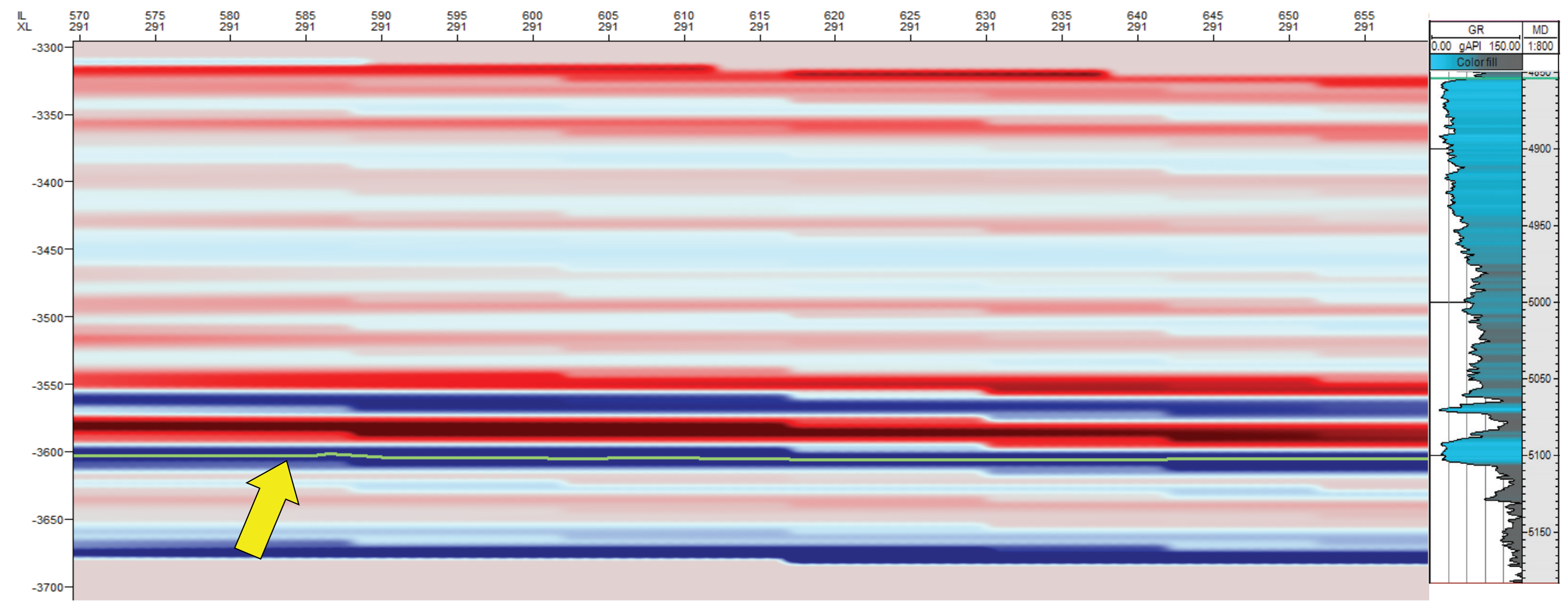


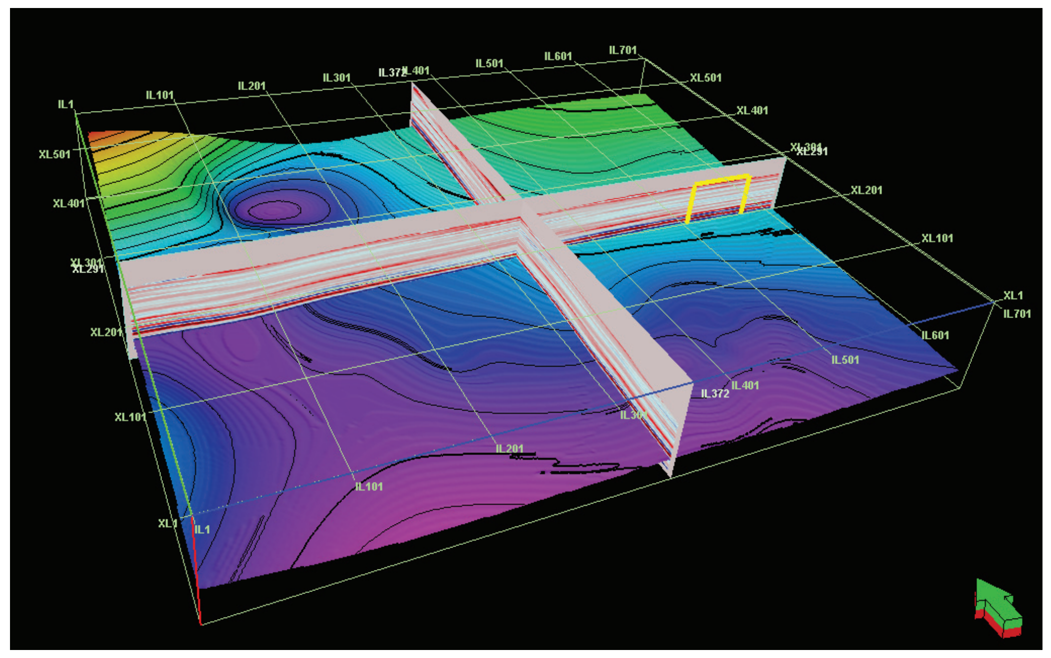
Seismic Derived Variography

Through traditional well log and core data, an excellent understanding of vertical variability can be attained. There is however much more uncertainty when considering horizontal variability. Seismic data, on the other hand, offers much improved spatial, but is limited to poor vertical resolution. In order to constrain estimates of vertical and spatial homogeneity, this study will use a combination of well log data and seismic attribute maps as proxies of the lateral extent for certain lithofacies. Through the use of a variogram map based on dimensions acquired from a seismic survey in Northeast Woods county (immediately south of Hardtner Field), a model with geologically reasonable constraints on lateral variability can be produced.

Synthetic Seismic Assisted Surfaces

Major well top picks within the "Miss Lime" (whether corresponding to formations, lithologies, or carbonate cycles) are based on a specific change in log character. For example, the basal limestone unit (Compton Limestone) can be identified by a rapid decrease in gamma ray at its base and an increase at its top. Thus, a gamma ray derivative model effectively displays both the base and top of this unit as strong positive and negative "reflectors" respectively. By converting a computed (functional) derivative model into a synthetic seismic volume, these "reflectors" can be picked, and the resultant surface represents a formational or lithologic boundary. While the accuracy of this surface is limited by both the modeling algorithm used and seismic picking method, the surface does represent the approximate position of a set of electrofacies. Thus, this method of synthetic seismic assisted surface picking is not proposed as a replacement for traditional well log correlations, but instead as a way to quality control surfaces generated from manual picking of well tops. In addition, in data sets with large numbers of well logs where picking individual tops can be tedious and somewhat subjective, extracting surfaces from derivative models can offer a faster and comparable alternative.

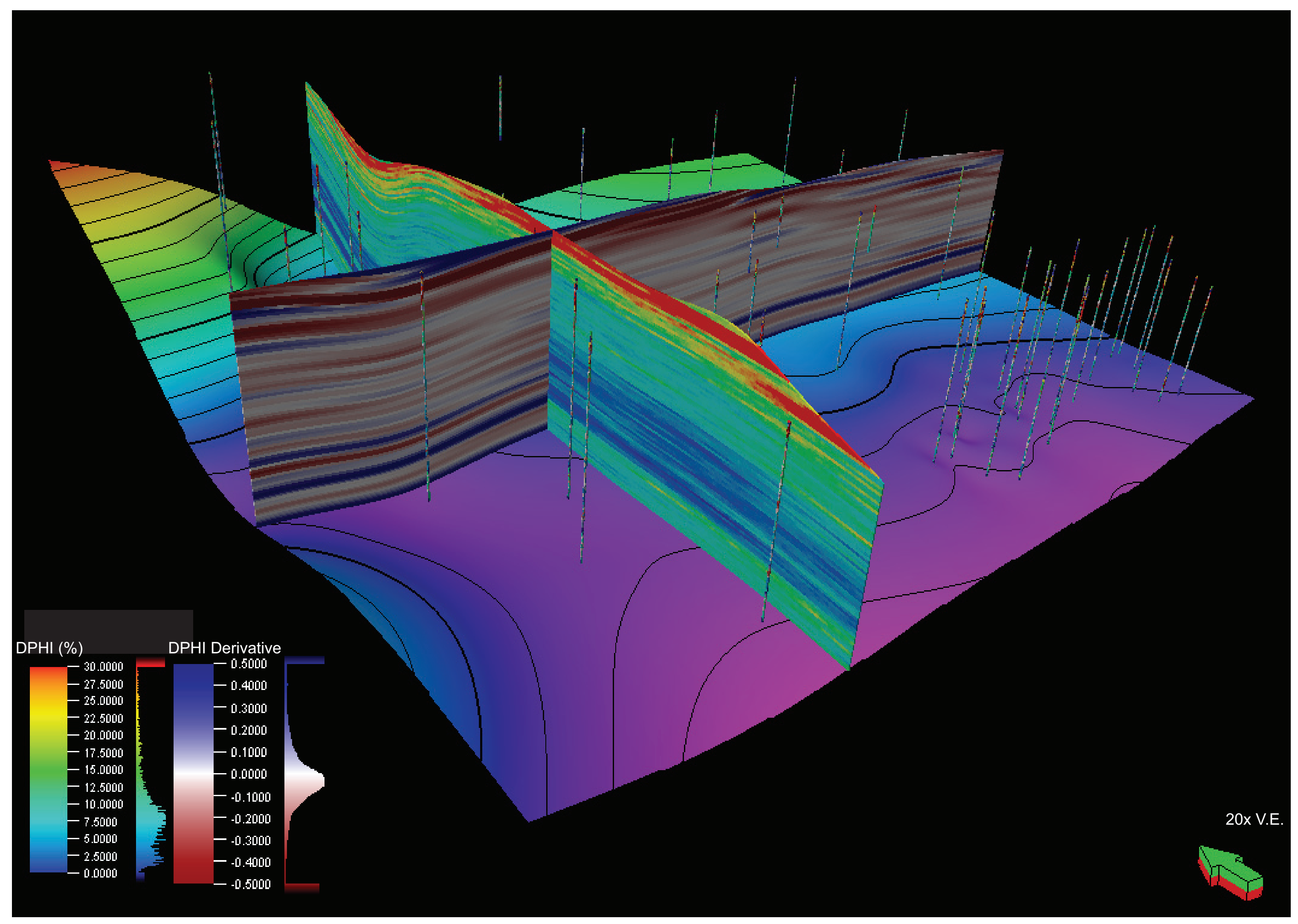




The figure above shows a cross line of a synthetic seismic volume generated from a gamma ray derivative model with a gamma ray curve for reference. The yellow arrow shows the reflector corresponding to the base of the limestone package near the based of the section.

The figure to the left shows cross lines and inlines of the synthetic seismic volume as well as the surface created from picking the reflector identified above.

Porosity Distribution



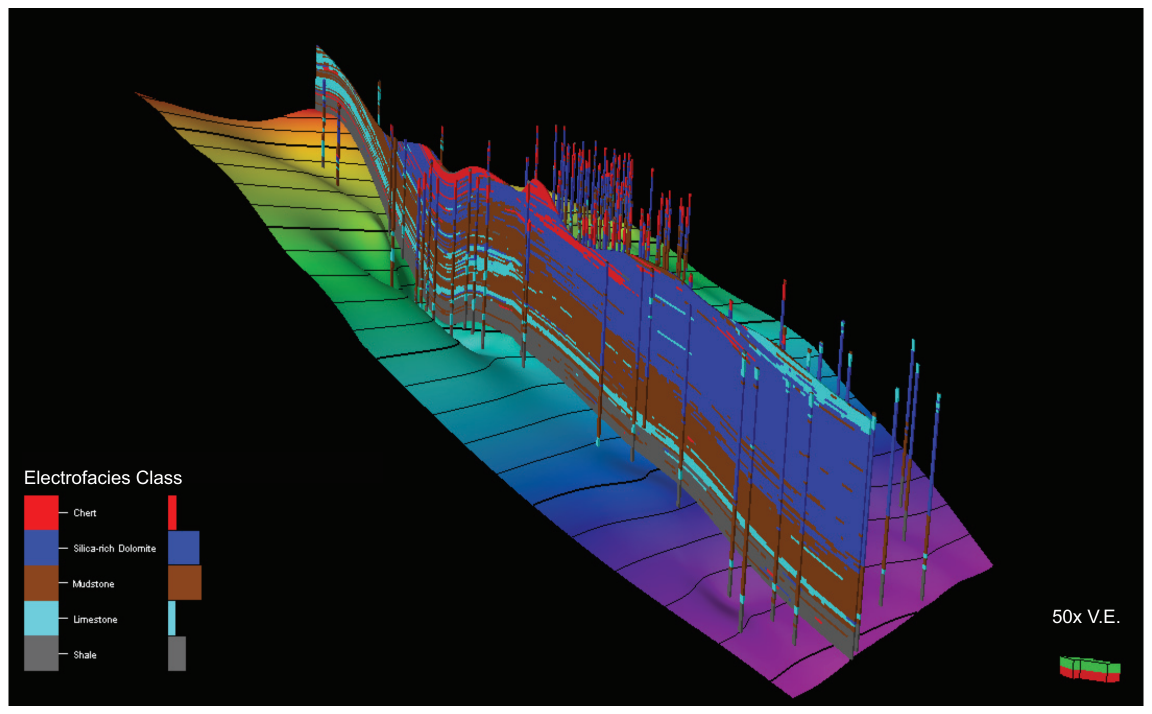
Petrophysical modeling reveals a highly porous zone near the top of the Mississippian section in Hardtner Field. This zone, often referred to as "chat," likely associated with increased diagenetic chert replacement, and generally exhibits best reservoir quality. A first derivative model of density porosity allows this reservoir zone to be easily traced, and can be used as a constraint when isolating this potentially productive interval. The position of this zone directly underneath the Pennsylvanian unconformity suggests that diagenesis is the main control on porosity. Structure map of the top of the Woodford is shown beneath model for reference.

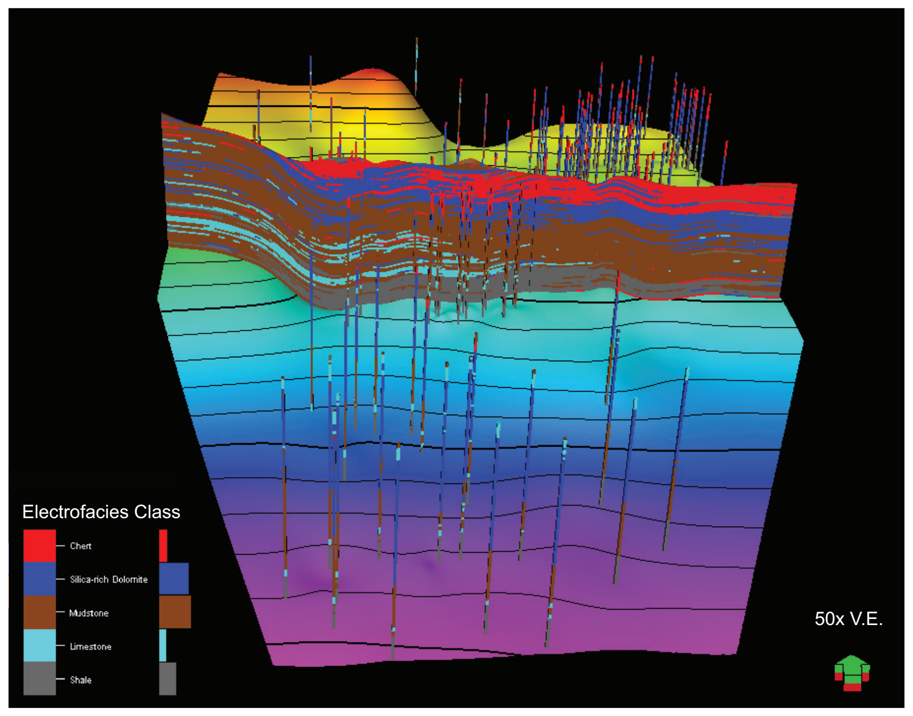
Proposed Classification Techniques

Artificial Neural Networks (ANNs) are useful classification tools that work by minimizing the error between a given output and an estimated or calculated output. This is accomplished through combining and weighting several input variables. Neural Networks are able to effectively construct complex decision boundaries for multiple classes, separating data into similar groups. In the context of this study, an ANN is used to relate electrofacies to lithofacies. Core descriptions identifying lithofacies are used as the target output, and different combinations of well log curves are used as inputs. The neural network combines and weights the inputs in an iterative process to recreate the core descriptions as closely as possible. Once a satisfactory match is achieved, the ANN is applied to non-cored wells using the same well log curves as inputs in order to “predict” the lithofacies at a given depth.

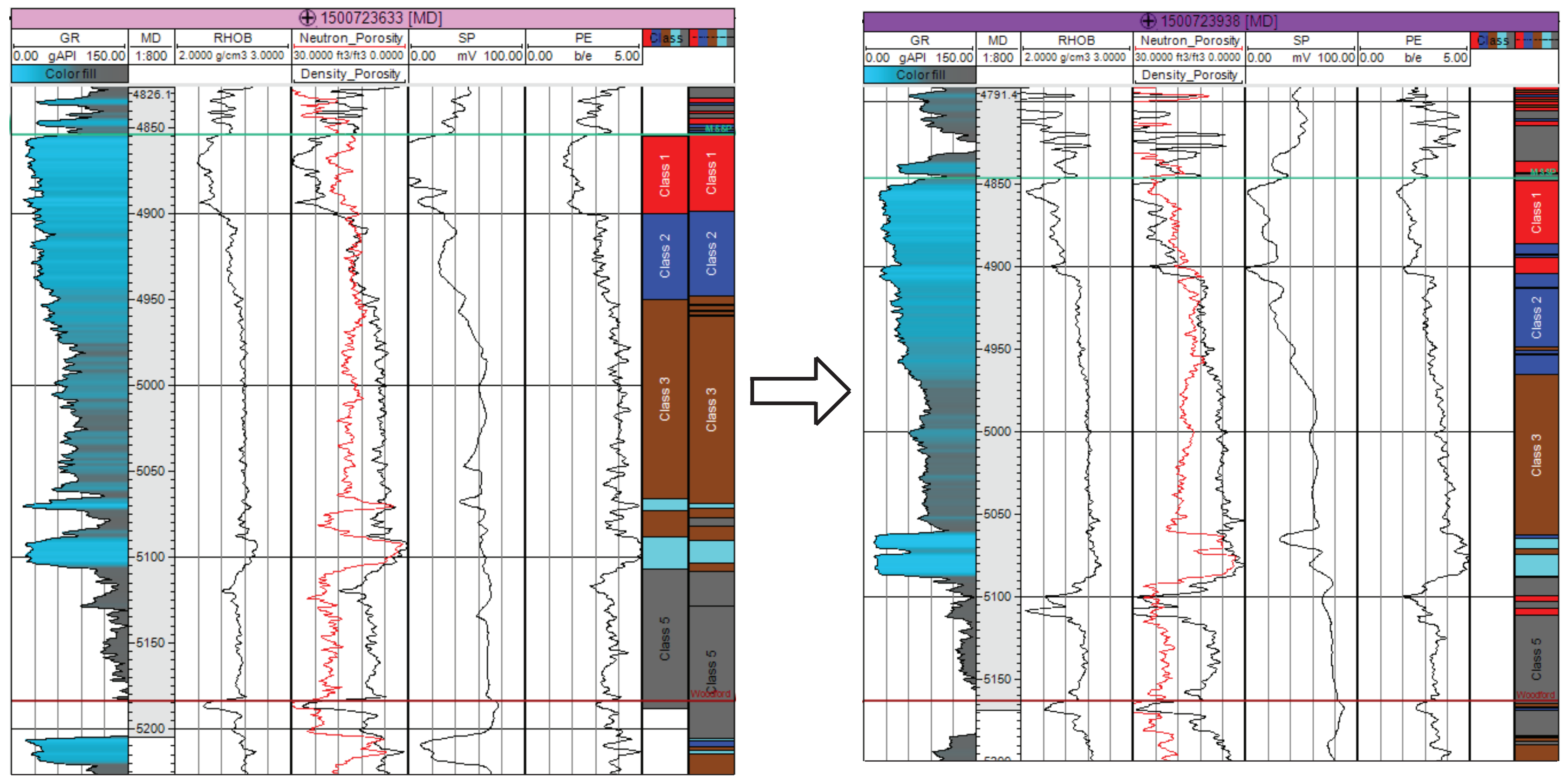
KNN (nearest neighbor clustering) classifies an unknown data point based on the most frequently occurring class of its nearest previously defined data points. The number of neighboring points considered (referred to as K) is defined by the user and should be adjusted to find an optimum value for each data set. The number of log curves used as inputs defines the dimensionality of the data set around the sampling point that is searched to find the surrounding points with the smallest euclidan distance.

A **Self Organizing Map (SOM)** is a type of unsupervised neural network. This means there is no target output provided. Instead, the data provided by inputs is separated into a certain user defined number of classes. These classes may or may not correspond to distinct lithofacies. A SOM produces a grid of outputs based on all possible combinations of inputs (well log curves), then assigns testing points to a position on the grid based on its specific input values. Successive points are placed a certain distance away according to how similar they are to previous testing points. As more data points are added, clusters being to form and classes are established. For the purposes of this study, classes produced using an SOM will be compared to the lithofacies classes defined in core samples.





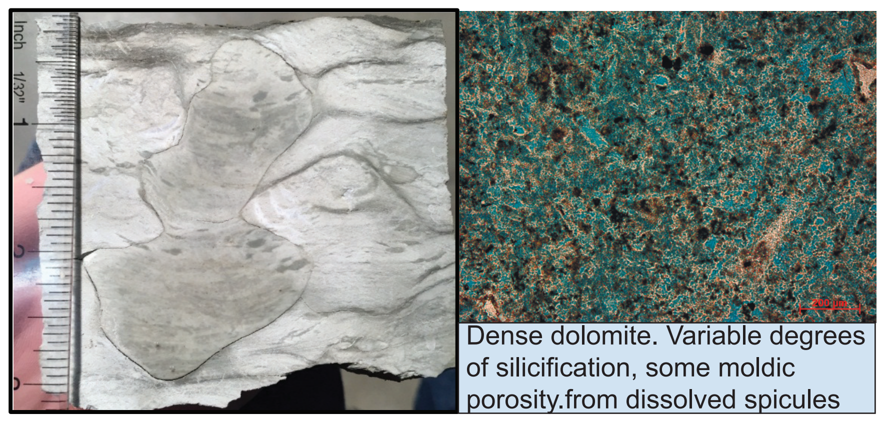
Electrofacies Modeling



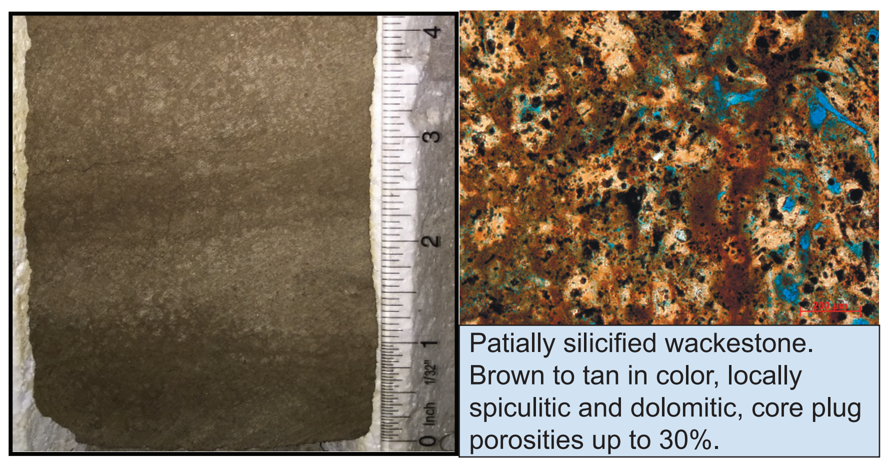
Artificial Neural Network classifying user defined electrofacies classes based on characteristic log signatures observed in Hardtner Field type log. inputs include GR, DPHI, NPHI, PE, and GR derivative. The figure on the right shows the ANN applied to another well in the field area (a blind test). General log characteristics that define each class are preserved in the blind test. The result is a log that is able to recognize and classify depth intervals into thier appropriate electrofacies classes.

Modeling of this low resolution electrofacies log provides a framework of the spatial distribution for each electrofacies. Preliminary modeling shows a decrease in limestone content (electrofacies class 4) towards the East and South of Hardtner Field. The model also suggests the appearance of limestone near the top of the Mississippian in Woods county, which is validated from core samples (Lindzey, 2015). Highly porous chert dominated lithologies near the top of the section are thicker towards the East and North. These chert intervals are typically associated with subarial exposure and subsequent silica replacement through successive fluxes of saturated meteoric water (Mazzulo, 2009; Rogers, 2001; Watney, 2001).

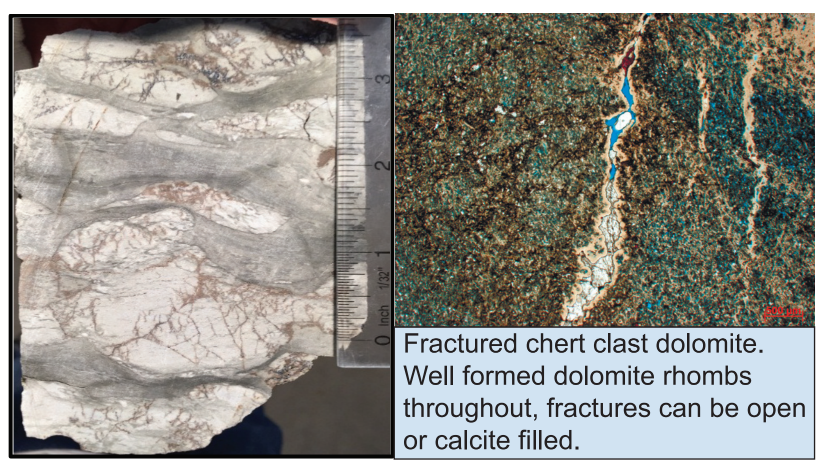
Core Defined Lithofacies



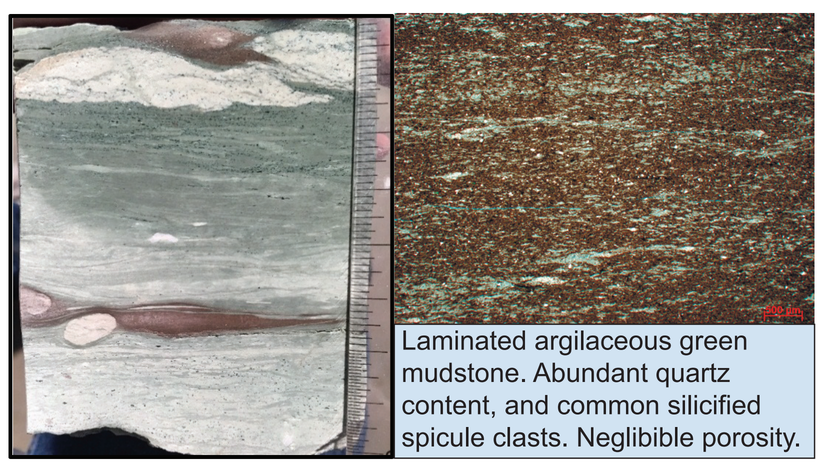
Dense dolomite. Variable degrees of silicification, some moldic porosity.from dissolved spicules



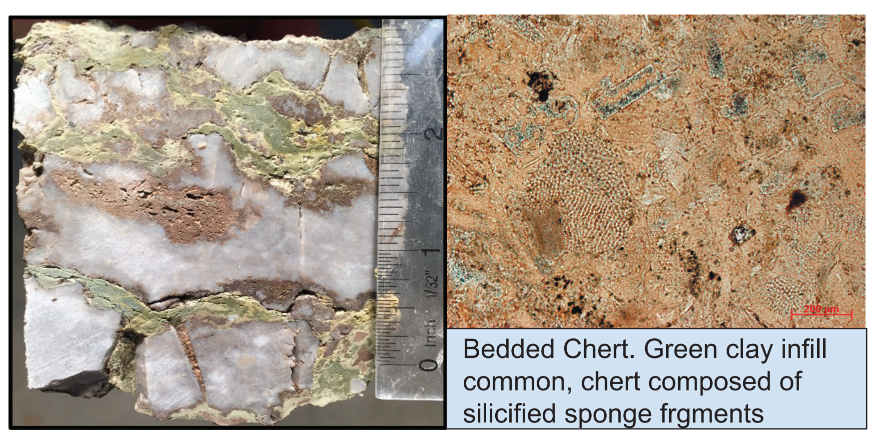
Patially silicified wackestone. Brown to tan in color, locally spiculitic and dolomitic, core plug porosities up to 30%.



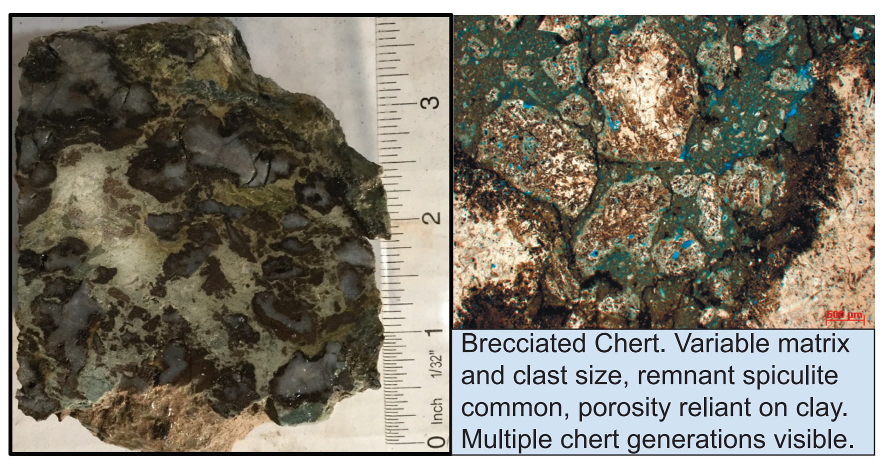
Fractured chert clast dolomite. Well formed dolomite rhombs throughout, fractures can be open or calcite filled.



Laminated argilaceous green mudstone. Abundant quartz content, and common silicified spicule clasts. Neglibible porosity.



Bedded Chert. Green clay infill common, chert composed of silicified sponge frgments



Brecciated Chert. Variable matrix and clast size, remnant spiculite common, porosity reliant on clay. Multiple chert generations visible.

Conclusions

- Best reservoir properties are found in the diagenetically altered “chat” interval associated primarily with silicified spiculitic lithofacies.
- First derivative curves are useful tools to visualize the trends in log character that define electrofacies.
  - Gamma ray derivative curves and models can systematically aid in producing a sequence stratigraphic interpretation. In the Hardtner Field area 4 coarsening upward cycles were identified using this approach.
- Despite limitations associated with data availability, Artificial Neural Networks are an effective tool for electrofacies classification
  - Prelimenary ANN electrofacies models show the spatial distribution of reservoir and non-reservoir intervals. This distribution is likely a function of depositional, diagenetic, and structural elements.

References

Lindzey, K., 2015 Geologically constrained seismic characterization and 3-D reservoir modeling of Mississippian reservoirs, north-central Anadarko shelf, Oklahoma: Master’s Thesis, University of Oklahoma

Mazzullo, S., B. W. Wilhite, and I.W. Woosley, 2009, Petroleum reservoirs within a spiculite-dominated depositional sequence: Cowley Formation (Mississippian: Lower Carboniferous), south-central Kansas: AAPG Bulletin, v. 93, no. 12, p. 1649-1689.

Rogers, S. M., 2001, Deposition and diagenesis of Mississippian chat reservoirs, north-central Oklahoma: AAPG Bulletin, v. 85, no.1, p 115-129.

Watney, W. L., W. J. Guy, and A. P. Byrnes, 2001, Characterization of the Mississippian chat in south-central Kansas: AAPG Bulletin, v. 85, no. 1, p. 85-113.