SPE-185115-MS

Evaluating Multiple Methods to Determine Porosity from Drilling Data

A.E. Cedola, A. Atashnezhad, G. Hareland, Oklahoma State University

This paper was prepared for presentation at the SPE Oklahoma City Oil and Gas Symposium held in Oklahoma City, Oklahoma, USA, 27—30 March 2017.

Abstract

Porosity can be obtained from drilling data by using different correlations that relate the porosity to the unconfined compressive strength (UCS), which is obtained from drill bit inverted rate of penetration (ROP) models. Knowing the porosity at a given depth can benefit in helping to define the formations being penetrated and to characterize variations in a reservoir, thereby benefitting in selective stimulation. In this paper, previous studies that present methods for calculating porosity from UCS values will be compared and evaluated with sections of porosity that have been calculated from log data taken from three wells in Alberta, Canada. The correlations that will be compared include: Onyia, Sarda, Erfourth, and the UCS-gamma ray methods. The Onyia, Sarda, and Erfourth correlations are previously published while the UCS-gamma ray method correlates UCS in conjunction with the gamma ray at the bit. The porosity values that are found through these correlations are then plotted and their trends compared to each other as well as to the porosity obtained from log data in different sections from the well in Alberta, Canada. This process will help to determine what formation types are best correlated to the individual correlation. Typical drilling data is used in an inverted ROP model to obtain UCS. The UCS and gamma ray values are then taken and related to the porosity through the correlations presented in this paper and compared to the porosity determined from log data. Examining the different correlations that have been analyzed in various types of formations yield information indicating which correlation is best correlated to a specific formation type. The comparison's show that the predictability for some correlations are reasonable for limited datasets and sections of the well. To reasonably predict porosity values for mixed lithologies or shale formations, the integration of gamma log data is necessary. The trends exhibited from the correlations show that the comparison between porosity in shale is better seen when using the integrated UCS-gamma ray correlation. Utilizing the new UCS-gamma ray model seemingly indicates that this useful new method can more accurately predict porosity variations in mixed lithologies and in shale reservoir sections. Bettering stimulation placement as well as minimizing logging in the reservoir can greatly reduce the overall cost of the operation. The improved selective stimulation process could also allow for higher production rates and/or potential reduced stimulation cost, thus increasing overall profit.

Background

Porosity determination can be a complex process. There have been many methods that utilize unconfined compressive strength (UCS) to find porosity. In these methods, UCS is found from laboratory testing and/or log data. While these techniques may yield fairly accurate UCS values, they can be extremely costly and potentially misrepresentative of large intervals. The accuracy of porosity found from drill cuttings can be greatly influenced by the size of the cuttings and desaturation time (Yu & Menouar 2015). Log analysis has also been used for porosity determination, however, certain logs may not accurately identify various lithologies within a formation. According to Heslop (1974), the gamma ray log is one of the only logs that are able to identify shale zones. To determine shale volume, a combination of gamma ray, density porosity, and neutron porosity must be known (Bhuyan and Passey 1994). Log analysis can also be affected by drilling fluids, which can over or underestimate porosity. The use of core analysis for determining porosity is considered the optimal approach, but this technique isn't commonly performed due to the high costs associated with coring (Smith and Ziane 2015).

Establishing empirical models has been useful in eliminating the need for excess logging tools and laboratory testing. In this paper, three methods that have been previously published will be analyzed and compared to determine their accuracy and applicability to field data. These methods are: the Onyia method (Onyia 1988), Sarda method (Sarda et al. 1993), Erfourth method (Erfourth et al. 2005) and a new Gamma Ray method presented within this paper.

Onyia Method

The Onyia method (Eq. 1) for determining a correlation between UCS and porosity uses Warren's roller cone penetration rate model to calculate UCS from drilling data. In this case, data from multiple logs were used to calculate the UCS and determine which log provided the most accurate results. Because the UCS is calculated directly from log and drilling data, there is potential for this method to be used in real time drilling (Onyia 1988). The Onyia method is applicable to a variety of lithologies, including both shale and sandstone.

$$\boldsymbol{\delta_{UCS} = 3.2205 + \frac{102.51}{\emptyset}}, \quad (1)$$

Sarda Method

The Sarda method (Eq. 2) utilizes a combination of log and laboratory data to establish a correlation between porosity and UCS in sandstones (Sarda et al. 1993). A correlation that had been developed for ceramic materials was adapted to determine UCS values at different porosity ranges: 0-7% porosity, up to 30% porosity, and 30% porosity and higher. For the purpose of this paper, the Sarda equation for porosity ranging from 0-30% will be used.

$$\boldsymbol{\sigma_{UCS} = 258e^{-9\emptyset}}, \quad (2)$$

Erfourth Method

The Erfourth method (Eq. 3) for relating UCS and porosity uses UCS data that has been collected from laboratory testing on core, cast, and tuff samples. Statistical analysis of the samples proved that both the cast and core samples are feasible for modeling rock UCS and porosity (Erfourth et al. 2005).

$$\boldsymbol{\sigma_{UCS} = 194.39e^{\left(-\frac{\emptyset}{12.55}\right)}}, \quad (3)$$

To observe any differences between the three previously published correlations, normalized UCS and porosity values were plotted in **Fig. 1**. The plot shows that the Onyia method yields much higher porosity values for low UCS zones while the Erfourth method becomes inaccurate for high UCS areas. The Onyia correlation also becomes relatively constant at a UCS value of 100 MPa.

An alternate method for obtaining UCS is to take it from drilling data, which is less costly and time consuming than precious methods. Utilizing an inverted rate of penetration (ROP) model yields results similar to those obtained from log or laboratory data (Hareland & Nygaard 2007). The inverted ROP model takes conventionally recorded drilling data and calculates the corresponding UCS. This method is beneficial because there are no additional costs associated. It can be used to determine UCS for extended intervals or an entire well.

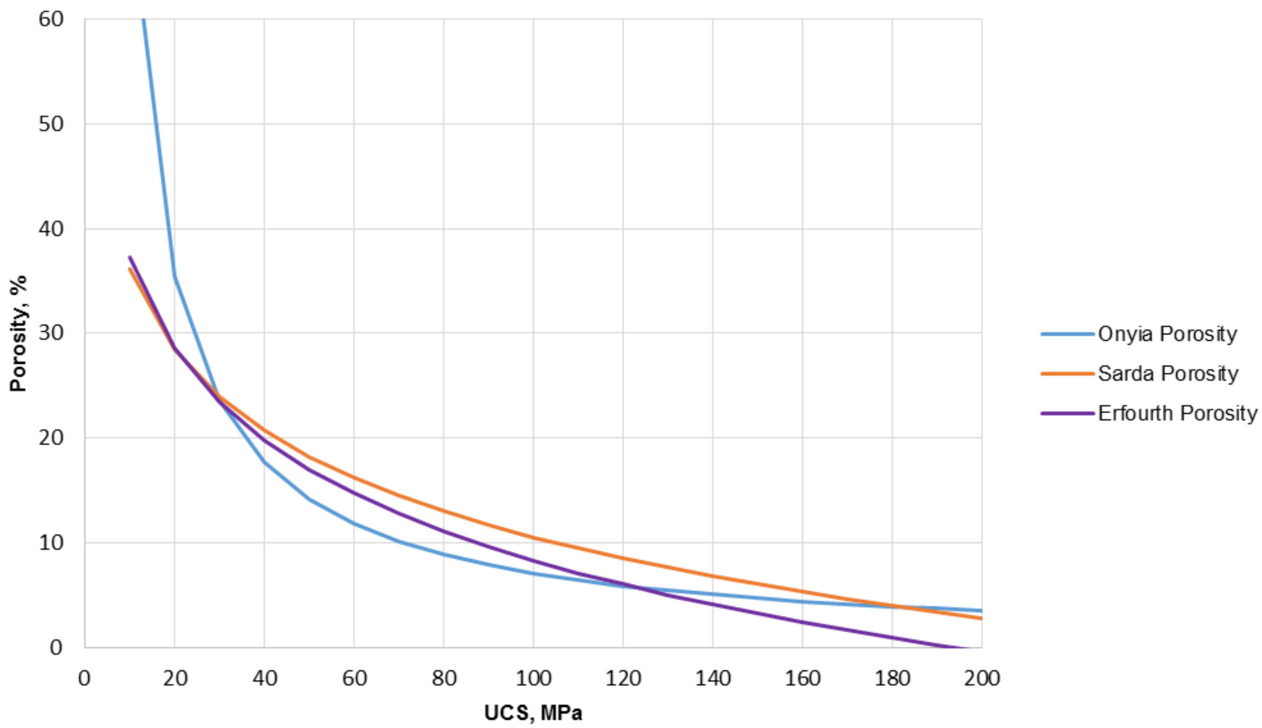

Fig. 1-Onyia, Sarda, and Erfourth porosity comparison for normalized UCS values

Gamma Ray Method

While the Onyia, Sarda, and Erfourth methods are good porosity indicators in sandstone, they lack the ability to accurately predict shale porosity. To establish accurate correlations for both sandstone and shale porosity versus UCS, data from multiple published sources was gathered and plotted (Horsund 2001, Chang 2004, Gutierrez et al. 2000, Lashkaripour 2002, Farquhar et al. 1993, Khaksaret al. 2009, Hawkins & Mcconnell 1991, Kim et al. 2015, Yao 2015). This data consisted of both core and cuttings analyses. A trendline was added and a correlation between the UCS and porosity was determined for sandstone and shale lithologies as seen in **Figs. 2 and 3**. These correlations will be referred to as the Cedola sandstone and Cedola shale correlations.

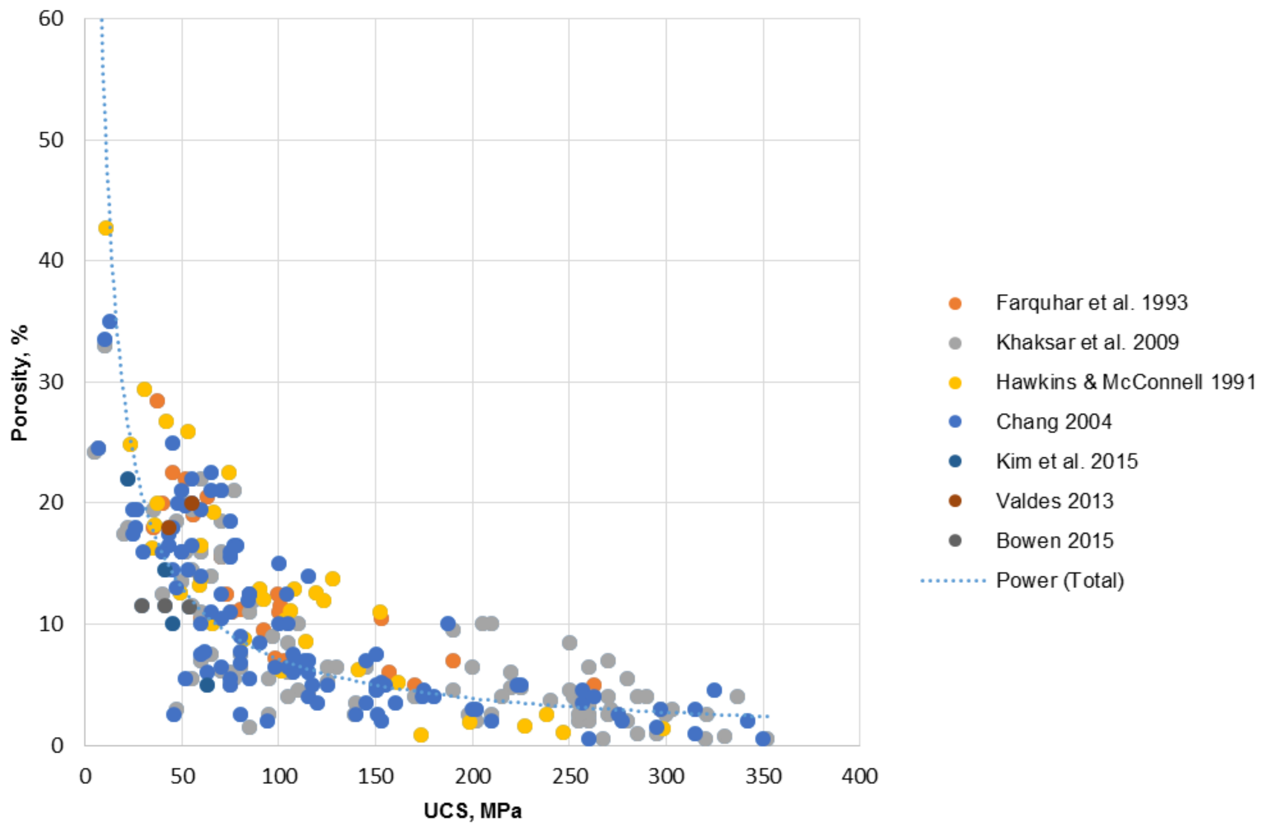

Fig. 2-Cedola sandstone correlation obtained from various sandstone formations core and cuttings analysis

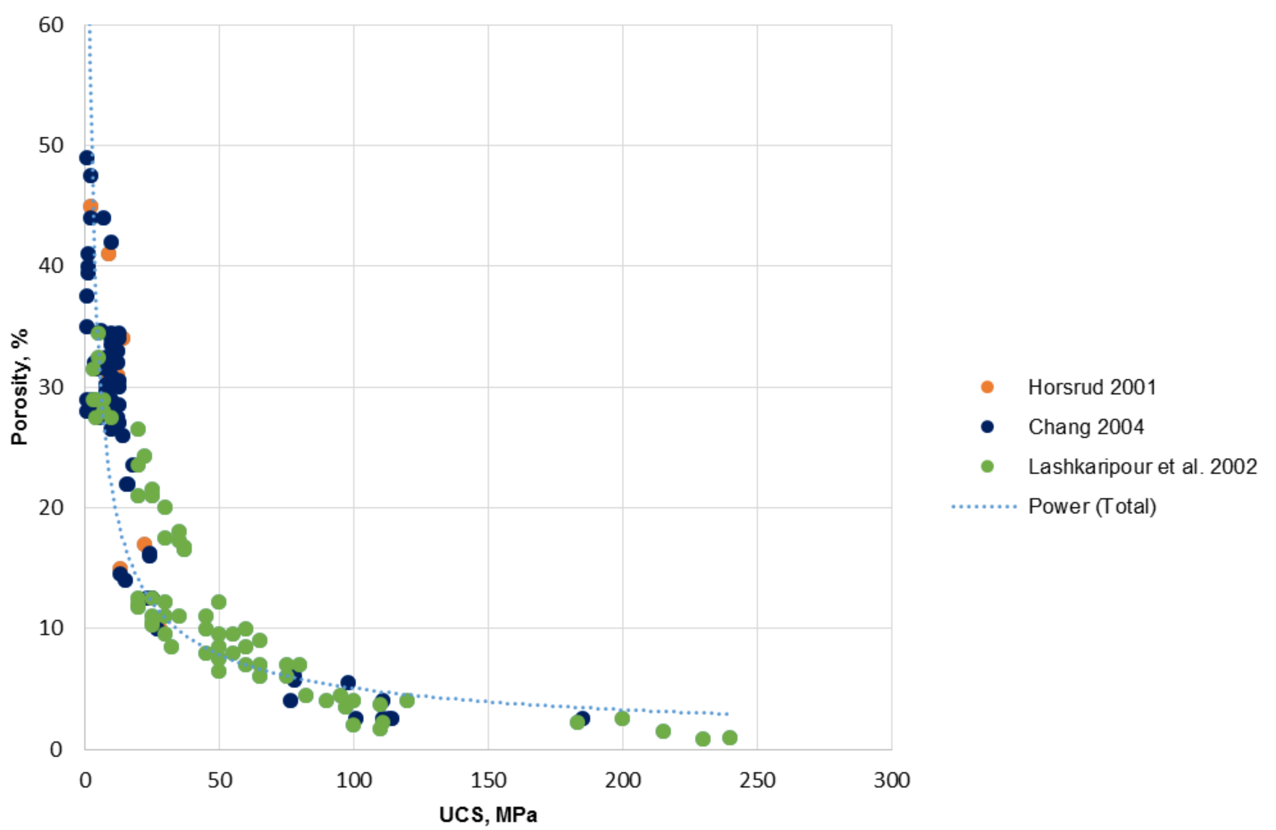

Fig. 3-Cedola shale correlation obtained from various shale formations core and cuttings analysis

The trendline equations for the sandstone and shale are given in Eqs. 4 & 5, respectively.

$$y = 424.8 \times UCS^{-0.825} \quad (4)$$

$$y = 92.529 \times UCS^{-0.63} \quad (5)$$

A comparison between normalized UCS versus porosity for the previously published methods and the Cedola sandstone and shale correlations is shown in **Fig. 4.** The plot shows that the Onyia and Cedola sandstone correlations are similar in both value and trend. The Cedola shale correlation has a similar trend to the Sarda and Erfourth correlations and it is seen that for all the correlations at high UCS values the porosities become much closer in values. Both the Cedola sandstone and shale correlations level out at UCS values of about 150 MPa.

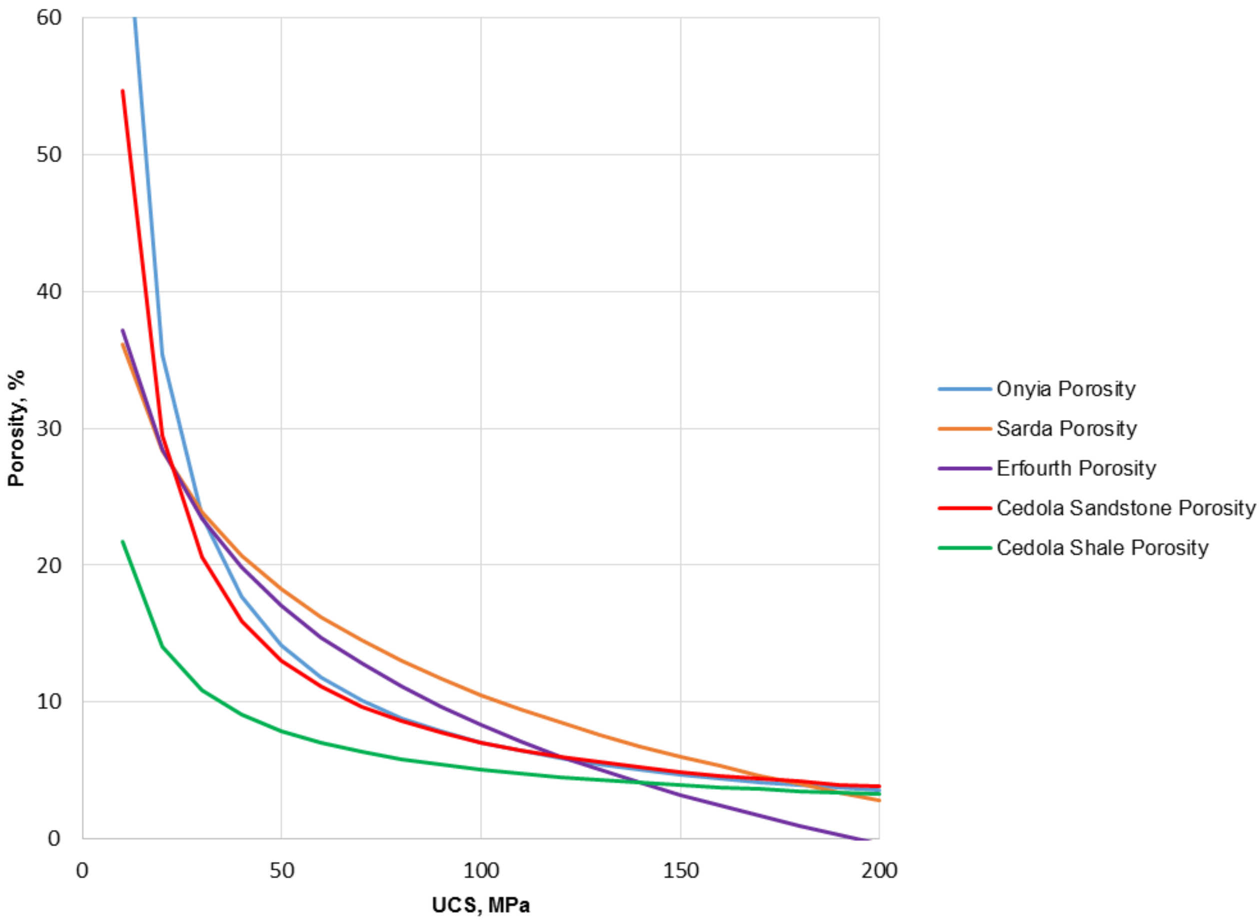

Fig. 4-Comparison between the Cedola sandstone and shale correlations to the Onyia, Sarda, and Erfourth methods

While it is believed that the Cedola sandstone and shale correlations are good porosity predictors in homogeneous formations, a new correlation must be used to evaluate the porosity in mixed lithologies. For these types of lithologies, the use of gamma ray log data will be considered and used to establish a Gamma Ray Porosity. The Gamma Ray Porosity has been compared in two ways: linearly and as a power function (**Figs. 5 and 6**).

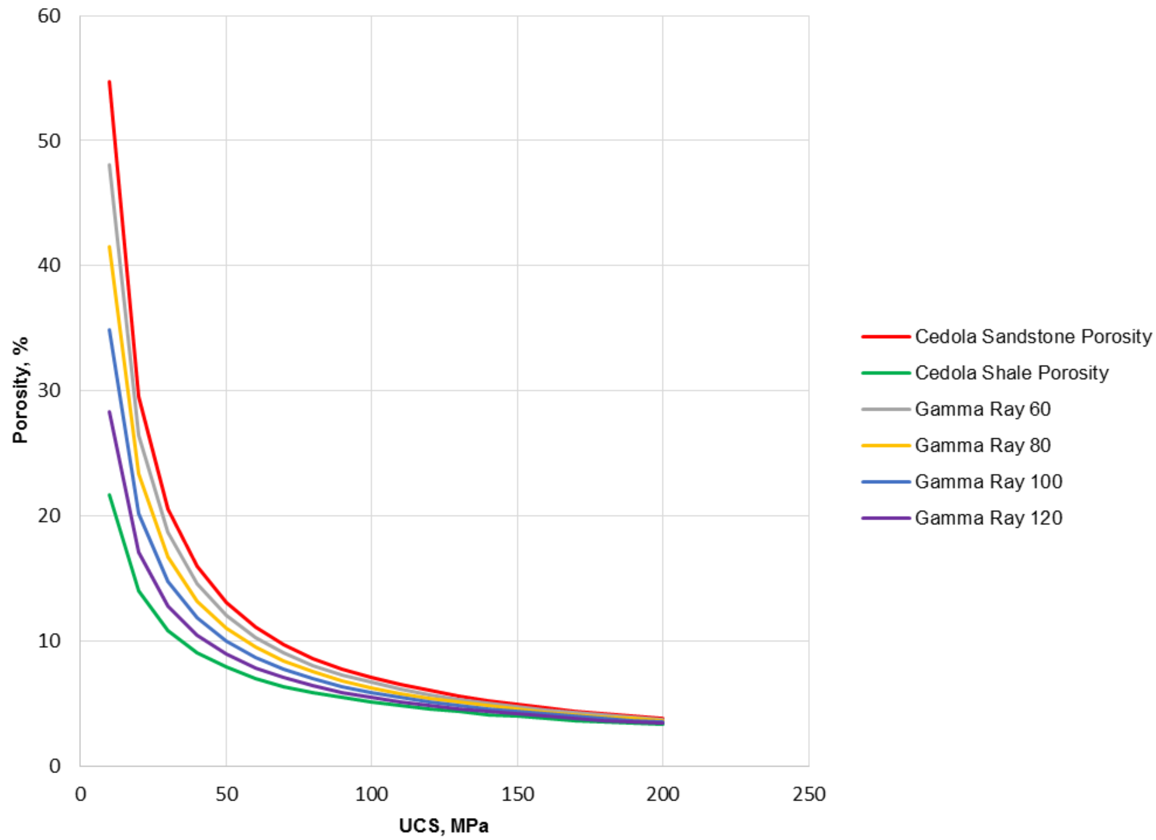

Fig. 5-Linear Gamma Ray Porosity plot

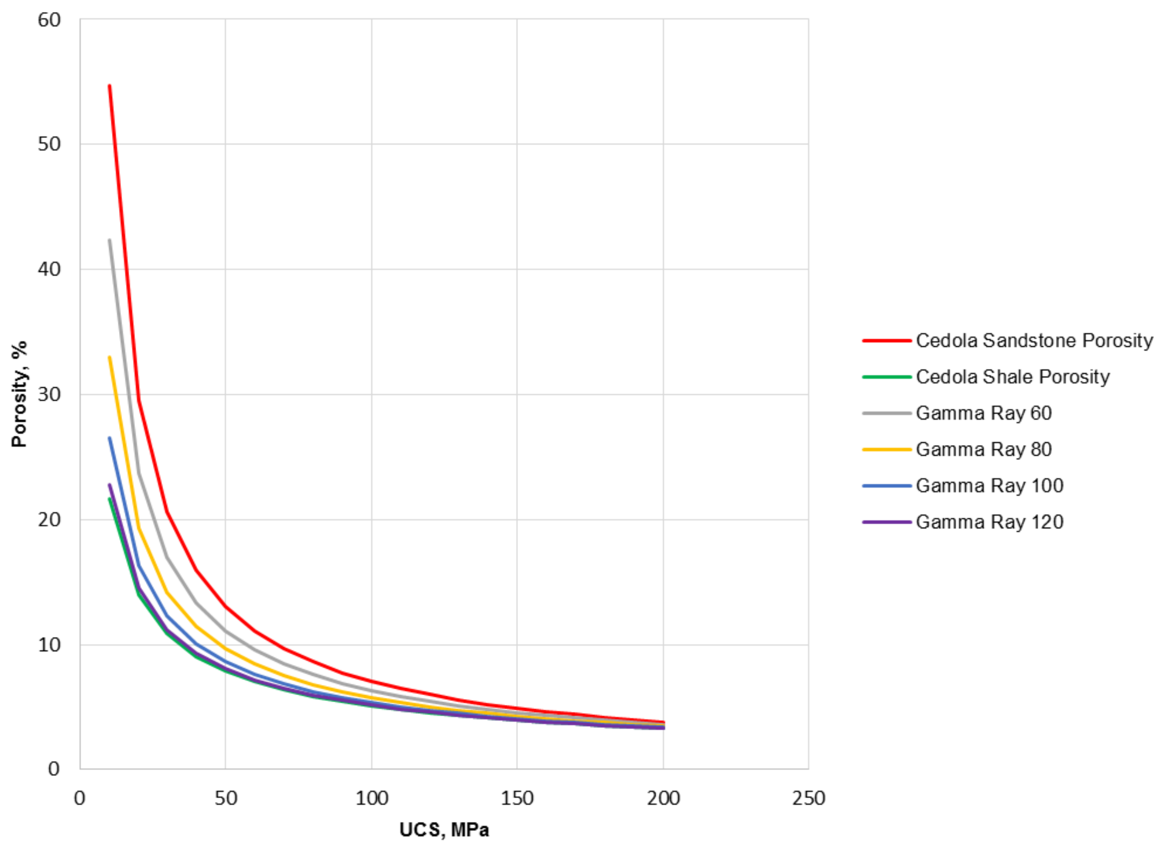

Fig. 6-Power Gamma Ray Porosity plot

Any gamma ray readings below 40 and above 140 are considered completely sandstone and shale, respectively. Because the Cedola sandstone and shale porosities are representative of entirely sandstone or entirely shale formations, they will be equivalent to the gamma ray readings 40 and 140 API. The Gamma Ray porosity equation is shown in **Eq. 7**.

$$\emptyset_{Gamma\ Ray} = \emptyset_{Cedola\ Shale} + (\emptyset_{Cedola\ Sandstone} - \emptyset_{Cedola\ Shale}) \times \left(\frac{140 - Gamma\ Ray\ Reading}{140 - 40}\right)^{a_1}, . \quad (7)$$

To verify the accuracy of UCS obtained from drilling data, a previous study in which neutron porosity and gamma ray data has been taken for sandstone and shale formations in ten wells and correlated against their respective UCS obtained from an inverted ROP model was analyzed (Andrews et al. 2007). The inverted ROP model takes bit, operational drilling data, and lithological data into consideration. From the study, a linear gamma ray porosity interpolation was found and the best fit correlation is used to find the power Gamma Ray porosity method. For both the linear and power Gamma Ray methods, the upper and lower bounds are equivalent to the Cedola sandstone and shale correlations, respectively. The linear interpolation shown in Fig. 5 is obtained using a gamma ray coefficient, a_1 equal to 1.0 while the results shown in Fig. 6 are based on the analysis of the ten wells and the gamma ray coefficient, a_1 equal to 2.1 which was found to be the best fit. The power Gamma Ray porosity values are more dependent on the formation composition and could be used to determine porosity in all lithologies.

Results and Discussion

A comparison between the correlations presented in this paper to the three previously published UCS-porosity correlations is done to see which method(s) is more accurate in both value and trend to log data porosity. Plotting the correlations for the three different lithological intervals gives insight as to which correlation works best in sandstone formations, shale formations, and mixed formations.

To analyze the Cedola sandstone and shale correlations potential for field application, drilling and log data from three previously drilled wells has been collected and separated by lithology. The Onyia, Sarda, and Erfourth correlations are plotted against neutron porosity to compare the correlation porosities to actual field data.

The shale plot comparison for the Onyia, Sarda, and Erfourth methods show that the neutron porosity is lower than any of the three methods (**Fig. 7**). The Onyia correlation result is unusual because this method has previously predicted accurate porosity values in sandstone, shale, and various other lithologies (Onyia 1988). The Cedola shale correlation shown in **Fig. 8** shows a similar match to the neutron porosity and is closer to the average porosity values reported for the Muskiki shale, 1.7-13.4% (Bachu & Underschultz 1992).

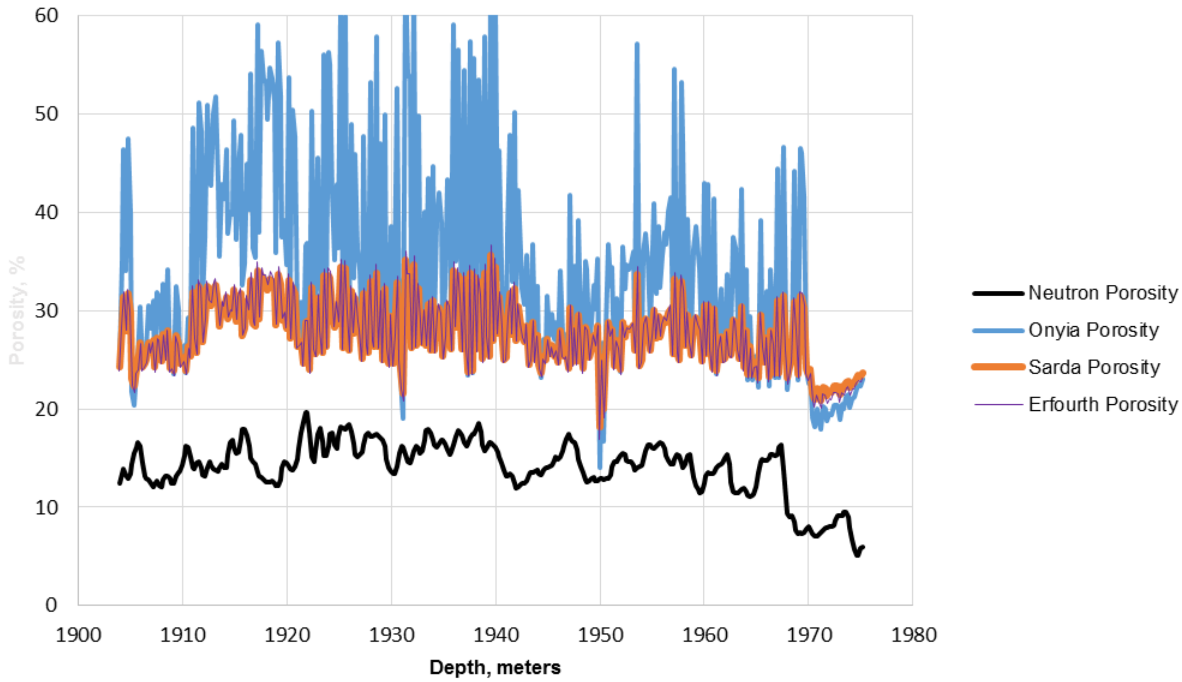

Fig. 7-Shale porosity comparison between the Onyia, Sarda, and Erfourth methods to the neutron porosity for the Muskiki shale

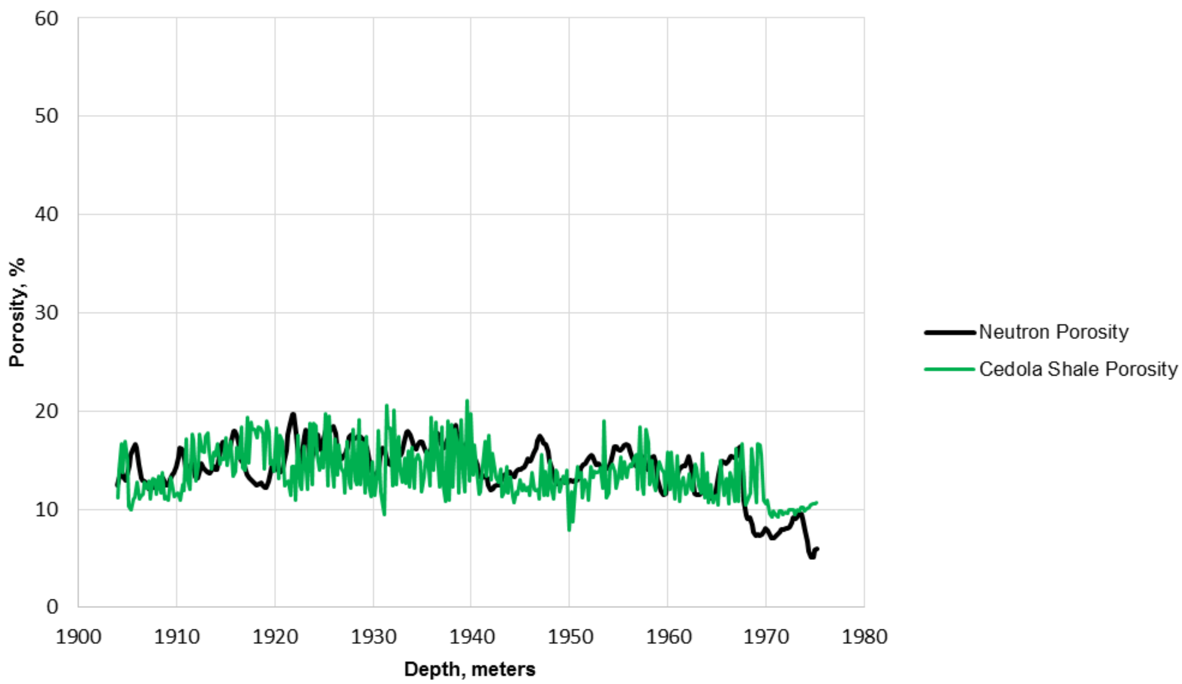

Fig. 8-Shale porosity comparison between the Cedola shale correlation and neutron porosity for the Muskiki shale

The sandstone porosity comparison shows great similarity between the Onyia, Sarda, and Erfourth plots to the neutron porosity (**Fig. 9**). The porosity values have a smaller range in variation and all three correlations match the neutron porosity data for a given depth interval. The Cedola sandstone correlation had similar porosity values to the three methods (**Fig. 10**). Such similarities indicate that UCS values obtained from drilling data predict sandstone porosity as accurate as correlations that require costly logging tools or laboratory tests. All correlations were within the average porosity range for the Falher sandstone, which does not exceed 15% (Harris 2014).

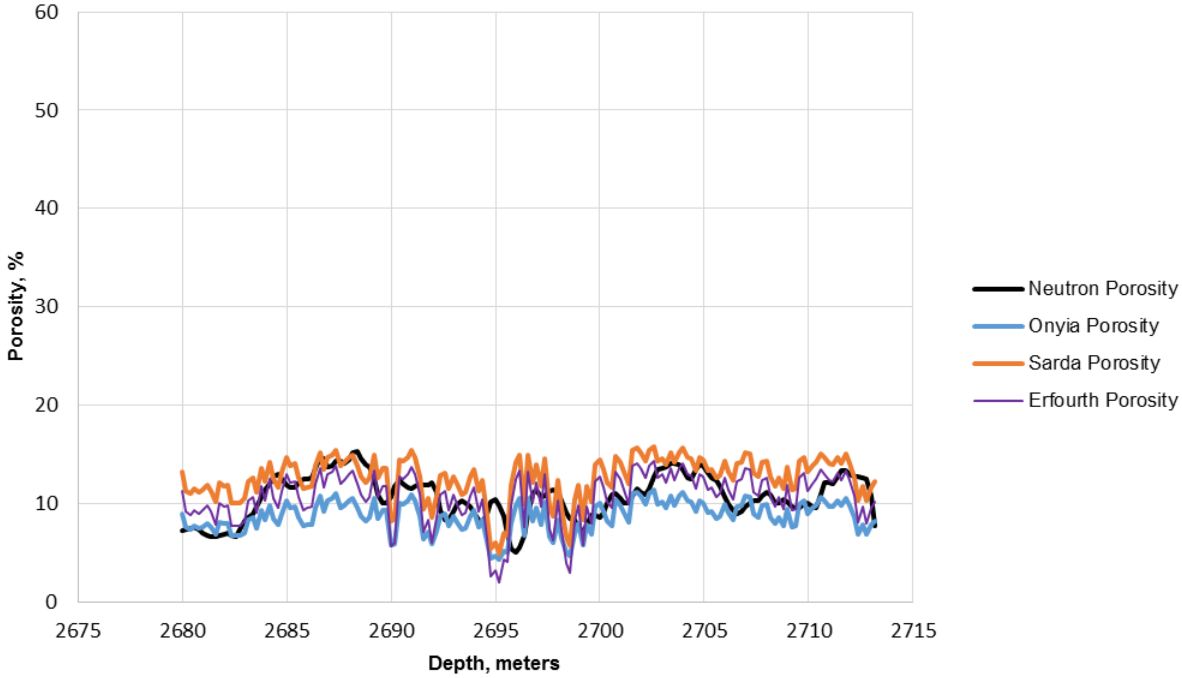

Fig. 9-Sandstone porosity comparison between the Onyia, Sarda, and Erfourth methods to the neutron porosity for the Falher sandstone

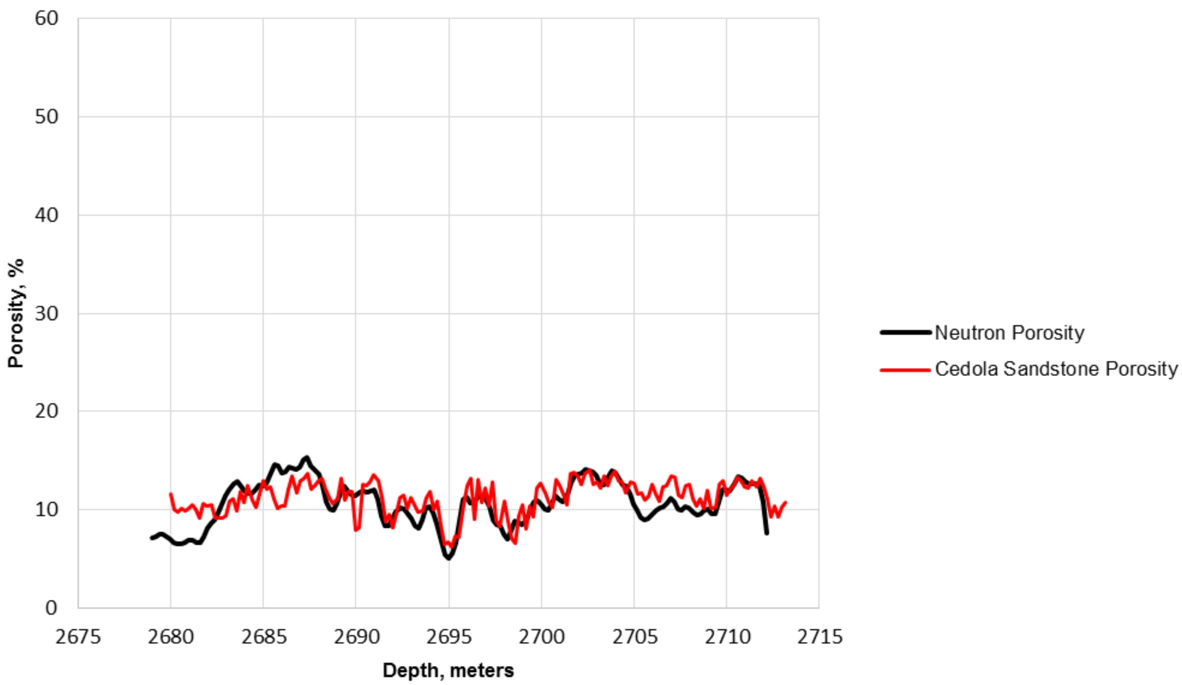

Fig. 10-Sandstone porosity comparison between the Cedola sandstone correlation and neutron porosity for the Falher sandstone

Previous methods for determining porosity in formations of complex lithology have required multiple types of log porosity combinations (Syngaevsky and Khafizov 2003). Analyzing a zone with mixed lithology indicates a large range in porosity values for the Onyia, Sarda, and Erfourth methods (**Fig. 11**). The Onyia method has the greatest porosity variation with some porosity values exceeding 100%. The Sarda and Erfourth porosities have similar trends. The lower the neutron porosity, the less accurate the three methods become. Such variance implies that the Onyia, Sarda, and Erfourth methods may have the ability to predict porosity in zones where sandstone is the predominant lithology but could also give inaccurate values in regions of mainly shale or shaly sands.

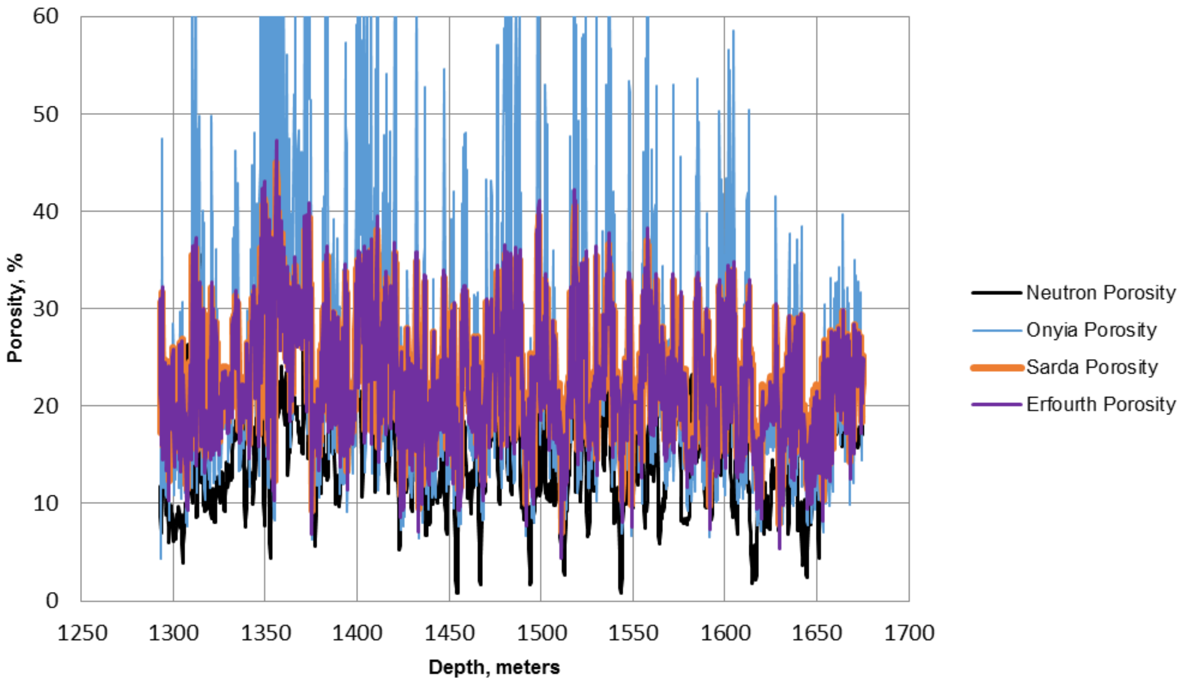

Fig. 11-Mixed lithology porosity comparison between the Onyia, Sarda, and Erfourth methods to the neutron porosity for the Belly River formation

A plot evaluating how the Gamma Ray correlation compares to neutron porosity is shown in **Fig. 12**. The plot shows that the Gamma Ray correlation doesn't match neutron porosity values that are significantly higher or lower than the average values. This is because the high neutron porosity values are in areas of high sandstone content while the low neutron porosity values are predominantly shale. For these areas, the Cedola sandstone and shale correlations prove more accurate in determining porosity. The Gamma Ray correlation has a better match to neutron porosity than the Onyia, Sarda, and Erfourth methods in a mixed lithology formation. This could be because both sandstone and shale porosities are included in the Gamma Ray method. The Onyia, Sarda, and Erfourth methods may be fairly accurate in sandy-shales, but the Gamma Ray correlation can better predict porosity in both sandy-shales, shaly-sands, and shale formations.

To visualize where the correlations presented within this paper are most accurate for a mixed lithology formation, a porosity versus depth plot has been created to determine how the Cedola sandstone, Cedola shale, and Gamma Ray correlations interact over various sand and shale contents (**Fig. 13**). The plot shows that while there are places where the Cedola sandstone or Cedola shale correlation matches with the neutron porosity, the Gamma Ray correlation does a much better job at predicting porosity in areas with a mixture of sandstone and shale.

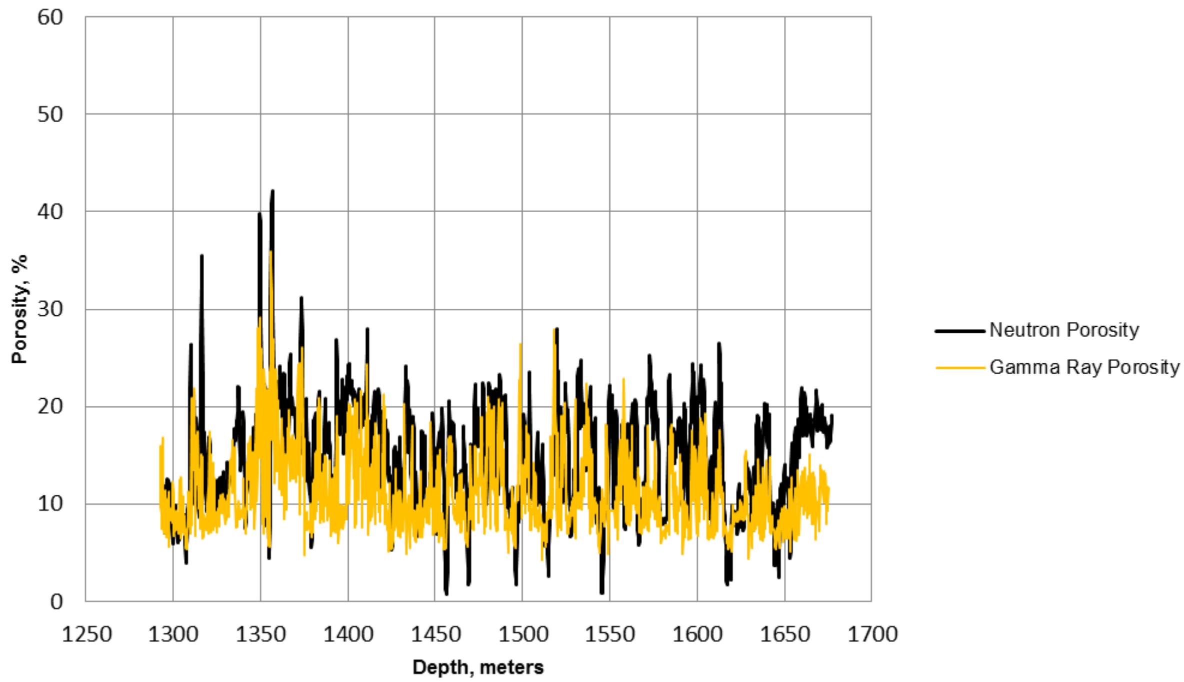

Fig. 12-Mixed lithology porosity comparison between the Gamma Ray correlation to neutron porosity for the Belly River formation

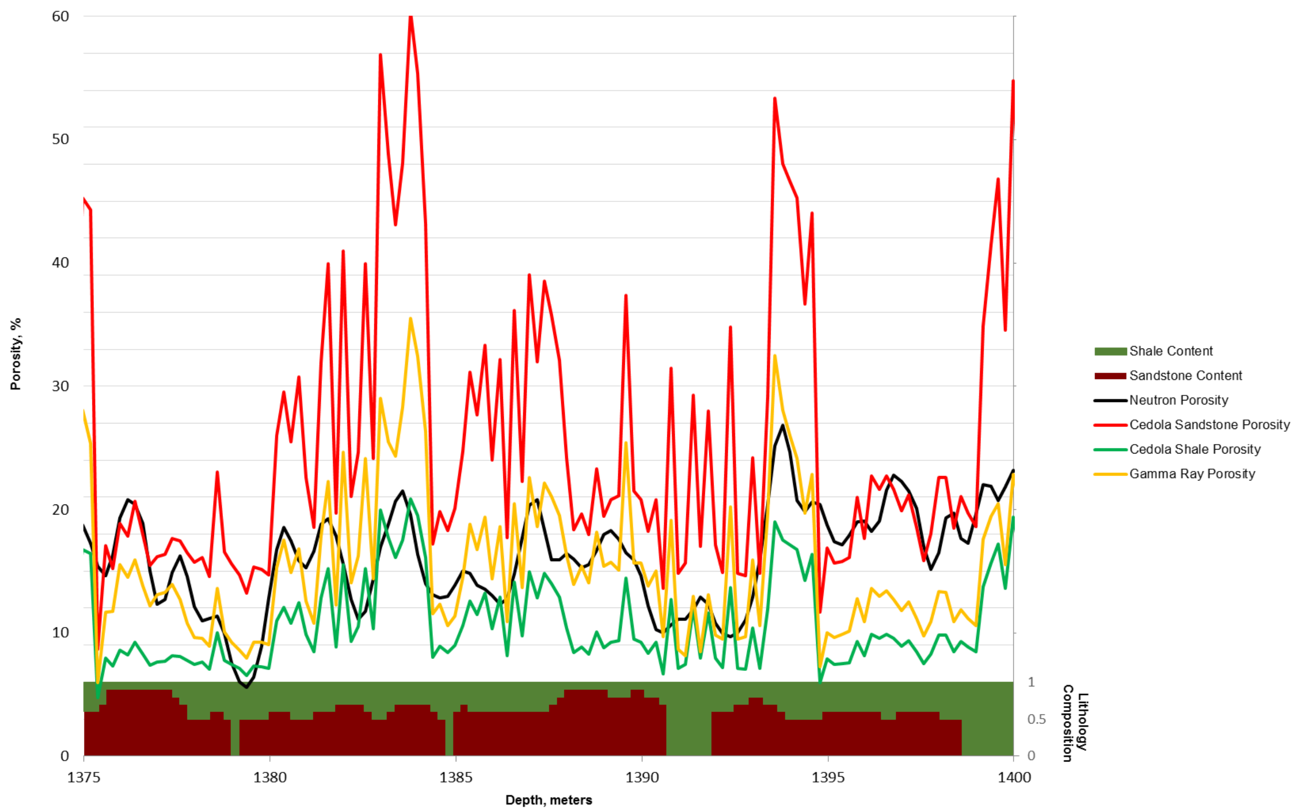

Fig. 13-Mixed lithology porosity comparison between the Cedola sandstone, shale, and Gamma Ray correlations to neutron porosity for a given depth interval within the Belly River formation

Application to Selective Stimulation

Understanding porosity variations within a well can affect stimulation placement and fracturing fluid design. Selectively stimulating a well can have a large impact on productivity and enhance fracture placement to better tap into hydrocarbon bearing zones. To determine optimal stimulation placement, geomechanical characterization near well bore must be known. This knowledge helps to identify areas where fractures are most likely to initiate and propagate as well as the required spacing to achieve maximum production (Glover et al. 2016).

The geomechanical data that is needed to establish selective stimulation schedules is found using well logs, cores, and/or cuttings analysis. Logs can show lithological composition and variation which can determine the areas that may be less successful at producing (Barree et al. 2014). Drill cuttings can help in reservoir characterization but aren't continuous for an entire well (Ortega & Aguilera 2014). While these methods can be indicative of areas in which selective stimulation could prove beneficial, the costs associated with such procedures could limit the amount of data collected.

Finding UCS and porosity from typical drilling data can reduce the cost associated with determining geomechanical properties as well as reduce the time needed to determine selective stimulation placement. Knowing the porosity for an extended interval can indicate where stimulation placement would optimize fracture initiation and propagation. UCS variations can be useful in determining zones where fracture propagation can best access the reservoir.

Conclusions

Utilizing drilling data to obtain correlations between porosity and UCS could prove beneficial in a variety of formations. The correlations are not only applicable to sandstone and shale formations, but the addition of gamma ray data allows such correlations to be feasible for predicting porosity in formations of mixed lithologies. While previously published methods for determining porosity from UCS yield relatively accurate porosity values for specific formations, the use of drilling data in conjunction with the gamma ray to determine porosity proves to be a potentially better indicator. Having a more accurate indication of porosity can benefit stimulation placement and in establishing a better sense of hydrocarbon bearing zones. The potential to reduce the need for logging tools could impact the overall operation cost while allowing for production maximization.

Nomenclature

UCS	Unconfined Compressive Strength, MPa
ROP	Rate of Penetration, meters per hour
ARSL	Apparent Rock Strength Log, MPa
Φ	Porosity, %
σ	Unconfined Compressive Strength, MPa
δ	Unconfined Compressive Strength, kPSI

References

Andrews, R., Hareland, G., Nygaard, R. et al. 2007. Methods of Using Logs to Quantify Drillability. Presented at the Rocky Mountain Oil & Gas Technology Symposium, Denver, Colorado, 16-18 April. SPE-106571-MS. http://dx.doi.org.argo.library.okstate.edu/10.2118/106571-MS.

Bachu, S. and Underschultz, J.R. 1992. Regional-Scale Porosity and Permeability Variations, Peace River Arch Area, Alberta, Canada. *AAPG Bulletin* **76** (4): 547-562.

Barree, R.D., Conway, M.W, and Miskimins, J.L. 2014. Use of Conventional Well Logs In Selective Completion Designs for Unconventional Reservoirs. Presented at the SPE Western North American and

Rocky Mountain Joint Meeting, Denver, Colorado, 17-18 April. SPE-169565-MS. http://dx.doi.argo.library.okstate.edu/10.2118/169565-MS.

Bhuyan, K. and Passey, Q.R. 1994. Clay Estimation From GR abd Neutron-Density Porosity Logs. Presented at the SPWLA 20th Annual Logging Symposium,

Chang, C. 2004. Empirical Rock Strength Logging in Boreholes Penetrating Sedimentary Formations. *Geology and Environmenal Sciences*, *Chungnam National University*, *Daejeon* **7** (03): 174-183

Erfourth, B.S., MacLaughlin, M.M., and Hudyma, N. 2005. Comparison of Unconfined Compressive Strengths of Cast versus Cored Samples of Rock-like Materials with Large Voids. Presented at the Alaska Rocks 2005, The 40th U.S. Symposium on Rock Mechanics (USRMS), Anchorage, Alaska, 25-29 June. ARMA-05-876.

Farquhar, R.A., Smart, B.G.D., and Crawford, B.R. 1993. Porosity-Strength Correlation: Failure Criteria from Porosity Logs. Presented at the SPWLA 34th Annual Logging Symposium, Calgary, Alberta, 13-16 June. SPWLA-1993-AA.

Glover, K., Cui, A., Tucker, J. et al. 2016. Improved Geology-Based Geomechanical Models Using Drill Cuttings Data for Selective Fracture Stage Placement in the Montney, Duvernay, and Beyond. Presented at the AAPG 2016 Annual Convention and Exhibition, Calgary, Alberta, Canada, 19-22 June.

Hareland, G. and Nygaard, R. 2007. Calculating Unconfined Rock Strength from Drilling Data. Presented at the 1st Canada-U.S. Rock Mechanics Symposium, Vancouver, Canada, 27-31 May. ARMA-07-214.

Harris, N.B. 2014. Falher and Cadomin diagenesis and implications for reservoir quality. Presented at the GeoConvention 2014: Focus, Calgary, Canada, 12-14 May.

Hawkins, A. and Mcconnell, B.J. 1991. Influence of Geology on Geomechanical Properties of Sandstones. Presented at the 7th ISRM Congress, Aachen, Germany, 16-20 September. ISRM-7CONGRESS-1991-051.

Heslop, A. 1974. Gamma-Ray Log Response of Shaly Sandstones. Presented at the Fifteenth Annual Logging Symposium of SPWLA, McAllen, Texas, June 2-5 June. SPWLA-1974-vXVn5a2.

Horsrud, P. 2001. Estimating Mechanical Properties of Shale from Empirical Correlations. *SPE Drill & Compl* **16** (02): 68-73. SPE-56017-PA. http://dx.doi.org.argo.library.okstate.edu/10.2118/56017-PA.

Kerkar, P.B., Hareland, G., Fonseca, E.R. et al. 2014. Estimation of Rock Compressive Strength Using Downhole Weight-on-Bit and Drilling Models. Presented at the International Petroleum Technology Conference, Doha, Qatar, 19-22 January. IPTC-17447-MS. http://dx.doi.org.argo.library.okstate.edu/10.2523/IPTC-17447-MS.

Khaksar, A., Taylor, P.G., Fang, Z. et al. 2009. Rock Strength from Core and Logs, Where We Stand and Ways to Go. Presented at the EUROPE/EAGE Conference and Exhibition, Amsterdam, The Netherlands, 8-11 June. SPE-121972-MS. http://dx.doi.org.argo.library.okstate.edu/10.2118/121972-MS.

Kim, K-Y., Zhuang, L., Yang, H. et al. 2015. Strength Anisotropy of Berea Sandstone: Results of X-Ray Computed Tomography, Compression Tests, and Discrete Modeling. *Rock Mechanics and Rock Engineering* **49** (4).

Lashkaripour, G.R. 2002. Predicting mechanical properties of mudrock from index parameters. *Bulletin of Engineering Geology and the Environment* **61** (1): 73-77. 10.1007/s100640100116.

Onyia, E.C. 1988. Relationships Between Formation Strength, Drilling Strength, and Electric Log Properties. Presented at the SPE Annual Technical Conference and Exhibition, Houston, Texas, 2-5 October. SPE-18166-MS. http://dx.doi.or.argo.library.okstate.edu/10.2118/18166-MS.

Ortega, C. and Aguilera, R. 2014. Quantitative Properties from Drill Cuttings to Improve the Design of Hydraulic-Fracturing Jobs in Horizontal Wells. *J Can Pet Technol* **53 (**01): 55-68. SPE-155746-PA. http://dx.doi.org.argo.library.okstate.edu/10.2118/155746-PA.

Sarda, J-P., Kessler, N., Wicquart, E. et al. 1993. Use of Porosity as a Strength Indicator for Sand Production Evaluation. Presented at the SPE Annual Technical Conference and Exhibition, Houston, Texas, 3-6 October. SPE-26454-MS. http://dx.doi.org.argo.library.okstate.edu/10.2118/26454-MS.

Smith, C.H. and L. Ziane. 2015. Mississippian Porosity and Permeability: Core Comparison to Nuclear Magnetic Resonance. Presented at the SPE Production and Operations Symposium, Oklahoma City, Oklahoma, 1-5 March. SPE-173592-MS.

Syngaevsky, P.E. and Khafizov, S.F. 2003. Application of Modern NMR Logging for Mixed-Lithology Carbonate Reservoirs (A Case Study). Presented at the Canadian International Petroleum Conference, Calgary, Alberta, 10-12 June. PETSOC-2003-016. http://dx.doi.org.argo.library.okstate.edu/10.2118/2003-016.

Valdes, C. and Raquel, C. 2013. *Characterization of Geomechanical Poroelastic Parameters in Tight Rocks*. Master's Thesis, Texas A&M University, College Station, Texas.

Yao, B. 2015. *Experimental Study and Numerical Modeling of Cryogenic Fracturing Process on Laboratory-Scale Rock and Concrete Samples*. Master's Thesis, Colorado School of Mines, Golden, Colorado.

Yu, Y. and Menouar, H. 2015. An Experimental Method to Measure the Porosity from Cuttings: Evaluation and Error Analysis. Presented at the SPE Production and Operations Symposium, Oklahoma City, Oklahoma, 1-5 March. SPE-173591-MS.