PS Combining Sequence Stratigraphy with Artificial Neural Networks to Enhance Regional Correlation and Determination of Reservoir Quality in the "Mississippian Limestone" of the Mid-Continent, USA*

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Search and Discovery Article #42091 (2017)**
Posted June 19, 2017

*Adapted from poster presentation given at AAPG 2017 Annual Convention and Exhibition, Houston, Texas, United States, April 2-5, 2017

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Abstract

The "Mississippian Limestone" of the U.S. Mid-Continent region is a complex, highly variable, mixed carbonate and siliciclastic system that serves as an important unconventional hydrocarbon reservoir. Recent studies have focused on developing and applying a sequence stratigraphic framework to enhance the understanding of depositional facies and reservoir architecture, and to enhance regional and sub-regional correlation. Throughout the region, the system is characterized by a 3-fold hierarchy of probable 2nd, 3rd and 4th order sequences and high frequency sequences. The third order sequences have proven to be the most reliable for correlation purposes due to distinct wireline log signatures that have been confirmed by ground-truthing the logs to multiple cores and tying to facies stacking patterns. An integrated approach utilizing well logs, sequence stratigraphy, core analysis, and 2D modeling is used to correlate and assess the reservoir quality of the "Mississippian Limestone" at both regional and sub-regional scales. Nine cored wells are used to create an artificial neural network (ANN) which is tested with k-means clustering methods to create a lithofacies log. The ANN is tested and trained to determine the lithofacies present based on well log signatures alone, in an attempt to pick up small scale changes in this heterogeneous carbonate system. This lithofacies log is applied to non-cored wells throughout the study area, which spans several counties, in order to predict the lithofacies in areas without core data. 2D geostatistical models are created from this data in order to correlate sequence stratigraphic frameworks, facies changes, and reservoir distribution in the Mississippian Limestone across the region.

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The "Mississippian Limestone" of the U.S. Mid-Continent region is a complex, highly variable, mixed carbonate and siliciclastic system that serves as an important unconventional hydrocarbon reservoir. Recent studies have focused on developing and applying a sequence stratigraphic framework to enhance the understanding of depositional facies and reservoir architecture, and to enhance regional-scale correlation. Throughout the region, the system is characterized by a 3-fold hierarchy of probable 2nd, 3rd and 4th order sequences and high frequency sequences. The 3rd order sequences have proven to be the most reliable for correlation purposes due to distinct wireline log signatures that have been confirmed by ground-truthing the logs to multiple cores and tying to facies stacking patterns.

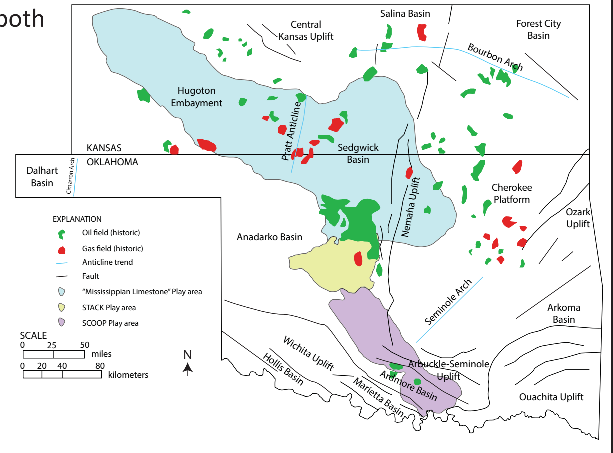
An integrated approach utilizing well logs, sequence stratigraphy, core analysis, and 2D modeling is used to correlate and assess the reservoir quality of the "Mississippian Limestone" at both regional and sub-regional scales. Previous studies have developed sequence stratigraphic frameworks for nine cored wells in the study area. The cores will be used to train an Artificial Neural Network to recognize patterns in wireline log data and determine the lithofacies present based on well log signatures alone. Once log-based facies interpretations are sufficient, the Neural Network will be applied to non-cored wells throughout the study area, which spans several counties, in order to predict the lithofacies in areas without core data. Three 2D geostatistical models will be created from this data in order to correlate sequence stratigraphic frameworks, facies changes, and reservoir distribution in the Mississippian Limestone across the region and to build upon previous studies of this complex system.

Project Goal and Objectives

The purpose of this study is to correlate and assess the reservoir quality of the "Mississippian Limestone" at both regional and sub-regional scales.

Objectives

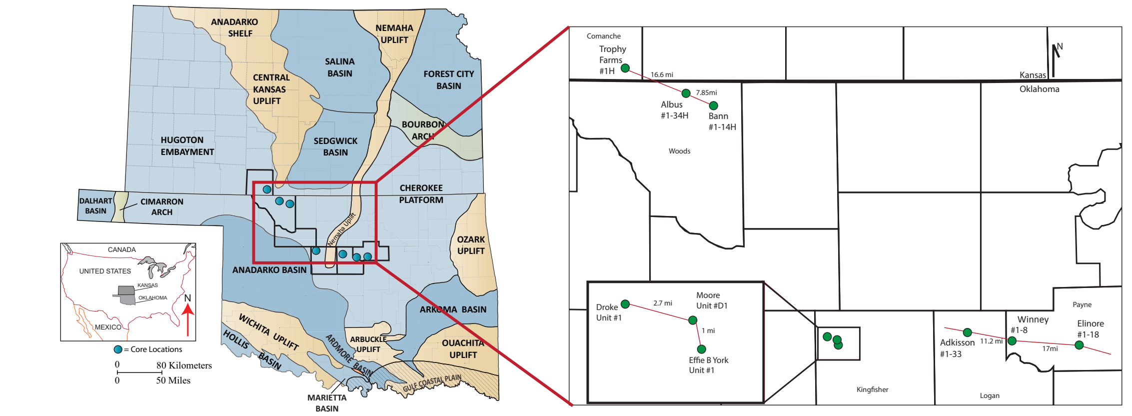
1) Train a neural network in Petrel using facies identified in nine cores in north-central Oklahoma to predict facies in non-cored wells.
2) Compare the models and facies in three sites in the study area. Correlate stratigraphic sequences (strike and dip orientation).
3) Generate 2D geostatistical models tied to a sequence stratigraphic framework that incorporate the cored wells and log-based facies predictions from proximal and distal positions in the basin.
4) Determine 2-D reservoir architecture at the sub-regional scale.



Play map for the "Mississippian Limestone" in Oklahoma and Kansas is shown in blue. Modified from Harris (1987), Northcutt and Campbell (1996), and Doll (2015). Courtesy of John Hunt.

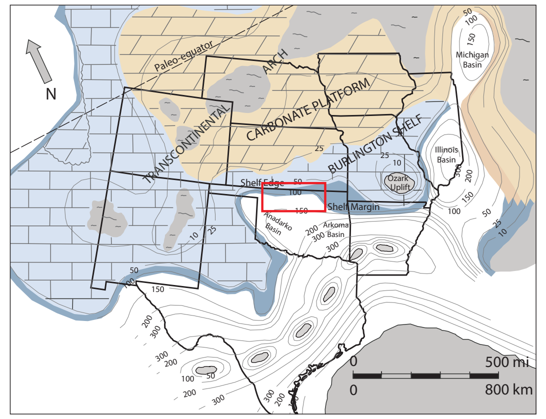
Study Area

Previously interpreted cores from three areas of the basin will be utilized in the study. Wireline logs and core descriptions will be used to train artificial neural networks.



Paleodepositional model of the Mid-Continent during the Early Mississippian. Modified from Gutschick & Sandberg (1983) and Chaplin (2010).

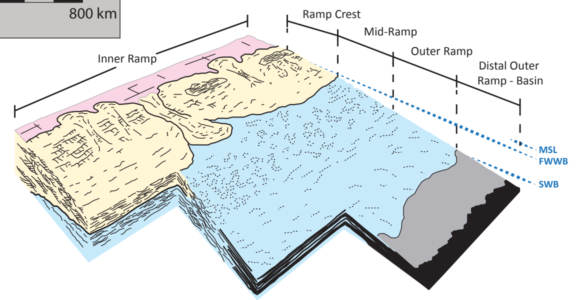
Geologic Background



The "Mississippian Limestone" was deposited across a regionally extensive carbonate platform in shallow marine conditions, on a distally steepened ramp (20-30° south latitude).

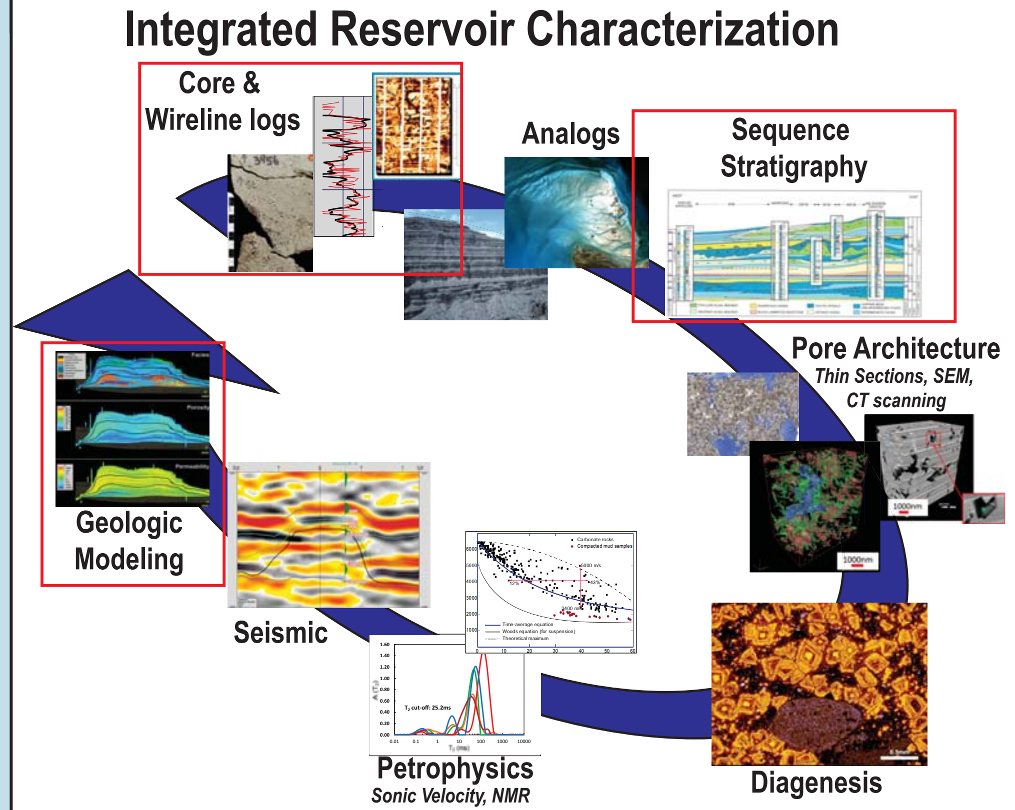
Left: Paleodepositional model of the Mid-Continent during the Early Mississippian. Modified from Gutschick & Sandberg (1983) and Chaplin (2010).

The facies identified in the nine cores are interpreted to have been deposited from the more proximal ramp crest to the distal outer-ramp with the basin towards the southwest.



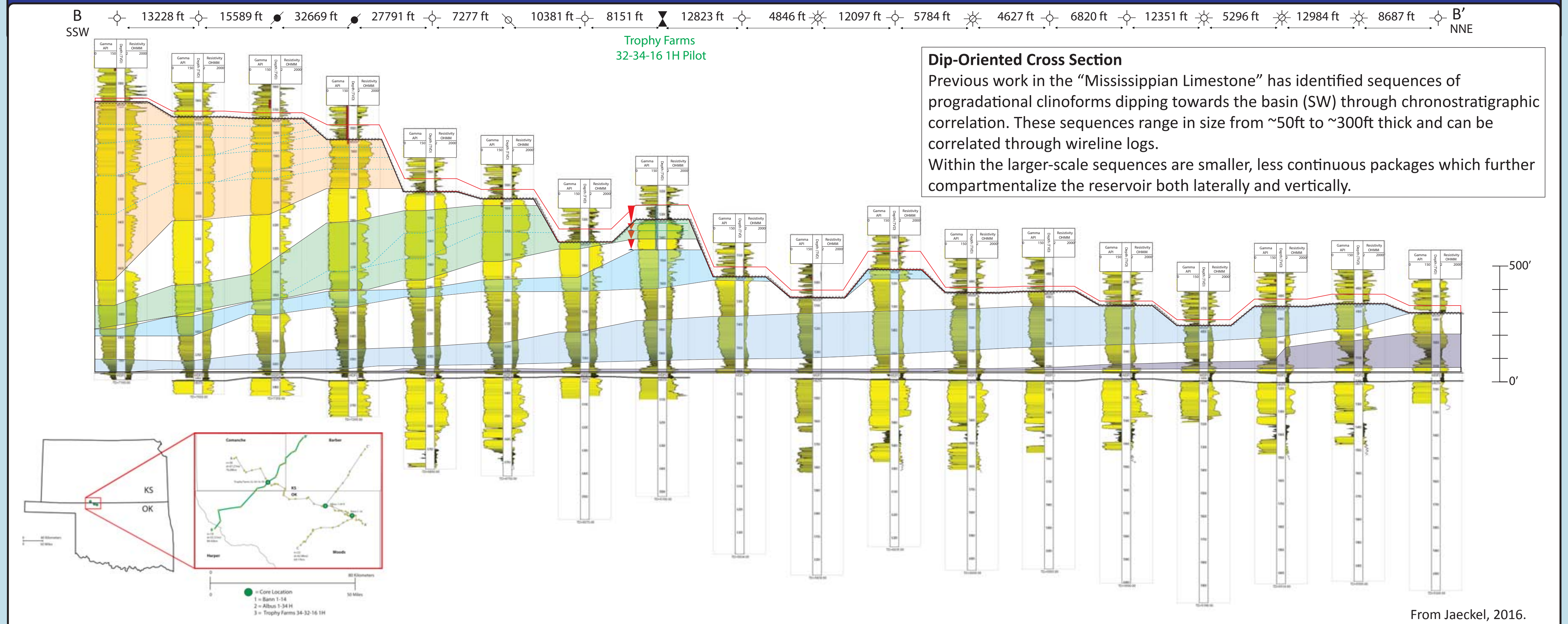
Right: A distally steepened carbonate ramp. Modified from Handford (1986).

Work Flow



1. Facies and reservoir quality from core descriptions and petrographic analysis for nine cores in the study area.
2. Wireline logs (GR, NPHI, DPHI, ILD) ground-truthed to core will be used to train artificial neural networks in Petrel.
3. Facies models will be based on core analysis and ANN facies interpretations and tied to the sequence stratigraphic framework.

Previous Work



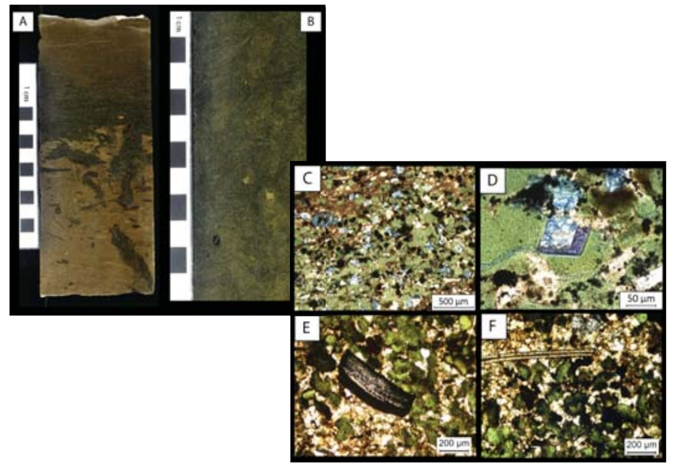
Dip-Oriented Cross Section

Previous work in the "Mississippian Limestone" has identified sequences of progradational clinoforms dipping towards the basin (SW) through chronostratigraphic correlation. These sequences range in size from ~50ft to ~300ft thick and can be correlated through wireline logs.

Within the larger-scale sequences are smaller, less continuous packages which further compartmentalize the reservoir both laterally and vertically.

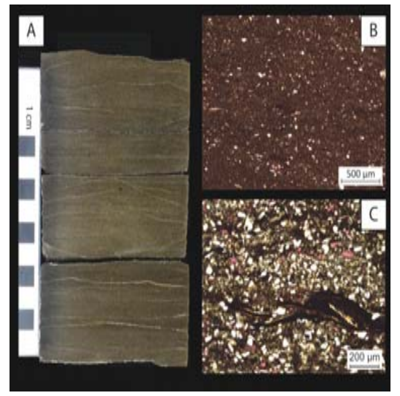
From Jaeckel, 2016.

Petrophysically Significant Facies



Facies 1: Glauconitic Sandstone

- Contains silt and sand sized glauconite, dolomite, and pyrite.
- Brachiopods, conodonts, and phosphatic bone fragments are common.
- ϕAVG = 9.5% K_{AVG}=0.36mD
- Deposited in a restricted, low energy environment. Most likely distal ramp.

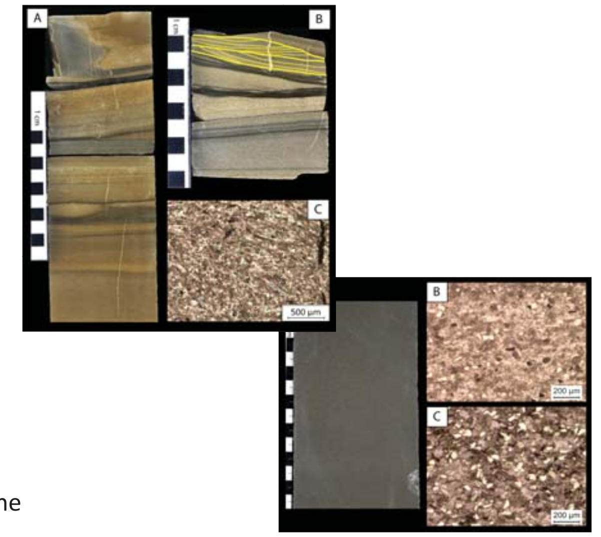


Facies 2: Burrowed Mudstone-Wackestone

- Mm scale burrows and laminated mudstone.
- High clay content, significant quartz silt, sponge spicules, and skeletal fragments.
- ϕAVG = 1.6% K_{AVG}=0.05mD
- Deposited in the outer- to distal-outer ramp environment. Below FWWB.

Facies 3: Bioturbated Wackestone-Packstone

- Moderately to heavily bioturbated with cm-scale burrows.
- Variable quartz silt, crinoids, brachiopods, and sponge spicules.
- ϕAVG = 1.6% K_{AVG}=0.006mD
- Mid- to outer-ramp with low to moderate energy.



Facies 4: Crinoidal Packstone-Grainstone

- Coarser grained facies.
- Traction current grainstones with occasional cross-bedding.
- ϕAVG = 3.2% K_{AVG}=0.009mD
- Mid-ramp environment or distal ramp crest.

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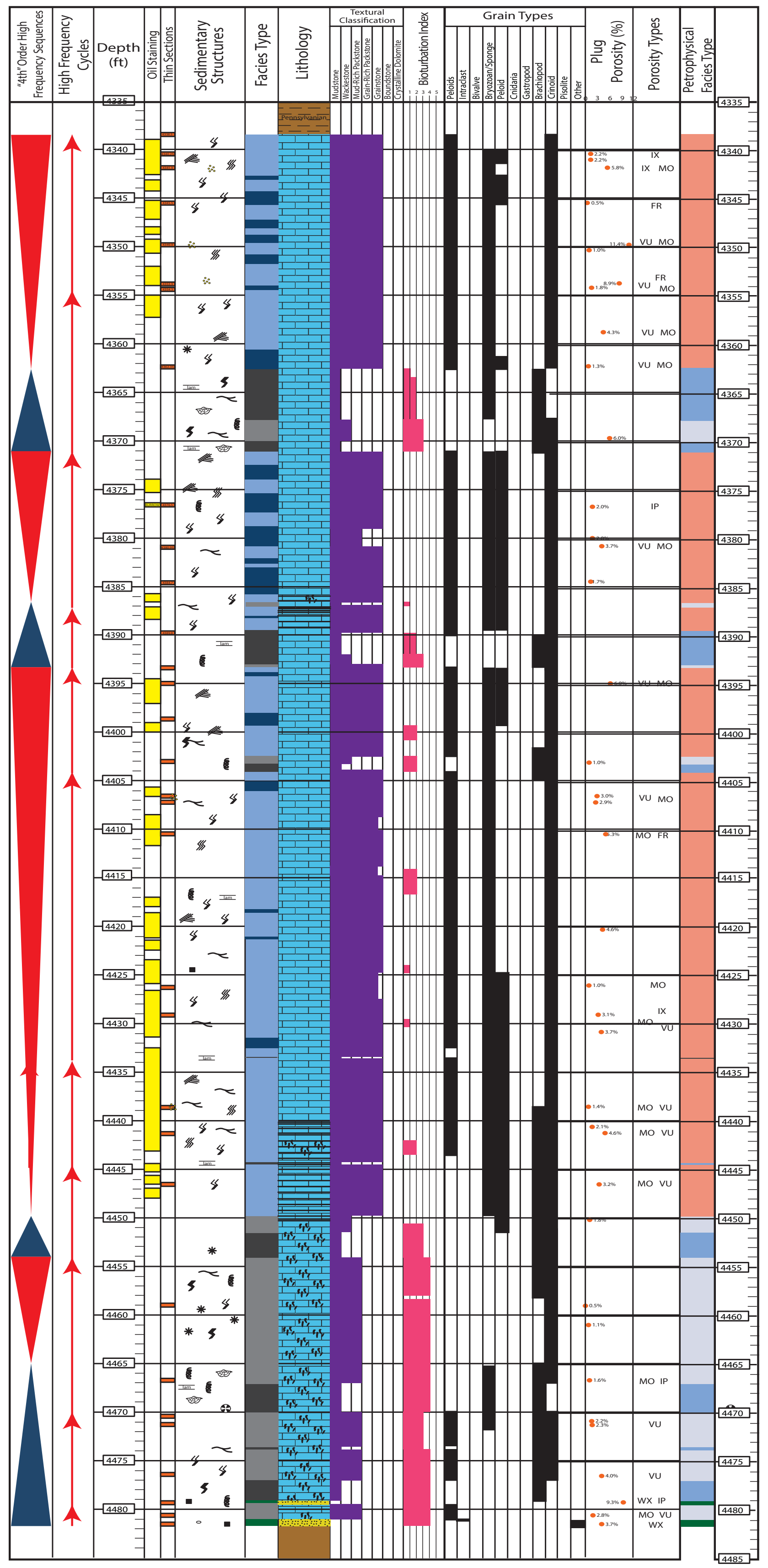
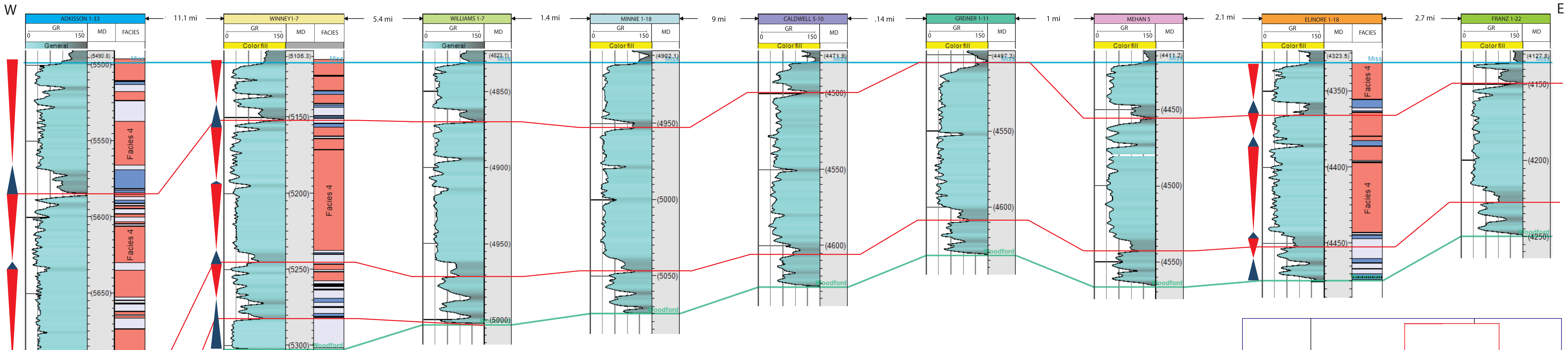
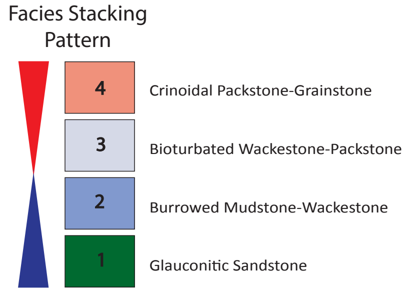
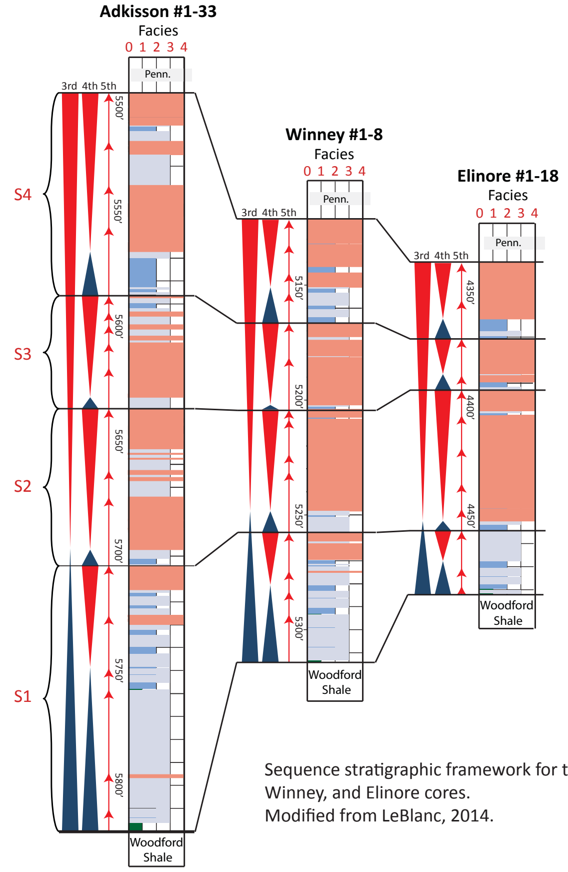
Elinore #1-18 Core Description

Depth Interval: 4335'-4485'









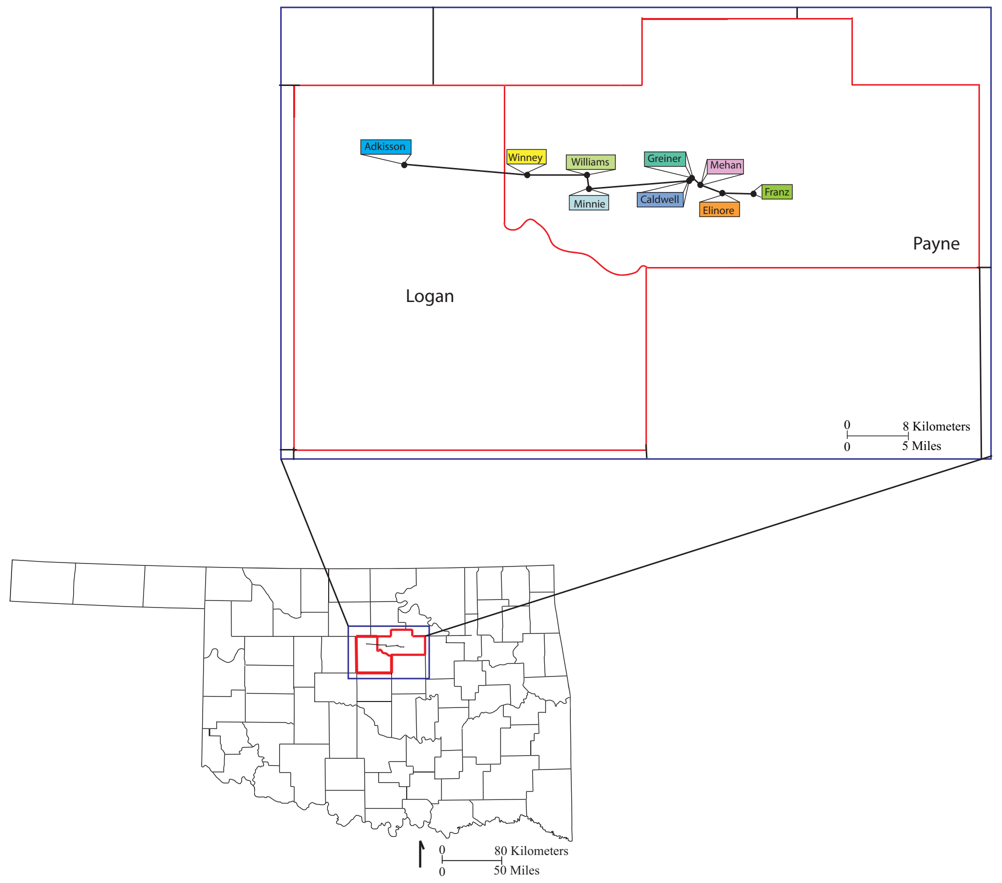
Sequence stratigraphic framework for the Adkisson, Winney, and Elinore cores. Modified from LeBlanc, 2014.

Strike-Oriented Cross Section

- The E-W oriented cross section above spans ~33 miles. During the deposition of the "Mississippian Limestone" the basin was located to the south-southwest.
- Sequences were identified and correlated throughout the cross section based on spikes in gamma ray signatures. All but one of the nine wells shows three distinct sequences and the two western-most wells show four distinct sequences.
- Three of the wells are ground-truthed to cores that also show these sequences.
- The GR-derived sequence correlation shows the lateral continuity of sequences in an E-W direction (strike). Previous interpretations of dip-oriented cross sections have shown prograding clinoforms toward the basin.

Application

- Once the facies are tied to wireline logs through ANN trained on core data, facies can more confidently be correlated laterally as well.
- Tying facies to porosity and permeability data will help determine reservoir distribution and architecture.



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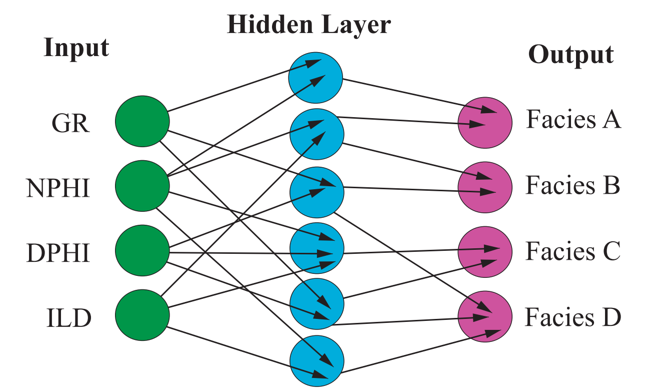
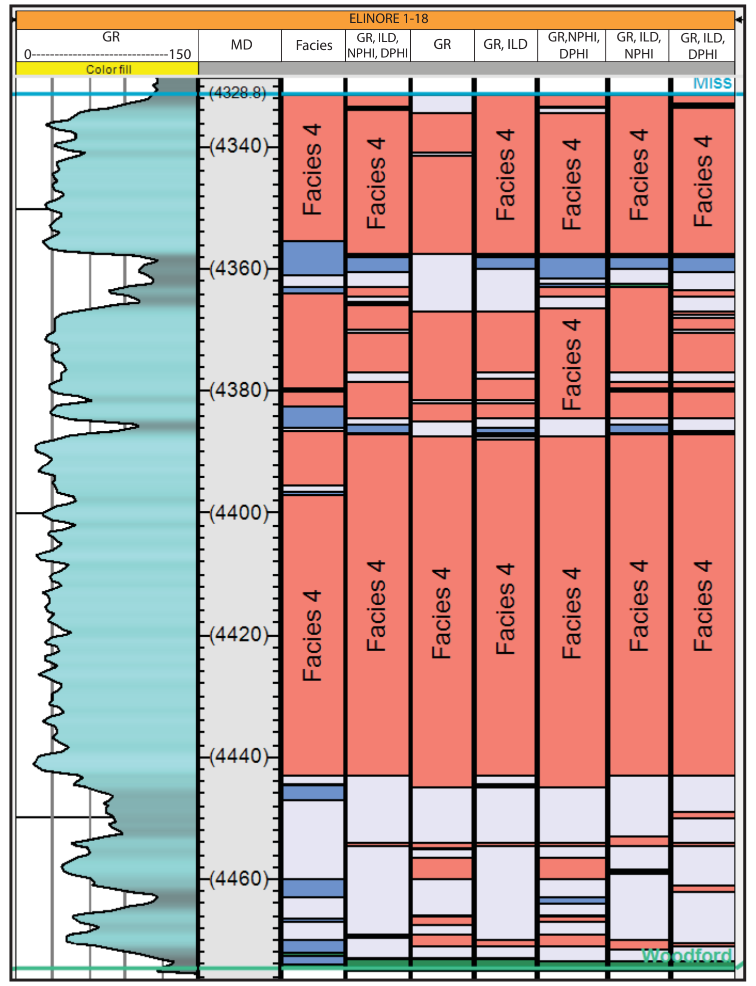
Artificial Neural Networks

Artificial Neural Networks (ANN) are a type of computational model intended to mimic the way the human brain recognizes patterns and interprets data. ANN are used to perform automatic interpretation and classifications of facies in this study. ANN can be trained to pick up on patterns, such as wireline log signatures of known facies in a core. Once the ANN can reasonably match facies based on log signatures alone, the ANN can be applied to non-cored wells as a way to predict the facies in the well.

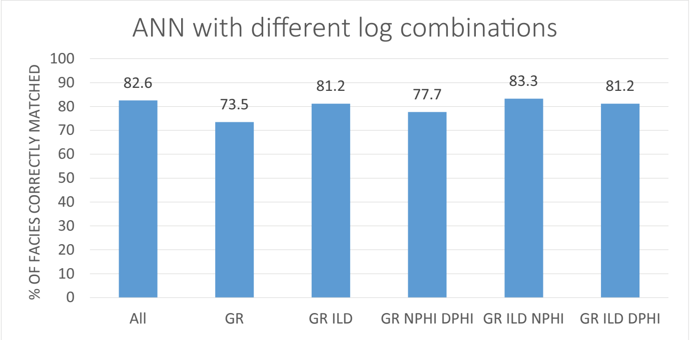


Conceptualization of a simple neural network. The input layer consists of different well logs associated with a core. In the hidden layer, weight connections are fine tuned to produce a better match between the computer output and the known output (facies).



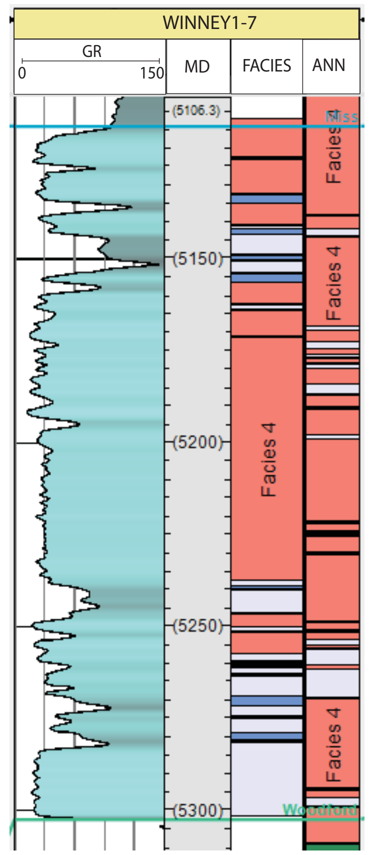
There are 9 wells with core and facies data that are used to train ANNs in this study. In order to determine which logs are the most useful in predicting the facies, various combinations of the four logs were used to train an ANN and then applied to a cored well. The figure to the left shows the predicted facies for the Elinore 1-18 well for each ANN.

The graph below shows the accuracy of each log combination. In general, each cored well showed the best results with all of the logs.



	Predicted Facies				
Actual	Facies 1	Facies 2	Facies 3	Facies 4	% Correct
Facies 1	2	0	1	0	66.7
Facies 2	2	6	21	11	15.0
Facies 3	0	1	44	5	88.0
Facies 4	0	2	7	185	95.4
				Total	82.6

This "confusion matrix" shows the relationship of the actual vs. predicted facies determined from the ANN. The green boxes represent the number of times a facies was correctly identified. The red boxes highlight the major discrepancies. Overall this ANN was correct 82.6% of the time when trying to identify facies based on well log signatures.



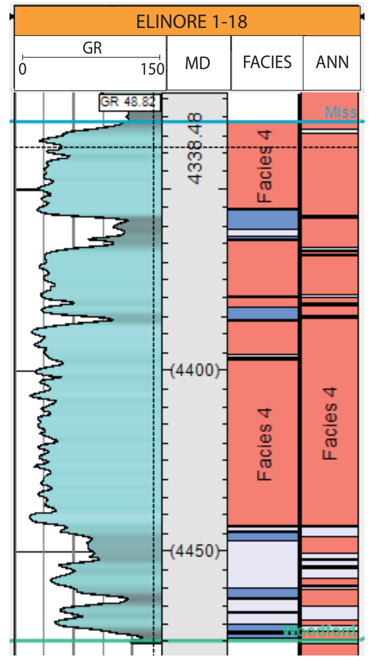
Prediction of Elinore Core from Winney ANN

	Predicted Facies				
Actual	Facies 1	Facies 2	Facies 3	Facies 4	% Correct
Facies 1	0	0	1	2	0.0
Facies 2	0	0	10	30	0.0
Facies 3	0	0	24	26	48.0
Facies 4	0	0	7	187	96.4
				Total	73.5

The ANNs are trained on wells with known facies data which means the most accurate predictions will occur on the well it was trained on. However, the goal is to predict facies in other, non-cored wells throughout the study area. These confusion matrices and wells show the facies predictions for the Winney and Elinore cored wells when the ANN for the other well was used. The accuracy decreases for both wells with facies 1 and 2 not being predicted correctly for both wells. This gives us further indication of which facies are the hardest to predict.

Prediction of Winney Core from Elinore ANN

	Predicted Facies				
Actual	Facies 1	Facies 2	Facies 3	Facies 4	% Correct
Facies 1	0	0	0	3	0.0
Facies 2	0	0	5	26	0.0
Facies 3	0	0	27	90	23.1
Facies 4	0	0	33	197	85.7
				Total	58.8



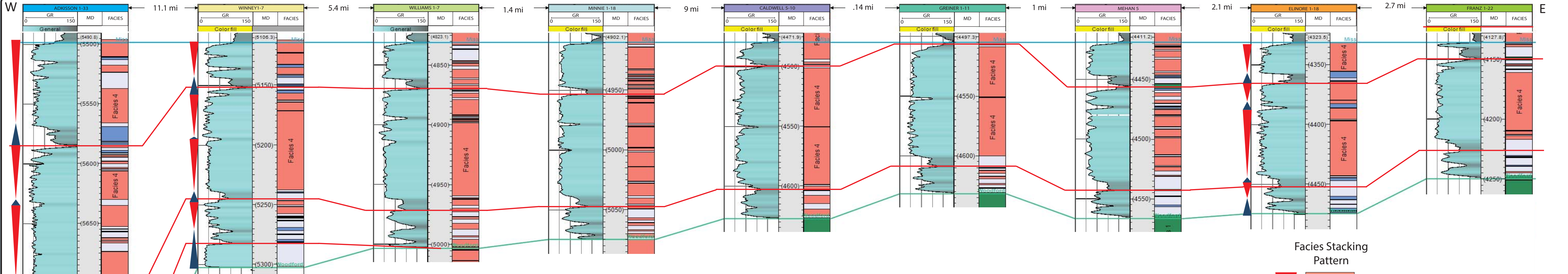
Limitations

Lithofacies vs. Petrophysical Facies

- Facies are identified and categorized through a number of observations (types of grains and skeletal material, grain size, amount of bioturbation, color, lithology, etc.) and while they may be distinct through thin section analysis, some of them are not reflected in distinct wireline log signatures. Since the prediction of facies in this study relies on the log signatures, additional grouping of petrophysically significant facies may be needed to maximize the accuracy of the ANN.

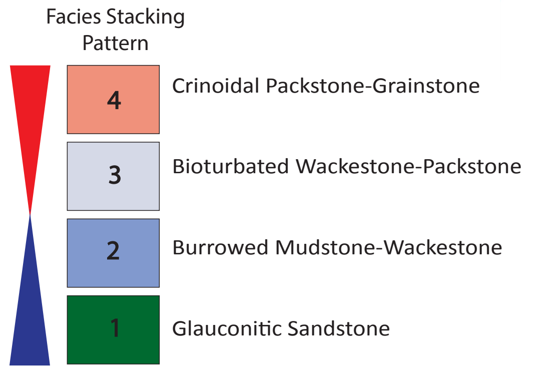
Logs

- Four logs have been chosen for this study for facies predictions across the study area. It's possible that the cored-wells can be trained more accurately on different logs, however, the ANN is limited in that it can only be applied to wells with the exact same suite of logs. This limits the number of wells available to use for ANN application.

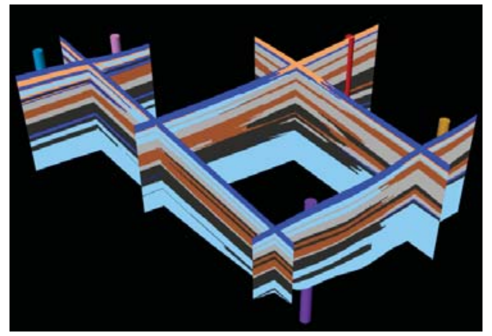


Petrophysical Facies Interpreted Through ANN

- This cross section shows the sequences based on GR signatures and how they relate to the facies determined through core- and wireline log-based artificial neural networks.
- Stacking patterns observed in ANN predicted facies throughout the cross section correlate reasonably well to the GR defined sequences.
- Minor variations in ANN predicted facies may be due to higher frequency sedimentological events and discrepancies in the ANN analysis of the well.



What's Next?



A Petrel-based facies model of the Pryor Quarry in eastern Oklahoma created using an indicator kriging algorithm. Shelley and Grammer (2017).

- Training ANN for cored wells using a series of different logs to see what logs are best for predicting facies in this kind of carbonate environment.
- Train ANN for the two other parts of the study area and correlate sequences for each cross section.
- Once ANN are applied to non-cored wells across the study area, 2D facies models will be generated using predicted and known facies.
- Regional and sub-regional correlations based on wireline logs and facies.

Key Points

1) The "Mississippian Limestone" displays a complex facies mosaic in response to the environment of deposition and multiple fluctuations in sea level.
2) ANNs can be used to create log-based facies for non-cored wells in the study area that are ground-truthed to core.
3) 2-D facies models for proximal and distal positions (strike and oblique to strike) in the basin will be tied to the sequence stratigraphic framework.
4) ANN-based geostatistical models can be used for regional correlation and prediction of facies and reservoir distribution.

Acknowledgements

devon
NEWFIELD
Marathon Oil
Samson Energy
Chesapeake
Chaparral
REDFORK ENERGY
SM ENERGY