PS Integrating Standard Petrophysical Analysis with Statistical Measures of Petrophysical Heterogeneity to Estimate Petrofacies in Mississippian Limestone, North-Central Oklahoma*

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

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[1]ConocoPhillips School of Geology and Geophysics, University of Oklahoma, Norman, OK, USA (fnu.suriamin-1@ou.edu)

Abstract

Mississippian carbonate and chert reservoirs of the mid-continent are extremely complex and exhibit different scales of mineralogical, lithological, and petrophysical heterogeneity. The Mississippian interval consists of four high-frequency cycles that are capped by unconformable surfaces related to subaerial exposure. Key lithologies from core description vary from chert-brecciated limestone, bedded chert-brecciated limestone, bioturbated grainstone and mudstone, and dense, unaltered limestone. Diagenetic products including silicification, dissolution, compaction, fracturing, and brecciation are observed throughout this interval. Relationships of petrophysical methods and statistical measures of heterogeneity are explored to predict petrofacies. Initially, detailed core description, standard petrophysical analysis, and the Multi-Resolution Graph-Based Clustering method are conducted. Statistical measures of heterogeneity, including Lorenz and Dual-Lorenz Coefficient, are calculated on bulk density, neutron porosity, and sonic well logs in the Mississippian interval to evaluate which well logs best capture heterogeneity and define the optimal number of clusters needed to define the petrofacies. The results of core analysis, petrophysical analysis, and numerical measures of petrophysical heterogeneity are integrated to estimate lithofacies in non-cored wells and to identify stratigraphic cycles in order to interpret the sequence-stratigraphic framework.

Integrating Standard Petrophysical Analysis with Statistical Measures of Petrophysical Heterogeneity to estimate Petrofacies in Mississippian Limestone, North-Central Oklahoma

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

Fnu Suriamin 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

1. Abstract

Mississippian Limestone of the mid-continent is an unconventional carbonate reservoir. It is extremely complex and exhibits different scales of mineralogical, lithological, pore structure, and petrophysical heterogeneity. The Mississippian interval consists of four high-frequency cycles that are capped by unconformable surfaces related to subaerial exposure. Key lithologies from core description vary from chert-brecciated limestone, nodular grainstone, peloidal laminated packstone-grainstone, skeletal packstone-grainstone, bioturbated packstone-grainstone, and bioturbated mudstone-wackestone. Diagenetic products including silicification, dissolution, compaction, fracturing, and brecciation are observed throughout this interval.

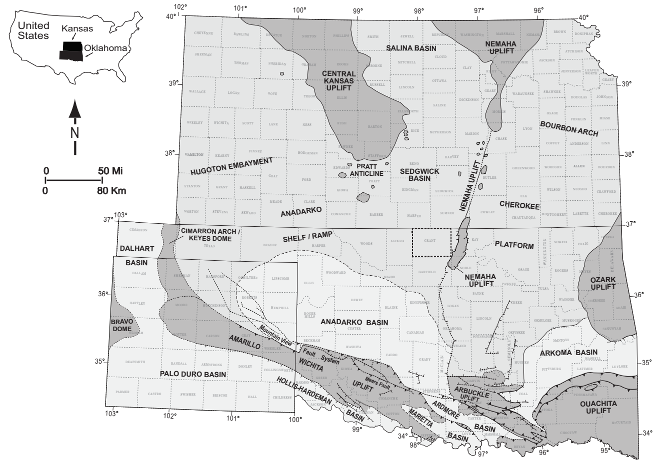
Relationships of petrophysical methods and statistical measures of petrophysical are explored to improve pore-types and petrofacies prediction in non-cored wells. Initially, detailed core description, thin sections analysis, and carbonate petrophysical analysis are conducted for determining lithology, lithofacies, reservoir properties, and pore-typing. Statistical measure of heterogeneity "Lorenz Coefficient" is calculated on gamma ray, resistivity, bulk density, neutron porosity, photoelectric, and sonic logs in the Mississippian interval to generate Heterogeneity logs. The Heterogeneity logs are used to investigate if the heterogeneity of petrophysical properties can be defined and numerically measured in this unconventional carbonate reservoir, explore which well-logs best capture heterogeneity in the reservoir, identify flow unit, and define the optimal number of clusters needed to predict petrofacies. The results of core-based lithofacies, petrophysical analysis, and numerical measure of petrophysical heterogeneity are integrated to train Neural Network and Multi-Resolution Graph-based Clustering models to predict petrofacies in non-cored wells. The predicted petrofacies are used to identify lithofacies vertical succession and carbonate cycles in order to interpret the stacking pattern and sequence-stratigraphic framework.

2. Research Objectives

Previous work has shown that geostatistical methods for measuring heterogeneity of petrophysical properties in carbonate reservoirs may increase predictability of reservoir compartmentalization or fluid flow zones and improve sampling strategy. This research uses similar methods and applied in an unconventional carbonate reservoir with objectives to:

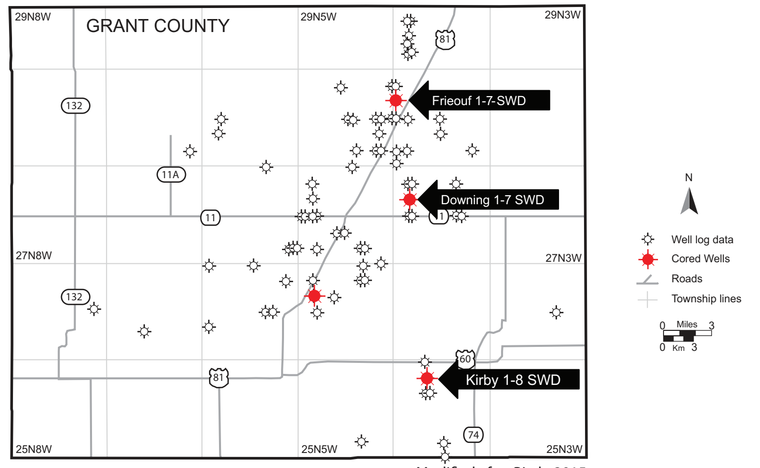
1. Accurately characterize petrophysical properties and pore types of the unconventional carbonate "Mississippian Limestone" reservoir in the north-central Oklahoma.
2. Investigate if heterogeneity of petrophysical properties of the Mississippian Limestone can be defined and numerically measured.
3. Investigate if measures of heterogeneity of petrophysical properties can be used to improve pore-types and petrofacies prediction.
4. Investigate if measures of heterogeneity of petrophysical properties can be used to identify key fluid flow zone and constrain porosity-permeability relationship.
5. Investigate the controls of the petrophysical properties heterogeneity in the Mississippian Limestone

3. Study Area and Geological Background



Modified after Campbell et al., 1988; Northcutt and Campbell, 1995; Johnson and Luza, 2008

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 most likely contributor to the subaerial exposure and unconformities seen in the Mississippian interval.



Modified after Birch, 2015

Figure 2. 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-logs data. Four of those wells are cored: Frieouf, Dewey, Downing, and Kirby. Frieouf 1-7 SWD, Downing 1-7 SWD, and Kirby 1-7 SWD are the key wells in this study.

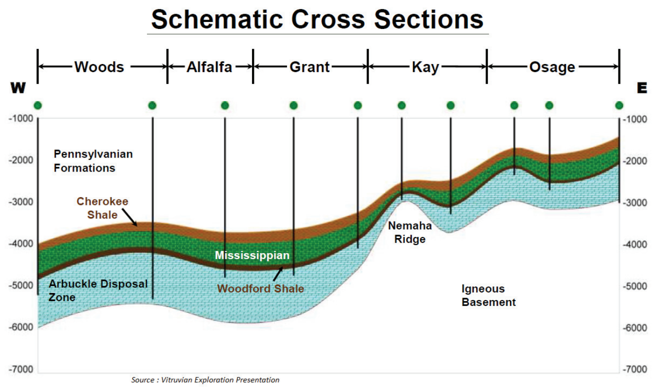
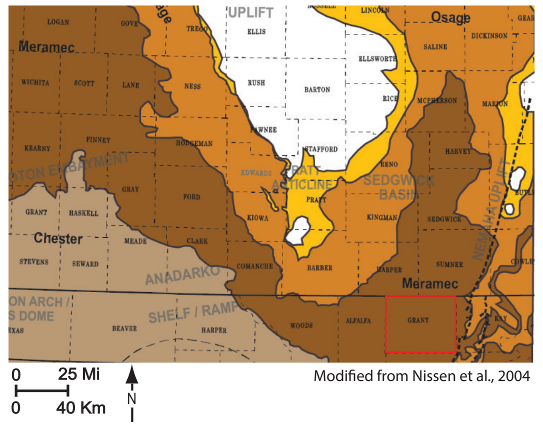
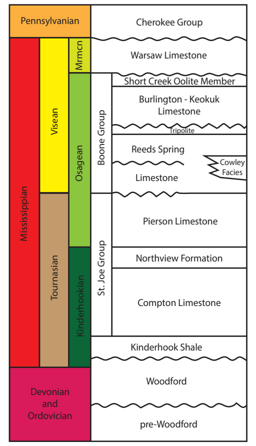


Figure 3. Schematic cross sections through northern Oklahoma from west to east. Note that Grant County lies directly west of the Nemaha Ridge, the major tectonic feature in the area. The Mississippian interval in Grant County is thinner to the east toward the Nemaha Ridge as the result of uplifting and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



Modified from Nissen et al., 2004

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, Meramecian, Osagean, Chesterian, and Kinderhookian units would all be present. In this study area, only Meramecian and Osagean units are present.

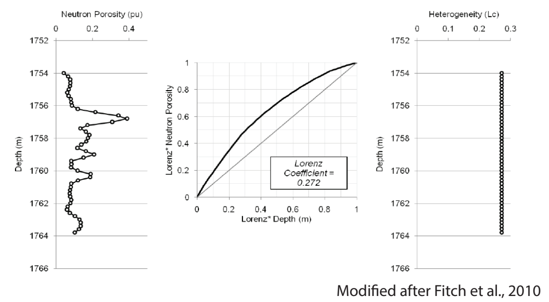


Modified after Mazzullo, 2011

Figure 5. General stratigraphic column showing an ideal Mississippian interval in the north-central Oklahoma. Note that there are numerous unconformities of various orders of magnitude in the Mississippian rocks.

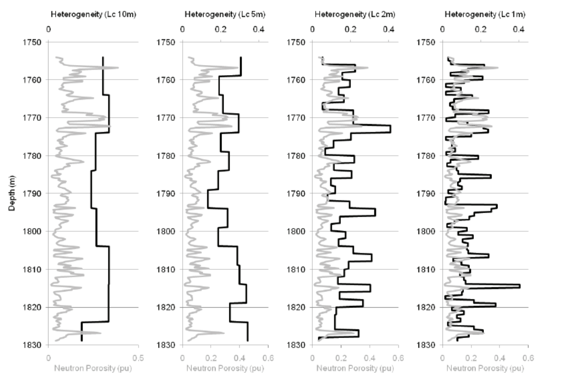
4. Methods and Proposed Workflow

This research applies a statistical method such as Lorenz Coefficient to measure petrophysical heterogeneity. To calculate the Lorenz Coefficient the cumulative value of a property (for an example neutron porosity), will be 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. This process is repeated for the consecutive 10m (33ft) data interval to create Heterogeneity Log for neutron porosity.



Modified after Fitch et al., 2010

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



Modified after Fitch et al., 2010

Figure 7. An example shows 10m, 5m, 2m, and 1m (33ft, 16ft, 7ft, and 3ft) interval Lorenz Coefficient Heterogeneity Logs plotted with the original neutron porosity curve.

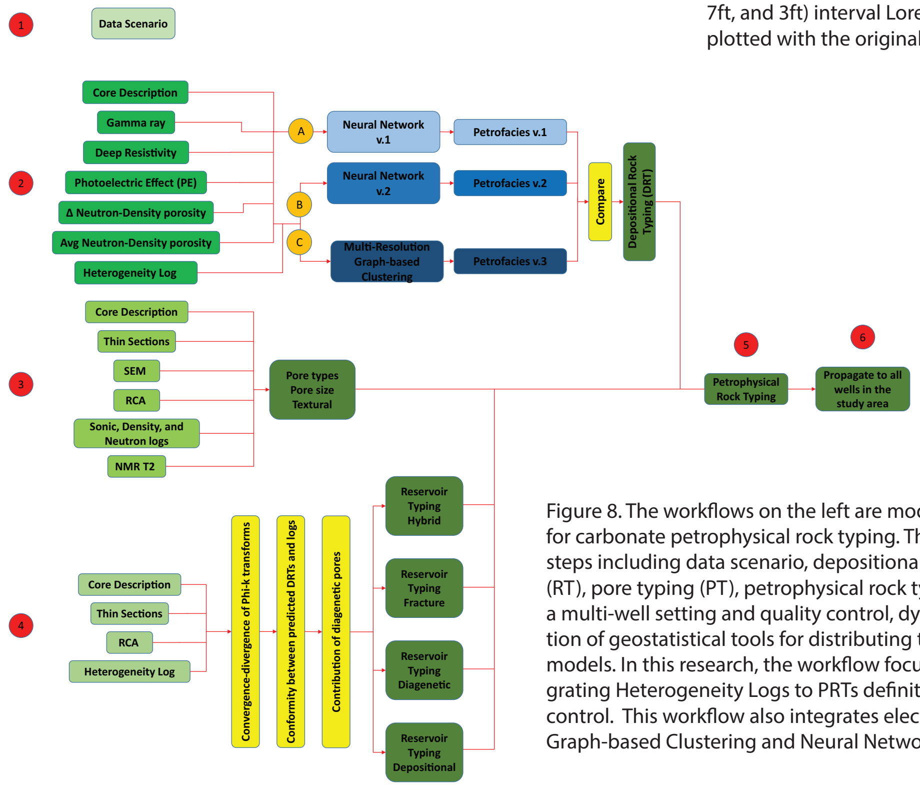


Figure 8. The workflows on the left are modified from Chevron Patent application for carbonate petrophysical rock typing. The original workflow consists of eight (8) steps including data scenario, depositional rock typing (DST), reservoir typing (RT), pore typing (PT), petrophysical rock typing (PRT) definition, PRT definition in a multi-well setting and quality control, dynamic validation of PRTs, and application of geostatistical tools for distributing the identified PRTs in 3-D static reservoir models. In this research, the workflow focuses on 6 steps from data scenario integrating Heterogeneity Logs to PRTs definition in a multi-well setting and quality control. This workflow also integrates electrofacies analysis using Multi-Resolution Graph-based Clustering and Neural Network techniques.

5. Preliminary Results - Core Description and Petrophysical Analysis

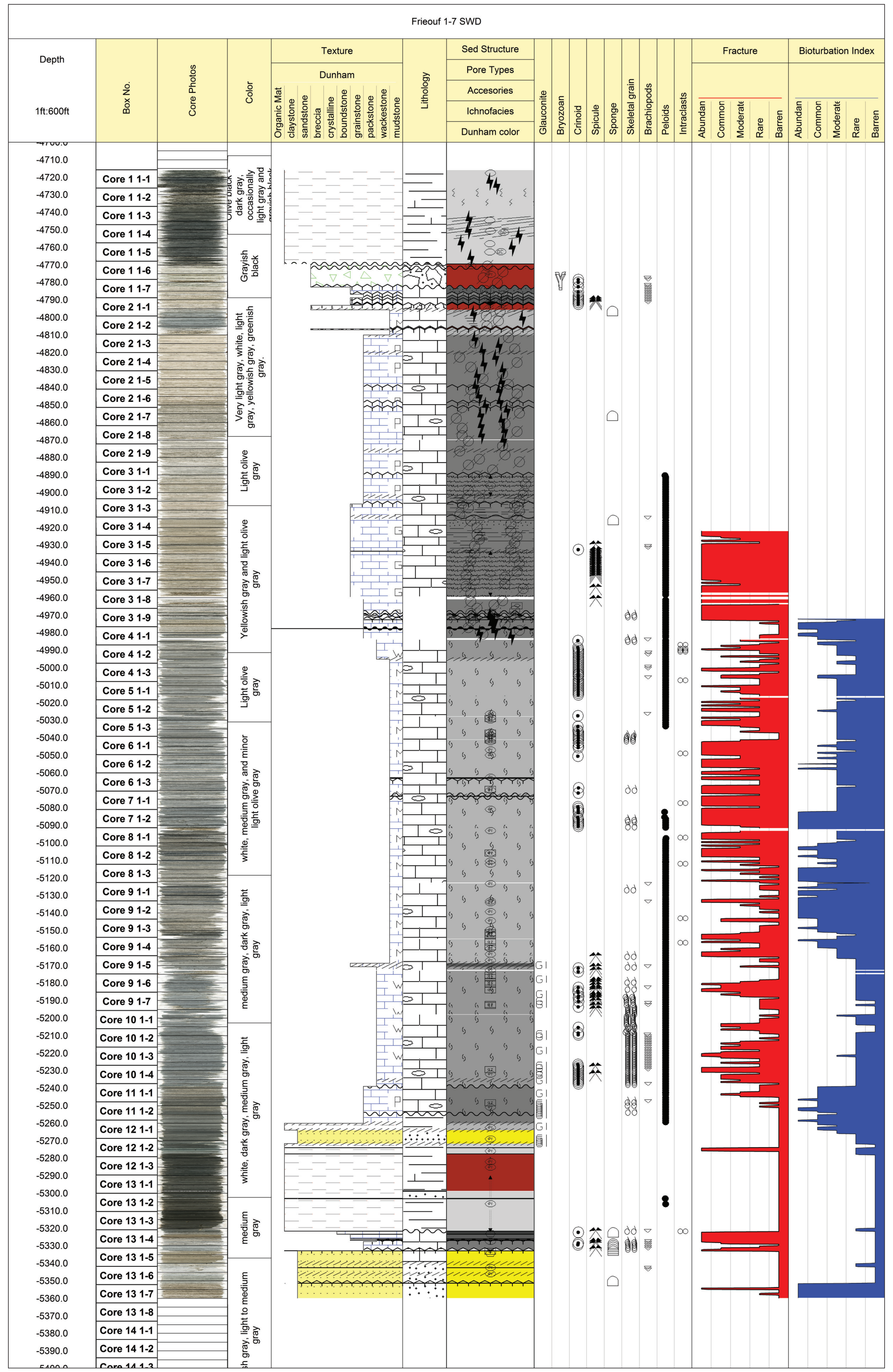


Figure 9. Preliminary core description of well Frieouf 1-7 SWD. This well is located in the north of study area. The deepest lithofacies is characterized by glauconitic sandstone. Shoaling-upward cycle is typically started with bioturbated mudstone-wackestone, bioturbated packstone, and capped by bioturbated grainstone or skeletal grainstone. Occasionally, the top section is characterized by nodular grainstone or peloidal laminated packstone-grainstone or chert-brecciated limestone.

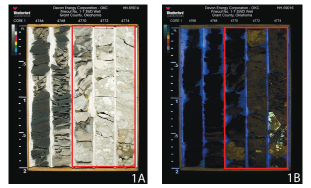


Figure 10. Core photos show chert-brecciated limestone on white light (1A) and UV light (1B). The chert-brecciated limestone is characterized by very light gray-light gray granule to boulder size grains, hard, some grains show rind, monomictic, subangular to angular in shape, matrix supported, poorly sorted, occasionally skeletal grains are observed, no visible porosity. Note that UV light photo shows ?calcite mineral fluorescence.

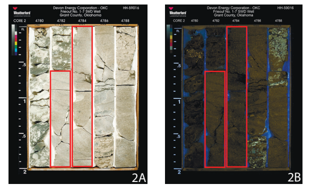


Figure 11. Core photos show skeletal packstone-grainstone on white light (2A) and UV light (2B). This lithofacies is typically described as light olive gray - yellowish brown, fine to medium sand size, hard, grain supported, massive, rare ?chicken-wire structure, common to abundant altered skeletal grains including crinoids, brachiopods, bryozoans, and ?spicules, stylolites and fractures are present, no visible porosity.

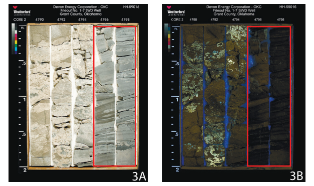


Figure 12. Core photos show peloidal laminated packstone-grainstone on white light (3A) and UV light (3B). This lithofacies is typically described as medium gray - dark gray, occasionally light gray, silt to very fine sand-sized peloidal grains and occasionally skeletal grains, hard, grain supported, sedimentary structures such as cross lamination and parallel lamination are commonly observed, occasionally massive, stylolites and fractures are present, bioturbated in part, no visible porosity.

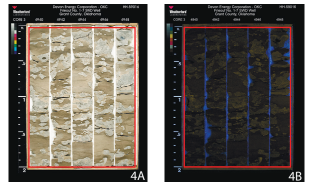


Figure 13. Core photos show nodular grainstone on white light (4A) and UV light (4B). This lithofacies is characterized by light olive gray, light greenish gray, yellowish gray, white, very fine to medium sand-sized peloidal and skeletal grains, hard, grain supported, parallel lamination and ?mud wispy laminated are commonly observed, stylolites are common, fractures are typically associated with the nodules, no visible porosity.

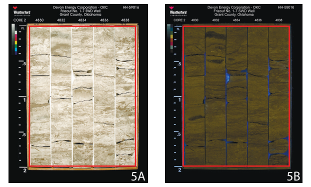


Figure 14. Core photos show bioturbated packstone-grainstone on white light (5A) and UV light (5B). This lithofacies is characterized by light to medium gray, white, yellowish gray, silt to very fine sand-sized peloidal grains, hard, grain supported, abundant bioturbation (mm to cm scale), blotchy texture, stylolites are moderate, ?faint cross bedding is rare, no visible porosity.

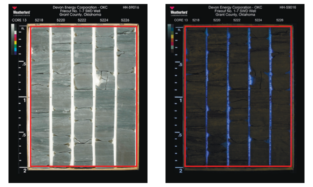


Figure 15. Core photos show bioturbated mudstone-wackestone on white light (6A) and UV light (6B). This lithofacies is characterized by grayish black, faint-weakly laminated, millimeter-sized bioturbations, hard, peloidal, glauconite, and altered skeletal grains such as spicules, ?brachiopods, and shell fragments are occasionally present, no visible porosity.

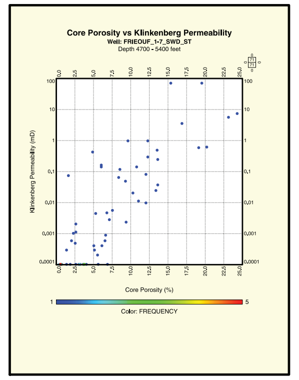


Figure 16. Porosity-Klinkenberg Permeability crossplot for all rock types in Frieouf 1-7 SWD well. The porosity values vary from 0.4 - 24.3 % while permeability values range from 0.0001 - 70.3 mD. Note that most of the permeability values are below 0.01 mD.

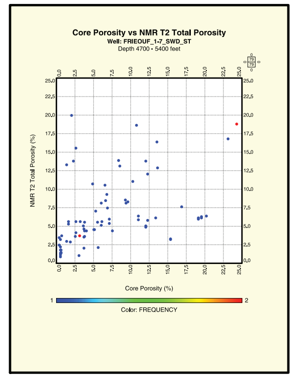


Figure 17. Core - NMR T2 Total Porosity-crossplot for all rock types in Frieouf 1-7 SWD well. Note that the data are scattered and obtaining a relationship between core and well-log data is very challenging. Integration of pore typing and "Heterogeneity log" for flow units is expected to solve this issue.

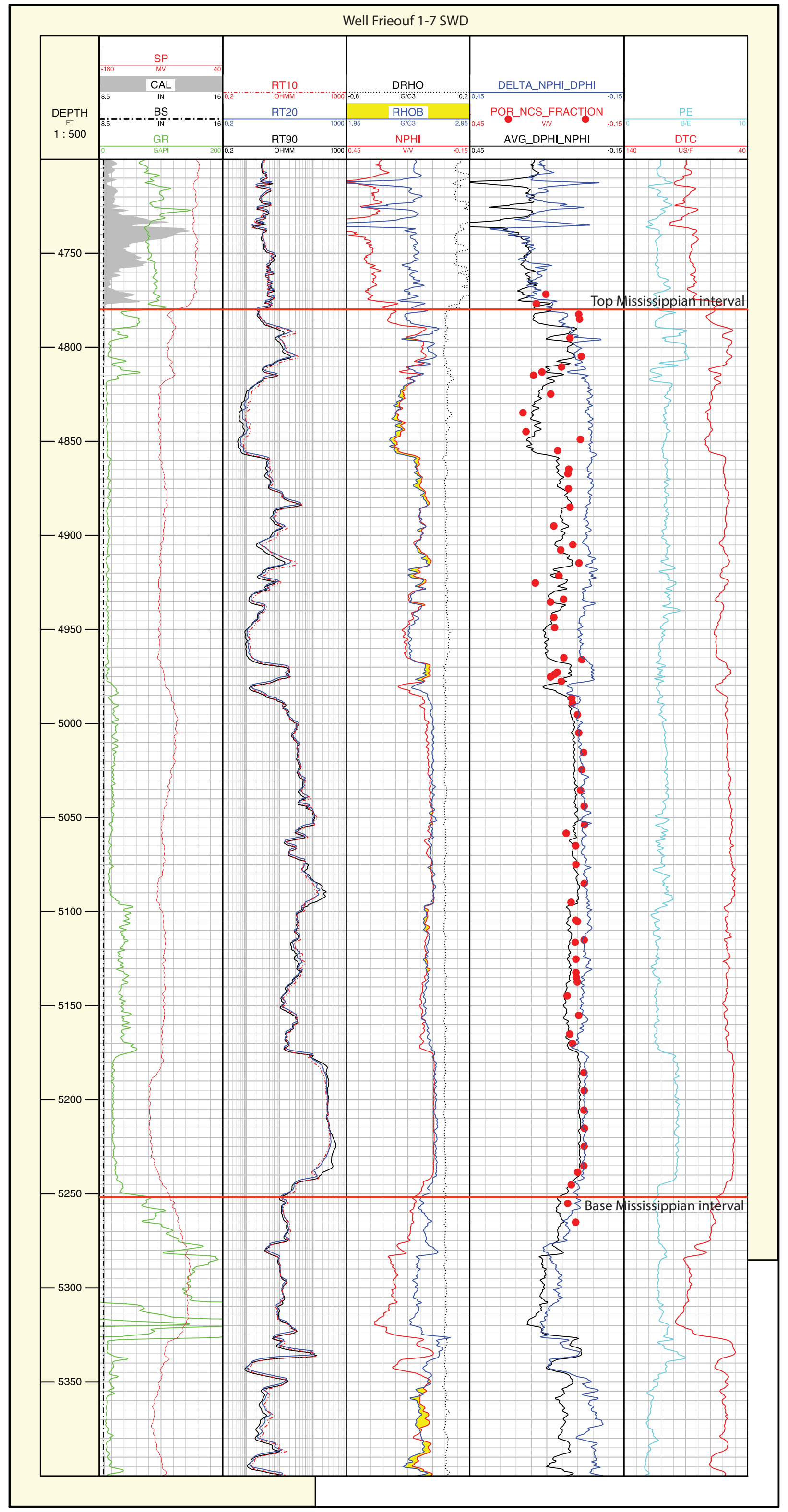


Figure 18. Typical well-logs available for this research including Spontaneous Potential (SP), Gamma Ray (GR), Resistivity, Density, Neutron porosity, photoelectric effect (PE), and sonic log. Several wells have spectral gamma ray, Nuclear Magnetic Resonance (NMR) and sonic log with compressional, shear, and stoneley travel times. Three (3) wells have routine core analysis data such as porosity, permeability, grain density, fluid saturation, and XRD data.

6. Future Works

Enhanced reservoir characterization is critical for continuous development of Mississippian limestone reservoirs of the Mid-continent. These reservoirs provide a great opportunity to test the concept of statistical measures of petrophysical heterogeneity for rock typing in an unconventional carbonate reservoir.

This research is in the early stages of designing the investigation, allowing a statistical analysis of data to test the hypotheses. Preliminary result of core description suggests that the Mississippian limestone in the study area consists of six (6) lithofacies including chert-brecciated limestone, nodular grainstone, peloidal laminated packstone-grainstone, skeletal packstone-grainstone, bioturbated packstone-grainstone, and bioturbated mudstone-wackestone. Shoaling-upward cycle is typically started with bioturbated mudstone-wackestone, bioturbated packstone, and capped by bioturbated grainstone or skeletal grainstone. Occasionally, the top section is characterized by nodular grainstone or peloidal laminated packstone-grainstone or chert-brecciated limestone. Following the core description, fifty eight (58) thin sections throughout the Mississippian interval in Frieouf 1-7 SWD well will be analyzed using transmitted light microscope and Scanning Electron Microscope (SEM) for determining pore-types, pore sizes, paragenesis, and mineral composition. The result will be integrated with routine core analysis and X-Ray Diffraction (XRD) data.

Petrophysical analysis will include:
a. Velocity-deviation log and separation of sonic and density-neutron porosities method - pore-types.
b. Nuclear Magnetic Resonance (NMR) - textural and pore size.
c. Stoneley wave analysis - permeability estimation
d. Multi-mineral analysis - volume of minerals.
e. Heterogeneity log - fluid flow units, ?rock typing.

In summary, the complementary attribute of each log and techniques will be used to evaluate this complex unconventional carbonate reservoir. Previous work has proven that Heterogeneity logs can be used to identify fluid flow zones in carbonate reservoirs. Therefore, applications of heterogeneity logs to better constrain fluid flow units and to improve rock typing are expected to better illuminate issues related to reservoir characterization of unconventional carbonate reservoirs.

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