https://www.scirp.org/journal/ns Natural Science, 2021, Vol. 13, (No. 7), pp: 282-300

A Petrophysical Approach to Evaluation from Measured While Drilling Gamma Ray, Case Study in the Powder River and Delaware Basins

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Keywords: Petrophysics, Gamma Ray, Measuring While Drilling, Workflow, Delaware, Powder River
Received: May 18, 2021 **Accepted:** July 27, 2021 **Published:** July 30, 2021

ABSTRACT

One of the most common subsurface data sets that is easily accessible and often underutilized is the acquired measuring while drilling (MWD) gamma ray (GR-GAPI) log. Data is acquired from a given gamma ray tool positioned within the drill string and pulsed up to the surface through the mud column in the wellbore. Typical use of the data is for subsurface geologists, drillers and others to correlate the data to known stratigraphic signatures and steer wells through horizontal target zones. Through that correlation, an association to the geologic stratigraphic column can be made and the team of subsurface scientists adjusts where, how fast, and why they choose to continue drilling. The technique of correlation applies to both the conventional and unconventional application. In the unconventional application, the data is also typically acquired along the length of the horizontal wellbore. From a petrophysical standpoint, just acquiring a gamma ray can limit the amount of information and ability to fully evaluate the properties along the length of the well. In this study, we share and demonstrate how to utilize the MWD GR for petrophysical evaluation beyond just a volume of shale or volume of clay interpretation. The workflow will allow full integration of a comprehensive petrophysical evaluation that can then be utilized to support all subsurface understandings and modelling efforts.

1. INTRODUCTION

In this case study, we utilize wells whose drilled wellbore path began as a vertical well to a pre-planned depth and then drilled horizontally at depth. Then, the well was drilled with a known depth versus horizontal angle drill rate to ensure reaching a maximum angle (180˚) to the Earth's surface by the time it reached the geologic formation of interest. The innovative application in the study is to use only the acquired MWD GR and derive a pseudo-log suite from the MWD GR that results in the triple combo suite (gamma ray, resistivity, neutron porosity, bulk density) needed for petrophysical evaluation. By establishing a workflow to take a well with minimal data and derive a full petrophysical property evaluation from it, it increases the data coverage available to generate geological maps, to correlate properties and variations and to support modelling efforts. Here, we present an example of a drilled well in the Powder River Basin as well as three wells in the Delaware basin. All wells were drilled with an oil-based mud. The Powder River basin well was drilled through the stratigraphic column until reaching the Turner sandstone interval which consists of tight (<1 mD permeability) silty-sands interbedded with organically enriched shales [1]. The goal was to maintain the wellbore in the most porous silty-sand interval that was targeted according to an offsetting vertical well with a gamma ray log. As the well was drilled, the path porpoises in and out of varying quality reservoir, as well as crossed through organically enriched shale-prone portions of the stratigraphy (**Figure 1**). A main contribution of this study is to provide a straight-forward deterministic approach through empirical correlations to expand the applicability of evaluations to well with minimal or missing data. As such, utilizing linear, exponential and logarithmic correlations from existing data sets provides a simple approach to a full evaluation. The work flow does not invoke a data science approach or rely on machine learning but rather takes a straight-forward approach to building out and interpreting a minimized raw data set.

The variation in the MWD GR that was acquired along the length of the lateral provides critical insight into the correlation length or depositional dimensions of a given deltaic-dominated Turner sand environment. Similar variation can be observed, and is important background content, to understanding the Wolfcamp system in the Delaware basin. The Wolfcamp stratigraphy represents a full expression of a low stand fan dominated system into a transition systems tract and finally into a high stand system tract (**Figure 2**) [2]. These systems tracts can be identified by changes in the resistivity (ohms) and acoustic (μs/ft) profiles. The length of the drilled horizontals in this study did vary. No drilling challenges were encountered, such as wellbore flow that needed to be mitigated or wellbore stability issues.

In the Powder River Basin well, cuttings samples were collected every ~50 feet as the horizontal well was drilled and the crumbled rock returned to the surface and collected out of the mudlogging shaker units. Cuttings were kept wet with the chemical cleaning. A subset of acquired cuttings was then selected for source rock LECO® total organic carbon (TOC wt %) and programmed pyrolysis laboratory measurements and quantification. Programmed pyrolysis was executed on a HAWK® instrument through a standard shale evaluation protocol [3]. Methodology and approach will be expanded on in the next section.

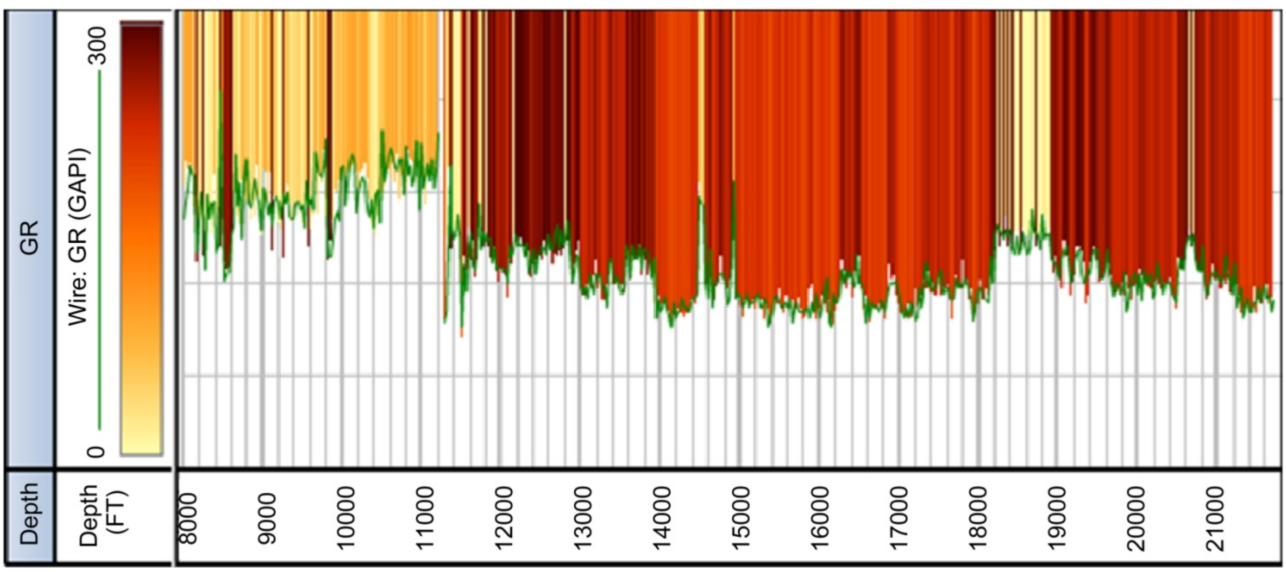


Figure 1. Drilled lateral length with acquired MWD GR (GAPI – green and color-filled) in the turner formation in the powder river Basin.

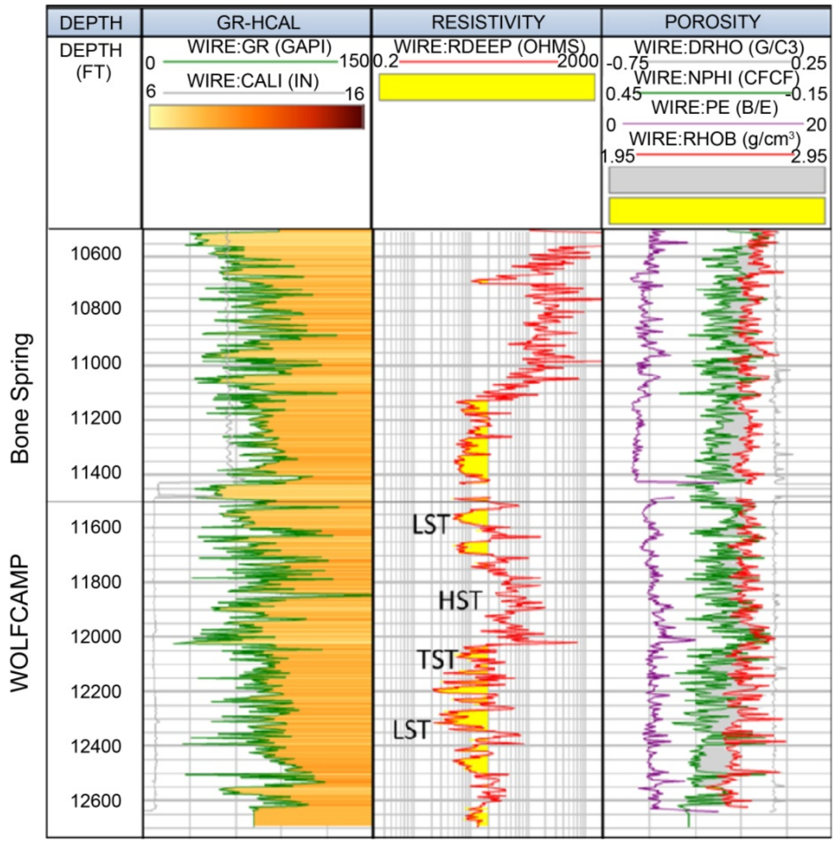
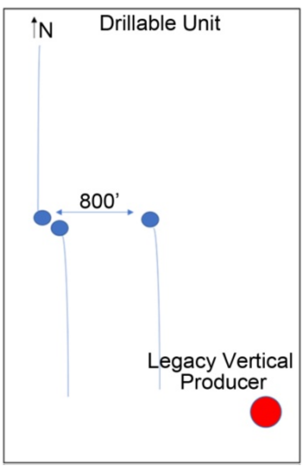


Figure 2. **Left to Right: Depth MD', Gamma Ray in green (GR – GAPI), Caliper in grey (CALI – Inches), Resistivity in red and filled yellow less than 20 ohms (RDEEP), Neutron Porosity in green (NPHI – CFCF DEC), Bulk Density in red (RHOB G/CC), Photoelectric Factor in purple (PE – B/E), Density Correction Factor in grey (DRHO – G/cc). LST = Low Stand Systems Tract, TST = Transgressive Systems Tract, HST = Highstand Systems Tract.**

Last, of importance to the study is to note that the Wolfcamp, Delaware Basin wells were drilled from a three well pad where the first well was oriented from south to north and wells 2 and 3 oriented from north to south (Figure 3(a)). All wells were drilled in the same target with a ±50 vertical feet window to



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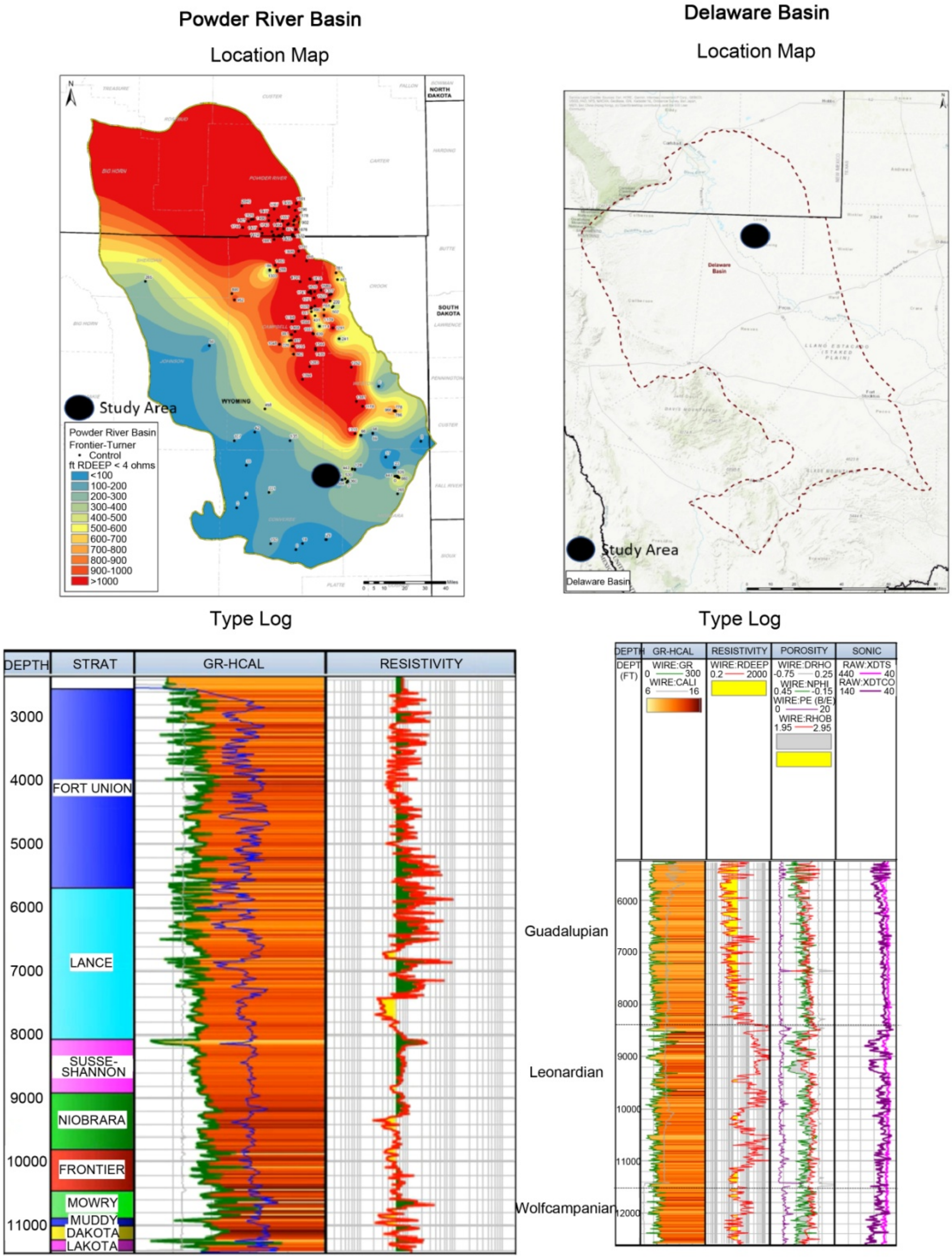


(b)

Figure 3. (a) Schematic layout and orientation of Delaware Basin 3-well pad of Wolfcamp targeted wells drilled. (b) Study areas for the wells utilized in the Powder River and Delaware Basin locations. Type log sections with stratigraphy denoted. In this study we focus on the Frontier-Turner in the Powder River Basin and the Wolfcamp in the Delaware Basin. In type log sections log displays include, Gamma Ray (GR-Gapi in green), Caliper (CALI-Inches in grey), Resistivity (Ohms-in red and color-filled), Neutron Porosity (NPHI-dec in green), Bulk Density (RHOB-g/cc in red), Photoelectric Factor (PE-b/e in purple), Compressional Sonic (DTC-μs/ft in purple), Shear Sonic (DTS-μs/ft in fuschia).

allow for the geosteering of the full horizontal length. As we compare the variability in the wells, the context of the wells being so spatially close as well as seemingly undifferentiated in the stratigraphic target becomes important to the learnings then integrated from petrophysical evaluation.

2. GEOLOGICAL SETTING

To briefly convey the geological setting for the wells shown in this study, we visit the Permian Basin system of Texas and the Powder River Basin of Wyoming. The well utilized in this study from the Powder River Basin is located in Converse county and is a single well drilled in an unconventional target. The three wells utilized in the Permian basin, more specifically the Delaware basin, are located in Loving County and are wells drilled on a multi-well pad in unconventional targets.

The Delaware basin Wolfcamp formation represents a Permian-aged stratigraphic depositional system. The Wolfcamp stratigraphy varies with depth and represents many cyclic events captured during its deposition into the basin [4]. The lithology is generally interbedded throughout however the relative proportions od carbonate versus silty-sand versus clay versus kerogen does vary (see **Figure 3(b)**). The Wolfcamp formation represents a world-class enriched source rock with interbedded reservoir units [5] [6] [7]. The formation has been and continues to be one of the main horizontally drilled targets currently in the oil and gas industry [8].

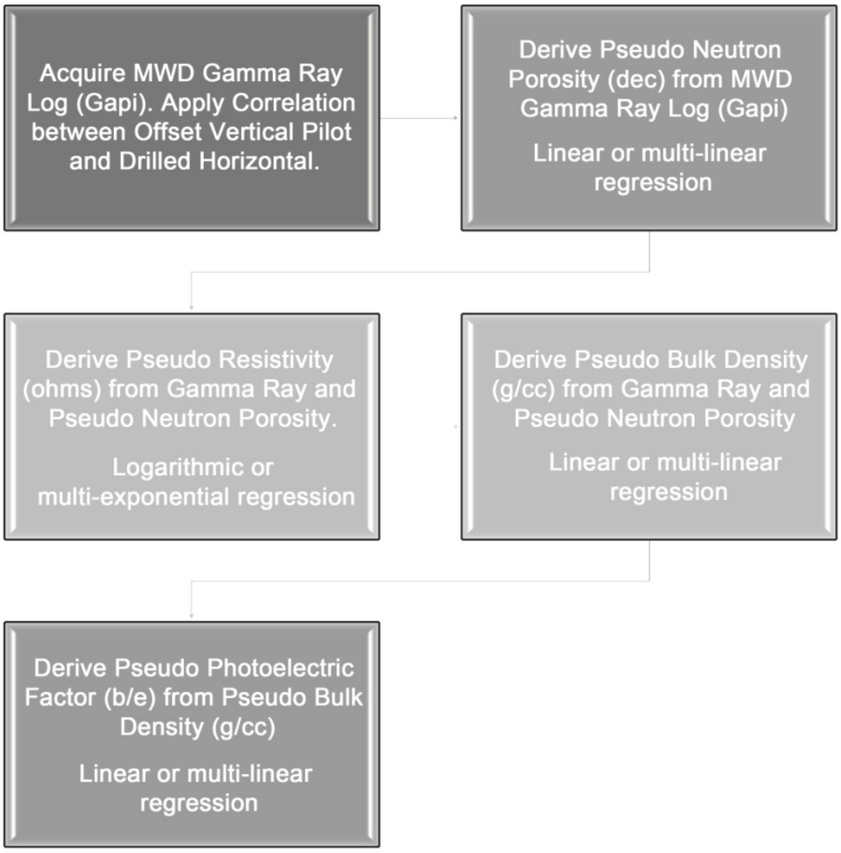
In the Powder River basin, the Niobrara formation is known for its prolific enriched source rock potential. The Turner sandstone is located immediately above the Niobrara unit and has been the subject of geological characterization for a number of years [1] [9] [10]. The Turner is also known in other locations for its equivalency to the Wall Creek and Frontier sandstone formations [9] [11]. The reservoir quality of the Turner sandstone does vary [1]. The Powder River basin continued to be a horizontally targeted oil and gas opportunity in the new decade.

3. METHODS

Typically, in order for a full petrophysical evaluation to be conducted, a triple combination log suite is available and can be utilized including a gamma ray (Gapi), resistivity (ohms), neutron porosity (dec), bulk density (g/cc) and photoelectric factor (b/e) log suite. However, in a number of wells in the Powder River and Delaware Basins, only a total gamma ray was acquired. To make use of these wells with limited log suites the following approach can be taken. The first steps in the workflow are to develop the correlations with a measured offset gamma ray log (GAPI). Then the correlations can be applied to the horizontal wellbore measured MWD GR log. Calculations and resulting log displays were done in the [12]. Interactive Petrophysics software (see references cited). The overall workflow as presented below can be visualized in **Figure 4(a)**.

- Step 1: Develop correlation between gamma ray and neutron porosity (**Figure 4(b)**).
- Step 2: Develop correlation between gamma ray and resistivity as well as resistivity and neutron porosity (**Figure 5(a)** and **Figure 5(b)**).
- Step 3: Develop correlation between neutron porosity and bulk density (**Figure 6**).
- Step 4: Develop correlation between bulk density and photoelectric factor (**Figure 7**).
- Step 5: Compare and contract direct linear and exponential correlations to a multi-linear regression analysis (**Figure 8**). The multi-linear regression analysis provides an increase in the robust approach to correlate not just one log to one log at a time but rather take multiple measured logs to increase the constraint in the derived pseudo-log.
- Step 6: Going beyond the needed triple combination, we correlated and derived the neutron porosity and bulk density to the compressional sonic log (**Figure 9**).
- Step 6B. Correlate and derive the compressional sonic to the shear sonic. The acoustics will allow the evaluation of geomechanical properties in this study.

Once all correlations are written and mathematics applied, a full *pseudo* triple or even quadruple combination log suite is now available for the subsurface expert to utilize (**Figure 10**). In addition, in this



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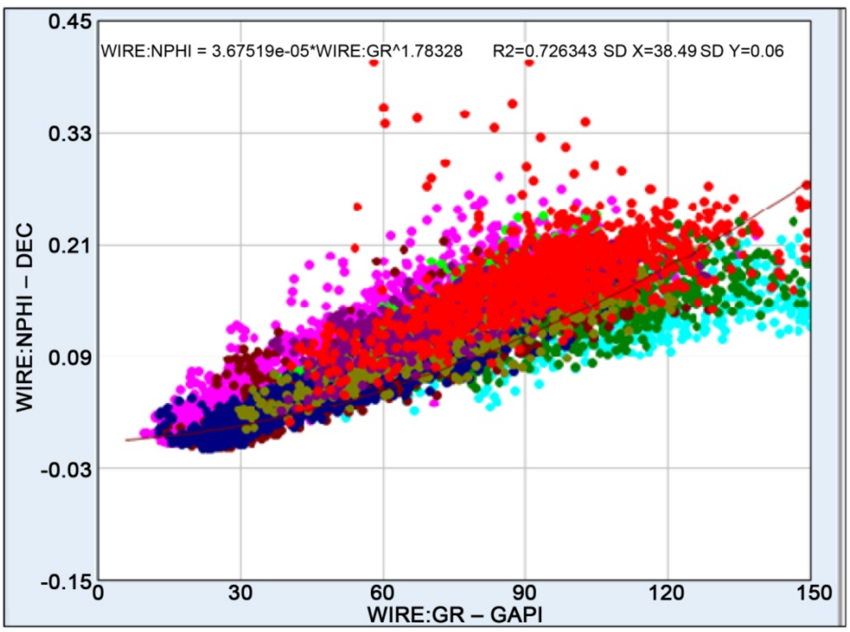
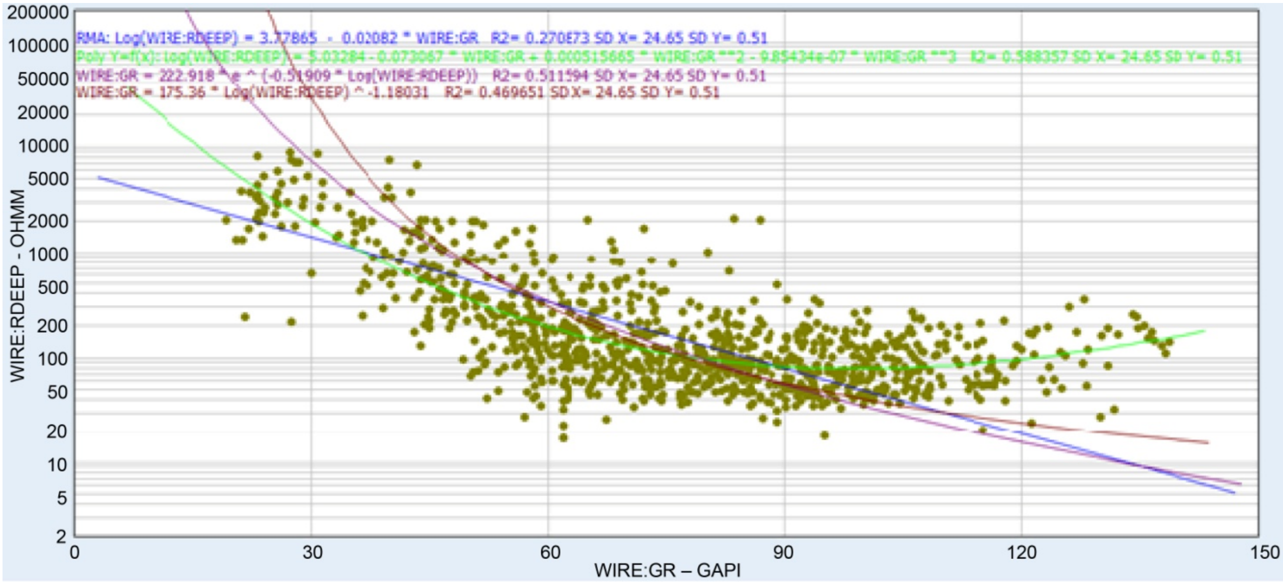


(b)

Figure 4. (a) Schematic of the workflow applied in the study where pseudo-log generation was utilized to develop a log-based data suite where only an original raw MWD GR was acquired. (b) Cross-plot of gamma ray (GR – GAPI) versus neutron porosity (NPHI – CFCF dec). Exponentially fit function provides a way to derive a pseudo NPHI from an existing GR.



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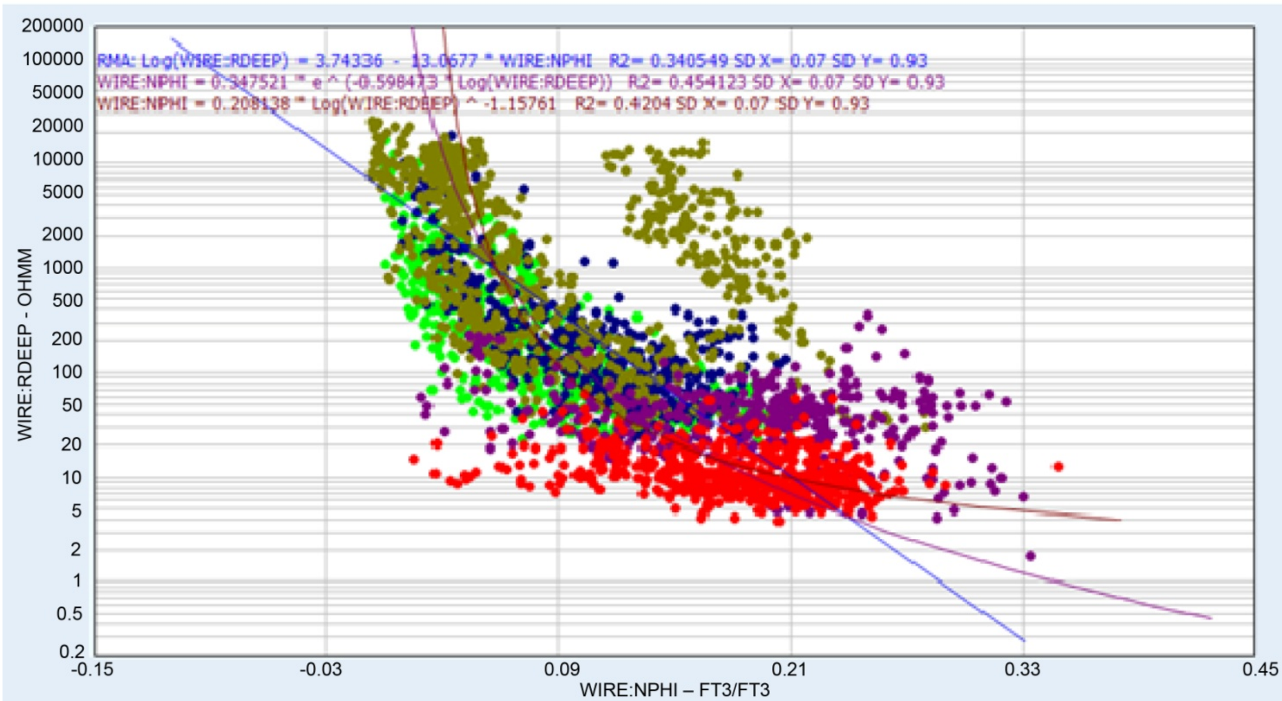


(b)

Figure 5. (a) Cross-plot of gamma ray (GR – GAPI) versus resistivity (RDEEP – ohms). The 3rd order polynomial function provided the best correlation to then utilize in developing a pseudo-resistivity where no prior measured log is present. (b) Similar to above constraining the correlation between neutron porosity and resistivity.

study we collected drill cuttings and then measured LECO® TOC and programmed pyrolysis. The measurements were then utilized to constrain and check the petrophysical wireline-based evaluation (Figure 11(a) and Figure 11(b)). The TOC (wt %), S1 (mg/g), S2 (mg/g) and TMAX (˚C) values are plotted versus the wireline derived interpretation. These geochemical parameters will then be used to derive an original

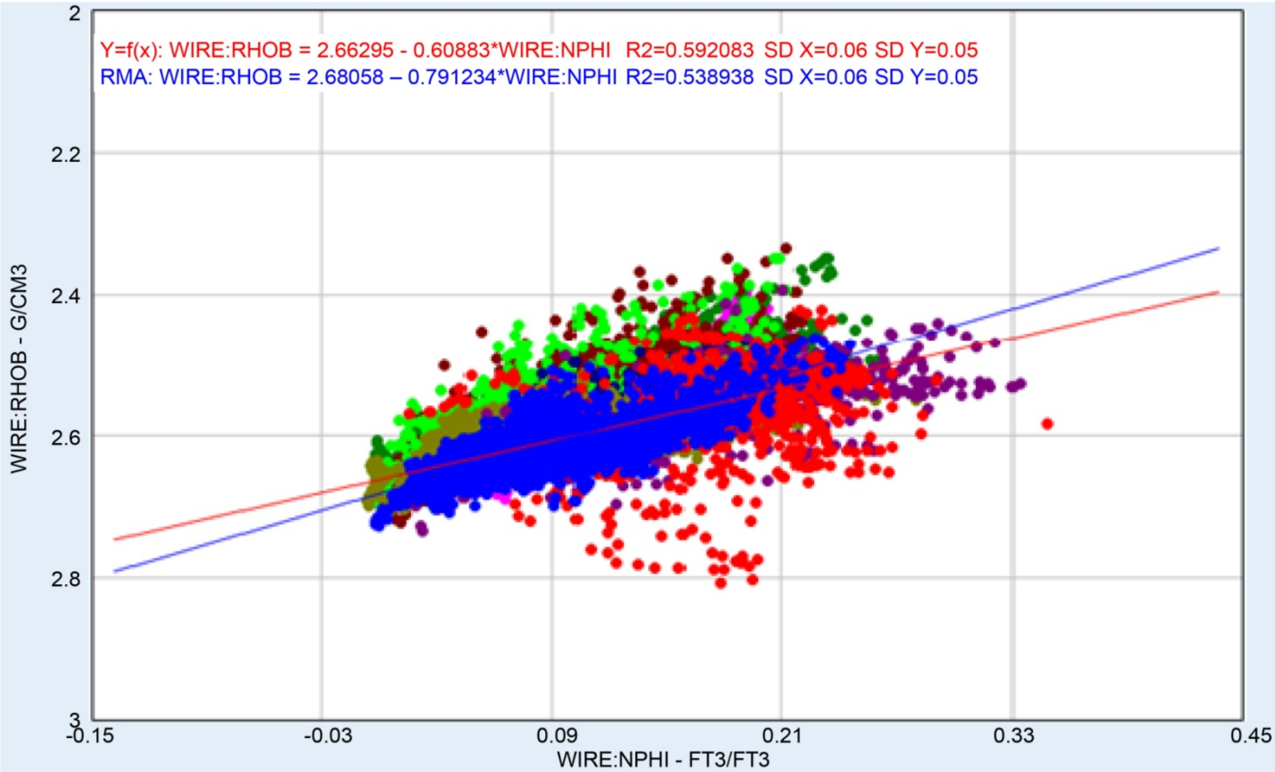


Figure 6. Cross-plot correlation of neutron porosity on the x-axis and bulk density on the y-axis.

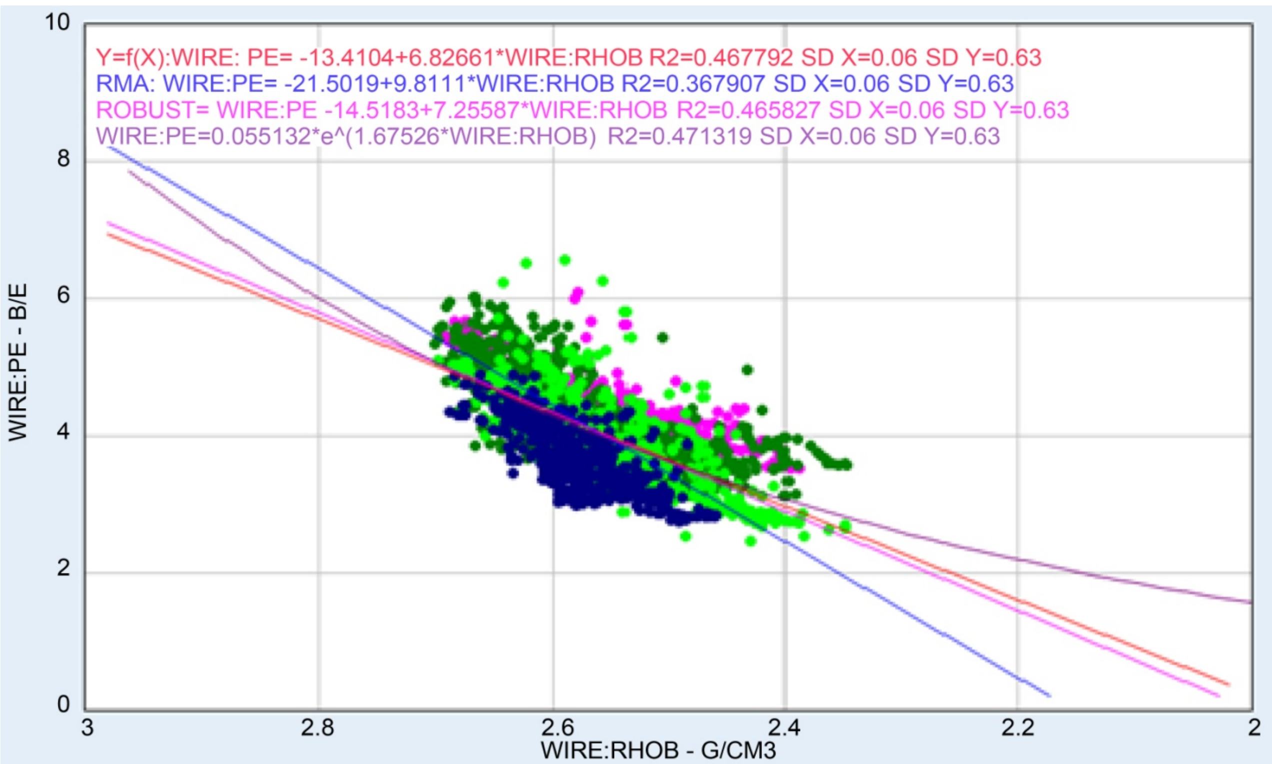


Figure 7. Cross-plot correlation between bulk density (g/cc) versus photoelectric factor (b/e). Linear or exponential fit for reference.

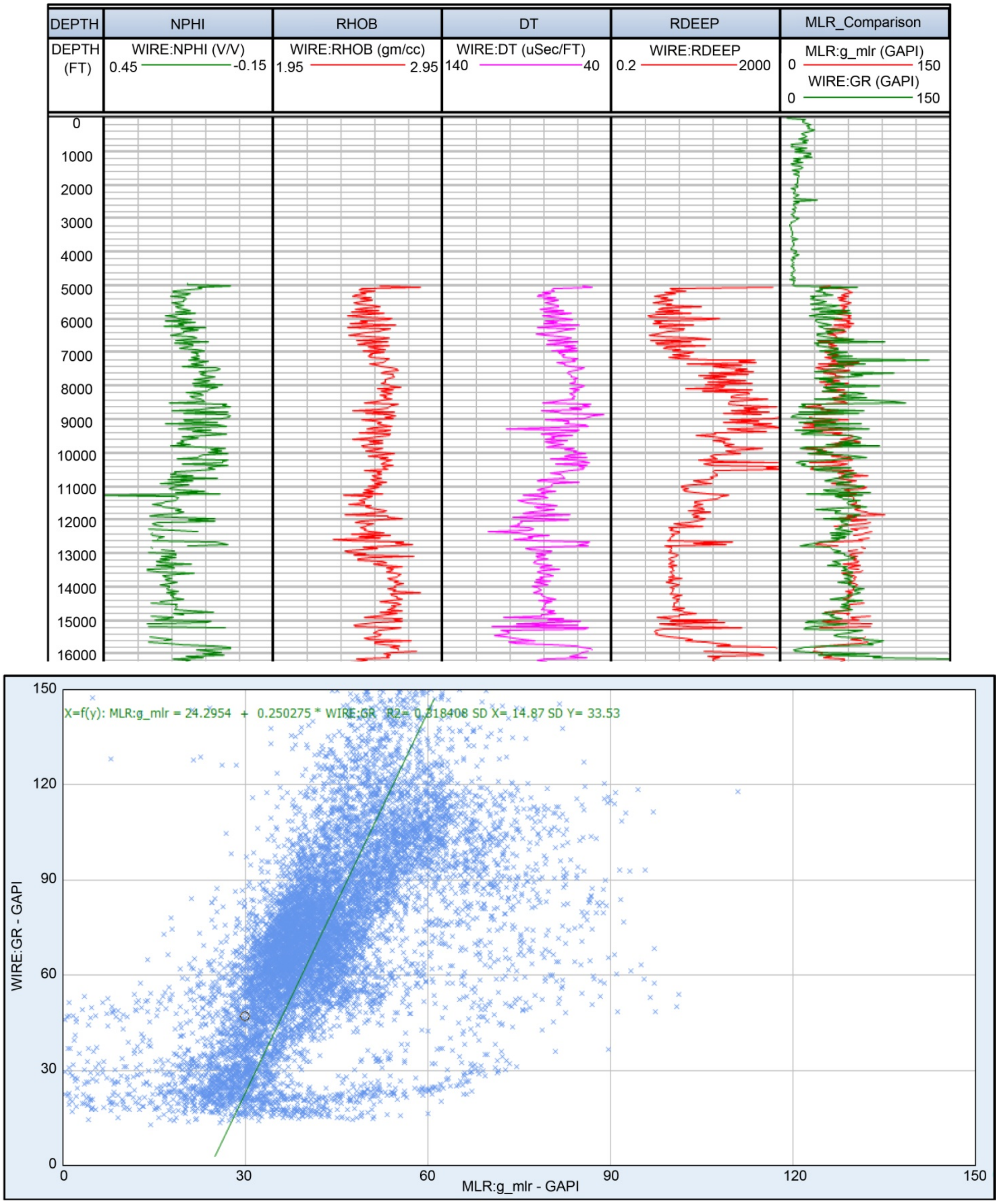


Figure 8. Wireline track displays of the raw logs chosen to construct the multi-linear regression model including NPHI, RHOB, RDEEP ad DT. The last track on the right displays the raw measured GR (green) versus the multi-linear regression interpreted GR (red). In addition, a cross-plot of the measured versus predicted curve can be observed.

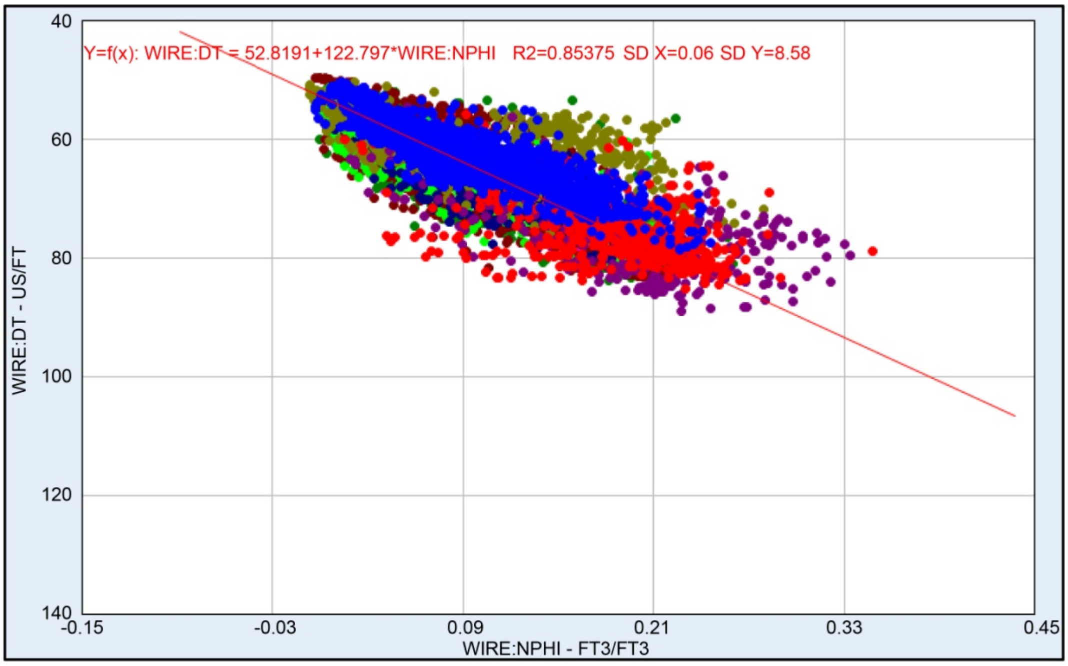


Figure 9. Cross-plot correlation of neutron porosity (CFCF, FT3/FTs, Dec) versus sonic travel-time (DT – us/ft).

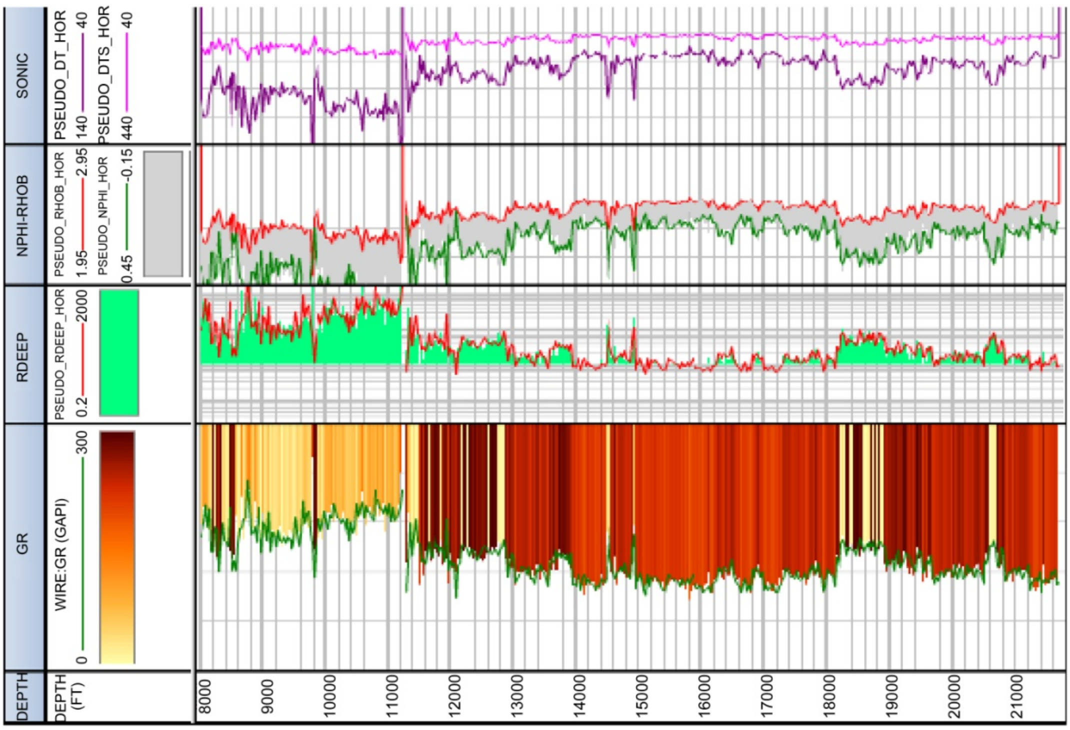


Figure 10. Powder River Basin horizontally drilled well where only an MWD GR curve (green and color-filled) was physically acquired. From developed correlation a quadruple combo log suite can be derived. Pseudo-Resistivity (ohms) in red and color-filled green, pseudo-neutron porosity (green) and pseudo-bulk density (red) with separation filled grey. Last track (top of image) displays pseudo-compressional and shear sonic logs (μs/ft).

hydrocarbon in place evaluation.

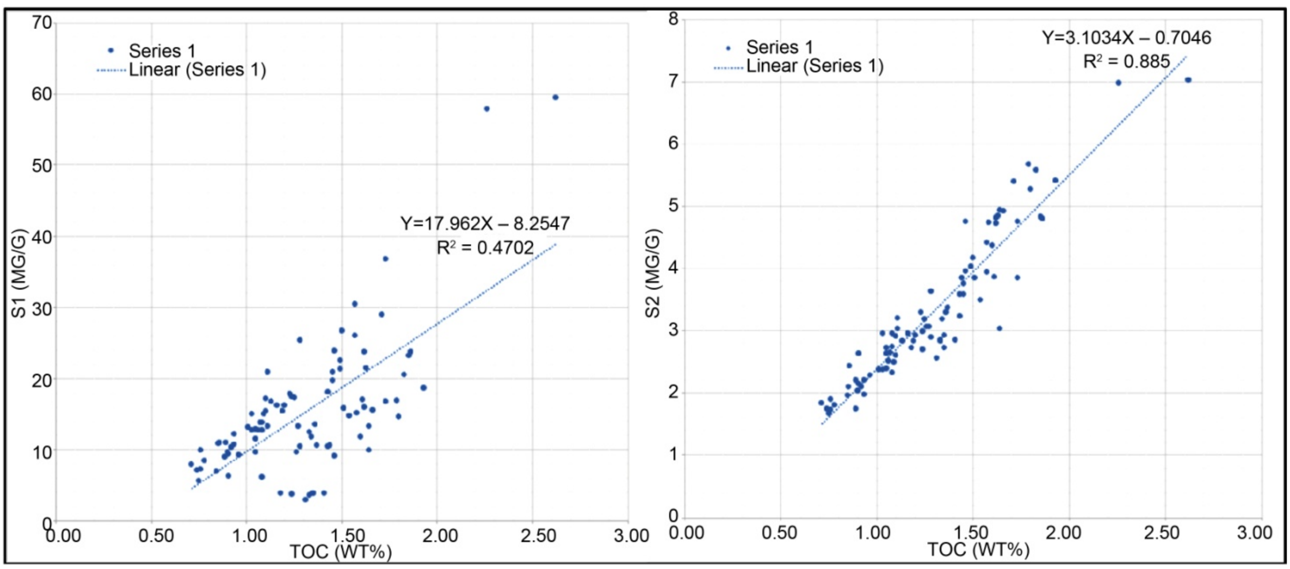
The pseudo-generated quadruple combination logs were then utilized to derive a lithological, total porosity, total water saturation, Poisson's Ratio and Young's Modulus interpretations along the length of the wellbore.

- Lithology was interpreted by calculating the volume of clay based on a clean gamma ray (GR) baseline defined in this study as 45 GAPI versus a shale gamma ray baseline defined in this study as 220 GAPI. Any GR below 45 GAPI was interpreted as a carbonate-prone stratigraphic bed.
- Total Organic Carbon = Correlation with Bulk Density and direct linear interpretation.
- Total porosity was evaluated by applying a constant matrix solution evaluation. Where Total Porosity (PHIT) = Bulk Density (Rhomatrix-defined here as 2.71 g/cc) − Bulk Density (g/cc)/Rhomatrix − Rhofluid (defined here as 0.85 g/cc for the oil-based mud system).
- Total water saturation was evaluated using a standard Archie-based equation where Total Water Saturation^Lithological Factor (Here defined as 1.9) = Resistivity of Water (Here ranging from 0.08 to 0.11)/Total Porosity^Cementation Exponent (Here defined as 1.9) × True Resistivity (ohms). The tortuosity factor used was an A = 1 [13].
- Poisson's Ratio was derived from the measured compressional sonic and bulk density as Poisson's Ratio = Lateral Strain/Longitudinal Strain
- Original Oil-In Place (OOIP) = 7758 × Total Porosity × (1-Total Water Saturation) × Area × height (thickness in feet)/Formation Volume factor (Bo)

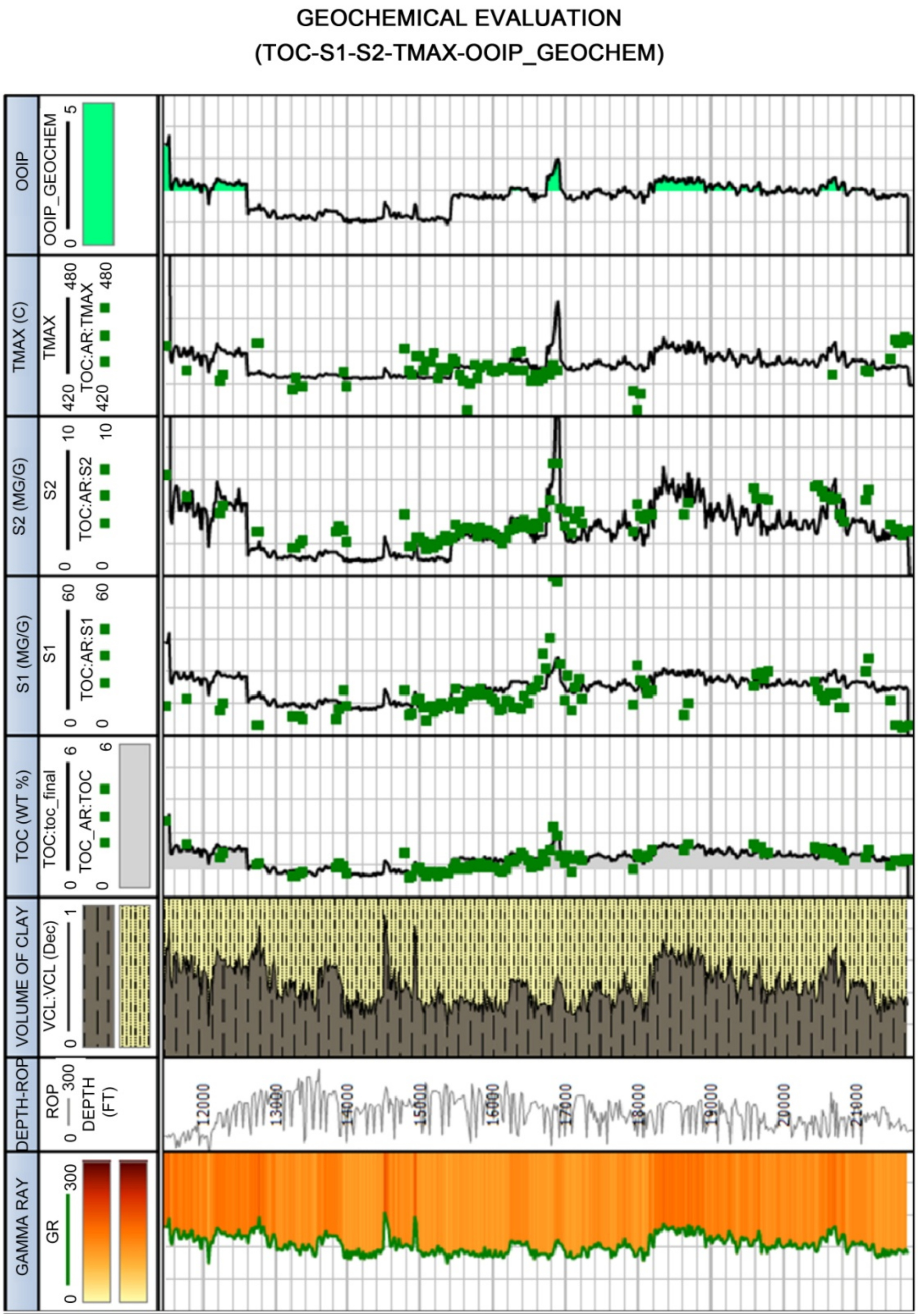
The above presented workflow is deterministic in scope and therefore single curve dependent and derived. If additional raw inputs were available, then a multi-linear regression approach or fuzzy logic would be a more appropriate workflow application (**Figure 8**) [14] [15]. However, given the starting condition of a single MWD GR log, without any other supporting measurements, the above approach was developed.

4. RESULTS AND INTERPRETATION

Now that we have applied the petrophysical workflow to generate the *pseudo* logs and have worked through a full petrophysical evaluation, let's investigate the variation in properties along the length of the drilled lateral sections. Well one was drilled within the Turner sandstone stratigraphic interval in the Powder River basin as the target. Observations along the length of the drilled horizontal well include the noted variability in the first 2/3 of the drilled length versus the last 1/3 of the drilled length. The first 2/3 of the drilled lateral up to approximately 18,200' TVD demonstrate a cleaner gamma ray signature resulting



(a)



(b)

Figure 11. (a) Laboratory measured geochemical correlations. These correlations can then be applied to the continuous wireline evaluation. (b) Geochemical integration along the PRB lateral. Properties can be derived because a pseudo-RHOB is now present. The green rectangles represent measured laboratory properties from acquired cuttings. Tracks bottom to top: Track 1 Gamma Ray, Track 2 Depth and Rate of Drilling Penetration (ROP), Track 3 Volume of Shale, Track 4 Total Organic Carbon (wt %), Track 5, S1 (mg/g), Track 6 S2 (mg/g), Track 7 TMAX (˚C), Track 8 Total Hydrocarbon In Place calculated from geochemical parameters (OOIP).

in lower volume of clay and increased volume of silty-sand in the lithological interpretation. Interpreted total organic carbon is very low defined as <1 wt % in the first 2/3 of the drilled lateral and increases >1 wt % at the 18,200 TVD' transition. Important to note is that the well was drilled with oil-based mud so the uncertainty/error on the TOC and programmed pyrolysis S1 (mg/g) measurements is higher (>0.02 mg/g) than if the well was drilled with water-based mud (< ±0.01 mg/g).

Regardless of the potential oil-based mud contamination increasing the uncertainty in the laboratory measurement, petrophysicists can still utilize the data to develop the correlations needed to apply a continuous evaluation (**Figure 11** and **Figure 12**). The increase in the total organic carbon in this stratigraphy is directly related to the wellbore drilled path exiting the more silty-sandstone prone stratigraphy and encountering more of a shale organically enriched interbed. The applicability of the measured versus derived TOC (wt %) is validated and can guide stratigraphic understanding along the length of the wellbore. Continued study is recommended to analyze the hydrocarbon generated from this organic-content, interbedded within the Turner sandstone interval. The hypothesis could lead to a better understanding and possibly increased prospectivity for the Turner sandstone stratigraphy outside of the known better reservoir quality fairways.

Following along the same identified break in trend as the measured and then calibrated log-based interpretation are the S1 (mg/g), S2 (mg/g), TMAX (˚C) and geochemically interpreted original-oil in place (MMBO/section) evaluation (**Figure 11**). The measured and then interpolated S1 (mg/g) is a direct indicator of volatile hydrocarbon presence (proxy) and should be used as a qualitative indicator when considered without additional context. Interesting to observe is that the first 1/3 of the well from heel to ~15,400 TVD' has a significantly lower (delta change of 5 - 10 mg/g) than the 2/3 or even 3/3 of the drilled wellbore. If considering the proxy for the most in-place volatile hydrocarbon we would suggest then that the latter 2/3 and 3/3 of the wellbore could outperform the first 1/3 of the well if isolated production were considered. The slight increase (~5 - 10 mg/g) between the 15,400 TVD' to 18,200 TVD' (second 2/3) versus the latter 3/3 (18,200 TVD' to TD) is driven by the increased presence of organically-enriched material. The same trend exists for the related S2 (mg/g), TMAX (˚C). One must be cautious as this approach is bias to the "shaley" end members for evaluation. While there may be decreased geochemically derived hydrocarbon in place in the first 1/3 of the wellbore, the increase in silty-shale and sand presence also increases the associated permeability (>0.001 mD and upwards of 1 mD) versus the shaley-dominated units where permeability related to a given porosity will range from 0.001 mD down into the nanodarcies. Therefore, increasing the overall deliverability or capacity to flow. A full integration of all properties is critical to make sure the potential prospectivity from all angles is considered.

To avoid any sampling or conceptual-model bias, we integrate the remainder of the petrophysical evaluation to observe any additional changes in derived properties. Observing the resistivity and bulk density trends we see that the silty-shale dominated Turner sandstone drilled sections versus the more shale-prone dominated sections have overall lower resistivity (<20 ohms color-fill threshold) and increased bulk density as well as neutron porosity which suggests a tightening up of the overall hydrocarbon fluid-filled pore volume available. The Turner sandstone is identified petrophysically as being a low resistivity low contrast pay challenge/play opportunity [1]. The total water saturation interpretation presented does not result in an entirely 100% waterfilled stratigraphic zone. Rather, note the presence of hydrocarbon fluid-filled volume in both the "sands" and "shales" respectively. While the total fluid-filled porosity increases in the shale-dominated sections, that increase is driven by clay-related (microporosity) presence as well as kerogen presence. That porosity to permeability correlation will result in less overall capacity to flow the hydrocarbons in place (**Figure 13**). Whereas the more sandstone-end member drilled sections will have an increased permeability and capacity to flow. The recognition and integration of that difference is critical. Without that understanding one might not view the tighter sandstone intervals as prospective. Fully integrating all of the information in log responses, measured core data and geological context can impact the ideas or understanding of a given rock and fluid volumes ability to produce hydrocarbons. Taking that one step further produced hydrocarbons at a given rate.

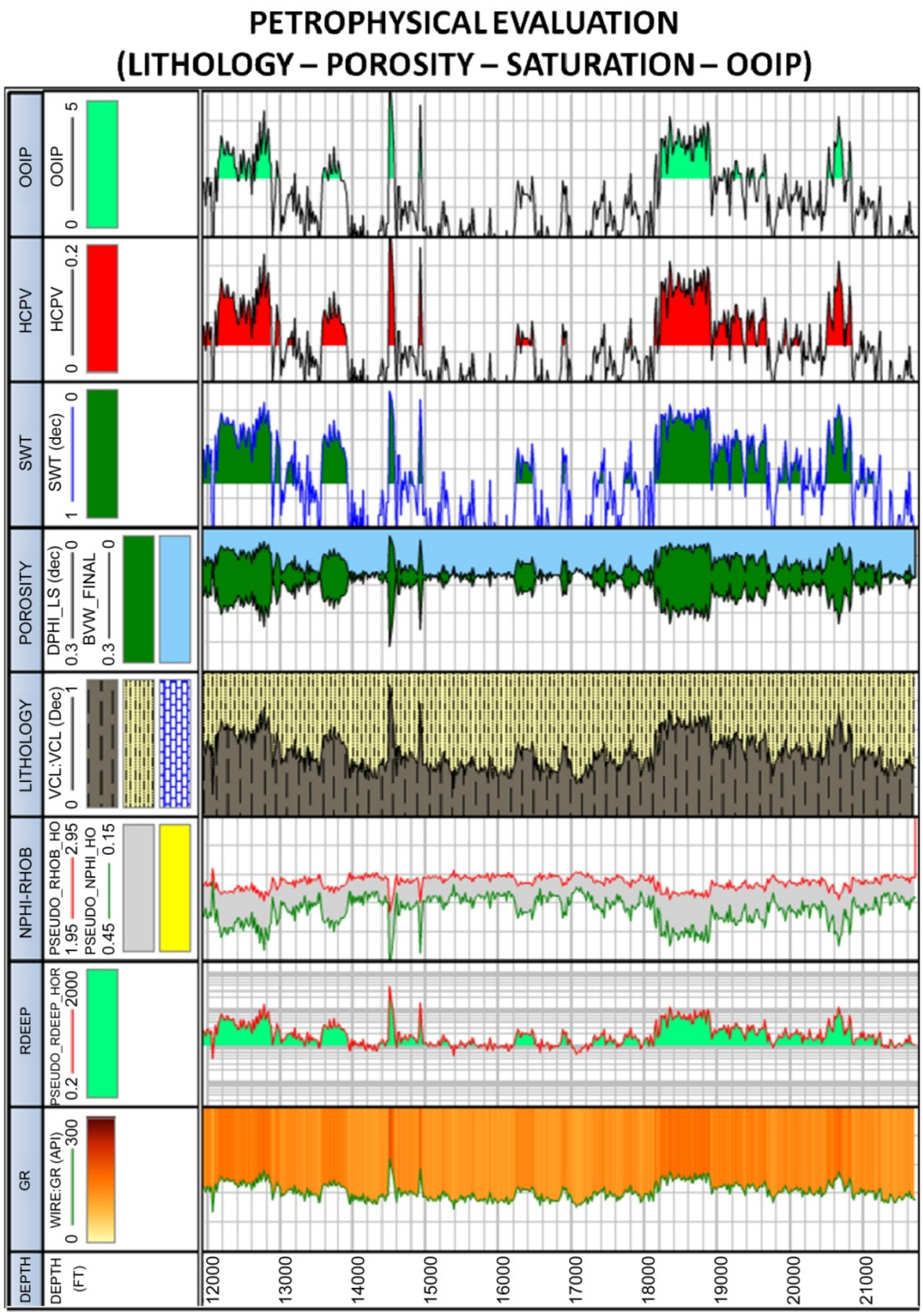


Figure 12. Continuous petrophysical evaluation along the PRB drilled lateral length. All properties now derived from developed pseudo-logs. Resulting in original-oil in place estimates (OOIP MMBO/Sec). Tracks shown from bottom to top include: Track 1 Total gamma ray in green (gapi), Track 2 Pseudo-Resistivity (ohms) in red and color-filled green, Track 3 pseudo-neutron porosity (green) and pseudo-bulk density (red) with separation filled grey, Track 4 derived volume of clay, Track 5, derived total and effective porosity with bulk volume water denoted, Track 5 total water saturation, Track 6 hydrocarbon pore volume (HCPV) which was derived by Total Porosity*1-Total Water Saturation, Track 7 hydrocarbon in-place (OOIP) per acre section (assumed a Bo of 1).

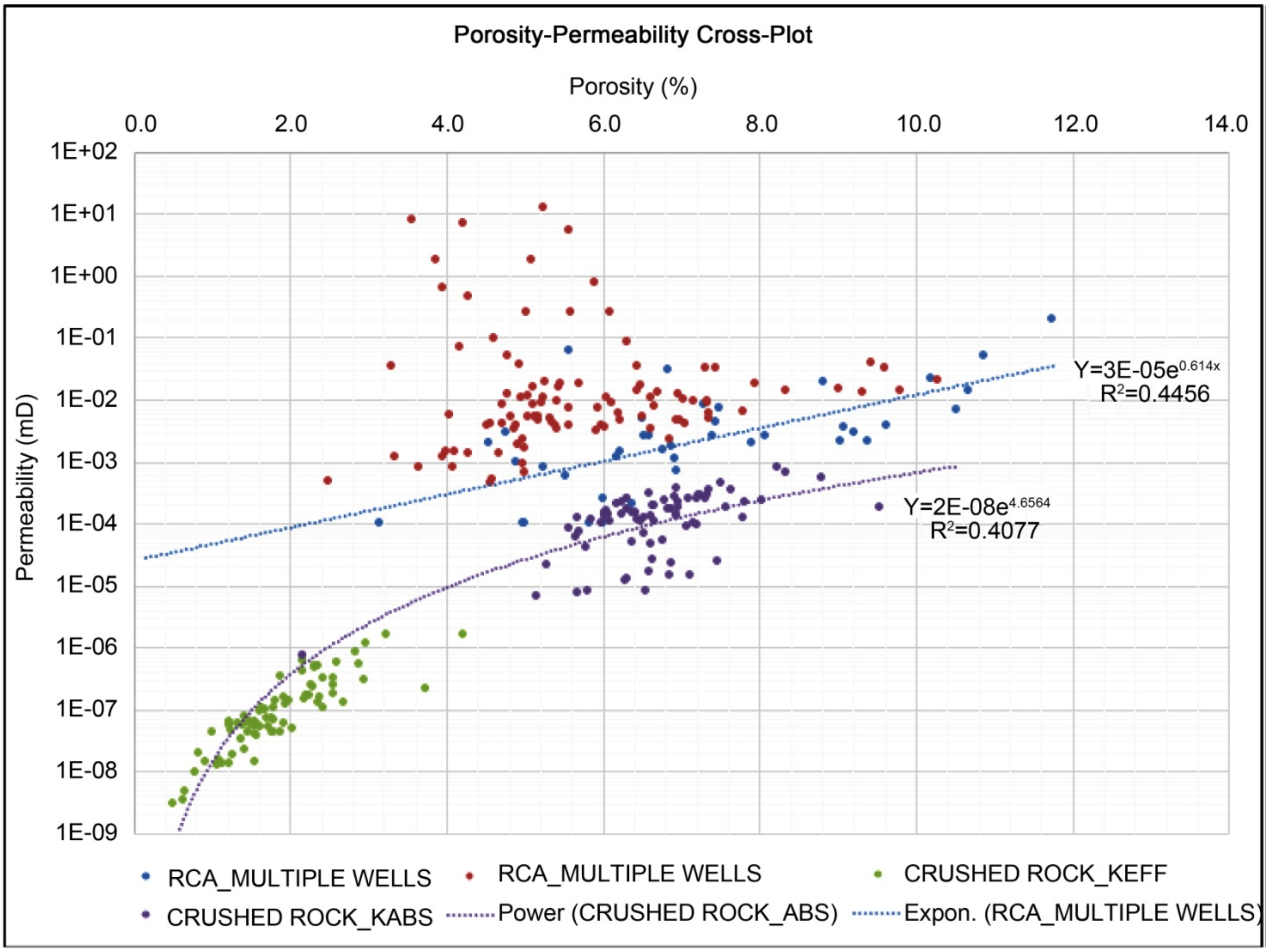


Figure 13. Cross-plot of measured total porosity (%) on the X-axis and measured permeability (mD) on the Y-axis. Routine core plug measured permeability is distinguished from crushed rock permeabilities for reference (principles in Luffel *et al.*, 1993).

Last, we compare the geomechanics derived which compliments the understanding we developed from the comprehensive log integration prior. The higher clay, more shale prone intervals are less brittle whereas the "tighter" (<1 mD), possibly diagenetically overprinted sands have increased brittleness (**Figure 14**). The impacts of the possible changes in stress and strain along the length of the drilled wellbore should be considered when designing a completions strategy. Each "zone" of significant stress change will impact how, where, when and why a pumped designed completion may be successful or not. Or even, may help or impact the rate at which a treated well will liberate and flow economic hydrocarbons.

As we digest all of the above on a single well case in the Powder River Basin, we can begin to place into the context the complexity, variability, and heterogeneity along a given lateral length path. To highlight the impact of the integrated workflow applied here stemming from just the presence on an MWD gamma ray log, we investigate the results of a three well drilled pad location in the Delaware basin. Placing the three wells from top to bottom in a visual panel so we can compare the well paths, one can observe the variations in lithology, storage (PHIT) and saturation (SWT) along the length of any given well and between wells (**Figure 15**). Executing our previously established work flow we can take only the measured MWD GR in each well and generate a full integrative display and interpreted properties for geological, geochemical, engineering and drilling disciplines to better understand the subsurface.

Through the approach, we have shared the subsurface expert has been empowered to understand

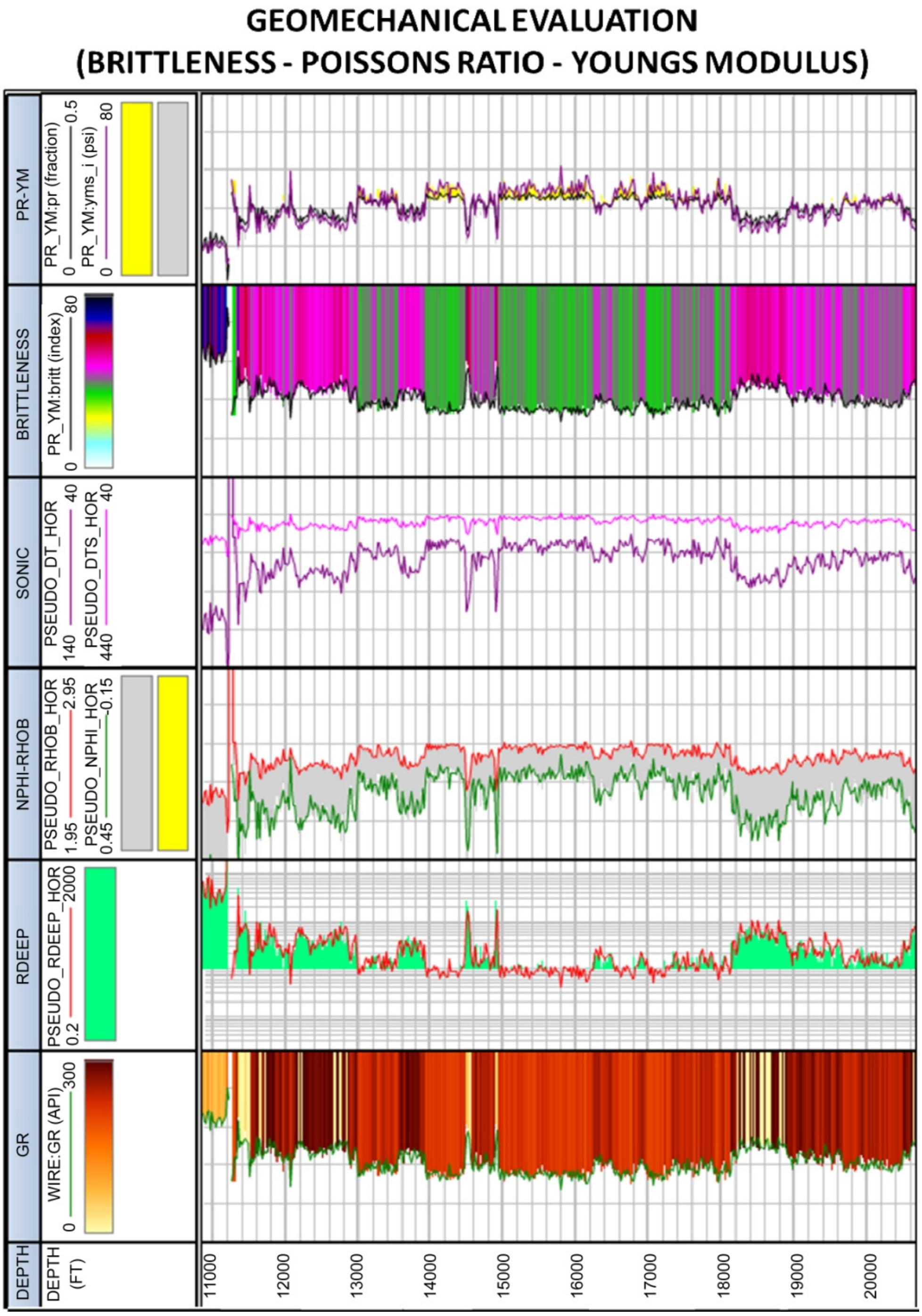


Figure 14. Geochemical evaluation log suite. Brittleness, Poisson's Ratio and Young's Modulus derived for integration and understanding in property changes along the lateral length. Tracks displayed from bottom to top: Track 1 Gamma Ray in green, color-filled for value in Gapi, Track 2 Pseudo-Resistivity (ohms) in red and color-filled green, Track 3 pseudo-neutron porosity (green) and pseudo-bulk density (red) with separation filled grey, Track 4 displays pseudo-compressional and shear sonic logs (μs/ft), Track 5 derived Brittleness by taking the volume of quartz and carbonate/volume of total clay in unitless indices, Track 6 derived Poisson's Ratio and Young's Modulus (psi).

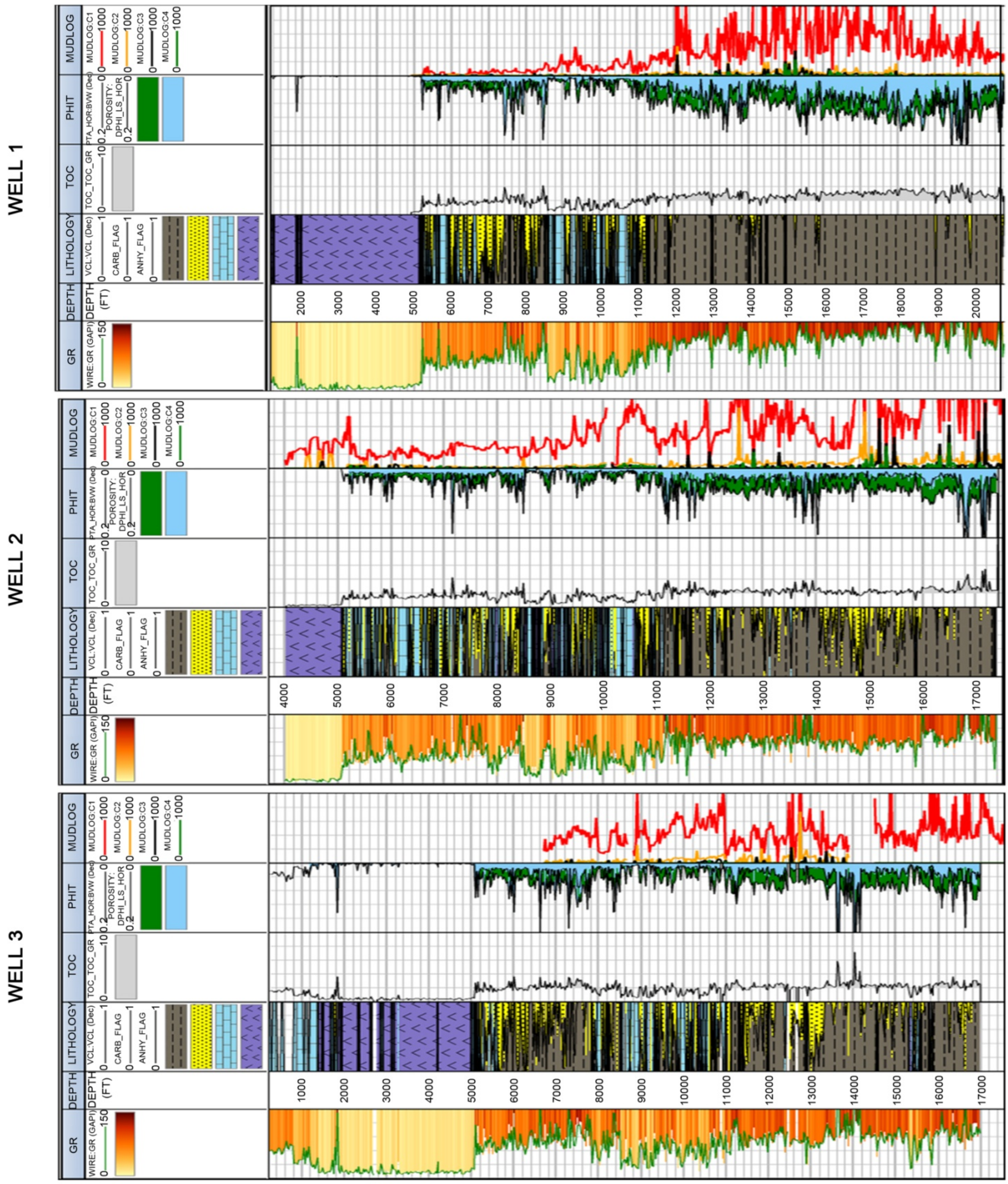


Figure 15. Three horizontally drilled wells in the Wolfcamp formation, Delaware basin. All wells drilled from the same pad location very minimally spaced apart. Variability in the drilled horizontal stratigraphy can be observed through pseudo-log derivation from the measured MWD GR. Also, variation results in the evaluation of petrophysical properties that highlight better or poor-quality hydrocarbon-filled zones along the length of the lateral wells.

some of the petrophysically applied science. Objectives to demonstrate how through applied science correlations and a simple executable workflow, a subsurface expert can take a single measured log and integrate to better unravel and model the subsurface characterization.

5. CONCLUSIONS

In this study, we focused on sharing knowledge and defining a straight-forward workflow to apply from drilled horizontal wells where only a measuring while drilling gamma ray log was acquired. By defining a step-by-step work flow, any subsurface specialist is now empowered to derive a full suite of pseudo-logs as well as a full petrophysical evaluation. Once the wireline-property based quantification is completed, a full understanding of the variations between drilled wells can be investigated and integrated. The workflow and value of information can be used to influence business driven decisions, such as target line selection, multi-well scale modelling efforts, geological and petrophysical context, drilling targets etc. The variation in these parameters and integration of the rock property understanding and quantification can then be used to compare against per stage fluid/production contribution post stimulated fracture efforts.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest regarding the publication of this paper.

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