Using Horizontal Well Drilling Data To Predict Key Rock Properties For Unconventional Wells In Canada And Optimize Hydraulic Fracturing Design

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Key Message

- Routinely acquired drilling data can compute formation un/confined compressive strength and Young's modulus.

- This presentation shows motivation behind the workflow and its application to understand lateral heterogeneity in Groundbirch Montney lobes.

- Workflow performs wellbore friction analysis to estimate downhole weight-on-bit and couples it with ROP models developed for PDC/Rollercone bits.

- Young's modulus/UCS signatures can be used in correlation with fracture gradient to engineer placement of perforation clusters along the lateral in the hydraulic stimulation design.

Technology Enablers

Challenges

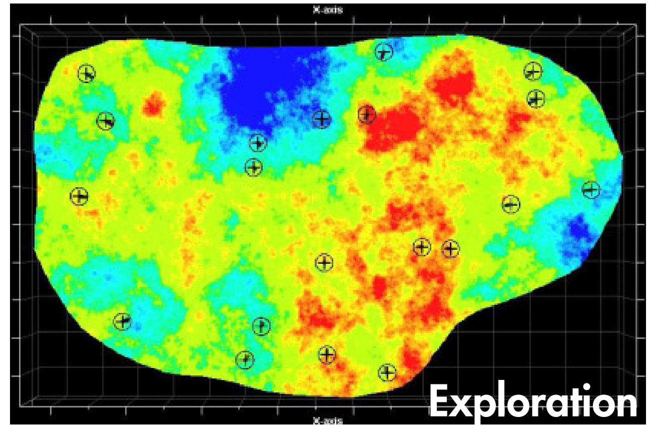
- Layers of rock with variable strength and toughness
- No direct estimation of Rock Young's modulus which controls fracture growth
- Wirline logs are acquired on a few wells
- Log require rig time and significant processing
- Extrapolation from sonic logs across plays introduces uncertainty

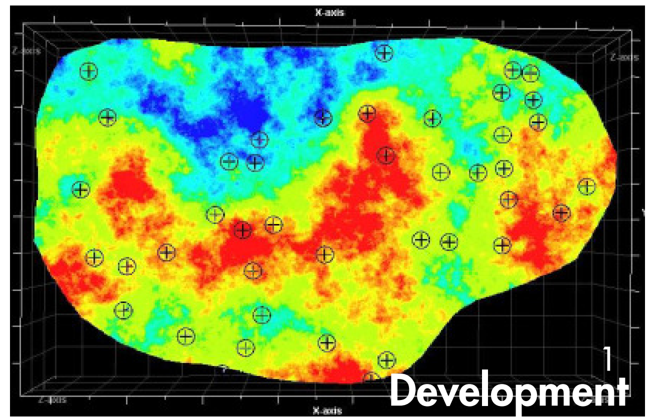
Solution

- Estimation of rock strength using drilling data could avail UCS and YM logs on every well drilled
- Depth- and time- based drilling data is acquired on every well
- Results can be calculated in real time
- Saves waiting on post-drilling wireline logging

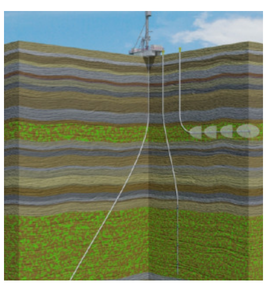
Business Impact

- Better well planning
- Better completion design
- Rock strength logs could be available on every well drilled from exploration to production.

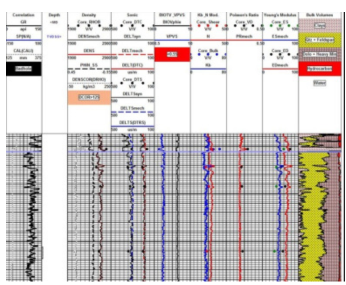




WELL DESIGN

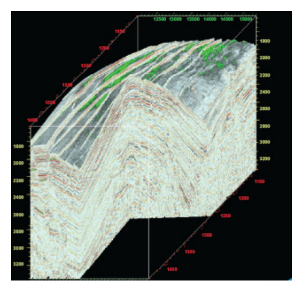


UCS, YM LOGS



FRACTURE PREDICTION

SEISMIC EVALUATION



REAL TIME OPTIMIZATION

1. Figure adapted from: Eshkalak, M.O.et al., Paper SPE 163690-MS, 2013 as an example of synthetic geomechanical logs.

Methodology (1/3)

1. Sheave HL, HL-wt of hook, HL after SPP → **2. Wellbore friction coefficient (μ), Calculated HL** → **3. Downhole Weight on Bit (DWOB)**

$$SheaveHL = \frac{HL_{obs}}{n_{lines}}.\frac{1-e^{n_{lines}}}{1-e}...(\downarrow)$$

$$SheaveHL = \frac{HL_{obs}}{n_{lines}}.\frac{e.\left(1-\frac{1}{e^{n_{lines}}}\right)}{e-1}...(\uparrow)$$

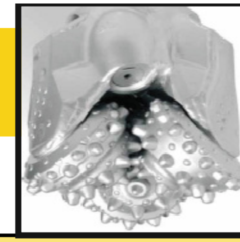
- e = individual sheave efficiency
- n_{lines} = no. of lines between blocks
- ↓ = when lowering the blocks
- ↑ = when raising the blocks

$$F_{top} = \beta w \Delta L\left(\cos\alpha \quad or \quad \frac{\sin\alpha_{top}-\sin\alpha_{bottom}}{\alpha_{top}-\alpha_{bottom}}\right) - \mu\times\beta w\Delta L\left(\sin\alpha \quad or \quad \frac{\cos\alpha_{top}-\cos\alpha_{bottom}}{\alpha_{top}-\alpha_{bottom}}\right)$$
$$+\left(F_{bottom}-DWOB \quad or \quad [F_{bottom}-DWOB]\times e^{-\mu|\theta|}\right)...(no\ bending)$$

$$F_{top} = \beta w \Delta L\left(\cos\alpha \quad or \quad \frac{\sin\alpha_{top}-\sin\alpha_{bottom}}{\alpha_{top}-\alpha_{bottom}}\right) - \mu\times\beta w\Delta L\left(\sin\alpha \quad or \quad \frac{\cos\alpha_{top}-\cos\alpha_{bottom}}{\alpha_{top}-\alpha_{bottom}}\right)$$
$$+\left(F_{bottom} \quad or \quad F_{bottom}\times e^{-\mu|\theta|}\right)...(bending)$$

- F_{top} = tension on the top of each drill string element
- F_{bottom} = tension on bottom of each drill string
- β = buoyancy factor
- w = unit pipe weight
- ΔL = length of each drill string
- α = inclination angle
- μ = wellbore friction coefficient

Methodology (2/3)



4. Sliding correction to DWOB, Relative abrasiveness constant calculation

5. ROP Models for a PDC drill bit

6. ROP Model for a Rollercone drill bit

$If\ RPM > 14, no\ correction\ in\ WOB$

$If\ RPM < 14, WOB\text{ - }slide = constant\ x\ \Delta p$

$$where,\ constant = \frac{\left(\frac{WOB}{\Delta p}\right)_{i-2} + \left(\frac{WOB}{\Delta p}\right)_{i-3} + \left(\frac{WOB}{\Delta p}\right)_{i-4}}{3}$$

	Sp. Gravity	Abrasiveness	GR (API)
Sand	2.6	1	10-30
Silt	2.67-2.7	0.85	50-70
Conglomite	2.4-2.9	0.71	10-140
Dolomite	2.84-2.86	0.65	<30
Limestone	2.7	0.57	<20
Shale	2.4-2.8	0.11	80-300
Coal, bituminus	1.35	0.1	20

$$ROP = \left[\frac{K_1.WOB^{a_1}.RPM^{b_1}.\cos(SR)}{CCS^{c_1}.D_B.\tan(BR)}\right] W_f.h(x).b(x)$$

$$W_f = 1 - a_3\left(\frac{\Delta BG}{8}\right)^{b3} \qquad \Delta BG = Ca\sum_{i=2}^{n} WOB_i.RPM_i.CCS_i.ABR_i$$

$$h(x) = a_2 \cdot \frac{(HSI \cdot \frac{JSA}{2 \cdot D_B})^{b_2}}{ROP^{c_2}} \qquad HSI = \frac{HHP}{A_B} = \frac{[Q.P_B/1714]}{[(\pi/4)D_B^2]}$$

$$b(x) = \frac{RPM^{(1.02 - N_b x0.02)}}{RPM^{0.92}}$$

$$ROP = \left[K_1 \frac{80.n_t.m.RPM^{a1}}{D_B^2.\tan^2\Psi}\left(\frac{WOB}{100.n_t.CCS}\right)^{b1}\right] W_f.h(x)$$

$$W_f = 1 - a_3\left(\frac{\Delta BG}{8}\right)^{b3} \qquad \Delta BG = Ca\sum_{i=2}^{n} WOB_i.RPM_i.CCS_i.ABR_i$$

Δp = differential pressure
RPM = surface RPM
WOB = weight on bit
RPM = top-drive / surface RPM
SR = PDC cutter side rake angle
CCS = confined compressive strength
D_B = diameter of bit
BR = PDC cutter back rake angle
W_f = bit wear function
h(x) = hydraulic efficiency function
b(x) = N_b effect function

N_b = number of blades
ΔBG = cumulative bit wear
Ca = bit wear coefficient
ABR = abrasiveness constant
HSI = horsepower per sq. inch
JSA = junk slot area
HHP = hydraulic horsepower
Q = pump flow rate
P_B = bit pressure drop
A_B = bit face area

n_t = avg. no. of inserts contacting rock
m = no. of inserts penetrations per revolution
Ψ = chip formation angle
$K_1, a_1, b_1, c_1, a_2, b_2, c_2, a_3, b_3$ – empirical constants

Methodology (3/3)

7. CCS to UCS, and Young's modulus calculation

$$UCS = \frac{CCS}{1 + a_s . Pc^{b_s}}$$

$$Ec = CCS.a_E.(1 + Pc)b_E$$

Pc = confining pressure
UCS = unconfined compressive strength
CCS = confined compressive strength
Ec = Young's modulus
a_s,b_s,aE,bE - empirical constants from laboratory triaxial test data for development TOPS

Input Data Compilation (1/4)

1. Sheave HL, HL - wt of hook, HL after SPP

2. Wellbore friction coefficient (µ), Calculated HL

3. Downhole Weight on Bit (DWOB)

Drill string data

- Depth in, Depth out
- Pipe ID, OD
- Nominal weight
- Length

Rig/mud motor data

- Wt of hook / top drive
- No. of lines, sheave ?
- Depth-in, -out, Mud motor const.

Survey data

- MD
- Inclination
- Angle

Depth based data

- MD, ROP, WOB, RPM
- HL, Pump vol., ?P
- SPP/Pump P, MWD Gamma

Time based data

- Bit depth, Depth
- HL, WOB, RPM
- Pump vol. / Flow in
- SPP/Pump P, ROP

Bit Operations

MD (m)	WOB Min/Max (kdaN)	Current RPM (rpm)	Flow rate (m^3/min)	SPP (kPa)	P bit (kPa)	% @ Bit	HHP (kW)	Hours (hr)	Footage (m)	ROP (m/hr)	Hours cum (hr)	Footage cum. (m)	ROP cum. (m/hr)
240.00	3.00/13.00	120	3.0000	7,200.00	1,621.27	22.52	81.096	5.00	240.00	48.00	5.00	240.00	48.00

Drillstring Details

Date/Time in	Date/Time out	BHA no.	BHA Length (m)	Min. ID (mm)	Purpose
1/4/2011 15:00	1/5/2011 23:30	1	240.000	311.00	drill surface hole

MD (m)	SW Up (kdaN)	SW Down (kdaN)	SW Rotn (kdaN)	Drag (kdaN)	Tq On Btm (N-m)	Tq Off Btm (N-m)	Footage (m)
240.00	46.00	45.00	45.00	1.00	8,134.9	4,203.0	240.00

Drillstring Components

Component type	# Jts	Length (m)	OD (mm)	Max OD (mm)	ID (mm)	Connection Name	Weight (kg/m)	Grade	Serial no.
Heavy Weight Drill Pipe	12	110.770	163.00		108.00		0.00	0	
Crossover	1	0.420	165.00		75.00		0.00	0	NX0028
Drill Collar	9	80.570	166.00		74.00		0.00	0	
Crossover	1	0.790	205.00		70.00		0.00	0	NXO1682
Drill Collar	2	18.620	210.00		73.00		0.00	0	Nabors
Non-Mag Drill Collar	1	9.030	201.00		85.00		0.00	0	DCNM800-12242
Pulser Sub	1	3.250	196.00		71.00		0.00	0	EMS775-18205
MWD Tool	1	5.860	201.00		96.00		0.00	0	TCNM800-480
Crossover	1	0.600	203.00		83.00		0.00	0	XONM80034277
Bent Housing	1	9.740	272.00		0.00		0.00	0	960-392
Tri-Cone Bit	1	0.350	311.00	311.00	0.00		0.00	0	11629330

Source: Daily Drilling Report/s

Input Data Compilation (2/4)

1. Sheave HL, HL - wt of hook, HL after SPP → **2. Wellbore friction coefficient (μ), Calculated HL** → **3. Downhole Weight on Bit (DWOB)**

Drill string data
- Depth in, Depth out
- Pipe ID, OD
- Nominal weight
- Length

Rig/mud motor data
- Wt of hook / top drive
- No. of lines, sheave ?
- Depth-in, -out, Mud motor const.

Survey data
- MD
- Inclination
- Angle

Depth based data
- MD, ROP, WOB, RPM
- HL, Pump vol., ?P
- SPP/Pump P, MWD Gamma

Time based data
- Bit depth, Depth
- HL, WOB, RPM
- Pump vol. / Flow in
- SPP/Pump P, ROP

Well detail Information

Reports | Instrumentation | Documents | Downloads | Office Based

Rig detail Information

Well Name:	SHELL HZ SUNSET B6-16-79-18W6	**Field:**	SUNSET
Operator:	SHELL CANADA UPSTREAM	**State/Province:**	British Columbia
Contractor:	NABORS CANADA	**Country:**	CANADA
Rig:	C0085	**Well ID:**	C6059
Company Man Name:	MARCEL ST LOUIS/ MYRON STENE	**Unique Well ID:**	N/A
Company Man Phone:	4036509066	**Location:**	6-16-079-18 W6M
Tool Pusher:	MIKE COMBDEN/BLAIN WAYLAND	**Contract Type:**	DAY WORK
Tool Pusher's Number:	7807174653	**License Number:**	26215
Spud:	03-Aug-2010	**Depth:**	4490
Day Number:	21	**24 Hour Depth:**	N/A
Estimated Days Remaining:	0	**Days Ahead/Behind:**	0 ON SCHEDULE
Proposed Depth:	4484	**Latest Activity:**	PRESSURE TEST BOP'S
		Proposed Release Date:	24-Aug-2010 08:00:00 PM
		RigWatch Version:	9.6.0.C-32

RIGWATCH Reports

Date/Time: 25-Aug-2010 07:10:20 AM **Mode:** N/A **Status:** PRESSURE TEST BOP'S

Source: Mywells.com

- Drilling Data
- Directional
- Data Export
- Import Survey Plan
- Import Hookload Theory

Input Data Compilation (3/4)

4. Sliding-DWOB, Relative abrasiveness calculation

5. ROP Models for a Rollercone/PDC drill bit

6. CCS to UCS and Young's modulus calculation

Drill bit data

- Bit no., Type, Dia.
- IADC Code
- Depth in, Depth out
- Wear in, Wear out
- Jet1-8 diameter
- No. & Dia. of cutters
- Back & side rake angle
- Cutter thickness
- Junk slot area
- No. of blades

Laboratorytriaxial data

- Effective confining pressure
- Effective confining strength

Source: Mywells.com

BIT SUMMARY

FROM : 27 Dec 2010 **TO :** 23 Jan 2011

WELL NAME / JOB#: SHELL HZ MONIAS F4-1 / C6631
OPERATOR: SHELL CANADA UPSTREAM
CONTRACTOR: NABORS CANADA
PROVINCE: British Columbia
SPUD DATE: 1/4/2011
RIG NUMBER: C0085

LICENSE NO: 26822
PROJECTED DEPTH: 4081
LOCATION: 4-11-081-21 W6M
FIELD: SUNSET
UNIQUE ID:

BIT#	SIZE	MFGR	TYPE	IADC Code				SL No.	JETS	TFA	DEPTH IN	DEPTH OUT	DISTANCE DRILLED	HOURS	ACCUM HOURS	ROP	DSS	DULL CODE							Reason Pulled
				1	2	3	4											ICS	OCS	MDC	Loc	B/S	Gage	ODC	
1	200.00	SECURITY	QH04RC	4	1	7		1162933 0	14.3 /14.3 /14.3 /23.8	926.70	0.00	613.00	613.00	20.25	20.25	30.27	1	3	7	BT	1	1	1	WT	TD
2	200.00	SECURITY DBS	FX74R	7	1	3		1162881 7	7.1 /7.1 /10.3 /10.3 /10.3 /10.3	0.00	613.00	899.00	286.00	5.25	25.50	54.48	3	2	4	BT	G	X	1	CT	DMF
3	200.00	SECURITY	FMH3753ZR	M	4	2	3	1164150 9	9.5 /9.5 /9.5 /7.9 /7.9 /7.9 /7.9	408.71	899.00	1,175.00	276.00	11.25	36.75	24.53	4	2	4	BT	S	X	0	WT	BHA
4	200.00	SECURITY DBS	FMH3753ZR	M	4	2	3	1164341 9	7.9 /7.9 /7.9 /7.9 /10.3 /10.3 /10.3	446.04	1,175.00	1,863.00	688.00	41.25	78.00	16.68	7	2	3	WT	S	X	0	CT	BHA
5	200.00	REED	R37DH2	5	4	7		AT4915	11.9 /11.9 /11.9	530.14	1,863.00	1,991.00	128.00	28.50	106.50	4.49	8	6	8	LT	G	F	8	WT	PR
6	200.00	REED	RD33DH	5	3	7		NN2600	12.7 /12.7 /12.7	380.03	1,991.00	2,038.00	47.00	8.00	114.50	5.88	10	6	8	LT	A	F	8	CD	PR
7	200.00	HUGHES	GX-38CDX	5	4	7		5178937	12.7 /12.7 /12.7	380.03	2,038.00	2,129.00	91.00	17.00	131.50	5.35	11	3	4	WT	A	E	1	LT	BHA
8	200.00	REED	MSF513M-B 2E	5	1	3		131274	11.1 /11.1 /11.1 /11.1 /11.1 /11.1 /11.1	677.38	2,129.00	3,544.00	1,415.00	57.00	188.50	24.82	15	3	4	WT	N	X	1	BT	TD

Input Data Compilation (4/4)

4. Sliding-DWOB, Relative abrasiveness calculation

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6. CCS to UCS and Young's modulus calculation

Drill bit data

- Bit no., Type, Dia.
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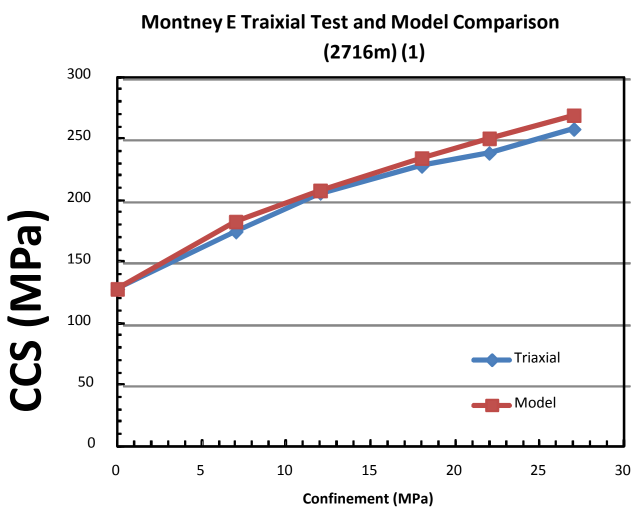
- Wear in, Wear out
- Jet1-8 diameter
- No. & Dia. of cutters
- Back & side rake angle
- Cutter thickness
- Junk slot area
- No. of blades

Laboratorytriaxial data

- Effective confining pressure
- Effective confining strength



MNTN_F	Horizontal	as	0.49	bs	0.43
MNTN_E	Horizontal	as	0.11	bs	0.7
MNTN_D	Horizontal	as	0.28	bs	0.57
MNTN_C	Horizontal	as	0.18	bs	0.6
MNTN_B	Horizontal	as	0.19	bs	0.65

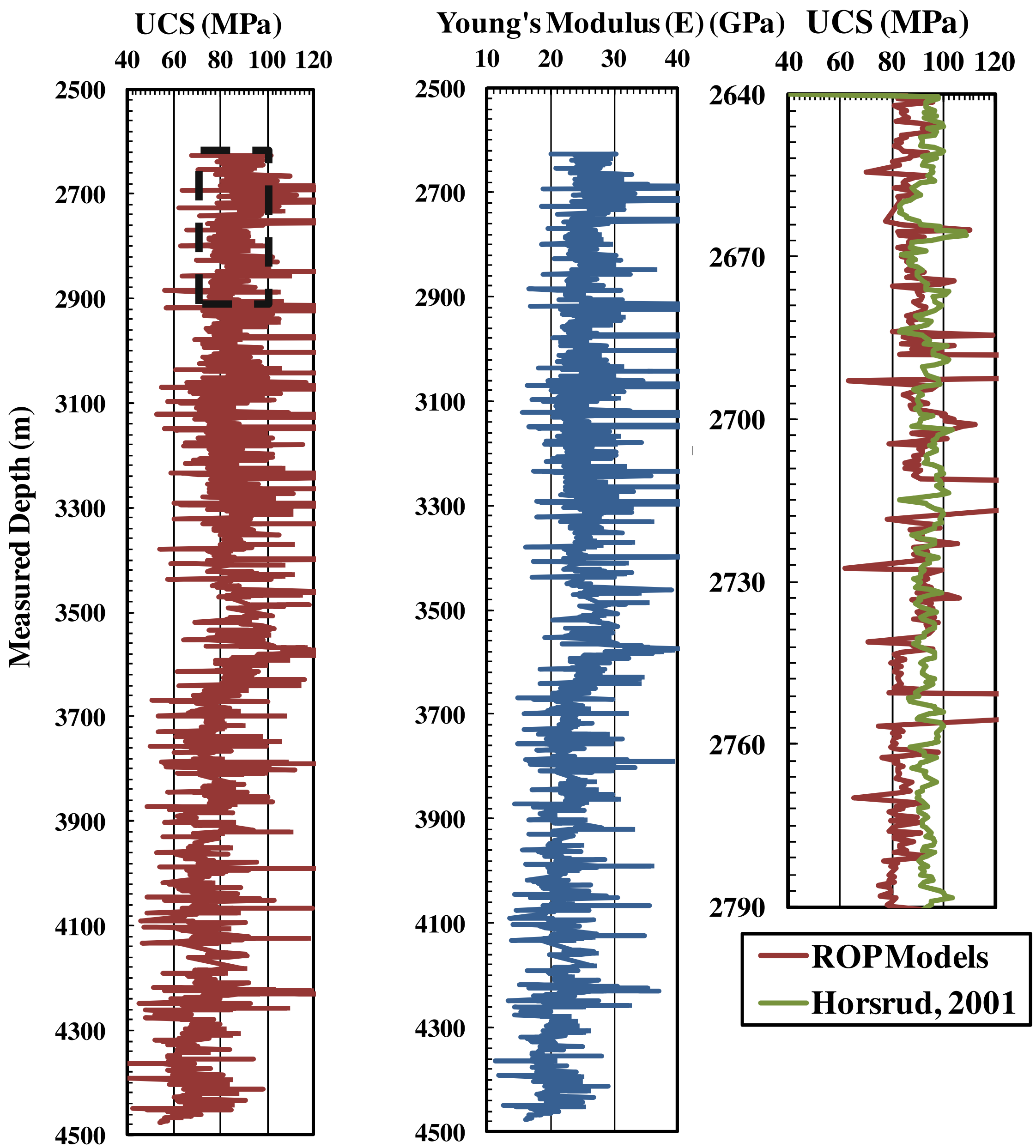
Source: Laboratory Measurements

Case Study – Well A, Sunset Area: Background

- Lower Triassic Montney Formation E lobe, Alberta, Canada
- Montney: Dark grey siltstone with minor sandstone to dolomitic siltstone
- 131-170F; 2-4.5 wt% TOC; 3-10% porosity; 30-70% gas saturation
- Pore pressure: 14.58 kPa/m (2.11 psi/m; specific gravity: 1.49)
- Lateral section: 2600-4490 m
- Underbalanced drilling with oil and water based mud
- ReedHycalog PDC drill bit 200 mm (7 7/8 in)

Era	Period	Formation Top	MD (m)
Mesozoic	Lower Cretaceous	Paddy	766.14
		Cadotte	793.22
		Harmon	835.89
		Notikewin	891.9
		Falher	952.65
		Wilrich	1171.42
		Bluesky	1237.51
		Gething	1267.49
		Cadomin	1420.55
	Jurassic	Nikanassin	1445.87
		Fernie	1616.11
		Nordegg	1721.52
	Triassic	Baldonnel	1751.1
		Pardonet	1740.35
		Charlie Lake Fm	1794.58
		Artex	2151.19
		Halfway	2162
		Doig	2211
		Phosphate (Upper)	2332
		Phosphate (Middle	2346.38
		Phosphate (Lower)	2377.6
		Montney	2392.19
		MNTN E Lobe	2396.32

ROP Mdel Output – Well A, Sunset Area



Avg. UCS: 99.57 MPa

Avg. YM: 29.64 GPa

- UCS prediction is consistent with that estimated from sonic logs.
- Laboratory geomechanical tests on horizontal samples measured avg. UCS of ~117 MPa and YM of ~37 GPa.
- Davey (2012) reported UCS of 117-136 MPa) for the Montney Formation.
- Results are also consistent with laboratory measurements by Hall and Jennings (2011) and Keneti and Wong (2011).
- Similar analysis on an identical Sunset Well B yields avg. UCS of ~109 MPa and YM of ~32 GPa.

Kerkar et al., 2014, SPE IPTC=17447-MS

Application: Improved hydraulic fracturing design

- Density logs provide: (assuming average formation density, ρ)

$$\sigma_v = \frac{\rho \text{ x } depth}{144}$$

- Sonic logs provide: Δt_{comp}, Δt_{shear} [μs/ft]

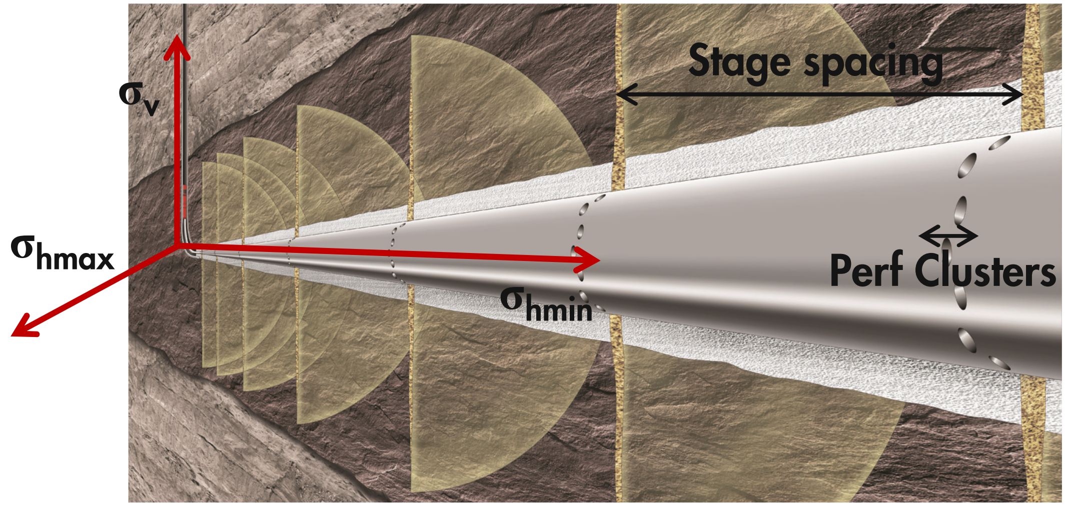
$$V_s = \sqrt{\frac{G}{\rho}} \quad V_p = \sqrt{\frac{K+4G}{\rho}} \quad \nu = \frac{1}{2}\cdot\frac{(V_p/V_s)^2 - 2}{(V_p/V_s)^2 - 1}$$

$$E = 2G(1+\nu) = 3K(1-2\nu)$$

For homogeneous isotropic materials.

- **Sonic logs provide critical information at cost and rig time.**

σ_{hmin} – minimum horizontal stress
σ_{cl} – closure stress
ν – Poisson's ratio
σ_v – overburden
P_{res} – reservoir pressure
E – Young's modulus
$\varepsilon_{tectonic}$ – strain
α – coefficient of thermal expansion
ΔT – temperature change
$\Delta\sigma_{width}$ – stress due to fracture
BHFP – bottom hole flowing pressure
G – shear modulus
K – bulk modulus



- Basic stress relationship:

$$\sigma_{h\min} = \sigma_{cl} = \frac{\nu}{1-\nu}(\sigma_v - P_{res}) + P_{res} \pm E.\varepsilon_{tectonic} + \alpha.\Delta T$$

- Assuming tectonic strain and temperature effects as negligible,

$$\sigma_{h\min} = \sigma_{cl} = \frac{\nu}{1-\nu}.(\sigma_v - P_{res}) + P_{res}$$

- Proppant stress:

$$\sigma_p = \sigma_{cl} + \Delta\sigma_{width} - BHFP$$

Rock Brittleness: Engineered Perforations (1/2)

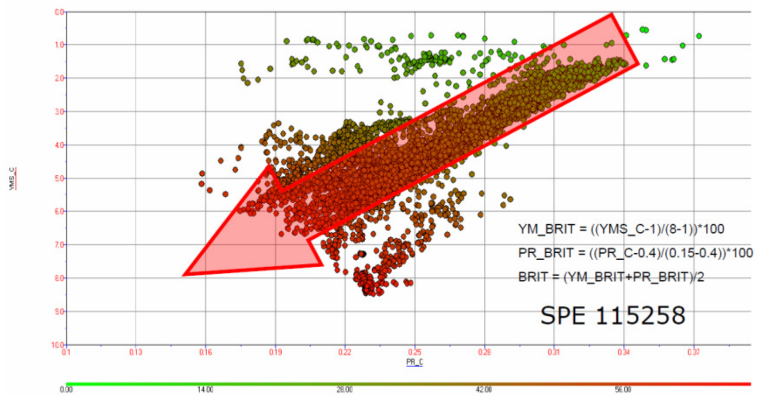
- Current practice: Equally spaced lateral clusters/stages
- Challenges:
  - Uneven hydraulic fracture growth
  - Non-productive clusters
- Opportunity
  - Engineer placement of perforation clusters along the lateral
  - Use of YM trends to understand relative brittleness of the rock

Geomechanical Considerations	Important For	Determined By
How brittle is the shale?	Fluid type selection	Petrophysical model
What is the closure pressure?	Proppant type selection	Petrophysical model
What proppant size and volume?	Avoid screenouts	Petrophysical model/tribal knowledge
Where should the frac be initiated?	Avoid screenouts	Petrophysical model/tribal knowledge

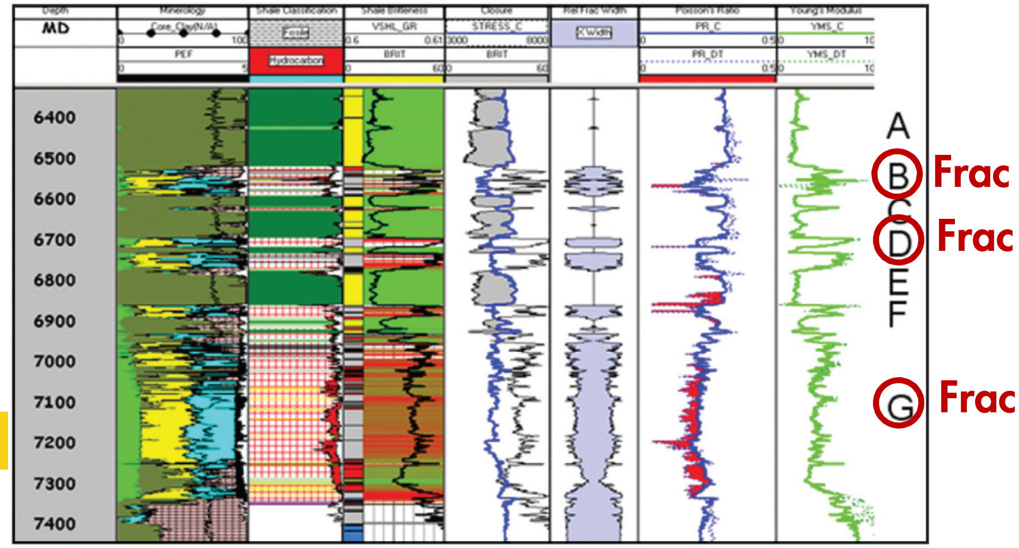
Rickeman, R. et al., , A Practical Use of Shale Petrophysics for Stimulation Design Optimization: All Shale Plays are not Clones of The Barnett Shale, Presented at the SPE Annual Technical Conference & Exhibition, Denver, Colorado, USA, 21-24 September, 2008.

Rock Brittleness: Engineered Perforations (2/2)

Fracture design based on geomechanical data[1]



Young's Modulus vs. Poisson's Ration and Brittleness Index



Poisson's Ratio, Young's Modulus logs for Haynesville

Lower PR ≈ More brittle rock

Higher YM ≈ More brittle rock

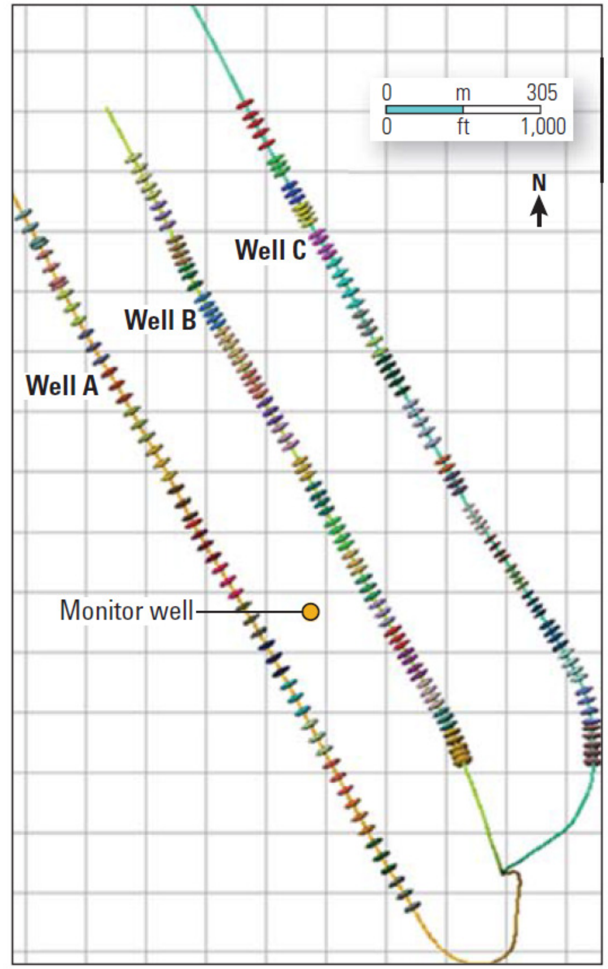
Brittleness	Fluid System	Fracture Geometry	Fracture Width Closure Profile	Proppant Concentration	Fluid Volume	Proppant Volume
70%	Slick Water			Low	High	Low
60%	Slick Water					
50%	Hybrid					
40%	Linear					
30%	Foam					
20%	X-Linked					
10%	X-Linked			High	Low	High

1. Rickerman, R. et al., Petrophysics key in stimulating shales, The American Oil & Gas Reporter, March 2009.
2. Rickeman, R. et al., , A Practical Use of Shale Petrophysics for Stimulation Design Optimization: All Shale Plays are not Clones of The Barnett Shale, Presented at the SPE Annual Technical Conference & Exhibition, Denver, Colorado, USA, 21-24 September, 2008.

Optimization of fracture placement – Schlumberger Trial

Design Summary									
Well	Completion Method	Fluid	Proppant Size	Lateral Length, ft	Stages	Average Stage Length, ft	Perforation Clusters per Stage	Design Proppant per Lateral, lbm/ft	Design Pumping Rate, bbl/min
Well A	Geometric	Slickwater	40/70	5,312	18	295	3	1,650	90
Well B	Engineered	Slickwater	40/70	4,528	20	226	3.7	1,585	90
Well C	Engineered	Slickwater	40/70	4,998	20	250	3.9	1,675	90

- Because all perforations in Well B and C were located in wellbore intervals of relatively low minimum principal stress,
  - The average fracture breakdown and treatment pressures were 7% and 3% lower respectively.
  - Fractures took 16% and 22% higher proppants at same pump rate (90 bpm).
  - Initial gas flowback rates were 33% and 40% higher than rates from Well A on the same 5/8 in. choke size.



- Seneca Resources Corporation and Schlumberger
- Marcellus shale, PA and NY
- Wells A, B and C from same pad with 800 ft apart

Ajayi, B. et al., Stimulation design fr unconventional resources, Oilfield Review, pp. 34-46, Summer 2013.

Key Message

- Routinely acquired drilling data can compute formation un/confined compressive strength and Young's modulus.

- This presentation shows motivation behind the workflow and its application to understand lateral heterogeneity in Groundbirch Montney lobes.

- Workflow performs wellbore friction analysis to estimate downhole weight-on-bit and couples it with ROP models developed for PDC/Rollercone bits.

- Young's modulus/UCS signatures can be used in correlation with fracture gradient to engineer placement of perforation clusters along the lateral in the hydraulic stimulation design.

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