[PS]Investigation of Petrophysical-Property Heterogeneity for Electrofacies Classification in Carbonate Reservoirs*

Fnu Suriamin[1] and Matthew J. Pranter[1]

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

Abstract

Electrofacies classification for rock typing in complex carbonate reservoirs is very challenging due to high degrees of heterogeneity in lithology, mineralogy, and pore structure. In extreme cases, multivariate pattern recognition and classification methods such as discriminant function analysis, principal component analysis, and cluster analysis using conventional well logs are insufficient for electrofacies classification, particularly in carbonate reservoirs with "low dynamic" log curves. This study investigates how heterogeneity of petrophysical properties can improve electrofacies classification for rock typing in carbonate reservoirs. It utilizes statistical measures of heterogeneity, Lorentz Coefficient, to quantify variability in petrophysical properties. Within this investigation, the Heterogeneity Logs based on wireline-log data including the gamma-ray, density, neutron, sonic, and photoelectric-factor log suite are calculated over set intervals of 10 m, 5 m, 3 m, and 2 m (33 ft, 17 ft, 10 ft, 7 ft) through Mississippian limestones of the Mid-continent. The investigation of Heterogeneity Logs shows a relationship between Heterogeneity Logs with geological features; for example, the lithofacies 6, the thick-bedded peloidal packstone-grainstone, shows relatively increasing Heterogeneity Log NPHI values. This relationship leads to consideration of using Heterogeneity Logs for fluid-flow zone characterization. The Heterogeneity Logs and other predictor variables from well-log data are selected and linked to core lithofacies to train Artificial-neural-network (ANN), Self-organizing-map (SOM), and Multi-resolution Graph-based Clustering (MRGC) models for predicting lithofacies in wells without core. Finally, the results are compared with the widely used ANN clustering technique which utilizes only the five predictor variables logs including gamma ray, deep resistivity, photoelectric effect, difference between neutron porosity and density porosity, and average of neutron porosity and density porosity.

References Cited

Birch, C.B., 2015, Reservoir-scale stratigraphy, sedimentology, and porosity characteristics of Mississippian reservoirs, northeastern Anadarko Shelf, Oklahoma: Master's thesis, University of Oklahoma, Norman, Oklahoma. 81 p.

Campbell, J.A., C.J. Mankin, A.B. Schwarzkopf, and J.J. Raymer, 1988, Habitat of petroleum in Permian rocks of the midcontinent region: in, Permian Rocks of the Midcontinent, W.A. Morgan and J.A. Babcock, eds.: Midcontinent Society of Economic Paleontologists and

Mineralogists, Special Publication No. 1, p. 13-35.

Dutton, S.P., 1984, Fan-Delta Granite Wash of the Texas Panhandle: Oklahoma City Geological Society, vol. Short Course Notes, p. 1-44.
Fitch, P., S. Davies, M. Lovell, T. Pritchard, and C. Sirju, 2010, Heterogeneity In Carbonate Petrophysical Properties: Application to Fluid Flow Units And Sampling Strategies: SPWLA 51st Annual Logging Symposium, Perth, Australia, Society of Petrophysicists and Well-Log Analysts.

Johnson, K.S. and K.V. Luza, 2008, Earth sciences and mineral resources of Oklahoma: Educational Publication 9, Oklahoma Geological Survey, 22 p.

LoCricchio, E., 2012, Wash Play Overview, Anadarko Basin: Stratigraphic Framework and Controls on Pennsylvanian Granite Wash Production, Anadarko Basin, Texas and Oklahoma: AAPG Search and Discovery Article, no. 110163, web accessed September 25, 2016, http://www.searchanddiscovery.com/documents/2012/110163locricchio/ndx_locricchio.pdf.

McConnell, D.A., 1989, Determination of Offset across the Northern Margin of the Wichita Uplift, Southwest Oklahoma: Geological Society of America Bulletin, v. 101, p. 1317-1332.

Mazzullo, S.J., 2011, Mississippian oil reservoirs in the southern midcontinent: New exploration concepts for a mature reservoir objective: Search and Discovery Article 10373, web accessed September 25, 2016, http://www.searchanddiscovery.com/pdfz/documents/2011/10373mazzullo/ndx_mazzullo.pdf.html.

Nissen, S.E., K.J. Marfurt, and T.R. Carr, 2004, Identifying subtle fracture trends in the Mississippian saline aquifer unit using new 3-D seismic attributes: Kansas Geological Survey Open File Report, no. 56.

Northcutt, R.A. and J.A. Campbell, 1995, Geologic provinces of Oklahoma: Oklahoma Geological Survey Open-File Report 5-95, 1 sheet, scale 1:750,000, 6-page explanation and bibliography.

Investigation of Petrophysical-Property Heterogeneity for Electrofacies Classification in Carbonate Reservoirs

Fnu Suriamin and Matthew J. Pranter

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

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

RCML
Reservoir Characterization and Modeling Laboratory
The University of Oklahoma

1. Abstract

Electrofacies classification for rock typing in complex carbonate reservoirs is very challenging due to high degrees of heterogeneity in lithology, mineralogy, and pore structure. In extreme cases, multivariate pattern recognition and classification methods such as discriminant function analysis, principal component analysis, and cluster analysis using conventional well logs are insufficient for electrofacies classification, particularly in carbonate reservoirs with "low dynamic" log curves.

This study investigates how heterogeneity of petrophysical properties can improve electrofacies classification for rock typing in carbonate reservoirs. It utilizes statistical measures of heterogeneity, Lorentz Coefficient, to quantify variability in petrophysical properties. Within this investigation, the Heterogeneity Logs based on wireline-log data including the gamma-ray, density, neutron, sonic, and photoelectric-factor log suite are calculated over set intervals of 10 m, 5 m, 3 m, and 2 m (33 ft, 17 ft, 10 ft, 7 ft) through Mississippian limestones of the Mid-continent.

The investigation of Heterogeneity Logs shows a relationship between Heterogeneity Logs with geological features; for example, the lithofacies 6, the thick-bedded peloidal packstone-grainstone, shows relatively increasing Heterogeneity Log NPHI values. This relationship leads to consideration of using Heterogeneity Logs for fluid-flow zone characterization.

The Heterogeneity Logs and other predictor variables from well-log data are selected and linked to core lithofacies to train Artificial-neural-network (ANN), Self-organizing-map (SOM), and Multi-resolution Graph-based Clustering (MRGC) models for predicting lithofacies in wells without core. Finally, the results are compared with the widely used ANN clustering technique which utilizes only the five predictor variables logs including gamma ray, deep resistivity, photoelectric effect , difference between neutron porosity and density porosity, and average of neutron porosity and density porosity.

2. Objectives

The Mid-continent Mississippian Limestone is known to be highly heterogeneous and extremely challenging to characterize. In the past, rock typing in the Mississippian carbonate reservoirs often focussed in relating core lithofacies with well logs including gamma ray, deep resistivity, photoelectric effect, difference between neutron and density porosity, average of neutron and density porosity, and a stratigraphic interval indicator to train a neural-network model to predict lithofacies in un-cored wells.

The Artificial-neural-network (ANN) method requires a large dataset and significant training time while the results would be often overfitted to the desired output. This study focuses on finding a novel and more accurate petrophysical rock-typing workflow for reservoir characterization. The objectives of this study are to: 1. characterize the unconventional carbonate reservoir system at the core, well, and field scales; 2. numerically measure heterogeneity of petrophysical properties in the Mississippian Limestone in north-central Oklahoma; 3. investigate if measures of heterogeneity petrophysical properties can increase predictability of lithofacies in un-cored wells, reservoir compartmentalization, and fluid-flow zones.

3. Geologic Setting

The Mid-continent Mississippian Limestone in north-central Oklahoma is located in the Anadarko ramp, the shallow ramp portion of the Anadarko basin, and a foreland basin associated with the Ouachita Orogeny.

In the study area, the Mississippian deposits show high- frequency transgressive-regressive cycles that result in a series of shallowing-upward cycles.

Previous studies suggest that there are three (3) diagenetic stages in the Mississippian Limestone: early silicification and dolomitization; subaerial exposure diagenesis (brecciation, silica dissolution, and fracturing); and hydrothermal alteration including dolomitization and pyritization.

Figure.1. Regional base map showing the major tectonic and basinal features of Oklahoma and Kansas. The study area of Grant County is marked in red box. It lies on the southwest edge of the Anadarko Ramp that progrades to the south. The Nemaha Uplift is the tectonic feature with the largest imprint on the geology in study area. It is the most likely contributor to the subaerial exposure and unconformities seen in the Mississippian interval.

Modified after Dutton, 1984; McConnel, 1989; Campbell et al., 1988; Northcutt and Campbell, 1995; Johnson and Luza, 2008; LoCricchio, 2012

Figure 2. Generalized stratigraphic column showing an ideal Mississippian interval in north-central Oklahoma. Note that there are numerous unconformities of various orders of magnitude in the Mississippian rocks.

Modified after Mazzullo, 2011

Figure 3. Schematic cross section through northern Oklahoma from west to east. Note that Grant County lies directly west of the Nemaha Ridge, the major tectonic feature in the area. The Mississippian interval in Grant County is thinner to the east toward the Nemaha Ridge as the result of uplifting and erosion.

Figure 4. Subcrop map of northern Oklahoma and southern Kansas. Grant County is outlined in red. Erosion has removed significant portions of the Mississippian rocks, especially to the north. In an ideal stratigraphy section, Kinderhookian, Meramecian, Osagean, and Chesterian units would all be present. In this study area, Kinderhookian, Meramecian and Osagean series are present.

Modified from Nissen et al., 2004

4. Data

Figure 5. Grant County map showing well locations (data provided by Devon). The data set consists of 55 wells with raster data, and 13 with digital well-log data. Three of those wells are cored: Devon Energy 1-7 SWD Frieouf, Devon Energy 1-7 SWD Downing, and Devon Energy 1-8 SWD Kirby. Devon Energy 1-7 SWD Frieouf, Devon Energy 1-7 SWD Downing, and Devon Energy 1-8 SWD Kirby are the key wells in this study. Core and lithofacies description of Devon Energy 1-7 SWD Downing and Devon Energy 1-8 SWD Kirby wells are available in Birch (2015).

5. Methods and Workflow

The heterogeneity of the Mid-continent Mississippian Limestone makes it challenging to predict lithofacies and correlate between wells using wireline logs. Basic 1D, 2D, and multidimensional statistical analyses were conducted for the available well-log curves in the cored well and the results were plotted to evaluate the input variables for clustering methods.

This research also applies a statistical method, Lorenz Coefficient, to measure heterogeneity of petrophysical properties. To calculate the Lorenz Coefficient, the cumulative value of a property (for an example neutron porosity) is sorted from low to high values and plotted against cumulative measured depth. The Lorenz Coefficient is defined as twice the area between the linear line of equality and the Lorenz curve (Figure 6). This process is repeated for the consecutive 10 m, 5 m, 3 m, and 2 m (33 ft, 17 ft, 10 ft, and 7 ft) data intervals to create the Heterogeneity Log for neutron porosity.

The heterogeneity logs (Figure 7) are investigated to determine their use to characterize variability in terms of grains, pore types, and the presence or absence of any dominant sedimentological features including fractures, sedimentary structures, nodules, diagenesis, and mineral compositions.

The Heterogeneity Log will also be integrated as input variables for chosen clustering methods to evaluate their use in lithofacies prediction in un-cored wells.

Figure 6. The procedure for calculating Lorenz Coefficient (Lc) in a 10-m (33-ft) interval. From left to right: (1) neutron porosity log, (2) Lorenz plot of the neutron data (red curve), (3) Lorenz Coefficient (Lc) Heterogeneity Log block created for 10-m (33-ft) interval.

Figure 7. An example shows 10 m, 5 m, 3 m, and 2 m (33 ft, 17 ft, 10 ft, and 7 ft) intervals for Lorenz Coefficient Heterogeneity Logs (red curves) plotted with the original neutron-porosity curve (blue curves).

Figure 8. The workflow is designed to predict lithofacies or rock types in un-cored wells. Statistical data analysis and feature selection are conducted initially to select input variables. Heterogeneity Logs are integrated with selected variables or well-log curves to train clustering models for predicting lithofacies in un-cored wells. Artificial-neural network v.1 is widely used in previous study. This method utilizes gamma ray, deep resistivity, photoelectric effect , difference between neutron porosity and density porosity, and average of neutron porosity and density porosity. Artificial-neural network v.2 will integrate selected curves and Heterogeneity Logs into the model. Other clustering models such as Self-organizing-map (SOM) and Multi-resolution Graph-based Clustering (MRGC) methods will also be tested to find a more accurate electrofacies clustering.

6. Core Lithofacies
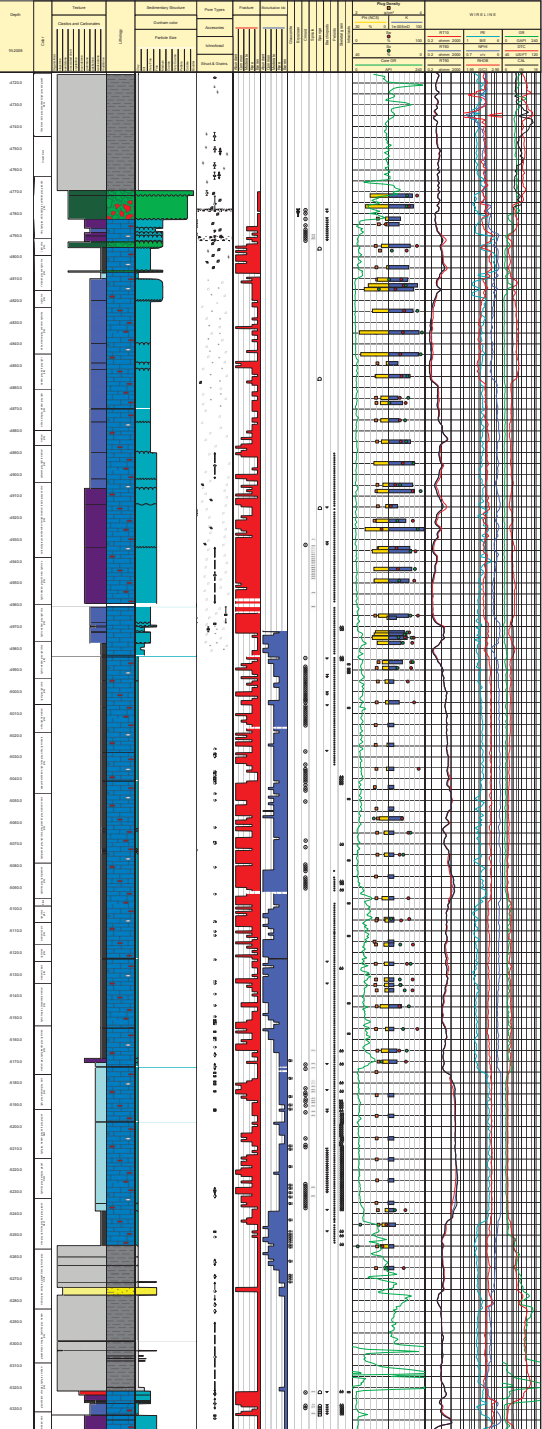## Devon Energy 1-7 SWD Frieouf

Figure 9. Core description of well Devon Energy 1-7 SWD Frieouf, one of the key cores that is located in the northernmost of the study area. Seven (7) lithofacies classes are observed based on detailed core description in the Mid-continent Mississippian Limestone including: 1. brecciated chert; 2. skeletal packstone-grainstone; 3. peloidal mudstone-wackestone; 4. bioturbated peloidal packstone-grainstone; 5. nodular peloidal packstone-grainstone; 6. bedded peloidal packstone-grainstone; and 7. bioturbated mudstone-wackestone. Examples of each lithofacies characteristics are depicted in the core and thin section images. Typical well-log responses of each lithofacies are shown on the right tracks; including Gamma Ray (GR), Resistivity (RT10, RT60, RT90), Bulk Density (RHOB), Neutron porosity (NPHI), photoelectric effect (PE), and Compressional Sonic travel time log (DTC). Several wells have Spectral Gamma Ray and Nuclear Magnetic Resonance. Routine-core-analysis data including porosity, permeability, grain density, and fluid saturation of selected depths are also plotted. Note that most porosity measurements in the bioturbated mudstone-wackestone are extremely low. This core penetrated the Woodford Shale and Hunton carbonates.
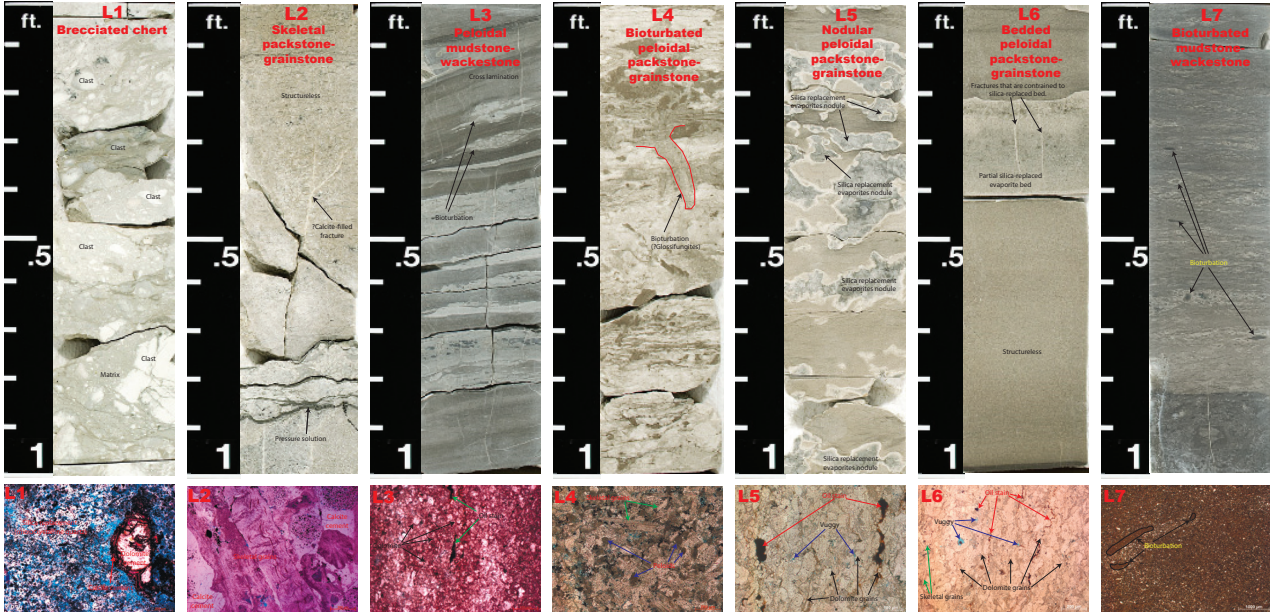
Figure 10. Core photos and thin section photomicrographs for each lithofacies observed in Devon Energy 1-7 SWD Frieouf: L1. brecciated chert, note that most of the clasts are cherts with both matrix-supported and grain-supported textures; L2. skeletal packstone-grainstone, note that this facies is structureless with common pressure solution filled fractures; L3. peloidal mudstone-wackestone, note the cross lamination and compacted bioturbation; L4. bioturbated peloidal packstone-grainstone, note the original texture is destroyed by bioturbation and possibly glossifungites ichnofacies, whitish areas are silica replacement. L5. nodular peloidal packstone-grainstone, note that nodules are irregular (convolute) in shape and show white rind with dark gray center. Silica-replaced evaporites exhibit laterally coalescing nodules that form horizontal anastomosing beds, organic-matter wisps exist between and drape them; L6. bedded peloidal packstone-grainstone, note the very light gray bed consists of silica-replaced evaporites and fractures are constrained to the bed. L7. bioturbated mudstone-wackestone, note the original texture is completely destroyed by bioturbation.

7. Statistical Data Analysis
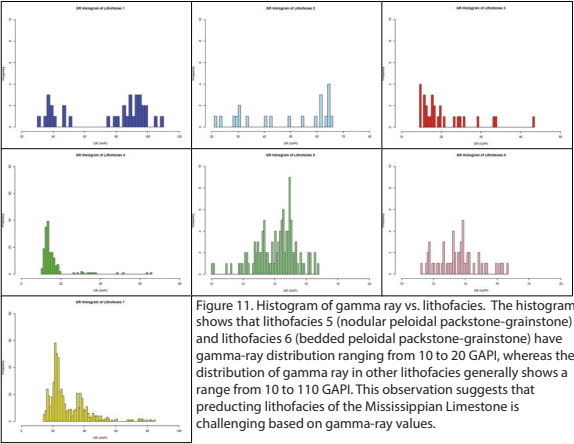
Figure 11. Histogram of gamma ray vs. lithofacies. The histogram shows that lithofacies 5 (nodular peloidal packstone-grainstone) and lithofacies 6 (bedded peloidal packstone-grainstone) have gamma-ray distribution ranging from 10 to 20 GAPI, whereas the distribution of gamma ray in other lithofacies generally shows a range from 10 to 110 GAPI. This observation suggests that preducting lithofacies of the Mississippian Limestone is challenging based on gamma-ray values.
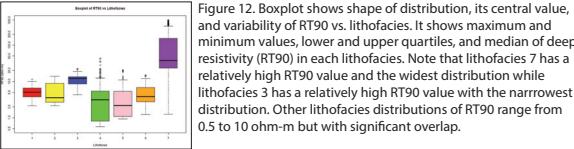
Figure 12. Boxplot shows shape of distribution, its central value, and variability of RT90 vs. lithofacies. It shows maximum and minimum values, lower and upper quartiles, and median of deep resistivity (RT90) in each lithofacies. Note that lithofacies 7 has a relatively high RT90 value and the widest distribution while lithofacies 3 has a relatively high RT90 value with the narrrowest distribution. Other lithofacies distributions of RT90 range from 0.5 to 10 ohm-m but with significant overlap.
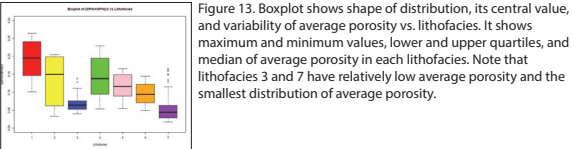
Figure 13. Boxplot shows shape of distribution, its central value, and variability of average porosity vs. lithofacies. It shows maximum and minimum values, lower and upper quartiles, and median of average porosity in each lithofacies. Note that lithofacies 3 and 7 have relatively low average porosity and the smallest distribution of average porosity.
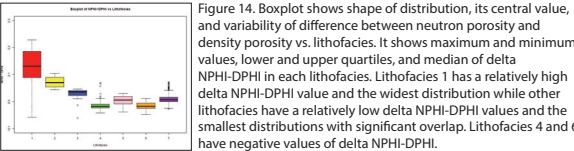
Figure 14. Boxplot shows shape of distribution, its central value, and variability of difference between neutron porosity and density porosity vs. lithofacies. It shows maximum and minimum values, lower and upper quartiles, and median of delta NPHI-DPHI in each lithofacies. Lithofacies 1 has a relatively high delta NPHI-DPHI value and the widest distribution while other lithofacies have a relatively low delta NPHI-DPHI values and the smallest distributions with significant overlap. Lithofacies 4 and 6 have negative values of delta NPHI-DPHI.
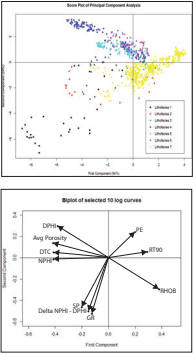
Figure 15. Score plot of principal component analysis. On first component, lithofacies 4, 5, and 6 show similar directions and are therefore challenging to be separated. However the three (lithofacies) may be separated from lithofacies 7 which has a different direction. It is difficult to separate lithofacies 1, 2, and 3 either on first or second component.
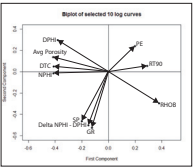
Figure 16. Biplot of principal component analysis. On first component, training data can be separated by porosity data (NPHI, DPHI, and Avg Porosity), sonic log, photoelectric effect (PE), and deep resistivity (RT90). On second component, gamma ray (GR), spontaneous potential (SP), and difference between neutron porisity and density porosity (Delta NPHI-DPHI) have a similar response direction.
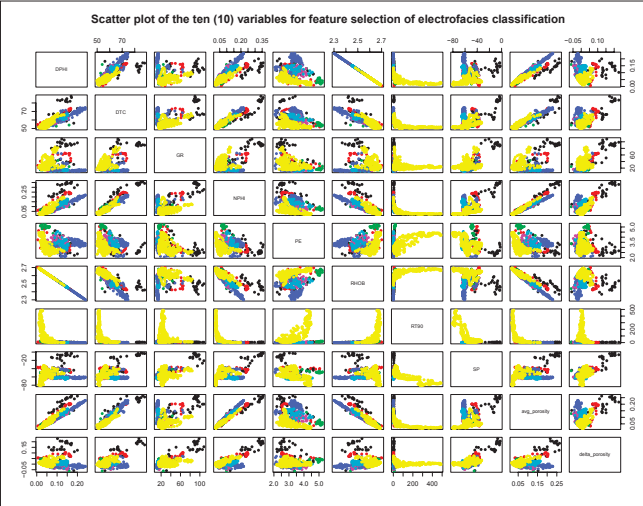
Figure 17. Pairwise scatter plot of ten (10) variables for feature selection of electrofacies classification. The plots are color-coded by electrofacies. Most, if not all, training data show significant overlap and are challenging to separate using basic statistical analysis as well as principal-component analysis.
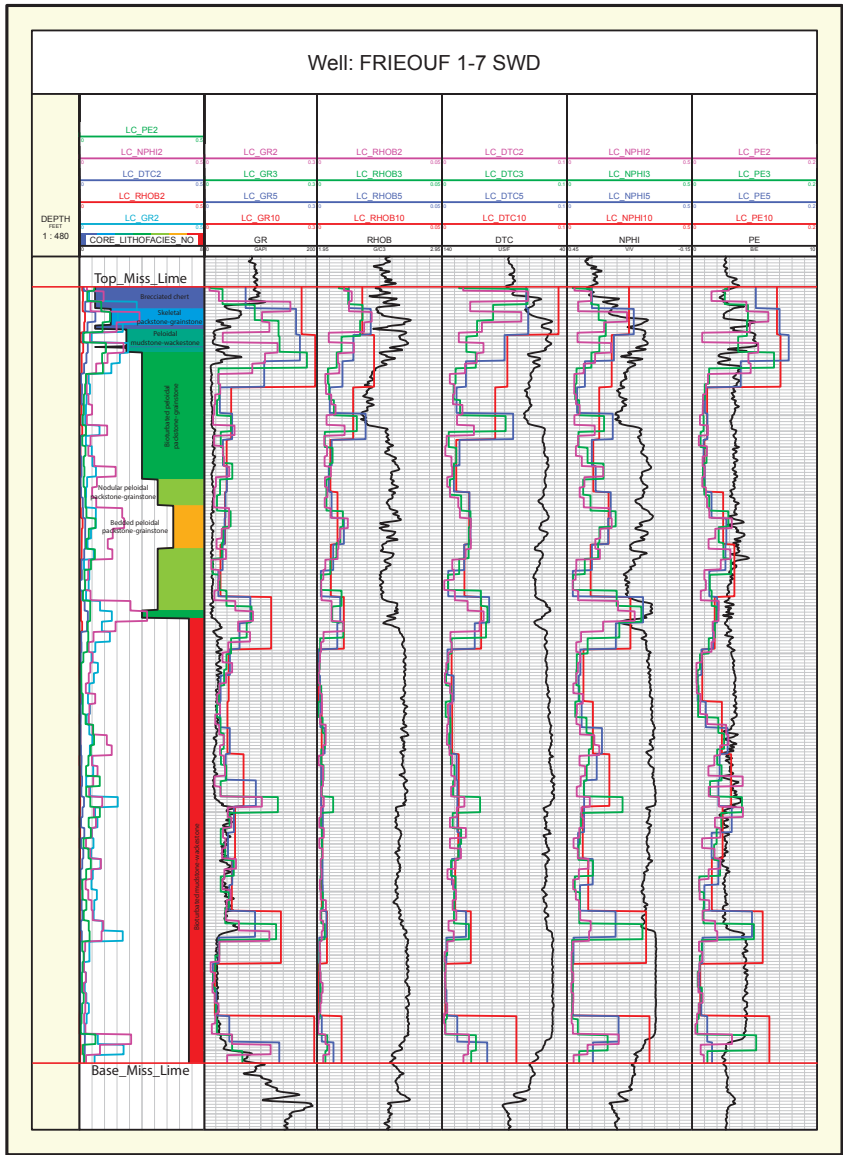
8. Heterogeneity Logs

Figure 18. The Lorenz Coefficient Heterogeneity Logs for the Mid-continent Mississippian Limestone interval of well Frieouf 1-7 SWD based on 10-m, 5-m, 3-m, and 2-m (33-ft, 17-ft, 10-ft, and 7-ft) windows. The observation suggests that 2 m (7 ft) Heterogeneity Log captures optimal heterogeneity in this Mississippian limestones interval. The 1-m window is also used to calculated the Heterogeneity Log. However, the response is similar to the original well-log signature.
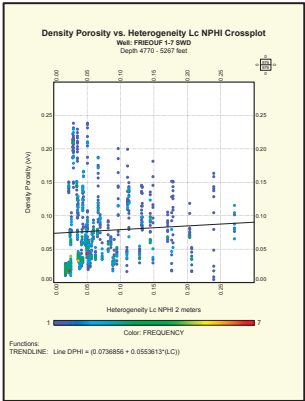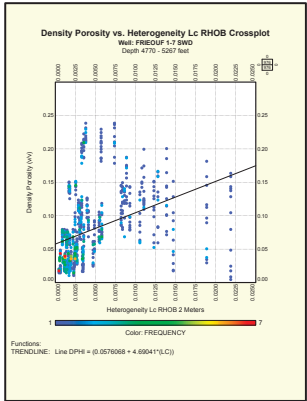

Figure 19. Two (2) crossplots on the left show heterogeneity - Lorenz coefficient of bulk density and neutron porosity versus density derived porosity (DPHI). The petrophysical property derived from the well log shows correlation to the Heterogeneity Logs. There are significant scatter in the cross plots. The multilinear regression suggest that density porosity increases with increasing heterogeneity in bulk density values and neutron porosity heterogeneity values. However, further investigation is needed.

9. Preliminary Observations

1. Based on detailed core description, there are seven (7) lithofacies classes in the Mid-continent Mississippian Limestone in study area. The lithofacies are: 1. brecciated chert; 2. skeletal packstone-grainstone; 3. peloidal mudstone-wackestone; 4. bioturbated peloidal packstone-grainstone; 5. nodular peloidal packstone-grainstone; 6. bedded peloidal packstone-grainstone; and 7. bioturbated mudstone-wackestone.

2. Basic 2-D statistical analysis provides useful information in terms of classifying the electrofacies. However, it has limitations in dealing with multidimensional well-log data and often misclassifies the lithofacies due to significant lithofacies overlapping.

3. The 2-m (7-ft) interval Heterogeneity Log is the best for capturing heterogeneity of petrophysical properties of well-log data.

4. The density porosity derived from bul density shows correlation to the Heterogeneity Log. The density porosity is observed to increase with increasing heterogeneity in bulk density values and neutron porosity heterogeneity values. This relationship may be used for flow-unit characterization; however, further research is required.

10. Future Work

Basic 2-D statistical analysis for petrophysical properties derived from well-log data such as permeability and water saturation will be conducted. In addition, measure of heterogeneity of other well-log data including resistivity, permeability, and water saturation will allow further investigation to reach the research objectives.

Following the measure of heterogeneity of petrophysical properties, relationships of the heterogeneity logs to geological features will be investigated. The investigation will integrate pore types, pore sizes, and mineral compositions derived from multi-mineral analysis, and flow zone indicator (FZI). Once the investigation of Heterogeneity Logs is completed, the next step will be feature selection. In this step, input variables for electrofacies clustering will be selected to provide curves which give the best homogeneous clustering.

The final step will be testing the selected input variables (well-log curves and Heterogeneity Logs) with Artificial-neural network (ANN) and other clustering methods such as Self-organizing Map (SOM) and Multi-resolution Graph-based Clustering (MRGC) for electrofacies classification to explore if the Heterogeneity Log improves electrofacies classification and reservoir characterization in this particular unconventional carbonate reservoir.

References

Birch, C. B., 2015, Reservoir-scale stratigraphy, sedimentology, and porosity characteristics of Mississippian reservoirs, northeastern Anadarko Shelf, Oklahoma, Master's thesis, University of Oklahoma, Norman, Oklahoma. 81 p.

Campbell, J. A., C. J. Mankin, A. B. Schwarzkopf, and J. J. Raymer, 1988, Habitat of petroleum in Permian rocks of the midcontinent region; in, Permian Rocks of the Midcontinent, W. A. Morgan and J. A. Babcock, eds.: Midcontinent Society of Economic Paleontologists and Mineralogists, Special Publication No. 1, p. 13-35

Dutton, S. P., 1984, Fan-Delta Granite Wash of the Texas Panhandle, Oklahoma City Geological Society, vol. Short Course Notes, p. 1-44.

Fitch, P., S. Davies, M. Lovell, T. Pritchard, and C. Sirju, 2010, Heterogeneity In Carbonate Petrophysical Properties: Application to Fluid Flow Units And Sampling Strategies, SPWLA 51st Annual Logging Symposium, Perth, Australia, Society of Petrophysicists and Well-Log Analysts.

Johnson, K. S. and K. V. Luza, 2008, Earth sciences and mineral resources of Oklahoma, Educational Publication 9, Oklahoma Geological Survey, 22 p.

LoCricchio, E., 2012, Wash Play Overview, Anadarko Basin: Stratigraphic Framework and Controls on Pennsylvanian Granite Wash Production, Anadarko Basin, Texas and Oklahoma, AAPG Search and Discovery Article, no. 110163.

McConnell, D. A., 1989, Determination of Offset Across the Northern Margin of the Wichita Uplift, Southwest Oklahoma, Geological Society of America Bulletin, vol. 101, p. 1317-1332.

Mazzullo, S. J., 2011, Mississippian oil reservoirs in the southern midcontinent: New exploration concepts for a mature reservoir objective: Search and Discovery Article 10373.

Nissen, S. E., K.J. Marfurt, and T. R. Carr, 2004, Identifying subtle fracture trends in the Mississippian saline aquifer unit using new 3-D seismic attributes, Kansas Geological Survey Open File Report, no. 56.

Northcutt, R. A. and J. A. Campbell., 1995, Geologic provinces of Oklahoma: Oklahoma Geological Survey Open-File Report 5-95, 1 sheet, scale 1:750,000, 6-page explanation and bibliography.