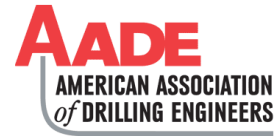


Real-Time Porosity from Surface Drilling Data Prediction And Verification

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Abstract

Porosity is a critical parameter during the drilling and completions process. Current methods to predict/determine porosity require expensive logging tools or time consuming laboratory tests. This paper outlines an empirical model developed to predict the formation porosity using surface drilling data and gamma ray (GR) at the bit without the need for log or lab data. An empirical model for porosity prediction through the use of drilling data has been developed using drilling strength or unconfined compressive strength (UCS) from drilling models. The UCS seen at the drill bit from an inverted rate of penetration (ROP) model and GR at the bit are used to estimate the formation porosity. Porosity calculated from log data from a well in Western Canada was used to validate the porosity model from drilling data with log calculated neutron density. The results from the model show good agreement between the model estimated porosity and porosity from the well log data. The comparison results show accurate quantitative matching as well as trends. The model presented can be applied to horizontal wells where the porosity can be mapped in addition to UCS values from the drilling data at no additional costs. Based on this formation porosity mapping log, better selective fracturing interval locations can be obtained taking the UCS and porosity of a formation into account.

Introduction

Porosity determination is crucial for identifying hydrocarbon bearing zones and optimal stimulation placement. Previous methods to estimate porosity include logging tools and laboratory testing. Core analysis techniques can be used to determine porosity, however, cores represent only a very small interval of the well and it can take time to obtain the results (Bodwadkar & Reis 1993). In zones with small scale heterogeneities, core samples can identify such differences but logging tools may not (Gyllensten et al. 2004). This implies that using one method to determine porosity measurements may be vastly different from the other. Wireline logging is subject to many errors. These errors can be due to a variety of factors including improper calibration, design, company, age, and alterations of data acquisition (Kane et al. 2005). Logging-while drilling (LWD) and wireline logging can give fairly accurate porosity estimations in limestone and sandstone lithologies, but these tools are less accurate in shales (Afonso de Andre et al. 2005). Wireline measurements may also be

affected by excess mud and borehole factors (Bonnecaze et al. 2002). In previous literature it has been stated that the optimal approach to produce accurate porosity measurements in a well involves a combination of both log and core analysis (Patchett & Coalson 1982).

Aside from using laboratory testing and logging measurements to determine porosity, unconfined compressive strength (UCS) can also be used to obtain porosity measurements. UCS can be measured in a variety of ways including laboratory testing, log-based correlations, image logs, and from drilling data (Nabaei et al. 2010). While laboratory testing is an accurate UCS predictor when reliable cores are available, these tests are destructive and may give incorrect UCS values if identical core samples are not tested (Khaksar et al. 2014). One of the major issues associated with log-based UCS correlations is that log measurements may not be as accurate in heterogeneous formations and could ultimately yield inaccurate UCS estimations (Borba et al. 2014). A previous study to determine the accuracy of UCS values correlated to the rebound hardness numbers (RHN) found from an Equotip Hardness Tester (EHT) in shales concluded that this method yields similar UCS values found from laboratory UCS tests but core samples at various depths are necessary to build a UCS log (Lee et al. 2014).

Horizontal Well Application

Predicting formation parameters in horizontal wells can be harder than in vertical wells. Neutron and density logging may predict inaccurate porosity values due to invasion and direction of permeability (Cowan & Wright 1997). In horizontal wells, wireline tools tend to stay on the bottom of the wellbore where solid cuttings could remain. Rather than obtain information about the selected zone, the measurements taken are indicative of the cuttings properties (Bigelow & Cleneay 1992). The geometry of horizontal wells is also different from the geometry seen in vertical wells and most of the log measurements consider the formation characteristics below the wellbore. The geometry in horizontal wells is important when the wellbore is not in a thick formation because log measurements would not pertain to the formation in question (Singer 1992).

Porosity determination in horizontal or deviated wells can be a challenging task. An understanding of formation characteristics can help benefit not only optimal perforating zones, but also perforation orientation within the horizontal wellbore (Benavides et al. 2003). While LWD tools can be used

to measure water saturation, lithology, and porosity in both vertical and horizontal wells, these measurements may not be as affective in deep reservoirs and can yield inaccurate values for certain lithologies (Jackson & Fredericks 1996). Gamma ray measurements, which are the primary tool for monitoring depth and formation characteristics, can provide skewed porosity data when deviating from the vertical wellbore (King 1989). Calvert et al. (1998) proposed that the reason for such variations in porosity measurements when transitioning from vertical to horizontal wells could be due to changing the tool orientation and logging environment.

Using drilling data to determine porosity in horizontal wells can allow for a better understanding of stimulation placement. Unlike other tools used to measure porosity, this method is not susceptible to sudden lithology variations or tool orientation. Selective stimulation can allow perforation placement to be chosen in zones where the perforations are most likely to produce, which has been a problem in many horizontal wells.

Real-Time Application

Obtaining real-time drilling data can be advantageous in knowing lateral placement, optimizing drilling parameters, and understanding geomechanical factors in the well (Han et al. 2010). Real-time data can also allow for drilling, completions, and well testing decisions to be made much more quickly (Sadykov et al. 2016). Having the ability to collect UCS and GR data at any point throughout the drilling process would allow for porosity at depth to be determined. Determining porosity in real-time can also reduce the amount of lost time due to drilling hazards (Pritchard et al. 2016). To determine porosity real-time, drilling and GR data is collected at surface as the well is being drilled. UCS values can be calculated from an inverted ROP model for continuously while drilling the well. The UCS, gamma ray data taken at the bit, and bit wear values (from the ROP models) can be used to determine porosity in real-time. The benefits of real-time drilling data and porosity prediction are a better understanding of sand control factors, stimulation design and optimization, and a better prediction of overall well performance (Brulè 2013).

Gamma Ray Method

Previous methods for estimating porosity in sandstone and shale formations are used to obtain an accurate correlation for porosity in a mixed lithology zone (Cedola et al. 2017). Knowing that gamma ray (GR) values can indicate the formation type over an interval, the measured GR can be used in conjunction with the Cedola Sandstone and Cedola Shale correlations to provide a porosity value in mixed lithologies.

To get UCS values, drilling data from a previously drilled well in Western Canada was collected. This data was inserted into an inverted rate of penetration (ROP) model and UCS values were calculated. The inverted ROP model works by taking certain drilling parameters and inserting the into ROP models dependent on bit type to determine accurate UCS values and is applicable to real-time application (Hareland et al. 2010 and Kerkar et al. 2014).

In order to develop a GR porosity correlation, the Cedola sandstone and Cedola shale correlations were used. These two correlations were developed by collecting porosity and UCS data from a variety of sandstone and shale reservoirs. The data collected has been found from both laboratory and log analysis. Figure 1 shows the UCS and porosity data that was collected for sandstone reservoirs as well as the Cedola sandstone correlation that was obtained. Figure 2 shows the plot used to determine the Cedola shale correlation from the collected shale data. The equations used to determine the linear GR correlation (Eqn. 1) and the power GR correlation (Eqn. 2) are shown below.

$$\Phi_{Linear GR} = \Phi_{Cedola Shale} + (\Phi_{Cedola Sandstone} - \Phi_{Cedola Shale}) * \left(\frac{140 - GR Reading}{140 - 40} \right) \quad (1)$$

$$\Phi_{Power GR} = \Phi_{Cedola Shale} + (\Phi_{Cedola Sandstone} - \Phi_{Cedola Shale}) * \left(\frac{140 - GR Reading}{140 - 40} \right)^{a1} \quad (2)$$

To evaluate whether a linear GR porosity or a power GR porosity correlation would be the most accurate, a plot in which the Cedola correlation with normalized UCS values for both linear and power GR porosity has been made and can be seen in Figure 3 and Figure 4, respectively. For both GR plots, the Cedola sandstone porosity values are equivalent to GR measurements at 40 API or less while the Cedola shale porosity values are used in place of GR reading taken at 140 API or higher. While both the linear and power GR correlations take sandstone and shale porosity into consideration, the power GR correlation has been chosen because it is more accurate in determining the porosity in zones with varying sandstone and shale frequencies and fractions.

To obtain the most accurate power GR porosity an optimal value for the constant, a1, must be determined. This process is done using GR, UCS, neutron porosity and the Cedola sandstone and shale calculations. The a1 constant is varied and plotted for each value to observe which has the best fit with the log porosity.

Results & Analysis

The Cedola sandstone and shale correlations for determining porosity work well in solely sandstone and shale lithologies. In a reservoir with mixed lithology zones, the power GR correlation should replace of the Cedola sandstone and Cedola shale correlation. To observe why GR porosity correlations are necessary in mixed lithology areas, a plot in which UCS versus log porosity data for mixed lithology sections of a previously drilled well in Alberta, British Columbia, Canada as well as the Cedola correlations has been made (Figure 5). It is apparent from the plot that because the data falls between the two Cedola trends, there are multiple

intervals within the well that are not solely sandstone or shale, but a fraction of each. To solve this issue, gamma ray and neutron log data for mixed formations in the well were collected. These parameters were inserted into the power GR porosity correlation equation and the absolute difference between the neutron porosity and the GR porosity was determined. The a_1 constant was varied over a range from -3 to 100 and the absolute difference for each of the porosity values has been plotted in Figure 6. The smaller the absolute difference between the neutron porosity and power GR porosity the more accurate the a_1 coefficient. Figure 6 shows that the smallest absolute difference is achieved at an a_1 value of 2.53, which is different from the constant of 1 for linear GR.

To verify the applicability of the GR correlation to mixed lithology intervals, porosity comparisons for two mixed lithology sections from a second Alberta well have been made and can be seen in Figures 7 and 8. The plots show that the GR porosity is a much better indicator in zones of mixed lithologies. It can be seen that the GR porosity in the Belly River formation (Figure 7) has similar trends to the neutron porosity taken from log data. The GR porosity calculations in the Dunvegan formation (Figure 8) are also very similar to the neutron porosity. The Dunvegan formation, which is known to be comprised of both sandstones and shales, can have porosities up to 20% (Hayes 2013). The Belly River formation can have average porosities ranging from 16-23% and is made up of sands, shales, and siltstones (Shouldice 1979). The GR porosity is primarily in average porosity ranges for both the Belly River and Dunvegan formation. Figure 9 shows a comparison between the Cedola sandstone, Cedola shale, and power GR porosities for the Belly River formation. In zones with higher sandstone content, the GR porosity values are much closer to the Cedola sandstone porosity values and in areas with high shale fractions the Cedola Shale correlation is similar. This is indicative of the fact that the GR correlation is influenced by the lithology mixture at any given depth.

Conclusions

Utilizing a combination of drilling and gamma ray log data has the ability to provide accurate porosity measurements. The power GR porosity correlation yields good results in sandstone, shale, and mixed lithology formations as compared to log derived porosity. Using the power GR method to determine porosity could greatly reduce the need for expensive logging tools and/or testing while providing similar results. This method allows for porosity measurements to be known at any point in a well and does not need to be adjusted for horizontal or deviated wells. Using at-bit gamma ray measurements to determine porosity is advantageous in that data from a target interval can be conveyed at a specific depth in a much faster and accurate manner. LWD tools are situated above the bit with a variety of equipment in between. The height added by the equipment makes it necessary for the formation to be further drilled in order to allow for LWD measurements. Having an understanding of porosity and lithology as measured from at-bit gamma ray while drilling in horizontal sections can greatly

impact hydrocarbon production and recovery through selective zone perforating and/or production. Real-time drilling and gamma ray data can be used to determine porosity at any point throughout the drilling process and could have a significant impact in identifying formations, understanding drilling fluid losses and drilling optimization.

Nomenclature

<i>GR</i>	<i>Gamma Ray</i>
<i>UCS</i>	<i>Unconfined Compressive Strength</i>
<i>ROP</i>	<i>Rate of Penetration</i>
<i>LWD</i>	<i>Logging-While-Drilling</i>
<i>RHN</i>	<i>Rebound Hardness Number</i>
<i>EHT</i>	<i>Equotip Hardness Tester</i>

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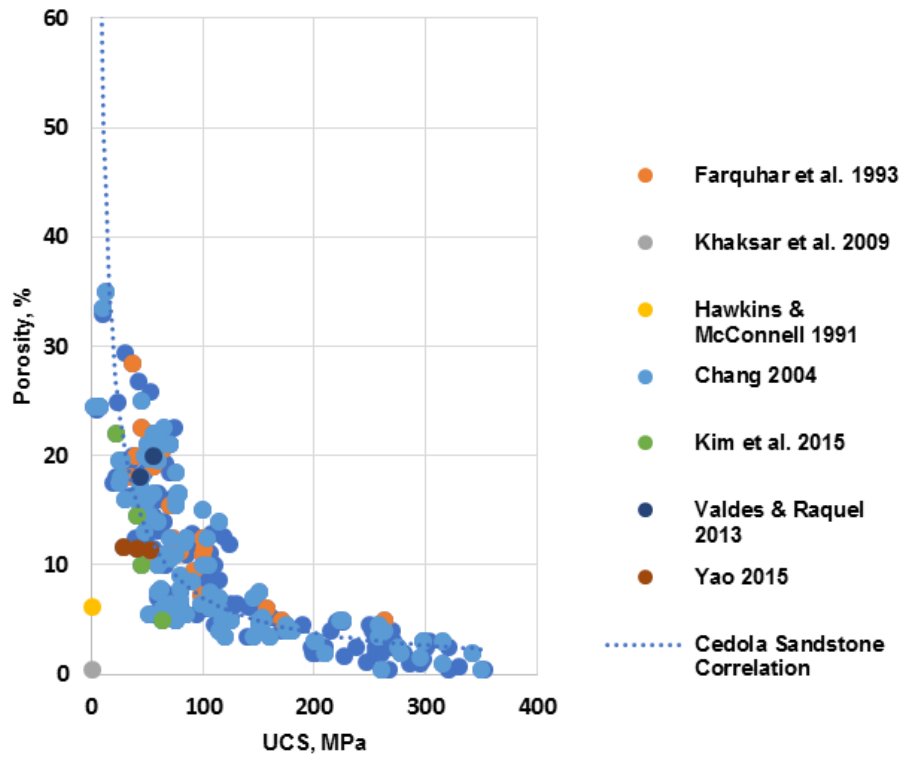


Figure 1. Cedola Sandstone Correlation (Cedola et al. 2017).

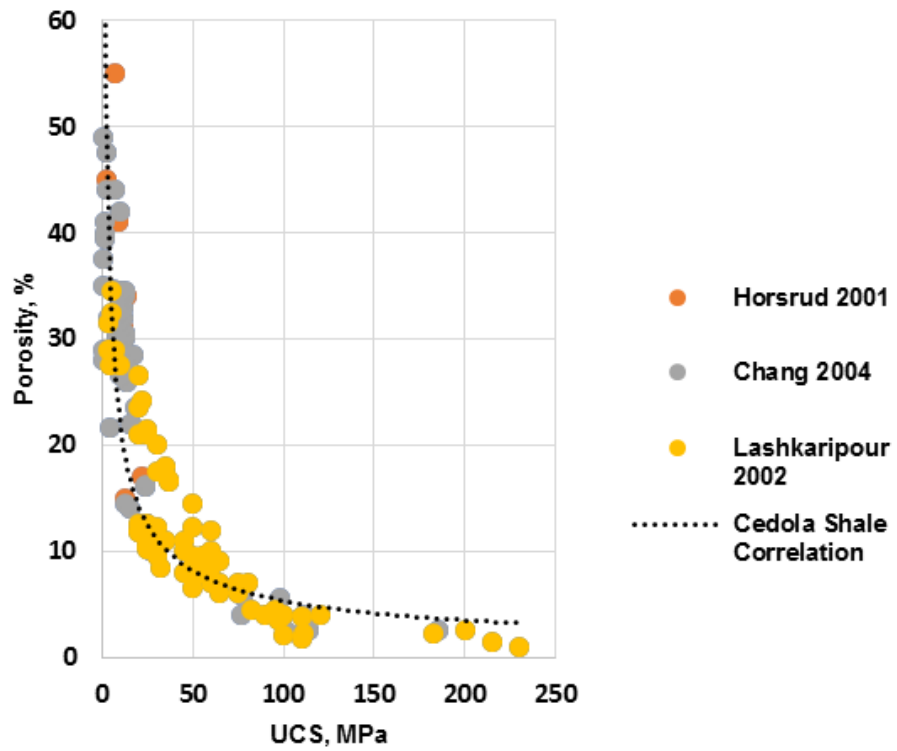


Figure 2. Cedola Shale Correlation (Cedola et al. 2017).

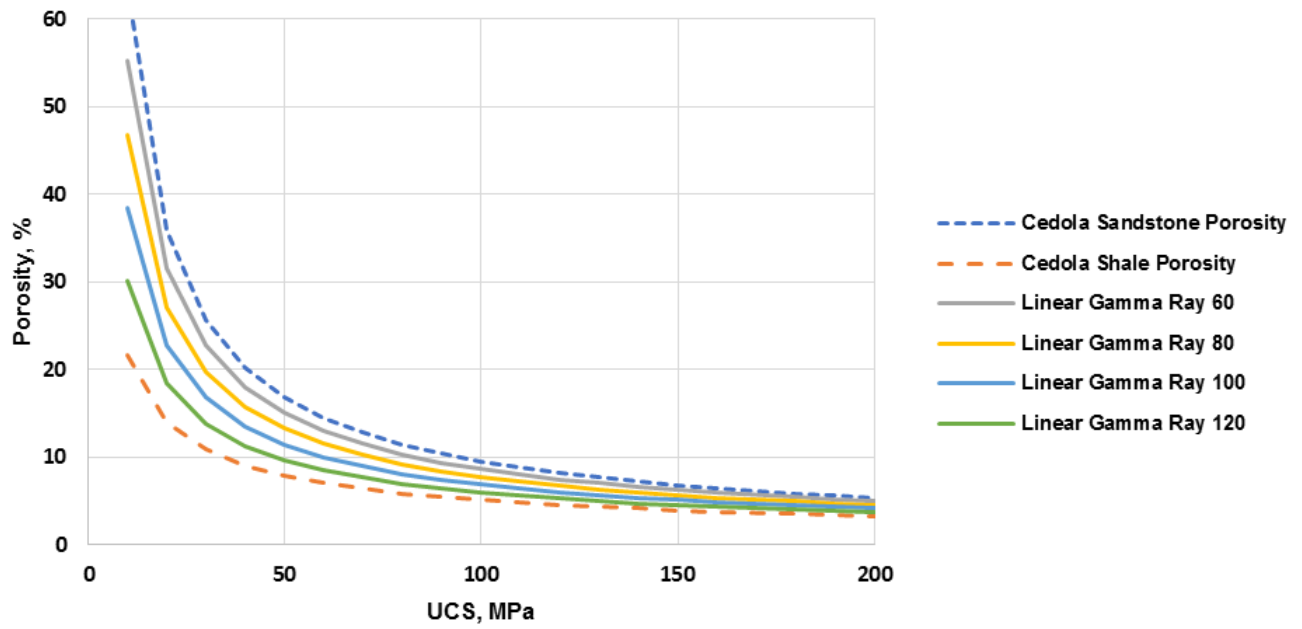


Figure 3. Linear GR Porosity Plot (Cedola et al. 2017).

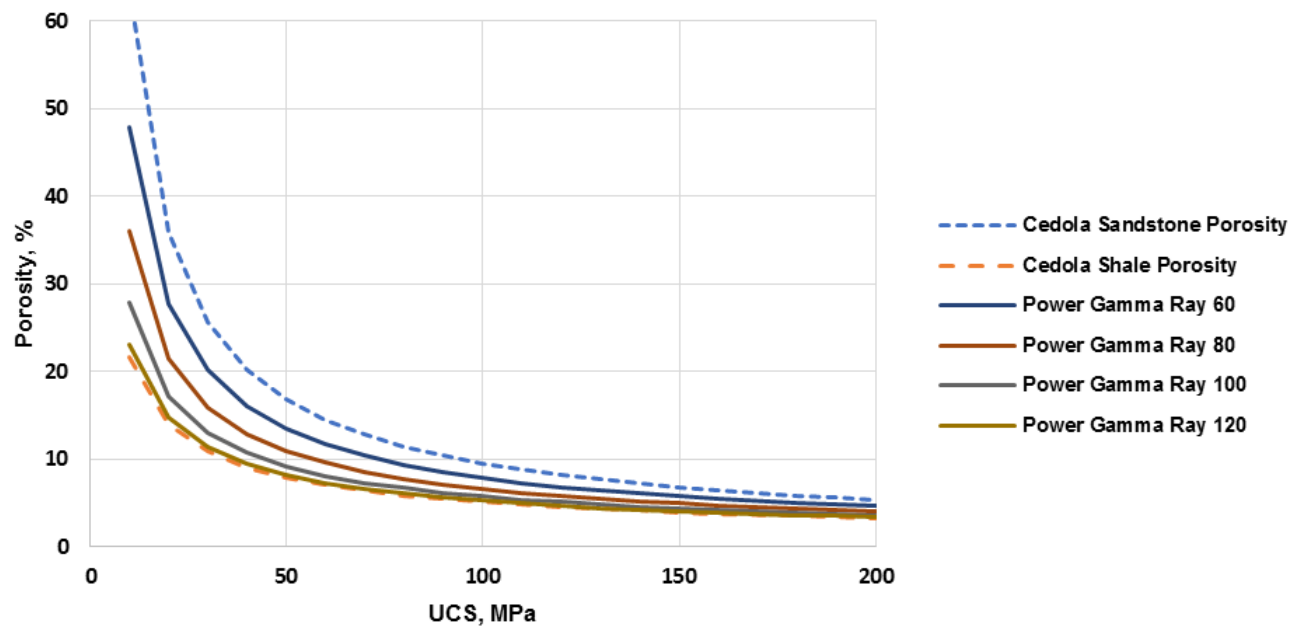


Figure 4. Power GR Porosity Plot (Cedola et al. 2017).

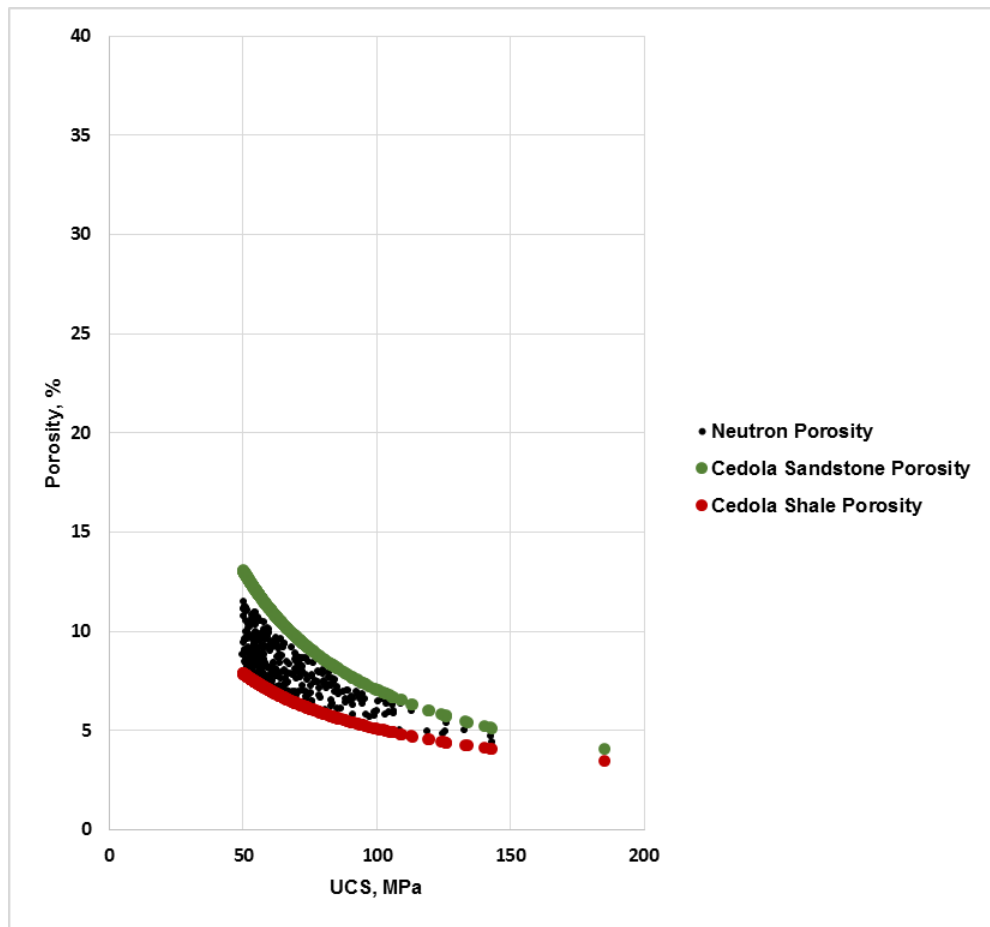


Figure 5. Cedola Sandstone and Cedola Shale Correlation Predictions in a Mixed Lithology Zone.

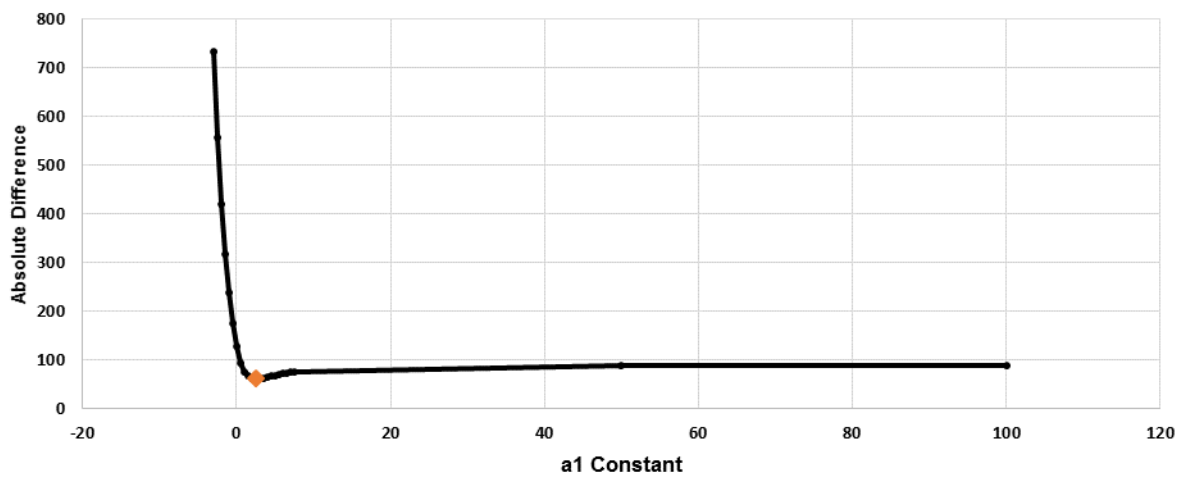


Figure 6. Optimal a_1 Constant Determination.

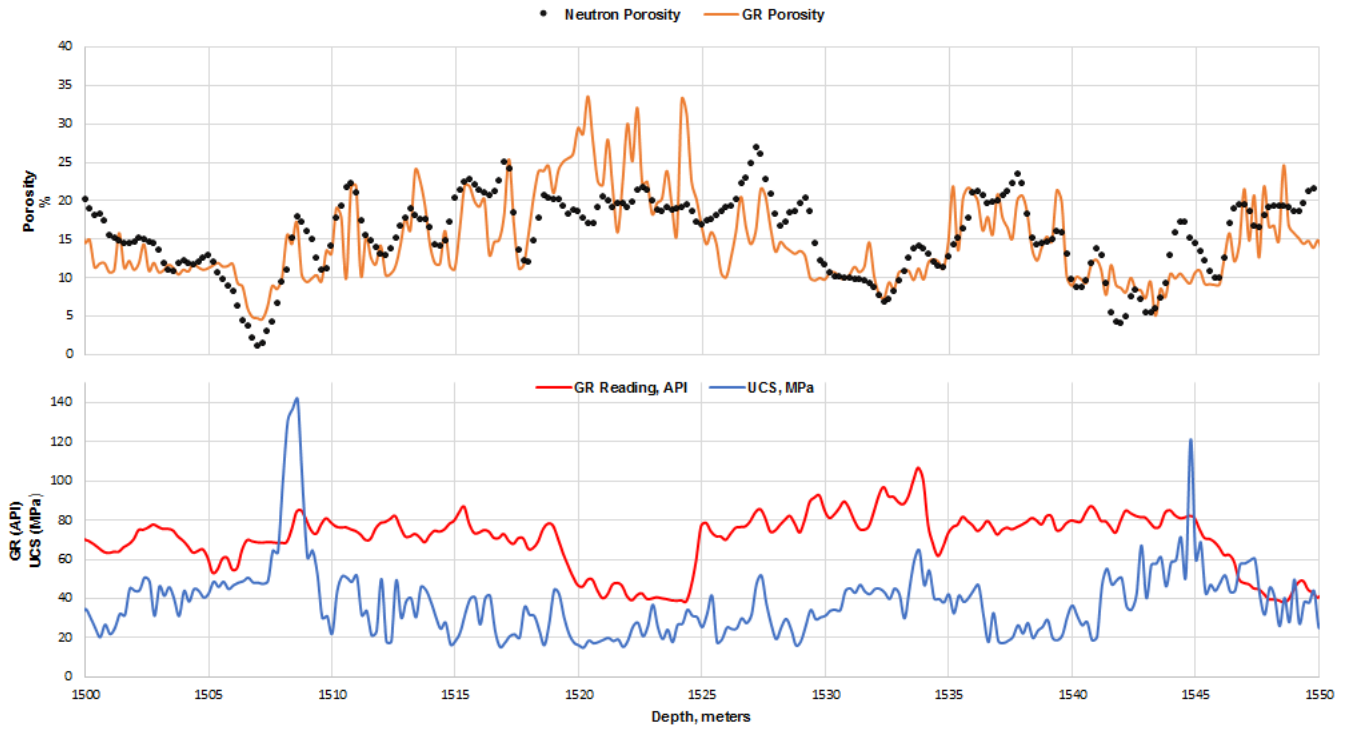


Figure 7. Mixed Lithology Neutron Porosity versus GR Porosity Comparison for the Belly River Formation.

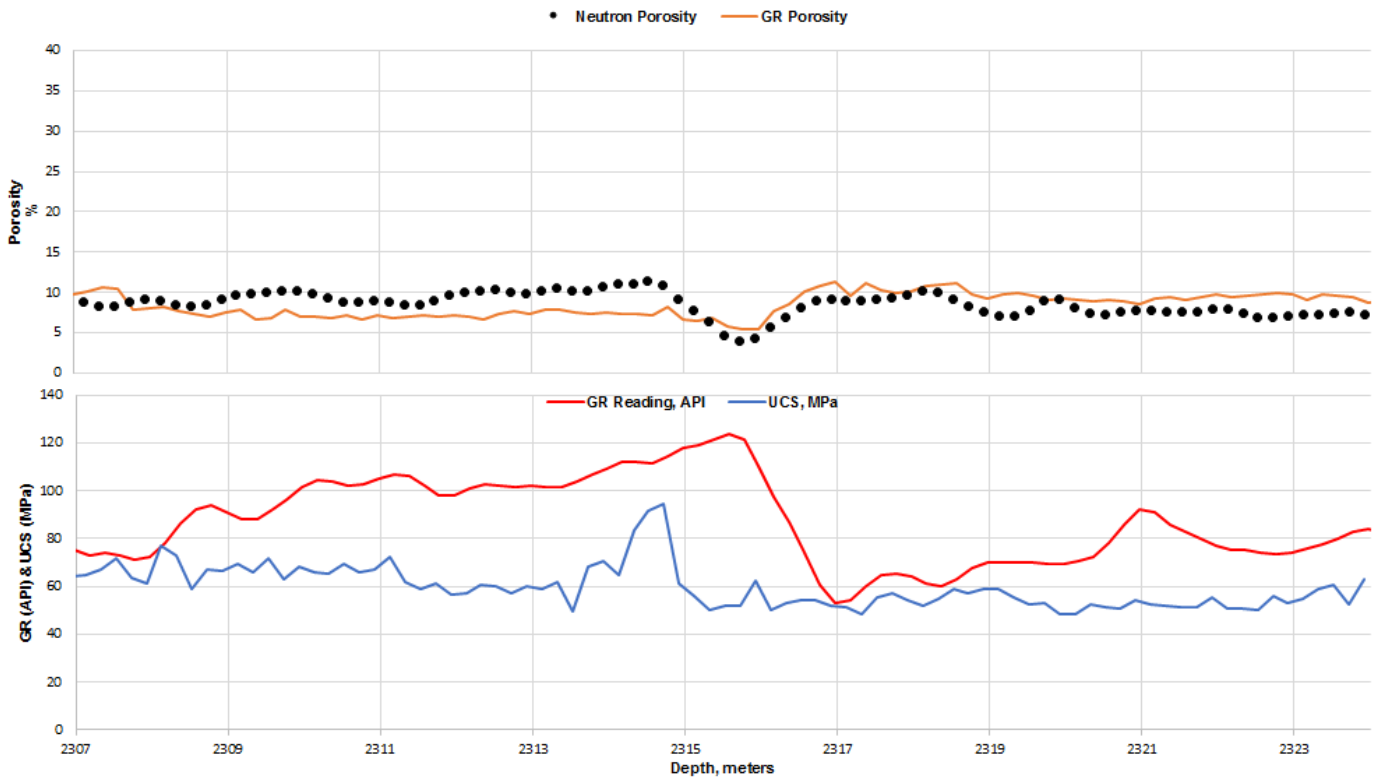


Figure 8. Mixed Lithology Neutron Porosity versus GR Porosity Comparison for the Dunvegan Formation.

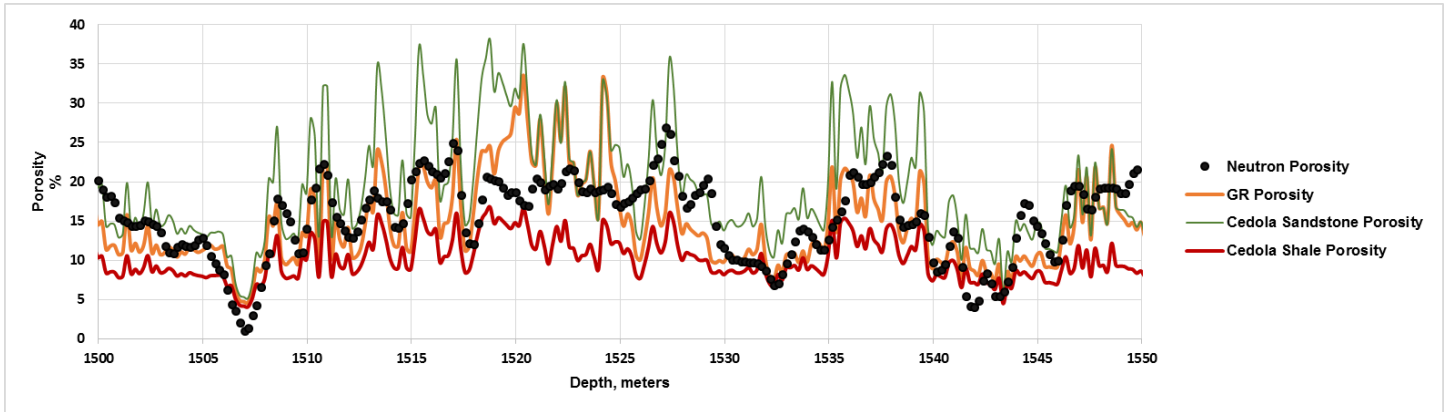


Figure 9. GR Porosity, Cedola Sandstone Correlation and Cedola Shale Correlation Comparison for the Belly River Formation.