URTeC: 3290

Integration of Geochemical and Petrophysical Measurements from Drill Cuttings for Unconventional Reservoir Characterization, Converse County, Powder River Basin

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This paper was prepared for presentation at the Unconventional Resources Technology Conference held in Austin, Texas, USA, 20-22 July 2020.

Abstract

The Cretaceous reservoirs of the Rockies have become an important component of future unconventional oil growth in the lower 48. Horizontal drilling within the Powder River Basin (PRB), is moving from appraisal towards co-development of horizontal targets within the Niobrara and Turner Sands formations. Here, novel laboratory techniques utilizing drill cuttings as a primary data source were developed to address the following questions: 1) What are the dominant chemofacies in the Niobrara and Turner Sands reservoirs of NE Converse County, WY, and 2) what is the relationship between chemofacies and petrophysical characteristics.

Petrophysical properties in the Niobrara and Turner Sands formations vary at the field scale, adding complexity to development planning. Additionally, direct measurement of petrophysical properties to calibrate vintage wireline logs prior to development is difficult due to limited core data. Drill cuttings are more abundant and have the advantage of covering a larger stratigraphic section compared to core. However, measuring porosity from drill cuttings with traditional laboratory techniques, specifically Nuclear Magnetic Resonance (NMR), is not widely employed in the industry.

To address these questions, drill cuttings and core from NE Converse County, WY, were analyzed using organic and inorganic geochemical techniques, including handheld X-ray Fluorescence (XRF), X-ray Diffraction (XRD), and LECO TOC (TOC). A new methodology of cuttings preparation for the NMR porosity measurement was used which removes fluid from the surface of the cuttings and focuses the measurement on the pore space fluids. This methodology minimizes surface water signal, which can be misinterpreted as pore volume. Previous attempts to eliminate the surface water signal used pore size distribution cutoffs, which are unreliable due to pore size distribution overlap.

In this study, the NMR Porosity measurements will be paired with geochemical analyses to examine the link between chemofacies and porosity. Integrating this relationship with wireline data will refine understanding of petrophysical characteristics in the Niobrara and Turner Sands, and help validate the new cuttings NMR method.

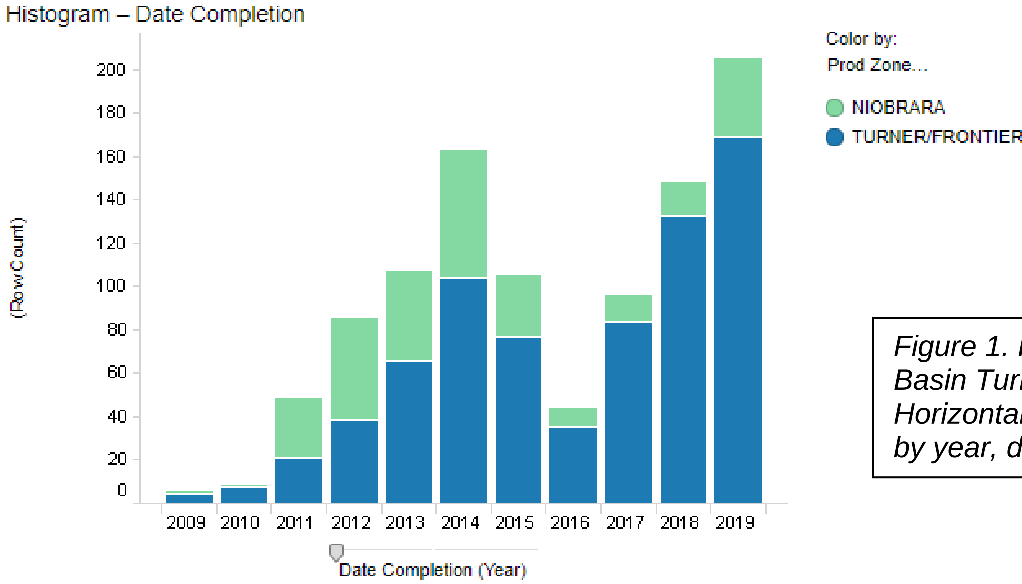


Figure 1. Powder River Basin Turner and Niobrara Horizontal well completions by year, data from IHS

Introduction

The Powder River Basin experienced an increase in the number of Horizontal drilling completions in the Turner and Niobrara over the past several years. A total of 146 Horizontal wells completed in the Turner in 2019 and 37 in the Niobrara. Up from 117 and 16 in 2018, respectively (Figure 1). The dip in wells per year in 2016 was driven by commodity prices, a factor that will curtail activity in 2020. Despite the commodity price cycle influence on activity, horizontal completions are on a long-term positive trajectory in the Turner and Niobrara of the Powder River Basin.

The Niobrara is less developed than the Turner in part due to variability in well results. Some of this is related to challenges in defining Niobrara sweet spots. One of the complexities in determining the sweet spots in the Niobrara is evaluating the formation petrophysically. Nearly the entire formation has excess resistivity, and density porosity; however, the pore size distributions that influence the productivity of the reservoir can be defined by NMR but not easily with density porosity and resistivity.

Although high-tier logs and core are the preferred data sources for reservoir characterization, these datasets are expensive and often sparse in the early stages of asset appraisal. Drill cuttings are more abundant and have the advantage of covering a larger stratigraphic section compared to core; however, the use of cuttings can introduce uncertainty into the data such as depth uncertainty, issues with sampling representativity and condition, or a lack of laboratory methods tailored to cuttings (Sanei et al. 2020). Specifically, the use of Nuclear Magnetic Resonance (NMR) for measuring petrophysical properties of cuttings is not widely employed in the industry (Mitchell et al. 2019). Therefore, when possible, the integration of cuttings with core and high-tier logs can be used to validate results and reduce uncertainty. In this study, NMR wireline log and geochemical analyses from core were paired with novel NMR laboratory techniques on drill cuttings to 1) validate the cuttings NMR workflow, 2) evaluate the dominant chemofacies in the Niobrara and Turner Sands reservoirs of NE Converse County, WY, and 3) examine the relationship between chemofacies and petrophysical characteristics.

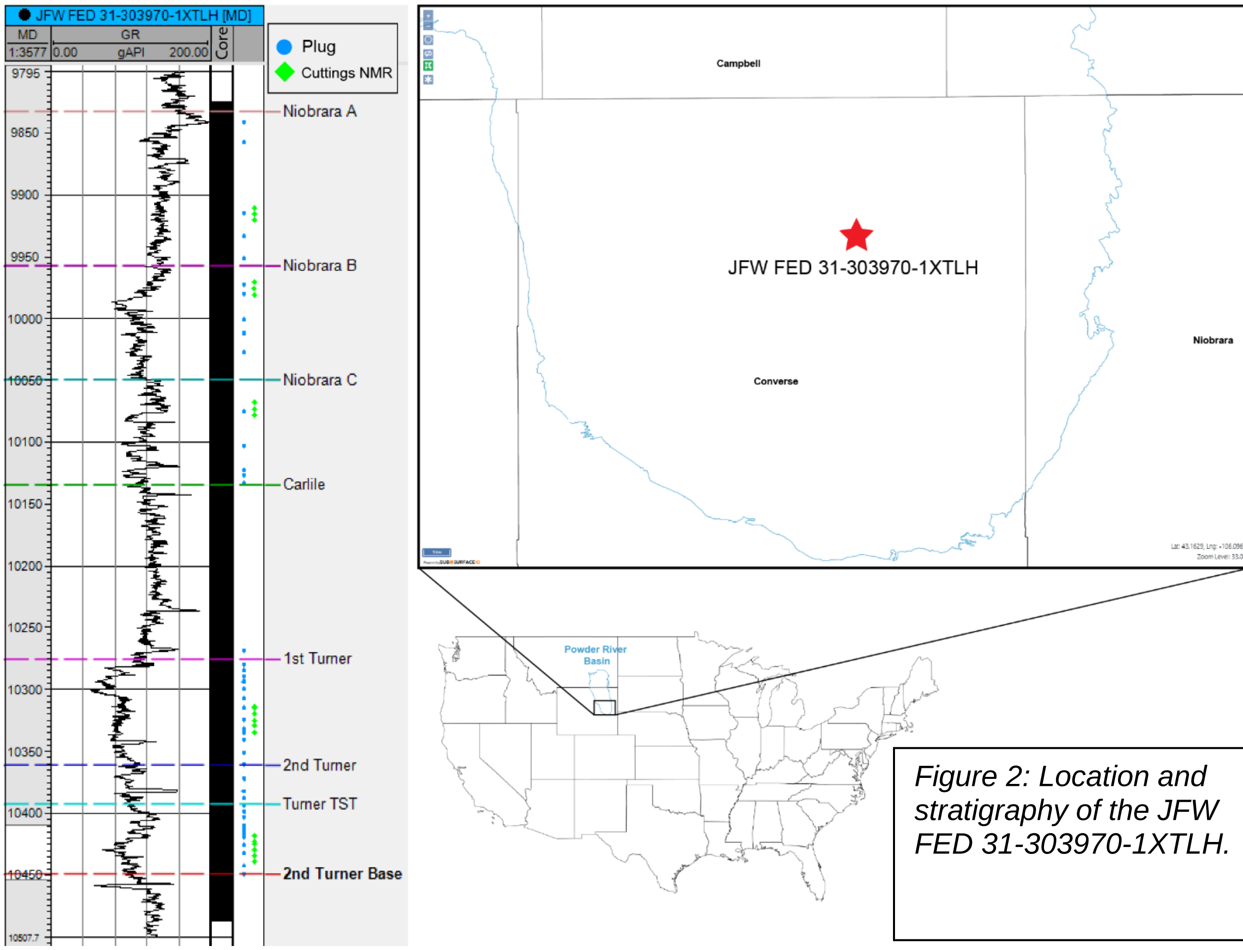


Figure 2: Location and stratigraphy of the JFW FED 31-303970-1XTLH.

Methods

The JFW FED 31-303970-1XTLH (JFW FED) well is located in the southern portion of the Powder River Basin, in northeastern Converse county, Wyoming (Figure 2). Six-hundred sixty-three feet of core were recovered from the JFW FED, representing the Niobrara, Carlile, and the 1st and 2nd Turner Sands (Turner) formations. Additionally, cuttings were collected at 3-10ft intervals during the coring process.

Geochemistry

Geochemical analysis by X-ray fluorescence (XRF) was undertaken on slabbed core and cuttings using Bruker TRACER 5 portable XRF spectrometers. Prior to analysis, the face of the slabbed core was scrubbed with water to remove drill mud contamination and to remove salts from formation brines that may have precipitated on the slab face. Cuttings samples were sieved to removed circulated material and cavings and then gently washed with water to remove residual drilling fluids. Cuttings samples were subsequently crushed and pressed into a pellet with a more uniform surface. Three XRF scans with different instrument settings were taken on the surface of each cuttings pellet and every 2 inches (5.08 cm) over the length of the core, with infill sampling at intervals where high lithologic heterogeneity was observed. The 3 scan settings are optimized to measure photon counts from 30 major and trace elements, which are converted to weight percent and parts per million using a proprietary calibration from a set of reference materials.

Hierarchical cluster analysis (HCA) in TIBCO Spotfire® was used to identify chemofacies in the Niobrara and Turner Sands using the abundances of the major mineral forming elements measured with XRF the slabbed core. Non-normalized weight percent Mg, Al, Si, S, K, Ca, Fe, and ppm Ni were clustered using Ward's Method and a half-square Euclidean distance measurement. The Niobrara was clustered separately from the Turner Sands to distinguish the subtle differences in chemistry that are often missed when lumping formations with largely different lithology.

Mineral quantification by X-ray diffraction (XRD) was undertaken using 45 core plugs sampled from the butt section of the core. Two grams of each plug were hand ground and micronized using a McCrone mill to achieve a uniform crystal size. Powders were analyzed separately for bulk and clays minerals using the Bruker D4. Bulk mineral diffractograms were interpreted using the TOPAS Rietveld Refinement software and a mineral reference database. Diffractograms of clay separates were interpreted using NewMOD, providing consistency in clay speciation and expandability.

Total organic carbon (TOC) was measured for 20 of the core plug sampled for XRD. One gram of material was washed, powdered, weighed, and acidified to remove carbonates. Powdered materials were analyzed using a LECO Carbon Analyzer and are reported in weight percent total organic carbon.

Cuttings NMR

After cuttings were washed and sieved for XRF, a split was made for 21 samples for NMR with Green Imaging Technologies. The principal problem with determining the porosity of cuttings (or crushed core samples) is establishing the bulk volume of the cuttings. The cuttings are small, jagged and unsymmetrical, making their bulk volumes impossible to determine via geometrical measurements. Instead the porosity of cuttings is determined using the following equation.

$$Porosity = \frac{Pore\ volume\ of\ cuttings}{Bulk\ volume\ of\ cuttings} = \frac{V_{cuttings}}{V_{total} - V_{cuttings+fluid} + V_{cuttings}}$$

V_{total} is the volume of a vial filled to a pre-determined level with the saturating fluid, $V_{cuttings}$ is the pore volume of the cuttings sample and $V_{cuttings+fluid}$ is the volume of liquid and pore volume of crushed core in vial. The vial is made of Teflon, an NMR-insensitive material, in order to prevent interference with the volume measurements. Using this equation, the bulk volume of the cuttings is not measured directly, instead it is calculated from three other easily achieved NMR measurements.

The CPMG T_2 NMR pulse sequence was utilized to determine each of the volumes employed in the equation above. All measurements were recorded on either an Oxford Instruments MQC+ benchtop NMR analyzer. Acquisition and analysis of the T_2 data were achieved via Green Imaging Technologies software.

The problem with the above method is that The $V_{cuttings}$ measurement is typically hampered by fluid remaining on the surface of the cuttings following their saturation. The excess fluid on the surface of the cuttings is easily mistaken for fluid in the pores, leading to an overestimation of the porosity. To compensate for this artifact, the NMR signal from surface fluid is eliminated prior to the $V_{cuttings}$ NMR measurement. Elimination of surface fluid signal is achieved via a combination of centrifuging the cuttings and rinsing them in D_2O. To validate the method, core plugs with previous NMR measurements were crushed down into “pseudo-cuttings” and put through the cuttings NMR workflow. Porosity measured from intact plugs was compared to the pseudo-cuttings porosity for method validation.

Results

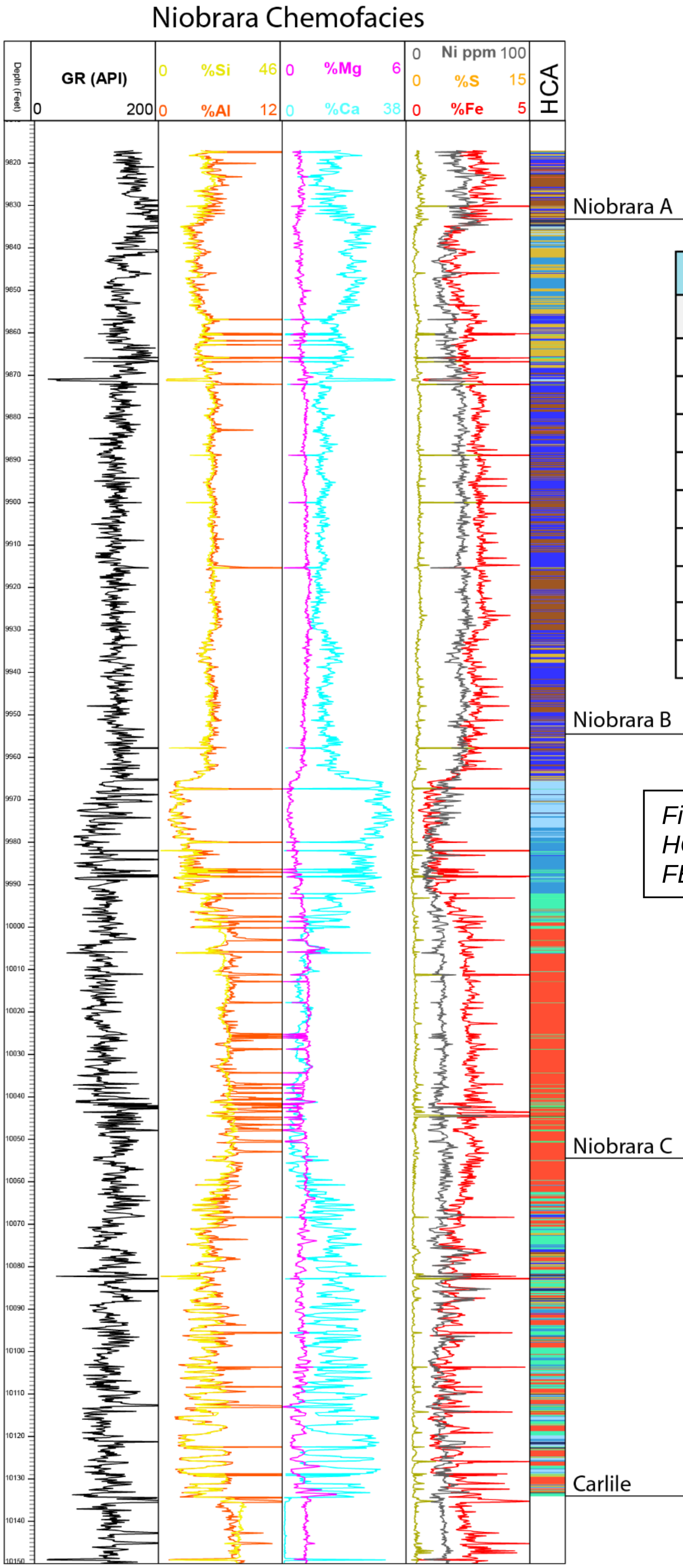
Geochemistry

Fourteen chemofacies were defined in the Niobrara and Turner Sands in the JFW FED. Chemofacies fall into 3 broad groups: siliciclastic mudstones (40.4%), carbonates (35.8%), and sandstones (23.6%).

Niobrara Chemofacies

The Niobrara is dominated by siliciclastic mudstones and carbonate group chemofacies (Figure 3). Siliciclastic mudstone chemofacies include 1. anoxic mudstone, 2. argillaceous mudstone, and 3. ash. The anoxic mudstone chemofacies is elementally characterized by high Al, Si, K, S, Fe, and Ni. Mineralogically, the anoxic mudstones are majority mixed layer illite/smectite clay with moderate quartz, moderate to high TOC (2-3 wt%), and high pyrite (5-6 wt%). Anoxic mudstones are most frequently observed at the top and base of the Niobrara A in 0.5-1 ft thick beds. The argillaceous mudstone chemofacies is elementally similar to the anoxic mudstone, but has higher Al and moderate to low S, Fe, and Ni. This difference is reflected mineralogically in a higher abundance of clay minerals (35-45 wt%) and lower TOC (1-2 wt%). Argillaceous mudstones are most prevalent in the lower Niobrara B and throughout the Niobrara C. In the Niobrara B, argillaceous mudstones form thicker, 3-10ft beds but are more thinly bedded in the Niobrara C (>2ft beds). The ash chemofacies contain the highest abundances of Al (8-20 wt%) and are more dominantly composed of clay minerals and plagioclase feldspar. Smectite and mixed layer illite/smectite are the most abundant clay minerals, and 45-55% of the illite/smectite is expandable. Ash chemofacies are found in thin beds (0.25-0.5ft) throughout the Niobrara A, B, and C but are most abundant at the base of the Niobrara B.

The next most abundant chemofacies group in the Niobrara are the carbonates, which include 4. chalk, 5. anoxic chalk, 6. sub-oxic chalk, 7. argillaceous chalk, 8. marl, and 9. anoxic marl chemofacies (Figure 3). The chalk chemofacies (4-7) are what is informally used to divide the Niobrara into its A, B, and C benches (Sonnenberg 2018). The chalk chemofacies are elementally characterized by high abundances of Ca (20-30 wt%) and are mostly composed of calcite (50-80 wt%). Anoxic and sub-oxic chalk chemofacies are differentiated by elevated levels of Ni, S, and Fe, with the anoxic chalk having slightly higher abundances of Ni, S, and Fe compared to the sub-oxic chalk. Additionally, the anoxic chalk contains higher TOC (>3.5 wt%) and more abundant pyrite. The anoxic chalk chemofacies occurs in thin beds (<1 ft) at the tops of the Niobrara A, B, and C units while the sub-oxic chalk chemofacies is most prevalent at the top of the Niobrara A. The argillaceous chalk chemofacies has high Ca with moderate Al and low Ni, S, and Fe. Although still dominantly composed of calcite, the argillaceous chalk chemofacies has moderate amounts of clay minerals (20 wt%), consisting of mostly mixed layer illite/smectite and minor amounts of chlorite and kaolinite, and is most frequently found at the tops of the Niobrara A and B. The marl chemofacies (8) has elevated levels of Ca, Al, Si, K, and moderate Mg. The anoxic marl chemofacies is elementally very similar to the marl chemofacies but has higher levels of Ni, S, and Fe. These marl chemofacies (8-9) are nearly equal parts calcite, clay, and quartz, with minor dolomite and moderate TOC (1-2 wt%). The principle mineralogic difference between these chemofacies is that the anoxic marl has a higher abundance of pyrite (>5 wt%). Stratigraphically, the anoxic marl chemofacies is found in 2 to 5 ft beds in the middle-lower Niobrara A while the marl chemofacies is found in thinner beds (<2 ft) predominately in the Niobrara C.



Niobrara	
Name	**Color**
Anoxic Mudstone	
Arg. Mudstone	
Ash	
Chalk	
Anoxic Chalk	
Sub-oxic Chalk	
Arg. Chalk	
Marl	
Anoxic Marl	

Figure 3: Depth plot of Niobrara HCA-chemofacies from the JFW FED core.

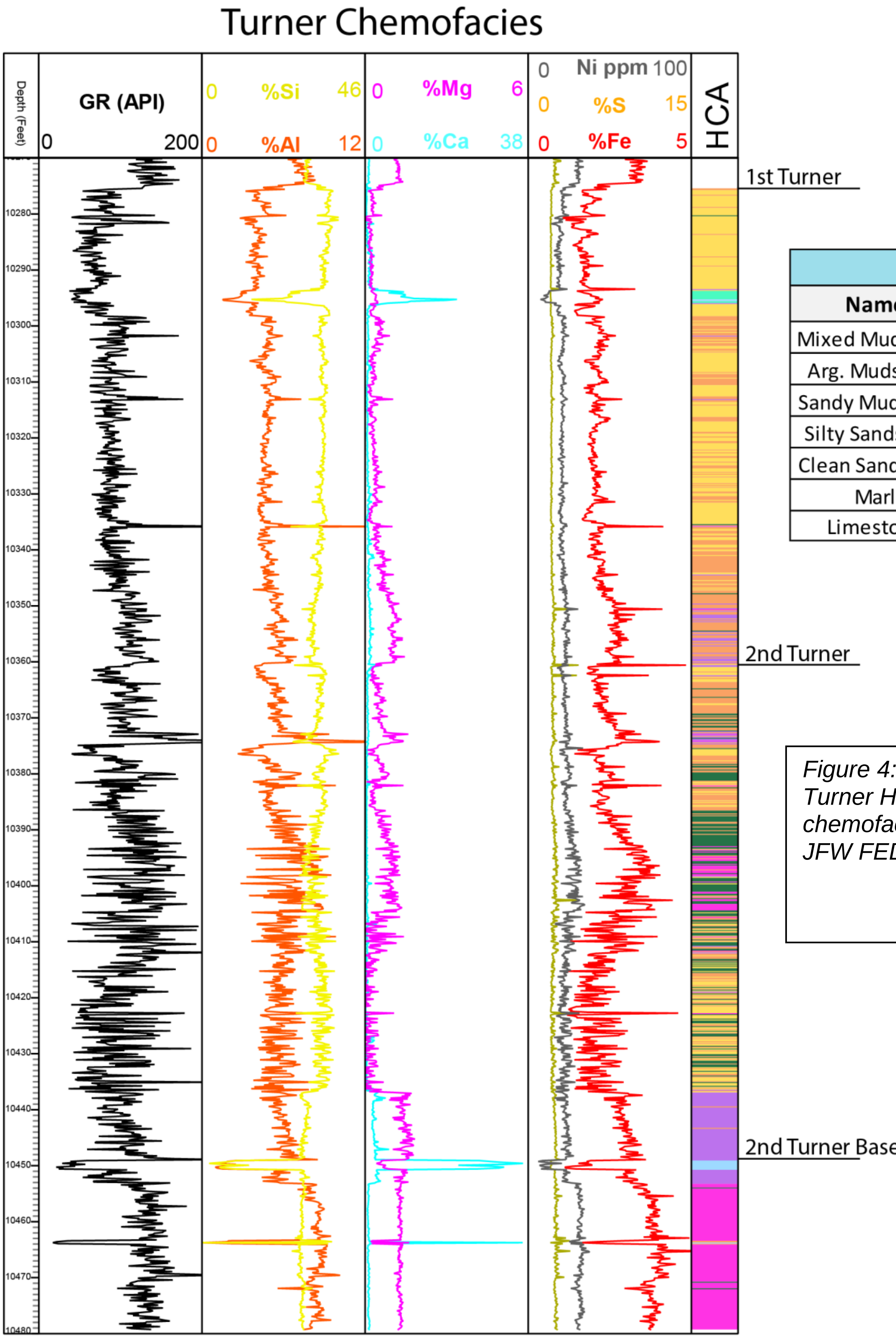
Turner Chemofacies

Chemofacies in the Turner are mostly sandstone and siliciclastic mudstone groups with minor carbonate chemofacies (Figure 4). Sandstone chemofacies include 10. silty sandstone and

11. clean sandstone. Although both chemofacies are characterized by elevated quartz concentrations (55-75%), the principle difference between the silty and clean sandstone chemofacies is the silty sandstone has >15 wt% clay minerals and more abundant plagioclase feldspar. Both sandstone chemofacies are characterized by minor amounts of calcite and dolomite (< 10 wt%). Of the clay minerals, mixed layer illite/smectite with 10-30% expandability is the most abundant, followed by minor amounts of chlorite. The elemental signature of the clean sandstone is high Si with moderate to low Ca, while the silty sandstone is high in Si with moderate Al and Mg. The clean sandstone chemofacies are found in more massive (3-8 ft) beds near the top of the 1st Turner and the base of the 2nd Turner, while the silty sandstone chemofacies is more thinly bedded (0.5-3 ft) and found more frequently at the base of the 1st Turner and top of the 2nd Turner.

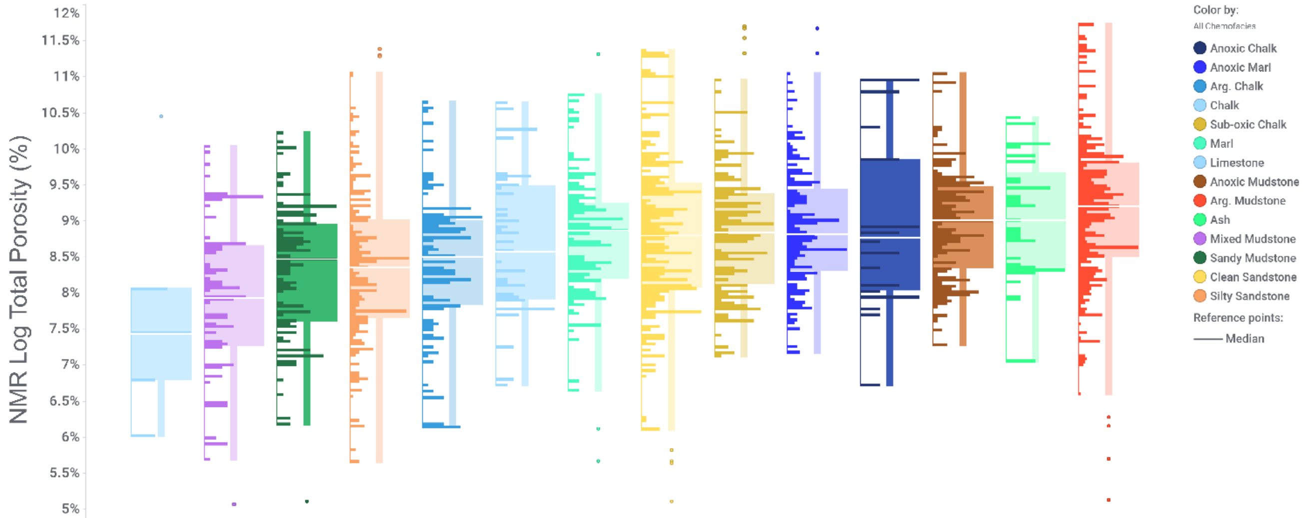
Siliciclastic mudstone chemofacies in the Turner include 12. mixed mudstone, 13. sandy mudstone, and 2. argillaceous mudstone. The mixed mudstone chemofacies is composed of 40-50 wt% quartz with moderate amounts of clay and minor dolomite, while elementally it is identified by high Si, Al, K, and moderate Mg, S, and Fe. Mixed mudstone chemofacies are mostly present at the top and base of the Turner in thick (>5 ft) beds but also occur in discrete, 1 to 2 ft beds at the top and middle of the 2nd Turner. The sandy mudstone chemofacies has high abundances of Al and Si, with relatively high S, Fe, and Ni. Mineralogically, the sandy mudstone chemofacies is nearly equal parts quartz and clay and is the most organic rich chemofacies in the Turner, with TOC between 0.8-1.0 wt%. The sandy mudstone chemofacies is only observed in the middle 2nd Turner and represents what is traditionally considered the Turner TST surface. The argillaceous mudstone chemofacies is compositionally similar to the argillaceous mudstones in the Niobrara, with high Al, Si, K and low S, Fe, and Ni, but has slightly lower concentrations of TOC. Argillaceous mudstone chemofacies co-occur with mixed mudstones at the top and base of the 2nd Turner.

Limestone chemofacies (14) constitute the smallest proportion of Turner and are characterized by high (>20 wt%) Ca and minor Mg and Fe (Figure 4). While no XRD data was collected in this chemofacies, elemental signatures indicate it is likely composed of majority calcite with minor dolomite. The limestone chemofacies is observed in discrete, 3-4ft beds in two locations: the top of the 1st Turner and the base of the 2nd Turner.



Turner	
Name	Color
Mixed Mudstone	
Arg. Mudstone	
Sandy Mudstone	
Silty Sandstone	
Clean Sandstone	
Marl	
Limestone	

Figure 4: Depth plot of Turner HCA-chemofacies from the JFW FED core.



	Limestone	Mixed Mud...	Sandy Mud...	Silty Sands...	Arg. Chalk	Chalk	Marl	Clean Sand...	Sub-oxic C...	Anoxic Marl	Anoxic Ch...	Anoxic Mu...	Ash	Arg. Mudstone
Count	13	133	155	341	195	103	206	388	202	415	26	279	43	678
Max	10.46%	10.05%	10.25%	11.39%	10.67%	10.66%	11.32%	11.39%	11.71%	11.68%	10.98%	11.06%	10.45%	11.75%
Avg	7.49%	7.86%	8.27%	8.33%	8.39%	8.70%	8.78%	8.82%	8.87%	8.90%	8.98%	8.98%	9.02%	9.18%
Median	7.43%	7.93%	8.47%	8.35%	8.50%	8.58%	8.87%	8.80%	8.84%	8.82%	8.77%	9.01%	9.01%	9.20%
Min	6.00%	5.07%	5.11%	5.64%	6.12%	6.70%	5.68%	5.11%	7.11%	7.16%	6.70%	7.26%	7.04%	5.13%

Figure 5: Box plots displaying the distribution of total porosity by chemofacies in the Niobrara and Turner. Boxes are colored by chemofacies and shaded to show the distribution of data in each chemofacies.

NMR

Total porosity measured from NMR log ranges from 5%-11.7% in the Niobrara and Turner units (Figure 5). In general, siliciclastic mudstone and anoxic to sub-oxic chalk chemofacies of the Niobrara (1-3, 5-6) have the highest average total porosity (9.06% and 8.93%, respectively), followed by the marls (8.84%) and sandstones chemofacies (8.58%) in the Turner and Niobrara (8-11), and finally the sandy and mixed mudstones (8.06%) and limestones (7.5%) in the Turner (12-14).

Total porosity measured from the 21 cuttings samples in the Niobrara and Turner ranges from 5.8% - 9.9%, while the NMR on core plugs from the same depth interval ranges from 6.7% - 11.2% and the NMR log ranges from 6.9% - 10.7% porosity (Figure 6). While the porosity range from cuttings and core plugs are similar to the porosity range from NMR log, on average a 1.95% porosity difference exists between cuttings and NMR log and a 1.45% porosity difference occurs between core plugs and NMR log (Figure 6 and 7). Marl, anoxic marl, silty sandstone, and sandy mudstone chemofacies have the largest difference in total porosity between the cuttings or core plug with the log.

Discussion

Petrophysical Characteristics of Niobrara and Turner Chemofacies

Although both the laboratory NMR and NMR log suggest that the range in total porosity of chemofacies overlap, other NMR results, such as T2 relaxation times, can be used as a proxy for pore sizes and their contribution to total pore volume (Dunn et al. 2002). Using T2 relaxation times from the NMR log, total porosity was divided into 13 porosity “bins”, with PO1 representing fluids in pores with the fastest T2 relaxation times and PO13 representing fluids in pores with the slowest T2 relaxation times (Figure 8- A and B). These porosity “bins” from the log and T2 distributions from cuttings NMR can be compared to understand the pore size distributions of each facies (Figure 8).

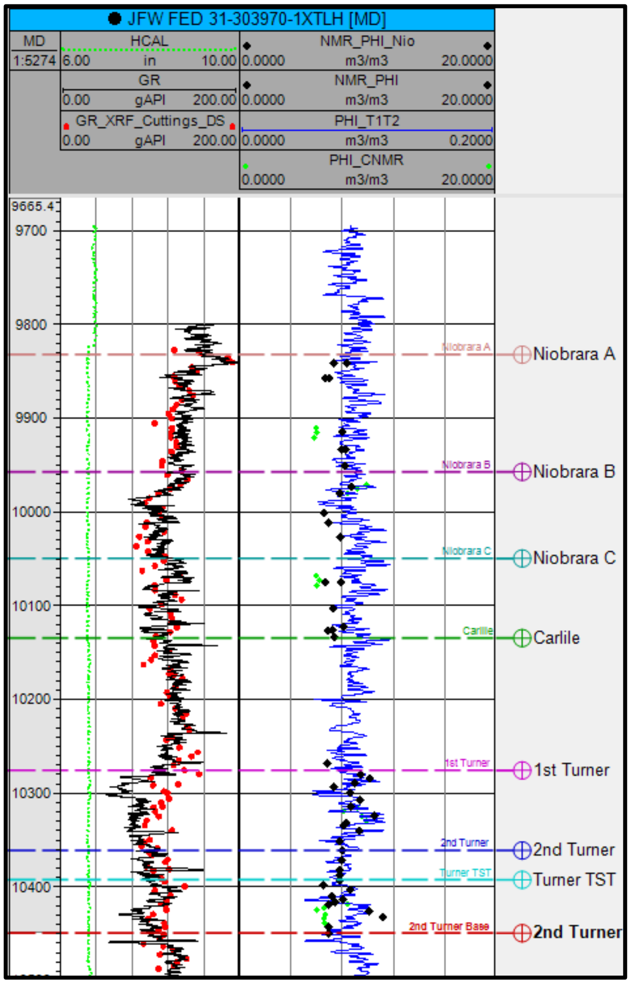
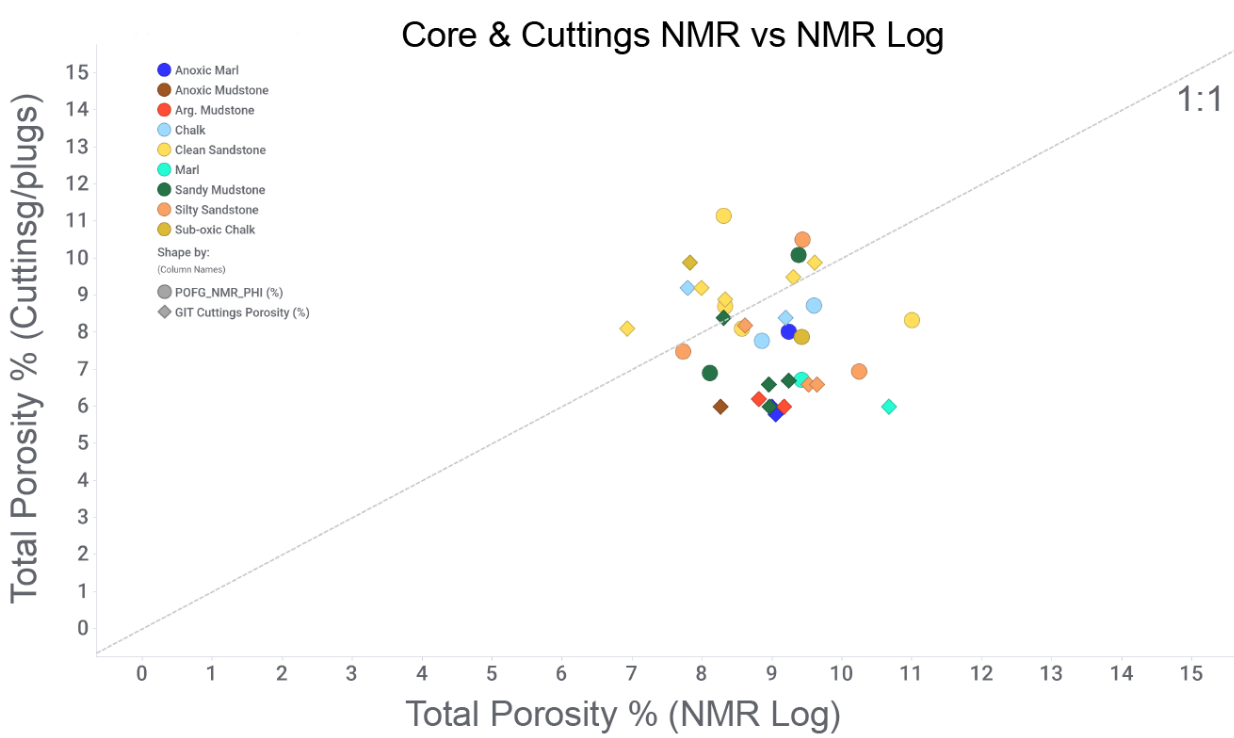


Figure 6 (left): Depth plot of NMR total porosity from cuttings, core plugs, and wireline log. Track 1 displays the gamma ray curve (black), red dots are cuttings XRF-calculated gamma ray used to shift cuttings to the log, and the green curve is the caliper. Track 2 displays the NMR total porosity from NMR log (blue curve, PHI_T1T2), NMR on core plugs (black dots), and NMR on cuttings (green dots).

Figure 7 (below): Cross-plot displaying the relationship between total porosity (%) measured from NMR log and laboratory NMR measurements on core plugs and cuttings over the same depth interval. Dots are NMR measurements on core plugs and diamonds are NMR measurements on cuttings. Data are colored by the corresponding chemofacies.



In general, pore size distributions are consistent between the cuttings and the log (Figure 8). In all chemofacies, a large portion of the total pore volume is associated with the smallest pores. Small pores are most prevalent in the siliciclastic mudstone chemofacies in the Niobrara (1-3), and the mixed mudstone and limestone chemofacies in the Turner (12 and 14). The chalk and marl chemofacies in the Niobrara (4-9) display a bimodal distribution of pore sizes, with small and medium sized pores contributing most of the pore volume. The sandstones and sandy mudstone chemofacies (10, 11, and 13) in the Turner have the highest proportion of large pores but also have the widest distribution of pore sizes. These results suggest that, although total porosity NMR measurements between the log and cuttings differ slightly, both techniques are measuring similar T2 distributions. This is further validation that the NMR workflow can be used to measure the petrophysical properties of drill cuttings in these lithologies.

Data Limitations and Considerations

When interpreting these data, or when using drill cuttings samples for analysis, in general, several considerations and data limitations should be kept in mind. The first is the question of “sample representativity”. Cuttings inherently have a higher degree of depth uncertainty compared to core and are susceptible to sampling bias of the mud logger. Additionally, cuttings are often collected at varying intervals between 5ft to 100ft, which can cause a smoothing effect by lumping different rock types together. However, uncertainty of sample representativity in cuttings can be reduced by pairing these cuttings dataset with logs (e.g. calculating a gamma ray from XRF to compare with logs).

A consideration specific to the use of cuttings for NMR measurements is the effects of cutting size and condition on data quality. Because pore sizes range from nm to cm, it is likely that the size of cuttings produced by the drill bit will influence which pores are preserved in the cuttings. Additionally, the stress induced on the cutting by drilling could change the original pore structure. While this study does not examine these effects, we acknowledge they have the potential to introduce error into cuttings-based NMR interpretations.

Even with all the data limitations and considerations, often core and high tier logs are unavailable or cost prohibitive, making careful utilization and integration of quantitative cuttings data a necessity.

Conclusions

Fourteen distinct chemofacies were defined in the Niobrara and Turner Sands from JFW FED core in NE Converse county, WY using XRF, XRD, and TOC. The Niobrara units are largely composed of siliciclastic mudstone and carbonate chemofacies while the Turner is mostly composed of sandstone and siliciclastic mudstone chemofacies. A novel cuttings NMR workflow was used in conjunction with traditional core NMR and an NMR log to characterize the porosity range and pore size distribution of each chemofacies and validate the cuttings NMR method. The siliciclastic mudstone and anoxic to sub-oxic chalk chemofacies of the Niobrara have the highest average total porosity (9.06% and 8.93%, respectively) while the sandstones chemofacies (8.58%) had the highest porosity in the Turner. T2 distributions indicate that most of the pore volume of the siliceous mudstones in the Niobrara and Tuner is associated with the smallest pores, while the chalks and marls in the Niobrara display a bimodal distribution of small to medium sized pores. In the Turner, the sandstones and sandy mudstones have the highest proportion of large pores and the widest distribution of pore sizes. Total porosity measured from NMR on cuttings deviates by an average of +/- 1.95% porosity from the NMR log at the same depth. However, average T2 distributions for chemofacies from cuttings NMR agree with T2 distributions from the NMR log. This is validation that a cuttings-based NMR workflow can be used to estimate the petrophysical properties of drill cuttings in these lithologies.

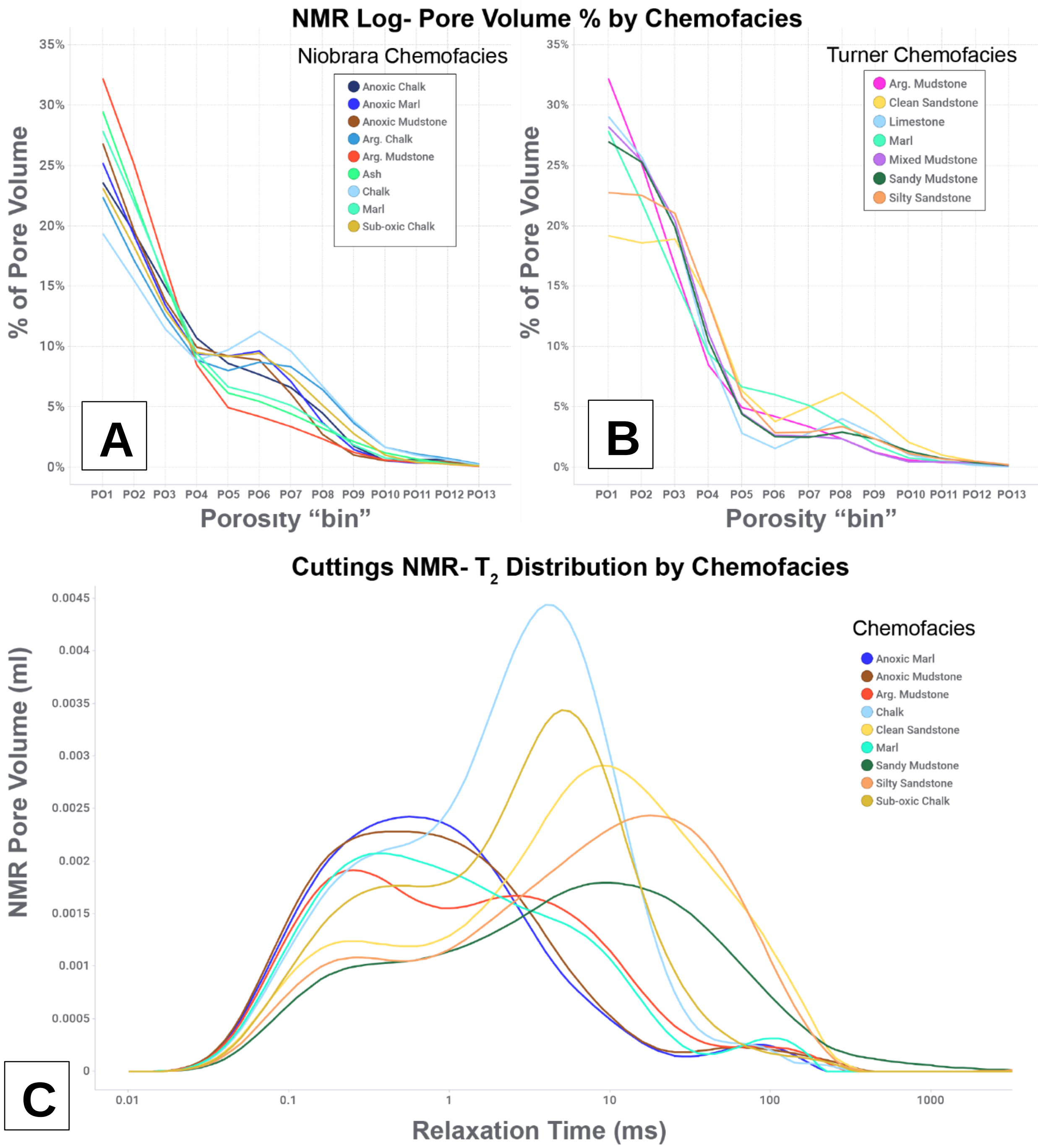


Figure 8: Comparison of T2 relaxation times from NMR log (A and B) and laboratory NMR measurements on cuttings (C). Plots A and B display porosity "bins" from PO1 to PO13 and are arranged from fastest to slowest relaxation, respectively. Individual lines represent the average contribution of each porosity "bins" as a percentage of the total porosity for the Niobrara and Turner chemofacies. Plot C displays the incremental pore volume at each T2 relaxation as measured from cuttings. Each line representing the average T2 distribution for each chemofacies.

Acknowledgments

The authors would like to thank Grayson Mill Energy for funding the data acquisition for this project, the staff in Core Services and Reservoir Geology and Geochemistry Department at Premier Oilfield Group, and the team at Green Imaging Technologies, INC.

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