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Well Test Techniques
CPG, DQI & DFITs

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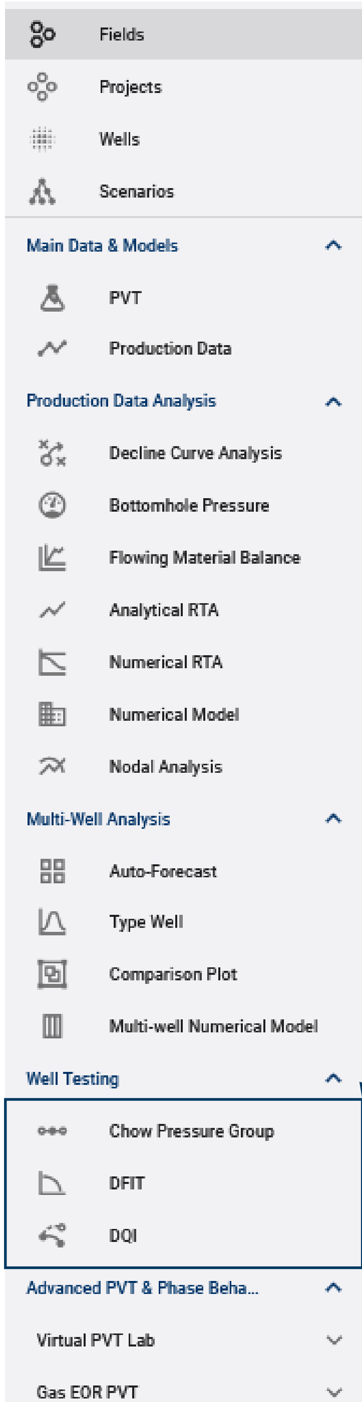
16 October 2024



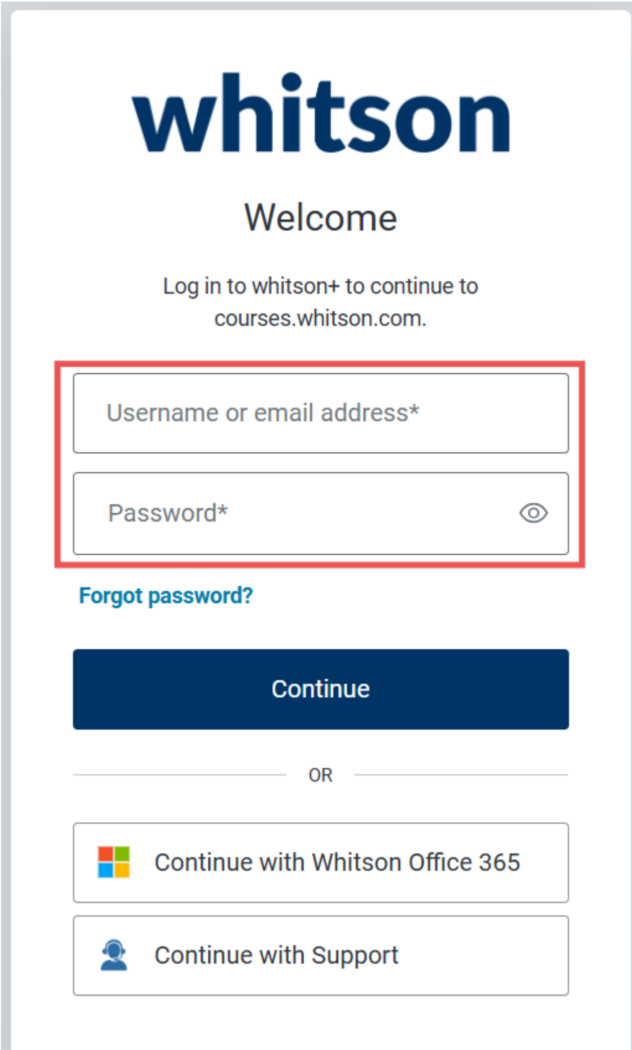
Agenda

- **whitson⁺** fundamentals

- **Part 1 – CPG**
  - CPG What and Why
  - CPG How (Workflow, Options)
  - CPG Exercise
- **Part 2 – DQI**
  - DQI What and Why
  - DQI How (Underlying Models, Sensitivities)
  - DQI Exercise
- **Part 3 – DFIT**
  - DFIT What and Why
  - DFIT How (Stress, Pressure and Permeability calculations)
  - DFIT Exercise

Software Basics

Access to whitson+



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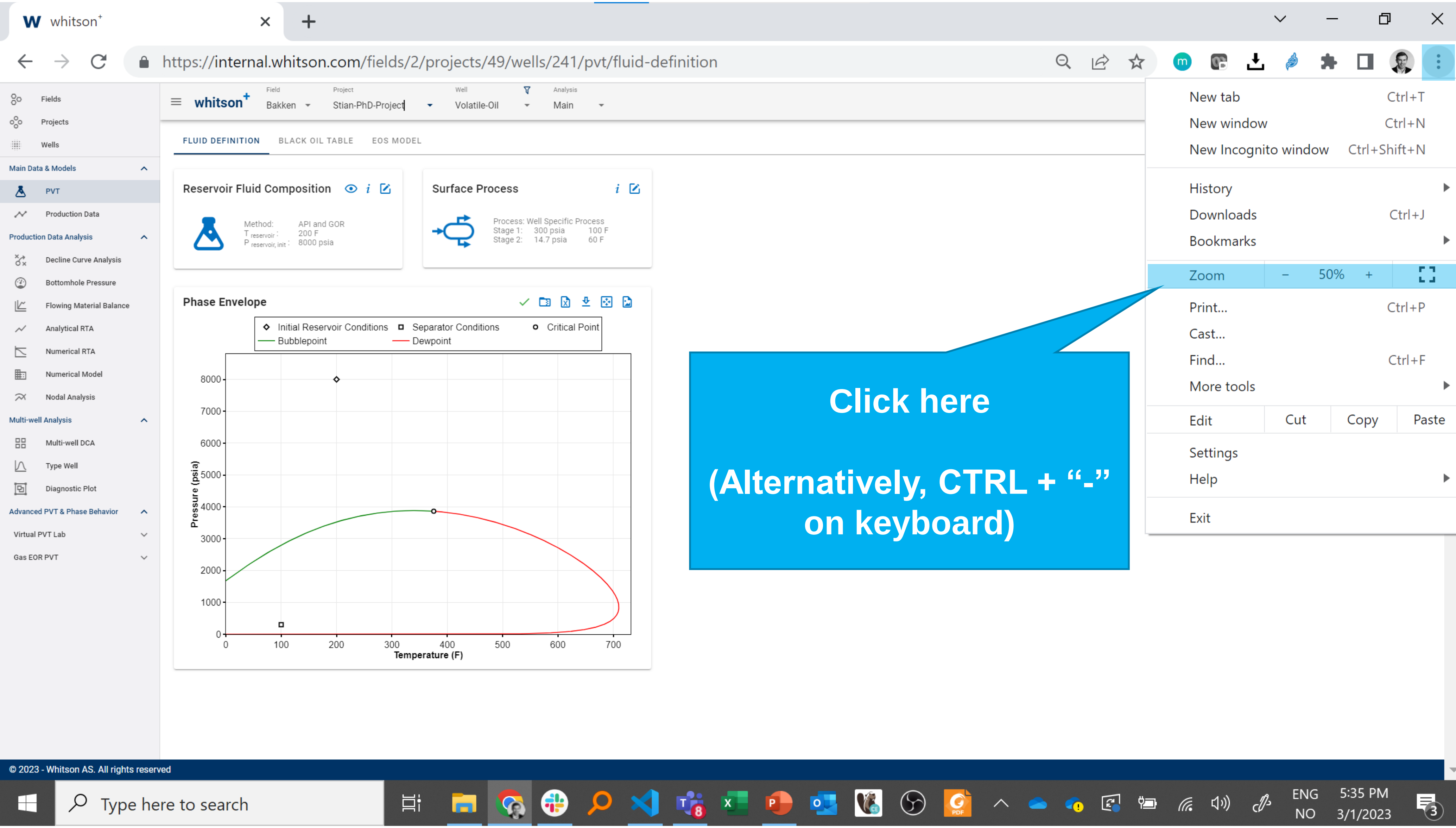
Username is your email

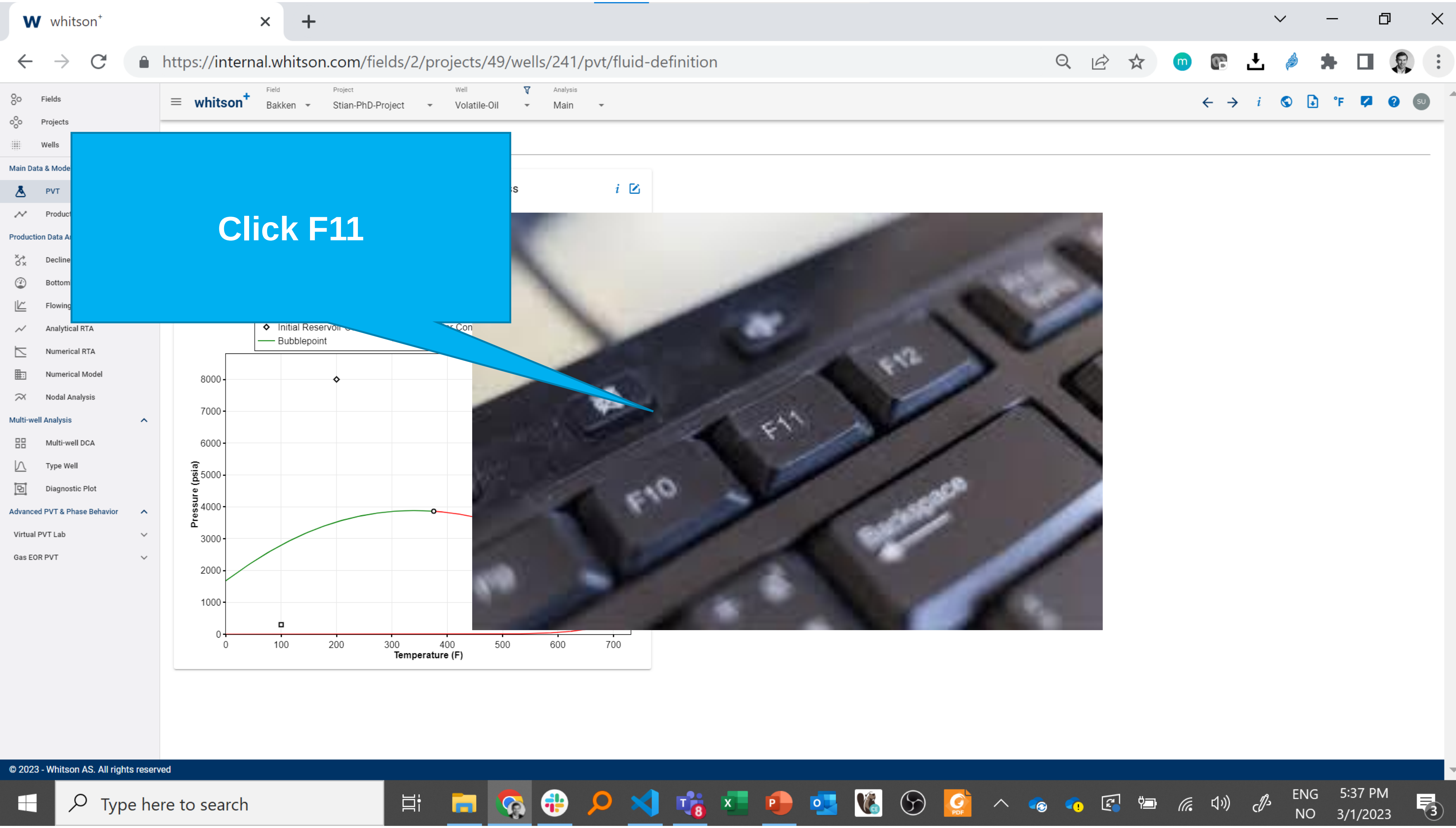
Password: WellTest2024

*Send an e-mail to support@whitson.com if you need help to login.
Need to use Google Chrome, Firefox or Microsoft Edge. Internet Explorer won't work.

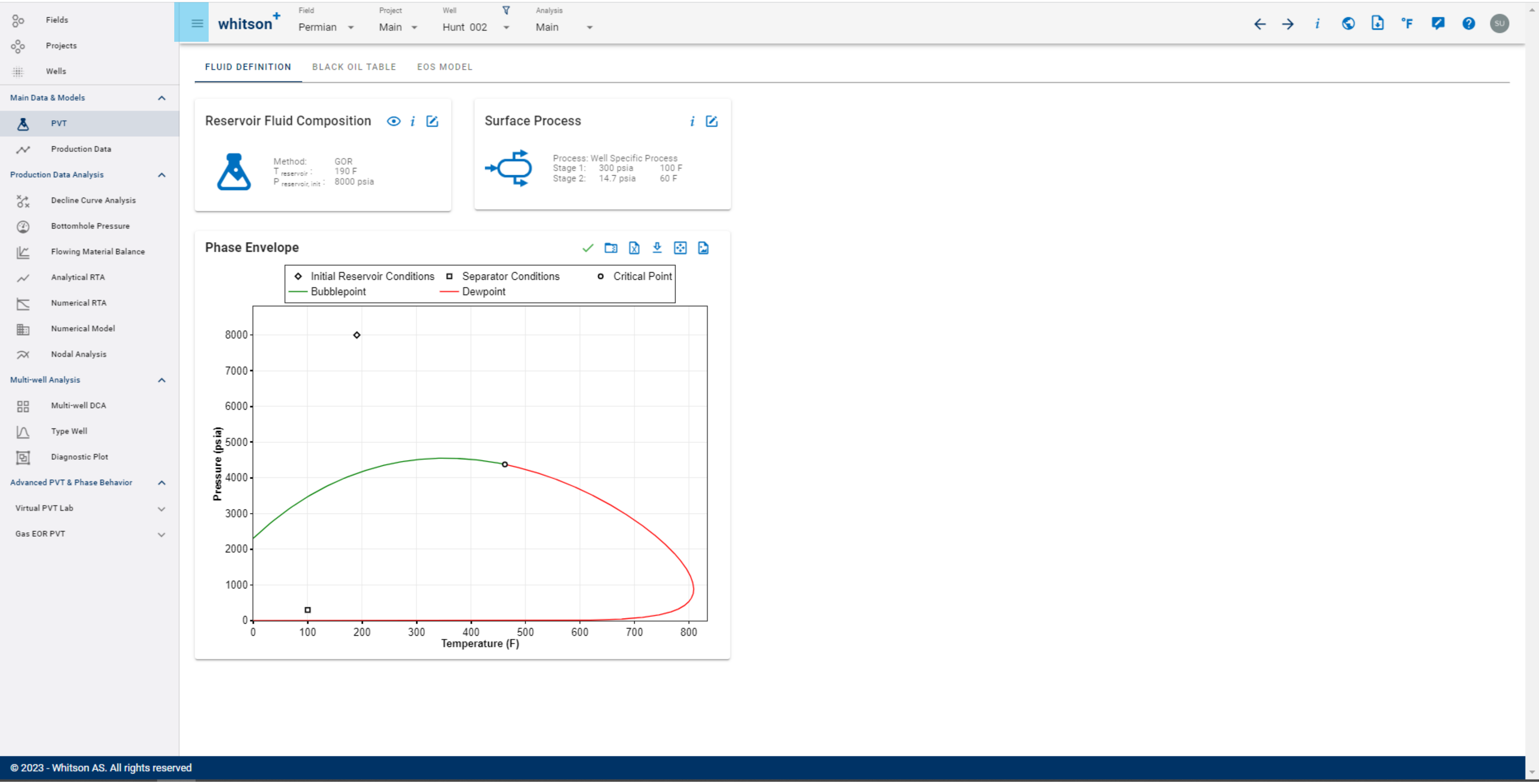
whitson⁺: Set Zoom to 70-80%



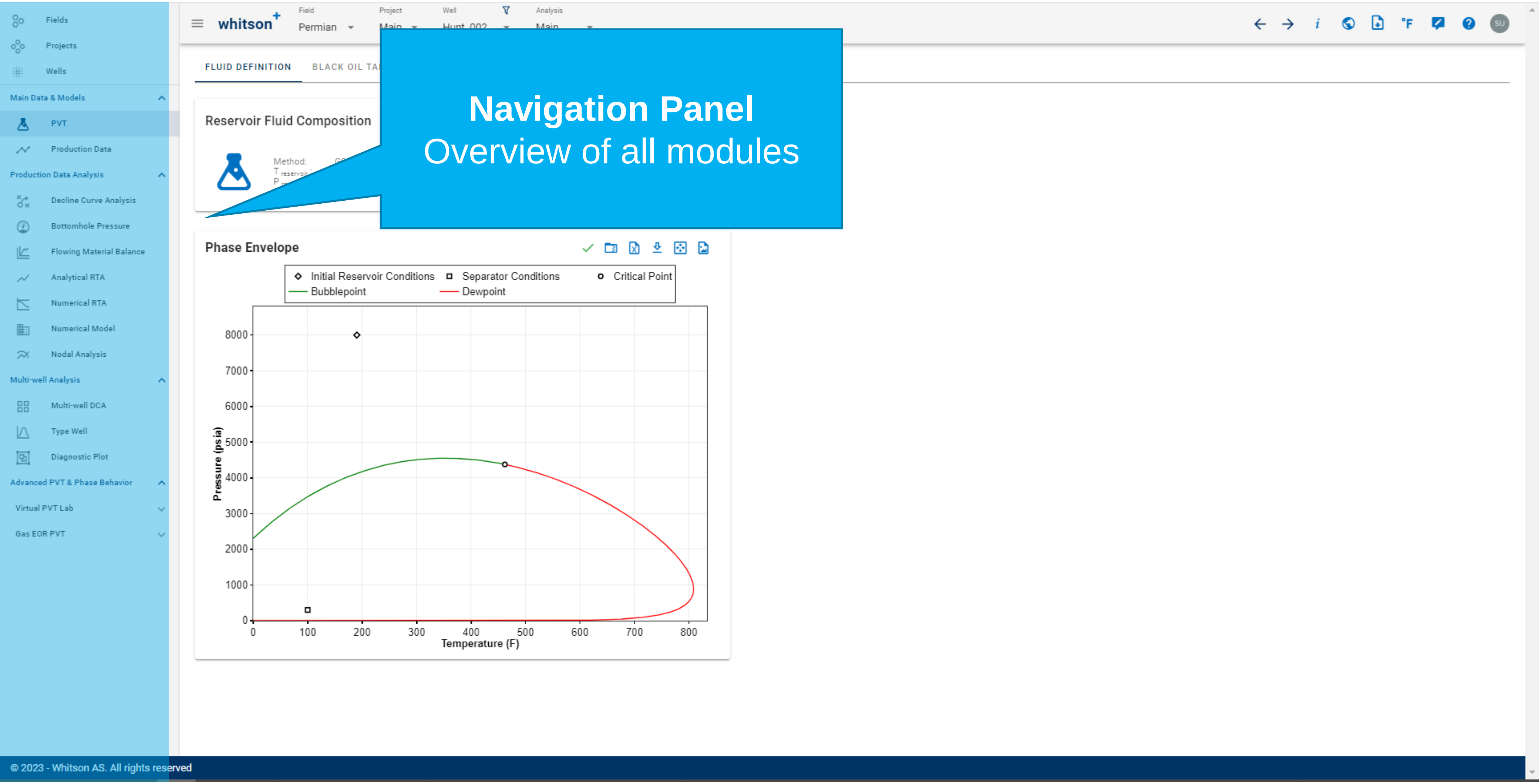
whitson+: Maximize Screen by “F11”



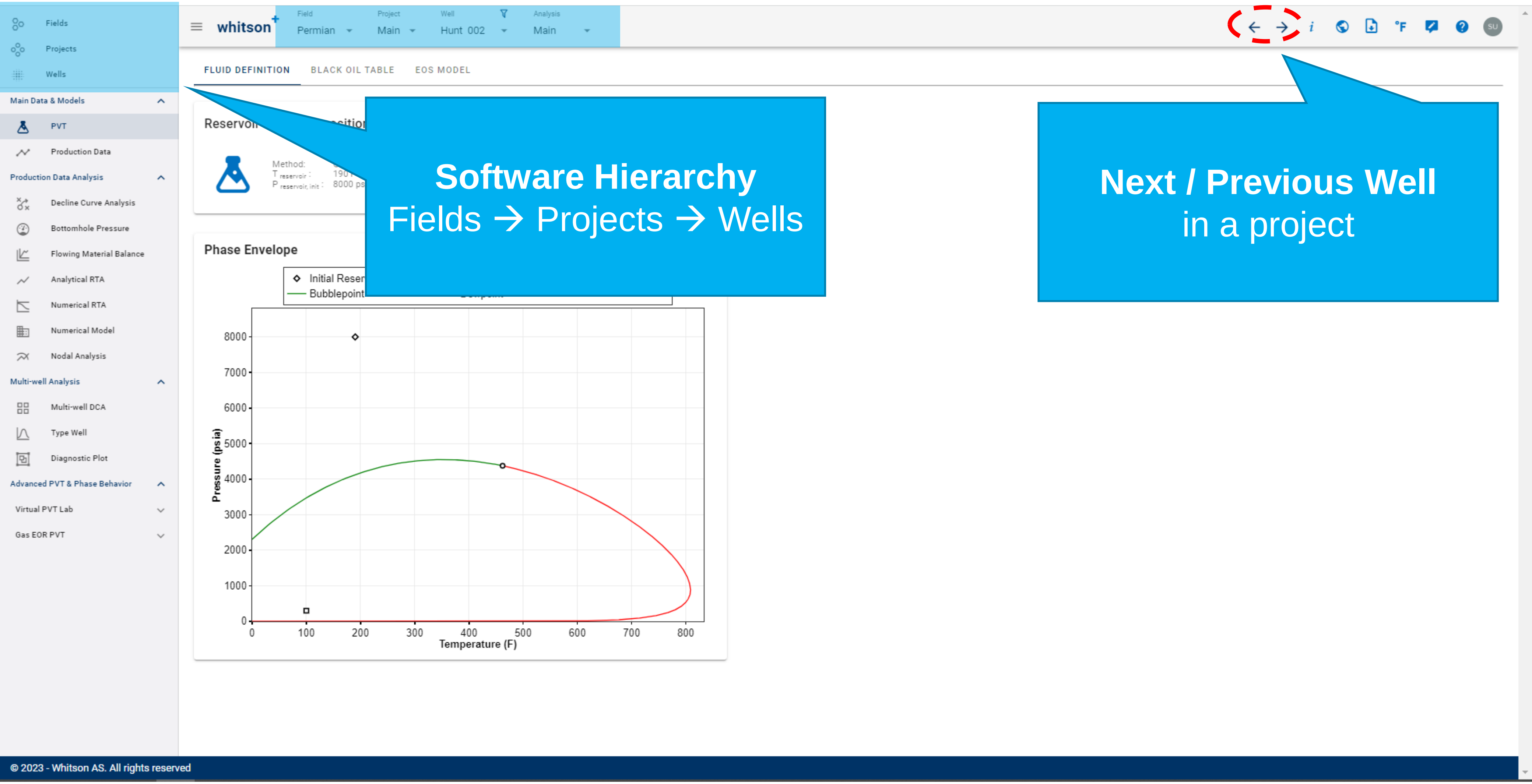
whitson+: More Screen Real Estate



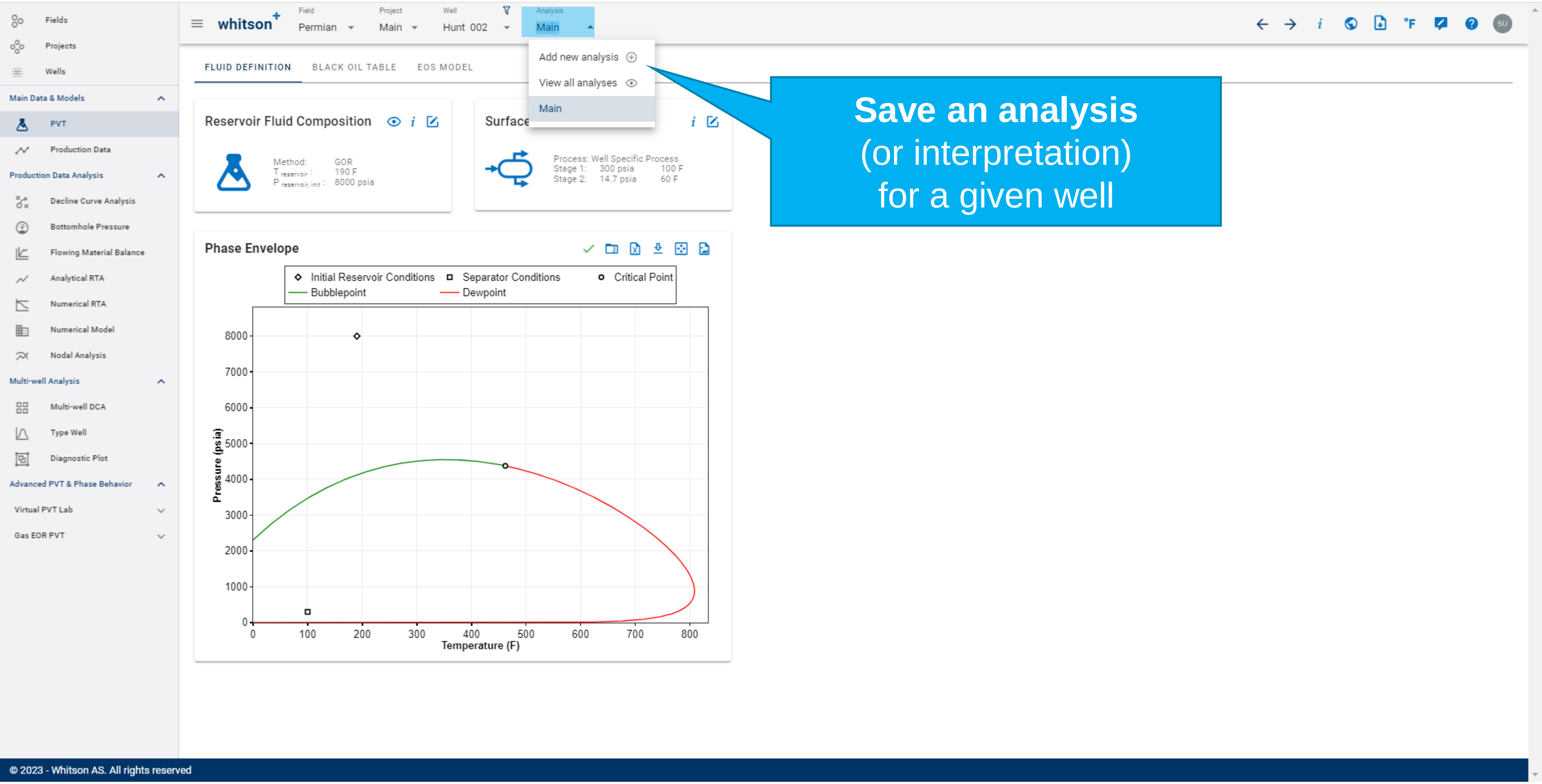
whitson⁺: Navigation Panel



whitson⁺: Software Hierarchy

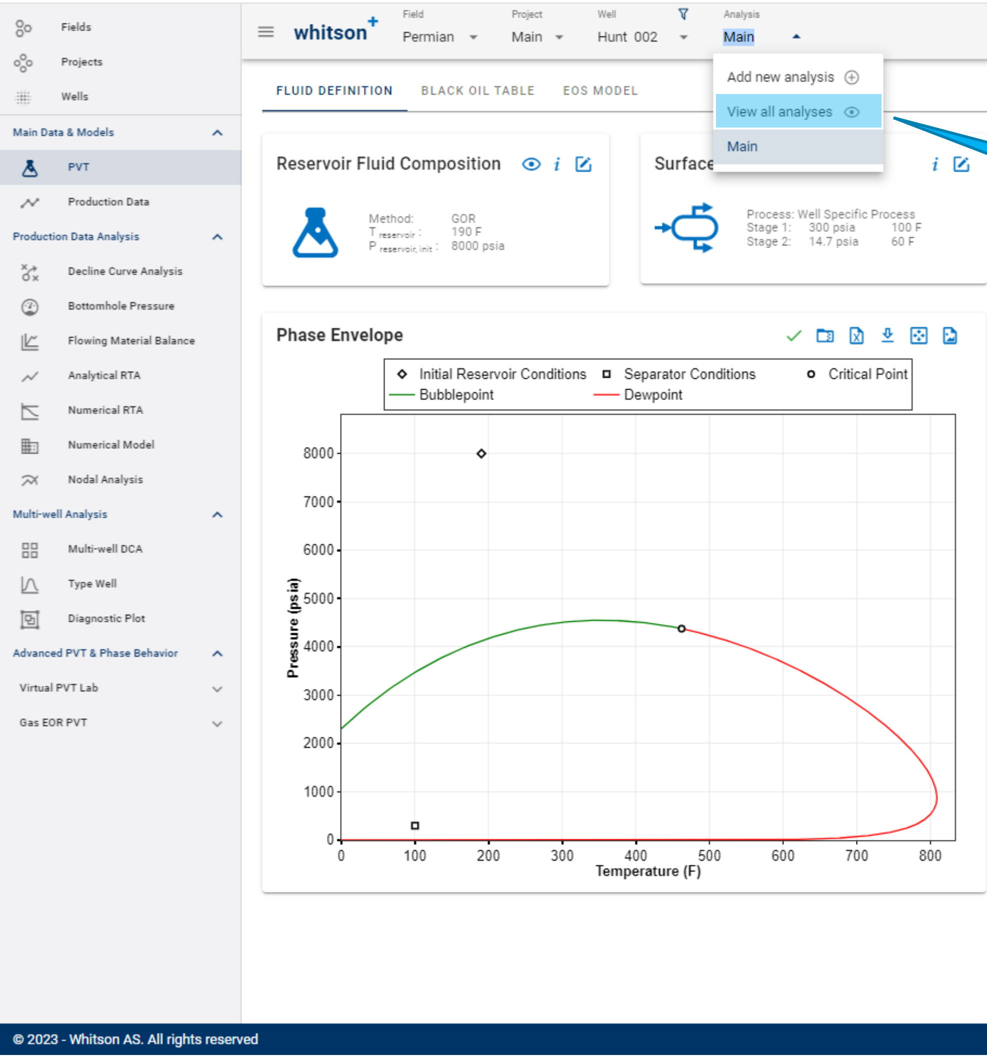


whitson+: Create Multiple Analyses for a Well



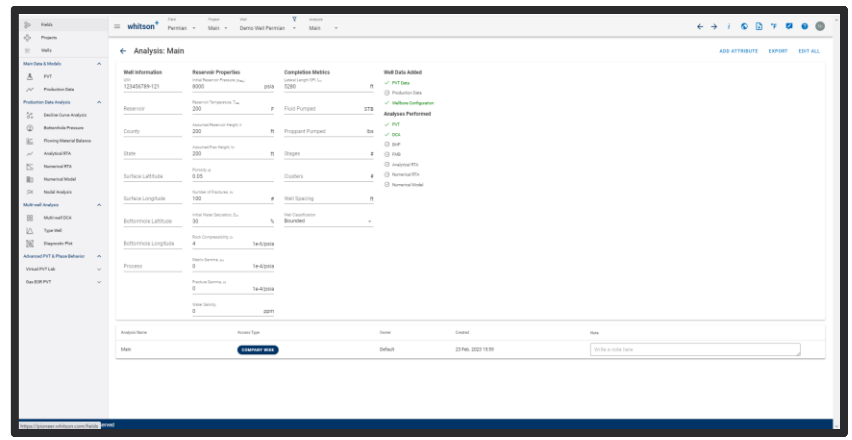
Save an analysis
(or interpretation)
for a given well

whitson⁺: Create Multiple Analyses for a Well

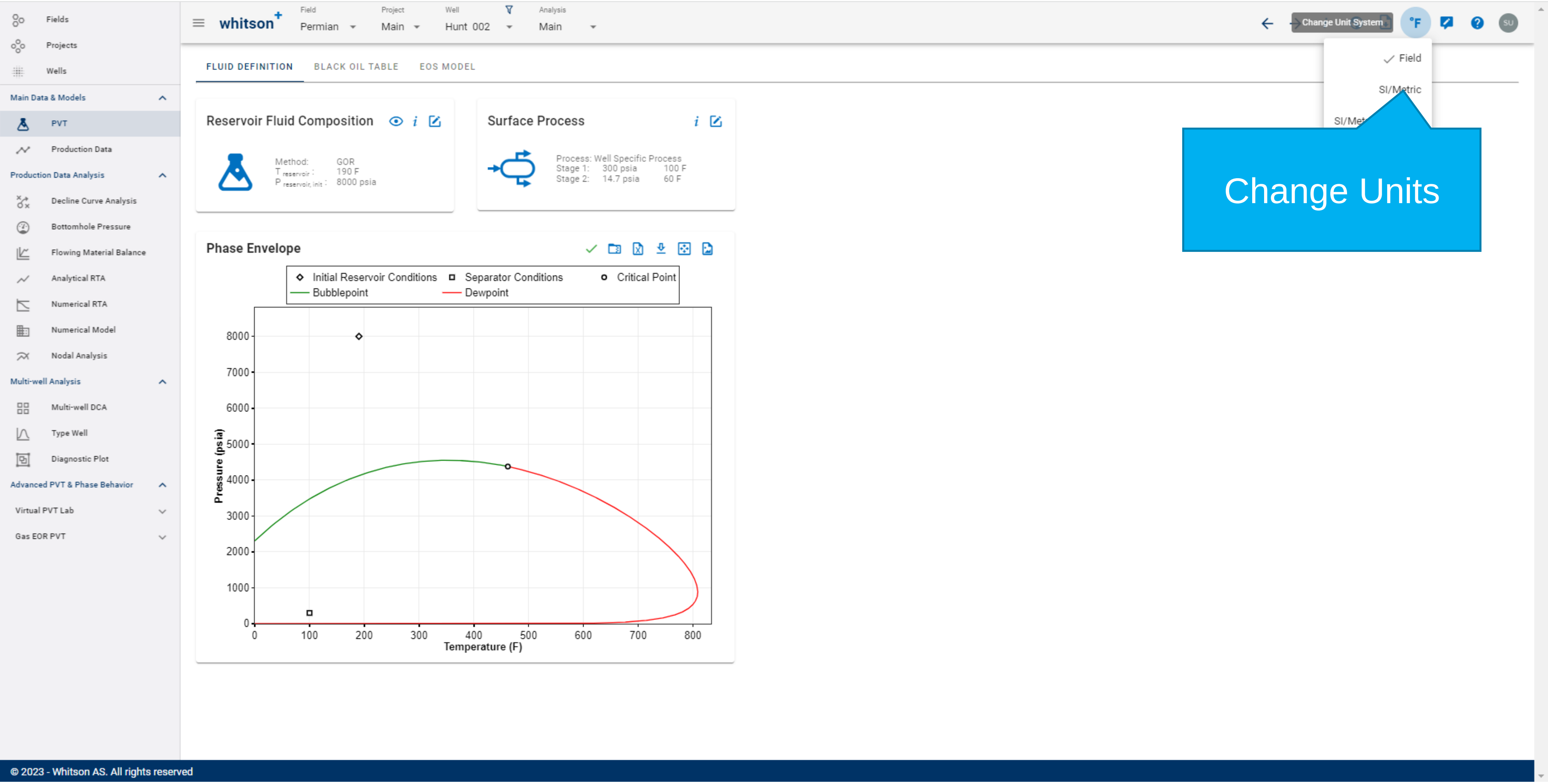


Click here and it will bring you to the well overview page

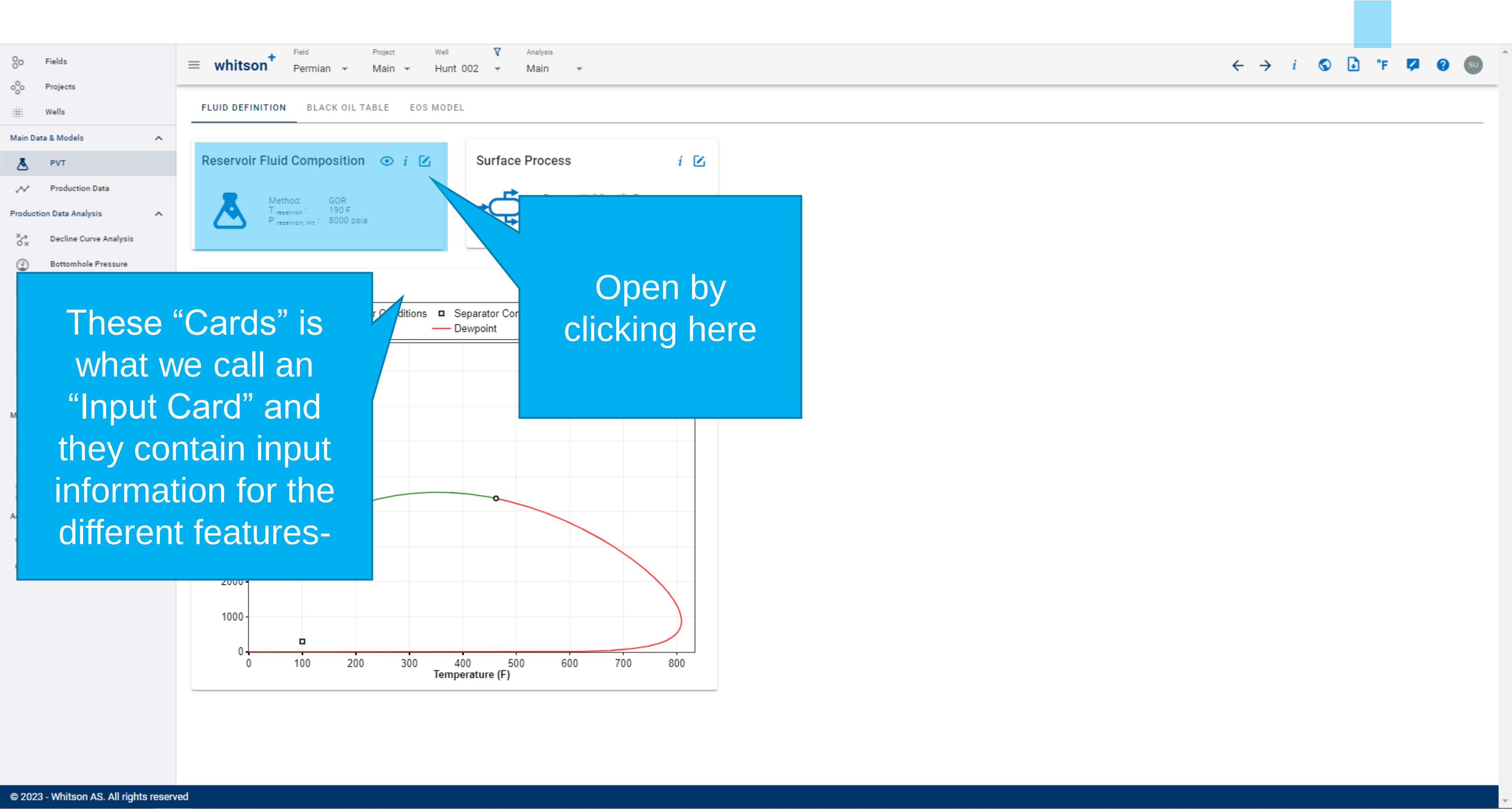
Well Overview page



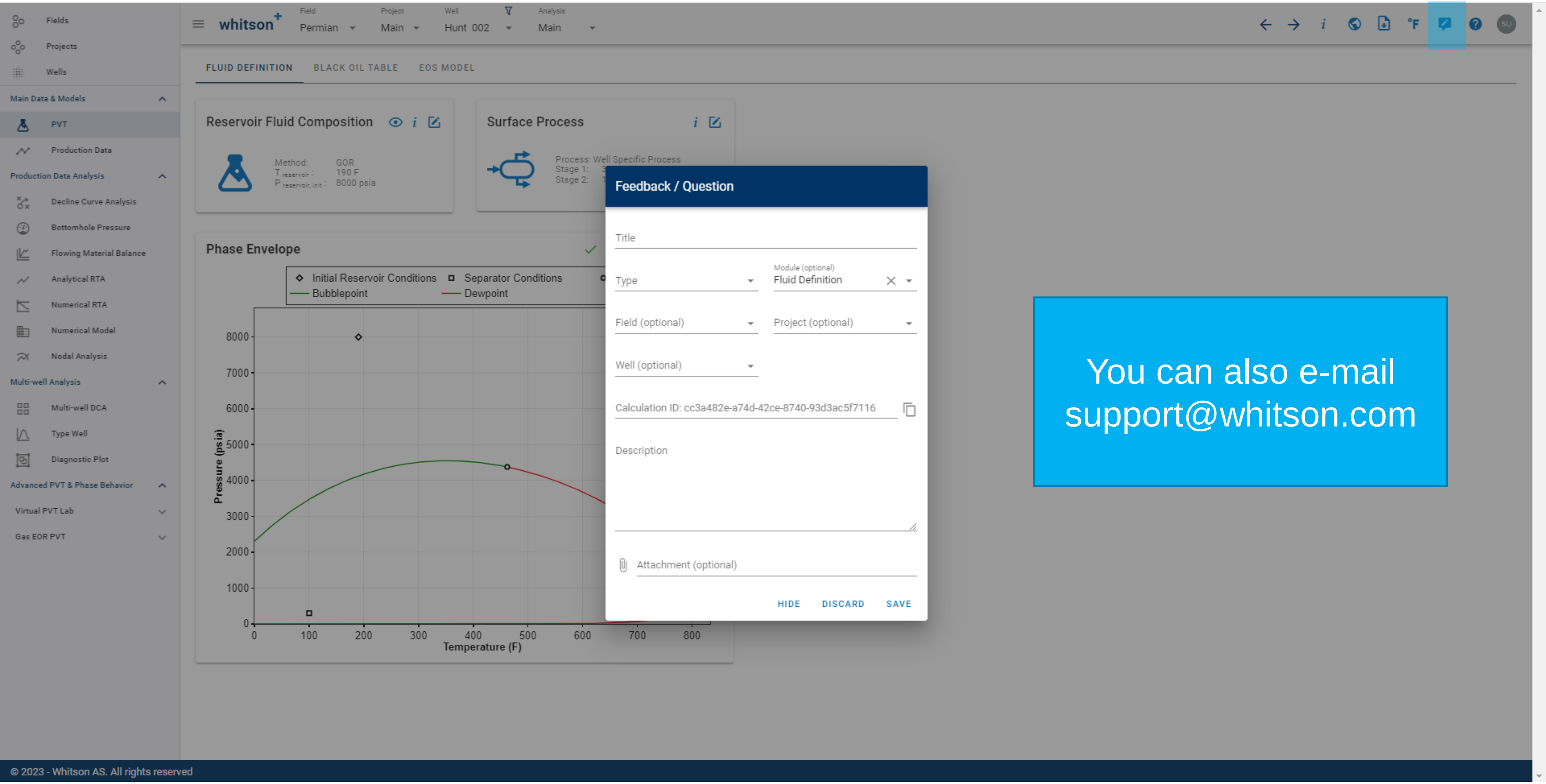
whitson+: Change Units



whitson⁺: Input Card

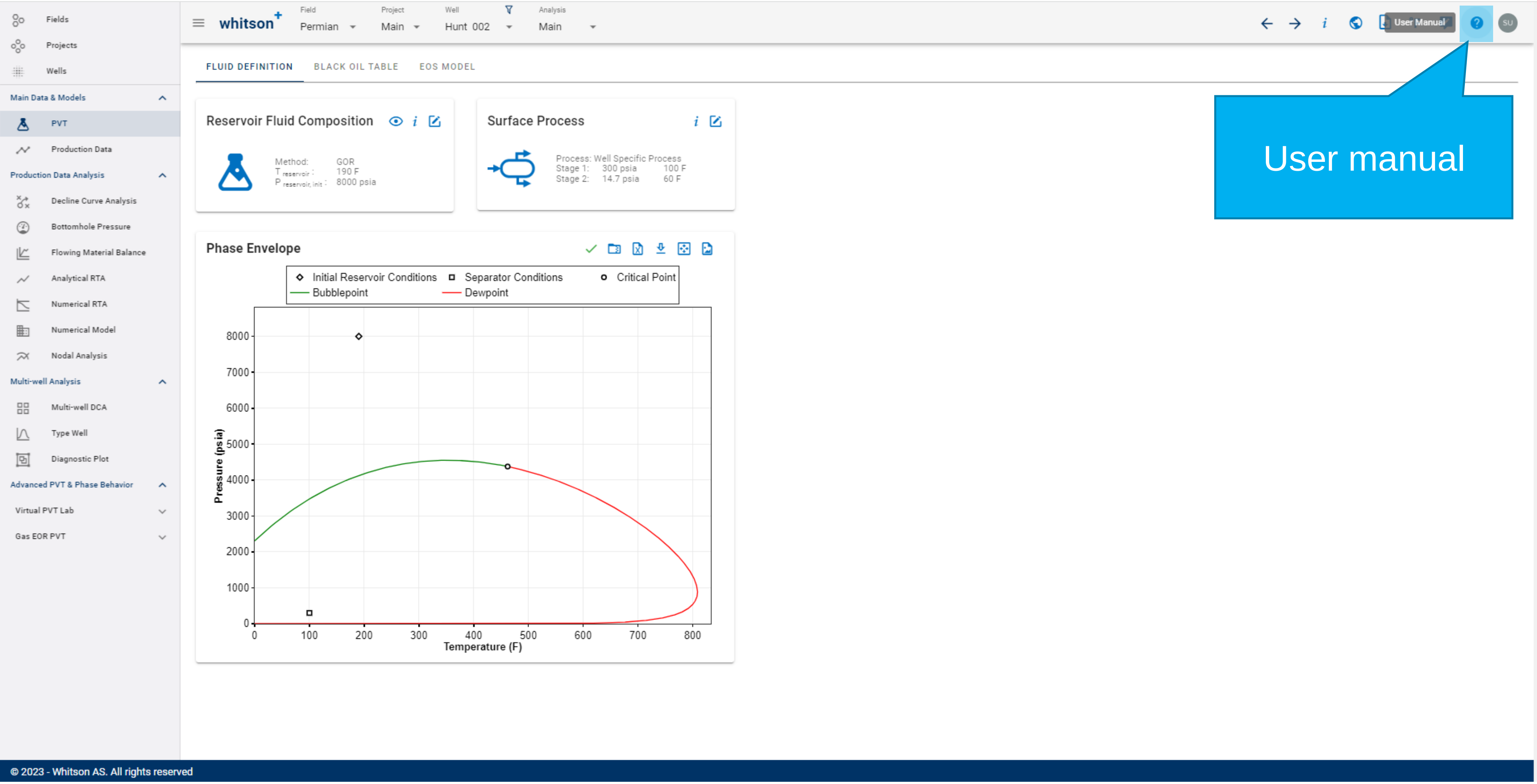


whitson+: Support Ticket



You can also e-mail support@whitson.com

whitson+: Manual



Important Shortcut: Refresh

- Refresh shortcut: “CTRL + R”
- Use if you experience
  - Bad connection
  - The browser is “stuck”

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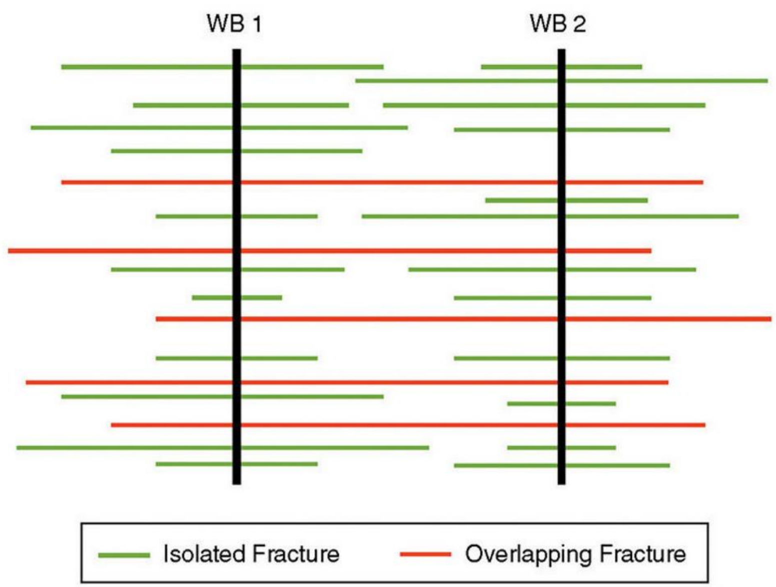
Part 1 - CPG

Why

CPG Meaning



CPG value	Level of Interference
0	No pressure interference
0-0.5	Weak
0.5-0.8	Moderate
0.8-1	Strong

- We assume CPG is an index that goes from 0 to 1.
- Higher the fracture overlap, the impact of shut in and drawdown felt at the monitoring well is higher.
- Higher the CPG values or MPI, higher the magnitude of pressure interference

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What

Chow Pressure Group - CPG

- The CPG analysis is used to detect and quantify pressure interference between offset and monitoring well pairs.

- CPG considers the BHP trend in the monitoring well before and after the offset well POP (Put on Production) to establish the magnitude of pressure interference (MPI)

- It is simply the pressure change with time over the corresponding derivative slope after the offset well comes online, given as –

$$MPI \approx Stabilized\ mean\ of\ CPG = \frac{\Delta p}{2 * \Delta p'}$$

- Chu et al (2017, 2018) integrated CPG analysis into the well interference test program at Pioneer to guide well spacing, completion volumes and its grading of the results of stacked and staggered well patterns.

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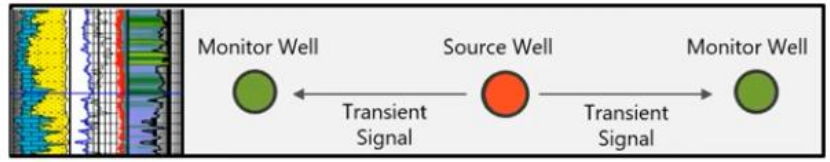
How

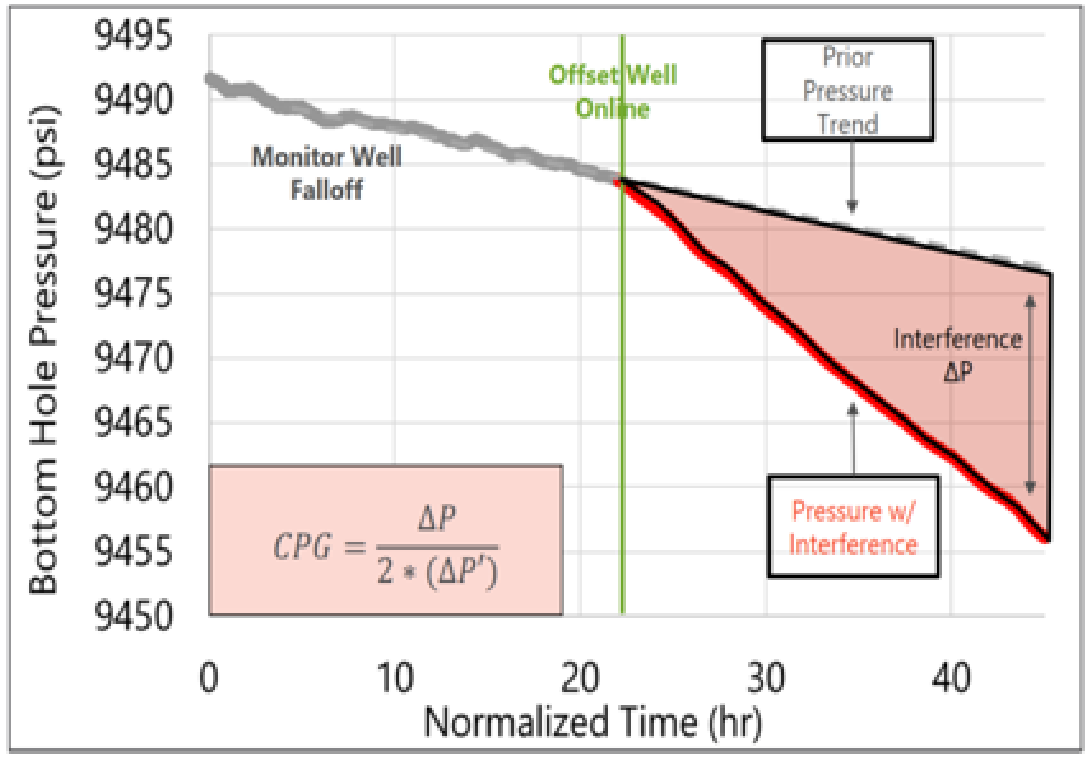
Drawdown CPG Example – RTA

Testing Design

- Run downhole gauge in one or several wells
- Monitor falloff and obtain stable conditions
- Systematically put offset wells on production
- **Monitor deviation from stable conditions**

Production or Rate Transient Test			
Initial Infill Conditions	**Source Well**	**Monitor Well**	**Data Analysis**
Flowing Wells	Shut In	**Remain Flowing**	Rates + Pressures





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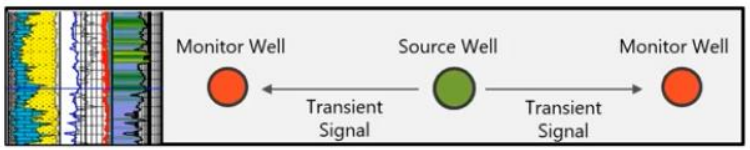
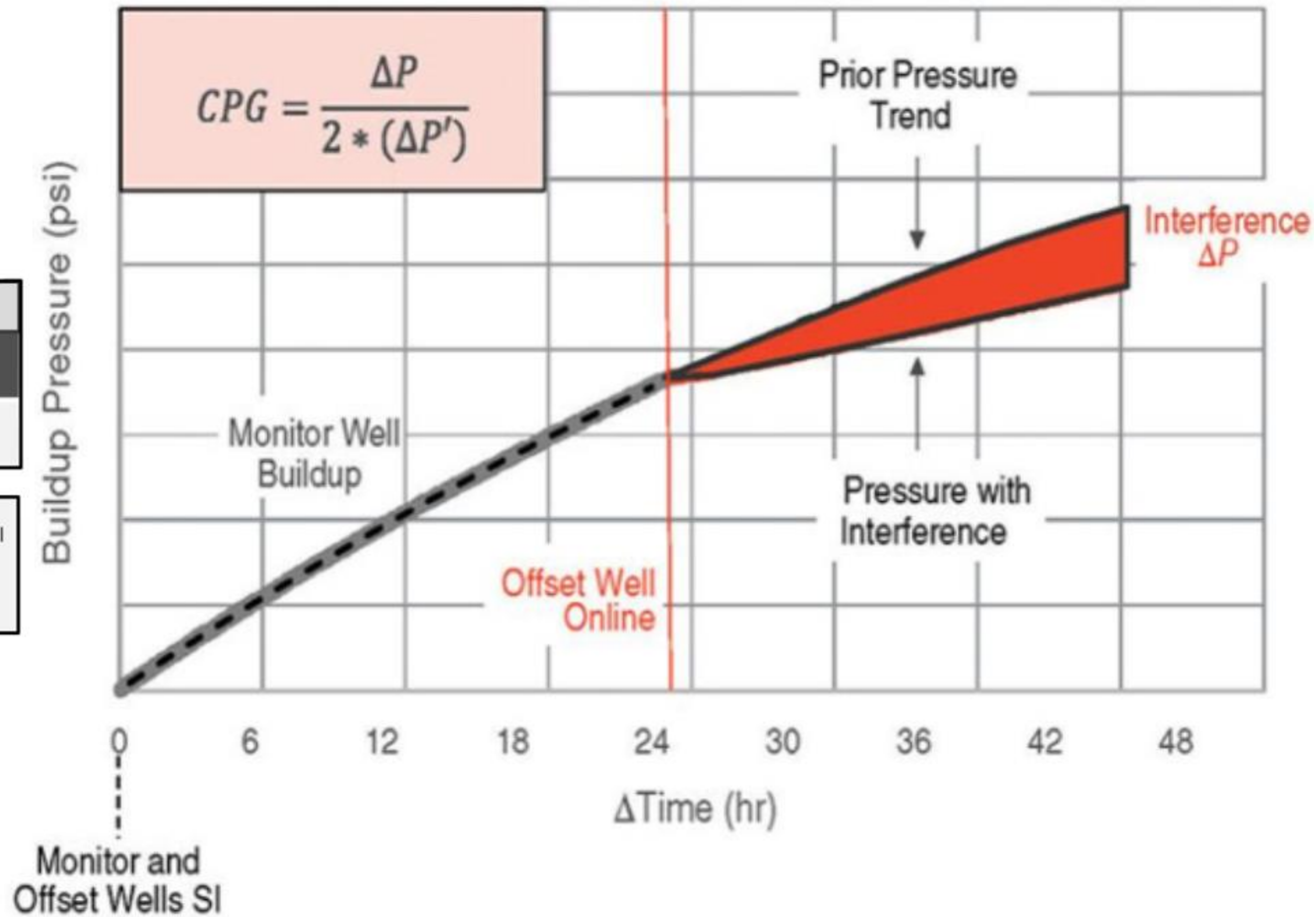
Buildup CPG Example - PTA

Pressure Transient Test			
Initial Infill Conditions	**Source Well**	**Monitor Well**	**Data Analysis**
Shut-In	Sequence Online	**Remains Shut In**	Pressure Only

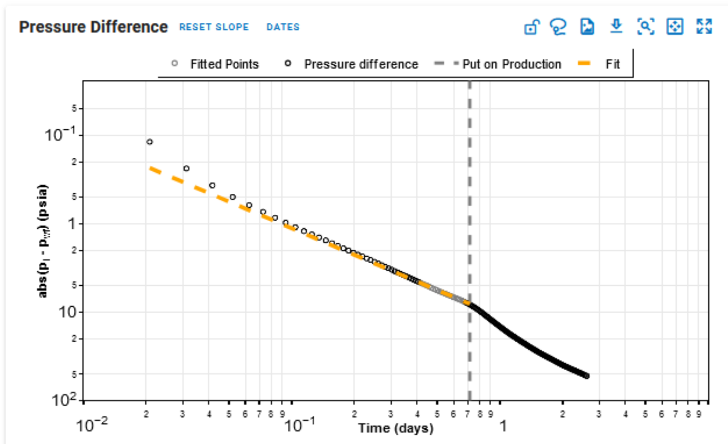


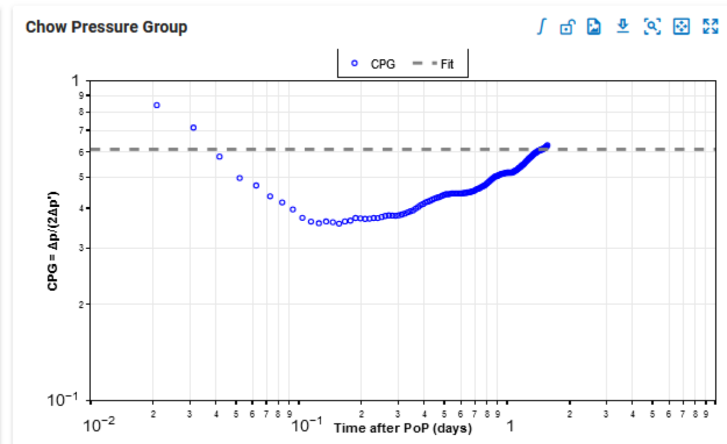


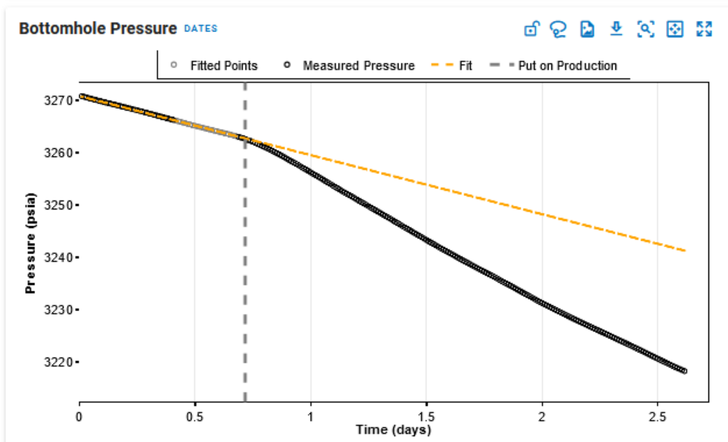
CPG Workflow Steps

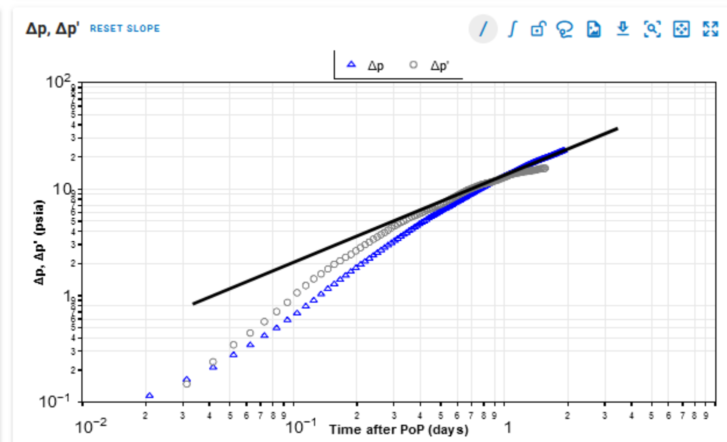
Steps

- Condition Data
- Select the time offset well is put on production (POP)
- Fit initial pressure trend
- Calculate Δp and $\Delta p'$
- Calculate CPG and select MPI









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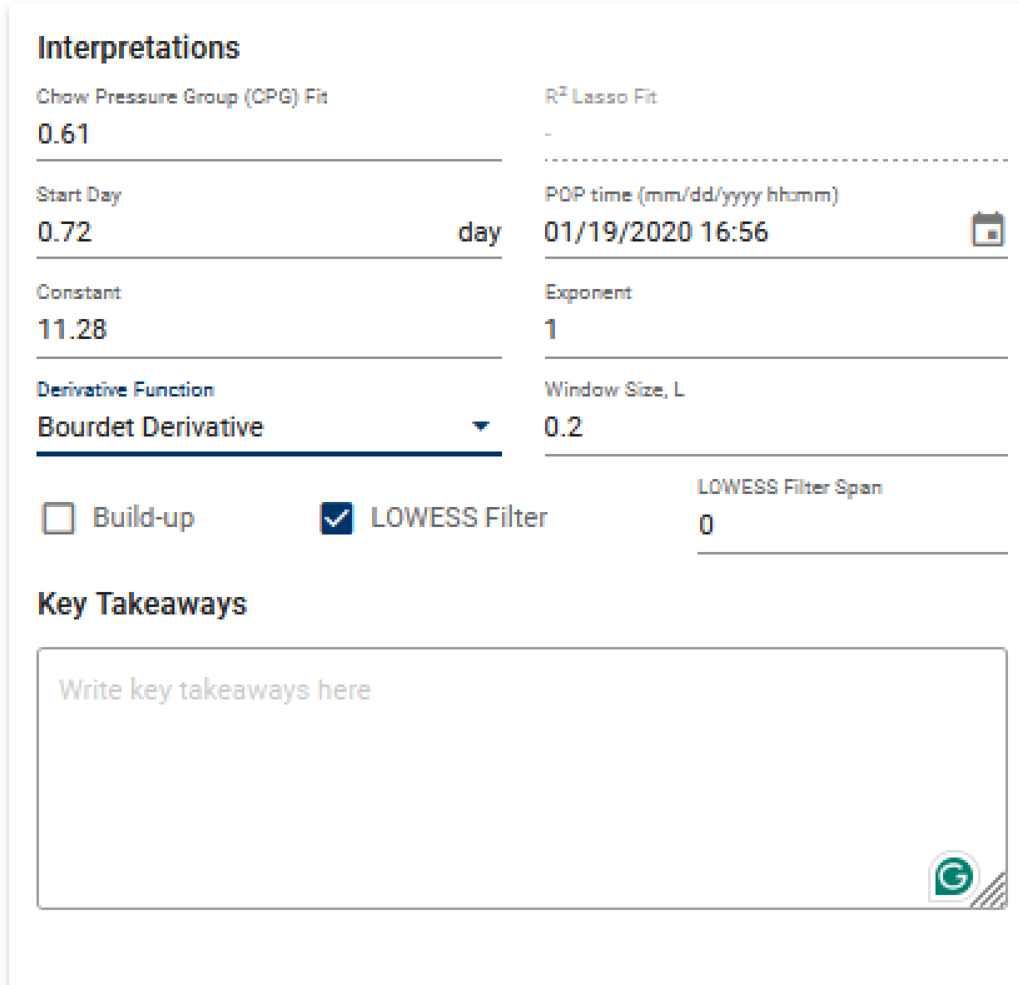
CPG Workflow Options

Variables

- Data conditioning method
- Data Frequency
- Pressure trend fit
- Derivative Function and window size
- Use of pressure integral vs normal derivatives



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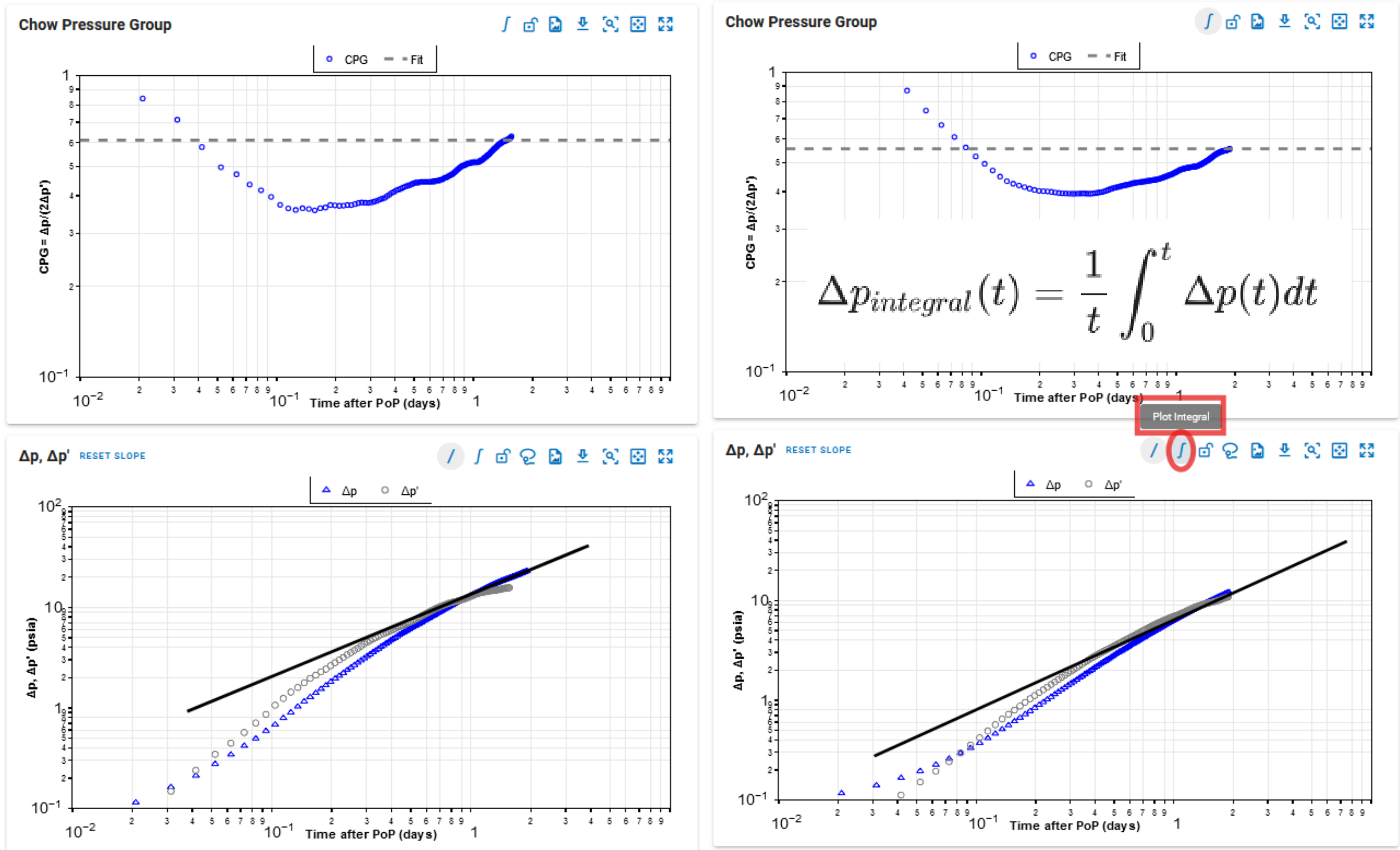
CPG Workflow Options

Pressure Integral

- Pressure data can be used to calculate the pressure integral as shown.
- Preserves the signature of the pressure response with respect to time
- Reduces the noise in the derivatives
- Increases stability in the derivative values, interpretability of the data for calculating MPI



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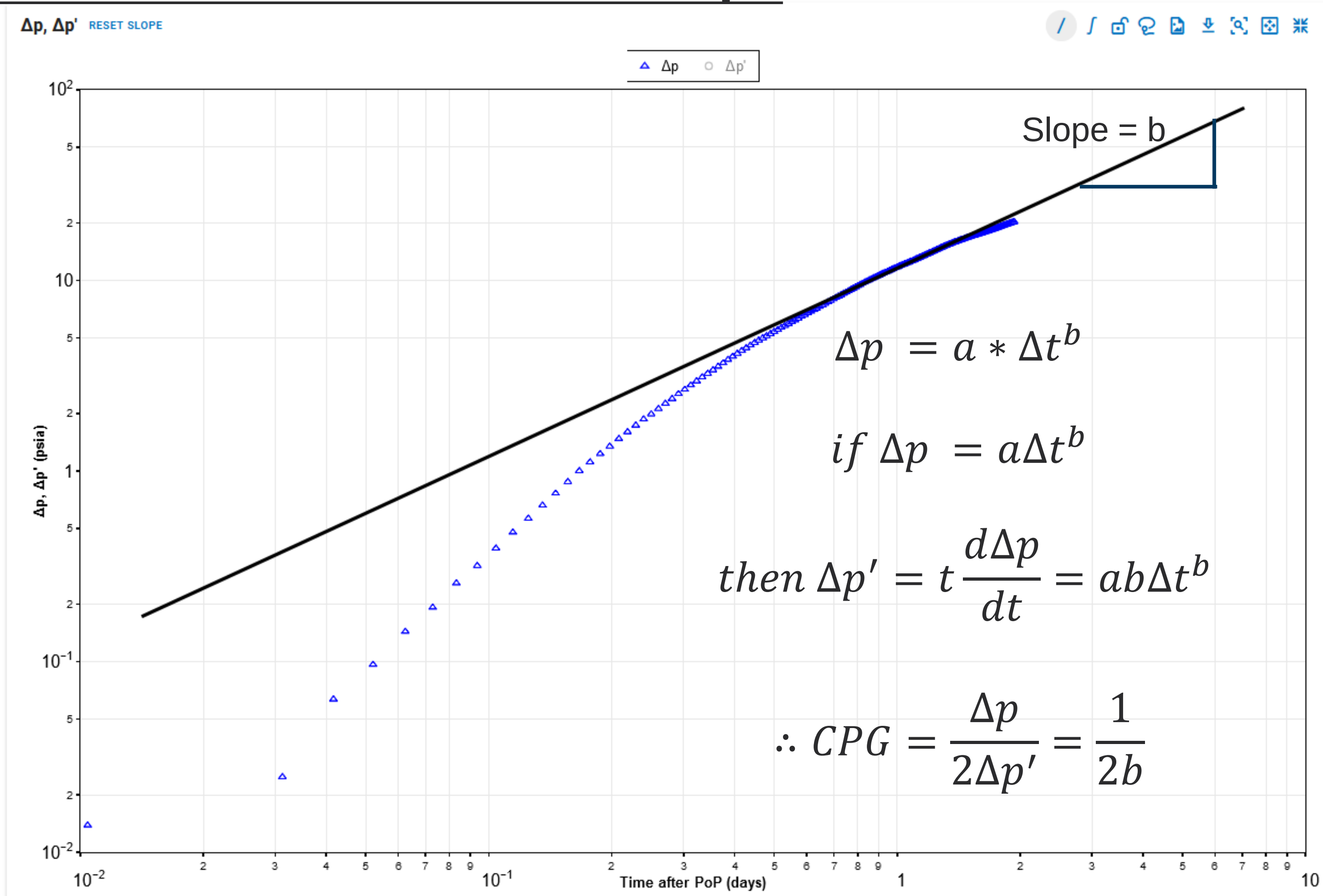
CPG Workflow Options

Stabilized CPG derived from ΔP slope



$$\Delta p \;= a * \Delta t^b$$

$$if\ \Delta p \;= a\Delta t^b$$

$$then\ \Delta p' = t\frac{d\Delta p}{dt} = ab\Delta t^b$$

$$\therefore\ CPG = \frac{\Delta p}{2\Delta p'} = \frac{1}{2b}$$

Easy way to gather the approximate MPI (stabilized CPG) value

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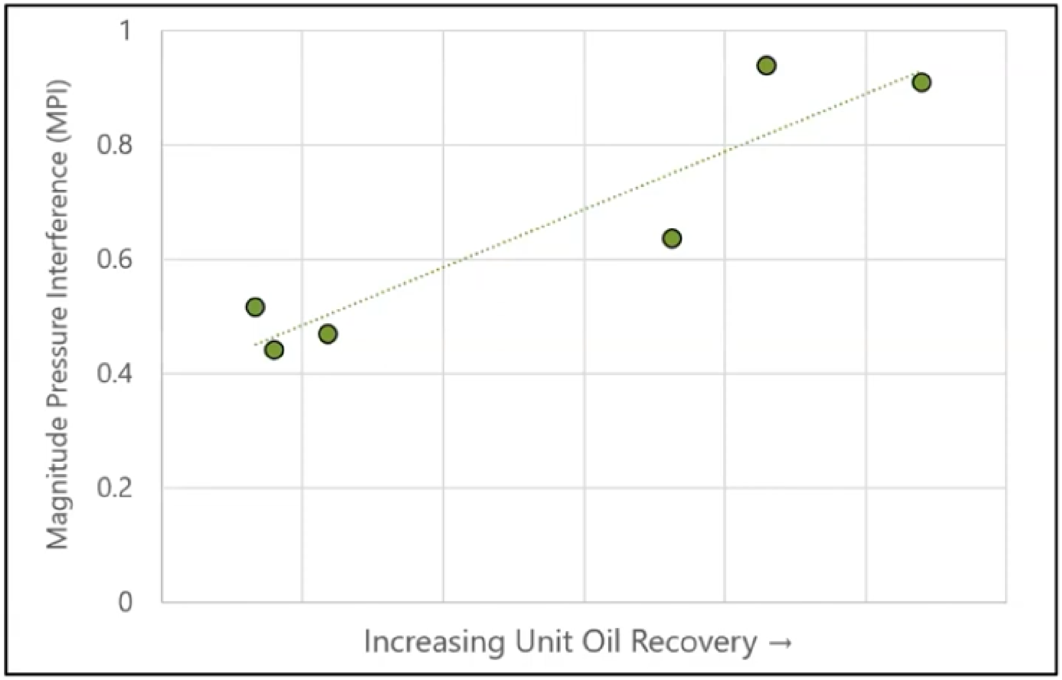
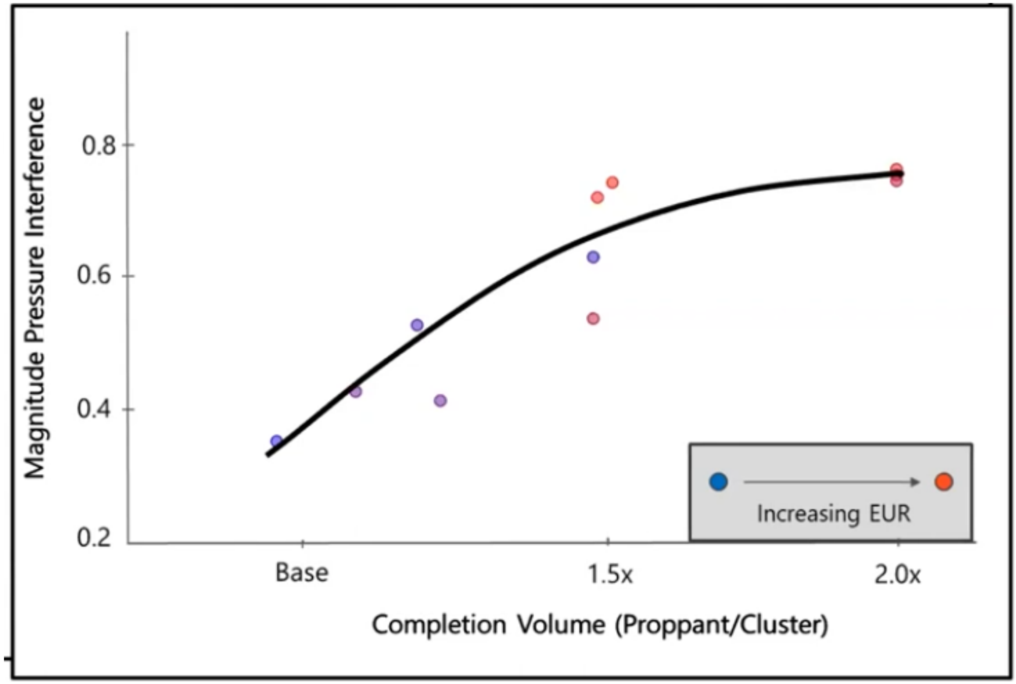
Value of CPG analysis

*Ingle et al, Devon: URTEC-2020-3040-MS





- Value to Team
  - Calibrate frac models
  - Refine expectations of contacted OOIP
  - Enhance characterization of appraisal sweet zone spots
  - Allows for considerations on completion fluid and volume
  - Develop it independently later?
- Key takeaways
  - Higher MPI led to higher unit recovery
  - Interference tests at various proppant vol. to assess impacts to MPI
  - Higher proppant/cluster led to higher MPI but + point of diminishing returns on proppant vol.
  - Built economic models of completion vol.

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Summary

- CPG analysis in interference tests can be used to assess the conductive fracture overlap and add value to field development decisions
- Short duration tests and data is cost effective to acquire
- Infill wells that have been shut-in are perfect candidates:
  - Gauges do not need to be run prior to well shut-in.
  - Well to well interference test typically takes less than three days.
  - Duration for entire unit might range from 5 to 15 days depending on wells/section, observation time to stabilization, etc)
- Additional references – SPE 191407, SPE 187180 (Chu et. al) - Kappa/Pioneer publications

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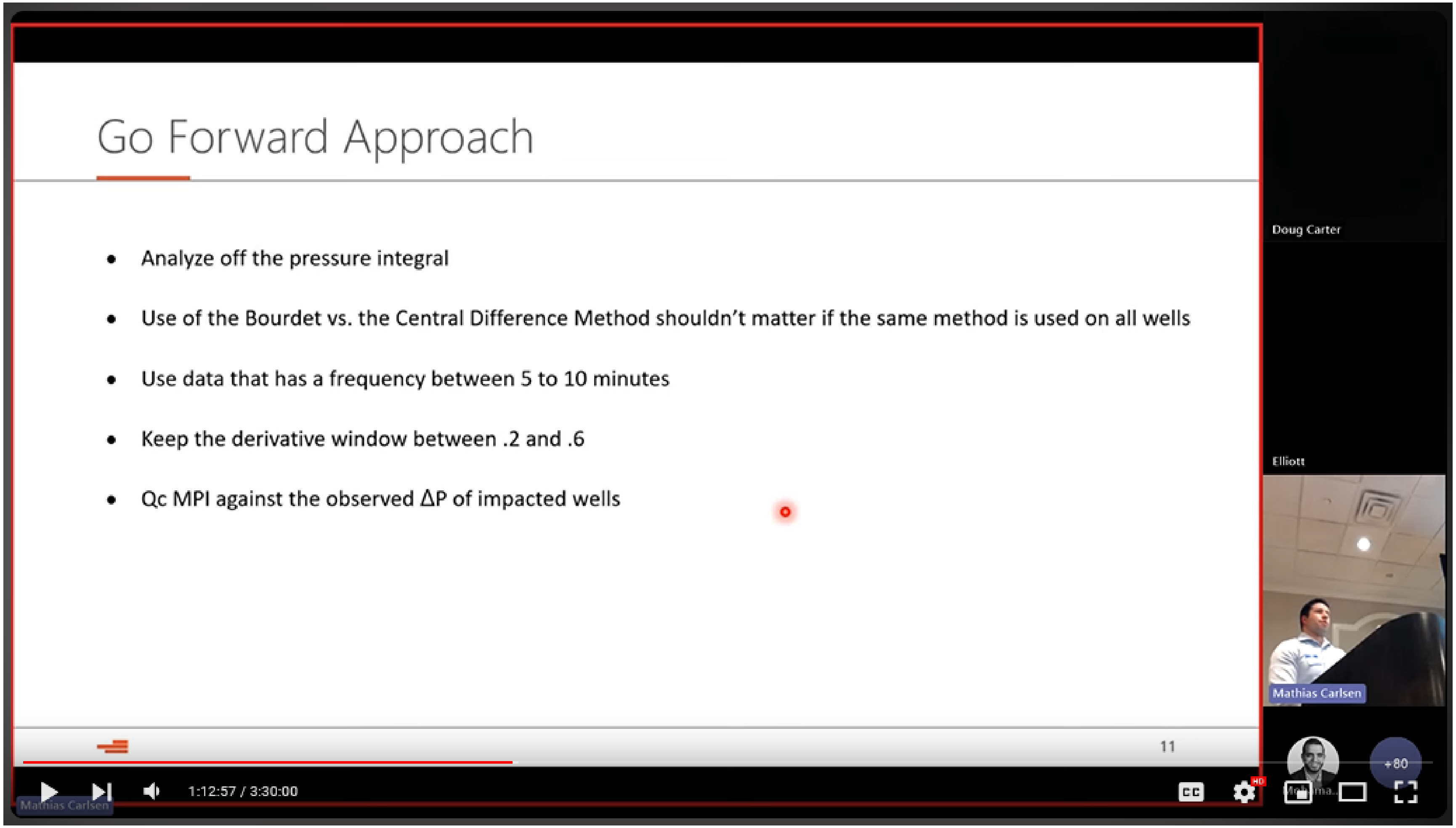
More References? How NOT to CPG



whitcon 2023 – Part 2: How NOT to CPG by Donovan Armistead, Devon

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Exercises

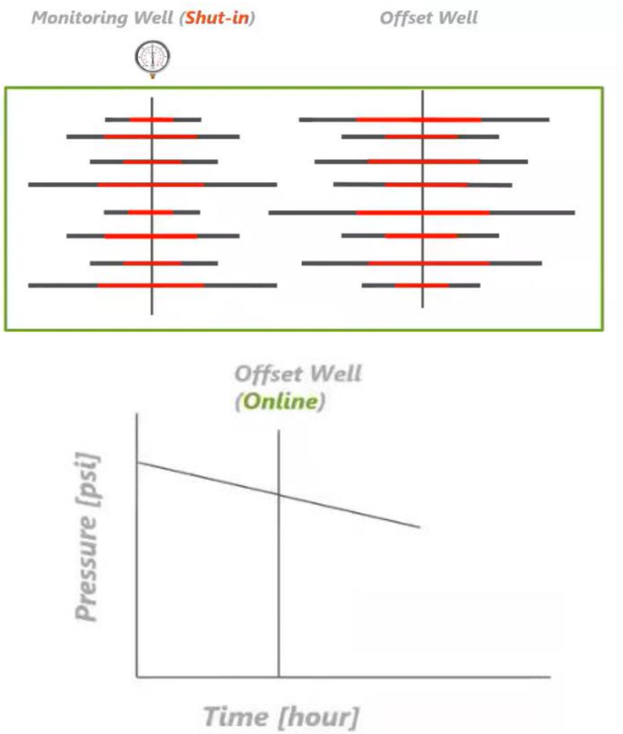
Part 2 - DQI

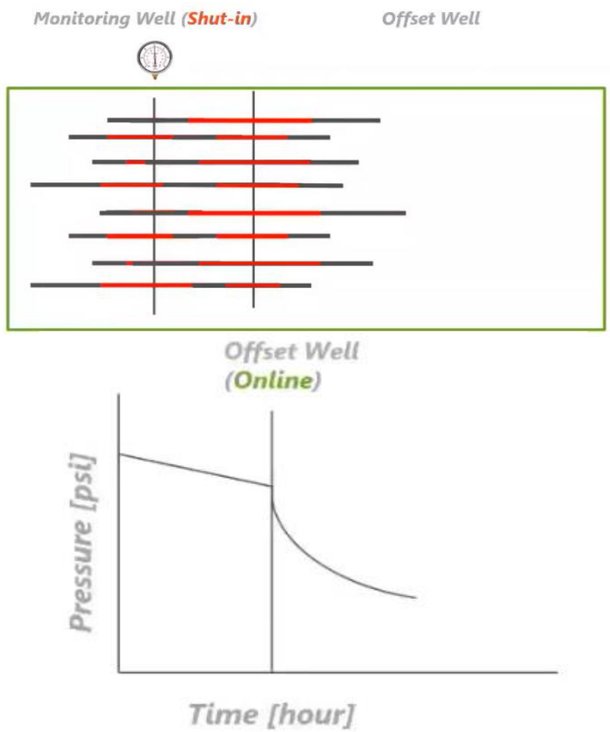
Why

DFIT Key Outcomes

- Quantifies Production Impact
- Hydraulic Diffusivity
- Fracture Conductivity

Devon Quantification of Interference - DQI





- DQI is the procedure to interpret well-to-well interference and calculate the degree of production impact between two wells.
- Offers insights into fracture properties, completion quality, and calculates maximum possible drained fracture length as a function of fluid properties.
- Results in calculation of DPI and dimensionless drainage length – which can be directly used for strategizing well spacing

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DQI versus CPG

Drawbacks of CPG:

- Not a quantitative estimate of the impact to producing rates
- Same value of CPG may not mean the same amount of production interference
- Accounts for the shape of the pressure interference only, does not account for timing of the interference response or the variability of fluid and rock properties.
- Difficulty in obtaining stabilized CPG values from field data
- Affected by factors such as pressure decline at the production well, matrix permeability, fracture skin and potential anomalous diffusion.
- CPG values from different formations, under different test conditions may not be comparable
- CPG value increases with increase in fracture conductivity but also increases with time – as flow regimes change, the CPG may keep increasing beyond 1.

Advantages of the DQI:

- Robust to differences in drawdown schedule and/or nonlinearities in the fracture flow.
- Relates the observations to fracture conductivity, a physical parameter that would otherwise be difficult to measure.
- Provides a framework for estimating how production will be impacted by interference.
- Considers the effects of fluid and rock properties (viscosity, compressibility, and matrix perm)

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What

Devon Quantification of Interference - DQI

- DQI is the procedure to interpret well-to-well interference
- DQI quantifies the hydraulic diffusivity (α) and fracture conductivity between the wells to calculate the dimensionless drainage length (L_D)
- The L_D is used to estimate a parameter called the DPI – degree of production interference, defined as –

$$DPI = \frac{q_{20\ days} - q_{bef}}{q_{bef}}$$

- This DPI can be directly linked to the magnitude of change in production expected in an active well when the offset well is shut-in:
  - DPI = 1 or 100% – producing rate should double.
  - DPI = 0.1 or 10% - producing rate should increase by 10%

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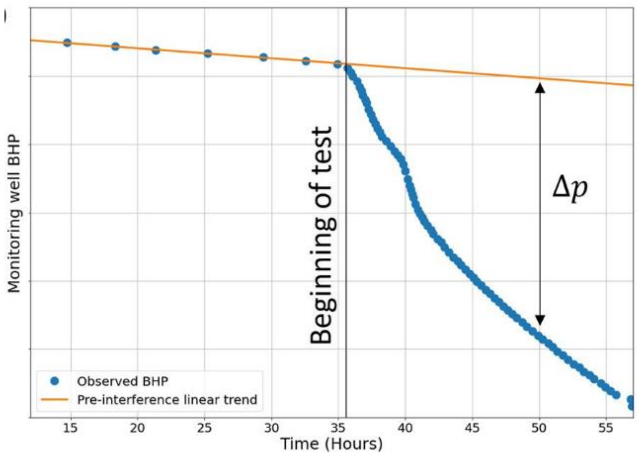
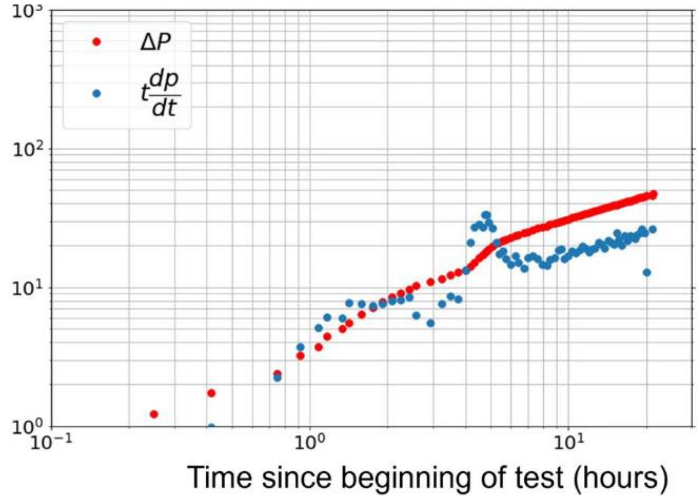
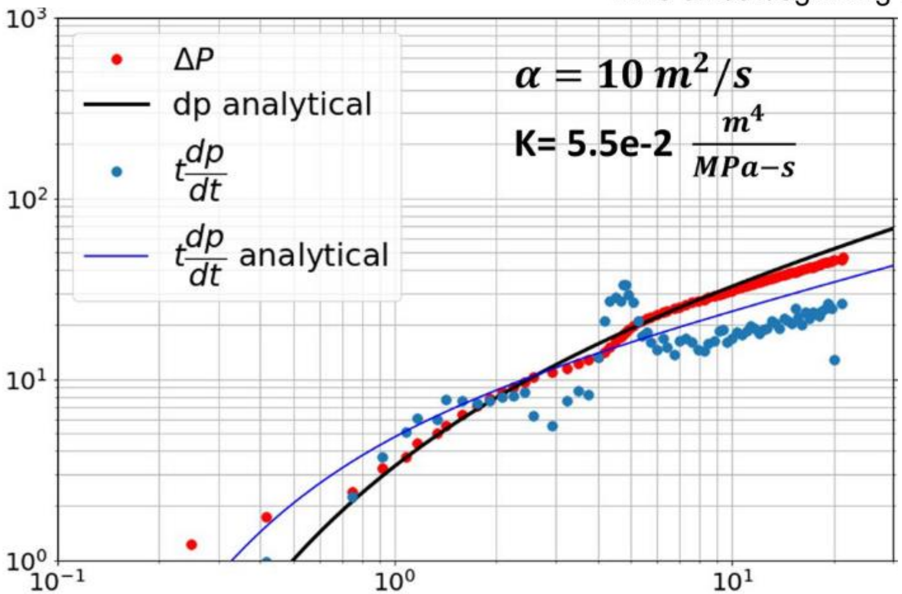
How

DQI Steps







Fit the line to the prior pressure trend and move the vertical line to offset well POP

Plot pressure change since the beginning of the test on a log-log plot and calculate the well test derivative

Autofit log-log plot to analytical models for DQI to estimate model parameters

Use estimated model parameters to calculate DPI

Use DPI to infer production impact between wells

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DQI – Underlying Analytical Model

$$P(y,t) - P(y,0) = \frac{2q_0\sqrt{\frac{\alpha t}{\pi}}}{K}\exp\left(-\frac{y^2}{4\alpha t}\right) - \frac{q_0 y}{K}\mathrm{erfc}\left(\frac{y}{2\sqrt{\alpha t}}\right)$$

Where, model parameters are:

$$\alpha = \frac{k_f W}{\mu(\frac{dW}{dp} + c_f W)} = \frac{C}{\mu(\frac{dW}{dp} + c_f W)}$$

$$K = \frac{C * H}{\mu}$$

- Use the estimated model parameters to estimate fracture conductivity (C) and calculate 'L' - the maximum possible drainage distance along the fracture if hypothetically it was unbounded and had infinite propped length

- Pressure response after the initial interference is fit with a solution to the 1-D diffusivity equation at an offset observation point 'y'

- Fit analytical equation to the interference response and resolve model parameters

$$L = \sqrt{\frac{\left(C_{fracture}\right)\left(\frac{k_r}{\mu}\right)_{frac,t}}{2\sqrt{\frac{\phi c_t k}{\pi}\left(\frac{k_r}{\mu}\right)_{mat,t}}\, t^{-0.5}}}$$

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DQI – Sensitivity to model parameters

- α – controls diffusivity – timing of the onset of pressure interference
- K – controls fracture conductivity – shape of the curve after the interference

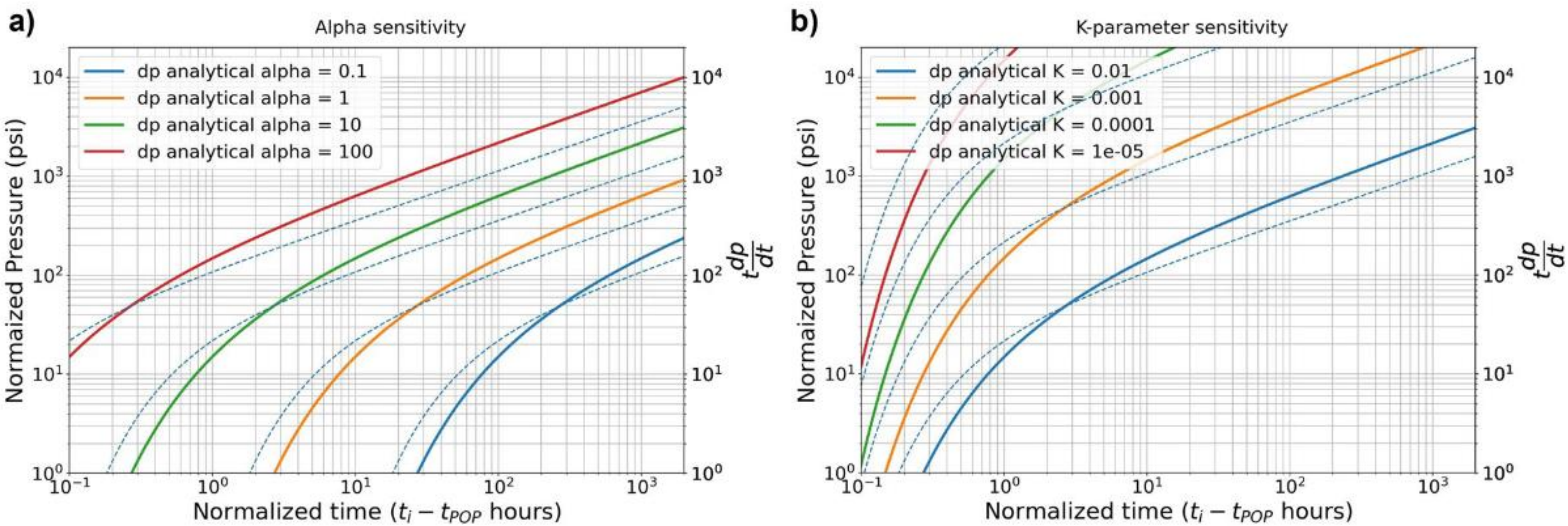

Fig. 2 The variation in dp (solid lines) and $t\frac{dp}{dt}$ (dashed lines) at the offset Monitoring Well calculated with the analytical solution with different values of **a** α (keeping K constant = 0.01), and **b** K-parameter (keeping α constant = 10). The units of α are $\frac{m^2}{s}$ and the units of the K-parameter are $\frac{m^4}{MPa*s}$

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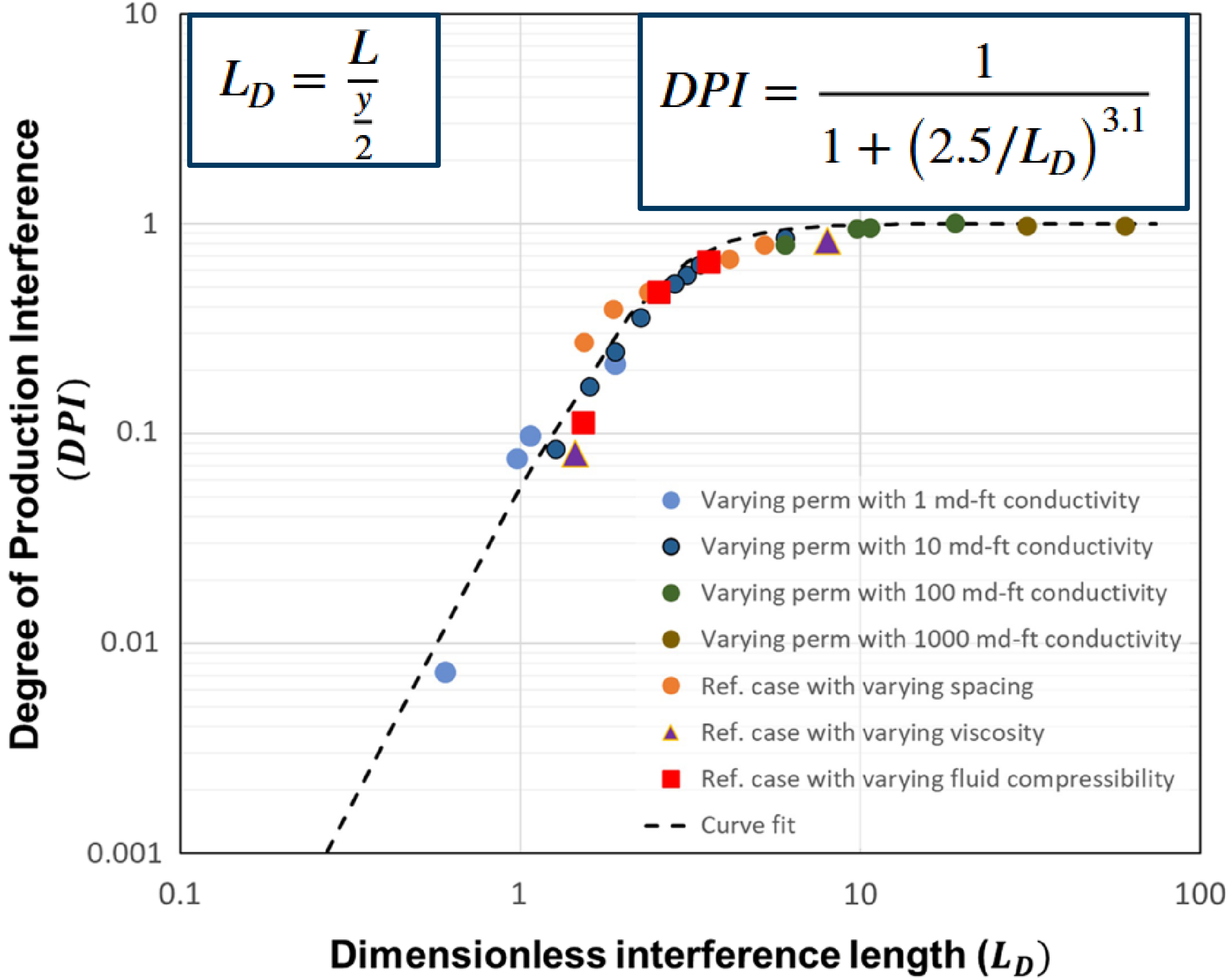
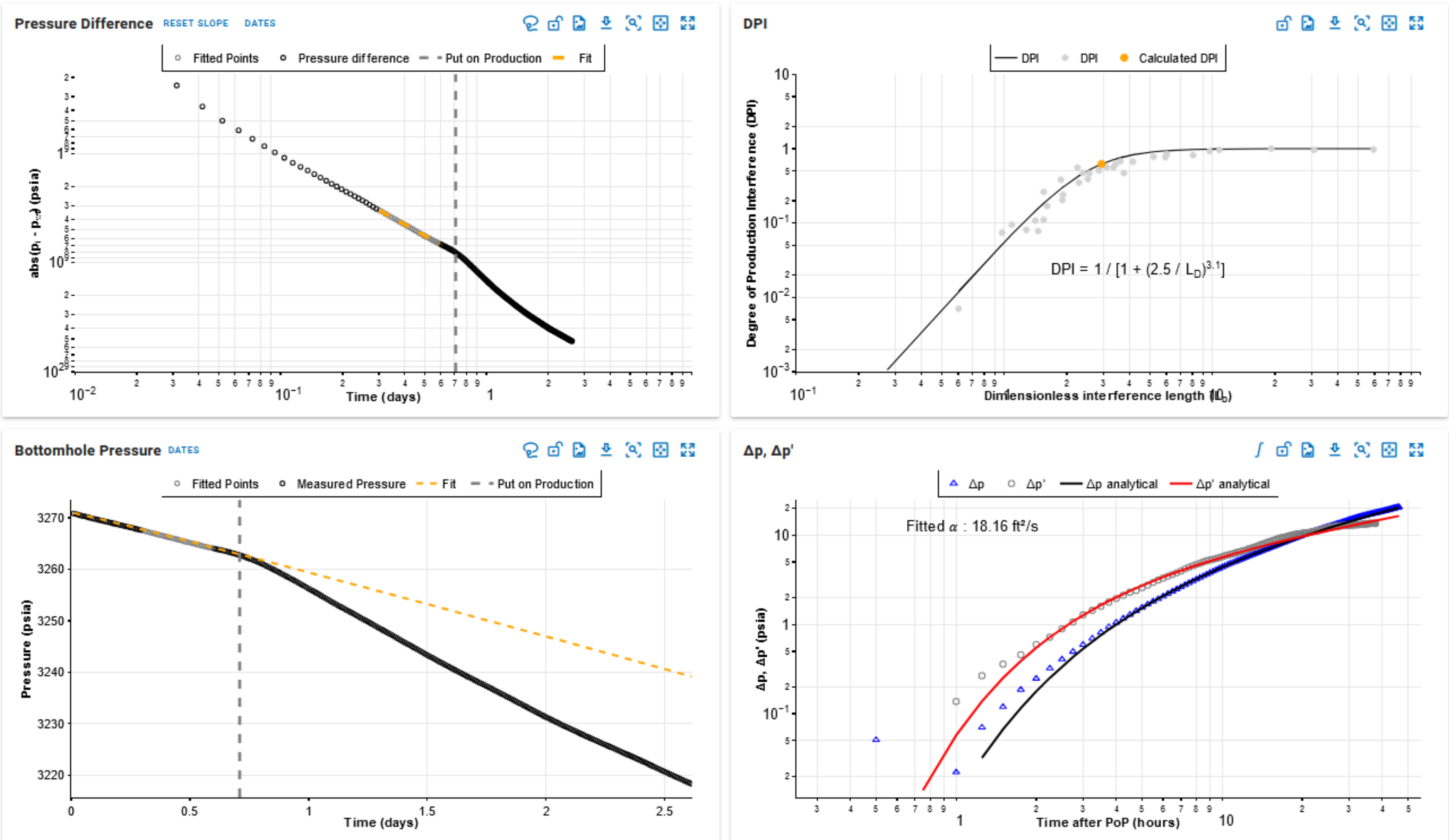
DQI – Sensitivity to varying fluid, completion



DQI on whitson+



AUTOFIT

Interpretations

Degree of pressure Interference, DPI (%) 62.1 %	Fracture conductivity, $k_f W$ 50.92 md-ft
Dimensionless Interference Length, L_d 2.93	Producing Frac Length, L 1465.78 ft

Steps

- Condition Data
- Select the time offset well is put on production (POP)
- Fit initial pressure trend and calculate Δp and $\Delta p'$
- AUTOFIT for model parameters
- Infer DPI, fracture conductivity and hydraulic diffusivity

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Summary

- DQI goes beyond CPG to maximize the value of downhole pressure gauges.
- Considers the fracture and rock properties, and fluid properties of the interfering fluid present in the fractures to calculate hydraulic diffusivity and fracture conductivity.
- Provides a framework for estimating how production will be impacted by interference.
- DPI is directly proportional to the dimensionless drainage length, expect higher DPI with higher L_D.
- DPI is a function of fracture conductivity and hence may change over time. As the fracture conductivity decreases, DPI should decrease.

Geomech. Geophys. Geo-energ. Geo-resour. (2023) 9:95
https://doi.org/10.1007/s40948-023-00632-1

RESEARCH

A new method for interpreting well-to-well interference tests and quantifying the magnitude of production impact: theory and applications in a multi-basin case study

**Mouin Almasoodi · Thad Andrews ·
Curtis Johnston · Ankush Singh · Mark McClure**

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Exercises

Part 3 - DFIT

Why

DFIT Key Outcomes

- Minimum Principal Stress
- Pore Pressure
- Permeability

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Why do we need these?

- **Minimum principal Stress**, $S_{h,min}$
  - Exploration and Development – Fault seal analysis
  - Drilling – Avoiding lost circulation and maintaining wellbore stability.
  - Completion and Production – Estimating net pressure, modelling hydraulic fracture geometry, long term sand production, compaction, subsidence, etc.
- **Pore Pressure**
  - Characterize depletion across the field and vertically in layers.
  - Determine the extent of drainage, optimize well spacing.

Without at least a good confidence estimate of the above from DFITs, we cannot proceed further to calculate permeability!

- **Permeability**, k
  - Core-derived, RTA-derived permeabilities are prone to assumptions, non-uniqueness.
  - DFITs uniquely derive an in-situ estimate of permeability.
  - Optimal well spacing differs for different k to maximize NPV.

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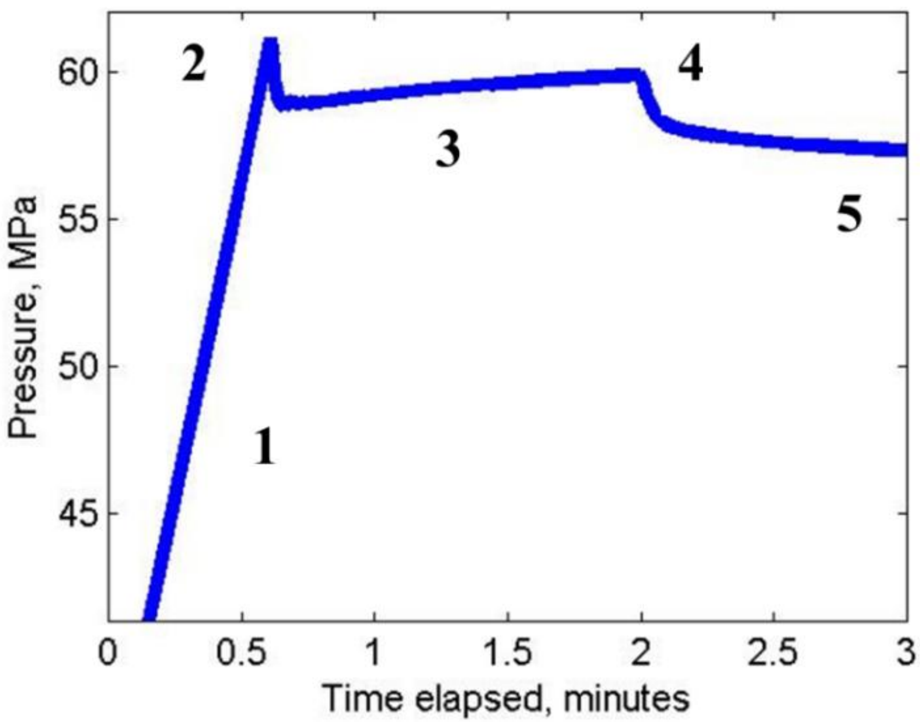
What

Diagnostic Fracture Injection/Falloff Tests

Typical Test Sequence in DFITs



- When –
  - Prior to stimulating a formation volume
- DFITs are -
  - **Low-volume pure water injection tests**
  - **At a sufficient rate and pressure**
  - **Followed by shut-in**
  - **To monitor the pressure falloff during shut-in**
- Costs –
  - ~15k – 75k USD

  Depends on duration of the test and BHP vs surface gauge

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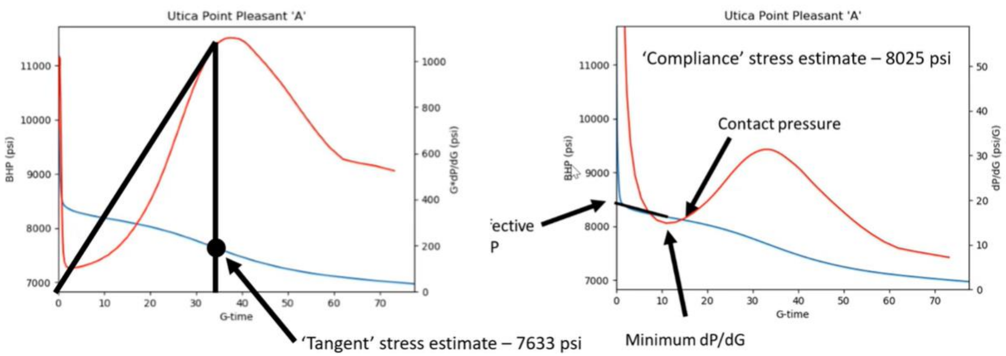
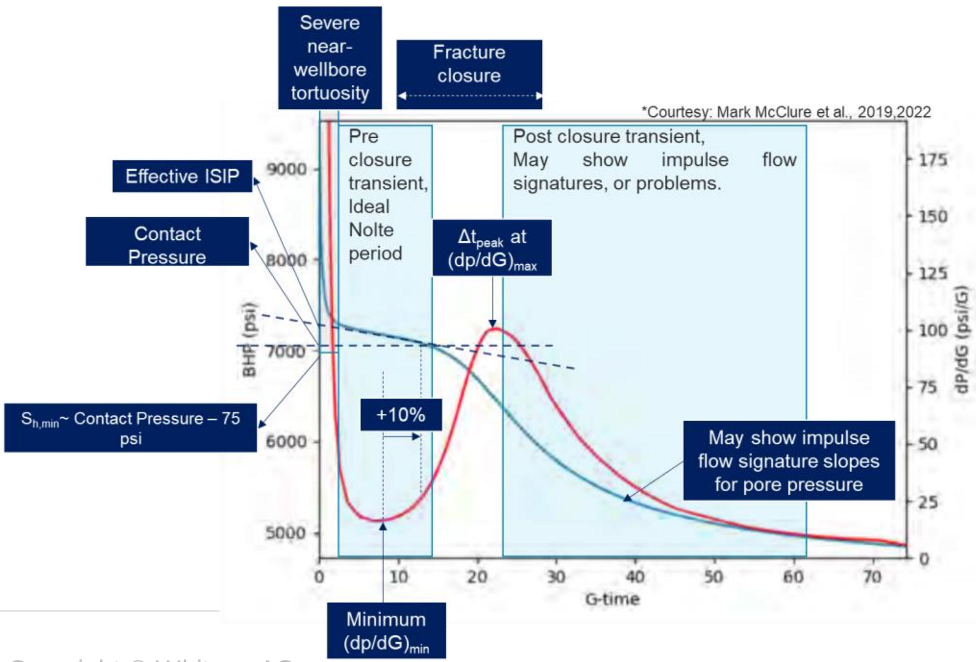
Diagnostic Fracture Injection/Falloff Tests





- Why the SPE 2019-123 Procedure?
  - Procedure diverges significantly from some of the recommendations given by 'holistic' DFIT procedure or the 'tangent method' (given by Barree et al. 2009)
  - Stress measurements using the older methods are too low, permeability estimates could be as high 10x to 1000x, leading to underestimation of effective fracture length.
  - This fracture compliance method is based on a return to older, classical methods of stress estimation.
  - DFIT Analysis in whitson^{+} focus on this new fracture compliance method for now..

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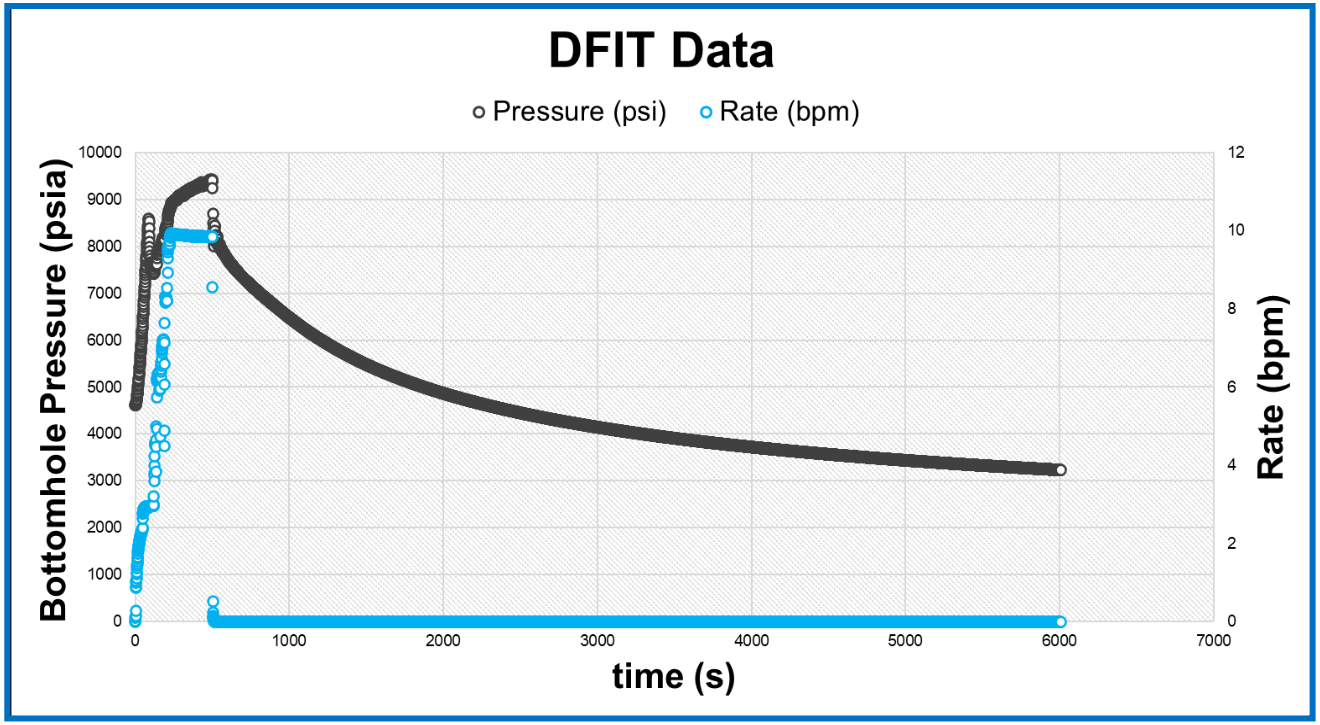
Plots Typically Used



- Pressure and rate vs time from the start of injection
- Pressure and it's derivative vs the G-function or H-function
- Pressure difference and it's well-test derivative, dp/dln(t), with respect to time since shut-in
- "Specialized" plots of pressure for impulse radial or impulse linear flow.

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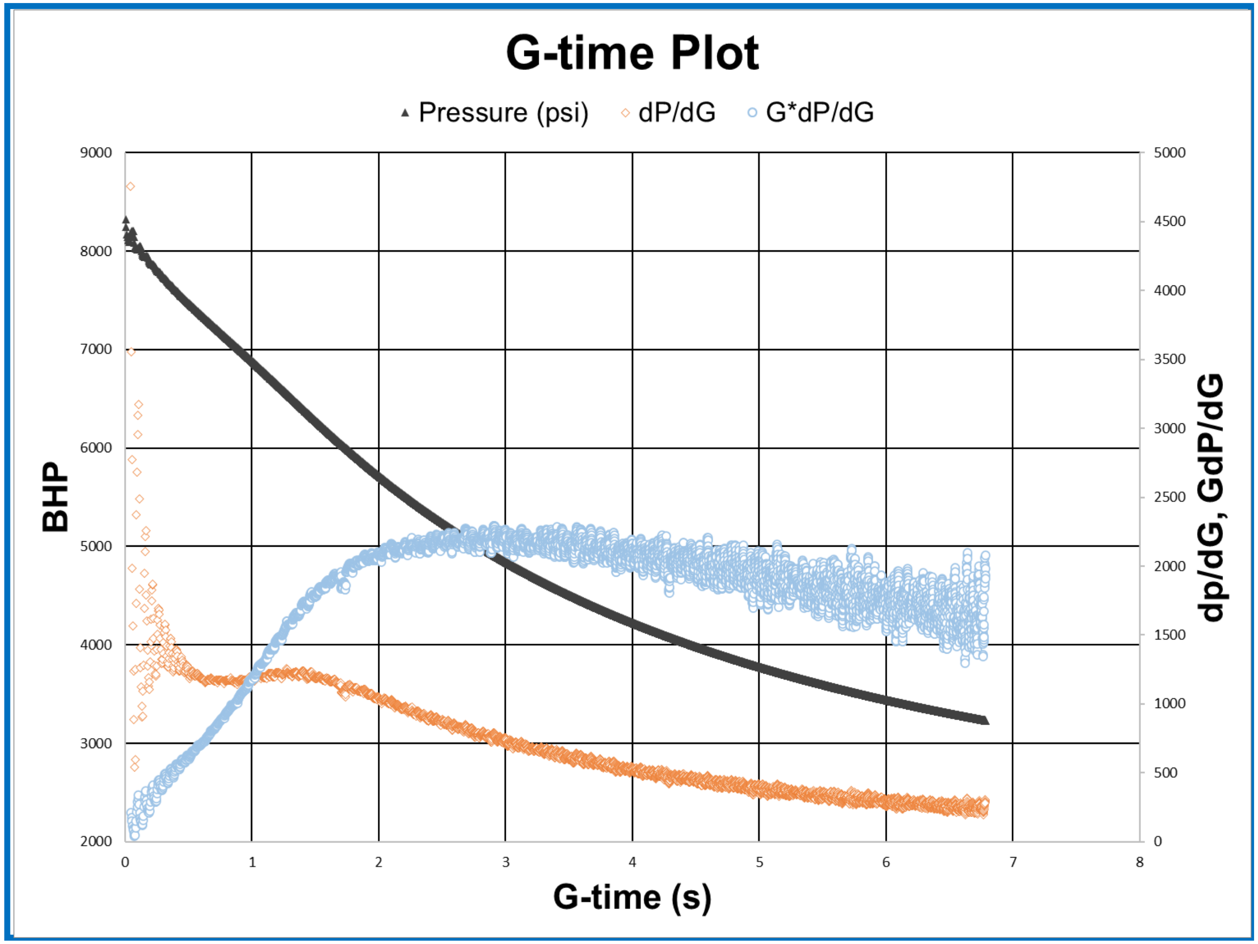
Plots Typically Used



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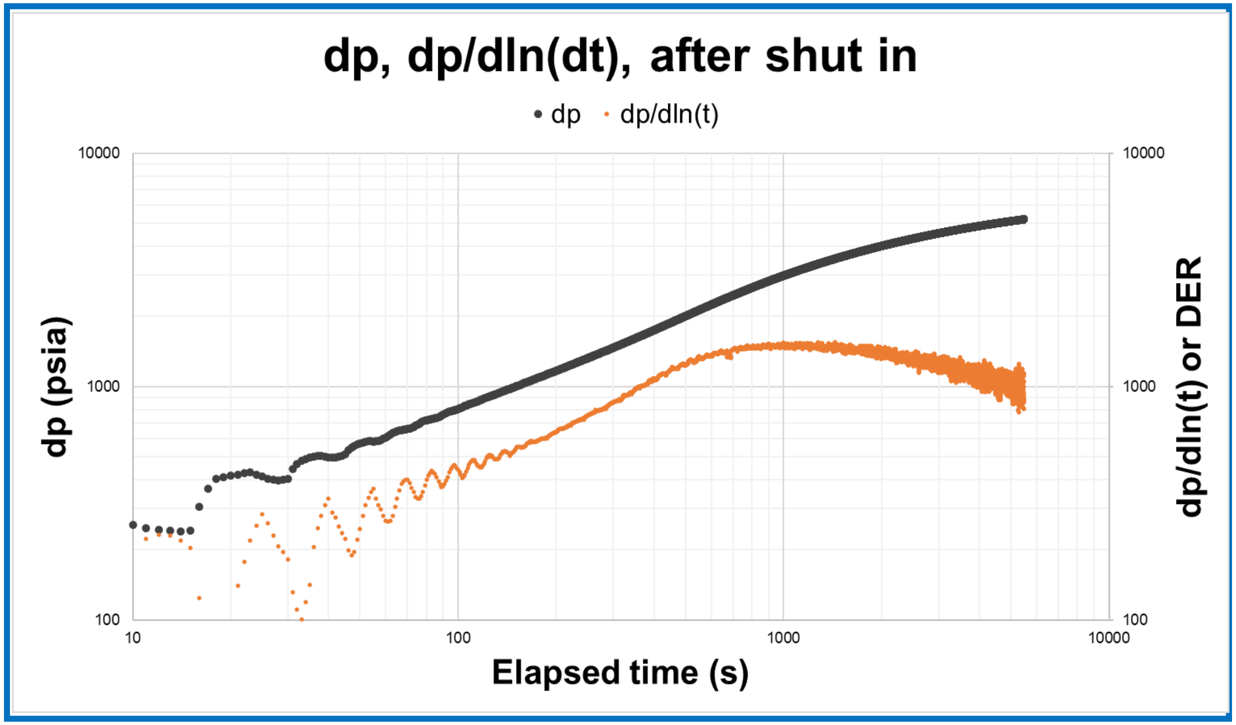
Plots Typically Used



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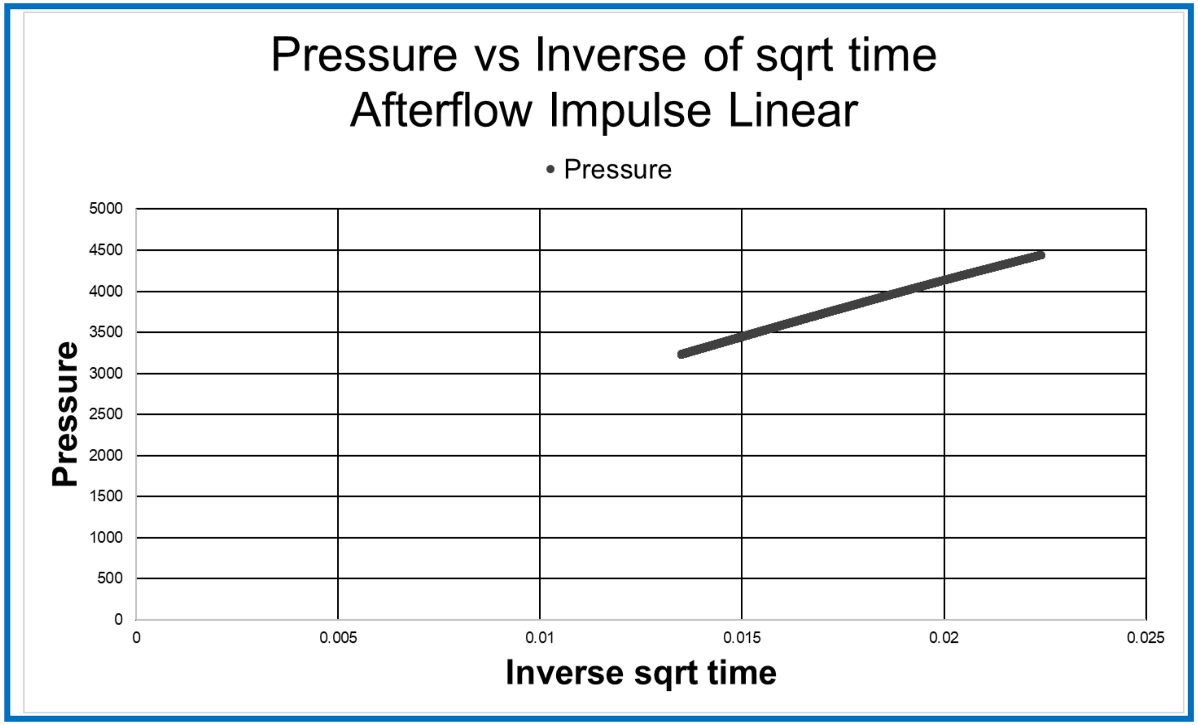

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How

Theoretical Background

Carter Leakoff

- Fundamental physics governing fluid leakoff rate
- Assumes pressure in the fracture remains constant

G-function and H-function

- Think superposition time functions for DFIT
- Used to estimate $S_{h,min}$

Late-time Impulse Flow Solutions

- Uses late-time data after fracture closure
- Used to estimate Pore Pressure

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Superposition Time functions for DFIT

G-function

$$V_{LS}(\Delta t) = 2AC_L\sqrt{t_e}(g(\Delta t) - g(\Delta t = 0))$$

$$V_{LS}(\Delta t) = \frac{\pi}{2}AC_L\sqrt{t_e}G(\Delta t)$$

- Controlled by Carter leakoff, assumes constant fracture pressure.

$$G(\Delta t) = \frac{4}{\pi}(g(\Delta t) - g(\Delta t = 0))$$

$$G(\Delta t) = \frac{4}{3}\left[\left(1 + \frac{\Delta t}{t_e}\right)^{1.5} - \left(\frac{\Delta t}{t_e}\right)^{1.5} - 1\right]$$

- Characteristics of dP/dG are interpreted for near wellbore tortuosity, effects of closure, leakoff.

$$\frac{dP}{dG} = \frac{1}{C_t}\frac{dV}{dG}$$

- Minimum dP/dG may still be elevated due to near wellbore tortuosity.

H-function

$$V_{LS}(\Delta t_k) = 4AH(\Delta t_k)\sqrt{\frac{k\varphi c_t}{\pi\mu}}$$

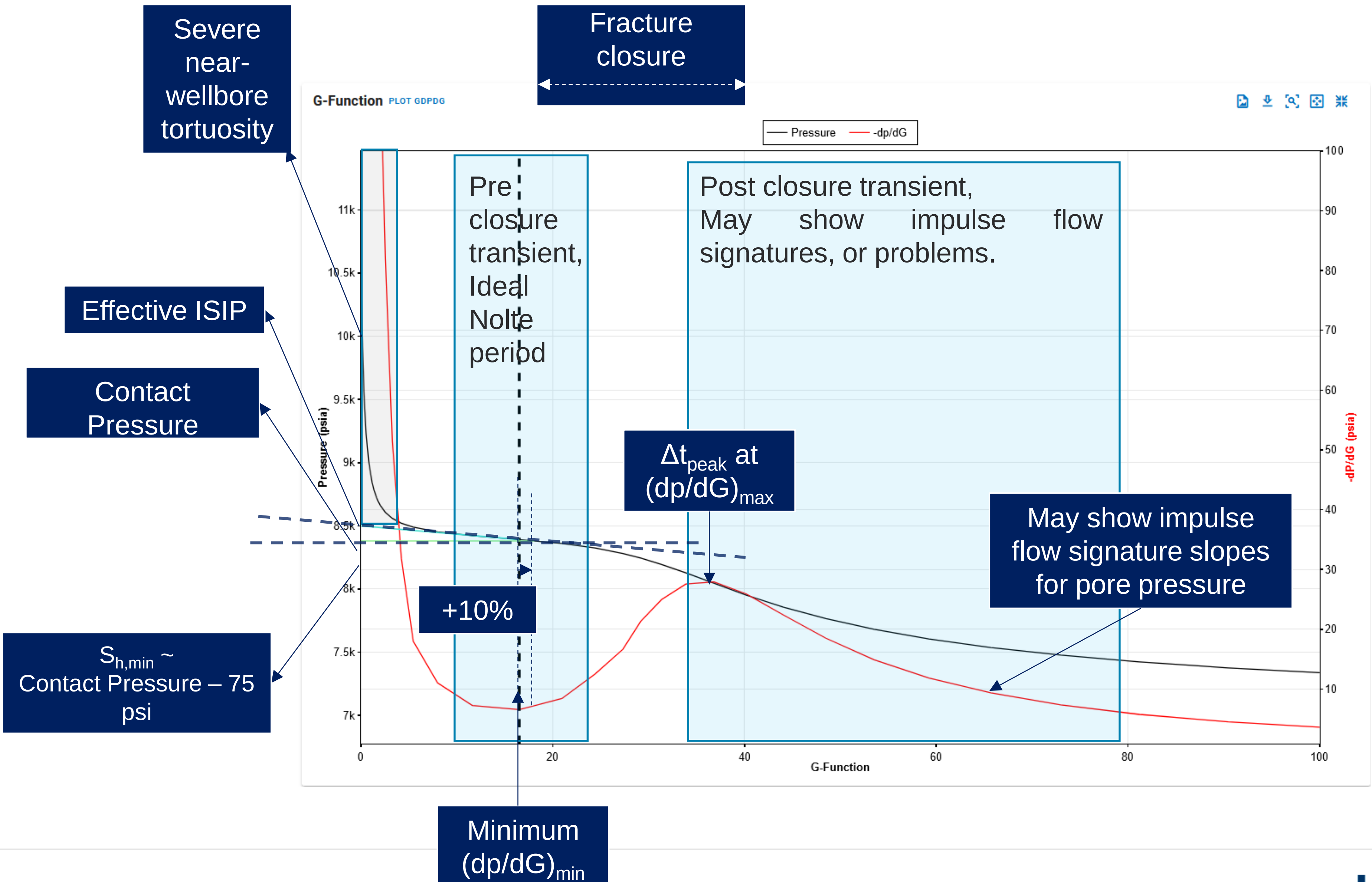
- Accounts for deviation from Carter leakoff, declining fracture pressure

$$H(\Delta t) = \int_{\frac{t_e}{2}}^{\Delta t + \frac{t_e}{2}} \frac{(P(\tau) - P_{res})}{d\tau}\sqrt{\Delta t + \frac{t_e}{2} - \tau d\tau}$$

$$H(\Delta t_k) \approx (P(\tau) - P_{res})\left(\sqrt{\Delta t_k + \frac{t_e}{2}} - \sqrt{\frac{t_e}{2}}\right) + \sum_{i=1}^{k}(P_i - P_{i-1})\sqrt{\Delta t_k - \Delta t_i}$$

- Uses a time convolution integral of the one-dimensional constant pressure solution for a better estimate of permeability.
- Allows for construction of relative stiffness plots for contact pressure.

Typical Interpretation of G function plots



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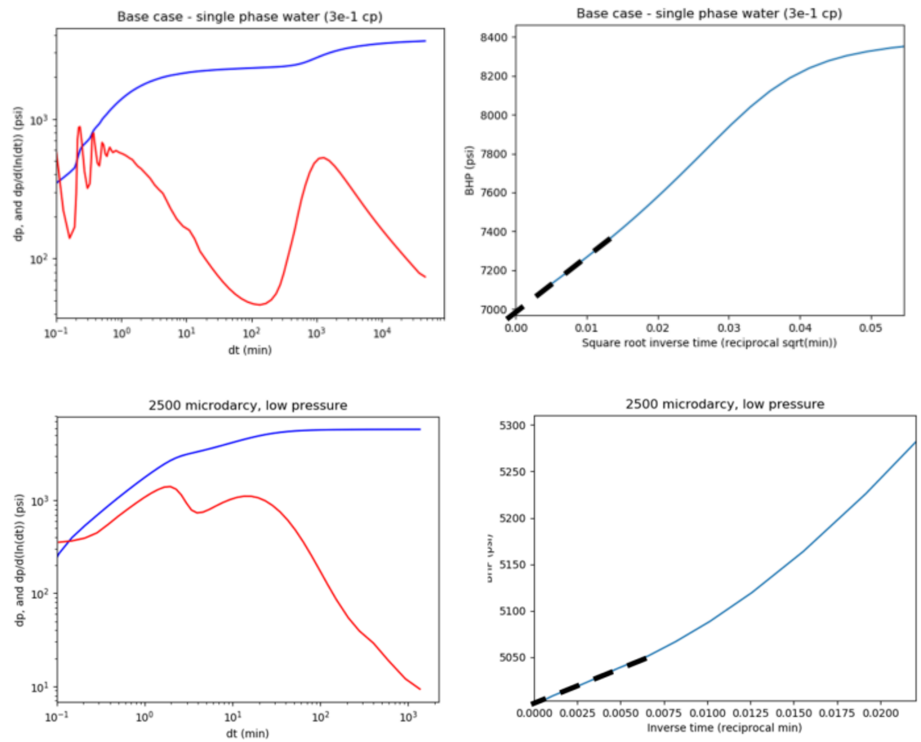
Late-time Impulse Flow Solutions

Impulse Linear Flow → -0.5 slope in dp/dln(t) after closure

Impulse Radial Flow → -1 slope in dp/dln(t) after closure, rare



- Plot the data in the identified section against the appropriate time function and extrapolate to find the intercept on the y-axis for estimating the Pore Pressure.

- Post-closure transients can also be used to estimate permeability.

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Permeability

Pick data and equations to work with

1. Preclosure Methods
G function or H function
2. Postclosure Methods
Impulse radial or linear

Each method has its own set of equations.

Assume Fracture Geometry

Radial Fracture – common

PKN Fracture –

needs frac height

The equations for stiffness change depending on the assumed geometry

Mass balance for Boundary Conditions

Mass balance equations can be written -

- At the end of injection,
- At minimum dP/dG or
- At peak dP/dG

Total Volume injected is known/measured in the DFIT test.

R_f or L_f

C_L

↓

k_{eff}

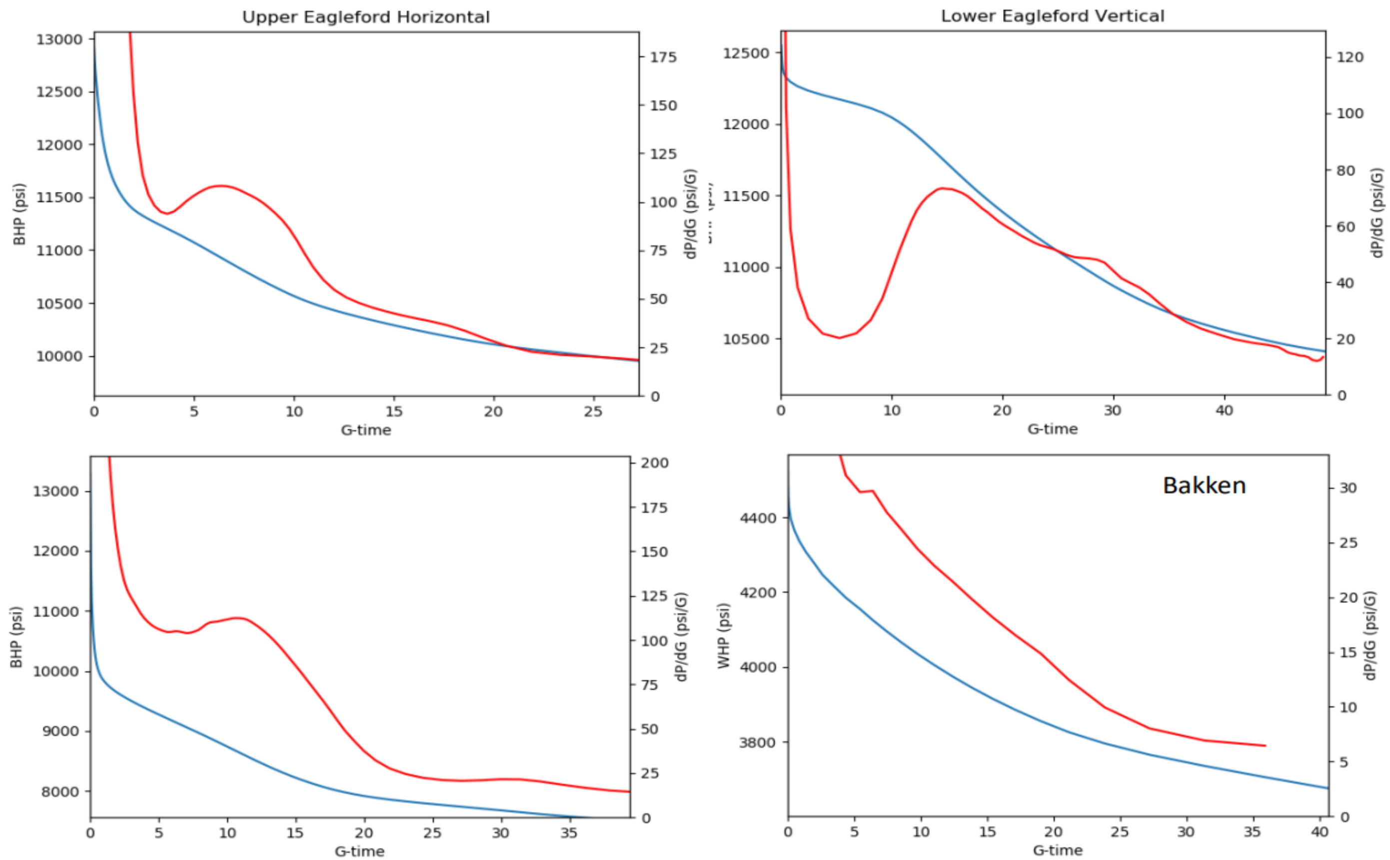
These equations consider wellbore storage and leakoff!

KEY:
Finding the combination of fracture extent (dimensions) and leak off rate (from C_L) that satisfy equations for the same injected volume as measured in the DFIT test.

SPE 2019-123 More Examples

Vertical wells have minimal wellbore tortuosity compared to horizontal wells

Storage and leakoff have a conflicting effect. Net result depends on permeability.



Adequate Response

No compliance response

DFIT Cheat Sheet

Closure interpretation	Postclosure interpretation	Stress estimate	Pore pressure estimate	Permeability estimate
C-A: Clear contact point	PC-A: Postclosure linear	Minimum in dP/dG	Extrapolate t^(-1/2)	Postclosure linear
C-A: Clear contact point	PC-B: False radial	Minimum in dP/dG	Extrapolate t^(-1)	h-function method divided by 1.5
C-A: Clear contact point	PC-C: False radial to genuine linear	Minimum in dP/dG	Extrapolate t^(-1/2)	Postclosure linear
C-A: Clear contact point	PC-D: Genuine linear to genuine radial	Minimum in dP/dG	Extrapolate t^(-1)	Postclosure radial and/or postclosure linear
C-A: Clear contact point	PC-E: Peak but no postclosure	Minimum in dP/dG	Extrapolate t^(-1/2) from peak	h-function method divided by 1.5
C-A: Clear contact point	PC-F: No peak	Minimum in dP/dG	None	None
C-B: Adequate contact poi	PC-A: Postclosure linear	Inflection point in dP/dG	Extrapolate t^(-1/2)	Postclosure linear
C-B: Adequate contact poi	PC-B: False radial	Inflection point in dP/dG	Extrapolate t^(-1)	h-function method divided by 1.5
C-B: Adequate contact poi	PC-C: False radial to genuine linear	Inflection point in dP/dG	Extrapolate t^(-1/2)	Postclosure linear
C-B: Adequate contact poi	PC-D: Genuine linear to genuine radial	Inflection point in dP/dG	Extrapolate t^(-1)	Postclosure radial and/or postclosure linear
C-B: Adequate contact poi	PC-E: Peak but no postclosure	Inflection point in dP/dG	Extrapolate t^(-1/2) from peak	h-function method divided by 1.5
C-B: Adequate contact poi	PC-F: No peak	Inflection point in dP/dG	None	None
C-C: No contact point	PC-A: Postclosure linear	None	Extrapolate t^(-1/2)	None
C-C: No contact point	PC-B: False radial	None	Extrapolate t^(-1)	None
C-C: No contact point	PC-C: False radial to genuine linear	None	Extrapolate t^(-1/2)	None
C-C: No contact point	PC-D: Genuine linear to genuine radial	None	Extrapolate t^(-1)	None
C-C: No contact point	PC-E: Peak but no postclosure	None	Extrapolate t^(-1/2) from peak	None
C-C: No contact point	PC-F: No peak	None	None	None
C-D: Rapid closure	PC-A: Postclosure linear	Within a few 100 psi of ISIP	Extrapolate t^(-1/2)	None
C-D: Rapid closure	PC-B: False radial	Within a few 100 psi of ISIP	Extrapolate t^(-1)	None
C-D: Rapid closure	PC-C: False radial to genuine linear	Within a few 100 psi of ISIP	Extrapolate t^(-1/2)	None
C-D: Rapid closure	PC-D: Genuine linear to genuine radial	Within a few 100 psi of ISIP	Extrapolate t^(-1)	None
C-D: Rapid closure	PC-E: Peak but no postclosure	Within a few 100 psi of ISIP	Extrapolate t^(-1/2) from peak	None
C-D: Rapid closure	PC-F: No peak	Within a few 100 psi of ISIP	None	None

*ResFrac Blog post on Practical Guidelines for DFIT interpretation

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Key takeaways

- DFITs are used to provide an estimate of minimum principal stress and pore pressure using the new ‘compliance method’ and dP/dG instead of G*dP/dG
- DFITs also provide the independent k estimate to resolve effective fracture area from RTA-derived $A\sqrt{k}$.
- DFIT interpretation, typically done in the past, using the ‘tangent method’ proposed by Barree et al. 2009, has shown to overestimate resolved quantities by upto 100x. Result – Suboptimal well spacing design, reduction of NPV.
- Only ‘good’ or ‘adequate’ indication of compliance responses can be used for k estimation.
- Many reasons could cause monotonic dP/dG – instant closure, severe wellbore tortuosity, natural fractures, operational issues etc. Interpretation can be relatively uncertain and we cannot estimate k.
- Permeability pitfalls?
  - Preclosure k estimate may be about 2 to 3x higher, and postclosure k estimate is usually lesser and more reliable, used in most reservoir engineering calculations.
  - Analyzing k from a ‘false’ radial flow regime (typically seen in gas shales, preceding true linear impulse flow) leads to 10-100x overestimate.

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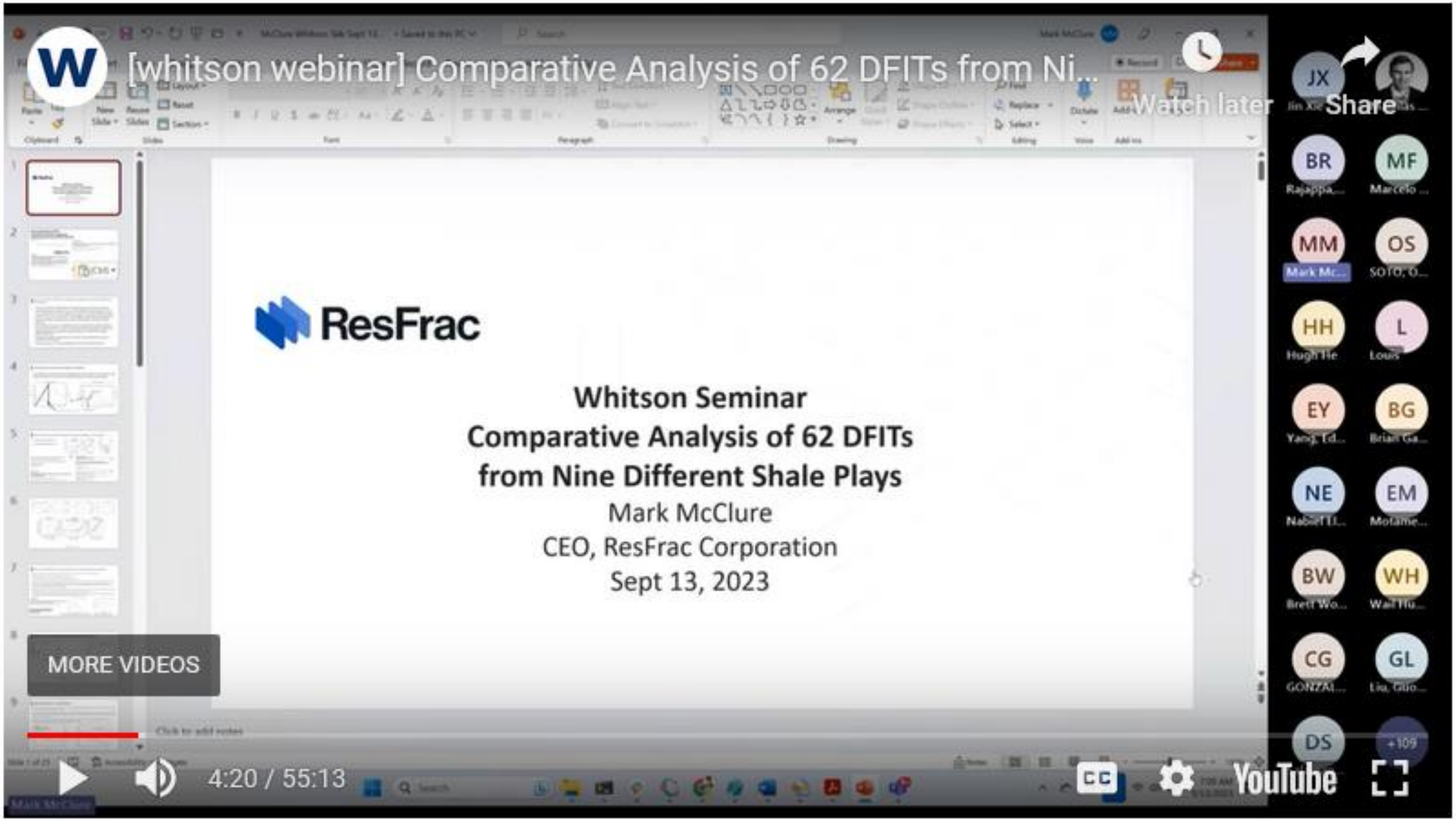
More References?



More References?

Practical guidelines for DFIT interpretation using the 'compliance method' procedure from URTeC-2019-123

September 5, 2023

Mark McClure[1], Dave Ratcliff[1], Ankush Singh[1], Chris Ponners[1], and Garrett Fowler[1]

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A Collaborative Study on DFIT Interpretation: Integrating Modeling, Field Data, and Analytical Techniques

Mark McClure*[1], Vidya Bammidi[2], Craig Cipolla[3], Dave Cramer[4], Lucas Martin[5], Alexei A Savitski[6], Dave Sobernheim[2], and Kate Voller[7]; 1. ResFrac Corporation, 2. Keane Group, 3. Hess Corporation, 4. ConocoPhillips Company, 5. Formerly with Apache Corporation, now with Marathon Oil Corporation, 6. Shell International Exploration and Production Inc., 7. Range Resources Corporation

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SPE-205297-MS

Best Practices in DFIT Interpretation: Comparative Analysis of 62 DFITs from Nine Different Shale Plays

Mark Mcclure, Garrett Fowler, and Matteo Picone, ResFrac Corporation

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The Fracture-Compliance Method for Picking Closure Pressure From Diagnostic Fracture-Injection Tests

Mark W. McClure and **Hojung Jung,** University of Texas at Austin; **Dave D. Cramer,** ConocoPhillips; and **Mukul M. Sharma,** University of Texas at Austin

Exercises

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