EPA Hydraulic Fracturing Technical Workshop #3
Fate and Transport

Characterizing Mechanical and Flow Properties using Injection Falloff Tests

Presented by
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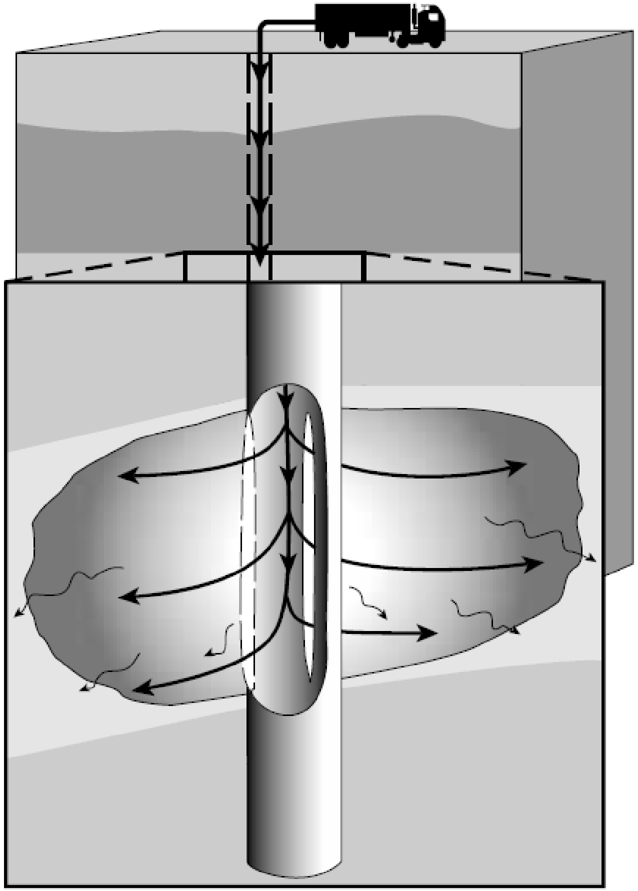
Agenda

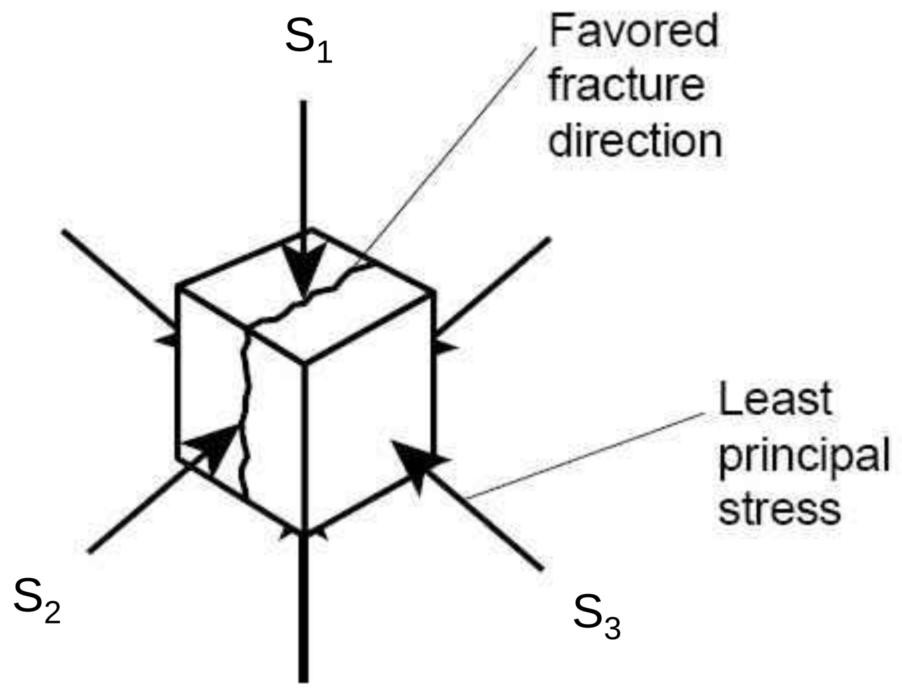
- Review the basics of fracture injection / fall-off tests.
- Describe fracture closure analysis for determining in-situ stress and non-ideal fracture closure mechanisms.
- Describe after-closure analysis for determining reservoir flow behavior, reservoir flow capacity (kh/u) and initial reservoir pressure (p_i).
- Discuss integration of this information for enhanced control of hydraulic fracturing.

Injection Fall-off Diagnostics



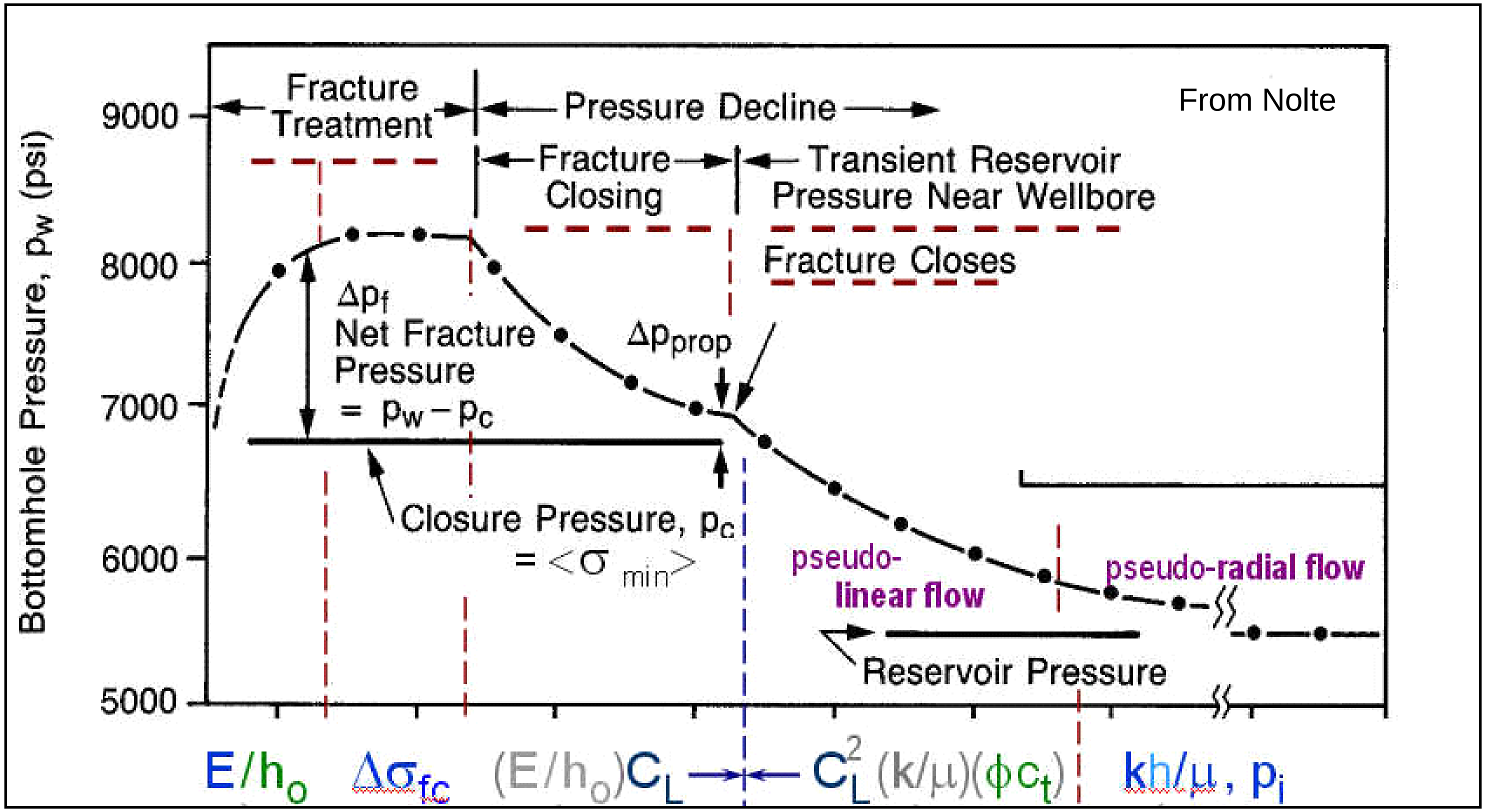
The process starts with the creation of a small hydraulic fracture, typically requiring less than 5 barrels for a shale gas interval.

Hydraulic Fractures Open Normal to the Least Principal Stress



This stress regime is typical for deeply buried reservoir rock.

Drivers of Bottomhole Pressure Behavior

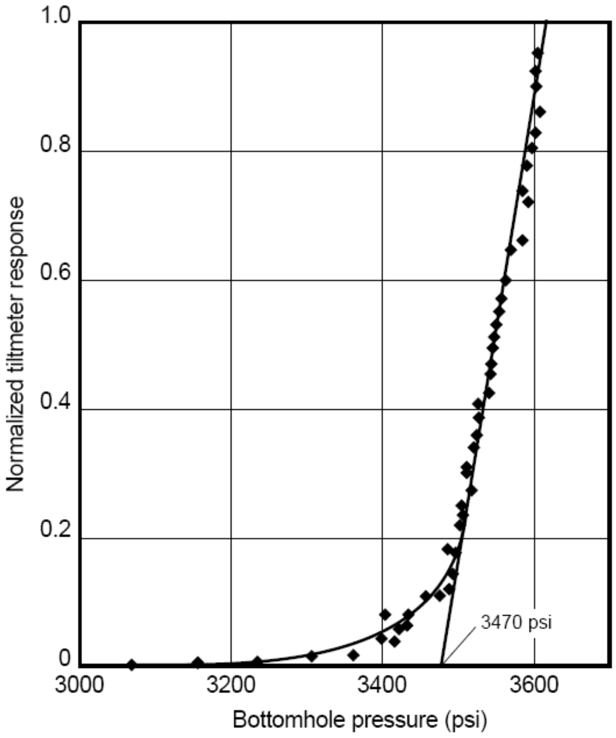


Initially, rock mechanical properties and in-situ stress influence the pressure fall-off response. Later, pressure fall-off behavior is dominated by reservoir flow properties and pore fluid pressure.

Fracture Closure

initial

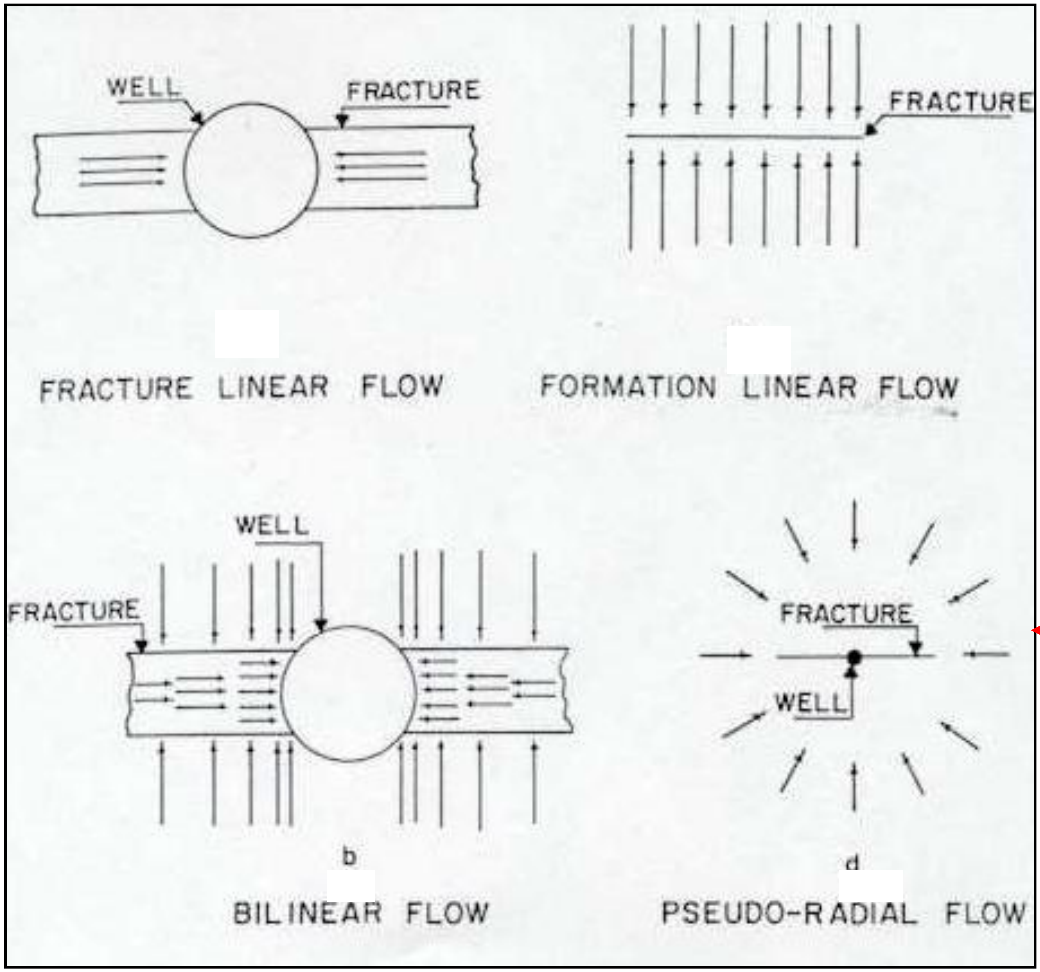
late time



Proportional to normalized fracture width
MWX Test Site Project

Asperities on opposing fracture faces touch in the initial stages of fracture closure. The adjacent void space imparts residual fracture conductivity.

Flow Regimes in Hydraulically Fractured Wells with Residual Fracture Conductivity



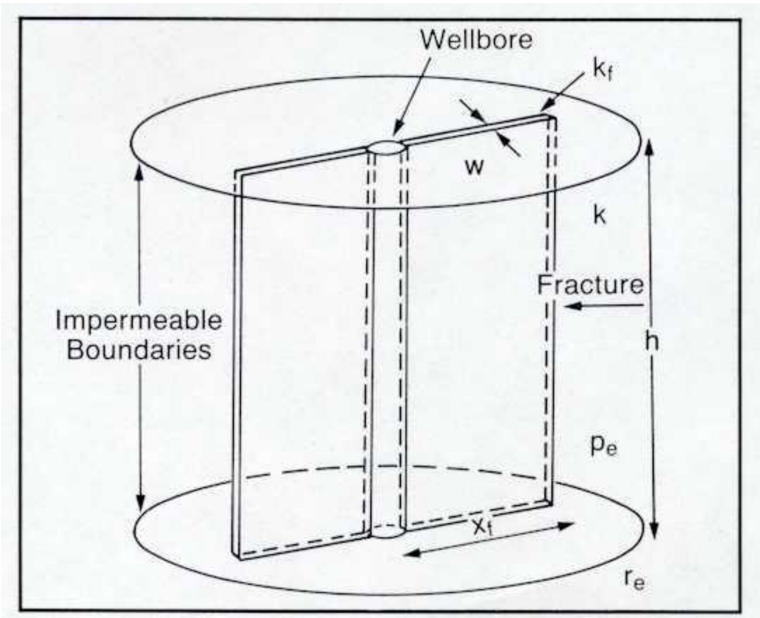
From Cinco-Ley

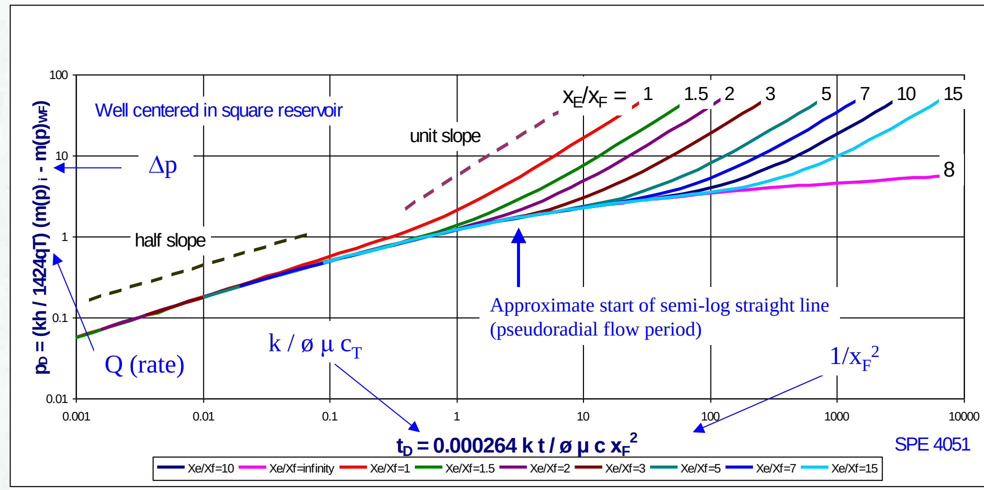
Achieved in the after-closure period.

Radial flow solutions can be used to derive far-field kh/u.

During the pseudo-radial flow period, the area of investigation is well beyond the region of the fracture.

Assumed Case for Modeling Purposes: Fracture-Enhanced Wellbore in Cylindrical Reservoir





<u>Hydraulic Diffusivity</u>

$= k / ø\ \mu\ c_T$

=fluid mobility / fluid storativity

<u>Fractured-Well Type Curve</u>

$t_D = 0.000264kt/\varphi\mu c_T \mathbf{x_F}^2$

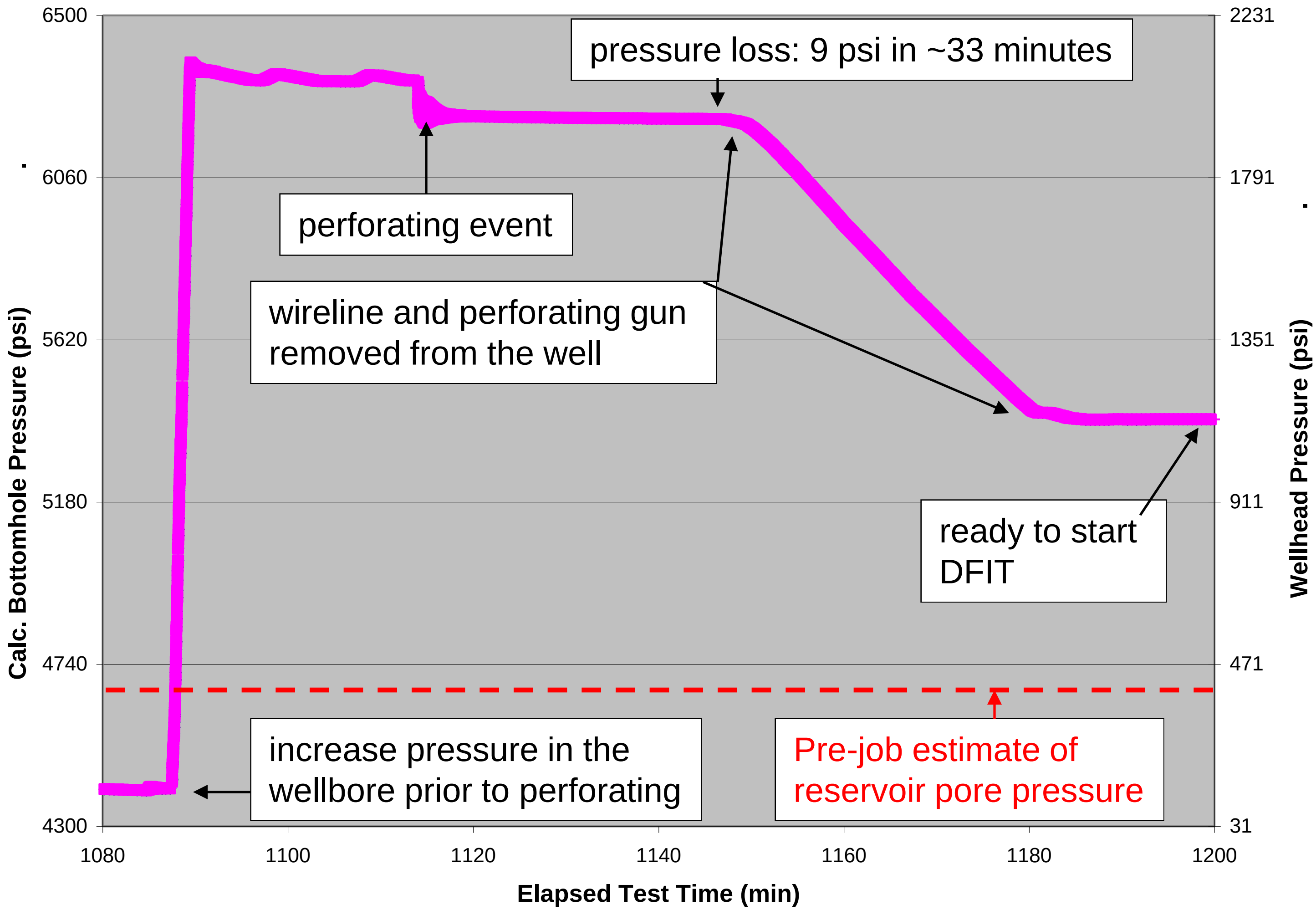
Start of pseudo-radial flow $t_D>1$

Hydraulic diffusivity determines the speed that pressure changes induced by production or injection are transmitted through the reservoir.

Pressure Memory Gauge

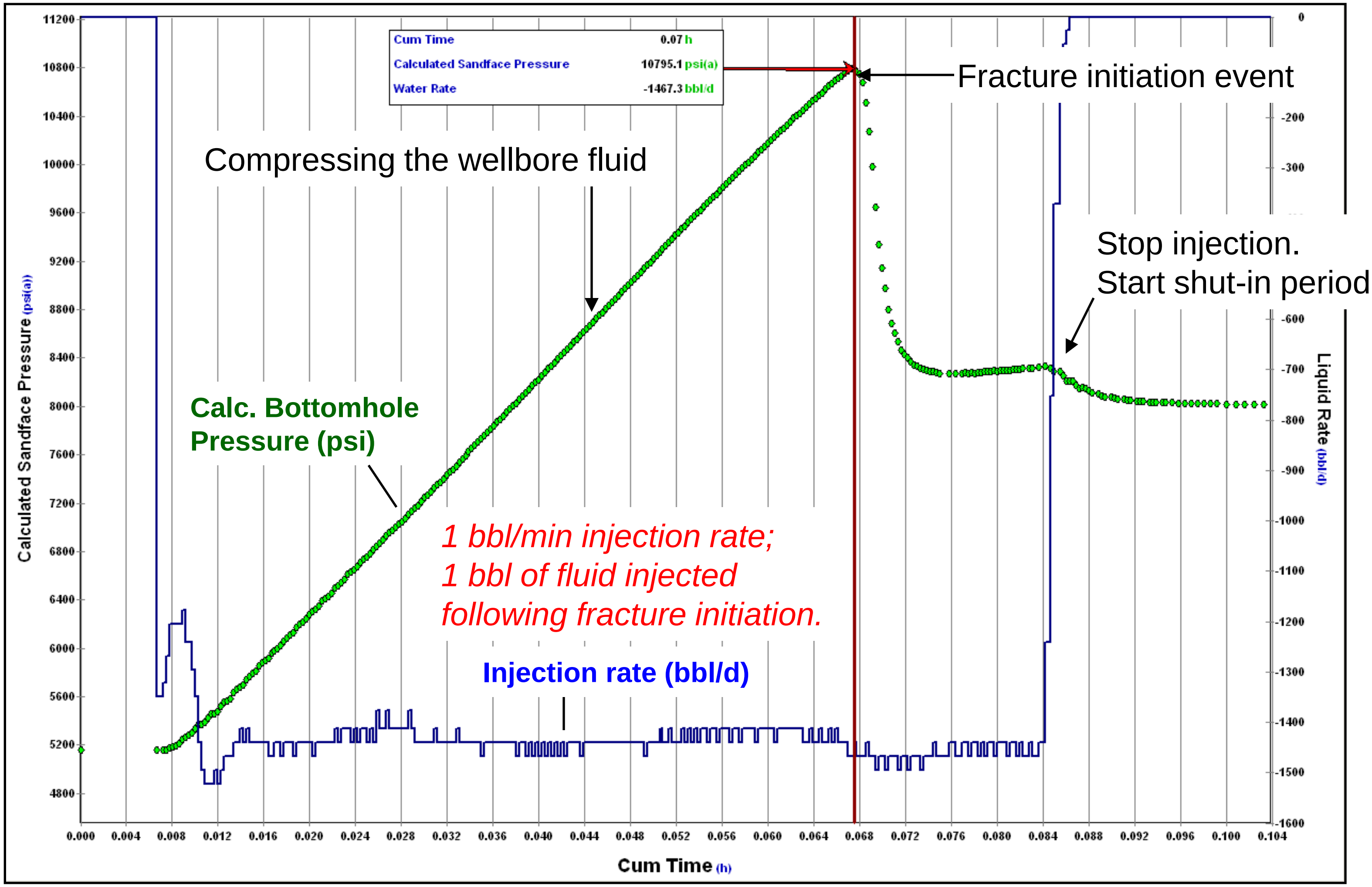
To facilitate doing long-duration tests, memory gauges are used to monitor and record the pressure fall-off downhole or more commonly at the wellhead.

Overbalanced Perforating



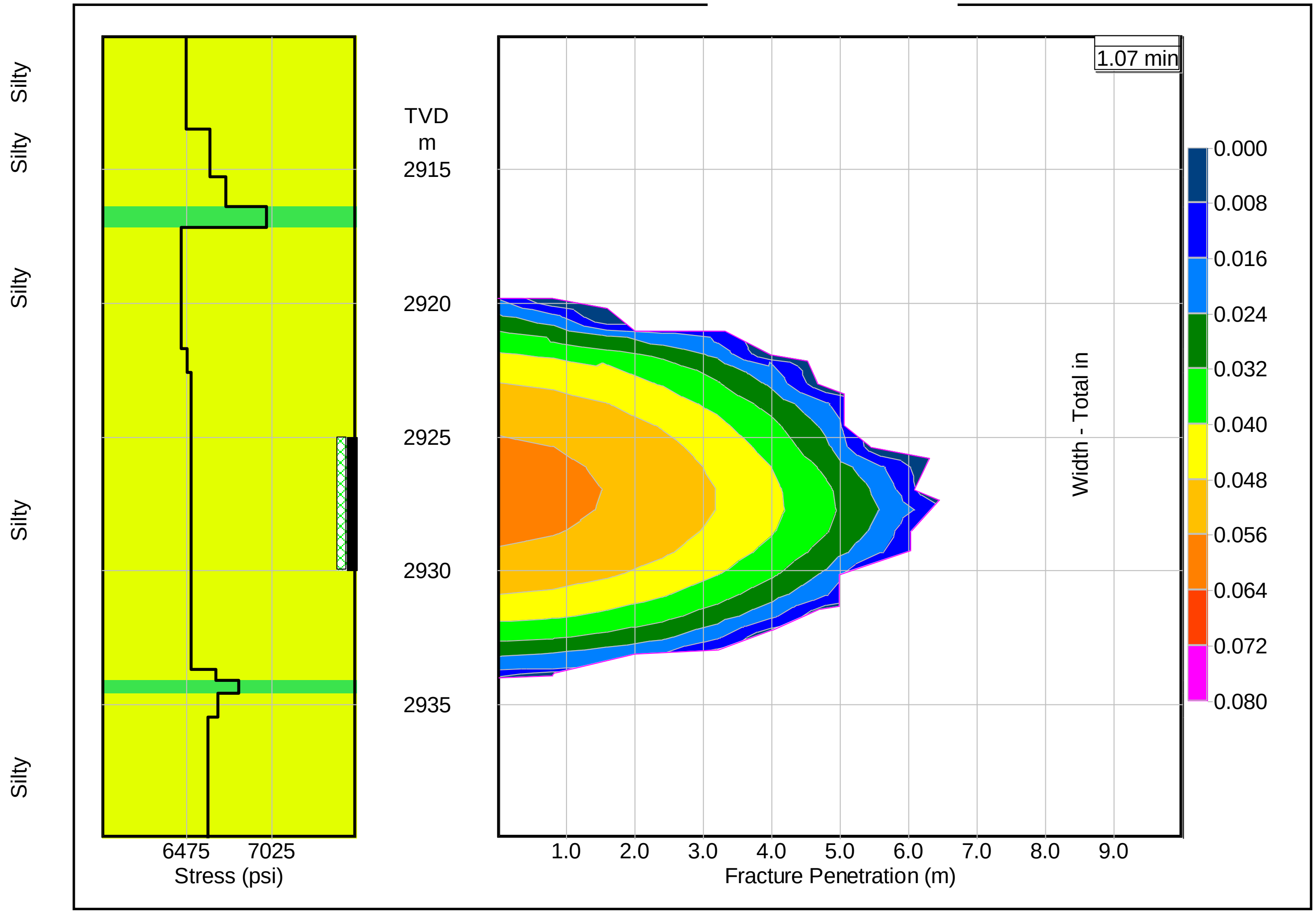
Maintaining the wellbore pressure above reservoir pressure prevents gas influx into the wellbore and enables closed-chamber analysis under certain conditions.

Propagating a Hydraulic Fracture



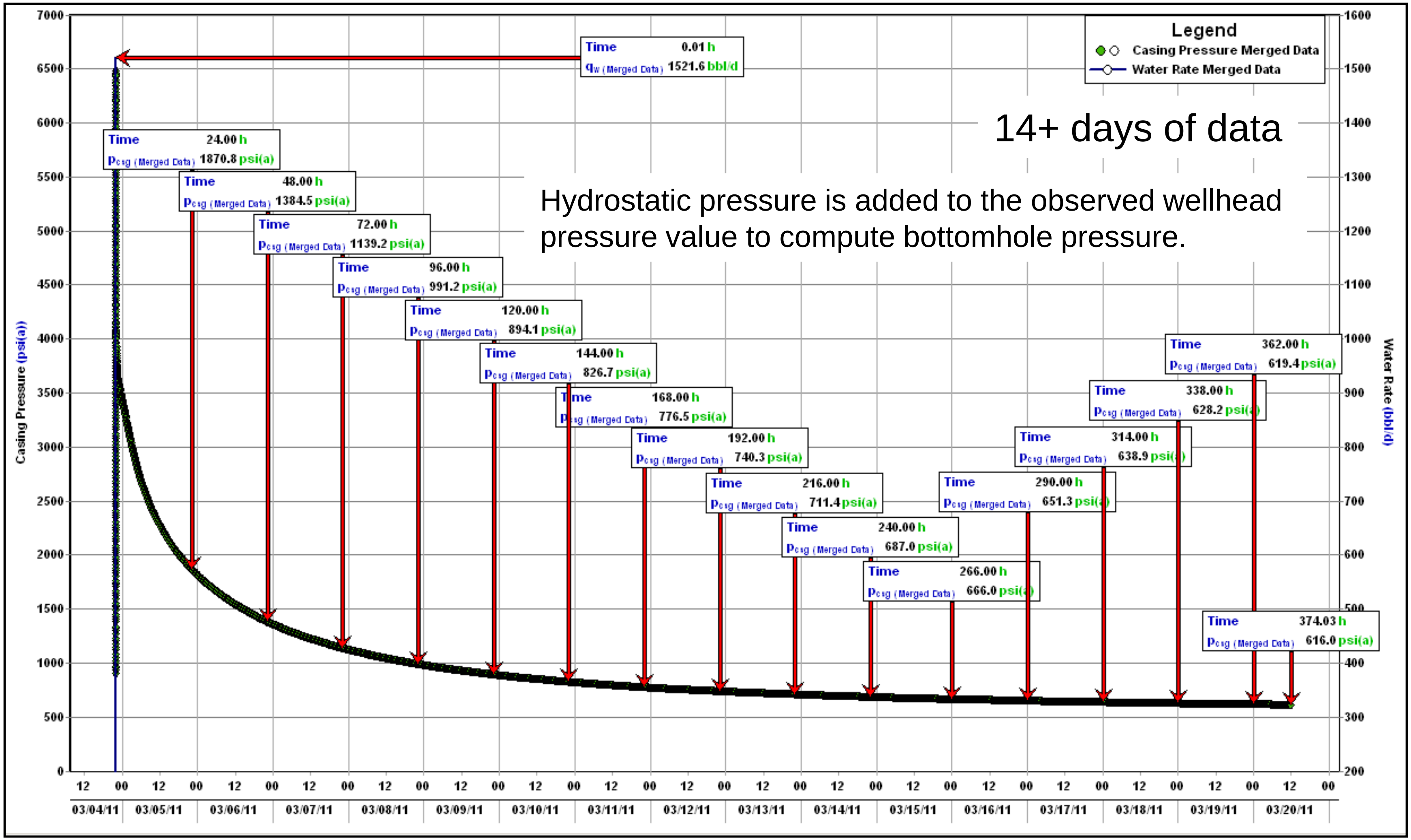
Injection time and volume are kept short to minimize fracture dimensions and satisfy the conditions of an impulse event.

Modeled Fracture Geometry



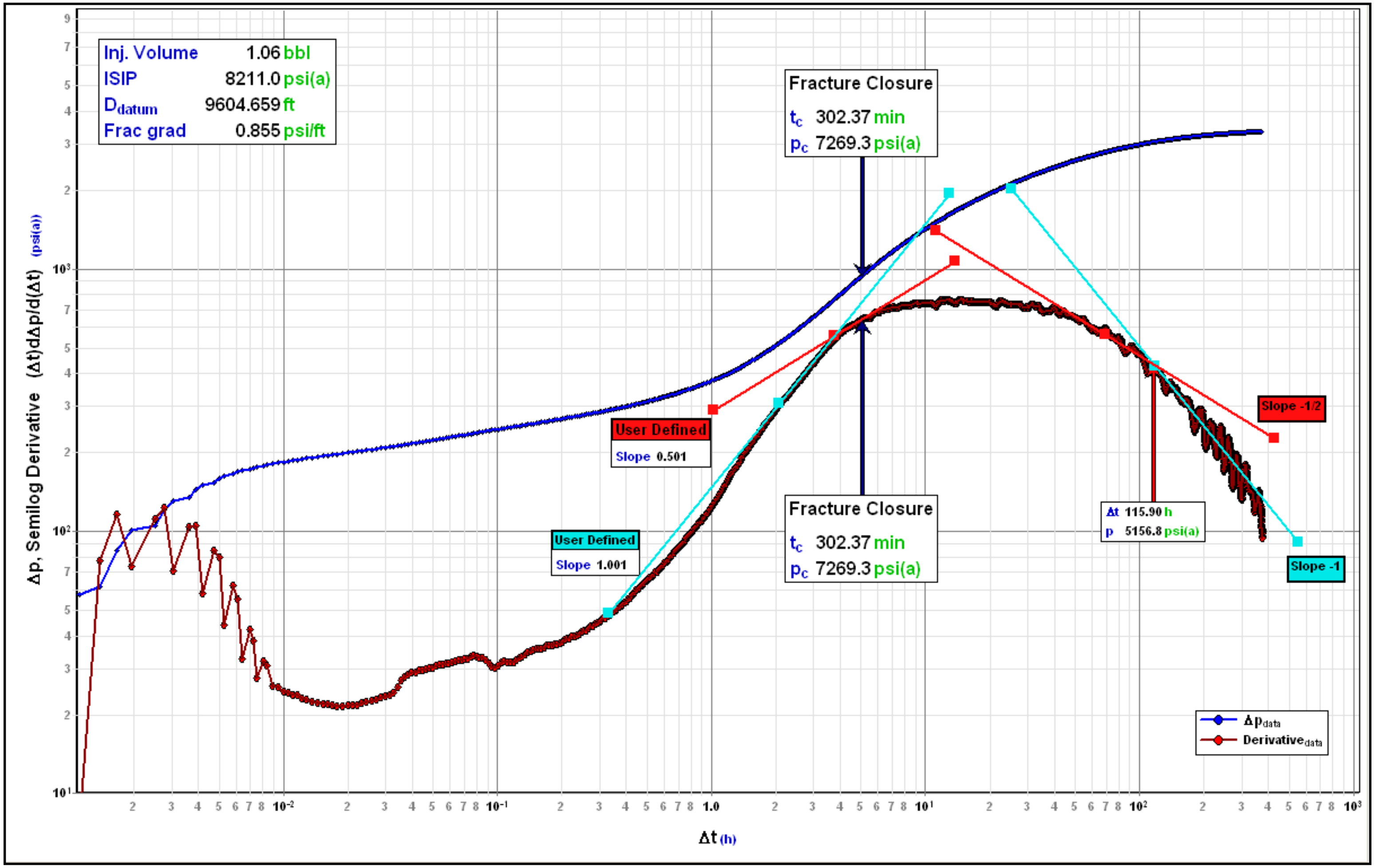
Even with a small injection, reservoir investigation is significant.

Pressure Fall-off History



Hydrostatic pressure is added to the observed wellhead pressure value to compute bottomhole pressure.

Diagnostic Log-Log Plot of Pressure Fall-Off



Derivative plot is used for identification of fracture closure behavior and after-closure reservoir flow regimes.

Log-Log Graph Characteristic Slopes

Log-Log Graph	Before Closure		After Closure		
	Bilinear	Linear	Bilinear	Pseudolinear	Pseudoradial
Δp_{wf} vs. t Δp_{awf} vs. t_a	1/4	1/2	–	–	–
$\partial \Delta p_{wf} / \partial t$ vs. t $\partial \Delta p_{awf} / \partial t_a$ vs. t_a	–3/4	–1/2	–7/4	–3/2	–2
$t \partial \Delta p_{wf} / \partial t$ vs. t $t_a \partial \Delta p_{awf} / \partial t_a$ vs. t_a	1/4	1/2	–3/4	–1/2	–1
$t^2 \partial \Delta p_{wf} / \partial t$ vs. t $t_a^2 \partial \Delta p_{awf} / \partial t_a$ vs. t_a	5/4	3/2	1/4	1/2	0

Primary derivative (dp/dt or $d\Psi/t_a$)

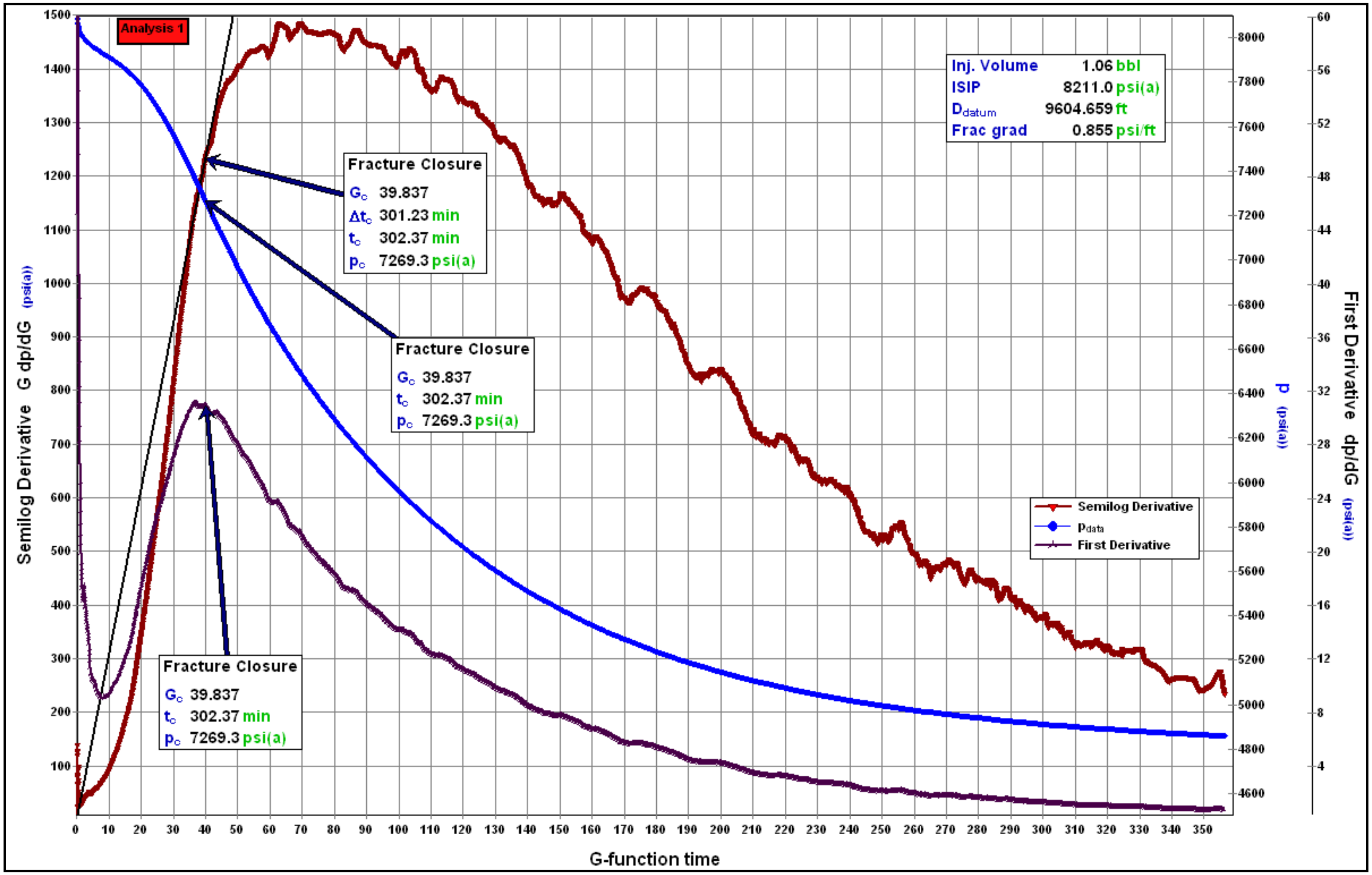
Semi-log derivative (t dp/dt or t_a $d\Psi/t_a$)

Impulse derivative (t^2 dp/dt or t_a^2 $d\Psi/t_a$)

From Barree (SPE 107877)

Diagnostic slopes depend on the derivative type used.

G Function Plots for Fracture Closure Identification



The semilog derivative is the primary plot for identifying fracture closure.

G-Time Functions for Analyzing a Closing Fracture

$\Delta t_D = (t - t_p) / t_p$

$g(\Delta t_D) = 4/3 \; ((1+\Delta t_p)^{1.5} - \Delta \; t_p^{1.5})$

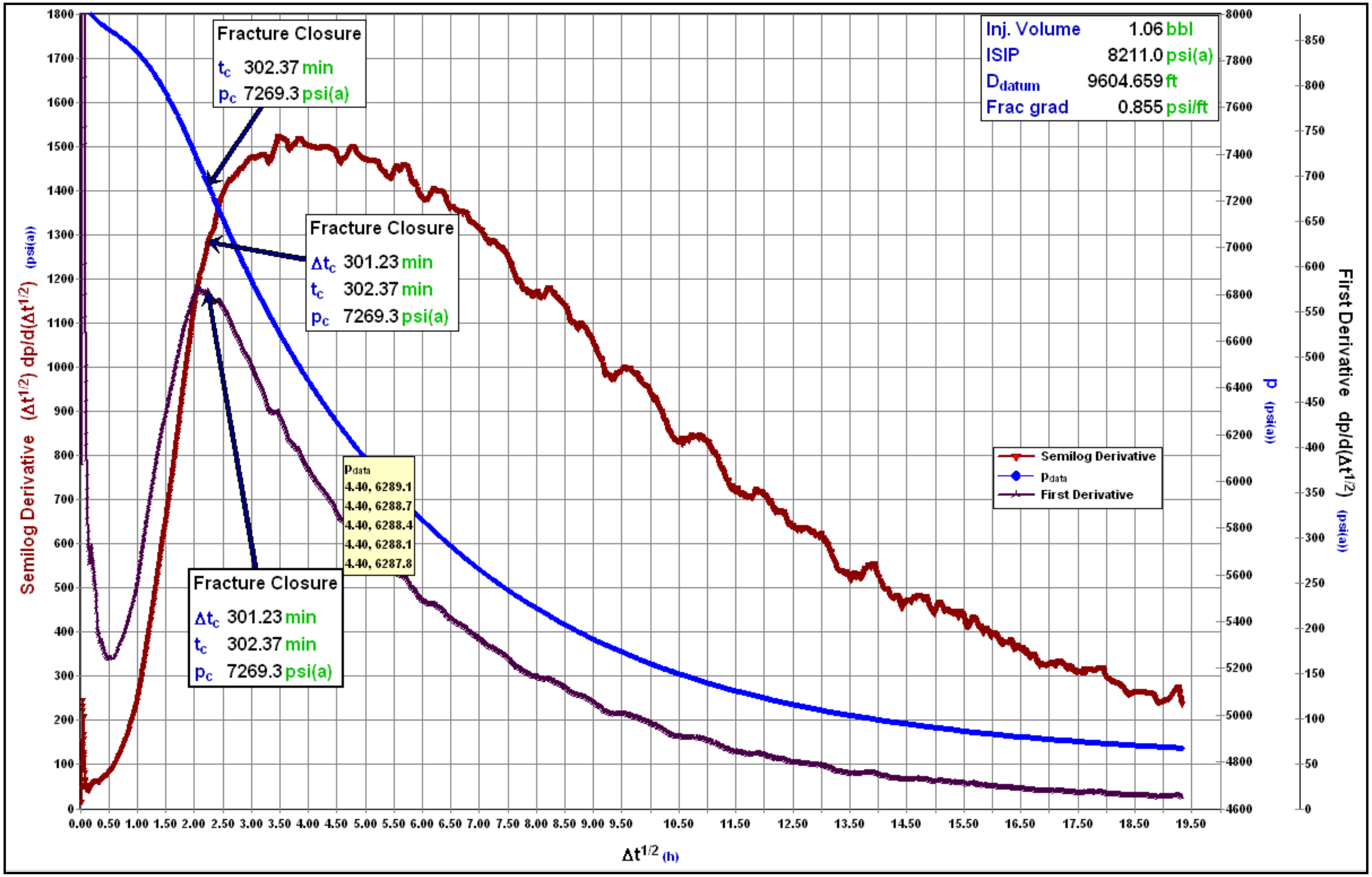
$G(\Delta t_D) = 4/\pi \; (g(\Delta t_p) - g_0$

$\eta = [G(\Delta t_D)_C] \quad [2 + G(\Delta t_D)_C]$

where,
t = total test time (pumping and shut-in)
t_p = pumping time
$G(\Delta t_D)$ = G-Function time in previous slide
$G(\Delta t_D)_C$ = G-Function time at fracture closure
η = fluid efficiency (i.e., fluid remaining in fracture   total fluid injection, at shut-in)

The G-Time Function linearizes the pressure response of a closing fracture under ideal conditions.

Square Root of Time Plots for Fracture Closure Identification



The 1st derivative plot is a secondary method for confirming fracture closure.

Poroelastic Equation for Estimating In-Situ Horizontal Stress

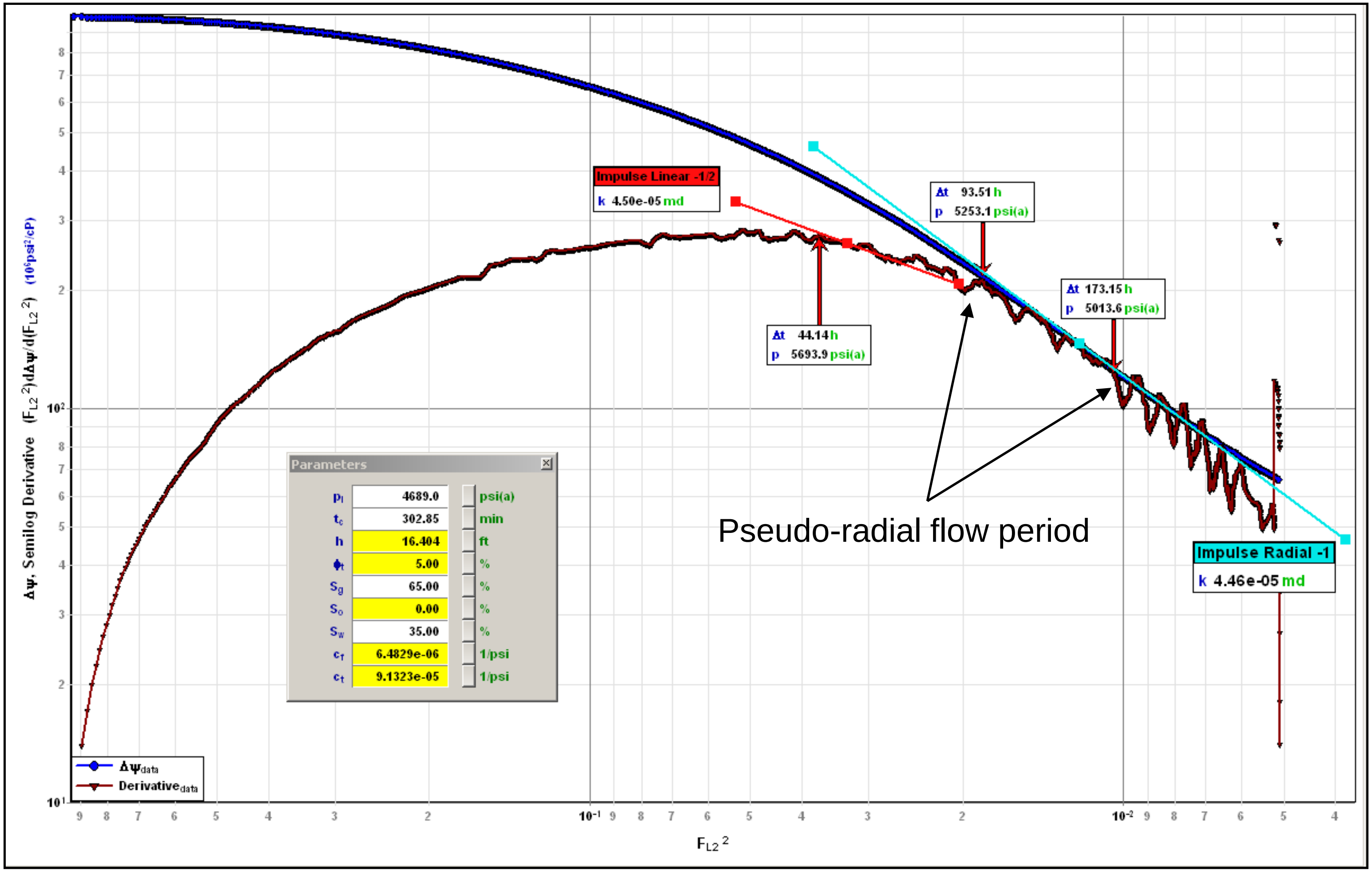
$$\sigma_h = \left[\frac{\nu}{1-\nu} \sigma_v - \alpha_v P_r \right] + \alpha_h P_r + \sigma_t$$

Where,

σ_v = overburden stress, psi = 10,752 psi (1.12 psi/ft; bulk density log)
v = Poisson's ratio = 0.23 (from dipole sonic log computation)
α_v = vertical Biot's parameter = 1.0
α_h = horizontal Biot's parameter = 1.0
P_r = reservoir pore pressure, 4693 psi (0.49 psi/ft; DFIT)
σ_t = external (tectonic) stress, psi = 0 psi (assumed)
σ_h = minimum horizontal stress, psi = 6503 psi (predicted from above)
σ_h = minimum horizontal stress, psi = 7269 psi (observed from DFIT)

The fracture closure method for deriving minimum in-situ stress can be used to evaluate and adjust the values derived from predictive equations.

After-Closure Flow Regime Type Curve



Pseudo-radial flow is indicated by 1.) the -1 slope trend in both ΔP & semilog derivative plots and 2.) equivalency of ΔP and semilog derivative values .

After-Closure Flow Regimes Plot Time Function

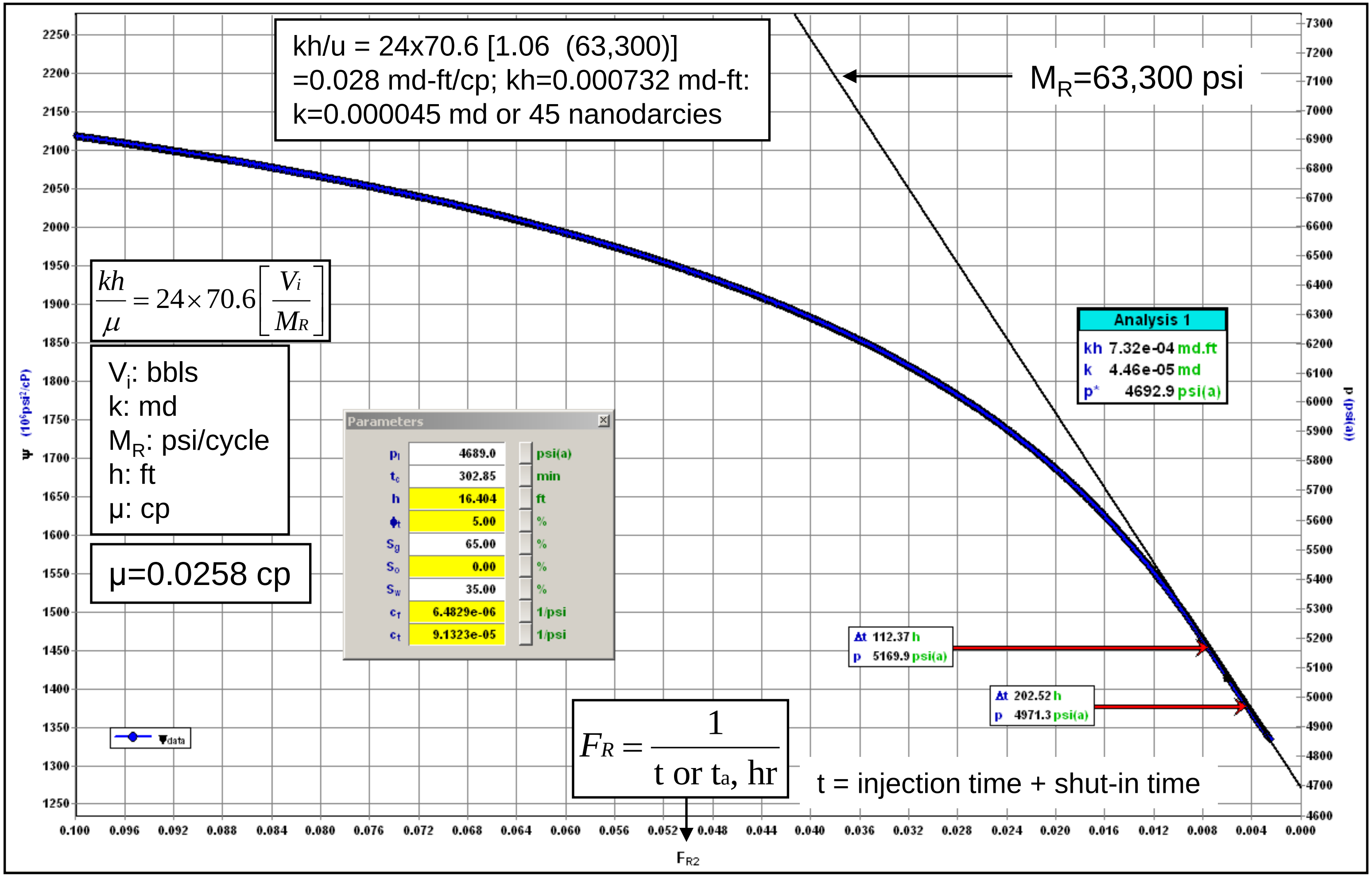
linear flow time function² = $F_L^{\,2}$

linear flow time function = $F_L = \frac{2}{\pi}\sin^{-1}\sqrt{\frac{t_c}{t}} \quad for\ t \geq t_c$

where,
t = total test time (including injection time)
t_c = time to fracture closure (including injection time)
Note: In gas reservoirs, the pseudo-time function (t_a) is used to adjust time.

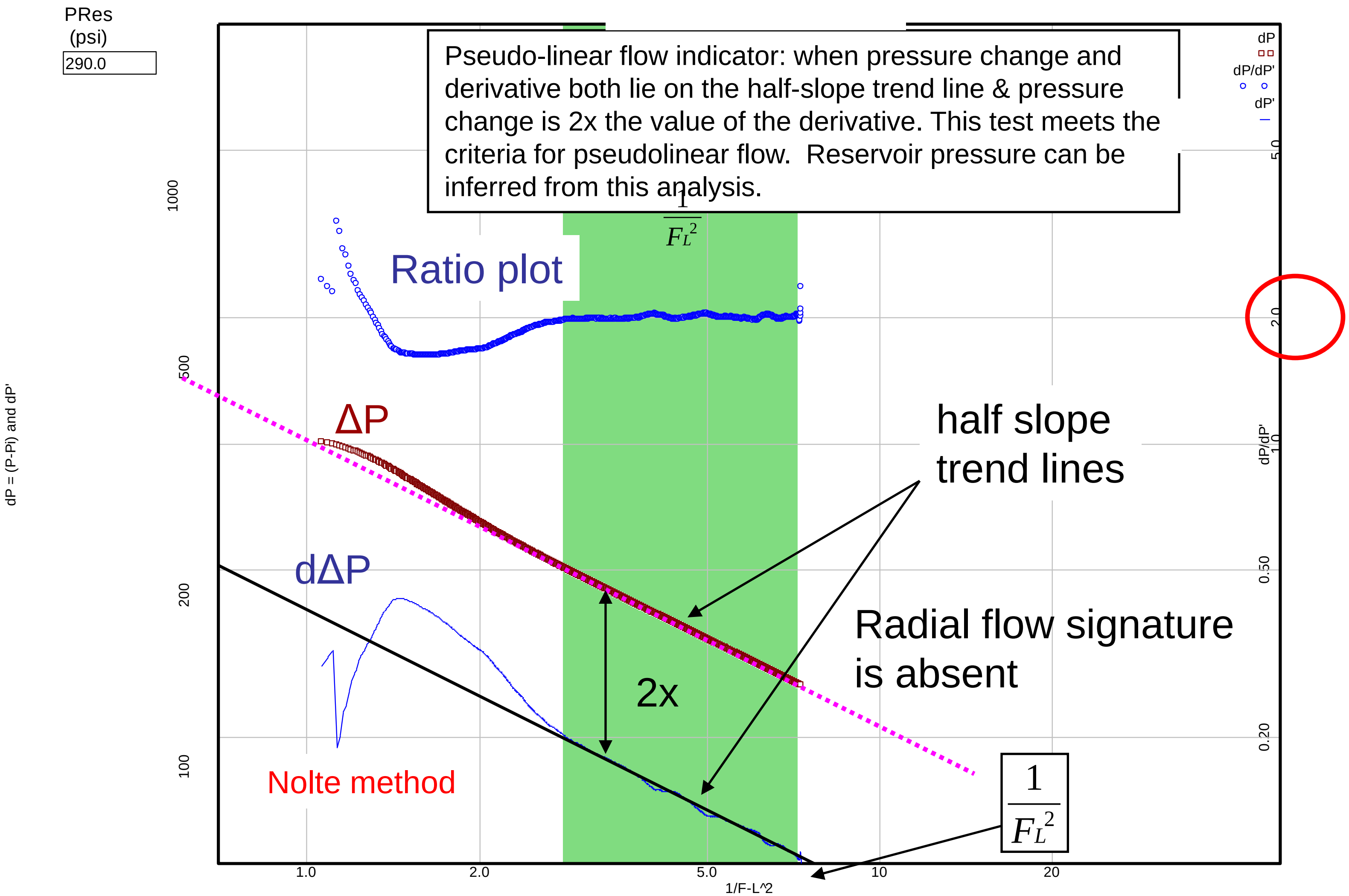
It's the linear flow time function squared, which is a function of total test time and fracture closure time.

After-Closure Radial Flow Plot



The solution derived with the Radial Flow specialty plot shows good agreement with the Type Curve plot.

After-Closure Flow Regime Plot: Linear Flow



Certain types of naturally fractured reservoirs exhibit long-term linear flow.

Summary

- **Injection Fall-off Testing is an efficient way to derive in-situ information on most rock types.**
  - A modest-size hydraulic fracture is created and pressure fall-off during shut in period is analyzed for fracture closure and after-closure radial flow period.
  - Injection rate and volume are tailored for interval thickness and leak-off characteristics.

- **Identification of fracture closure provides information on rock stress.**
  - A combination of derivative-based diagnostic plots are used.
  - Non-ideal fracture propagation (e.g., fracture height growth, fissure opening, multiple fracture closures) can be identified and evaluated.

- **After-closure analysis is used to derive rock transmissibility (kh/u) and pore fluid pressure.**
  - Radial flow is identified and evaluated by type curves and specialty plots.
  - Computations are based on well testing theory.

- **The resulting information is employed to assist in controlling the hydraulic fracturing process.**
  - The information is used in hydraulic fracture modeling to predict fracture geometry, proppant placement, fracture conductivity, etc.
  - Treatment design is modified as necessary to achieve treatment objectives.