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Methods of Using Logs To Quantify Drillability

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Abstract

Correlations between sonic logs and the formation drillability for different lithology types have been developed from data taken from 10 wells in North America. The gamma ray log was used in conjunction with drilling data to calculate the drillability. The drillability from penetration rate models is back calculated from bit design and reported field wear in conjunction with meter by meter operating parameters, formation type and pore pressure. Then this drillability was correlated with sonic logs for different lithologies as defined by the gamma ray log. The different formation types clearly show different correlations for the normalized correlations between drillability and sonic logs. The non-homogeneous lithologies are also correlated and normalized to rock strength from the sonic logs where the percent formation type mixtures are determined from the gamma ray.

Data from multiple wells is presented showing the accuracy of the presented approach where more than 100,000 data points were statistically analyzed and evaluated in the development of the equations presented herein.

The drillability from inverted penetration rate models has been verified to give good representation of rock strength based on comparison with triaxial laboratory data and makes the use of this model more versatile. The correlations provide improved estimations of rock strength which can be used in drilling performance simulation and wellbore stability studies.

Introduction

The optimization of the drilling process by the use of a drilling simulator can significantly improve results with the input of proper rock properties. The Unconfined Compressive Strength (UCS) of the rock is one of the most important properties and is also the most difficult to obtain.

The ultimate objective of well logging is to evaluate subsurface formations by providing an indirect measurement of fluid and rock characteristics. Well logging has been

known to provide information on rock strength but the usage of electric logs for calculating drillability is less common.

Correlations of rock strength with logs can be obtained from laboratory uniaxial tests where the stress at shear fracture in a core specimen is correlated to the value of the log properties at the core sample depth. The disadvantage with the proposed procedure is that lab data is available only for the area where the well was cored and does not account for insitu strength. This gives less accurate representation of the entire well.

The “Optimizer”¹ is also capable of estimating unconfined rock strength as apparent rock strength (ARS). The current process of estimating ARS from the drilling simulator involves the use of a reference well that closely matches the characteristics of the planned well. The drilling inputs (WOB, RPM, Flow Rates, etc.) and outputs (Bit Wear, ROP, etc.) of the reference well are used to generate a drillability log or an Apparent Rock Strength Log (ARSL) for the planned well.

The reliability of this procedure is dependent on the quality of the field drilling data recorded. Although this technique has proved to give accurate predictions with successful results, refinements can be made to provide greater confidence in the predictions by using log data as a second source for calculating rock strength. At times the drilling data are not recorded with great accuracy and thus adversely affects the prediction of the ARSL. Also problems encountered while drilling such as down-hole and stick-slip vibration will have an effect on the quality of the prediction.

Background

Apparent Rock Strength Log (ARSL)²⁻⁴

The ARSL is a strength log generated by the “Optimizer”. The ROP and field drilling data are used to predict apparent rock strength under actual drilling conditions. The apparent rock strength found from the Optimizer is a function of operational parameters, bit properties, lithology, pore pressure, and rate of penetration.

Review of Onyia’s Paper⁵ Relating Formation Strength to Electric Log Properties

Correlations between log data and the formation drillability have been looked at in the past. Onyia investigated previous drilling correlation attempts and concluded that the

results were not suitable in dynamic rock strength predictions. The tests were taken with limited rock types and samples under atmospheric conditions in a static laboratory setting.

Onyia conducted tests involving the Induction, Sonic, Density, Gamma Ray, and porosity logs. Data was taken from a research test well in Roger's County, Oklahoma. The lithologies encountered in Onyia's study were shale, sandstone, limestone, dolomite, granite porphyry and some mixed lithologies.

The induction logs were found to produce poor predictions in some zones. The reliability of the induction logs for rock strength predictions can be affected by shale zones, porosity, and formation fluids. For rocks of bulk density between 2.5 and 2.9 gm/cc a relationship with rock strength was found to exist with some accuracy. The Gamma Ray log produced no good correlations with rock strength and a direct correlation does not appear to exist. Density porosity did not correlate well with rock strength and sonic porosities were recommended.

Sonic models produced the best agreement with the tri-axial test results analyzed for the comparison. Onyia concluded that the sonic model may be used to develop a continuous rock strength model.

Technical Discussion

Determination of Lithology

Experience in the areas where the wells were drilled specifies that the formations are mainly composed of shale, sandstone, and small amounts of coal. With this information known, the homogeneous lithologies of sandstone and shale were separated using a gamma ray cutoff value (below 50 API for sandstone and above 110 API for shale). Linear interpretation of the gamma ray log values (Equation 1) was used to determine the shale fraction of the mixed lithology.

$$\rho_{corr} = \rho_{log} - V_{sh} * \rho_{sh} \quad \dots\dots\dots(1)$$

Bulk density values below 1.1 gm/cc were determined to contain coal within the formations.

Sonic Logs, Compaction and Porosity Correlations to the ARSL

Sonic Logs

The ARSL was plotted versus the sonic travel time to determine the trend of the data. The correlation in Figure 1 resembles the form of exponential decline. No data points for the sonic travel time were observed below 45 $\mu\text{sec}/\text{ft}$; therefore, a boundary condition of 40 $\mu\text{sec}/\text{ft}$ was used to develop Equation 2.

$$\delta_{ARS} = \frac{K_1}{(\Delta t_c - 40)^{K_2}} \quad \dots\dots\dots(2)$$

An average representation of porosity was developed from a normalized rock strength ($\frac{\delta_{ARS}}{\delta_{ARS-\max}}$) versus neutron porosity relationship shown in Figure 2. Neutron porosity was chosen since poor correlations were found using the density porosity from Onyia's research (rock strength is closely

related to porosity and therefore important to include when developing a correlation). The resulting empirical relationship is given by,

$$\frac{\delta_{ARS}}{\delta_{ARS-\max}} = 1 - \phi_N^{.18} \quad \dots\dots\dots(3)$$

Compaction

As a rock compacts, the grain contact area and contact stress increase which causes the bulk and shear modulus to increase. Rock compaction also reduces the porosity, in effect increasing the density and reducing the sonic travel time. Further compaction is resisted by either stiffness in the rock frame or by increases in the pore pressure.

Sonic, density and resistivity logs of a normally pressured formation will generally increase with depth of burial. At surface levels shale has higher porosity than sandstone. As depth increases and the rock compacts, the porosity is reduced and the density increases due to the greater overburden pressure. Since shale is normally composed of softer minerals, the compaction is greater within this lithology.

Figure 3 shows the predicted rock strength from equation 2 (only sonic equation) versus sonic travel time for the regression constants found for sandstone and shale. The sonic travel time near 70 $\mu\text{s}/\text{ft}$ indicates the cross-over point between the sandstone and shale correlations. For the sonic travel times less than 70 $\mu\text{s}/\text{ft}$ the strength of the shale is more than sandstone and for values more than 70 $\mu\text{s}/\text{ft}$ the sandstone strength is higher is more than the shale. This figure is not based on depth and if the sonic travel times of sandstone and shale are compared for the same depth interval, sandstone generally has a lower sonic travel time than shale. This explains why the sandstone normally has the greater strength than shale at the same depth interval.

A modified Sclater and Christie⁶ correlation of depth versus porosity for sandstone and shale was used to determine a relationship between sandstone and shale compaction.

Using the modified Slater and Christie correlation, pure sandstone is used as the reference indicator to include compaction into the equation. Therefore, it is assumed no additional compaction occurs within the pure sandstone zones since shale experiences much greater compaction over depth than sandstone. The ratio between the sandstone and shale porosity terms using the modified Slater and Christie Method were plotted against depth. A polynomial fit was used to develop Equation 4 to determine compaction as a function of depth. Equation 4 is multiplied by Equation 3 for shale and part-mixture lithology. For pure sandstone lithology, Equation 4 will reduce to Eq. 1 since we are assuming no compaction occurs.

$$f = \frac{(1 - \phi_{N-\text{SS}}^{.18})}{(1 - \phi_{N-\text{Shale}}^{.18})} = -0.0016d^4 + 0.018d^3 - 0.0757d^2 + 0.312d + 0.5 \quad \dots\dots\dots(4)$$

Equation 5 combines the sonic equation with the porosity and compaction terms.

$$\delta_{ARS} = \frac{K_1(1-\phi^{18})f}{(\Delta t_c - 40)^{K_2}} \dots\dots\dots(5)$$

Discussion and Results

Correlating Sonic Logs to the ARSL

The non-linear constants for Equation 5 were determined by separating the well data in different sections. The individual well data sets and the data sets of all ten wells combined were used to determine the regression constants by:

1. All lithology without any separation
2. Lithology separated by pure sandstone and shale
3. Separation by Formation

The results of the regression constants clearly show a trend between the sandstone and shale. The upper limits of the regression constants relate to the pure shale, the lower limits are related to the sandstone and the regression constants without any separation of lithology lie between the sandstone and shale regression constants.

The developed equation was statistically compared to by the additions of the porosity term and the compaction term. The P-values for all methods were found to be less than 0.0001 which indicates a good fit with Optimizer ARS. The Mean Square Error (MSE) for the different methods of the equation were found to decrease with the addition of the porosity and compaction term; therefore, the final developed equation provides more accurate results for ARS predictions.

Comparison of UCS Correlations for Sandstone, Shale and All Lithology Constants.

The sandstone, shale, and all lithology constants are used in the developed equation to calculate the ARS. The correlations are compared in Figure 4 using the data set of Well # F without any separation of lithology. The shale correlation produces the highest ARS predictions. The sandstone and all lithology constants produce similar predictions, with the "all lithology" values producing slightly higher values. Sandstone contains a lower minimum value of sonic travel time and the maximum range for ARS is similar for both sandstone and shale. The regression constants will therefore produce a higher value of ARS for the same values of sonic compressional time for sandstone.

Correlating Logs to the ARSL by Formations

During drilling operations, formations exhibit similar traits. Comparable traits between log predictions and the Optimizer ARS are expected for the correlations of ARSL when separated by formations. The regression constants for "all lithology" were used to predict the ARS and compared to the ARS from the Optimizer using drilling field data. Also, a separate correlation was developed using the constants for sandstone, shale, and all lithologies. For data points greater than 90% sandstone and 90% shale lithologies, their respective constants were used to calculate rock strength. For the remainder of the data points which are part mixtures, the all lithology constants were used.

Belly River, Mannville, Falher and Gething

Figures 5 to 8 show a good match between the predicted ARS from logs to the Optimizer ARS from field drilling data. Since these formations are primarily part-mixtures of sandstone and shale, the correlation using the all lithology constants and the combination of constants is almost an identical match to each other.

Lea Park and Colorado

These formations are composed mainly of shale with traces of coal. The predicted ARS using log data have a good fit with the ARS using the field data as shown in Figures 9 and 10. The ARS predictions using the all lithology constants produce slightly better predictions than the values using the combination of constants. These are pure shale sections so the constants for shale were used to calculate the ARS values for the "combo" correlation. As discussed earlier, use of the shale constants were found to produce higher ARS values and in these cases over-predicted the rock strength as shown in the highlighted zones of Figures 9 and 10.

Poor Correlations of Logs to the ARSL by Formations

The ARS is dependent upon many different factors from drilling inputs (WOB, RPM, Flow Rates, etc.) and outputs (Bit Wear, ROP, etc.) to the drilling crew itself. If the log data has not been quality controlled, it should also be noted that logs (sonic and neutron) may be affected in specific areas by various factors such as formation fluids that may influence the data and override the variations caused by rock strength. In this study there existed formations in the analyzed 10 wells where the predicted sonic strengths varied considerably from the Optimizer ARS. Also isolated areas in various wells produced discrepancies between the two strength logs. Below we will analyze and explain the deviations encountered.

Cardium

The Cardium Formation consists of marine siltstone, sandstone, chert and conglomerate. The predicted ARS values from log data are not in close agreement with the Optimizer ARS values from field drilling data as shown in Figures 11. The caliper logs for Well # B shown in Figure 12 indicate an over-gauged hole which is a sign that excessive down-hole vibration occurred during the drilling. This is common due to the unique hardness of the formation. The Optimizer cannot account for severe drilling problems such as down-hole and stick-slip vibrations and will therefore produce inaccurate values for the ARS.

Kaskapau

The Kaskapau formation is marine shale layered with clay. Figure 13 shows a large deviation between the predicted ARS from logs and the Optimizer ARS from field drilling data. The discrepancy between the rock strengths is due to a combination of reasons:

1. Depth uncertainties for the weighting-up of mud
2. Sonic log readings affected by formation gas
3. Clearance of bottom-hole-assembly (BHA) from over-gauged hole due to down-hole and stick-slip vibrations.

The Kaskapau formation is an area known to contain formation gas. During this formation the drilling mud is

weighted-up. The exact location of where the mud is weighted-up is not known and an average location and mud weight is used for the input data. The calculation of the ARSL from the Optimizer is dependent on these values and the imprecision of the input data will provide inaccurate values of the ARS.

The next problem is related to the sonic log readings and the effect gas has on the values. The formation gas produces a “gas effect” on the sonic, density, and neutron porosity logs corrupting the readings.

The final problem with the Kaskapau formation is due to the over-gauged hole created in the Cardium formation. The ARS results will remain inconsistent until the BHA clears the over-gauged hole drilled from the Cardium formation.

Comparison of Developed Equation to Onyia’s Equation

Figure 14 shows the sonic compressional travel time versus the Optimizer ARS from the field drilling data. Also plotted on the figure is the predicted ARS from well logs using Onyia’s equation and the developed equation using the all lithology constants. Onyia’s and the developed equation correlations produce similar trends with each other and to the Optimizer ARS. The developed equation covers a larger portion of the Optimizer ARS and this is mainly due to the addition of the compaction and porosity terms. Figure 15 shows a very good fit between the comparison of Onyia’s equation and the developed equation using data from Well # 1.

Recommended field usage

Results in this study⁷ are in strict sense only valid for the Alberta fields studied (Wild River, Cecilia, Berland River and Obed). Other fields with similar lithology (sandstone, shale, and coal) should be analyzed using the same process to compare results. However the good agreement between the Onyia model and these data indicates that they can be used over a larger geographical area. The results indicate the “All Lith” constants for equation 5 is the best choice when predicting ARS from log data. However, when fields of different lithology are encountered they should be studied and new regression constants should be developed using the same process as described above. We recommend to use gamma ray values to separate the sandstone, shale, and part-mixture lithologies when determining the “f” term. A further improvement in this process is to correct the sonic and neutron logs for formation gas. For formations that regularly encounter difficulties while drilling such as Cardium and Kaskapu it is recommended to use the ARS from drilling data.

Conclusions

Based on the results of this study, the following conclusions can be made from the prediction of ARS from sonic log data:

1. Predicted ARS from sonic logs correlate well with ARS derived from the Optimizer for different lithology types.
2. Correlations developed by separating homogeneous lithology types showed minimal improvements in the accuracy of ARS predictions. The pure shale correlations produced

slightly less accurate results than the sandstone and “all lithology” correlations.

3. The predictive ARS compared by formations agreed well to ARS developed by the Optimizer for each formation.

4. Predictions of ARS from sonic logs are not affected by changes to drilling operational parameters or problems encountered while drilling

5. The developed equation produced similar results to Onyia’s correlation. This confirms that these correlations can be used in wider geographically areas.

Nomenclature

d	=Depth (km)
f	=Shale/sand porosity ratio (dimensionless)
GR_{log}	=Gamma Ray value from logs (API)
K_1, K_2	=Regression Constants (dimensionless)
V_{sh}	=Shale fraction (fraction)
δ_{ult}	=Unconfined Compressive Strength (psi)
δ_{ARS}	=Apparent Rock Strength (psi)
$\delta_{ARS-max}$	=Maximum Apparent Rock Strength (psi)
Δt_c	=Sonic Compressional Travel Time (μsec/ft)
ϕ_N	=Neutron Porosity (fraction)
$\phi_{N-Shale}$	=Shale Neutron Porosity (fraction)
ϕ_{N-SS}	=Sandstone Neutron Porosity (fraction)
ρ	=Bulk Density (gm/cc)
ρ_{corr}	=Corrected Bulk Density (gm/cc)
ρ_{log}	=Bulk Density from logs (gm/cc)
ρ_{sh}	=Pure Shale Density (gm/cc)

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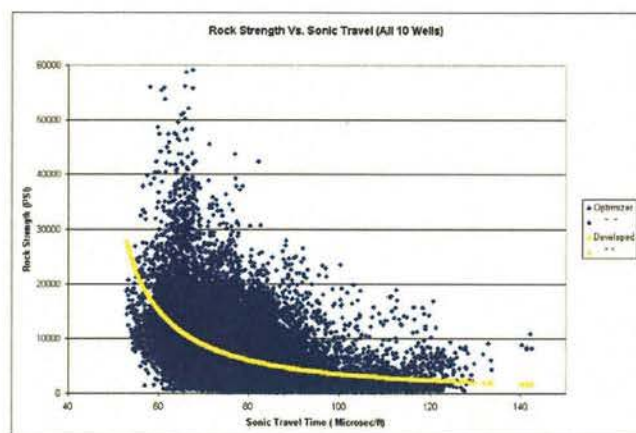


Figure 1. ARS versus the sonic travel time to determine the trend of the data.

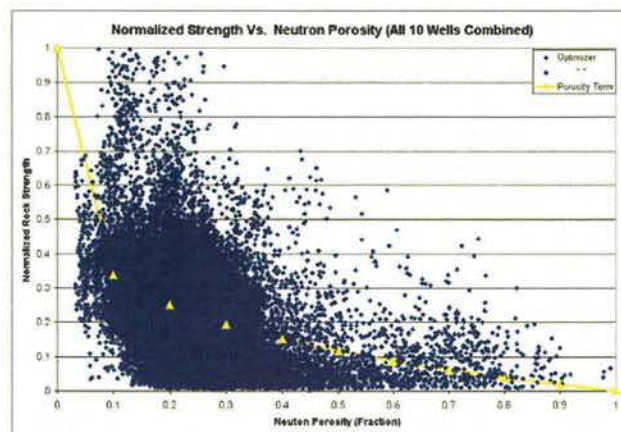


Figure 2. Normalized rock strength versus neutron porosity to determine best fit porosity equation.

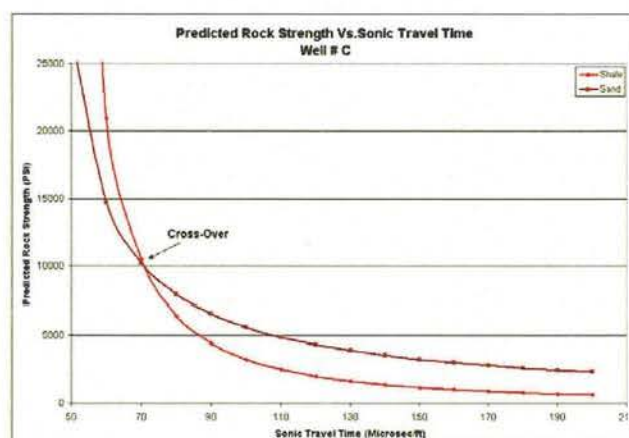


Figure 3. Predicted rock strength versus sonic travel time.

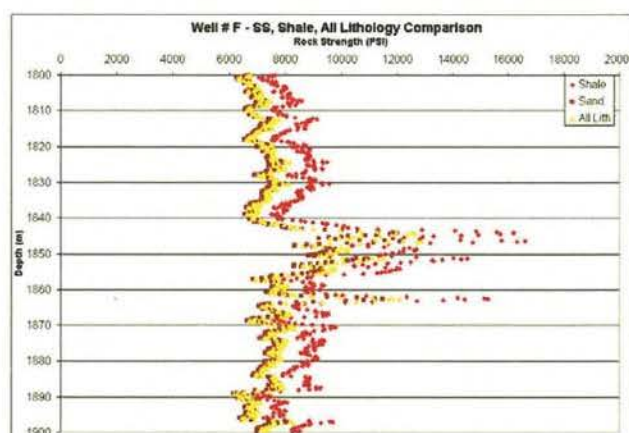


Figure 4. Comparison of sand, shale and all lithology regression constants using well data from Well # F.

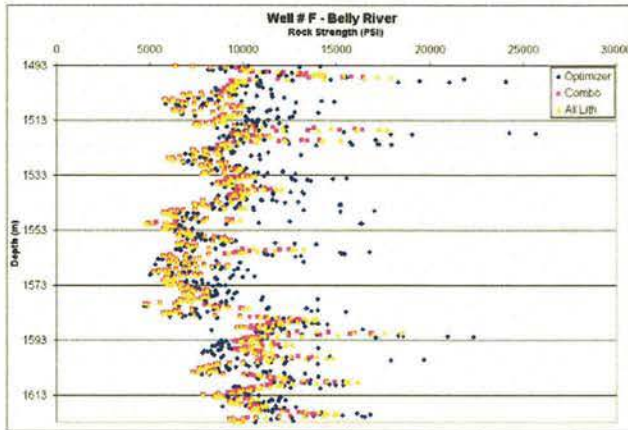


Figure 5. Well # F ARS values for the Belly River Formation.

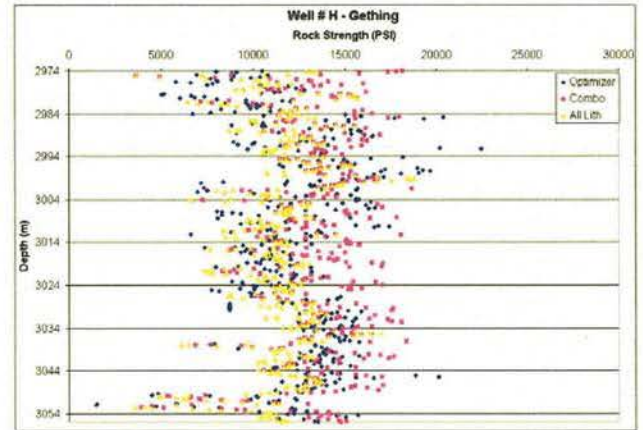


Figure 8. Well # H ARS values for the Gething Formation.

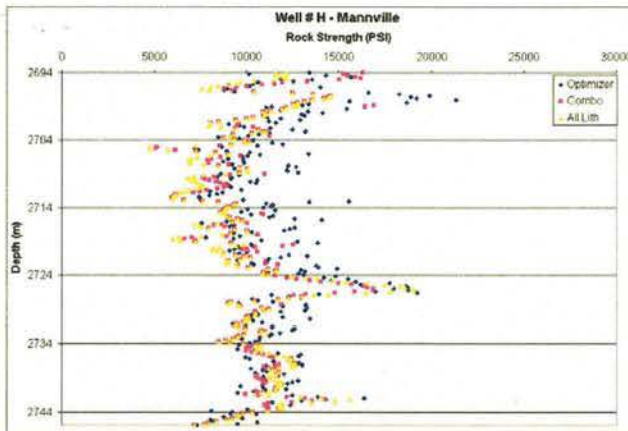


Figure 6. Well # H ARS values for the Mannville Formation.

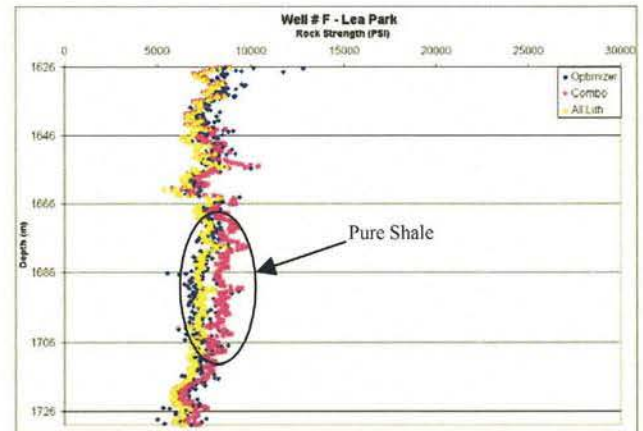


Figure 9. Well # F ARS values for the Lea Park Formation.

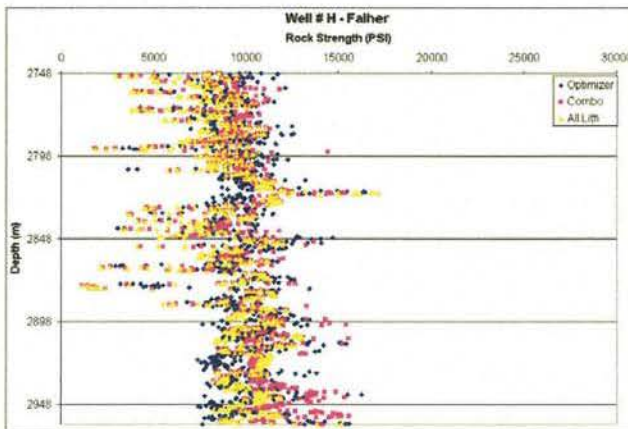


Figure 7. Well # H ARS values for the Falher Formation.

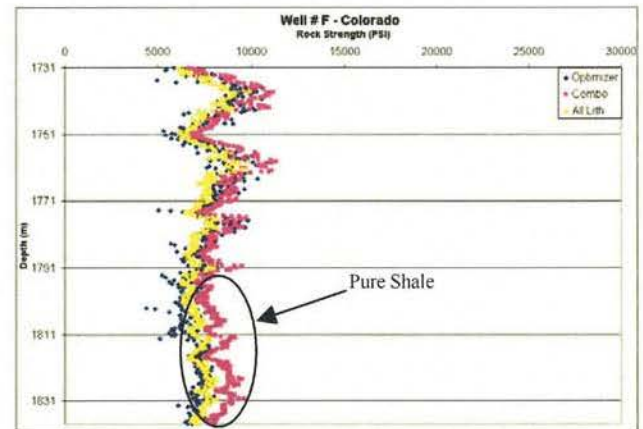


Figure 10. Well # F ARS values for the Colorado Formation.

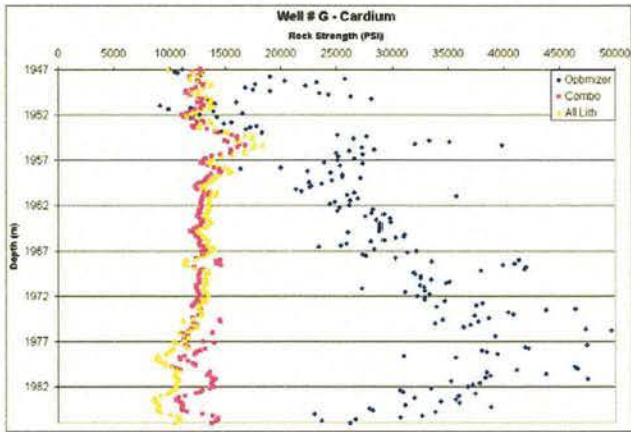


Figure 11. Well # G ARS values for the Cardium Formation.

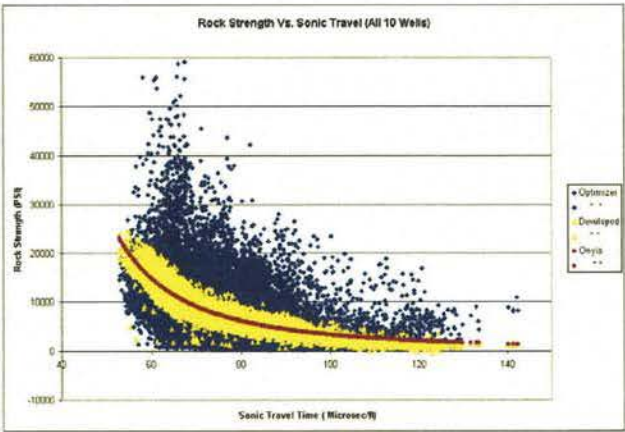


Figure 14. Comparing Onyia's results with the predicted and simulator strengths by sonic travel time for all wells.

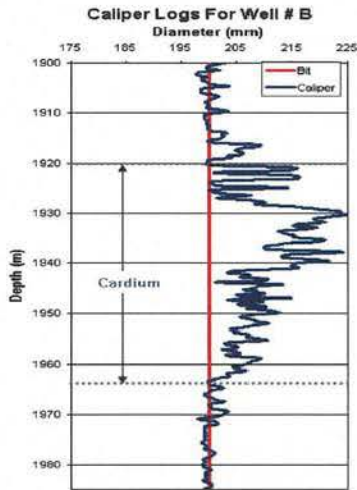


Figure 12. Caliper log reading of Cardium formation for Well # B.

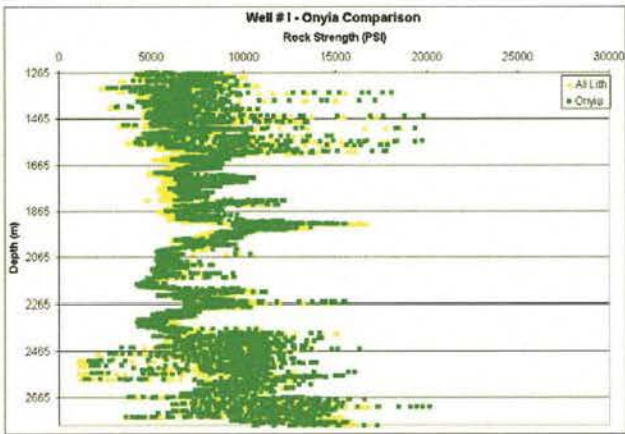


Figure 15. Well # I comparing Onyia's results with the predicted and simulator strengths.

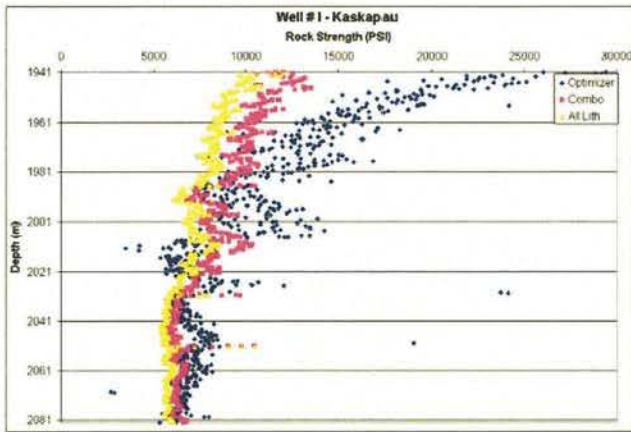


Figure 13. Well # I ARS values for the Kaskapau Formation.