# Geomechanical Index Log from Drilling Data for Selective Stimulation and Engineered Completion

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## Summary

Rock mechanical and reservoir property logs play an important role in selecting perforating intervals to optimize a stimulation treatment and maximize production. Studies have shown that the initial gas flow back rates from wells stimulated by engineered completions were 33% to 40% higher than nonengineered or geometrically completed wells (Ajayi et al, 2013). Since the majority of unconventional wells are never logged, the wells are perforated without this critical reservoir information. It is now possible to have a detailed rock mechanical and reservoir property log available for any unconventional reservoir, at a fraction of the cost of running downhole logging tools.

This paper will discuss how D-Series logging technology uses routinely collected surface drilling data to generate a convenient geomechanical index log without the use of expensive downhole tools. Conventional logging techniques involve core analysis and well logs using sonic and resistivity imaging tools. In this study, the drilling data from two horizontal sample wells were used to calculate the geomechanical properties as well as rock brittleness and a fracability index for the Montney shale and the lower Eagle Ford formation in North America.

## Theory / Method / Workflow

D-Series technology is a user-friendly logging software consisting of two standalone modules, D-WOB and D-ROCK as shown in Figure 1. The D-WOB module uses a wellbore friction model to estimate coefficient of friction and downhole weight on bit (DWOB) from the surface measurements of applied weight on the bit, hookload, RPM along with the directional survey data and detailed drill string information. The 3D wellbore friction model (T&D model) was developed by dividing the entire length of the drillstring into many small elements (like FEA) to obtain more accurate analytical results from the extended reach (ER) directional drilling (Aadnoy et al., 2010 and Fazaelizadeh et al., 2010). The estimated DWOB is an input to the D-ROCK module that uses an inverted rate of penetration (ROP) model along with other drilling data, drill bit specifications and reservoir specific formation constants, to calculate rock mechanical and reservoir properties. The ROP models for PDC (Polycrystalline diamond compact) and Rollercone drill bits were developed considering the effects of bit wear, bit hydraulics and drill bit cutting structure (Hareland et al, 2010 and Wu et al, 2010). The D-ROCK module uses inverted ROP model to calculate confined compressive strength (CCS) from available drilling data and estimates corresponding unconfined compressive strength (UCS) and Young's modulus (E) using the correlations between CCS, UCS and E (Kerkar et al, 2014 and Tahmeen et al, 2015).

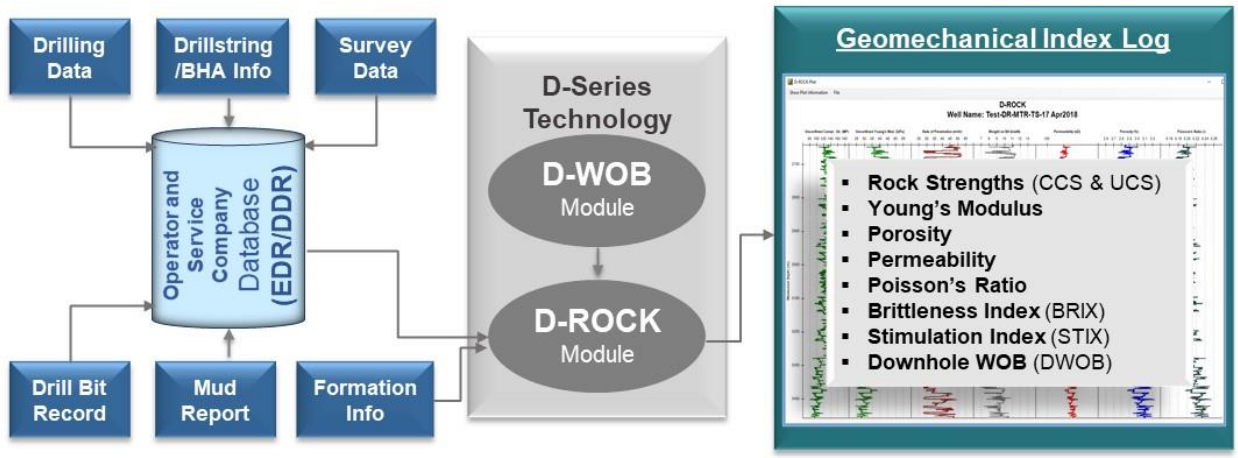


Figure 1 System overview of D-Series technology

The empirical models of porosity, permeability and Poisson's ratio were developed and integrated into D-ROCK to generate a detail geomechanical log from drilling data (Cedola et al, 2017 and Tahmeen et al, 2017). Effective fracking index, STIX was developed to obtain a more useful geomechanical log from D-ROCK for selective stimulation design and engineered completion in an unconventional reservoir (Tahmeen et al, 2019). The STIX was defined as a function of rock brittleness concept (ratio of Young's modulus, E and Poisson's ratio, $\nu$), UCS, porosity ($\phi$) and permeability (K) as below:

$$STIX = \frac{E}{\nu} \times UCS^{-a_X} \times \emptyset^{b_X} \times K^{c_X} \tag{1}$$

The coefficients $a_X$, $b_X$ and $c_X$ should be calibrated based on the geomechanical analysis for the specific reservoir formation. Different operators might use these coefficients with different goals for the different formations in terms of looking to stimulate stiffer/brittle rock or higher permeability/porosity zones. Rock brittleness is an important reservoir property to characterize unconventional shale reservoirs for optimal stimulation design. The Young's modulus and Poisson's ratio cross-plot is a widely used rock brittleness indicator in the oil and gas industry. The higher Young's modulus and the lower Poisson's ratio indicate that the rock is more brittle, while the higher Poisson's ratio and the lower Young's modulus indicate the rock is less brittle. D-ROCK uses a well-known brittleness definition (Eq. 2, Eq. 3, and Eq. 4) and estimates the brittleness index (BRIX) using the calculated geomechanical properties (Tahmeen et al, 2020). The value of BRIX varies between 0% and 100%. A higher percentage of BRIX is an indication of more brittle formation rock.

$$E_{Brit} = \left(\frac{E - E_{min}}{E_{max} - E_{min}}\right) \times 100 \tag{2}$$

$$\nu_{Brit} = \left(\frac{\nu - \nu_{max}}{\nu_{min} - \nu_{max}}\right) \times 100 \tag{3}$$

$$BRIX = \frac{E_{Brit} + \nu_{Brit}}{2} \tag{4}$$

Here E and $\nu$ are Young's modulus and Poisson's ratio respectively, calculated from the drilling data using the D-ROCK module. $E_{min}$ and $E_{max}$ are standard minimum and maximum values of Young's modulus, whereas $\nu_{min}$ and $\nu_{max}$ are standard minimum and maximum Poisson's ratios in the unconventional shale reservoir.

The units of geomechanical properties are quite different from one another and therefore the previous STIX model (Eq. 1) needed to be normalized. In addition, the ratio of Young's Modulus and Poisson's Ratio ($E/\nu$) of the previous STIX model was replaced by the calculated brittleness index (BRIX). The reservoir specific coefficients (i.e., ax, bx and cx) are not required to define the new stimulation index as shown below:

$$STIX = \frac{f(UCS) + f(BRIX) + f(\phi) + f(K_P)}{4} \tag{5}$$

$$f(UCS) = \left(\frac{UCS - UCS_{max}}{UCS_{min} - UCS_{max}}\right),\ f(BRIX) = \left(\frac{BRIX - BRIX_{max}}{BRIX_{min} - BRIX_{max}}\right),\ f(\phi) = \left(\frac{\phi - \phi_{min}}{\phi_{max} - \phi_{min}}\right)$$

$$f(\phi) = \left(\frac{K - K_{min}}{K_{max} - K_{min}}\right)$$

The STIX is normalized to define its values between 0 and 1. The higher value indicates potential sweet spots in formation. The minimum and maximum values of the geomechanical properties (UCS, BRIX, porosity and permeability) might vary for different formations in terms of looking to stimulate stiffer/brittle rock or higher permeability/porosity zones. The unique potential use of these values is that they could be available in published articles and can be optimized for each individual reservoir in terms of net present value (NPV).

## Results, Observations, Conclusions

In this article, the drilling data from two horizontal sample wells, Well A in the Montney shale formation and Well C in the lower Eagle Ford formation were used to investigate a detailed geomechanical index log. The calculated rock mechanical and reservoir properties including confined & unconfined compressive strengths (CCS & UCS), Young's modulus, porosity, permeability and Poisson's ratio, are summarized in the table in Figure 2. For the selected drilled depth from 2650m to 3450m in the lateral section of the wall A, the coefficient of friction was estimated between 0.08 to 0.17. In this study, the average unconfined compressive strength (UCS) and Young's modulus for the Montney formation (Well A) were observed at 123.24 MPa and 36.7 GPa, respectively. While performing a similar calculation for Well C in the lower Eagle Ford formation, the UCS was found in ranges between 53.2 MPa and 129.8 MPa with an average of 72.2 MPa. The Young's modulus was found in ranges between 16.1 GPa and 41.8 GPa with an average of 30.4 GPa, and permeability between 273.6 nD and 1247.4 nD, respectively. In addition, the average porosity was estimated at 6.4% and the Poisson ratio was in the range of

0.221 to 0.356 with an average of 0.278. The calculated geomechanical properties are consistent and in good agreement with the reported test analysis investigated by other researchers, as shown in the table in Figure 2.

| Shale Formation | Study Wells and Published Reference | UCS (MPa) | Young's Modulus (GPa) | Permeability (nD) | Porosity (%) | Poisson's Ratio (-) |
|---|---|---|---|---|---|---|
| Montney | **Well A** (D-Series) | 87.9 – 158.8 Avg. 123.24 | 26.4 – 52.8 Avg. 36.7 | 167.8 – 230.9 Avg. 199.7 | 2.67 – 3.22 Avg. 2.92 | 0.158 – 0.254 Avg. 0.204 |
| | Published Reference | 117 -136 (Davey, 2012) | 35 - 55 (Duenas, 2014) | Avg. 130 (Duenas, 2014) | 2 - 5 (Duenas, 2014) | 0.09 – 0.28 (Vishkai, 2017) |
| Lower Eagle Ford | **Well C** (D-Series) | 53.2 – 129.8 Avg. 72.2 | 20.7 – 41.8 Avg. 30.4 | 273.6 – 1247.4 Avg. 729.8 | 4.26 – 9.29 Avg. 6.4 | 0.214 – 0.347 Avg. 0.278 |
| | Published Reference | Avg. 86.2 (Hu, 2014) | 25 - 34 (Sone, 2012) | 300 -1100 (Walls, 2011) | Avg. 6.9 (Walls, 2011) | 0.2 - 0.45 (Alidi, 2017) |

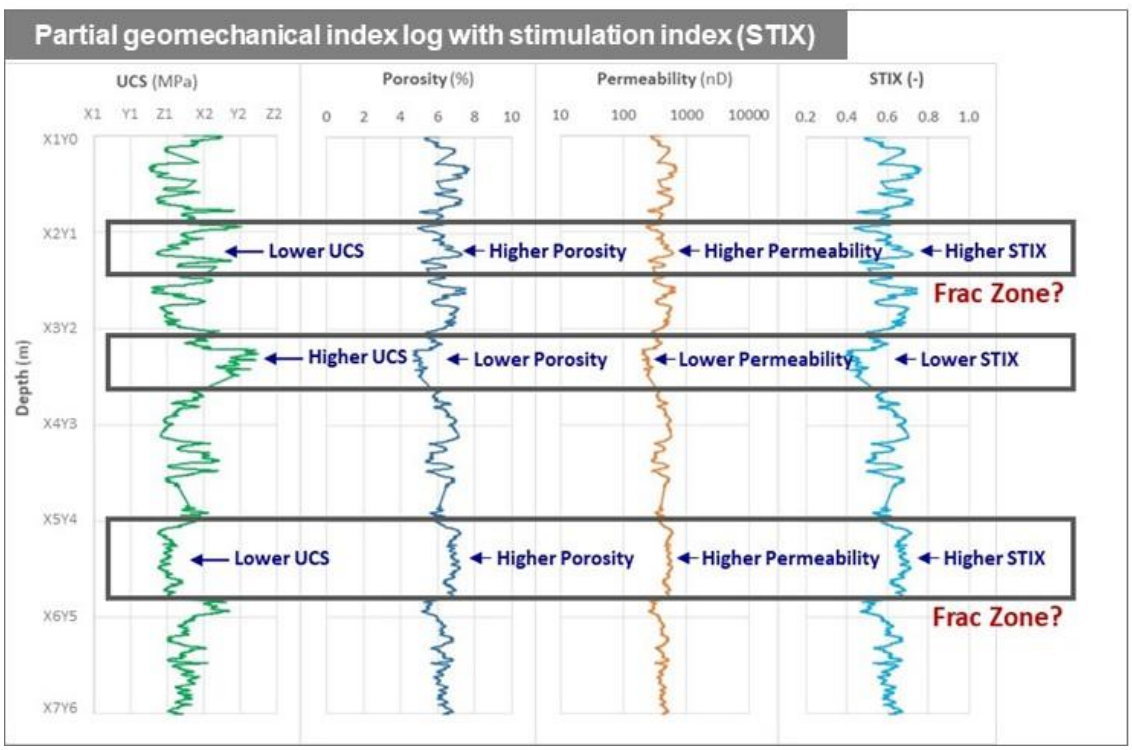


Figure 2 Summary results and geomechanical index log (partial) with STIX

The graphical representation of the normalized STIX profile along with the corresponding UCS, porosity and permeability profiles from the D-ROCK platform for a sample depth interval (Well C) is shown in Figure 2. The potential stimulation locations for the selective engineered completion should be the depth intervals with higher STIX and lower UCS in addition to higher porosity and permeability zones determined from D-ROCK. The zone with low STIX, high UCS, low porosity and low permeability should be avoided for fracking.

The D-Series technology could be used to potentially evaluate unconventional reservoirs as well as to map sweet spots, perform effective engineered stimulation, and optimize the hydraulic fracturing process for maximizing well productivity from the recognized behavior of geomechanical properties, brittleness index and stimulation index. A detailed geomechanical index log can be available near real-time for all directional wells drilled in unconventional reservoir. There is no risk of trapping expensive logging tools downhole and losing valuable rig time.

## Novel/Additive Information

Unlike the current practice using logs of 1 in 10 or 1 in 20 wells, a complete rock mechanical and reservoir property log can be obtained on every well. Although these studies reveal encouraging results, some disagreements were also observed which may be due to data uncertainty and complexity of data measurements while drilling the extended reach horizontal wells in unconventional reservoirs.

Recent investigations on Marcellus shale formation revealed that engineered completions were more effective than nonengineered completions as shown in Figure 3 (Ajayi et al., 2013).

**Design Summary**

| Well | Completion Method | Fluid | Lateral Length, ft | Stages | Average Stage Length, ft | Perforation Clusters per Stage | Design Proppant per Lateral, lbm/ft | Design Pumping Rate, bbl/min |
|---|---|---|---|---|---|---|---|---|
| Well 1 | Nonengineered | Slickwater | 3,375 | 14 | 241 | 5 | 1,670 | 80 |
| Well 2 | Nonengineered | Slickwater | 2,312 | 7 | 330 | 5 | 1,220 | 80 |
| Well 3 | Nonengineered | Slickwater | 2,140 | 7 | 306 | 5 | 1,320 | 80 |
| | Average | | 2,609 | 9.3 | 292 | 5 | 1,400 | 80 |
| Well 4 | Engineered | Slickwater | 4,500 | 12 | 375 | 5 | 1,080 | 80 |
| Well 5 | Engineered | Slickwater | 3,950 | 12 | 329 | 4.5 | 1,230 | 80 |
| Well 6 | Engineered | Slickwater | 3,925 | 12 | 327 | 4.5 | 1,240 | 80 |
| | Average | | 4,125 | 12 | 344 | 4.7 | 1,180 | 80 |

(Ajayi et al., 2013)


Figure 3 Nonengineered/geometric and engineered completions summary (Ajayi et al, 2013)

In the “Design Summary” table of Figure 3, Well 1, Well 2, Well 3 were completed using a geometric or nonengineered stimulation design and Well 4, Well 5, Well 6 were completed using engineered stimulation design. The bottom chart is a modified representation indicating a more effective completions summary of the last three wells with selective stimulation design and engineered completion methods that measured average 5.7% lower treating pressures, 10.3% higher pumping rates and 106% higher 30-day cumulative productions per lateral length.

Selectively fracturing the horizontal well, versus a geometric even spacing, could improve proppant placement, reduce break down pressures and increase production.

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