# An Efficient and Optimized Approach to Multiple Fracturing of Horizontal Wells

## Injectivity Frcating and Assurance

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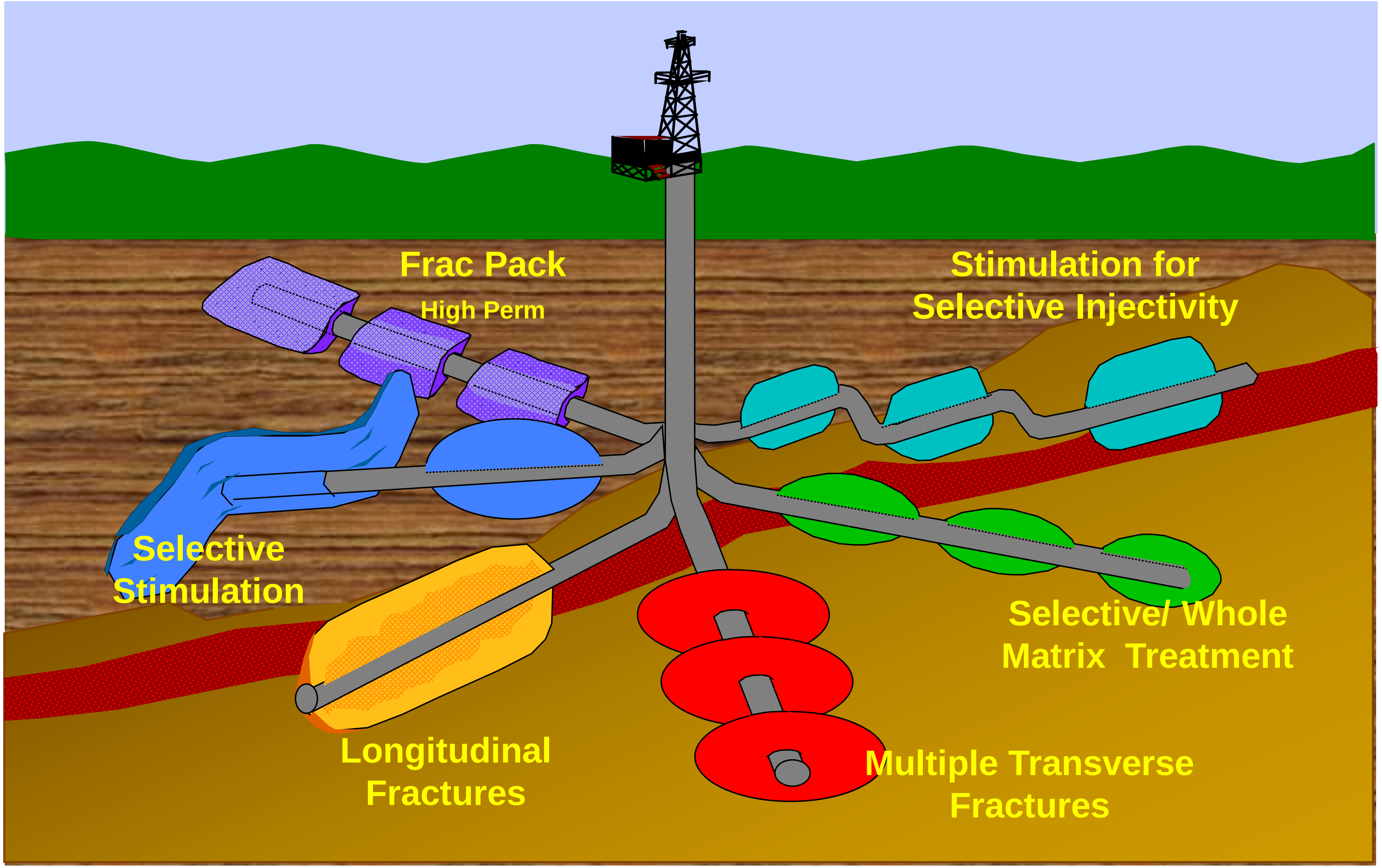
Advantek

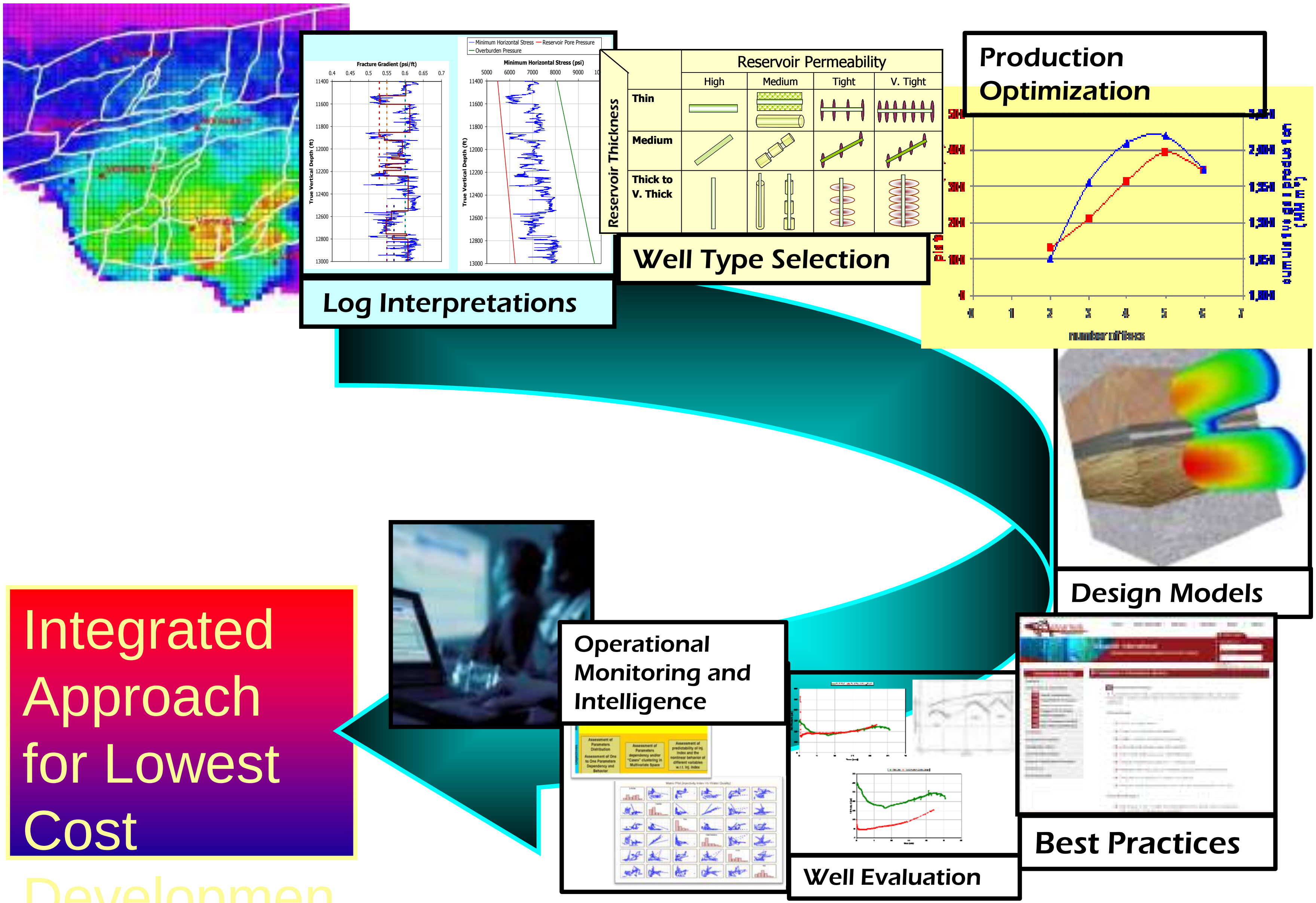
# Outline

- Introduction
- Geomechanics
- Multiple Fracturing of Horizontal Wells
- Injection Performance Test
- Monitoring, Assurance and Compliance
- SRV Assessment
- Concluding Remarks

# Variety of Fracturing Configurations



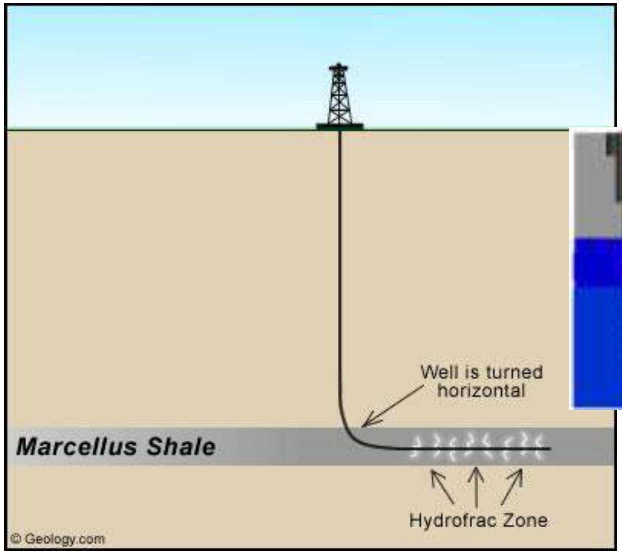
# Integrated Stimulation Process Optimization

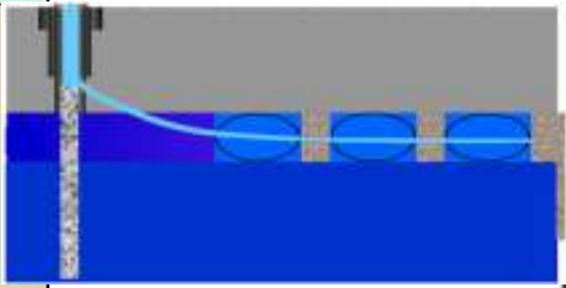


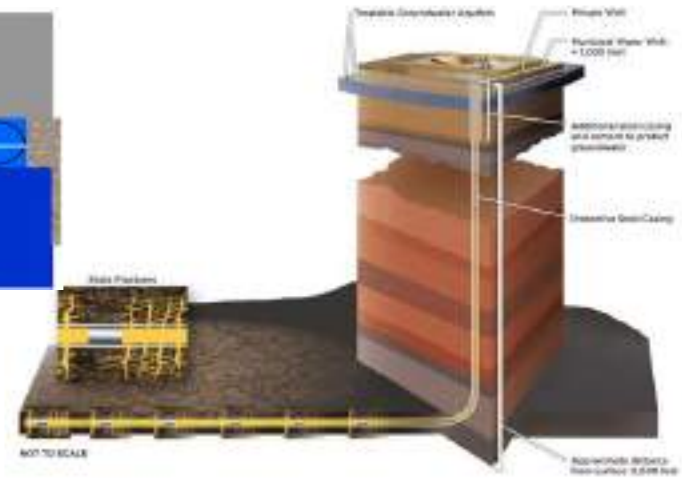

Integrated Approach for Lowest Cost Development

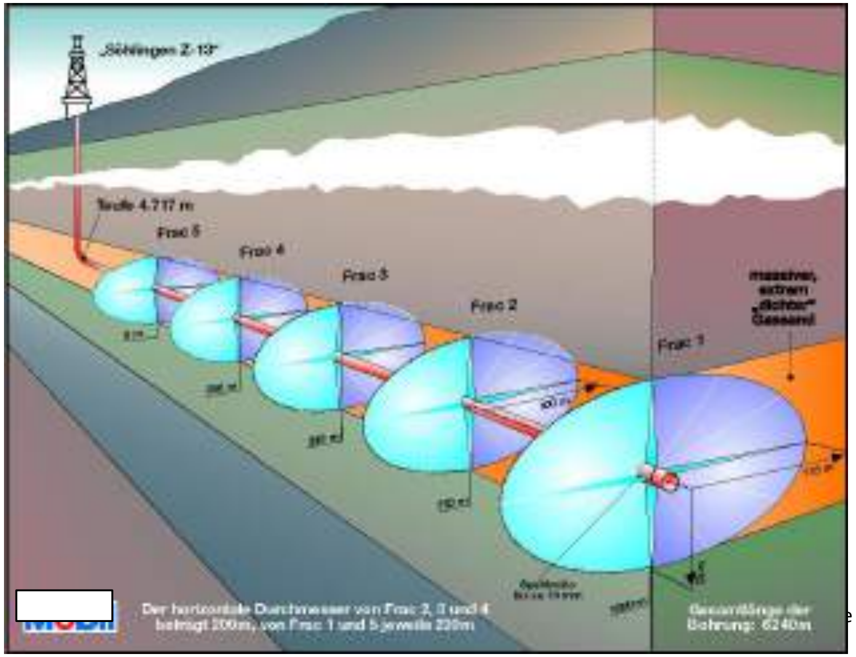
# Shale Gas Rock Successful Exploitation - Key Enabling Technologies

## Horizontal Drilling
## +
## Hydraulic Fracturing

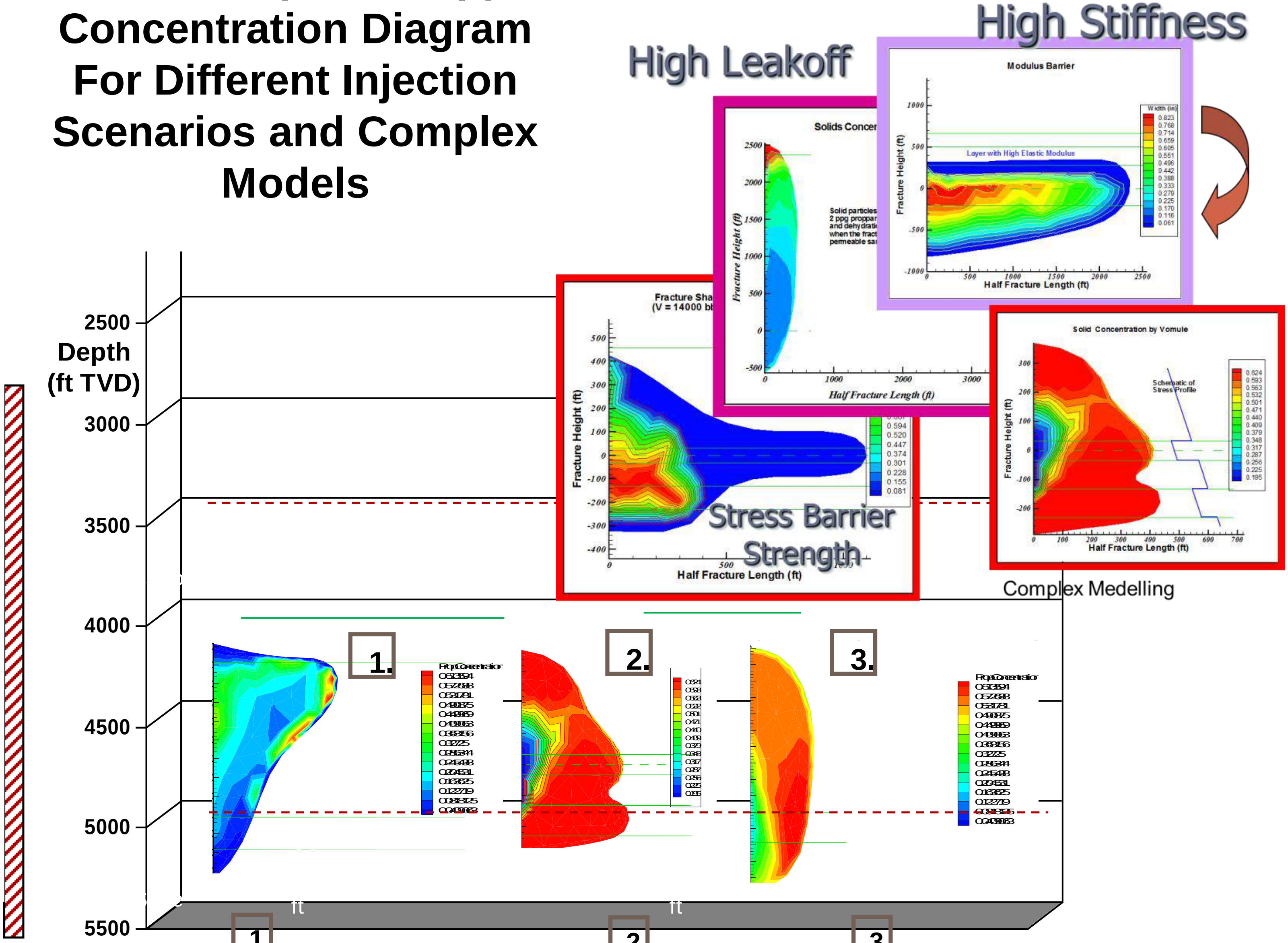







# Fracture Shape & Proppant Concentration Diagram For Different Injection Scenarios and Complex Models




4752 ft Injection Point
Mid Sand Layers Modeled
5390 bbls Injected
0.81 psi/ft Shale Stress Gradient

3280 ft Injection Point
Mid Sand Layers Modeled
14000 bbls Injected
0.85 psi/ft Stress Gradient

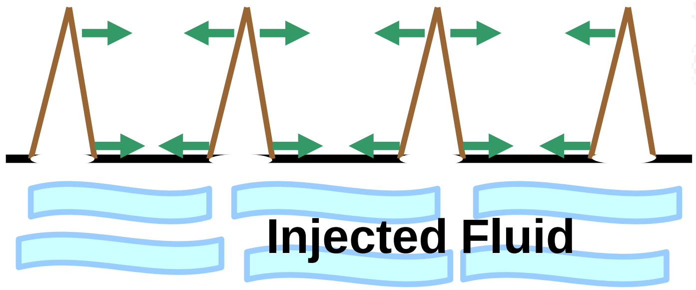
4752 ft Injection Point
Mid Sand Layers Not Modeled
13400 bbls Injected
0.81 psi/ft Stress Gradient

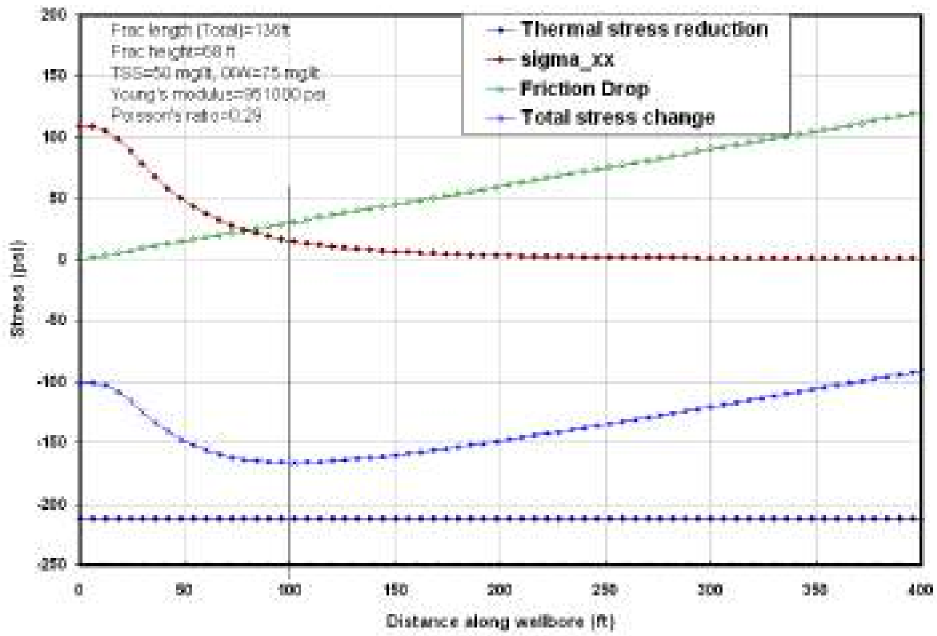
al

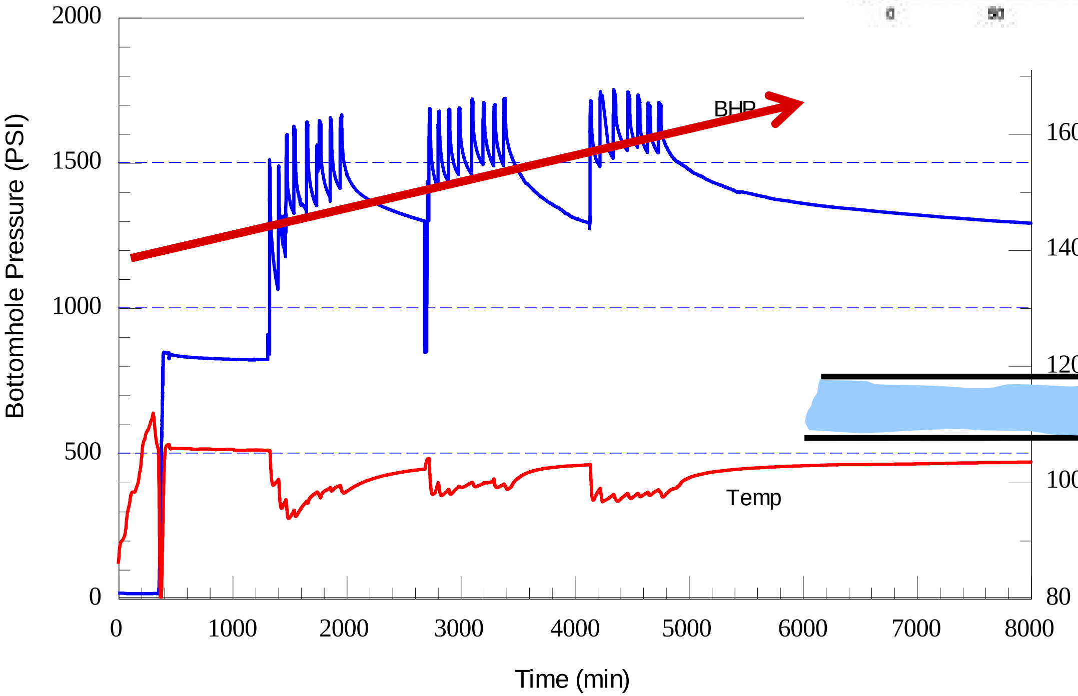
# Pressure during Sequential Pumping

Stress along Well due to Concurrent Parallel Fractures

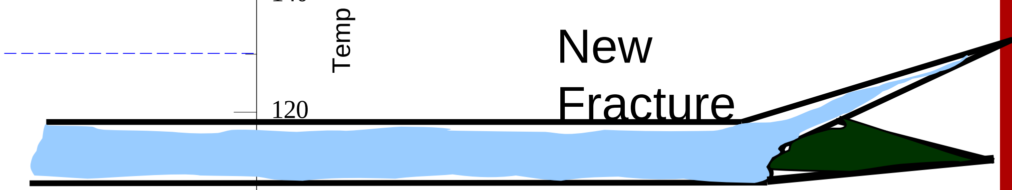
**Concurrent Fractures**



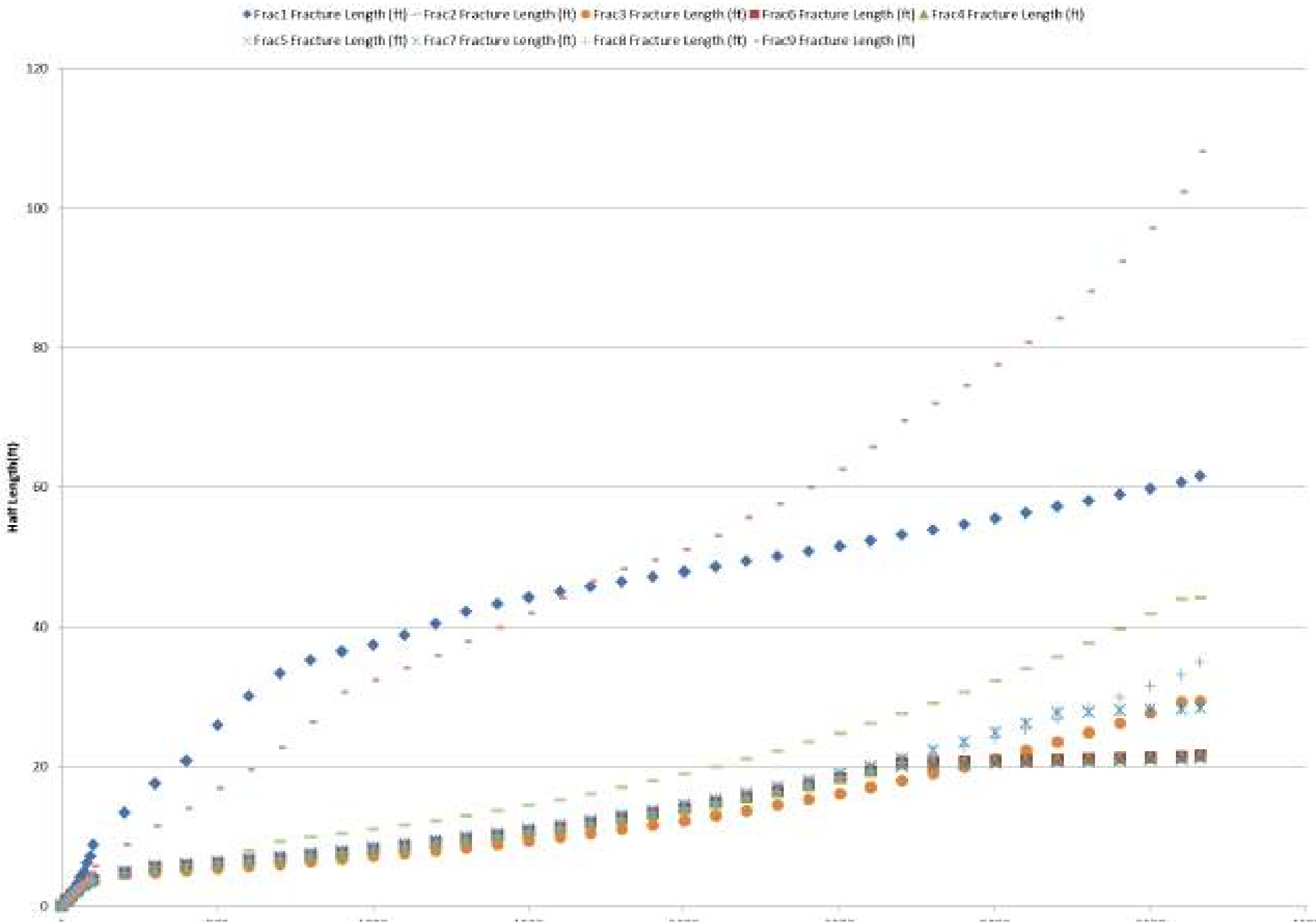



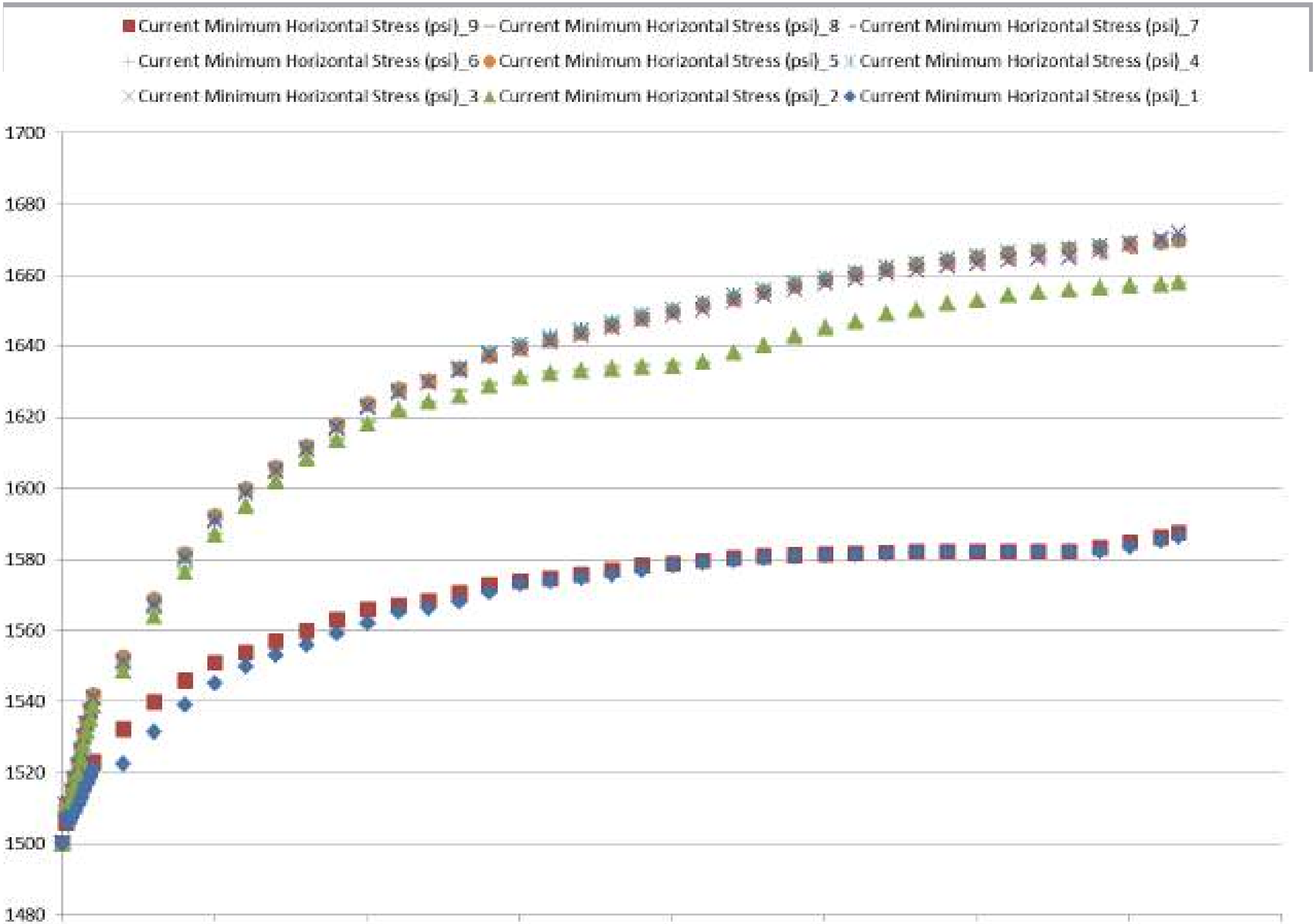




Pressure Increase due to Series Fractures

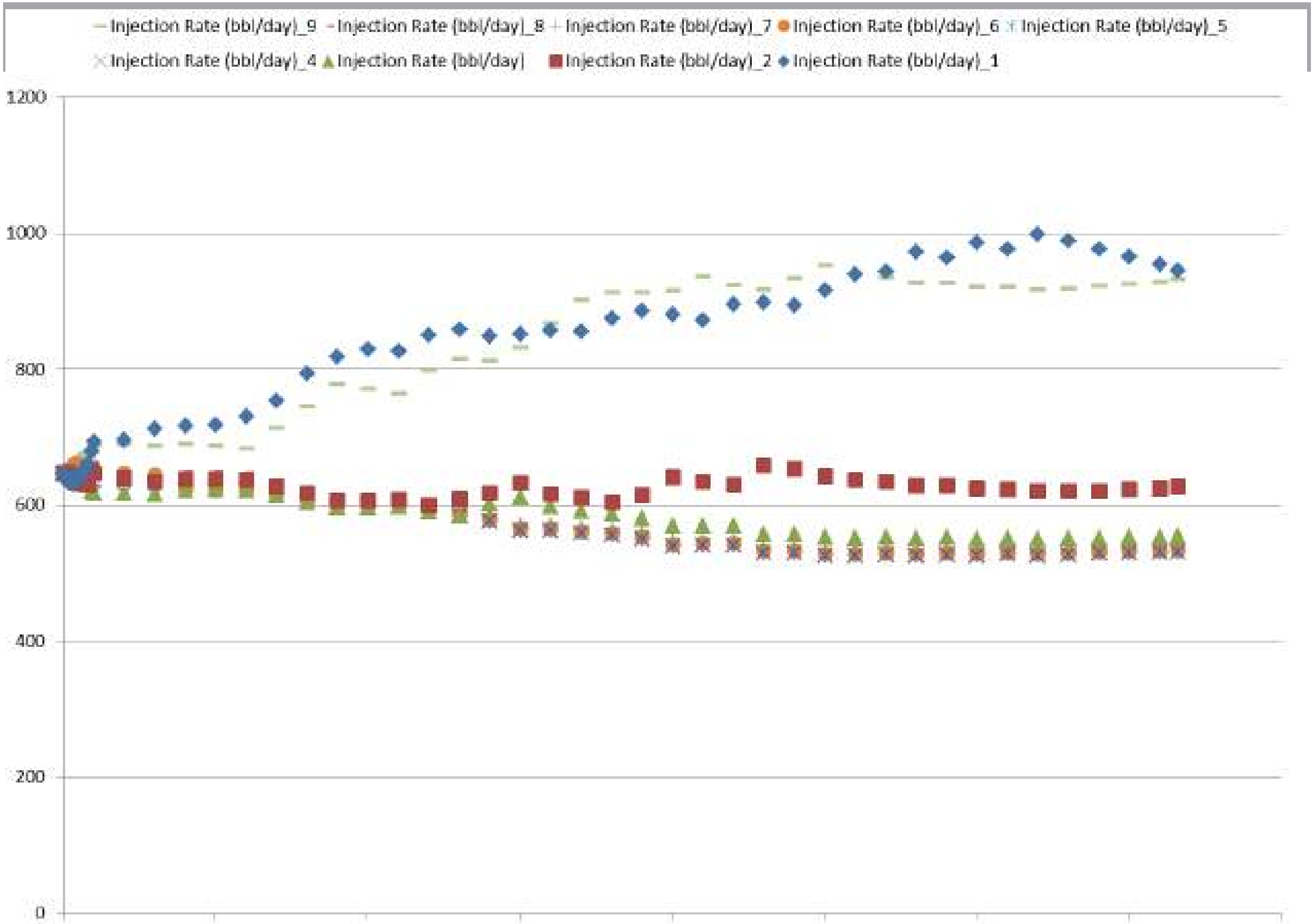



**Plugged Tip Zone**

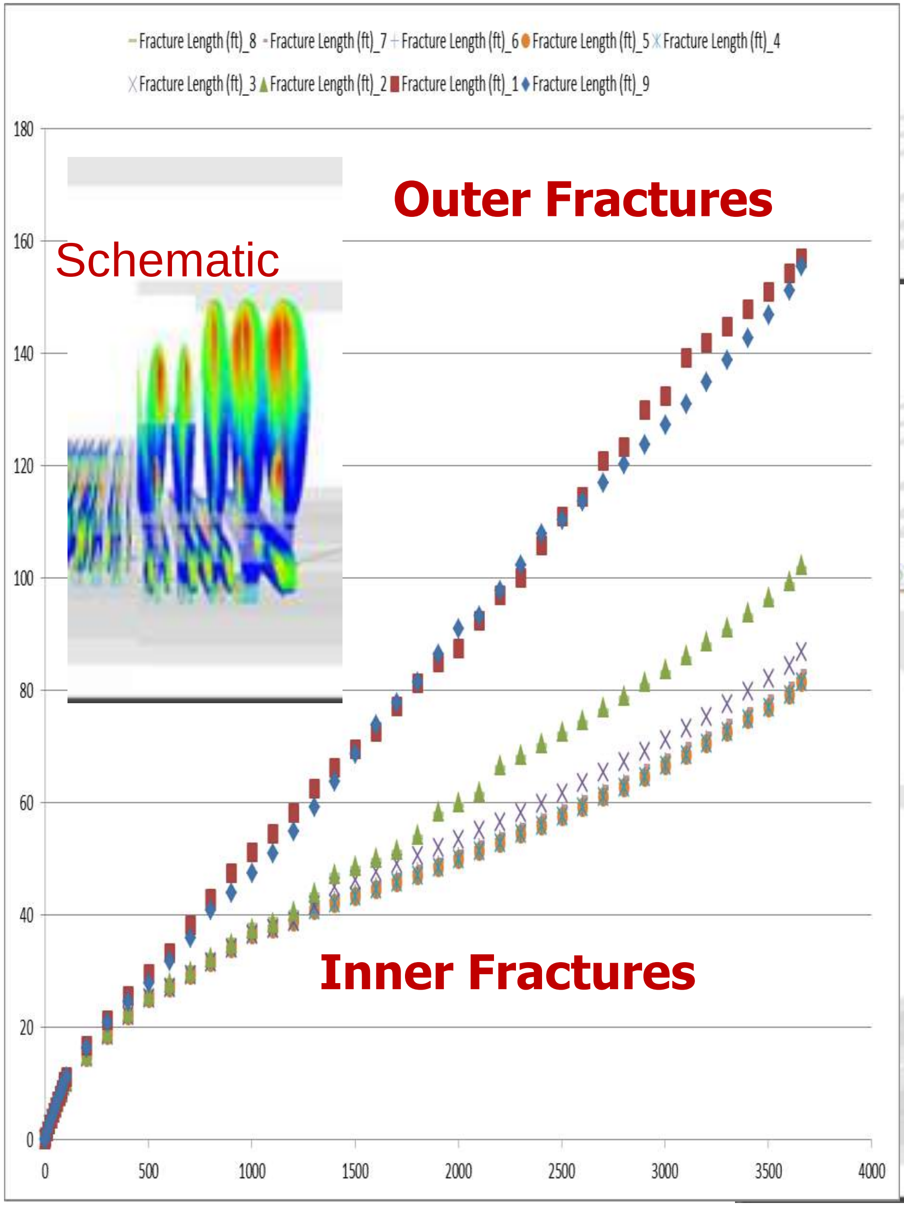

Frac1 Fracture Length (ft)
Frac2 Fracture Length (ft)
Frac3 Fracture Length (ft)
Frac6 Fracture Length (ft)
Frac4 Fracture Length (ft)
Frac5 Fracture Length (ft)
Frac7 Fracture Length (ft)
Frac8 Fracture Length (ft)
Frac9 Fracture Length (ft)
Half Length (ft)
120
100
80
60
40
20
0

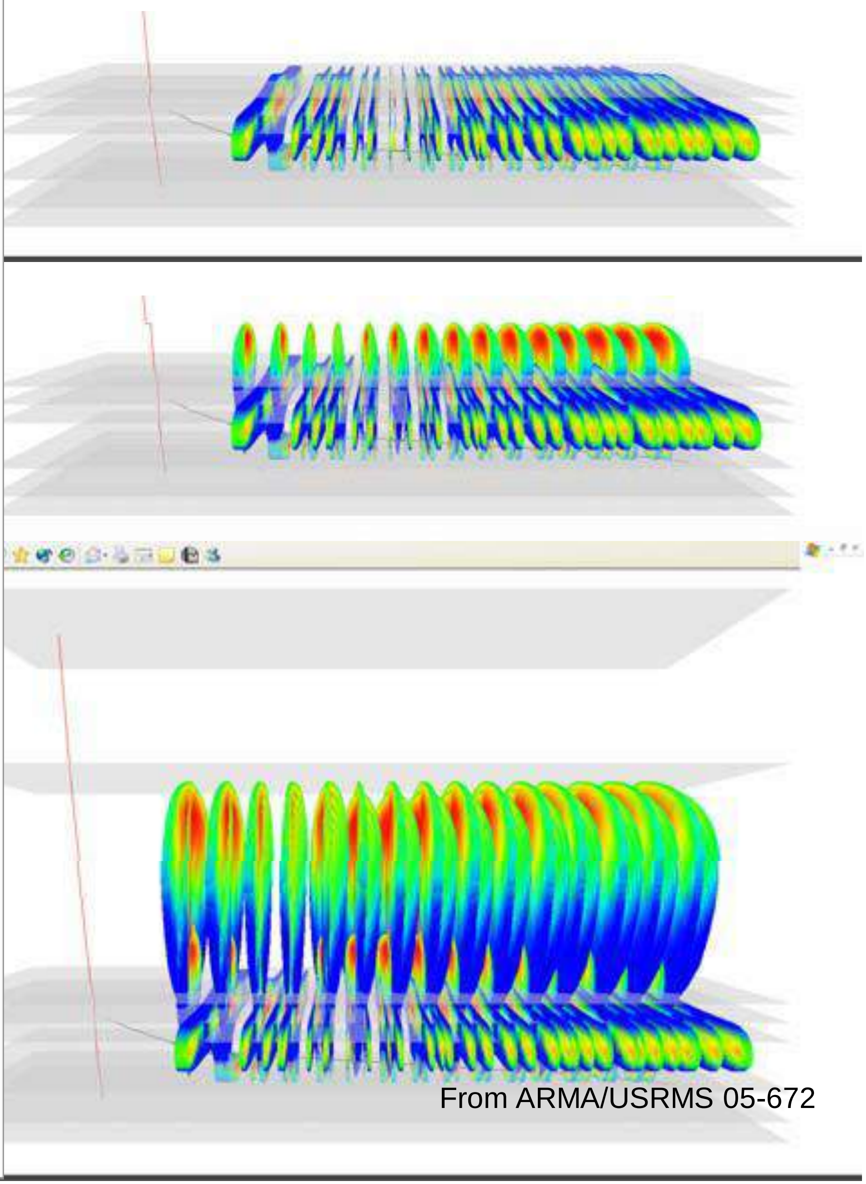


Current Minimum Horizontal Stress (psi)_9
Current Minimum Horizontal Stress (psi)_8
Current Minimum Horizontal Stress (psi)_7
Current Minimum Horizontal Stress (psi)_6
Current Minimum Horizontal Stress (psi)_5
Current Minimum Horizontal Stress (psi)_4
Current Minimum Horizontal Stress (psi)_3
Current Minimum Horizontal Stress (psi)_2
Current Minimum Horizontal Stress (psi)_1
1700
1680
1660
1640
1620
1600
1580
1560
1540
1520
1500
1480


Injection Rate (bbl/day)_9
Injection Rate (bbl/day)_8
Injection Rate (bbl/day)_7
Injection Rate (bbl/day)_6
Injection Rate (bbl/day)_5
Injection Rate (bbl/day)_4
Injection Rate (bbl/day)
Injection Rate (bbl/day)_2
Injection Rate (bbl/day)_1
1200
1000
800
600
400
200
0

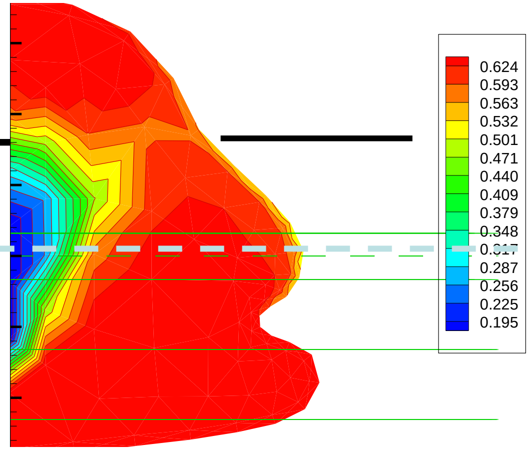
# Stress Impact during multiple fracturing in a Horizontal Well

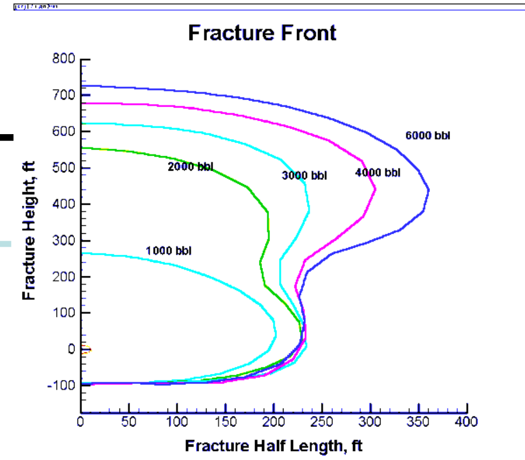


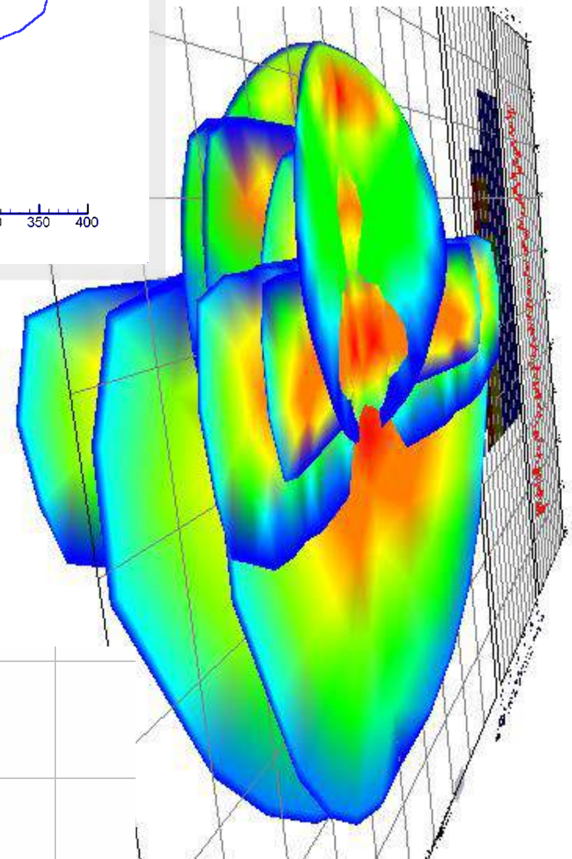

Multiple Intervals

Single Interval

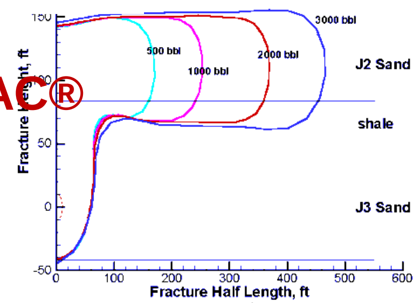


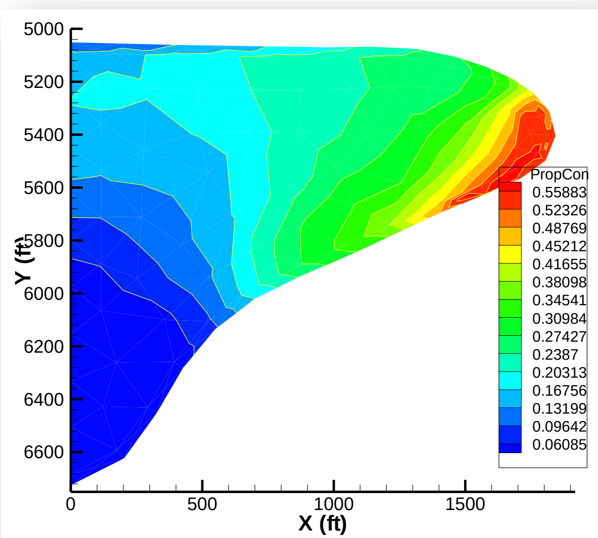



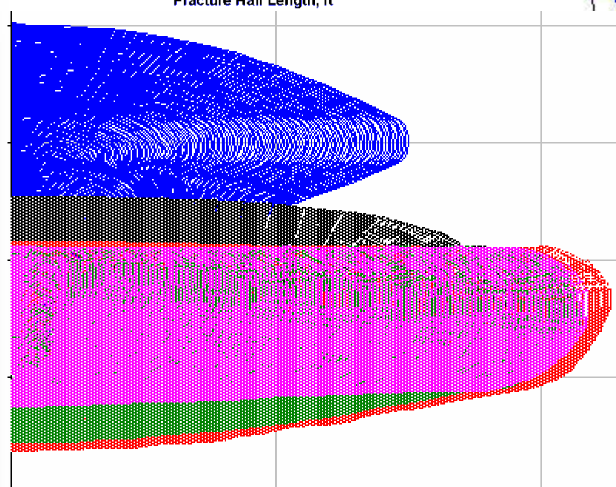

Fracture Front



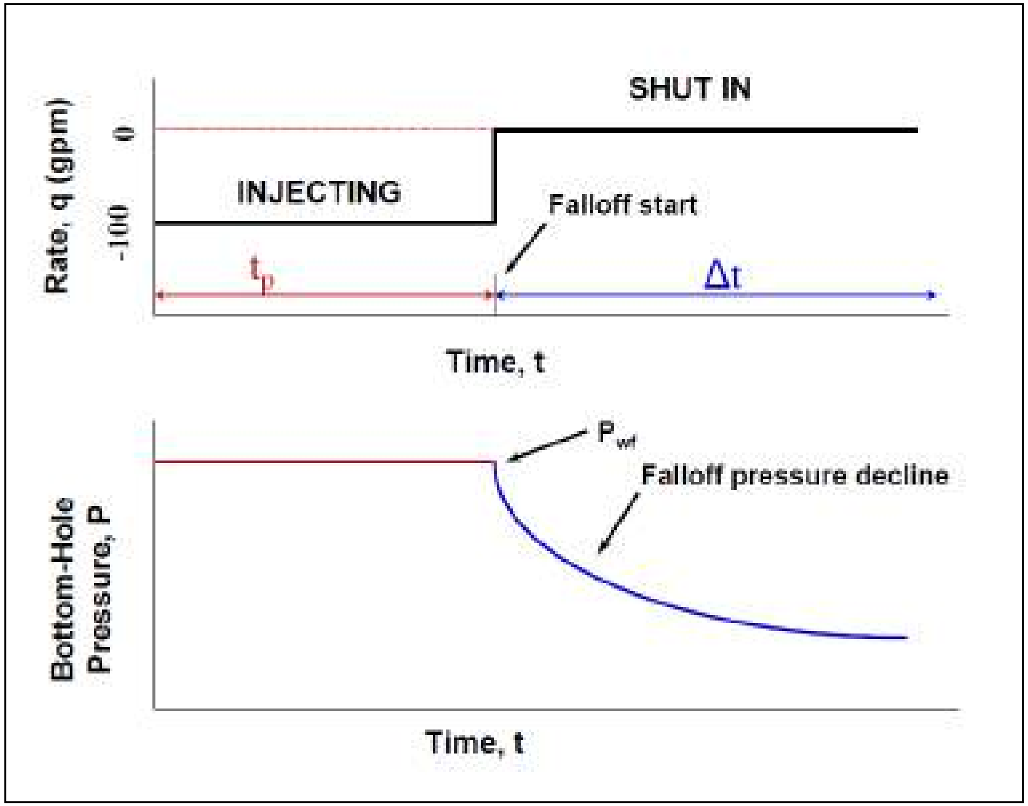
# Simulated fracture using @FRAC®



# Pressure Falloff Data

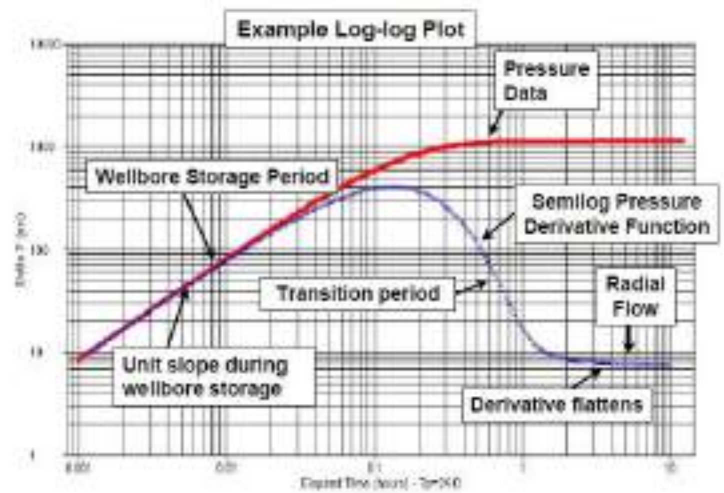


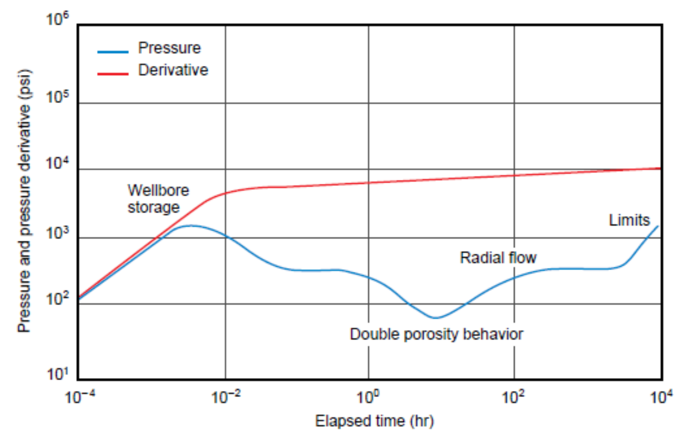

**Pressure Transient Theory** is used to determine **Reservoir Parameters** from the measured **Pressure Response (Flow Regimes)**

PTA-IFOTool

# Conventional Pressure Transient Response

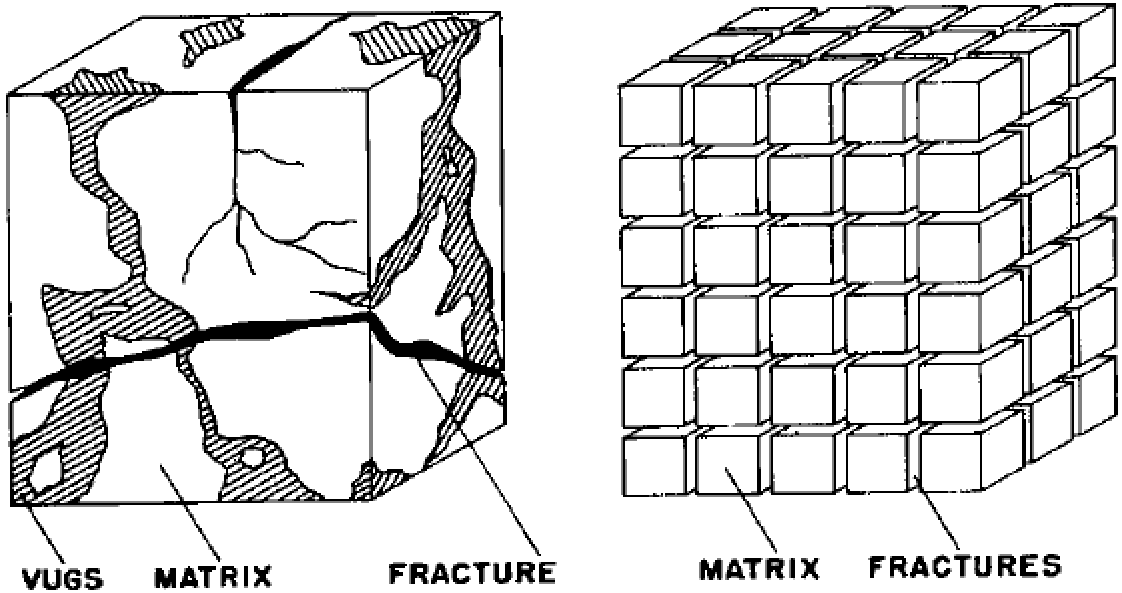
- Relies on pressure and derivative plots after shut-in to draw information about reservoir characteristics.
- Typical flow regimes such as wellbore storage, linear, and radial flow can be deduced from the plots.
- Different flow regimes can be observed by modification of the basic governing equations and the boundary conditions.
- Modifications include , for example, consideration of complications imposed by geometry, reservoir boundaries, porosity, mobility etc.



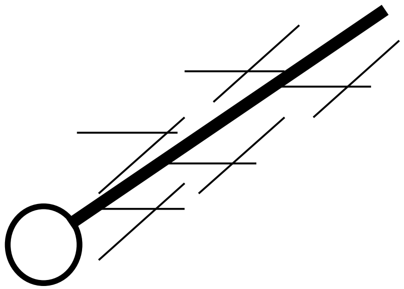

Pictures: Courtesy of EPA and Schlumberger

# Dual porosity model

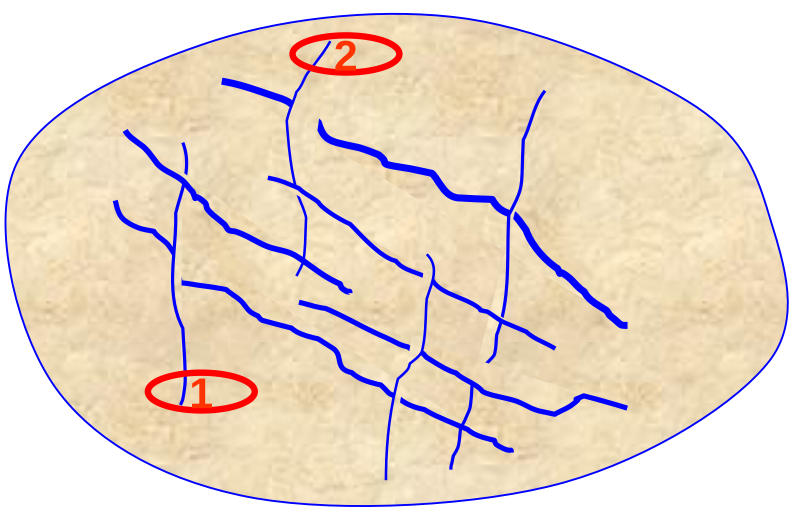


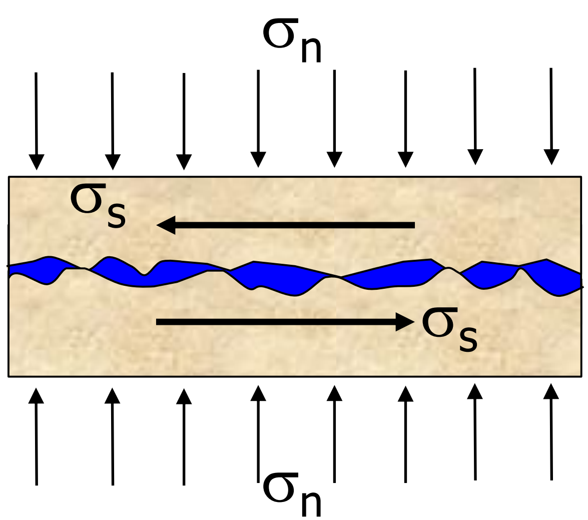

ACTUAL RESERVOIR MODEL RESERVOIR

(Warren and Root, 1963)



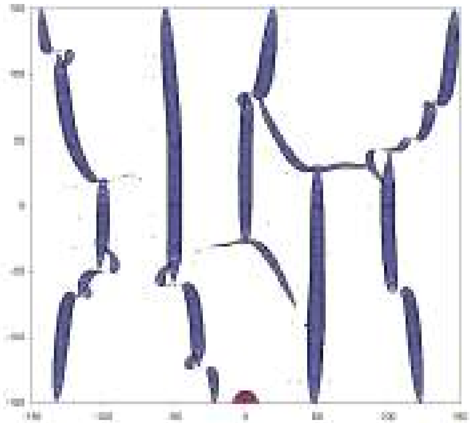
**Conjugate Fractures**

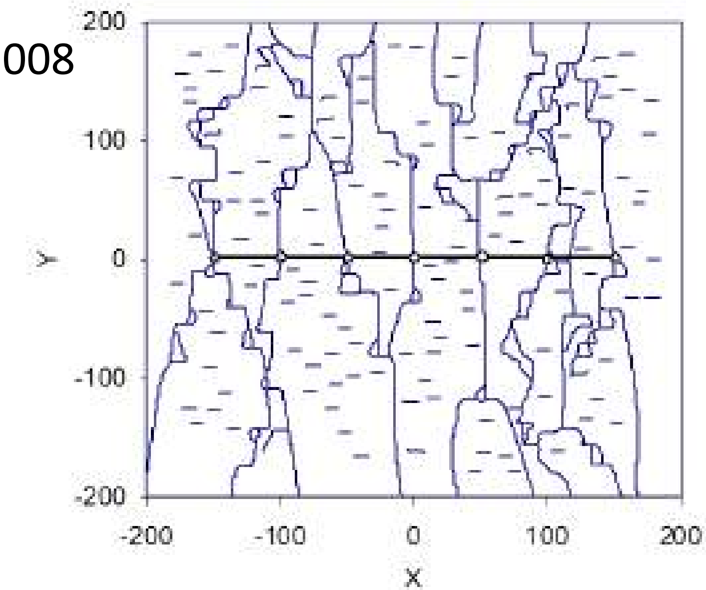


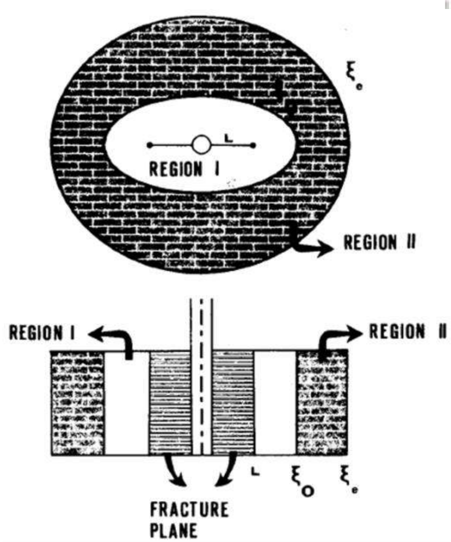



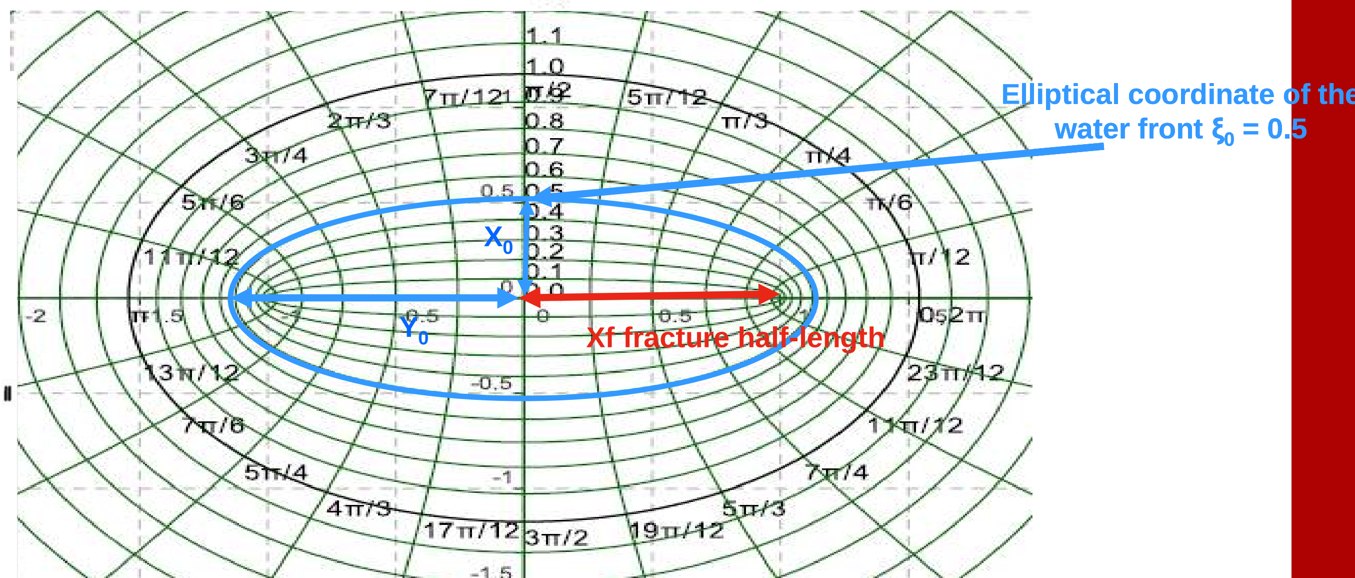
# Problem Configuration

Olson, 2008

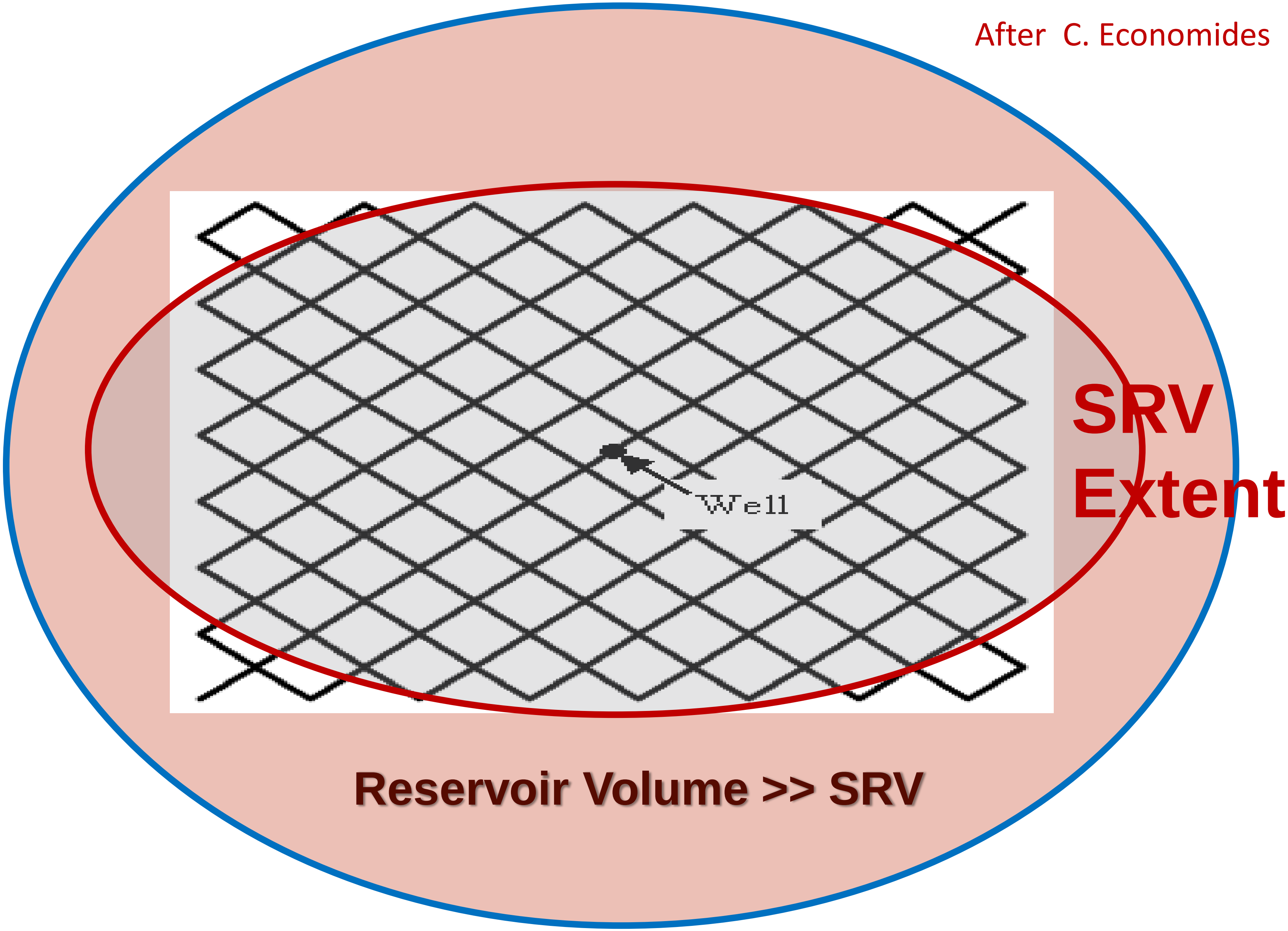




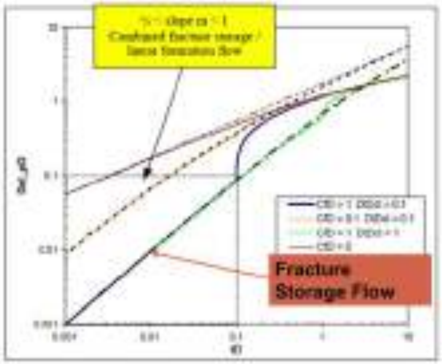



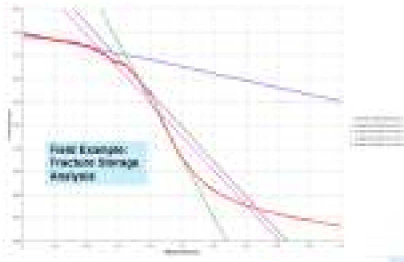



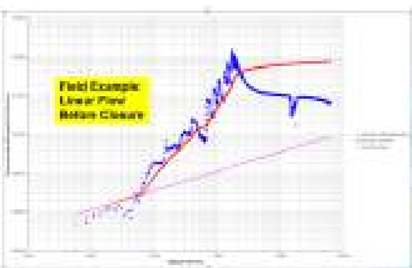
After C. Economides

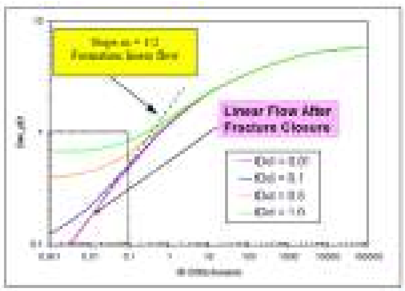


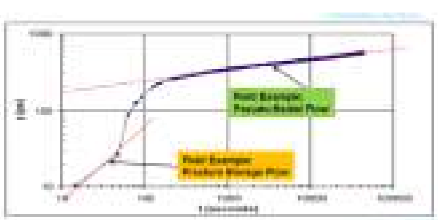
# PTA-IFO Conventional Methods of Analysis

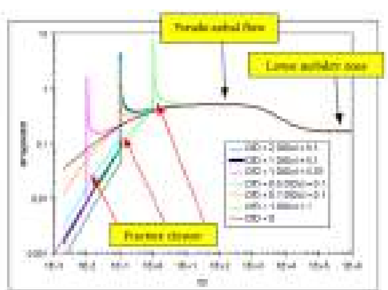


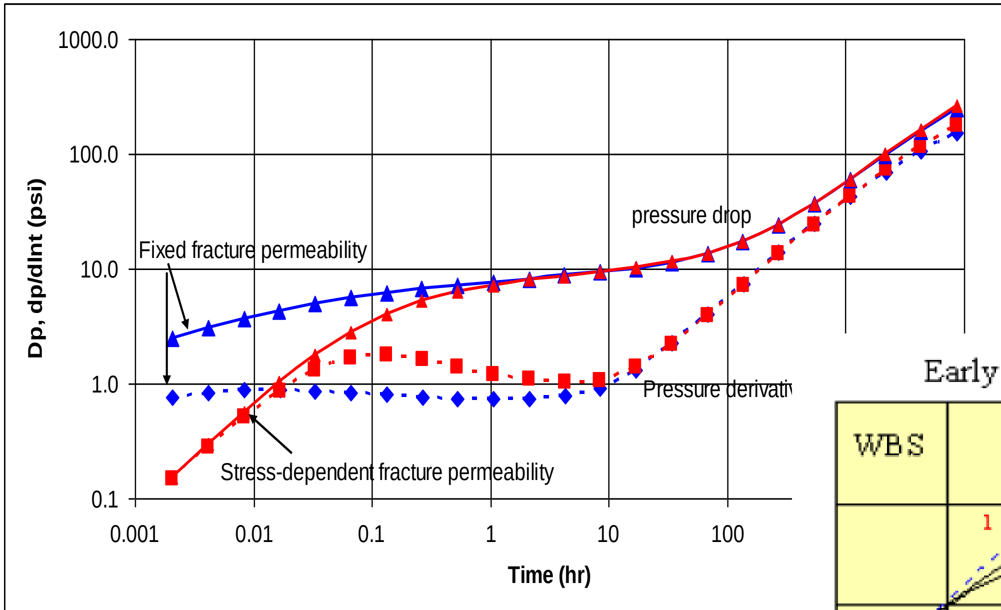


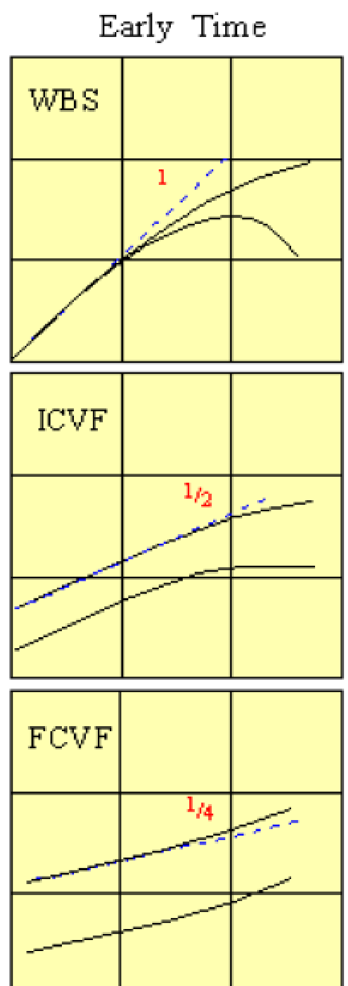





- Method 1: Using Storage Dominated Flow
  - Recognized by a straight line on the pressure vs. time plot.
  - The slope of this linear part of pressure curve is equal to q/Cf from which **Fracture Storage Coefficient** can be determined. From Cf, **Fracture Length** can be calculated, considering different fracture types (PKN, CGK, Elliptical).
- Method 2 : Using Linear Formation Flow
  - Recognized by a straight line with a half slope on the log-log plot
  - From semi-log analysis and using fluid and relative permeability data, the ratio {viscosity/(permeability*porosity*total compressibility)} can be calculated.
  - From a plot of Pf vs. square root of time, the above ratio is related to flow and Fracture Dimensions (h*L) so that **Fracture Length**. Can be calculated.
- Method 3: Using late time Pseudo-Radial Flow
  - **Permeability** of Inner and Outer Zones plus **Mobility discontinuity** can be determined




(After Economidis and Ghassimi,)




# :onventional Pressure 'ransient Analyses for 'ractured Wells

Two typical models for a single vertical fracture:

- Infinite-Conductivity Vertical Fracture (ICVF)
- Finite Conductivity Vertical Fracture (FCVF)

Typical type curves does not show dramatic and sharp change in pressure and derivative plots.

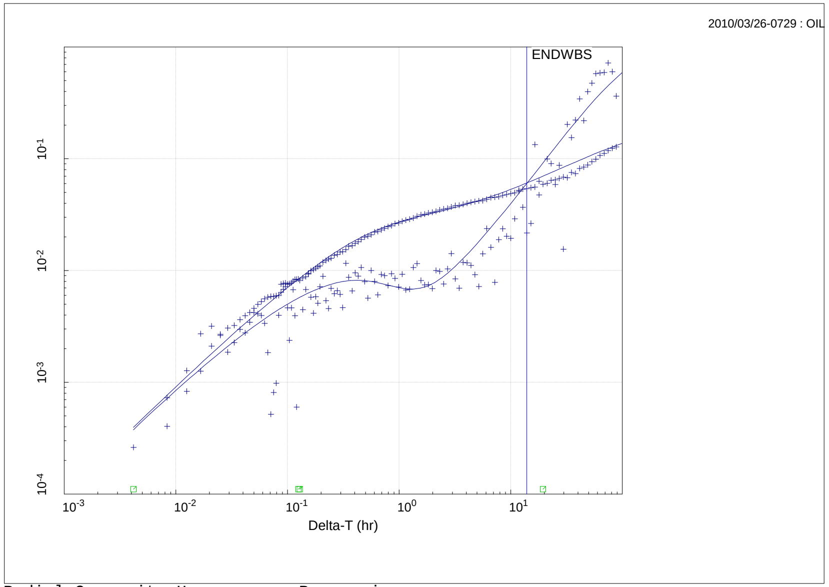
Slope of the type curve indicate different flow regimes (linear or bi-linear flow) and fracture conductivity.

Picture: Courtesy of Schlumberger

# Technology Premise

## Pressure Transient Response in Multi-Fractured Vertical Wells

- The multiple fractures create a fracture network system that appears to mimic the signature of radial composite flow with more complexities.
- The inner zone has what appears to be an increased permeability that is brought about due to the elevated conductivity of the fracture network in comparison to the native formation permeability and mobility.
- Figure shows analyses of a multi-fractured injection well using a radial composite mode. The reasonable match, however, does not accurately reflect the system physics and fails to correctly provide the understanding of the fracture network makeup.




Radial Composite Homogeneous Reservoir

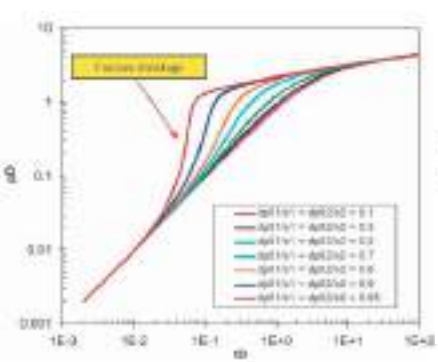
** Simulation Data **
well. storage = 0.39474 BBLS/PSI
Skin(mech.) = -4.1053
permeability = 2.4799 MD
Perm.(inner) = 38.500 MD
Stor.rto+x o/i = 0.034984
Inner Radius = 116.87 FEET
Skin(Global) = -5.0419
Mobility+x o/i = 0.064412
Perm-Thickness = 148.79 MD-FEET
Initial Press. = 6554.01 PSI
Smoothing Coef = 0.,0.

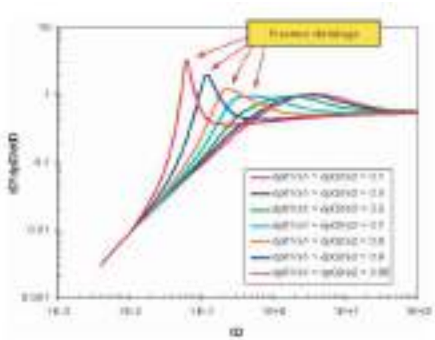
Static-Data and Constants
Volume-Factor = 1.000 vol/vol
Thickness = 60.00 FEET
Viscosity = 1.000 CP
Total Compress = .1827E-04 1/PSI
Rate = -4219. STB/D
Storivity = 0.0002192 FEET/PSI
Diffusivity = 179.0 FEET^2/HR
Gauge Depth = N/A FEET
Perf. Depth = N/A FEET
Datum Depth = N/A FEET
Analysis-Data ID: GAU001
Based on Gauge ID: GAU001
PFA Starts: 2010-03-26 00:00:15
PFA Ends : 2010-03-29 23:33:15

# Current Limitations of Fracture Diagnostic Techniques

| Parameter | Technique | Limitation |
|---|---|---|
| Fracture Height | Tracer logs | Shallow depth of investigation: shows height only near the wellbore |
| | Temperature logs | Difficult to interpret: shallow depth of investigation shows height only near wellbore |
| | Stress profiling | Does not measure fracture directly: Must be calibrated with in-situ stress tests |
| | P3D models | Does not measure fracture directly: estimates vary depending on which model is used |
| | Microseismic | Optimally requires nearby offset well: difficult to conduct in the field |
| | Tilt meters | Difficult to interpret: expensive and difficult to conduct in the field |

| Parameter | Technique | Limitation |
|---|---|---|
| Fracture Length | P3D Models | Length inferred, not measured: estimate s vary greatly depending on which model is used |
| | Well testing | Large uncertainties depending upon assumptions and lack of pre-fracture well test data |
| | Microseismic | Optimally requires nearby offset well; difficult to interpret; expensive |
| | Tiltmeters | Difficult to interpret; expensive and difficult to conduct in the field |
| Fracture Azimuth | Core techniques | Expensive to cut core and run tests; multiple tests must be run to assure accuracy |
| | Log Techniques | Requires open hole logs to be run; does not work if natural fractures are not present |
| | Microsesmic | Analysis intensive; expensive for determination of azimuth |
| | Tilt meters | Useful only to a depth of 5000 ft; requires access to large area; expensive |







(EPA 816-R-04-003 )

# Pressure Transient Response for a Closing Fracture (Ideal Theoretical Type Curves, Single Vertical Fracture)

- Fracture closure is characterized by a sudden rapid change in pressure (determines the fracture closure pressure).
- Mixture of fracture storage flow and linear formation flow before closure.
- After closure, flow from the fracture into the formation will show a transition from linear formation flow to pseudo-radial flow.
- Fracture closure is characterized by a sharp peak

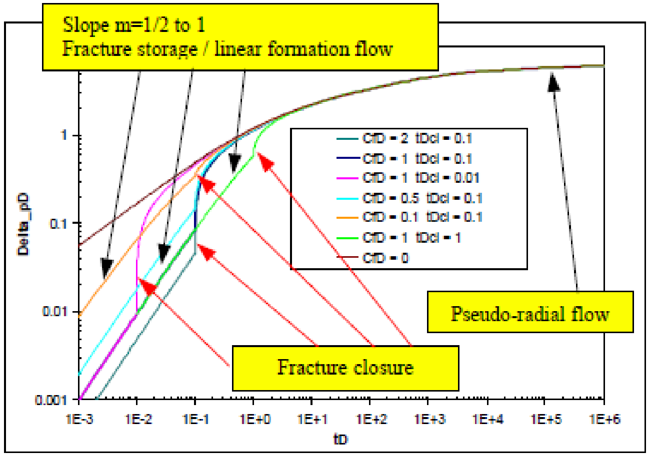
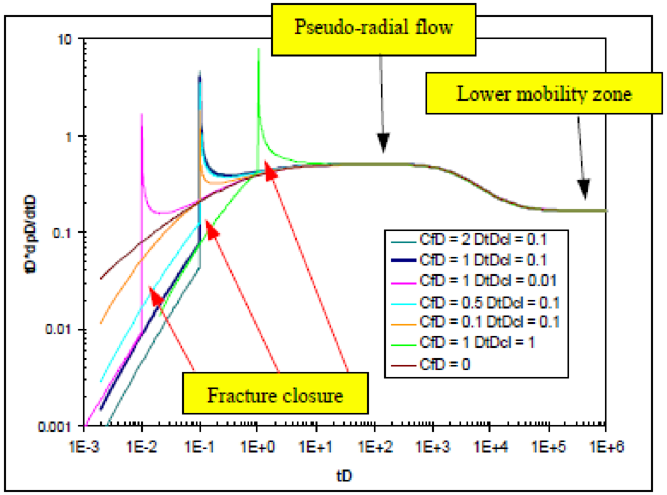
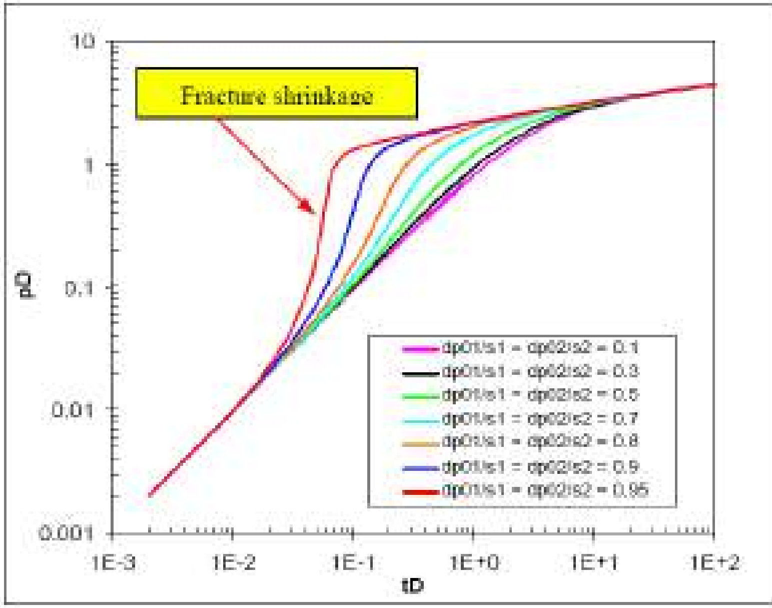


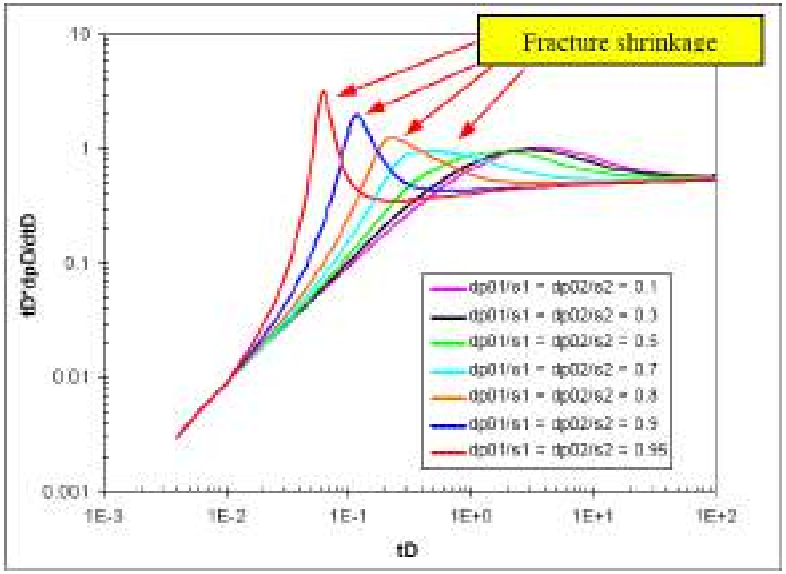

Fig. 3. Computed pressure change $\Delta p_D$ after shut-in for various fracture compliances $C_{fD}$ and fracture closure times $t_{Dcl}$. Two-zone case; mobility contrast $\kappa = 0.33$; $\xi_0 = 5$.



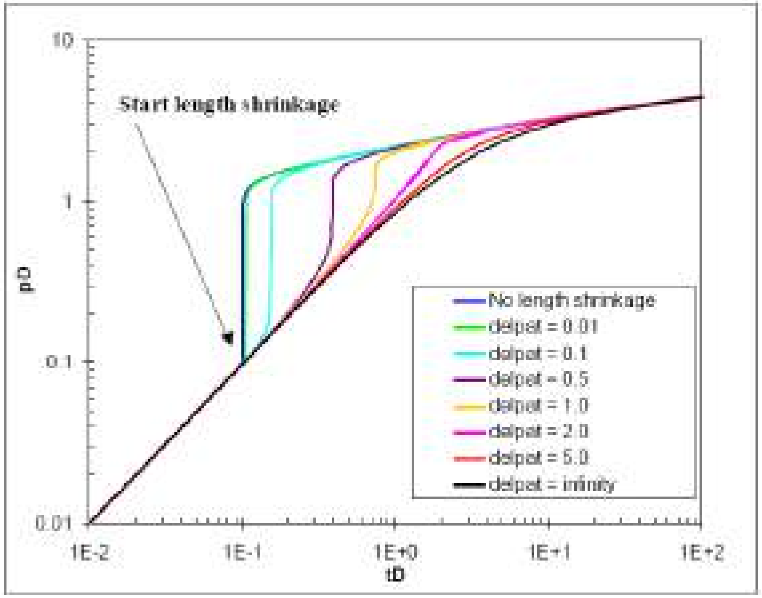

Pictures: Courtesy of van den Hoek (SPE 77946)

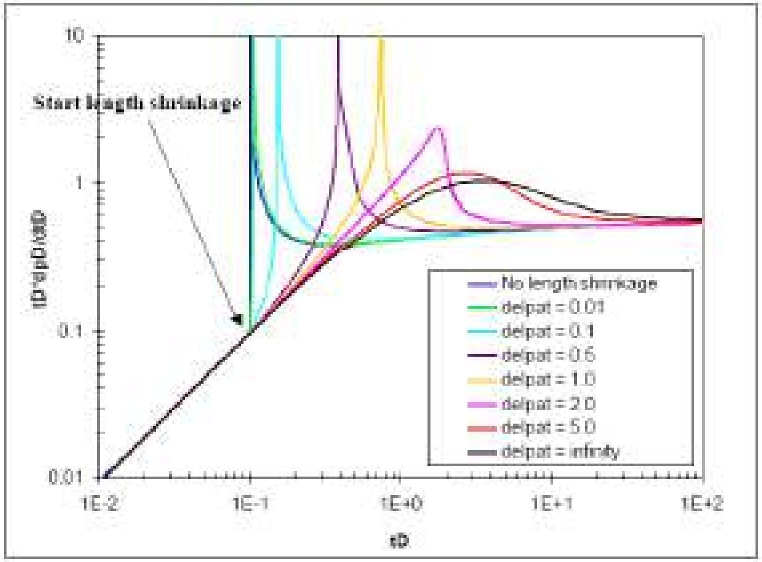
# HEIGHT SHRINKAGE



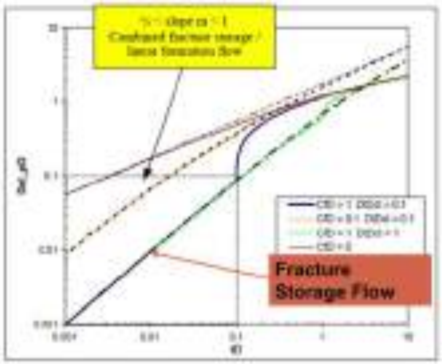



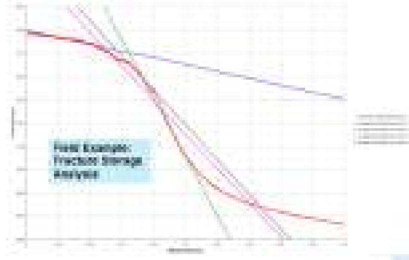

# LENGTH SHRINKAGE

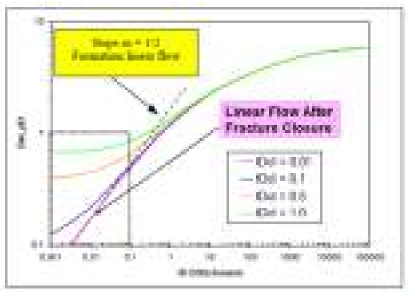


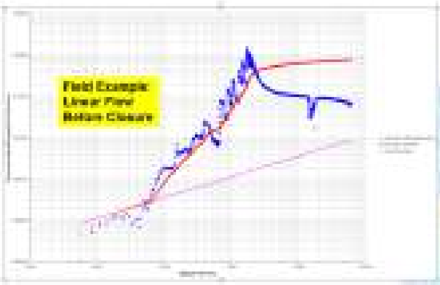



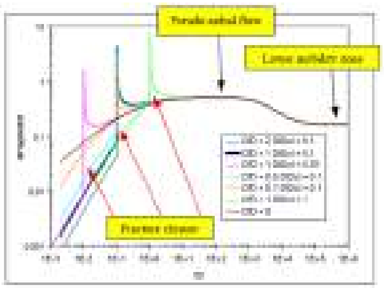
# PTA-IFO Fracture Characteristics Determination during DFIT

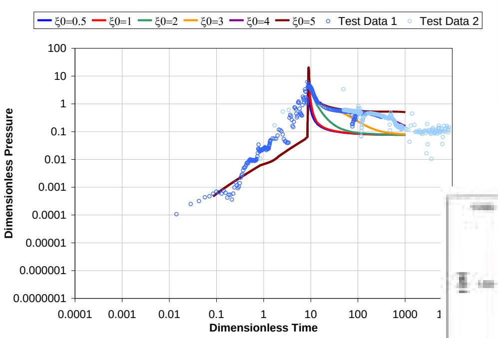


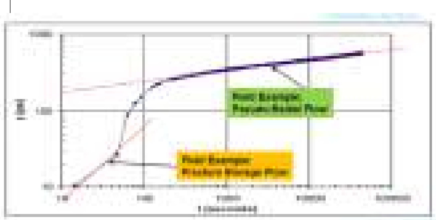





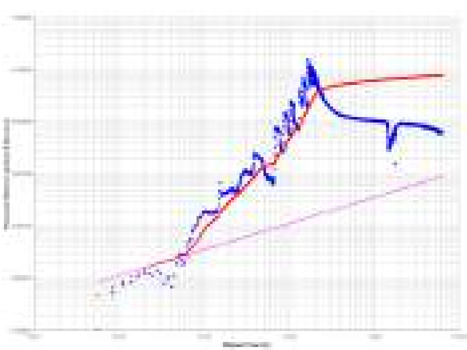



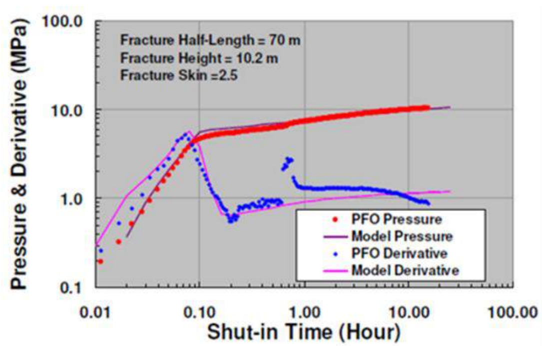

- Method 1: Using Storage Dominated Flow
  - Recognized by a straight line on the pressure vs. time plot.
  - The slope of this linear part of pressure curve is equal to q/Cf from which fracture storage coefficient can be determined. From Cf, **fracture length** can be calculated, considering different fracture types (PKN, CGK, elliptical).
- Method 2: Using Linear Formation Flow Before Fracture Closure
  - Recognized by a straight line with a half slope on the log-log plot.
  - Occurs for longer closure times where a combination of storage flow and linear formation flow takes place before fracture closure.
  - Type curve matching and the use of an existing analytical expression gives the fracture storage coefficient from which **fracture length** can be calculated.
- Method 3 : Using Linear Formation Flow After Fracture Closure
  - Recognized by a straight line with a half slope on the log-log plot.
  - Occurs for short closure times.
  - From semi-log analysis and using fluid and relative permeability data, the ratio {viscosity/(permeability*porosity*total compressibility)} can be calculated.
  - From a plot of Pf vs. square root of time, the above ratio is related to flow and fracture dimensions (h*L).
- Method 4: Using late time Pseudo-Radial Flow
  - Mobility discontinuity can be determined

# @IPT and @IPTSH Data Input and Estimated Parameters

| All Data Input | Parameters Estimated Using Conventional Analyses Methods | Parameters Estimated Using Type-Curve Matching |
|---|---|---|
| Injection Rate | Permeability of the Inner zone | Permeability of the Inner zone |
| Volume Injected | Fracture Storage Constant | Fracture Storage Constant |
| Fluid Compressibility | Fracture Half Length | Fracture Half Length |
| Injection Fluid Viscosity | Mobility Ratio | Frcature Skin |
| Reservoir Porosity | | Frcature Conductivity |
| Formation Volume Factor | | Rate of Fracture Length Shrinkage |
| Formation Height (Thickness) | | Injection Layer Stress |
| Reservoir Poisson's Ratio | | Containment layer Stress |
| Reservoir Young's Modulus | $C_{fV}^{GDK} = 2\pi \frac{(1-\nu^2)}{E} h_f x_f^2$ | Diffusivity Ratio |
| Total Compressibility | | Mobility Ratio |
| Mobility Ratio | | Permeability of the Outer zone |
| Mobility Front, Elliptical | $C_{fV} = \frac{\partial V_f}{\partial p_f}$ | $C_{fV}^{PKN} = \pi \frac{(1-\nu^2)}{E} h_f^2 x_f$ |
| Diffusivity Ratio | | |
| Injection Layer Stress | | |

Fracture Storage Coefficient is related to Formation Elastic properties, and fracture Length and Height.
Mobility is defined as the Ratio of Permeability to Fluid Viscosity, Mobility Ratio = Inner Zone Mobility/Outer Zone Mobility
Diffusivity is defined as the Ratio of Mobility to (Porosity x Compressibility), Diffusivity Ratio = Inner/Outer Zone Diffusivity

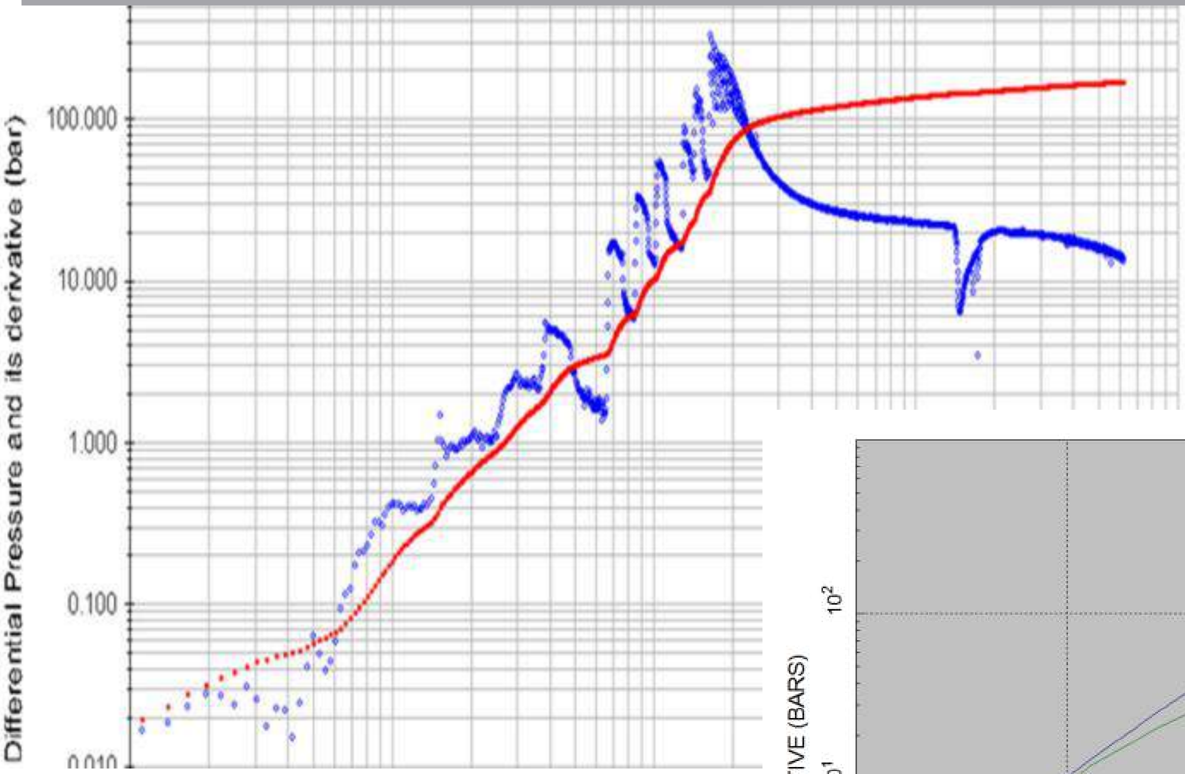


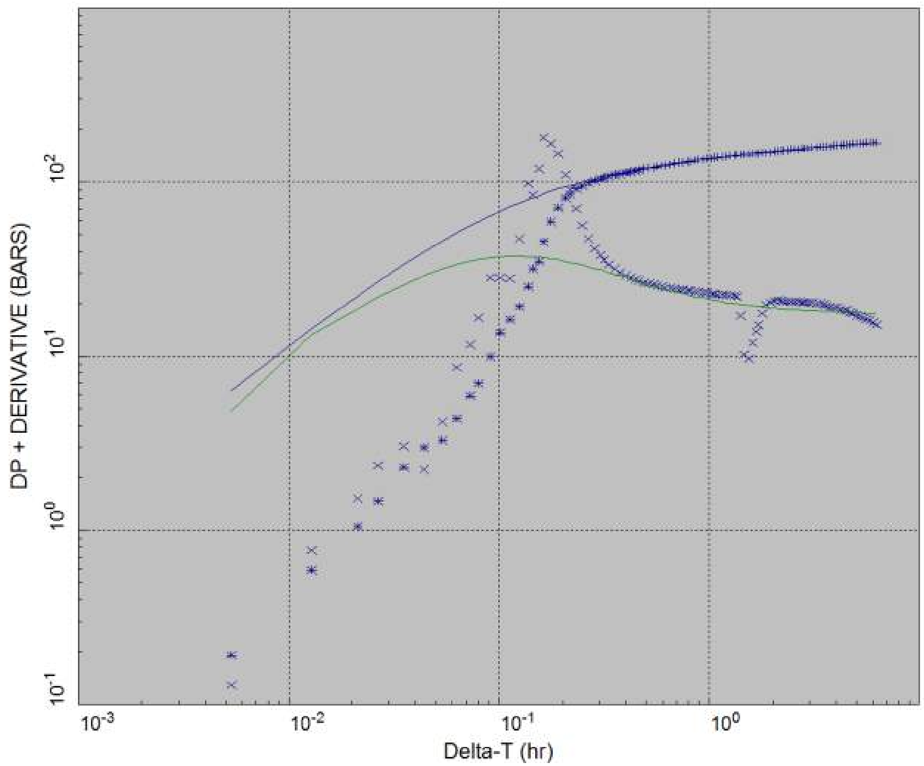



$$C_{fV}^{Elliptical} = \frac{2\pi}{3}\frac{(1-\nu^2)}{E}\frac{\min(h_f,2x_f)}{E(m)} h_f x_f$$

$$m = 1-\left[\min\left(\frac{h_f}{2x_f},\frac{2x_f}{h_f}\right)\right]$$

# Example Case – Comparison between PIE and @IPT Plots



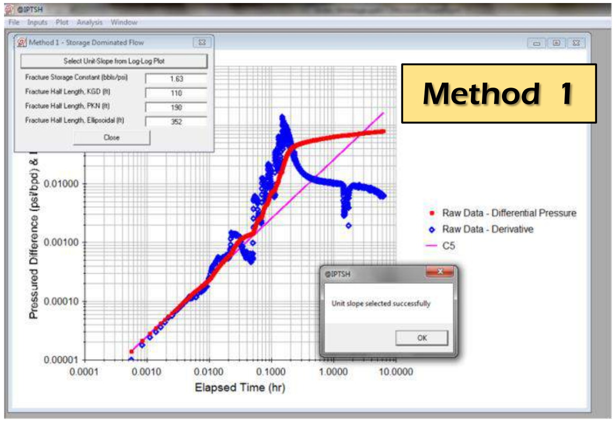




**Actual Field Record of a fractured Injector during Fall Off**

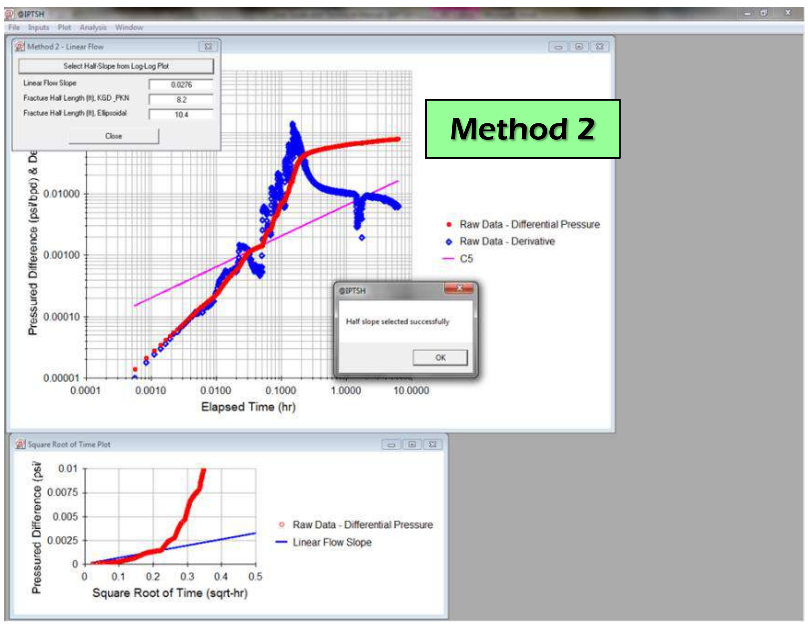
# PTA-IFO Type-Curve Matching

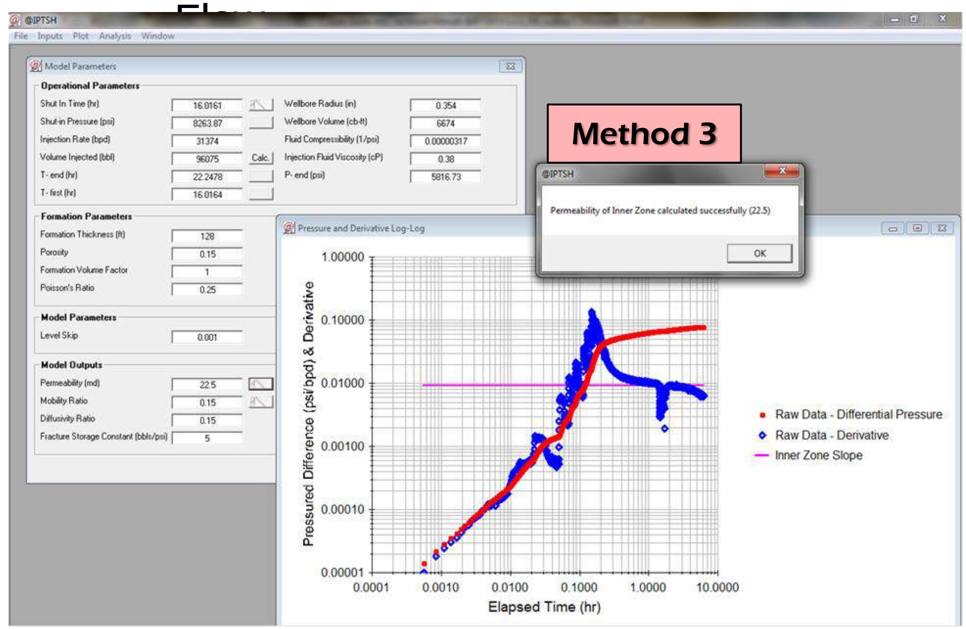
- Model Selection
  - Infinite Conductivity-Dual Mobility
  - Finite Conductivity-Single Mobility
  - Finite Conductivity-Dual Mobility
- Fracture Types
  - KGD
  - PKN
  - Elliptical
- Fracture Shrinkage Modes
  - Height Shrinkage Only
  - Length Shrinkage Only
  - Combined Height and Length Shrinkage

# Type-Curve Generation before Matching

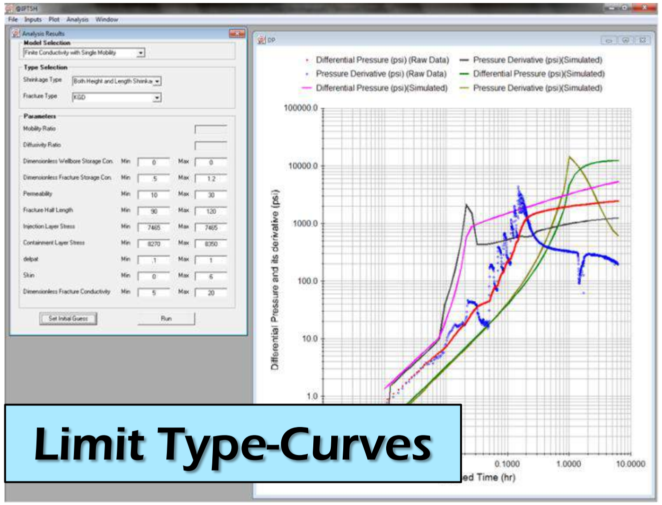


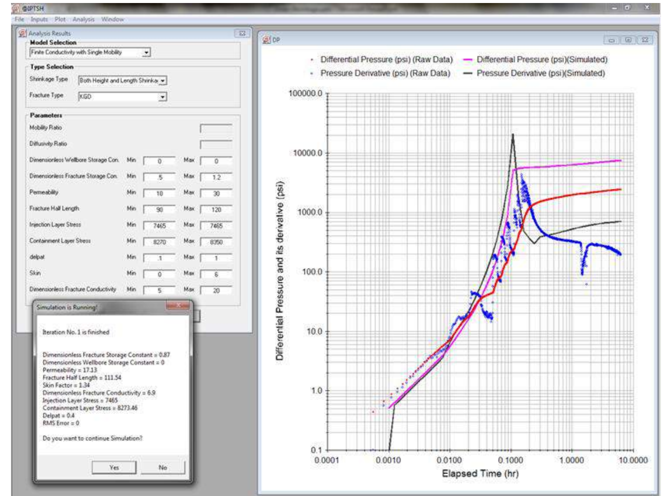

- Method 1: Using Storage Dominated Flow
  - Fracture storage constant has been determined and Fracture Half Length has been estimated for three types of fracture geometry.
- Method 2 : Using Linear Formation Flow
  - Data here does not clearly show linear flow; however, Fracture Half Length has been estimated for three types of fracture geometry.
- Method 3 : Using Radial Formation Flow

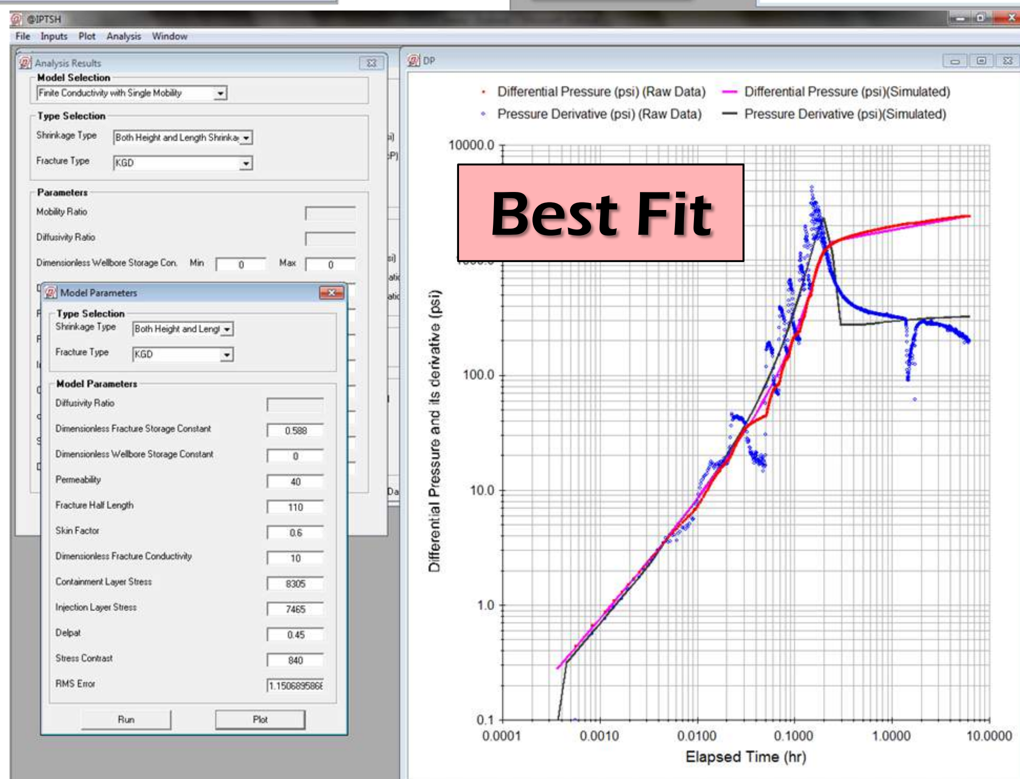


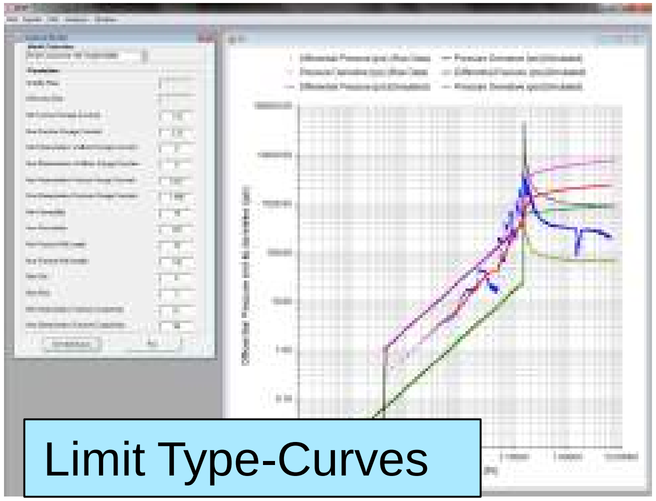
# Results of Shrinking Fracture by Type-Curve Matching

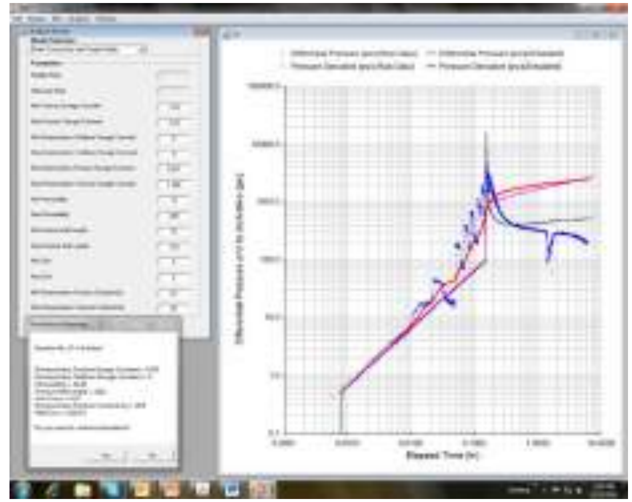


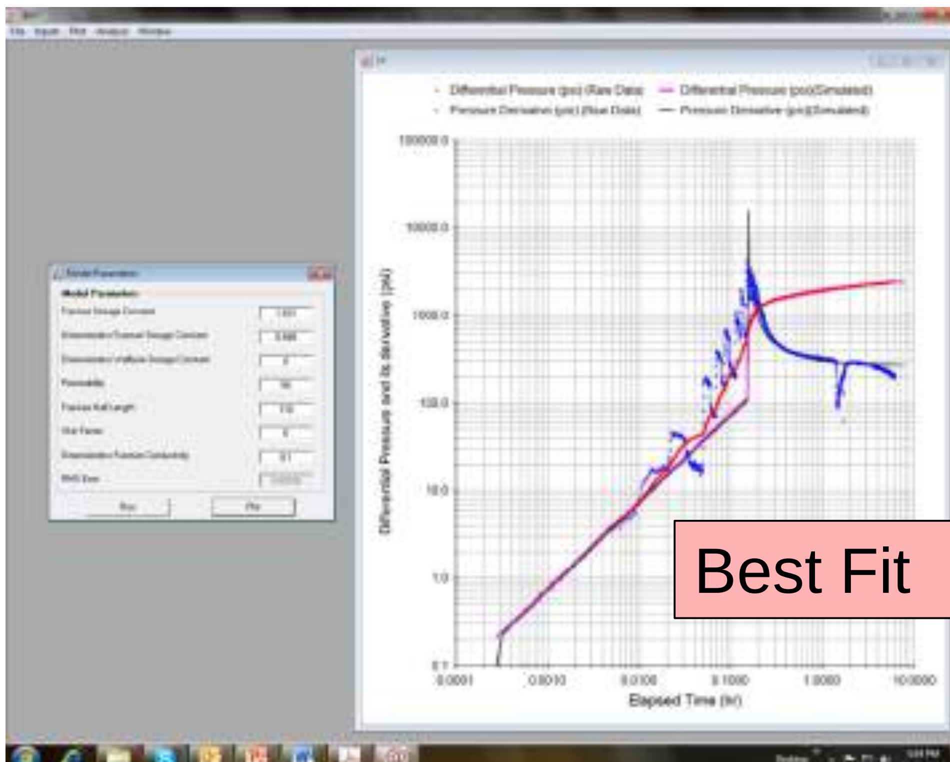



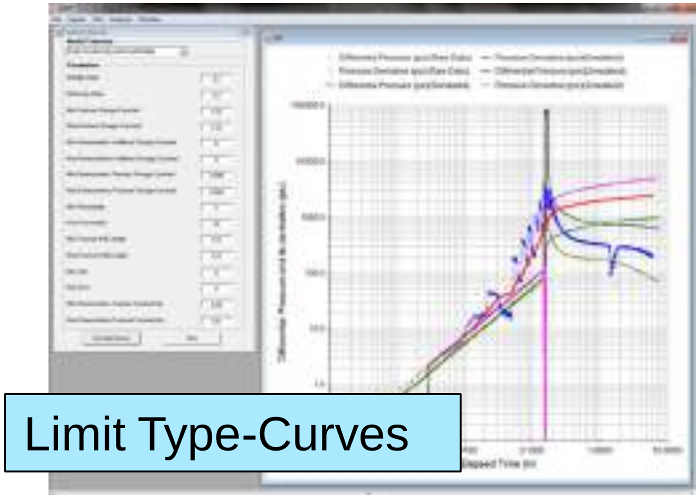
# Results of Type-Curve Matching (Single Mobility)

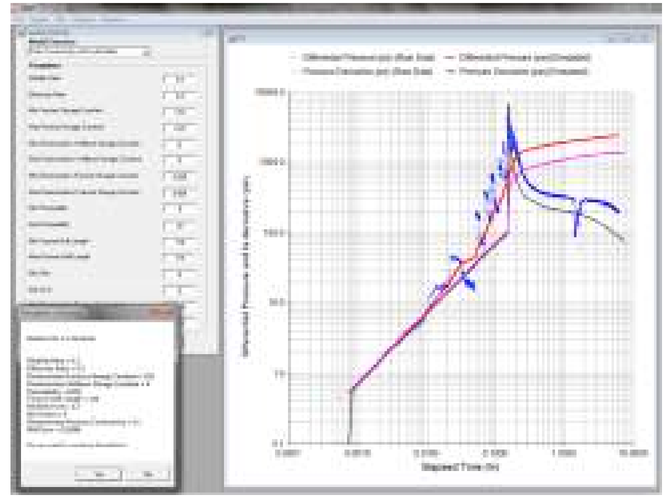


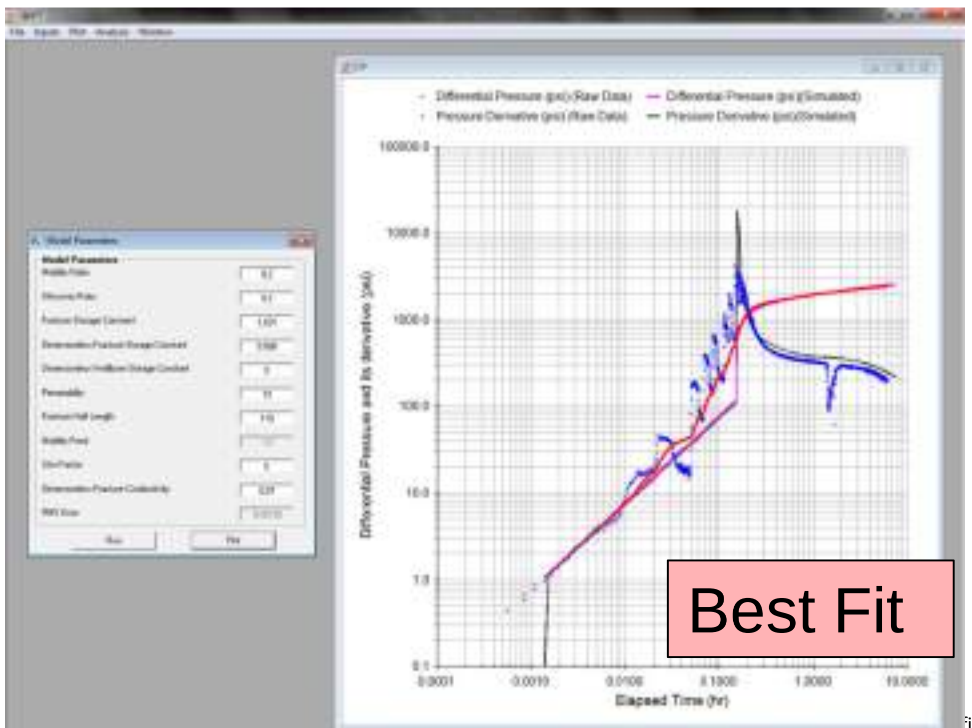





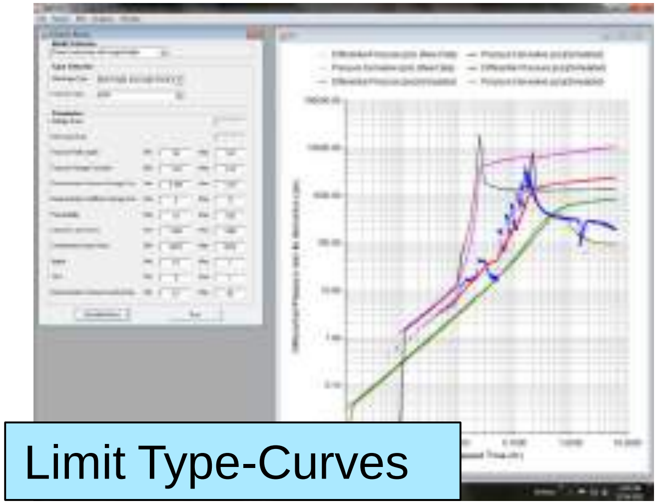
# Results by Type-Curve Matching (Dual Mobility)

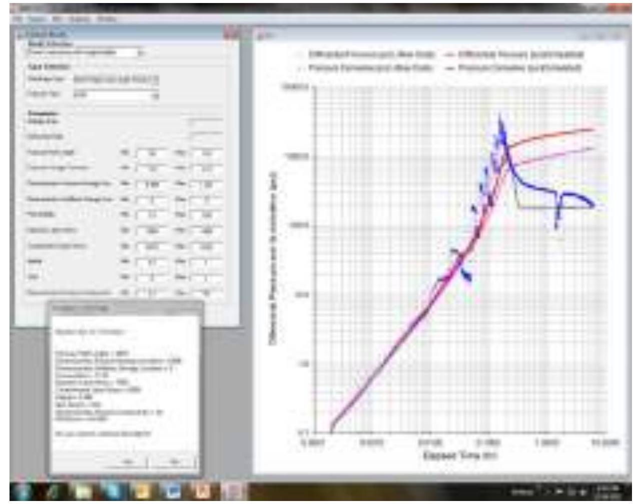


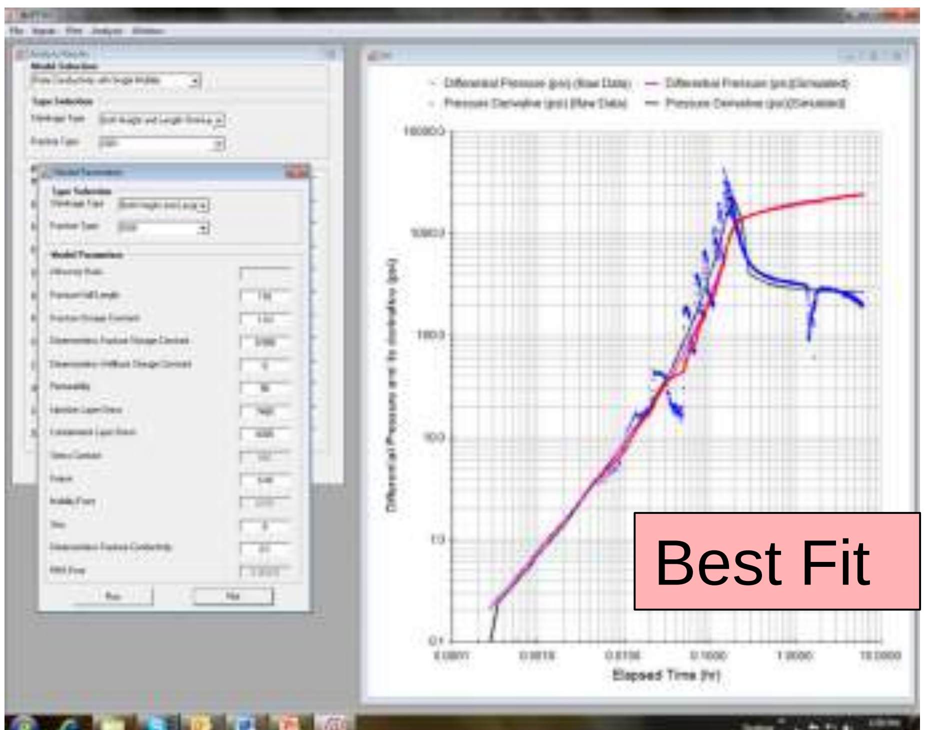





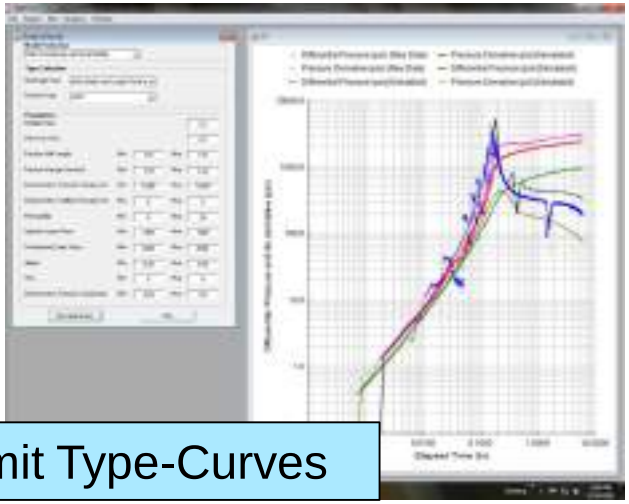
# Results of Type-Curve Matching (Shrinking Fracture in Single Mobility)



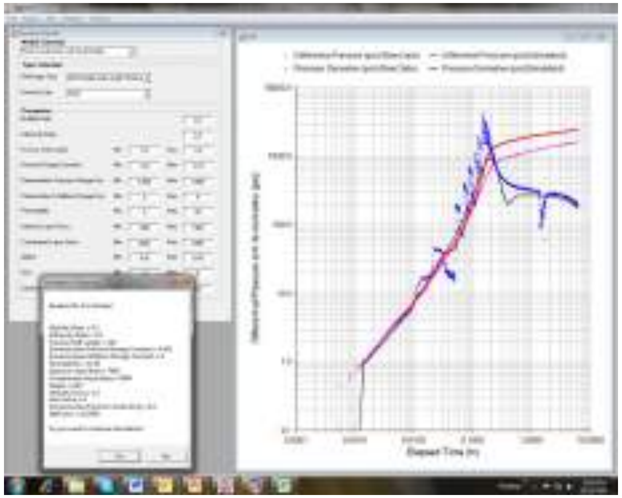



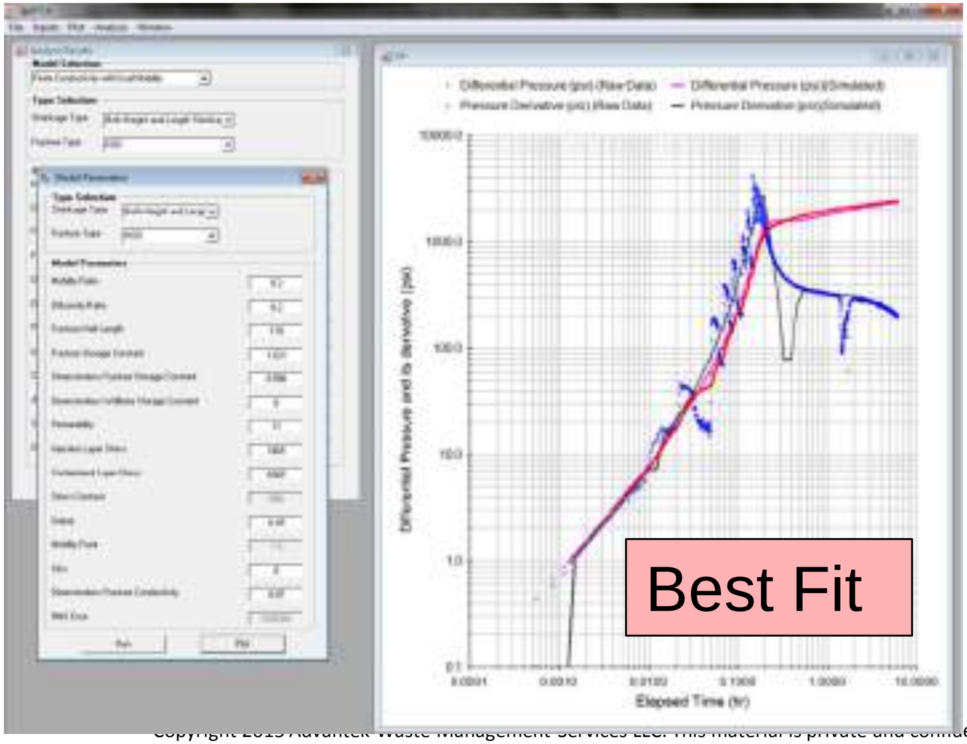


# Results of Type-Curve Matching (Shrinking Fracture in Dual Mobility)



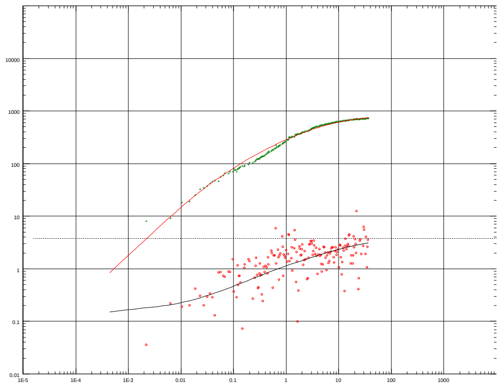
Limit Type-Curves



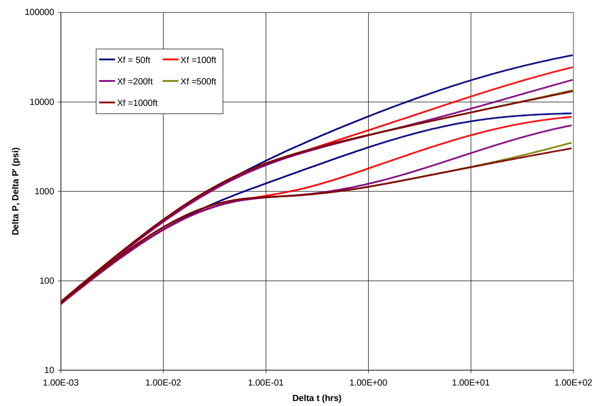


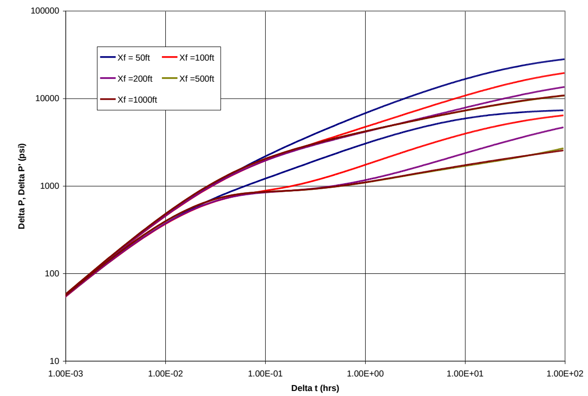

Best Fit

# Using PTA during IFO to Estimate SRV



Log-Log plot: p-p@dt=0 and derivative [psi] vs dt [hr]



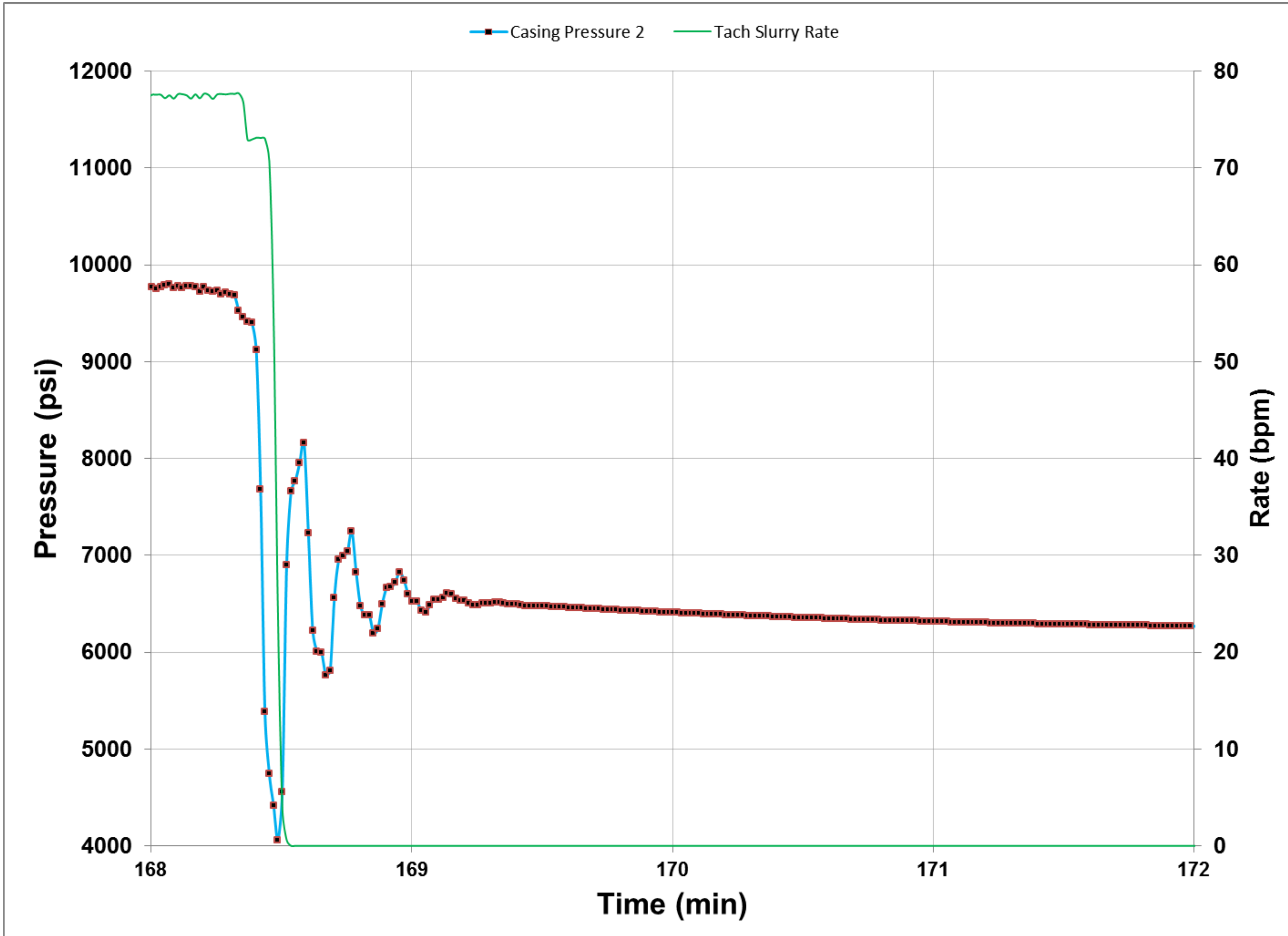

Pressure and Pressure Derivative Plot

Injectivity Model

Fall-off Model

Transient analysis of post injection pressure decline is used to develop a picture of the stimulated reservoir volume, and system structure and dynamics.

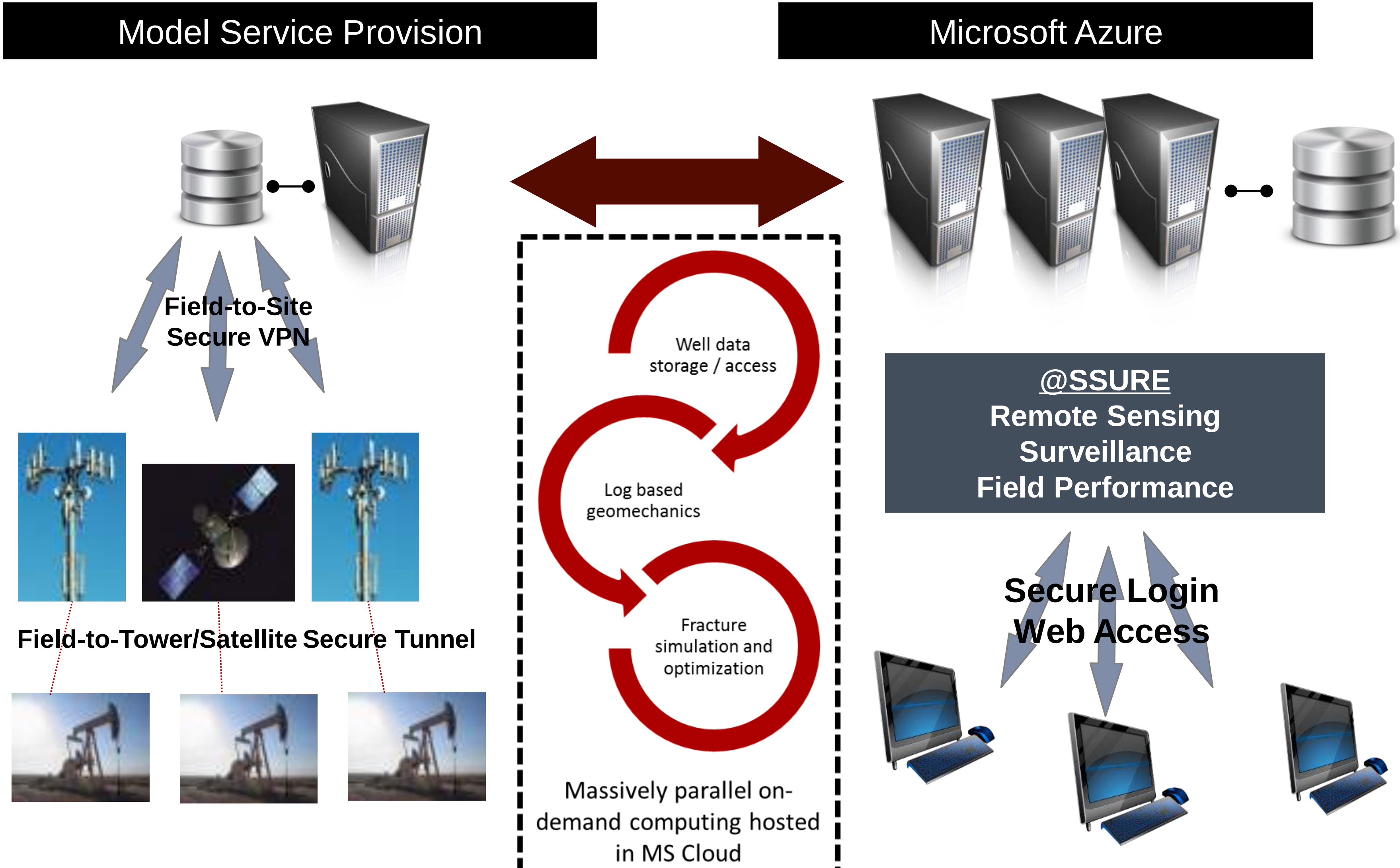
- Transient analysis will help define fracture geometry and the dominant system characteristics.
  - Do boundaries exist?
  - Are stimulated zones being created?
  - Does the analyzed fracture penetrate into or through the stimulated zone and what does this mean in analyzing and describing the system?
- Once analysis has defined a model, pressure responses characteristic of different generated fracture lengths can be predicted and cross correlated during performance reviews.



Casing Pressure 2
Tach Slurry Rate
12000
11000
10000
9000
8000
7000
6000
5000
4000
Pressure (psi)
80
70
60
50
40
30
20
10
0
Rate (bpm)
168
169
170
171
172
Time (min)

# Injection Assurance Platform (@SSURE)

**@SSURE provides secure cloud access between clients and field ops for surveillance**



# Concluding Remarks

- Cloud Computations are fast and inexpensive as well as connective
- Engineers can have effective real-time monitoring and simulation
- Fracture models have been advanced to provide efficient and realistic assessment of multiple concurrent fracturing of horizontal wells
- Pressure transient analysis of fall off data following fracture treatments or injection operations have been utilized
- The case of fractured injectors with closing and shrinkage fractures shows that significant geomechanical details may be obtained from the data
- A more direct methodology is proposed for the determination of stimulated Reservoir volume (SRV), if it exist.
- Water hammer effects provide potential for closer fracture assessment and would require further analysis which is underway. (HIT link)

# Concluding Remarks (continue)

- Both the extent and the permeability elevation of the SRV are easily assessed from the PFO results.
- A measure of fracture length, height and containment stress contrast may be estimated closely, which helps is assessing fracture migration outside the target zone.
- Breaching, loss of containment and fluid migration must always be significant factors in job design and implementation.
- Assurance is a primary factor in stimulation via complete data collection, sophisticated modeling and live monitoring.
- Pressure transient tests have advanced and are currently successful for better identification of fractures.
- Multiple fractures in single wells must be designed with sufficient certainty and complexities and need close monitoring

# Thank You
# Any Questions?

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