Early Warning Systems – Using a PTA Approach on DFIT's to Understand Complex Hydraulic Fractures

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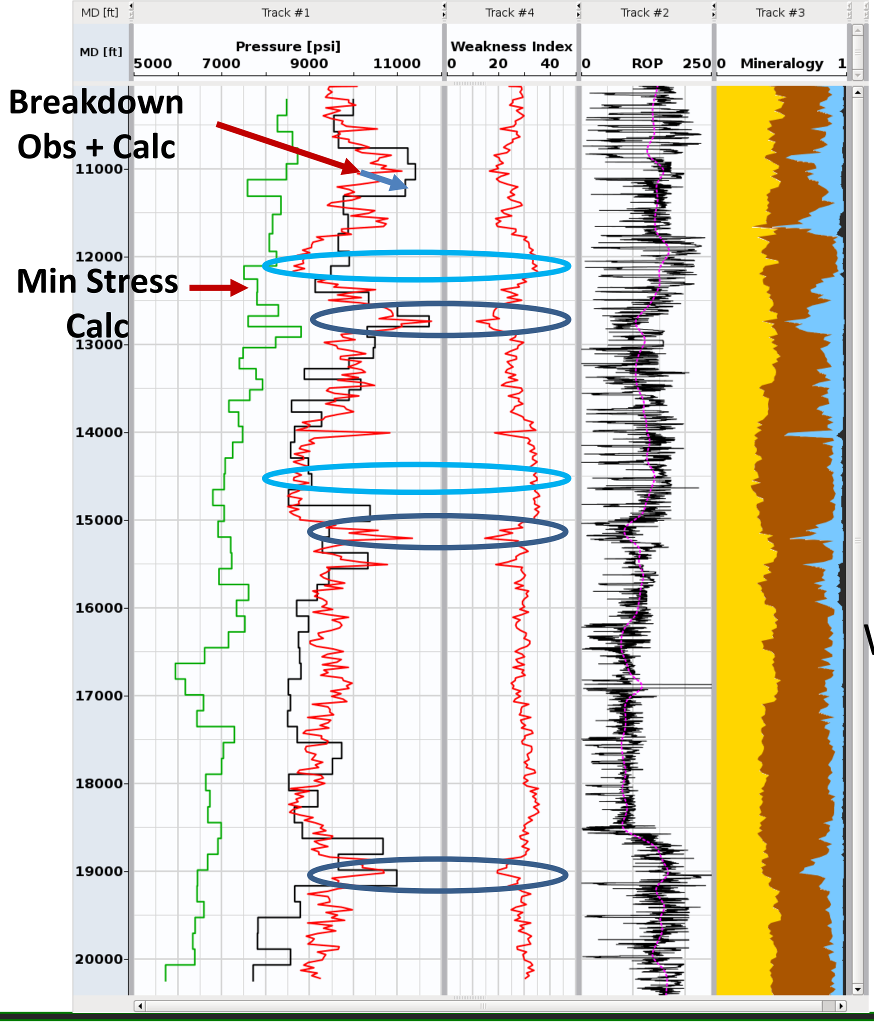
Fracturing Complexity Agenda

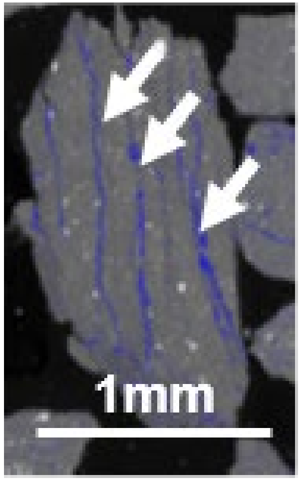
- Definition (High Treating Pressures !?)
- Identification
- Classification
- Examples
- Instantaneous Shut-in Pressure (ISIP)
- Closure Stress
- Modern DFIT Analysis (Pressure Transient Analysis)
- Conclusions

Identification
First Idea

- Breakdown Pressure
- Cuttings
- Logs

- Model Min Stress + Breakdown Pressure



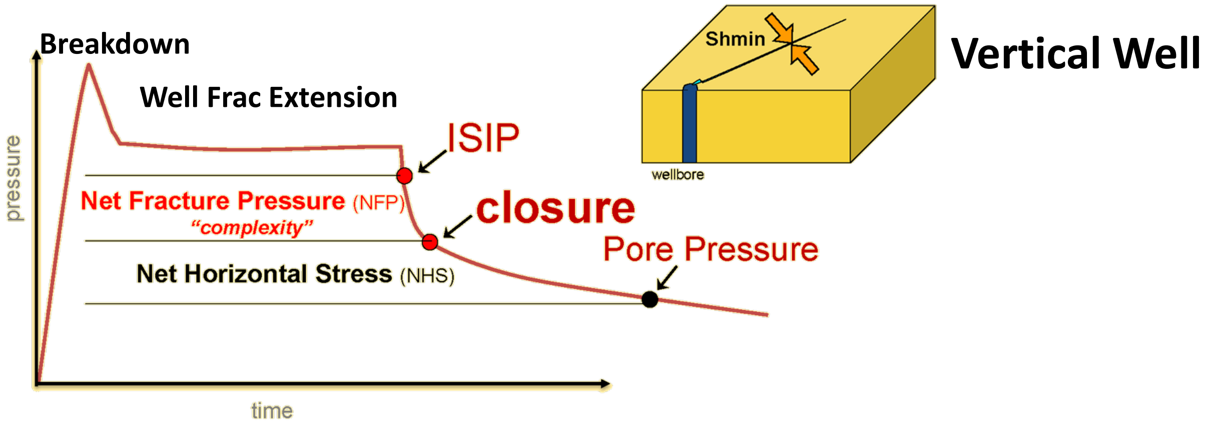


Weakness Index is Planes of Weakness Count + Elastic Properties

Identification - Second Idea
Data Frac Injection Tests (DFIT's)

Potocki
(2012, 2015)

ISIP = Instantaneous Shut-in Pressure
Pressure at sand face when friction removed



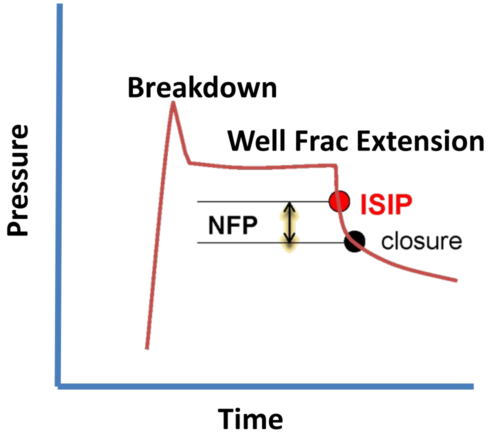
Dan Potocki, Gussow Conference 2015

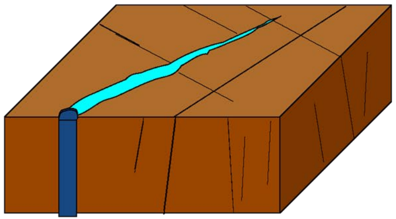
Low Complexity

How NFP Reveals Complexity

Net Fracture Pressure = ISIP – Closure

ISIP = Low





Vertical Well

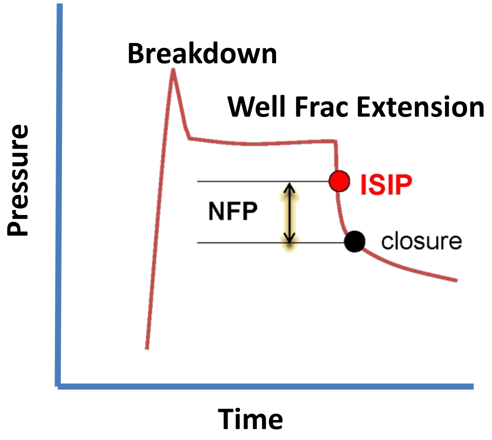
Dan Potocki, Gussow Conference 2015

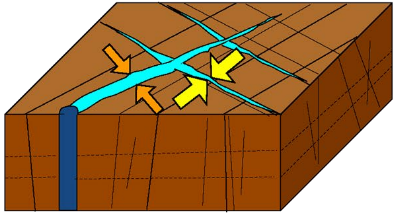
Mild Complexity

ISIP

How NFP Reveals Complexity

NFP = ISIP – Closure





Vertical Well

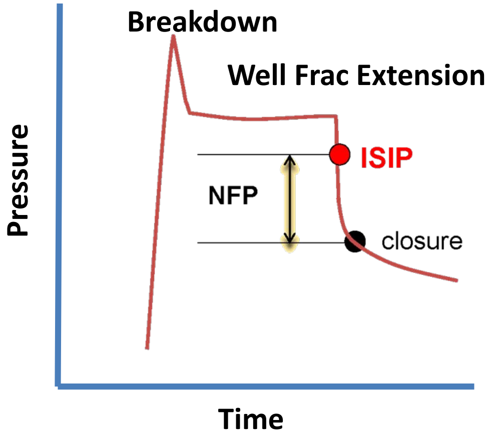
Dan Potocki, Gussow Conference 2015

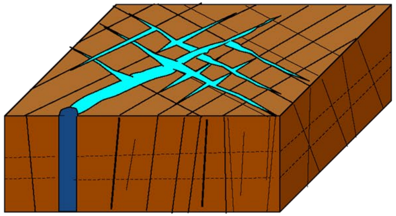
Intermediate Complexity

How NFP Reveals Complexity

NFP = ISIP – Closure

ISIP



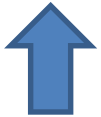


Vertical Well

Dan Potocki, Gussow Conference 2015

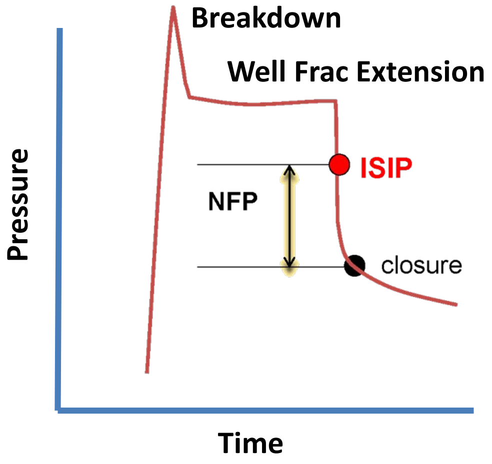
High Complexity

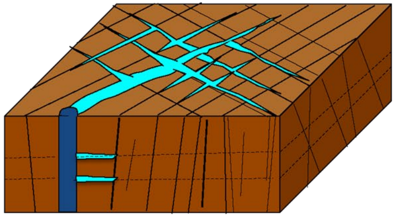
ISIP



How NFP Reveals Complexity

NFP = ISIP – Closure





Vertical Well

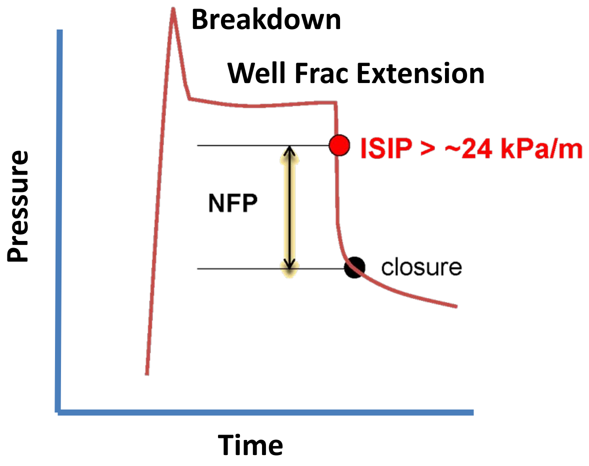
Dan Potocki, Gussow Conference 2015

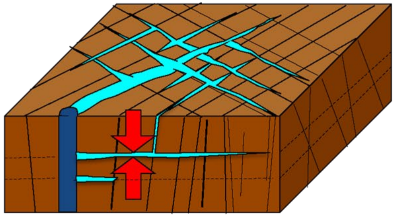
Highest Complexity

ISIP

How NFP Reveals Complexity

NFP = ISIP – Closure

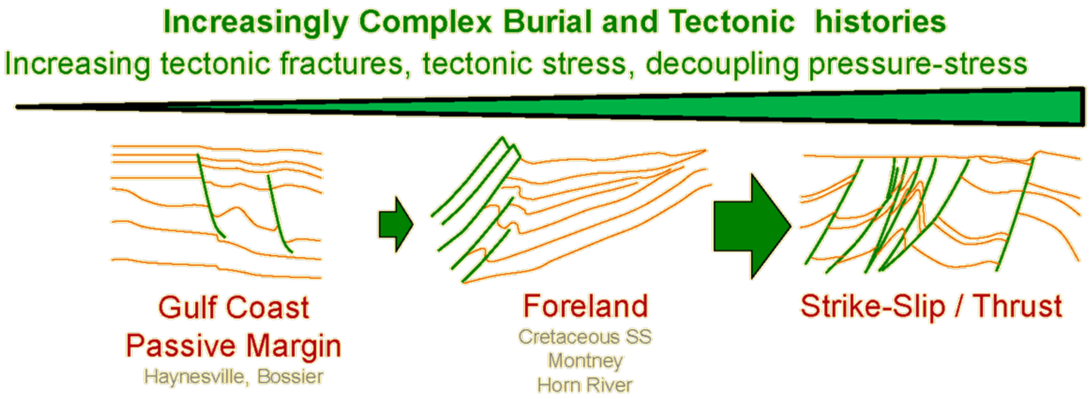




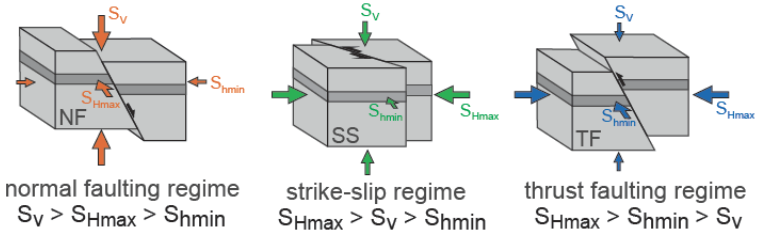
Vertical Well

Dan Potocki, Gussow Conference 2015

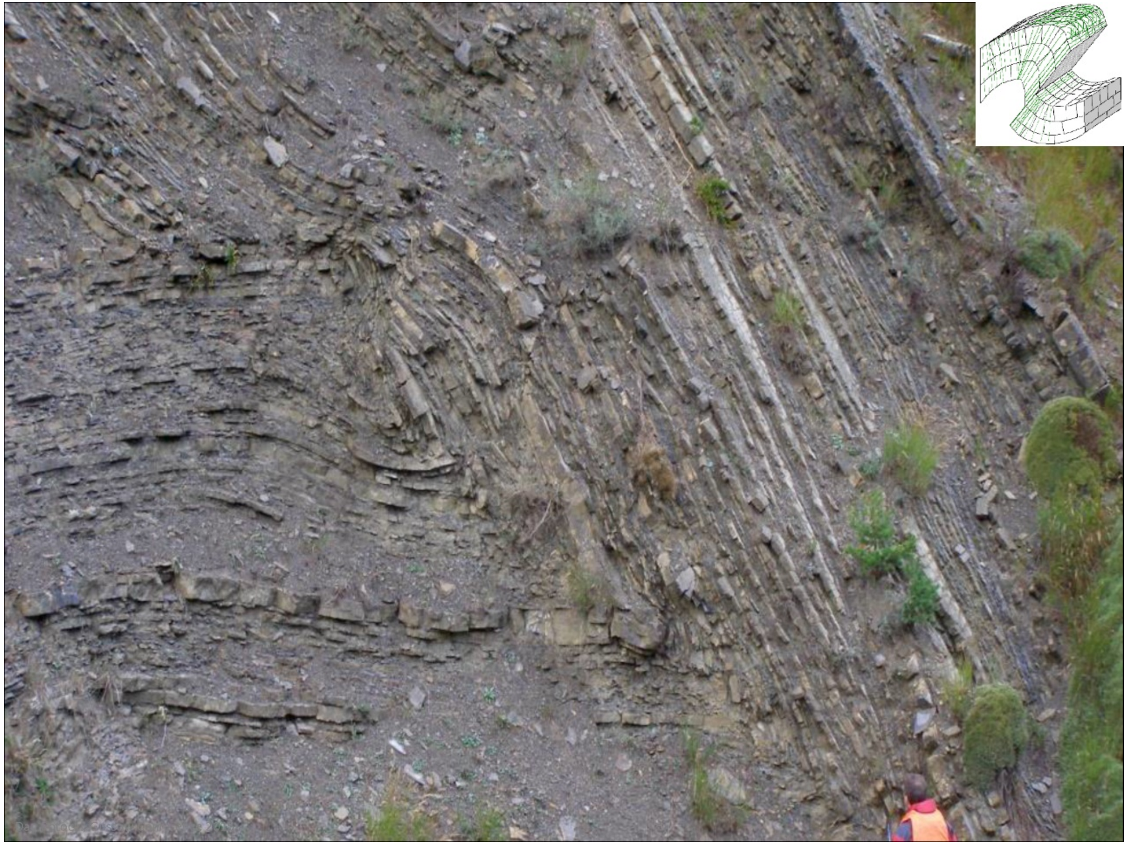
Classification (Potocki 2012, 2015)
First Order – Tectonic Setting

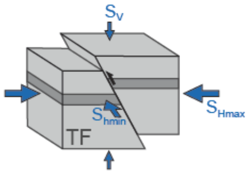


Anderson Criteria



Strike Slip/Thrust Fault (Potocki 2015)

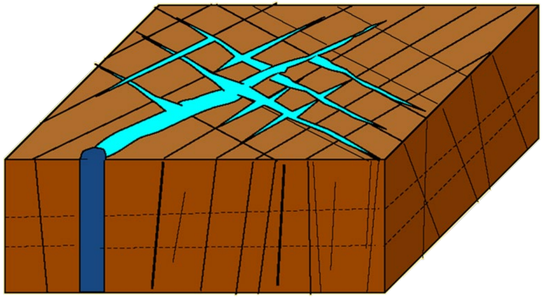




thrust faulting regime
$S_{Hmax} > S_{hmin} > S_V$

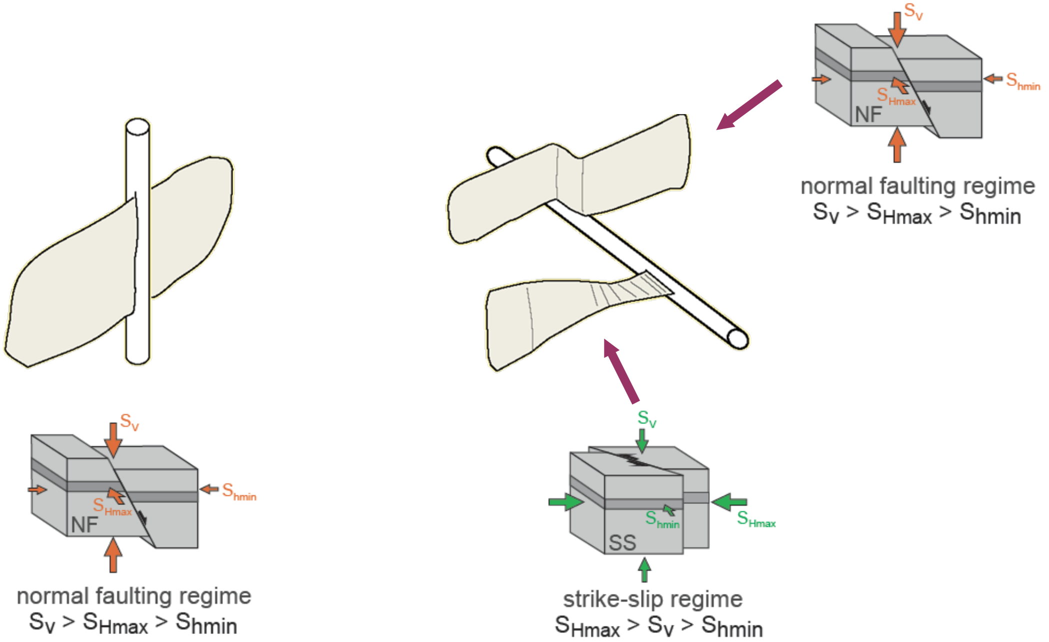
Second Order - Overprints

- > Natural Fractures then > Complexity



Second Order - Overprints

Wellbore Orientation

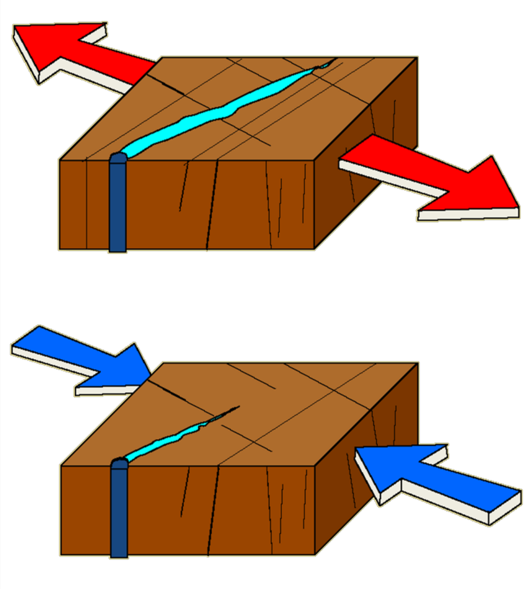


Hor Wells > Complexity than Vertical Wells - Due to Flow Path Tortuosity

Second Order – Overprints
NHS = Closure - Pore Pressure

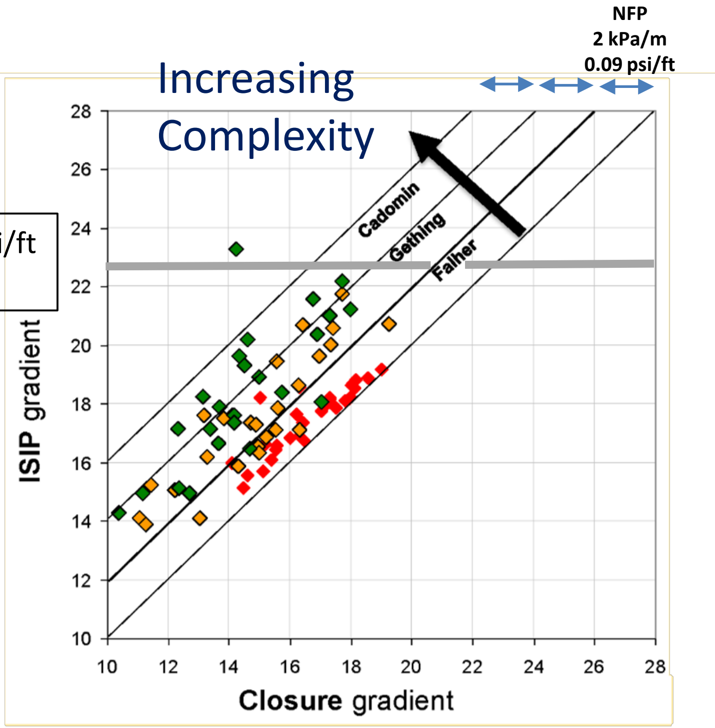
- NHS = Small (More Complexity)
  - Over Pressured

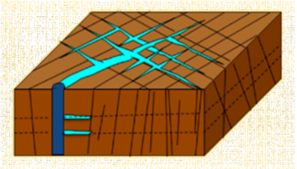
- NHS = Large (Less Complexity)
  - Normal to Under-Pressured



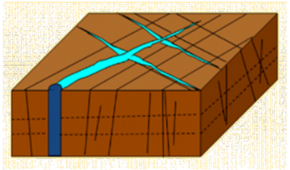
Gradient Analysis – Replace Pressures
DFIT's Reveal Stimulation Complexity

Sv = 22.6 kPa/m or 1 psi/ft
Complex > 22.6 kPa/m

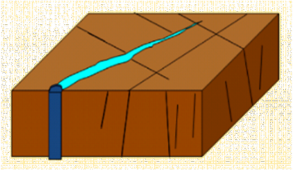




Cadomin
Higher Complexity



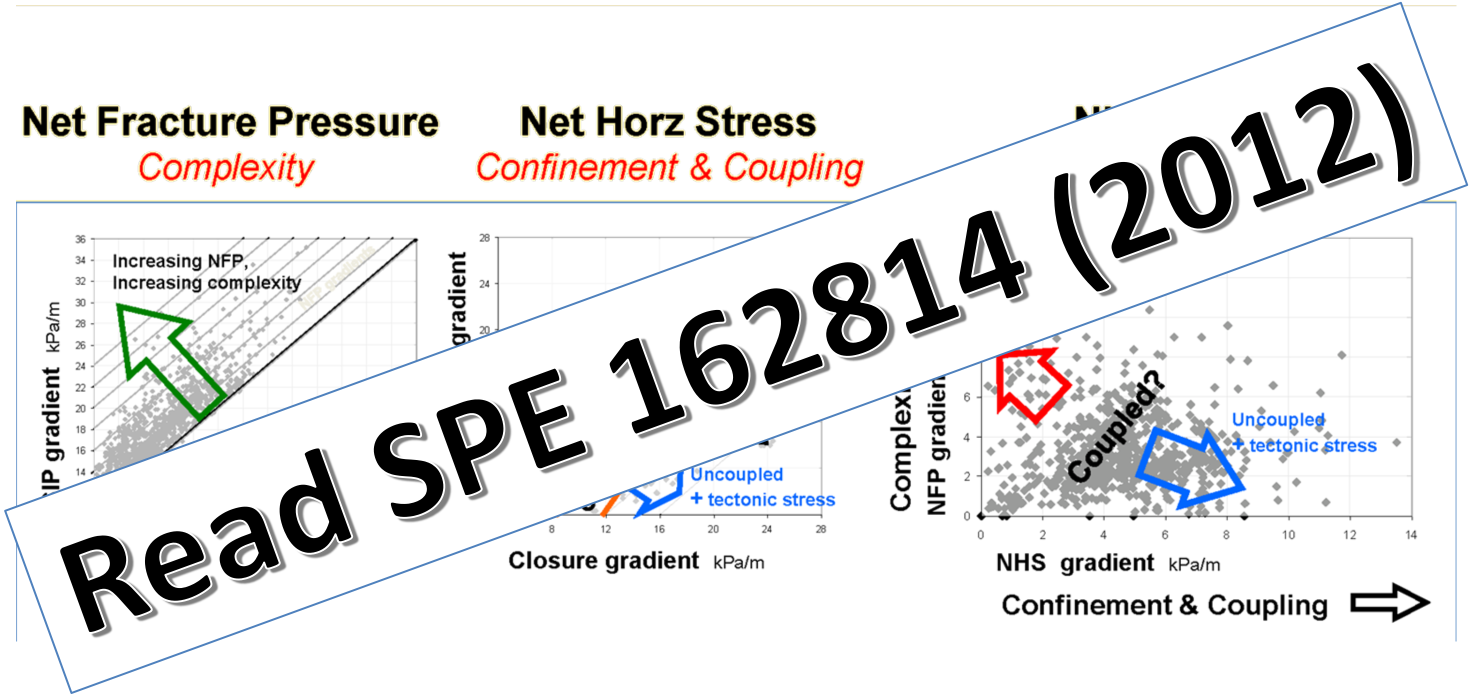
Gething
Increasing Complexity



Falher
Low Complexity

Dan Potocki, Gussow Conference 2015

Complexity Diagnostics – 3 Plots



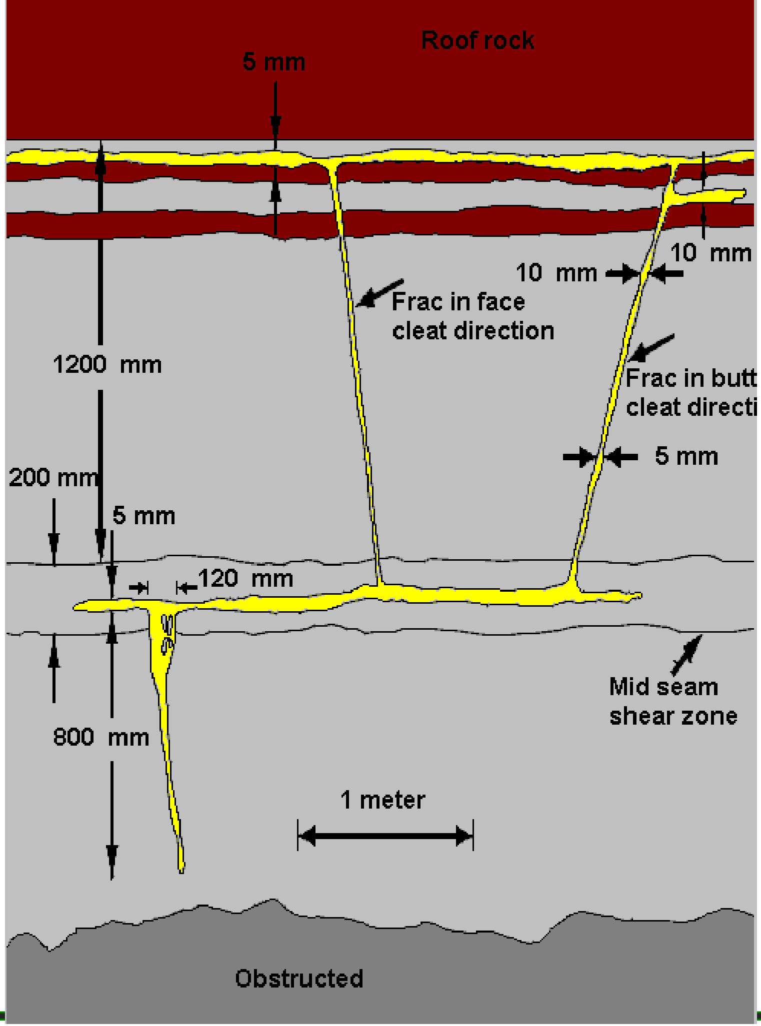
Final Classification (Potocki 2012, 2015)

- First Order - Tectonic Setting
  - Passive Margin (lowest stresses)
  - Foreland (higher stresses)
  - Active Strike Slip/Thrust Basins (highest stresses)
- Second Order - Overprints
  - Natural Fractures
  - Wellbore Geometry
    - Vertical Well (simplest)
    - Direction of horizontal well within stress regime
  - Net Horizontal Stress (NHS)
    - Closure Stress – Pore Pressure
    - Lower NHS > Complexity
  - Brittle/Ductile Rocks (not discussed here)

Mine Back Example
Rob Jeffrey's Group
CSIRO Australia

Maximum Complexity

Vertical section through Fracture at ECC 90 site, German Creek Coal Mine Queensland, Australia



Example Modeling Work – Tan et al (2018)

J. Geophys. Eng. 15 (2018) 1542 P Tan *et al*

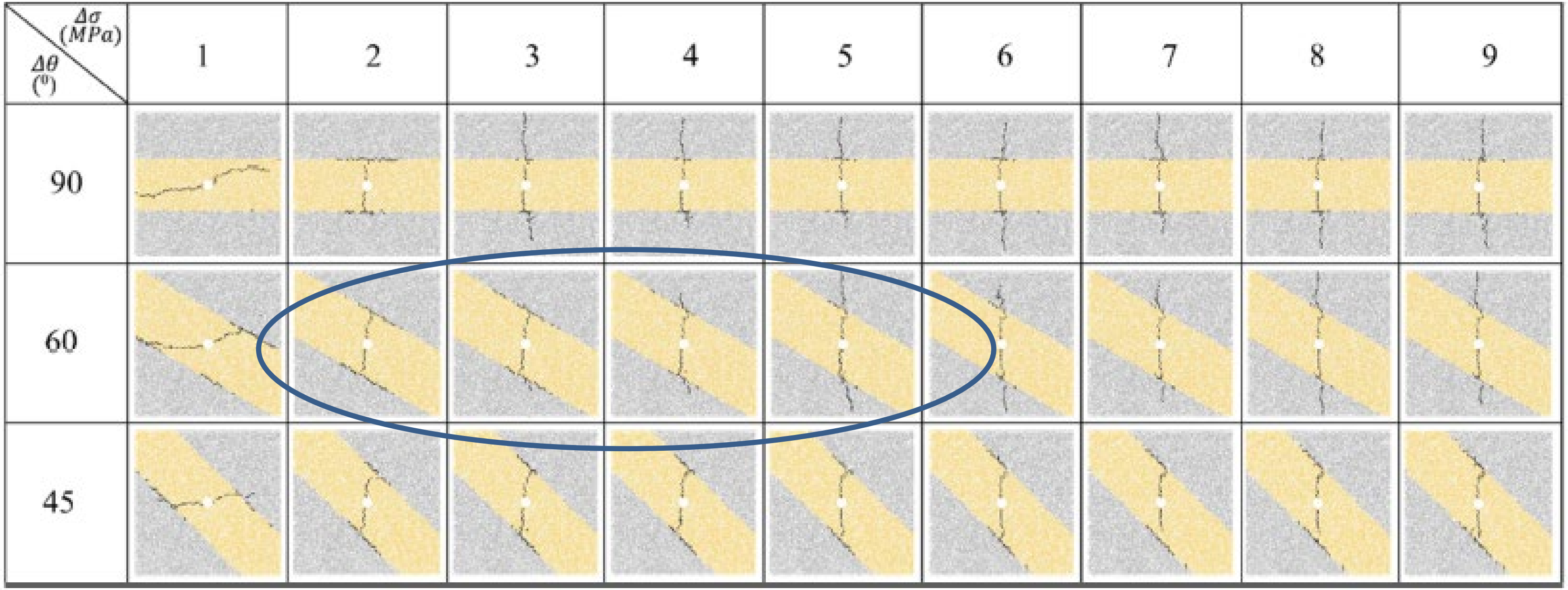


Figure 4. Angles of the layer interface and *in situ* stress difference.

Example Modeling Work
Rahimi-Aghdam et al (2019)

- Geomechanical properties fully specified
- Verification that complexity can be modeled

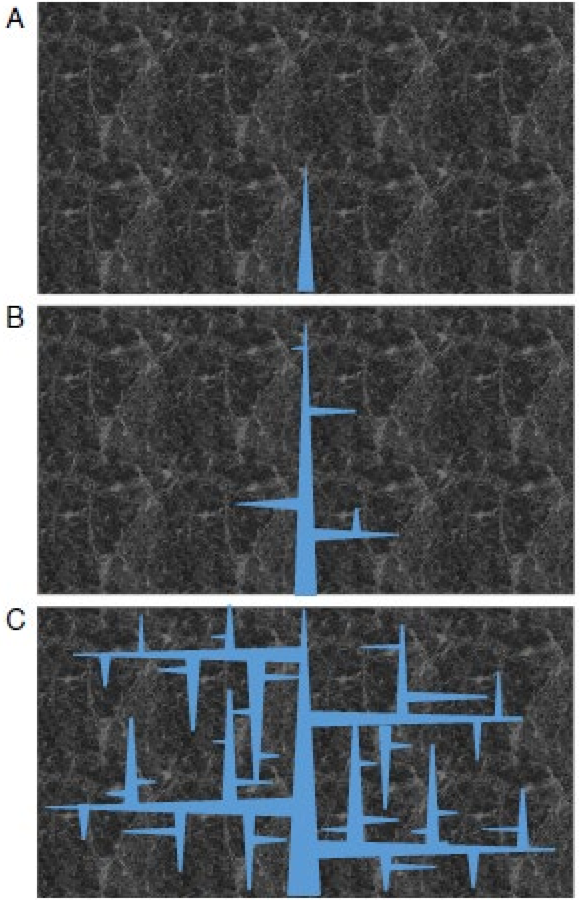
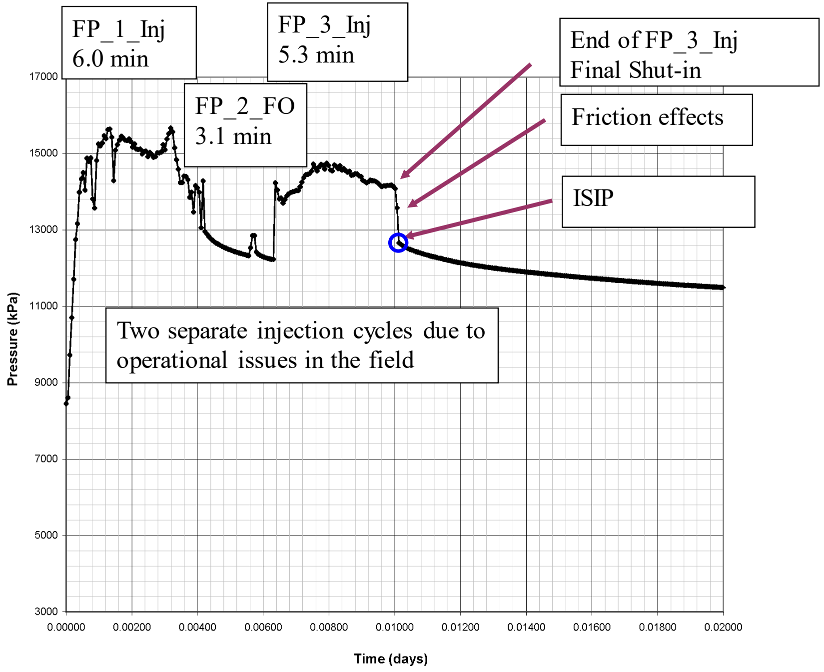


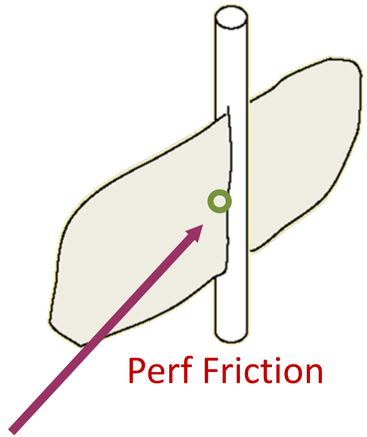
Fig. 1. Schematic branching due to natural fractures. (A) Water is injected at high pressure through damaged zones and weak layers, (B) crack branching initiates due to the presence of damaged zones and natural fractures, and (C) dense cracking happens in all directions, due to the presence of damaged zones, weak layers at closed natural fractures (downward view normal to bedding plane).

High Complexity Examples - Conclusion

- Conventional frac models inaccurate
  - Assumed geometry too simple
- Reservoir Drainage Volumes
  - Frac Height = smaller
  - Frac Length = longer (frac hits)
  - Area = bigger than expected
- Development Consequences
  - Well spacing too close
  - Not enough vertical stacks

Vertical Well - ISIP
“Pressure at sand face when friction removed”





ISIP = pressure just inside the fracture and past the perfs

Modern DFIT Analysis (2012 +)
"The Times They are Changing"

- ISIP
  - Problems with horizontal wells
  - Pre-Closure Flow regime identification
  - Far Field Extension Pressure (FFEP) Concept
- Closure
  - Tangent Closure (Barree et al (2007))
  - 'Compliance Closure' concept (McClure et al (2016))
  - My 'preliminary' opinion - ½ way between them
    - Based upon multi-cycle DFIT's in same zone
      - Fall-off
      - Pump-in flow backs

Horizontal Well – ISIP ?

Far Field Extension Pressure (FFEP)
Pressure after near wellbore effects are over

Rate=1.8 stb/m
Injection Time
17.3 minutes

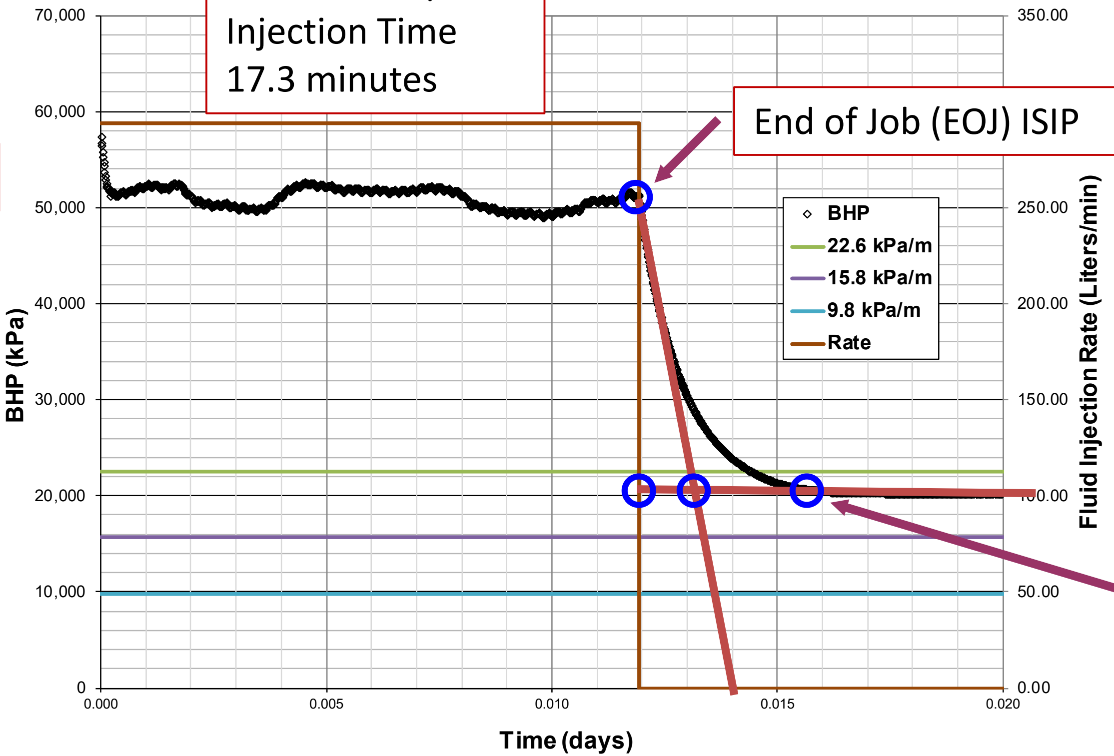
End of Job (EOJ) ISIP

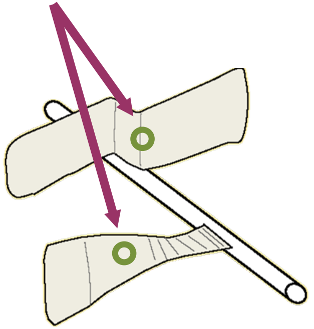
2.2 psi/ft

1.0 psi/ft

0.6 psi/ft

0.43psi/ft





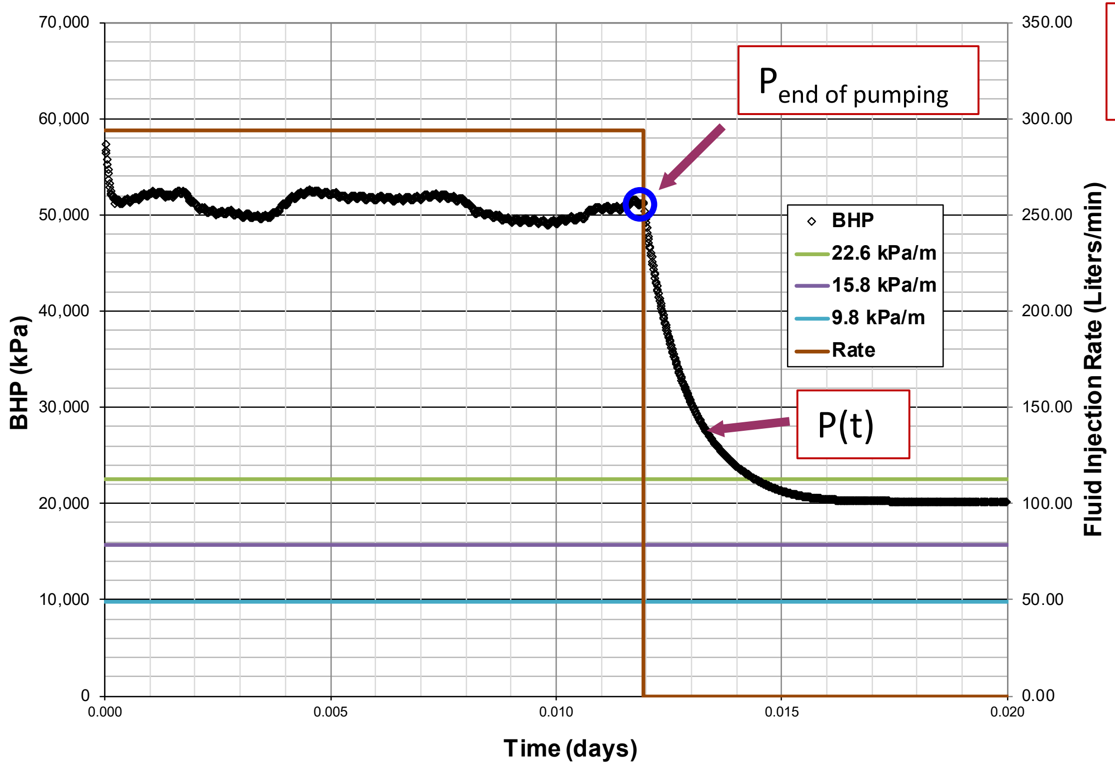
Perf Friction (large)
Tortuosity Friction (smaller)

Shut-in Time
5.3 minutes

Pre-Closure Analysis

- Holistic Method (Barree et al , 2007)
  - Pressure Dependent Leak-off
  - Height Recession/ Transverse Storage (HRTS)
- PTA Method (Bachman, Hawkes, Nicholson)
  - Identifies all flow regimes pre + post closure

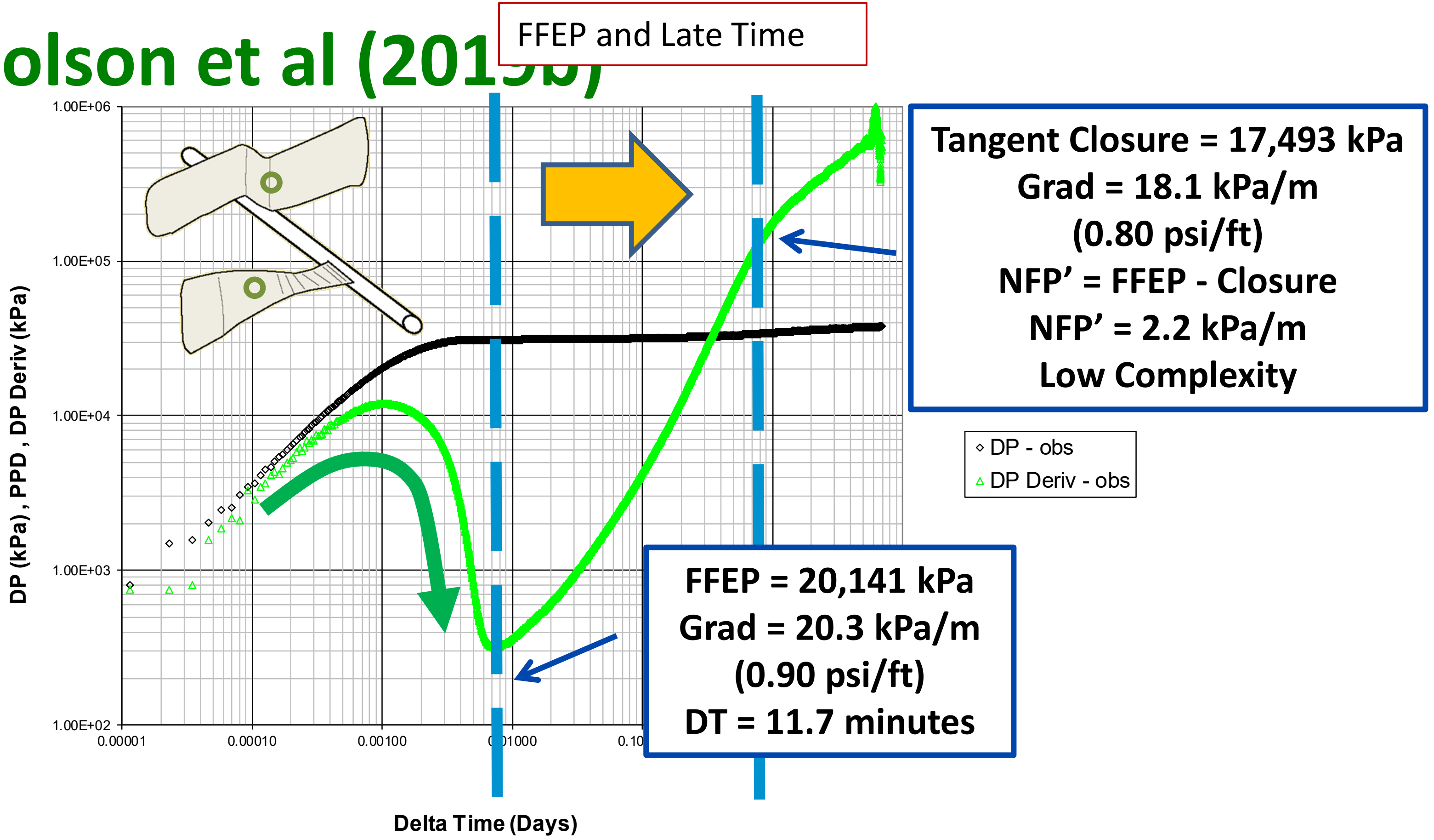
Preliminaries to PTA Log-Log Plot



$DP = P_{end} - P(t)$

$\text{Delta Time} = t_{end} - t$

PTA - Identification of Perf Friction
Nicholson et al (2019b)

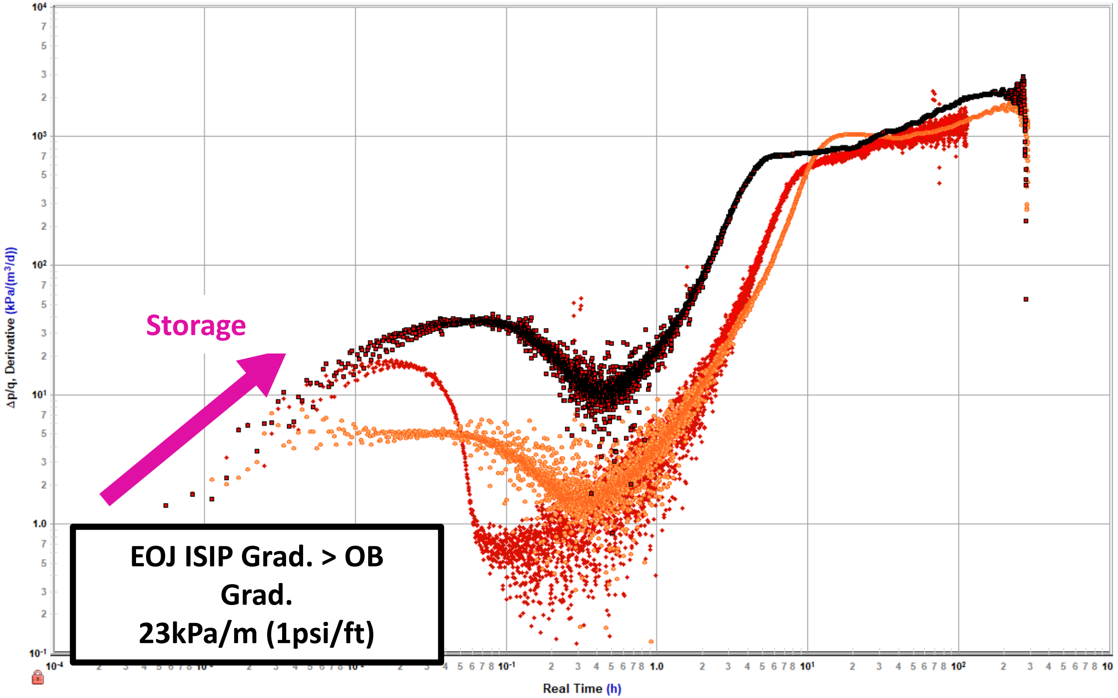


Montney Formation - NE British Columbia

- Normal to Strike/Slip Environment
- Gas – Condensate - Oil

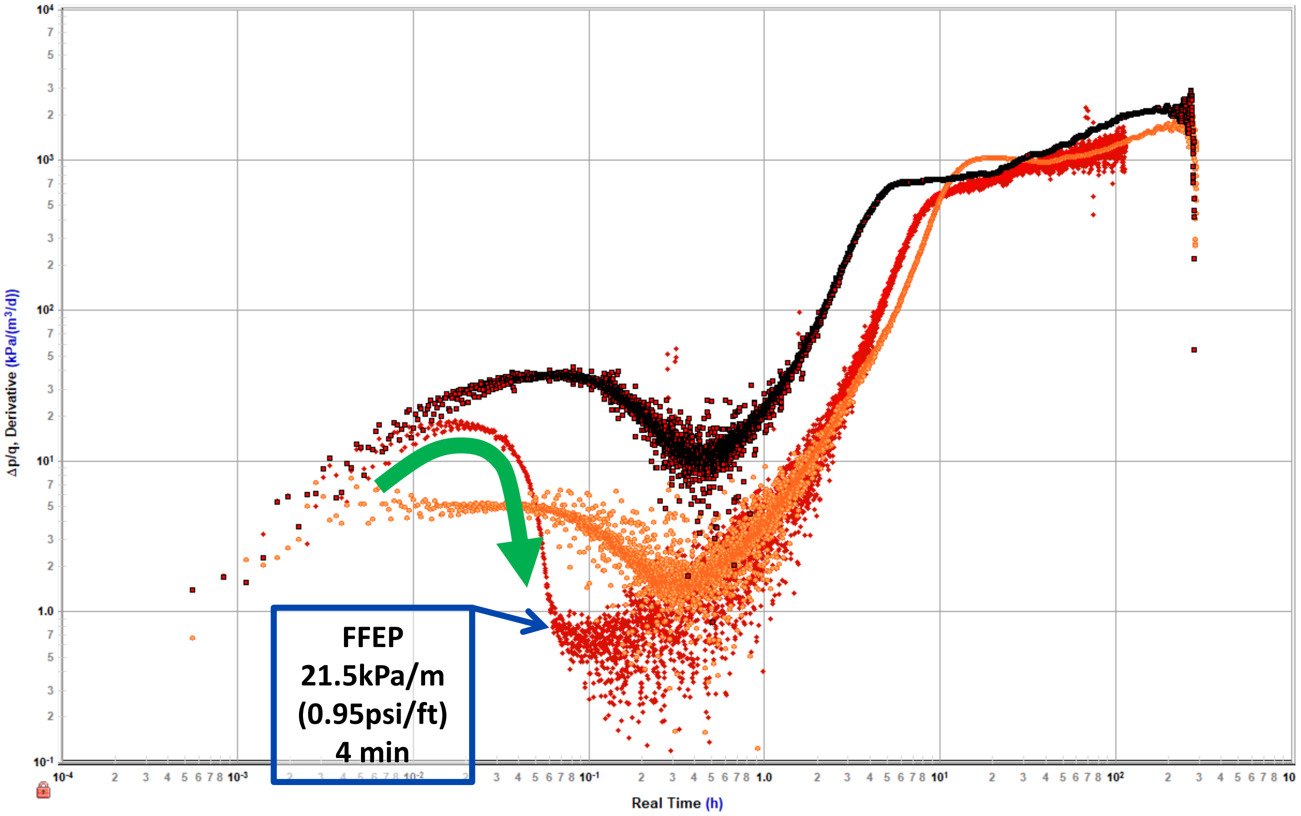
Lower Montney Examples Nicholson et al (2019b)

- Kiskatinaw Seismic Monitoring and Mitigation Area (KSMMA) in NE BC
- Overlay of 3 tests to compare results…*The whole is more than the sum of the parts!*
- Only Bourdet Derivative shown to simplify image
- **All tests have EOJ ISIP > 23kPa/m**



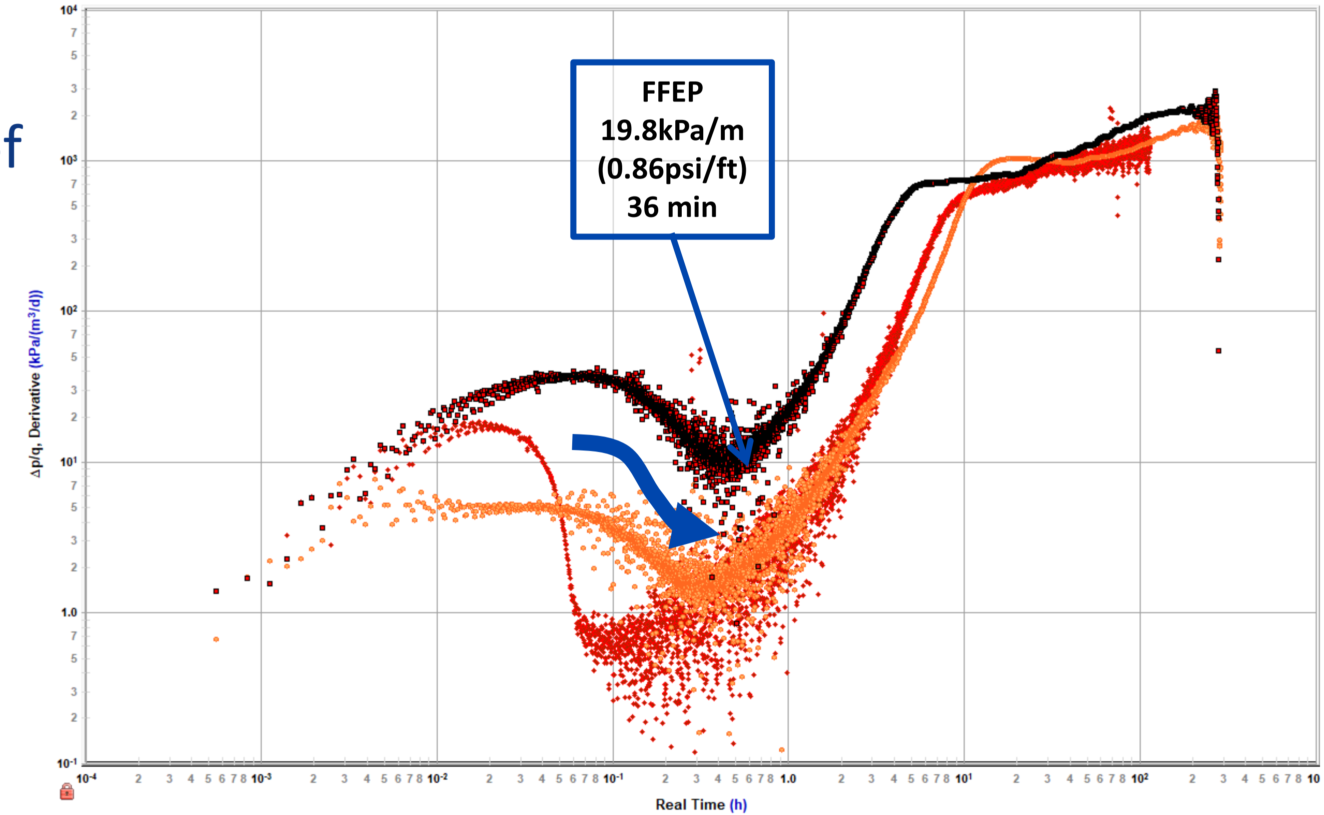
RED TEST - FFEP Determination

- Pick FFEP at end of **Friction**



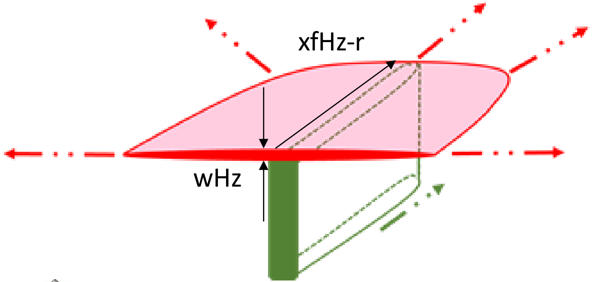
BLACK TEST - FFEP Determination

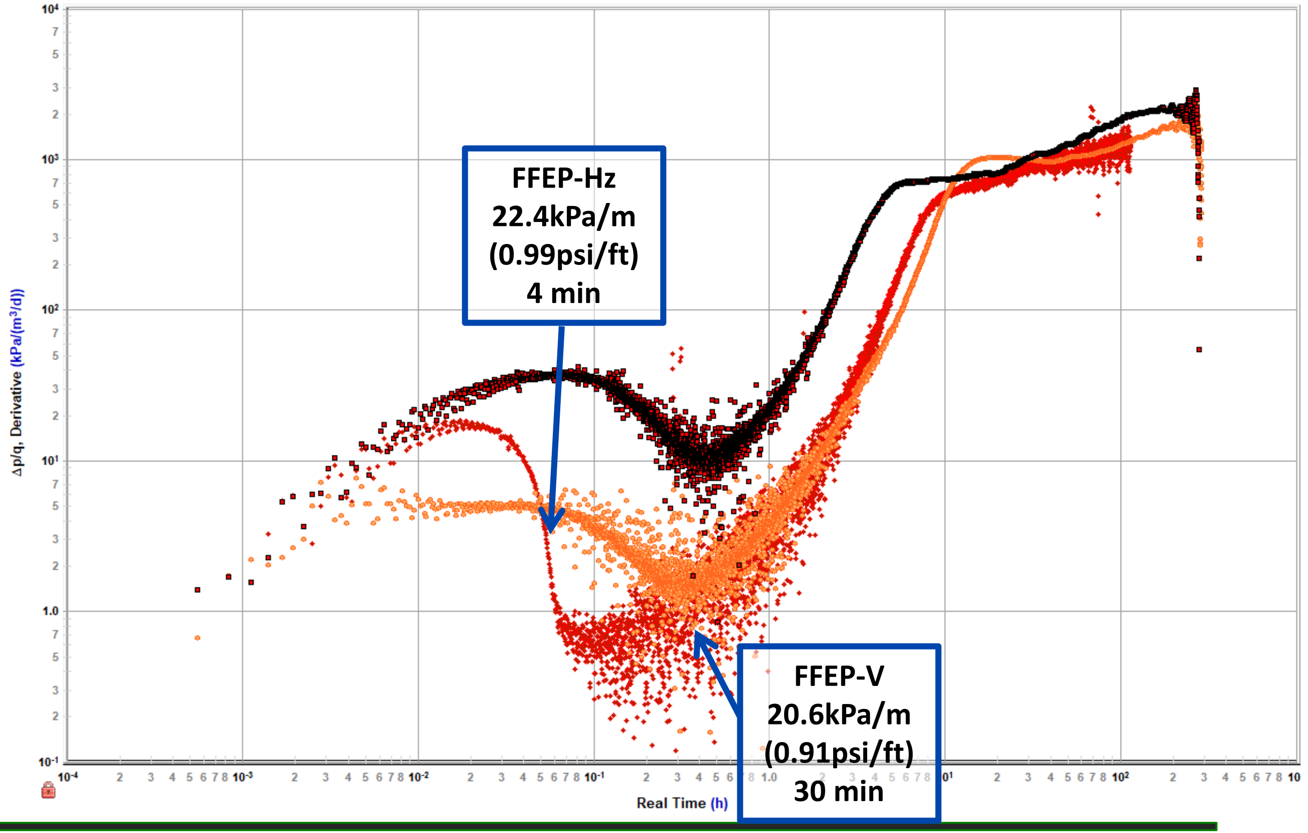
- Pick FFEP at end of **Tortuosity**



ORANGE TEST - FFEP Determination

- More complex test
- Likely multiple plane fractures (Vert + Hz)
- Pick 1st FFEP at end of Radial/Hz-Tip Extension…**FFEP-Hz** (slip vs. lift)
- Pick 2nd FFEP at end of Tortuosity…**FFEP-V**
- Possible weak connection between hz & vert fractures





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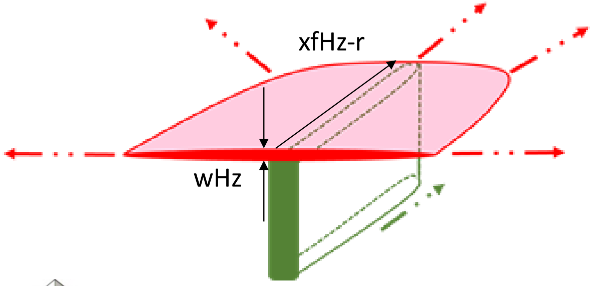
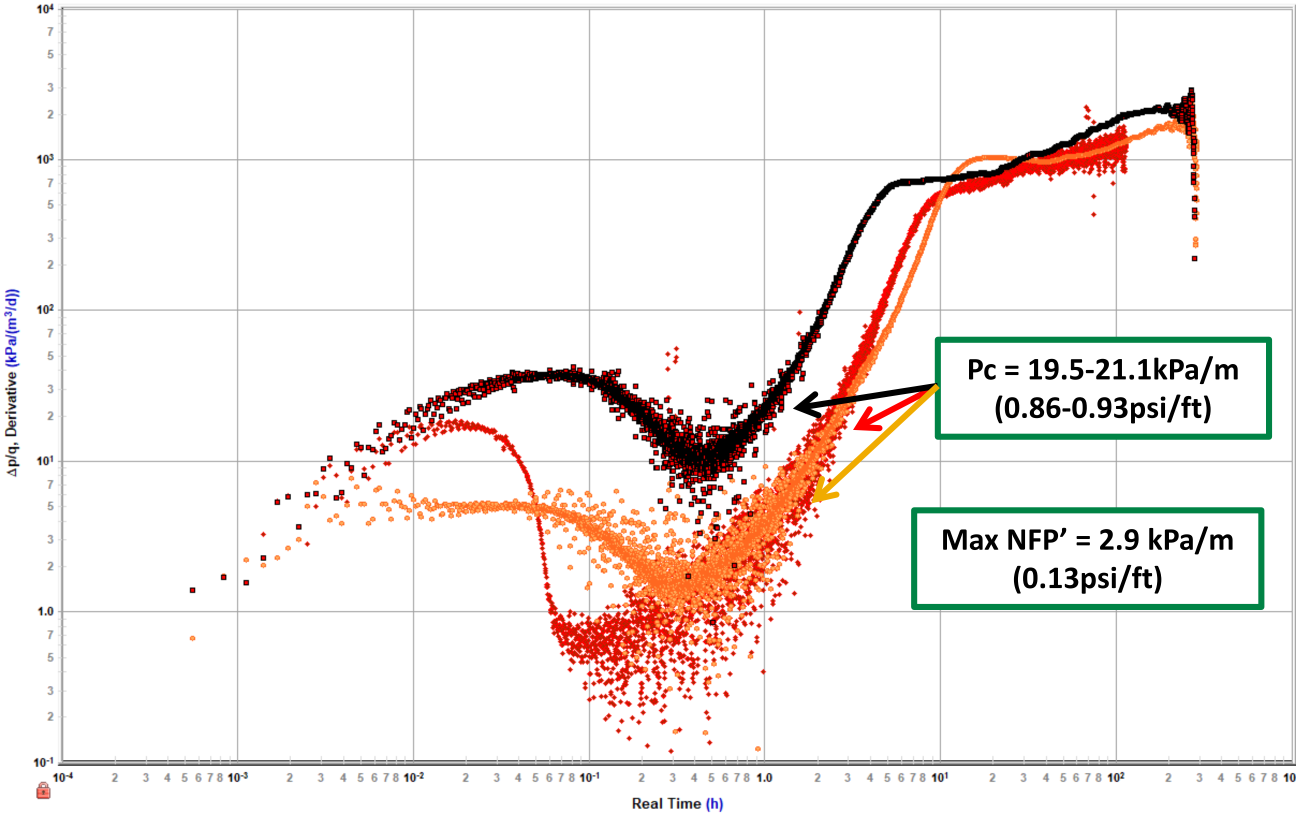
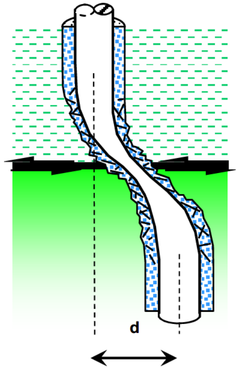


3 Montney Tests - Findings

- EOJ ISIP gradients > OB Grad....but...
- Closure pressure gradients are below OB gradient
- Fractures are predominantly vertical with possible hz plane activation as indicated by **Orange** test.

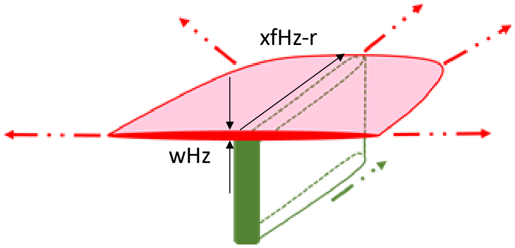


Montney Formation - Casing Deformation Study McLellan (2019)



- Casing Deformation across Montney
  - In Build Section of Well

- Numerous DFIT tests show indication of horizontal plane fractures
  - Hawkes (2013)
  - Nicholson (2019a, 2019b)



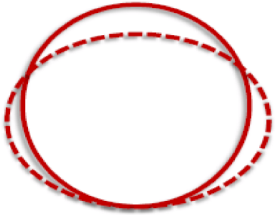
Montney Formation - Casing Deformation Study McLellan (2019)

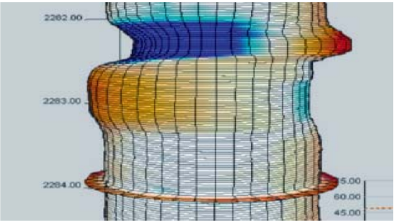
Examples of Montney Casing Deformation Occurrences During Hydraulic Fracturing

Early Recognition of Montney Casing Deformation: Jim Stannard, Sr VP, Progress Energy, CSUR 2012.

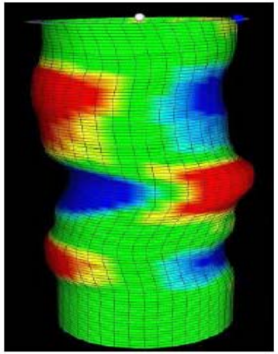
THE PROBLEM

- Casing ID's reduced from 96mm down to as low as 70mm during completion
- Makes drilling out plugs difficult or impossible
- Likely due to rock slippage, not pressure
- More common in wells with tough fracs





Casing shearing in Altares Member of the Montney Formation, 2282-2284m. Sanders et al, Bull. Can Pet. Geology, 2018.



Buckling deformation in 114mm casing in Shell's Groundbirch field, 2013. N. Suarez, M.Eng. Thesis, University of Calgary 2015.

Conclusions

- Replace ISIP with ‘Formation Fracture Extension Pressure’ (FFEP)
- Use Potocki’s complexity analysis with FFEP
- Horizontal Plane Fractures exist
  - Mine Backs
  - Casing deformation
  - Identifiable on DFIT’s
- Consider 10-15 minute Shut-downs on select stages during treatments.
- For complex fracturing drainage volumes shapes may drain less height and more area
  - Affects well spacing decisions

Acknowledgements

- CGG
- My colleagues from across the industry and …

by Stephan Pastis April 02, 2007

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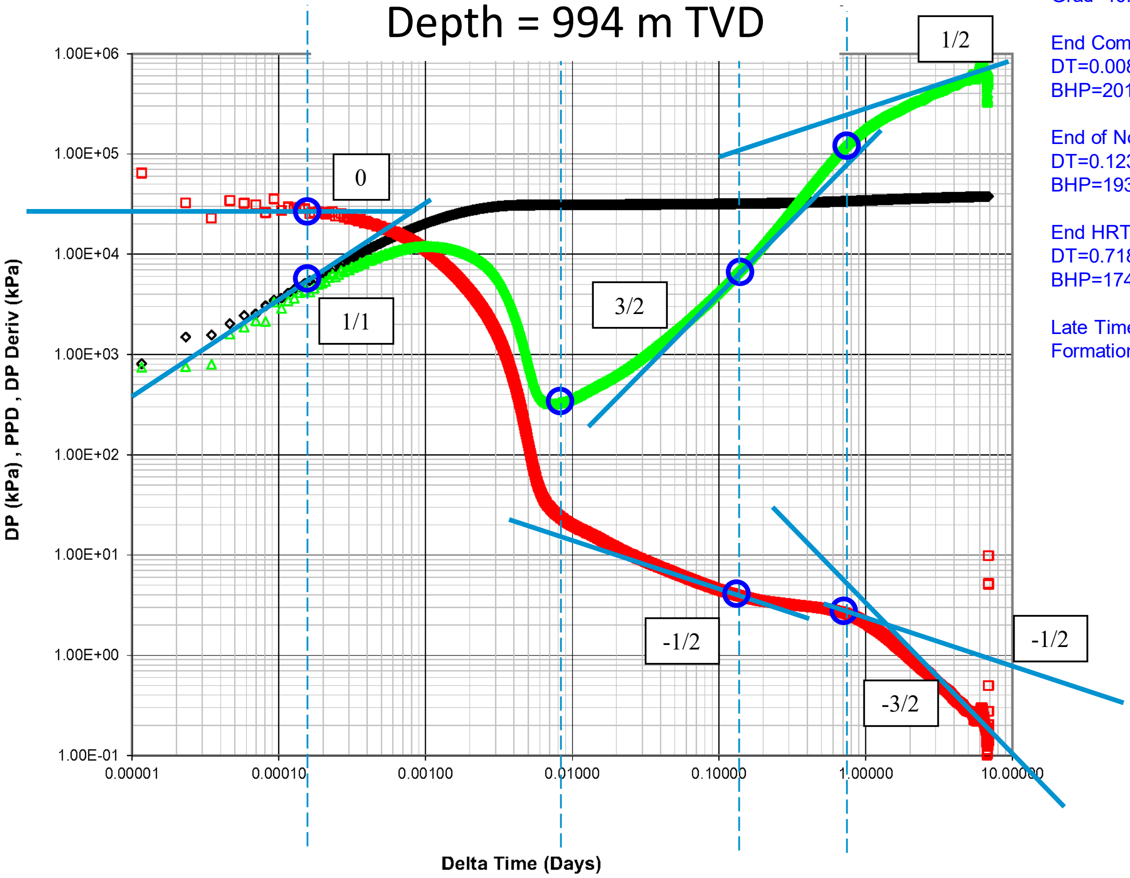
Appendix

Lithic Glauconitic Well
Depth = 994 m TVD



End WBS, DT=0.00015, G=0.03, BHP=46069, Grad=46.4

End Complexity, DT=0.00815, G=1.05, BHP=20142, Grad=20.3

End of Nolte Flow, DT=0.12329, G=6.68, BHP=19339, Grad=19.5

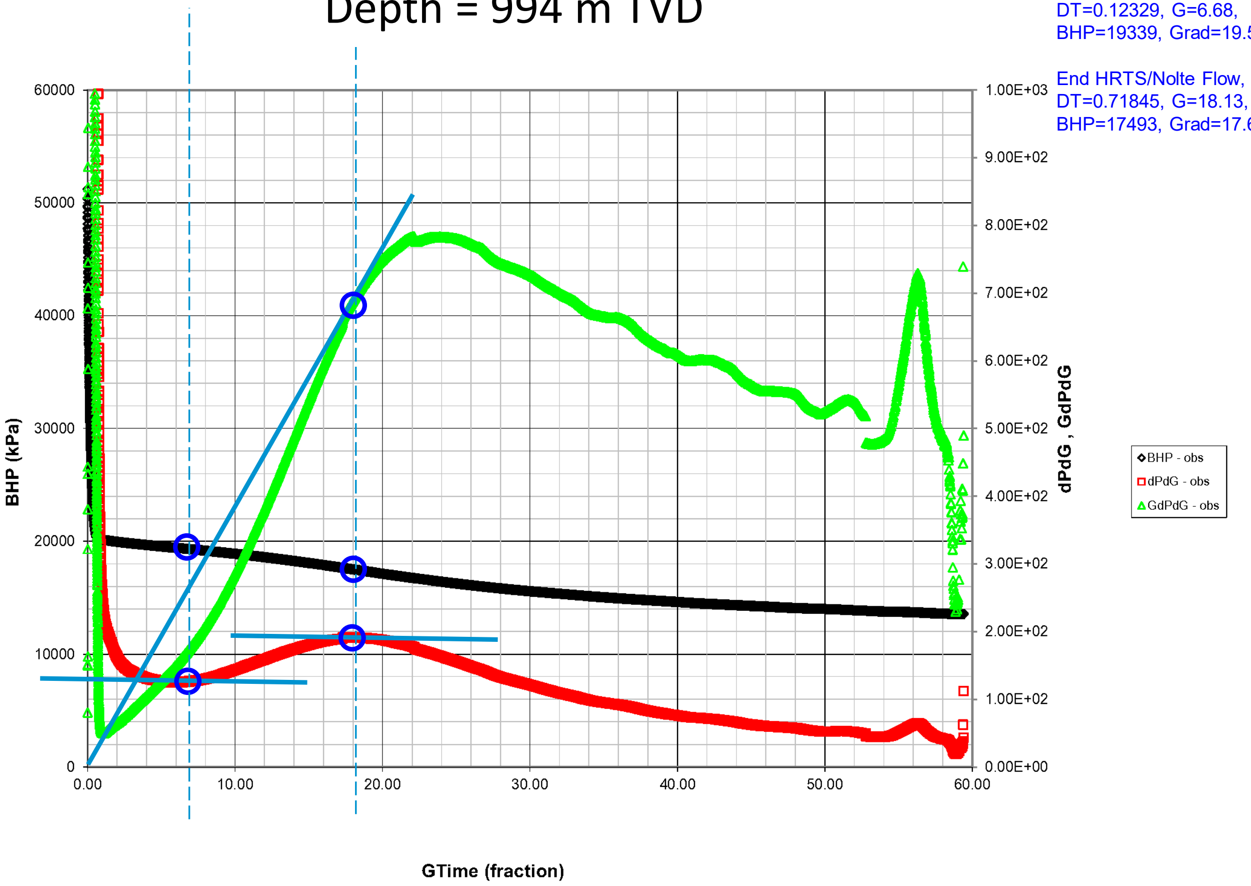
End HRTS/Nolte Flow, DT=0.71845, G=18.13, BHP=17493, Grad=17.6

Late Time Transition to Formation Linear Flow

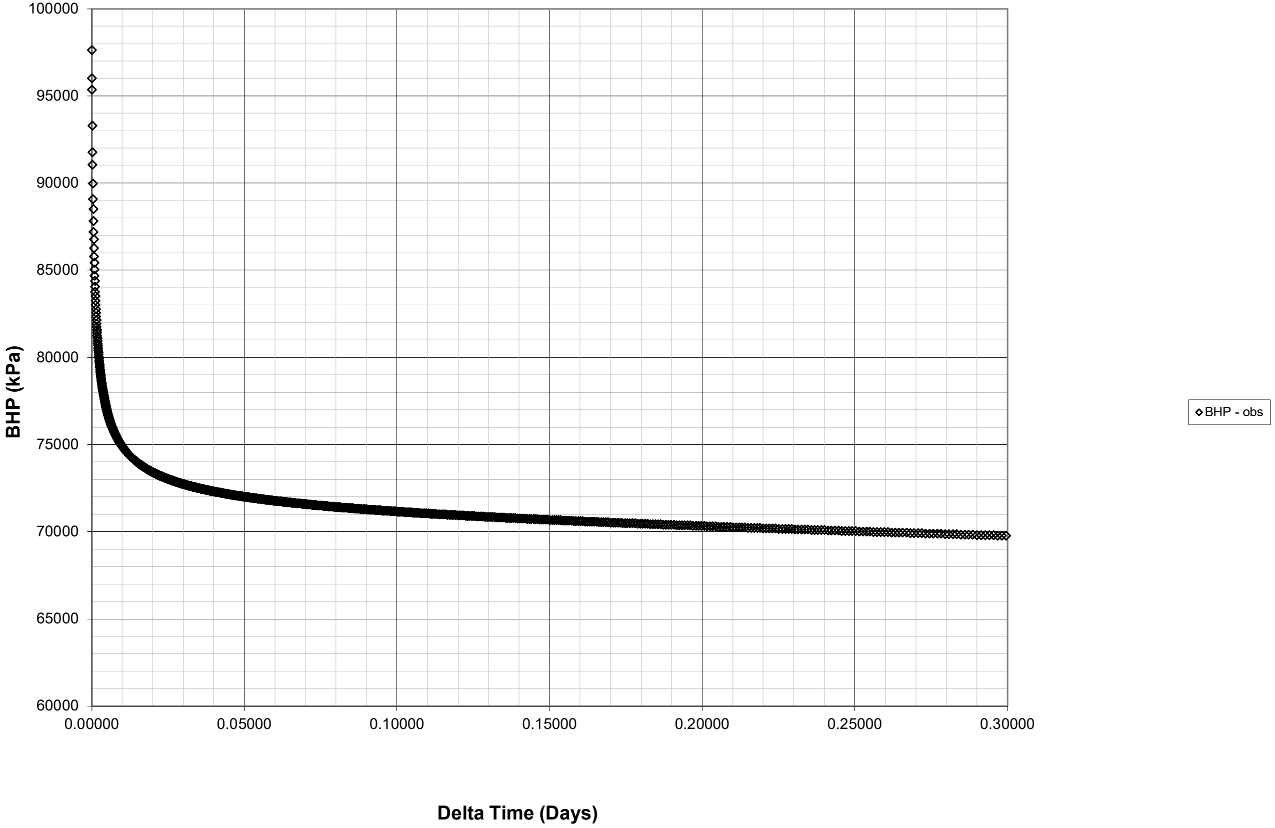
Lithic Glauconitic Well
Depth = 994 m TVD

End of Nolte Flow,
DT=0.12329, G=6.68,
BHP=19339, Grad=19.5

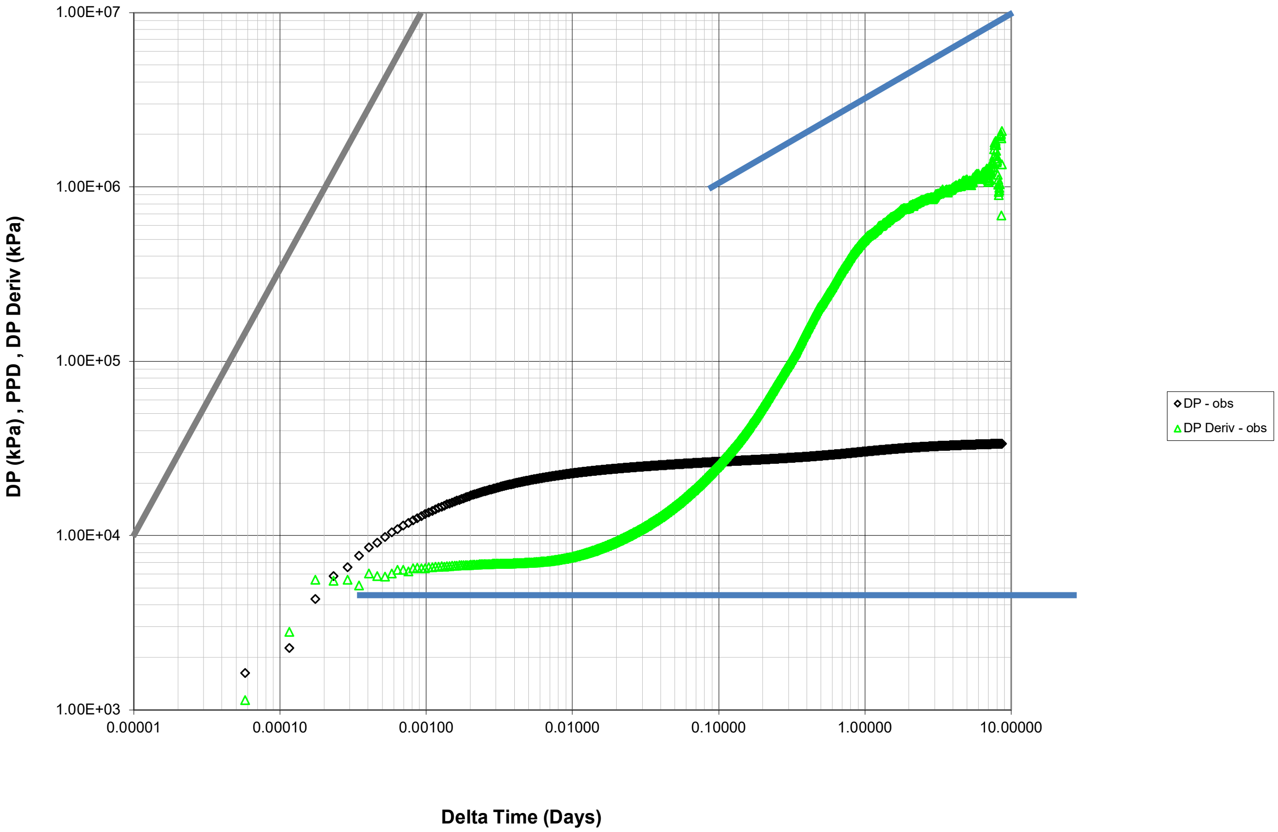
End HRTS/Nolte Flow,
DT=0.71845, G=18.13,
BHP=17493, Grad=17.6



SPE 196194 Figure 5 Case - 3408 m TVD
Flow Period FP_0002_FO - Q=0.0 L/min
FP Start=0.00492 days, FP End=8.64896 days



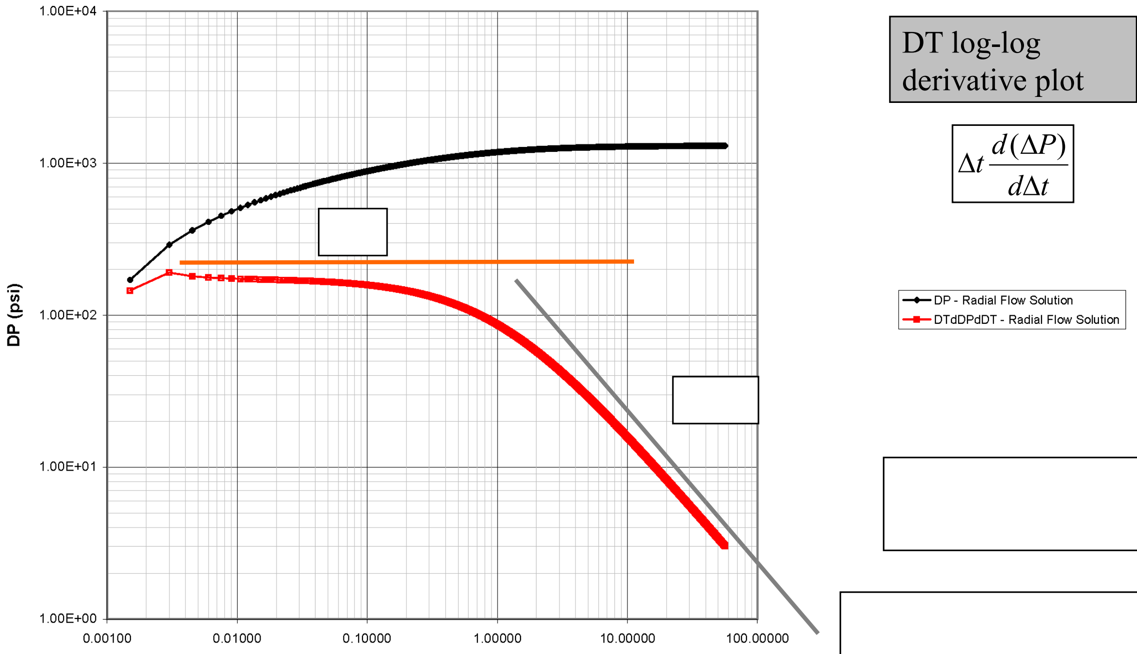
SPE 196194 Figure 5 Case - 3408 m TVD
Flow Period FP_0002_FO - Q=0.0 L/min
FP Start=0.00492 days, FP End=8.64896 days

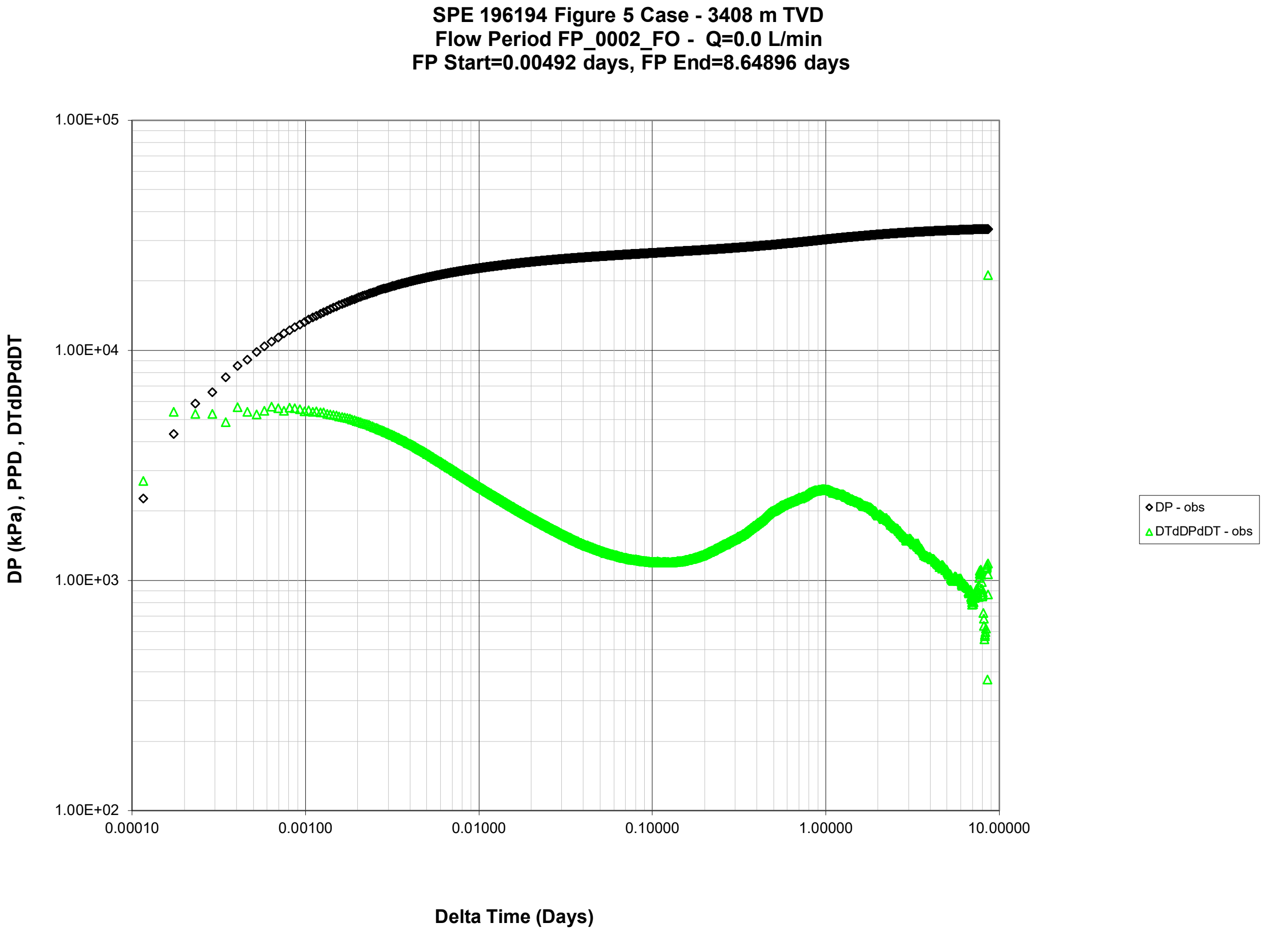


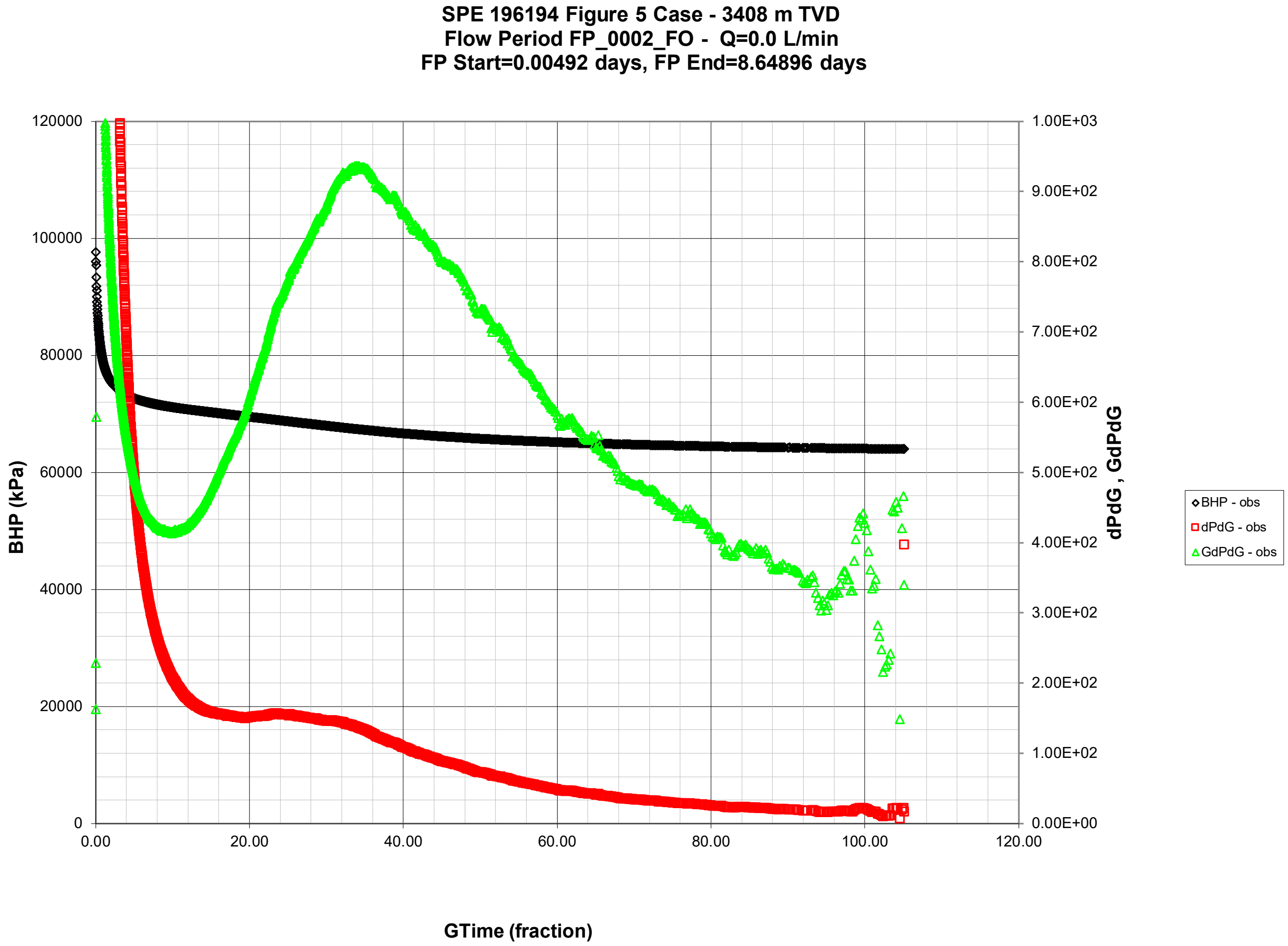
Early Time Slope = 0
Late Time Slope = -1.0

DT log-log derivative plot

$$\Delta t \frac{d(\Delta P)}{d\Delta t}$$




SPE 196194 Figure 5 Case - 3408 m TVD
Flow Period FP_0002_FO - Q=0.0 L/min
FP Start=0.00492 days, FP End=8.64896 days
1.00E+05
1.00E+04
1.00E+03
1.00E+02
DP (kPa) , PPD , DTdDPdDT
0.00010
0.00100
0.01000
0.10000
1.00000
10.00000
Delta Time (Days)
DP - obs
DTdDPdDT - obs


SPE 196194 Figure 5 Case - 3408 m TVD
Flow Period FP_0002_FO - Q=0.0 L/min
FP Start=0.00492 days, FP End=8.64896 days
BHP (kPa)
dPdG , GdPdG
GTime (fraction)
0
20000
40000
60000
80000
100000
120000
0.00
20.00
40.00
60.00
80.00
100.00
120.00
0.00E+00
1.00E+02
2.00E+02
3.00E+02
4.00E+02
5.00E+02
6.00E+02
7.00E+02
8.00E+02
9.00E+02
1.00E+03
BHP - obs
dPdG - obs
GdPdG - obs

Oilsands Zone - 1 Fall-off + 5 Flowbacks
Review Fall-off Only