Society of Petroleum Evaluation Engineers
Denver Chapter Luncheon Meeting
Denver, COLORADO | 15 May 2014

# *Well Performance in Unconventional Reservoirs — State-of-the-art Analysis/Interpretation, and Models*

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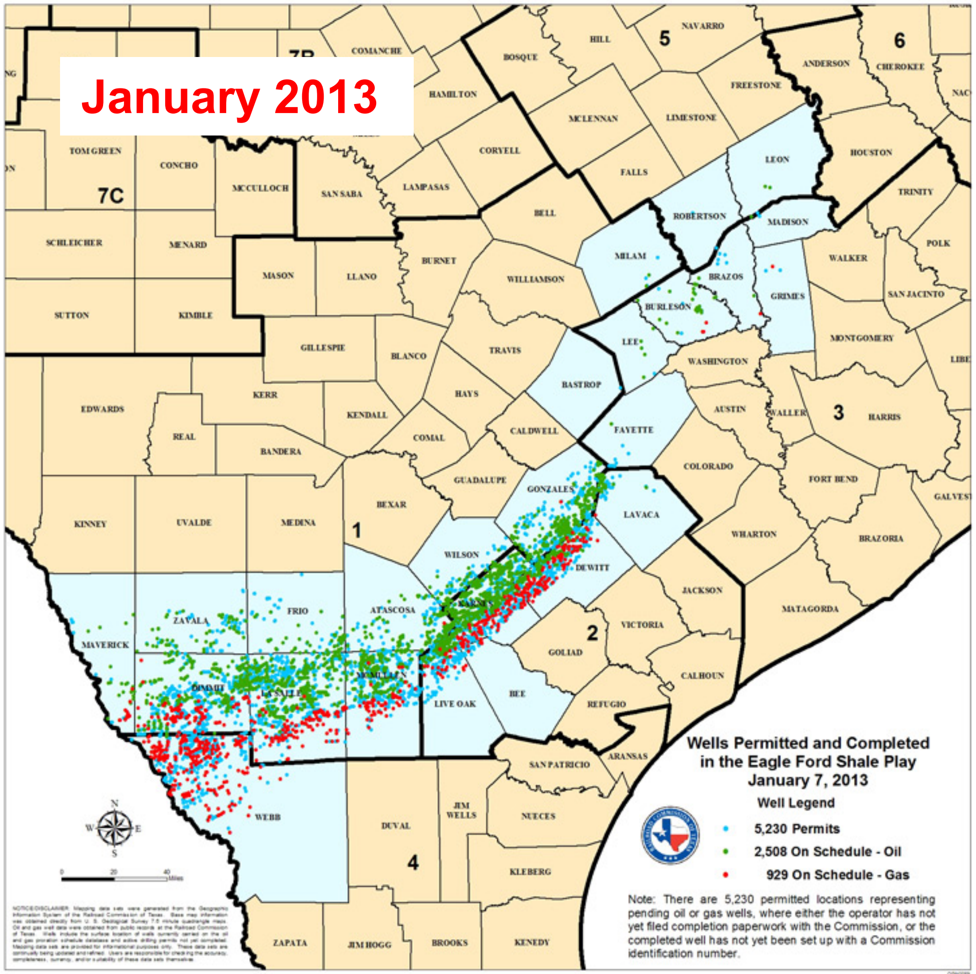
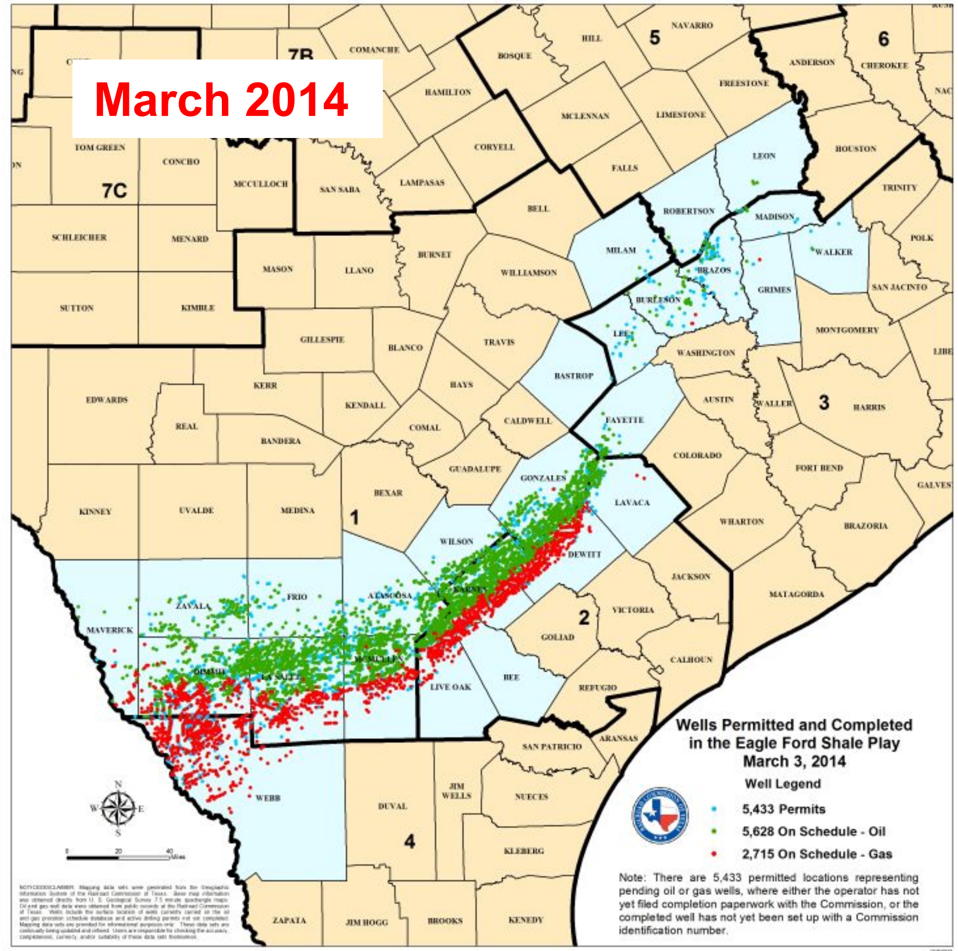
# Production from Unconventional Resources:




- **Discussion**: *Eagle Ford Well Count from Texas Railroad Commission*
  - Wells completed and permitted in the Eagle Ford Shale.
  - January 2013 ≈ 3,400.
  - March 2014 ≈ 8,400.

# Production from Unconventional Resources:

Ref. Curtis et al. (2012)

M.E. Curtis et al. / International Journal of Coal Geology 103 (2012) 26–31

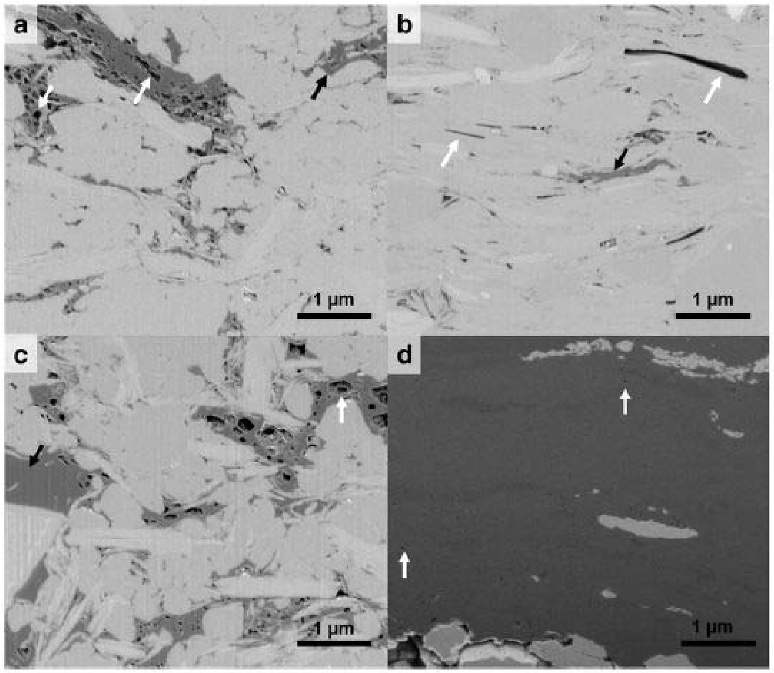
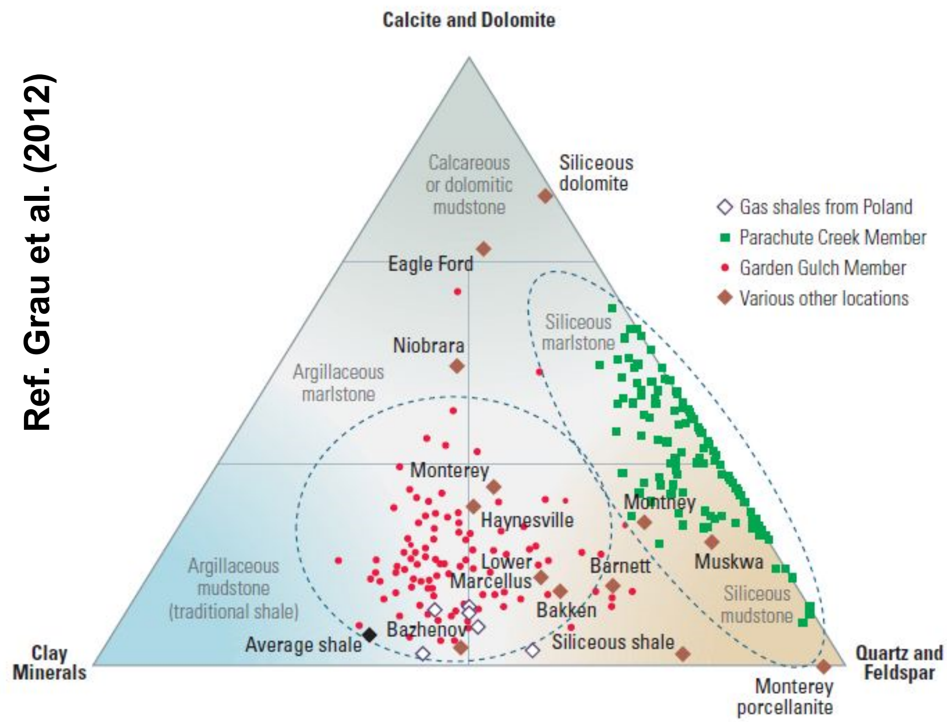



Fig. 1. BSE images of a) Barnett, b) Haynesville, c) Horn River, and d) Kimmeridge shales. Some regions of organics and pores have been labeled with black and wl respectively.

Ref. Grau et al. (2012)




^ Shale mineralogy. Worldwide average shale composition regardless of organic content (black diamond) is high in clay minerals and contains some quartz and feldspar with little or no calcite or dolomite. Organic-rich shales (other diamonds and dots) tend to have a wider variety of compositions. Oil shales from the Green River Formation are highlighted in dotted blue ovals. Those from the Parachute Creek Member (green squares) have low clay-mineral content, while oil shales from the Garden Gulch Member (red dots) are richer in clay minerals. Gray lines subdivide the triangle into compositional regions. (Adapted from Grau et al, reference 32.)

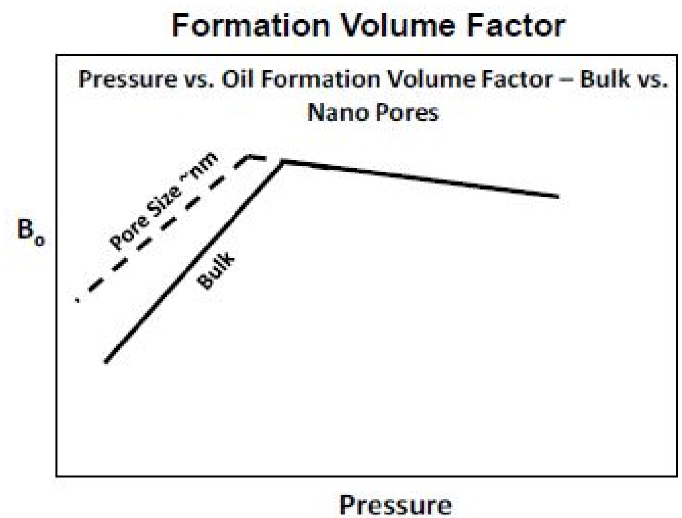
***Major challenge in relating basic flow phenomena to reservoir-scale models.***

## Issues/Comments:

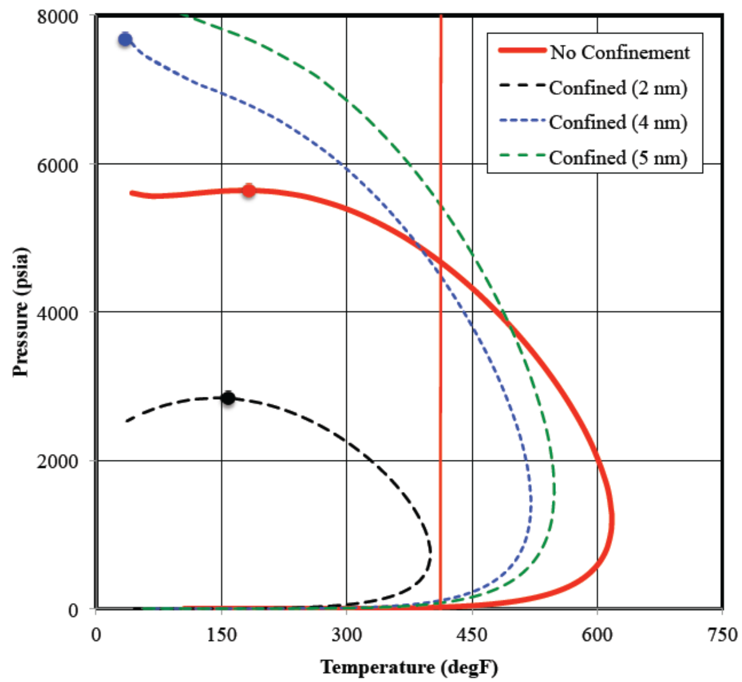
- **Fluid storage in the nano-pores, organic matter, adsorbed?**
- **Flow path can be as small as 10-20 molecular diameters?**
- **Mineral composition varies widely—Each play is unique.**

# Production from Unconventional Resources:

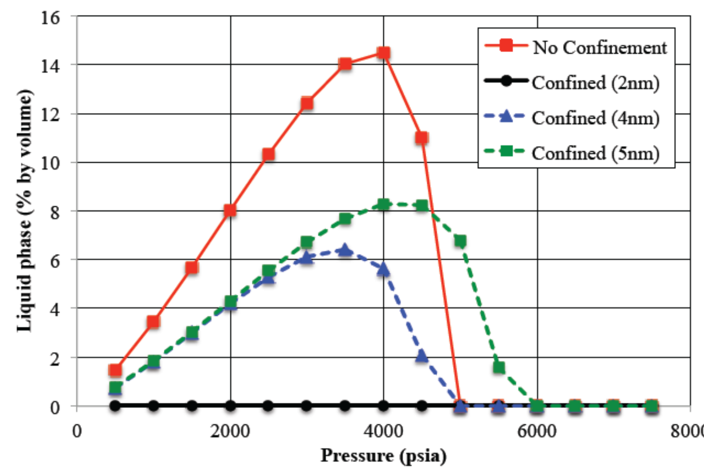
- Challenges associated with sampling the reservoir fluid.
- Near critical fluids — composition issues and variations in $p_{crit}$ and $T_{crit}$.
- Phase envelope shift and suppresion of the bubble point.
- Molecular dynamics work to resolve PVT in nano-pores?




From: Brent Thomas (Weatherford) — Schematic on $p_b$ suppression (undersaturated oil)



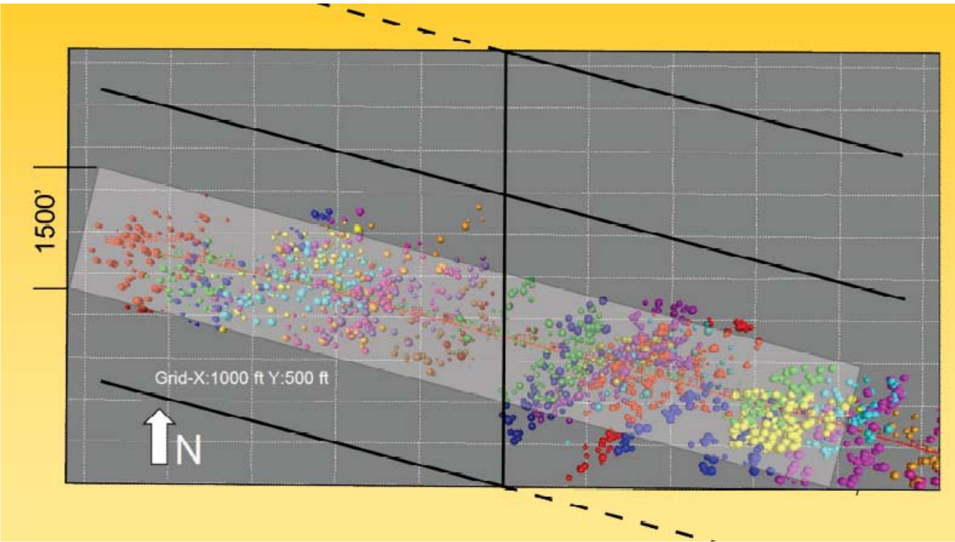

Phase diagrams of confined and unconfined heavy gas condensate mixture (Pedersen et al, 1989). (vertical( red) line is the reservoir temperature)

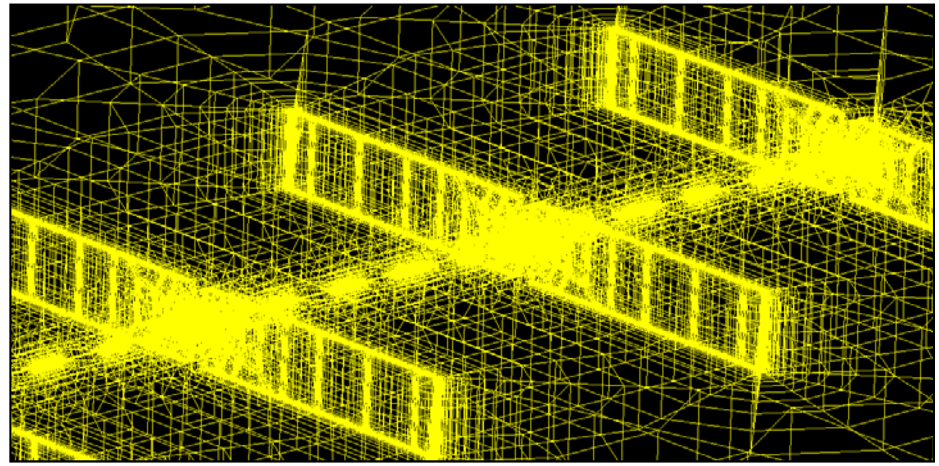



The percentage of liquid drop out (% by volume) of a heavy gas condensate mixture (Pedersen et al, 1989) at 400$^0$F. (400$^0$F is reservoir temperature — see plot at left)

From: Sapmanee, K. (2011). "Effects of Pore Proximity on Behavior and Production Prediction of Gas/Condensate," M.S. Thesis, University of Oklahoma, 2011.

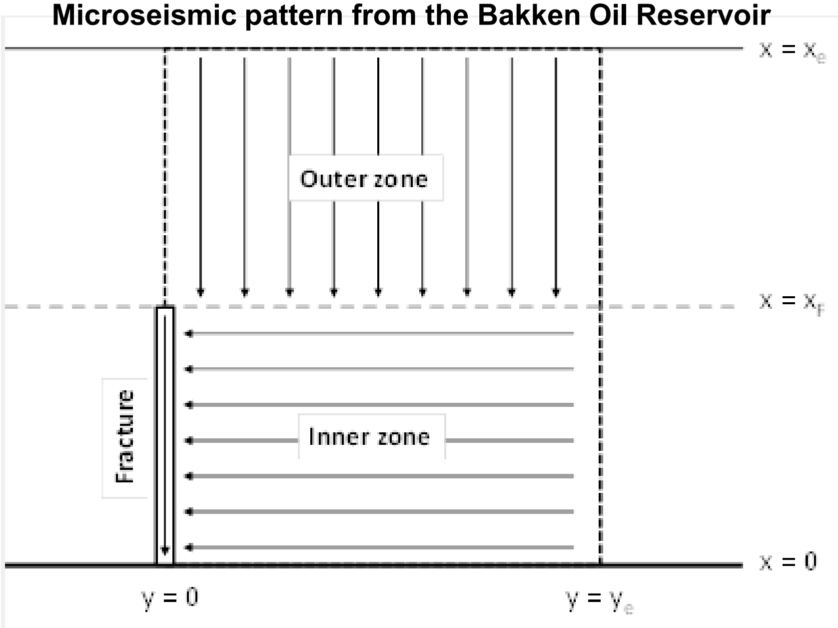
# Production from Unconventional Resources:



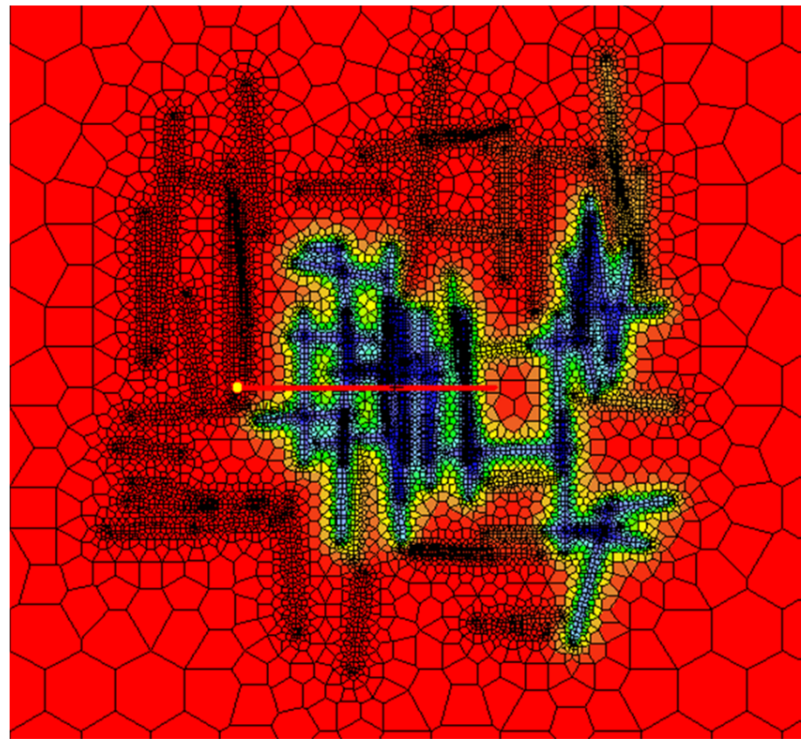



From: Kappa Engineering — Numerical simulation configuration for a multi-frac horizontal well

From: Whiting Petroleum Presentation (2010) — Microseismic pattern from the Bakken Oil Reservoir

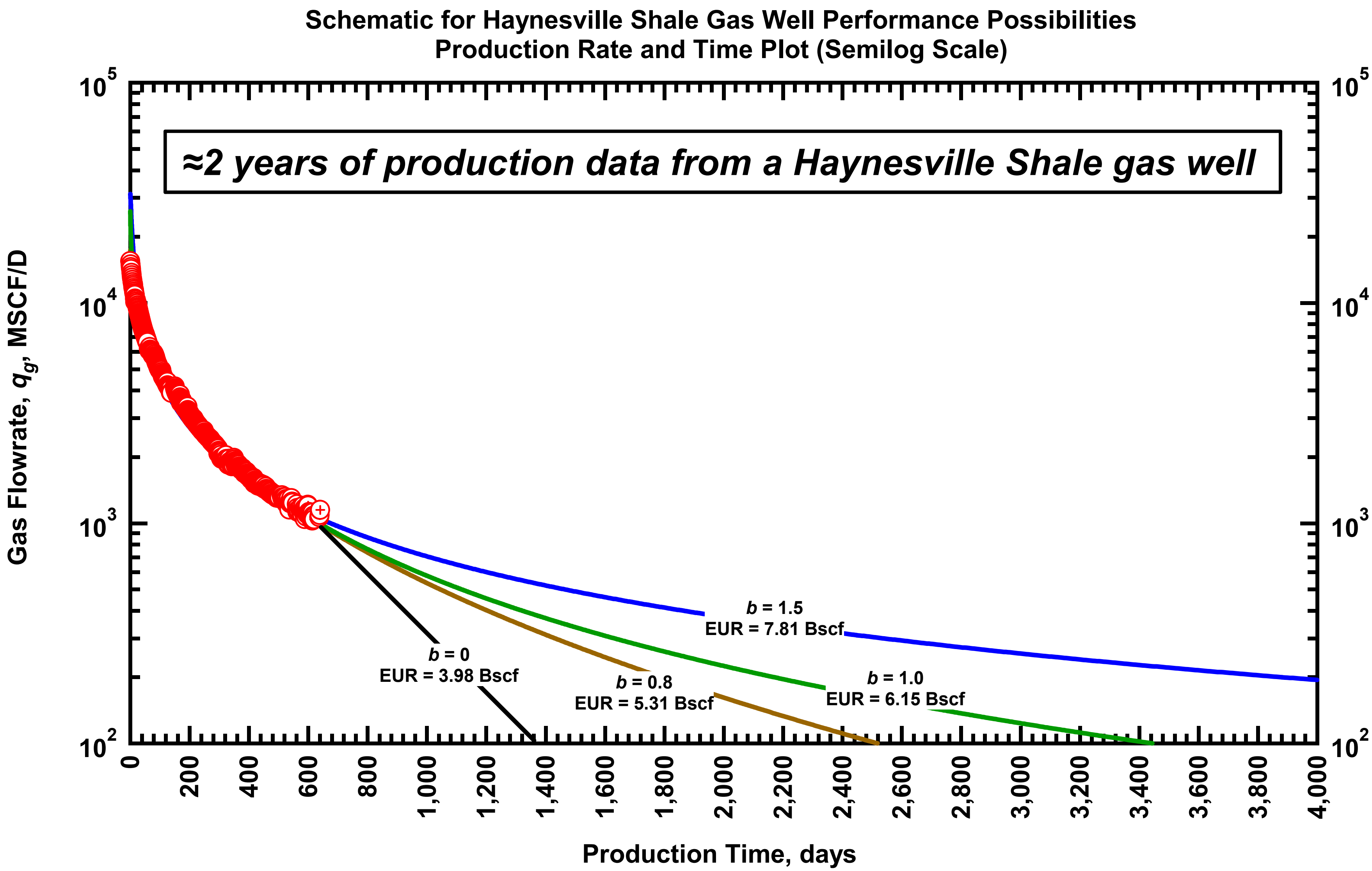



From: Ozkan et al. (2010) — Trilinear flow solution model configuration



From: Kappa Engineering — Pressure distribution for a discrete fracture network (DFN) model

# Problem Statement: *Uncertainty on Outcome*




- **Decline Curve Analysis**: ***Haynesville Performance Possibilities***
  - **Significant uncertainty on *EUR* based on the selection of *b*-value.**

# Presentation Outline:

- Decline Curve Analysis
  - Modified hyperbolic equation
  - Time-rate characteristic behavior
  - Advanced decline curve relations
  - Comparative studies
- Production Diagnostics
  - Diagnostic plots
  - Flow regimes and characteristic behavior
- Analysis and Modeling
  - Horizontal well with multiple fractures model
  - Analysis and modeling examples
  - Multi-well modeling and well spacing
  - Uncertainty and non-uniqueness
- Concluding Remarks

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# *Decline Curve Analysis*

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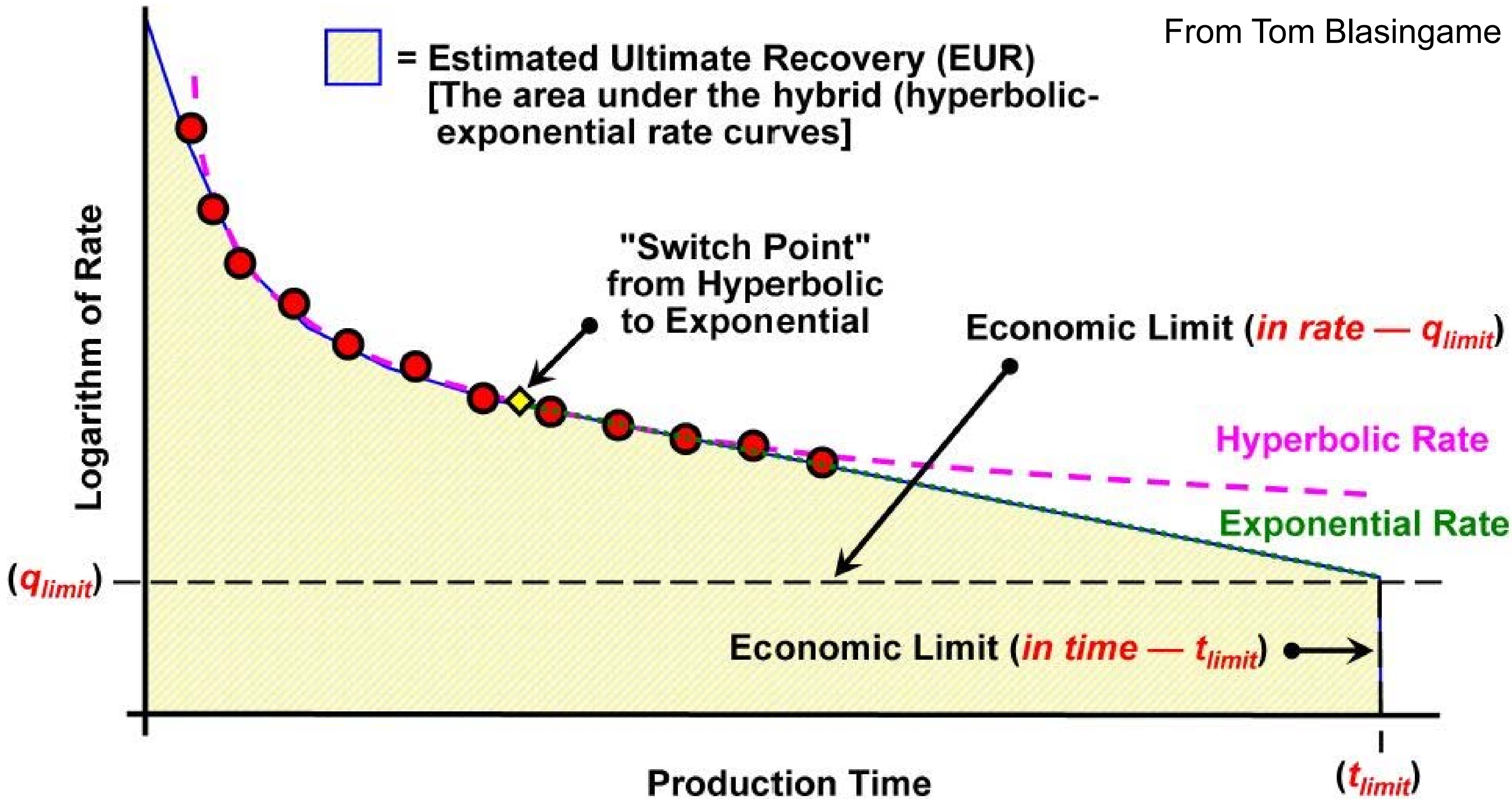
# Decline Curve Analysis: *Modified Hyperbolic Equation*




- **Decline Curve Analysis:**
  - The schematic represents the most common approach (aka. modified hyperbolic) to estimate ultimate recoveries (EUR).
  - This approach could be "non-unique" in the hands of most users, and often yields widely varying estimates of reserves with time.

# Decline Curve Analysis: *Time-Rate Diagnostics*

**Basis for decline curve relations:**

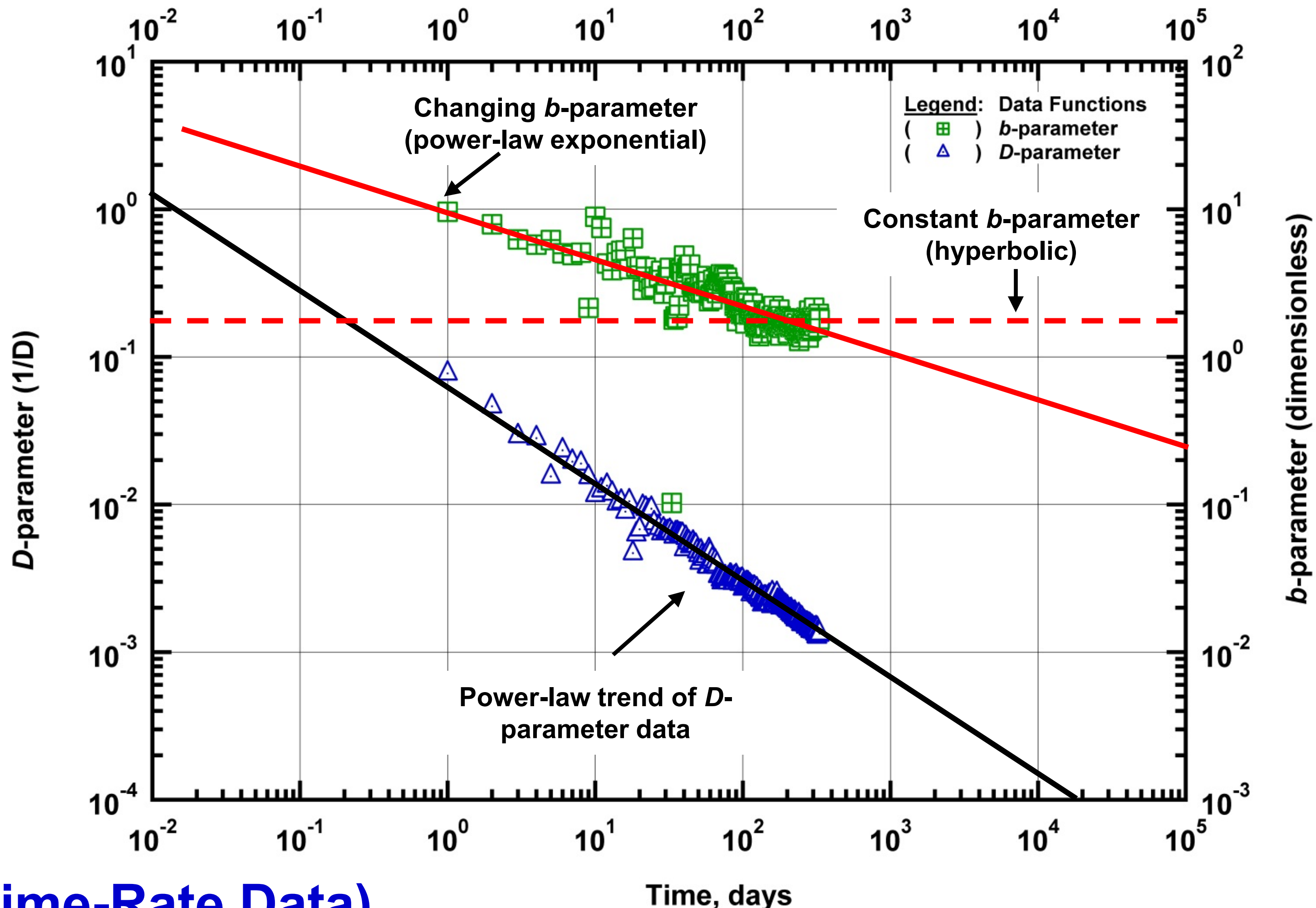
***D*-parameter:**

$$D \equiv -\frac{1}{q_g}\frac{dq_g}{dt}$$

***b*-parameter:**

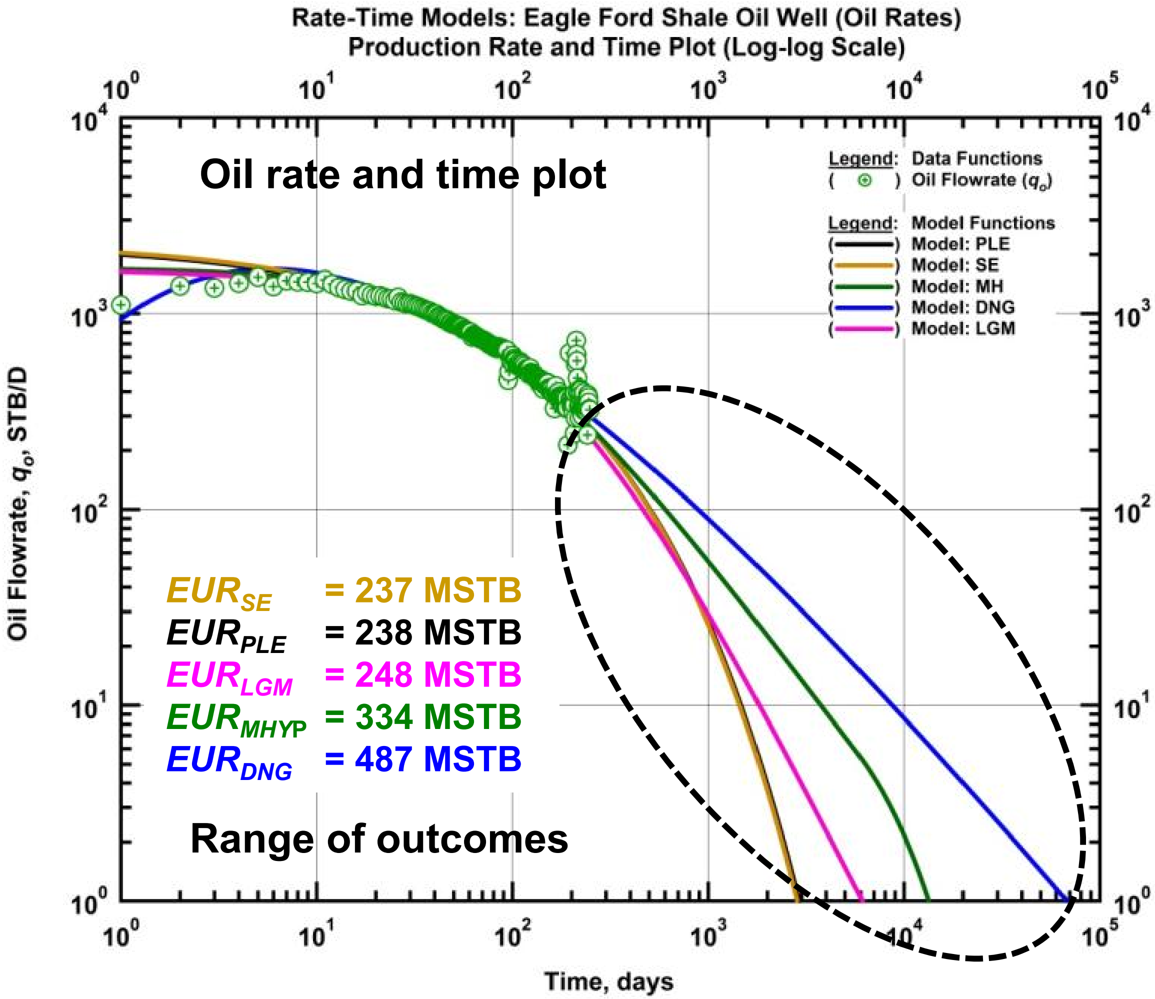
$$b \equiv -\frac{d}{dt}\left[\frac{q_g}{dq_g/dt}\right]$$

Shale Gas Well (300 Days of Production)
*D*- and *b*-parameters versus Time Plot (Log-log Scale)




- **Flow Regimes: (Time-Rate Data)**
  - Identify diagnostic/characteristic behavior exhibited by data.
  - Evaluate *D*(*t*) and *b*(*t*) continuously (at all points).
  - Power-law exp. relation is based on power-law behavior of *D*-parameter.

# <u>Decline Curve Analysis</u>: *Eagle Ford Oil Example*




***Advanced decline curve relations (recently introduced)* — (ref. SPE 162910)**

1. **Power-law Exponential* (2008)**
2. **Stretched Exponential* (2009)**
3. **Duong (2010)**
4. **Logistic Growth (2011)**
5. **Transient-Hyperbolic (2013)**
6. **... ???**

**(*Power-law exponential and stretched exponential relations are almost identical relations, but introduced differently.)**

- **Each decline curve model can be described as empirical (no direct link with theory) and generally center on a particular flow regime and/or characteristic behavior.**
- **Can time-rate analysis truly represent well performance?**

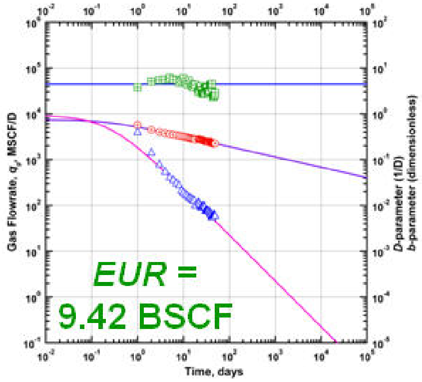
# Decline Curve Analysis: *Continuous EUR*

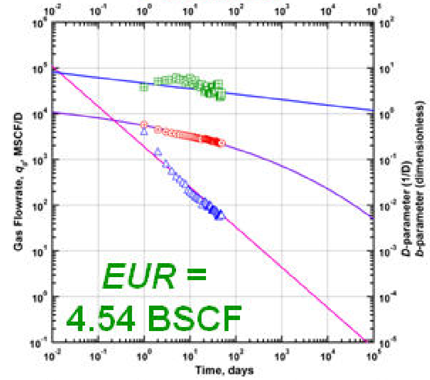
*Analyze All Intervals Using the Hyperbolic Relation*

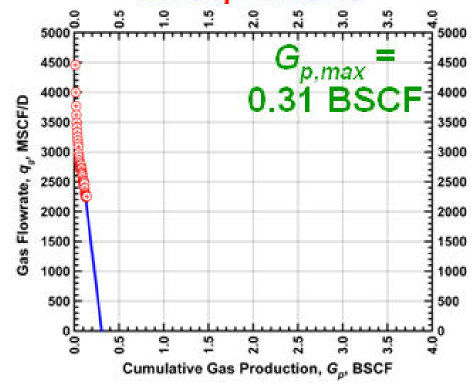
*Analyze All Intervals Using the Power-Law Exponential Relation*

*Find Lower Limit Using $q_g$ vs. $G_p$ Straight Line Extrapolation*

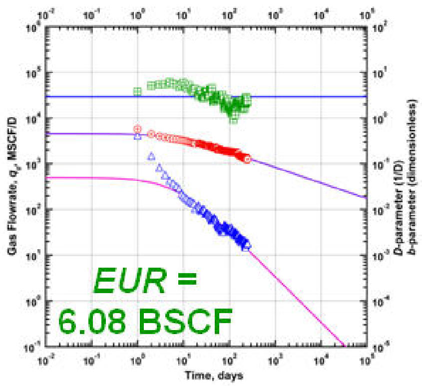
50 days

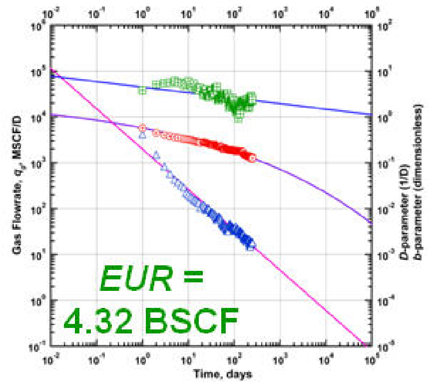


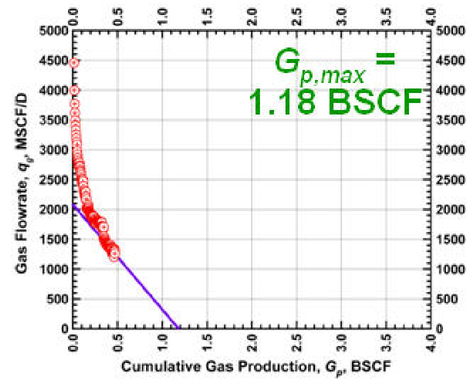




250 days

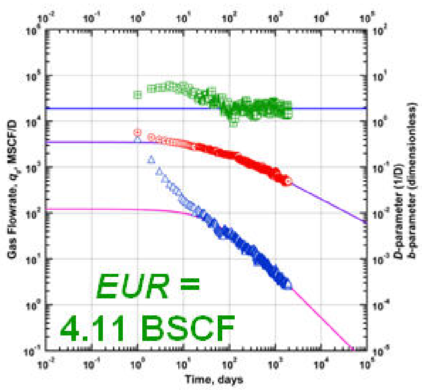


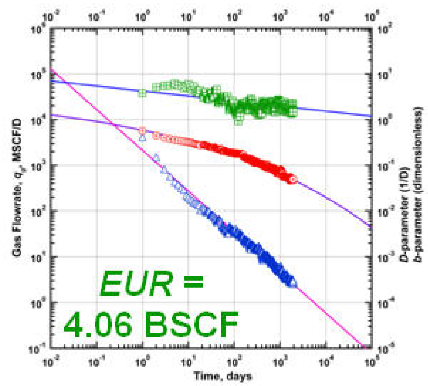



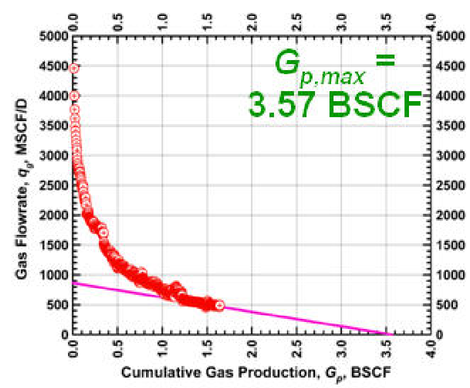




⋮

1,930 days



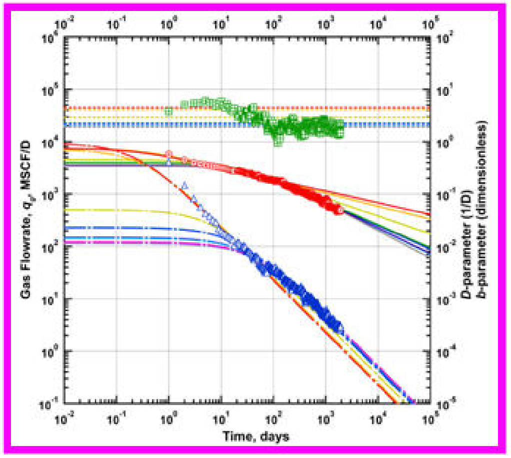



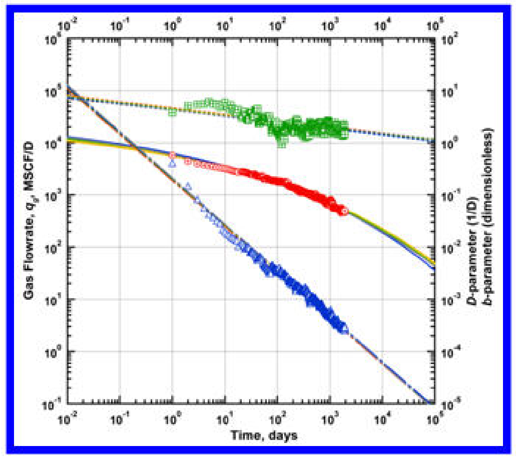
# Decline Curve Analysis: *Continuous EUR*

## *Plot $G_p$ Data and EUR Estimates from Models vs. Time for All Intervals*

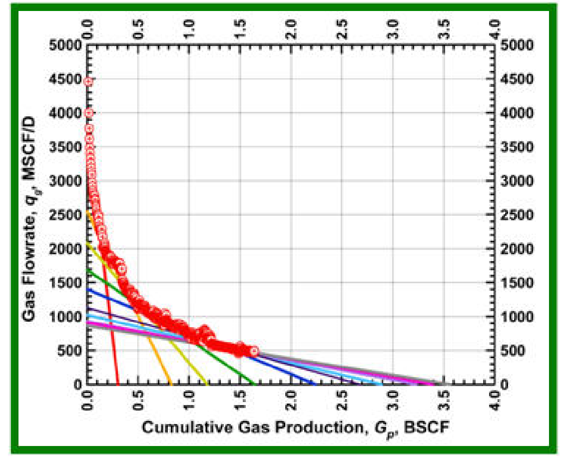
$EUR_{hyp}$




$EUR_{PLE}$

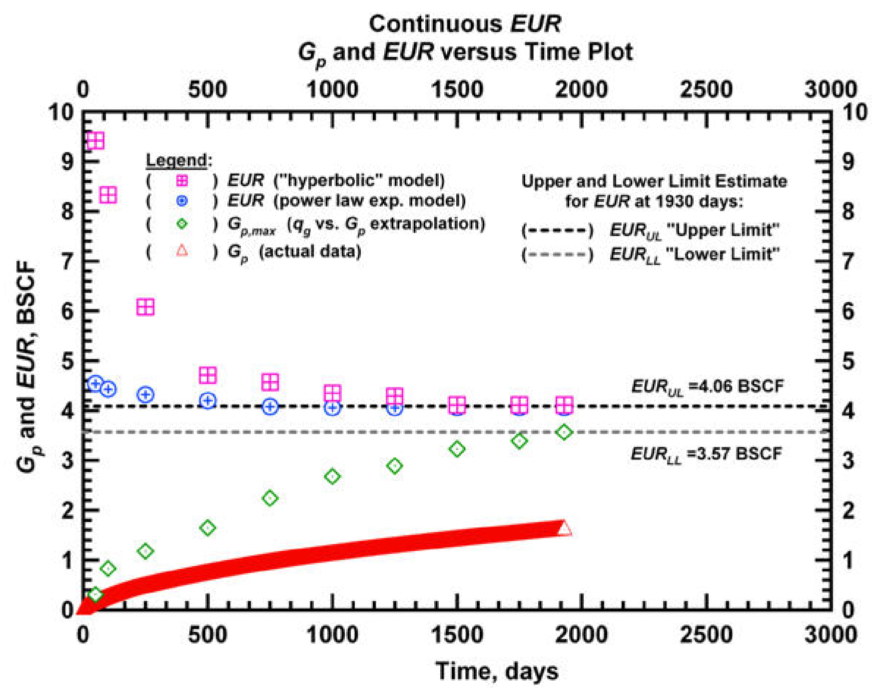



$G_{p,max}$




*Identify the Upper Limit for EUR Using the Power Law Exponential Model*

*Identify the Lower Limit for EUR Using the Straight Line Extrapolation Technique*



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# *Production Diagnostics*

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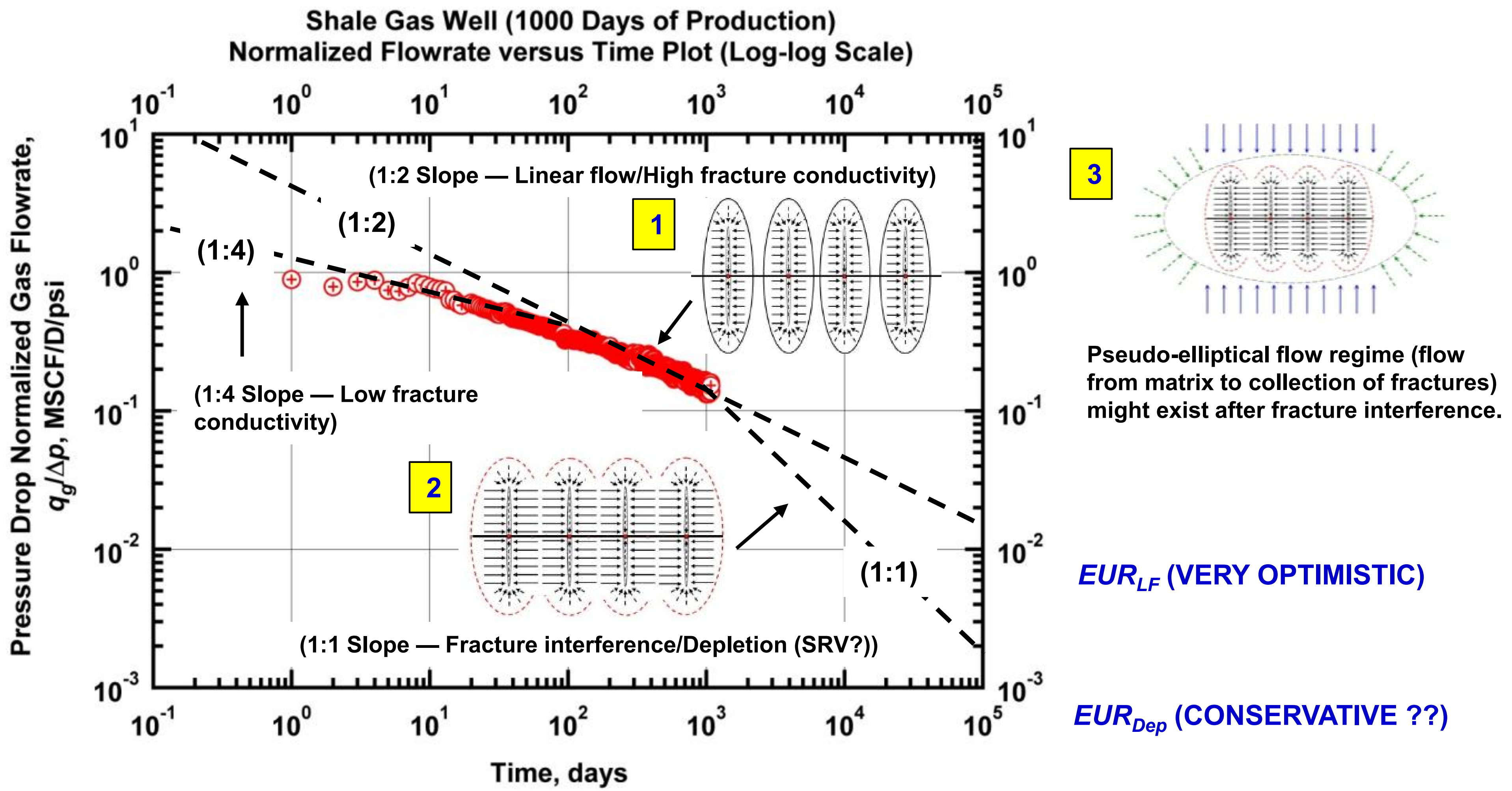
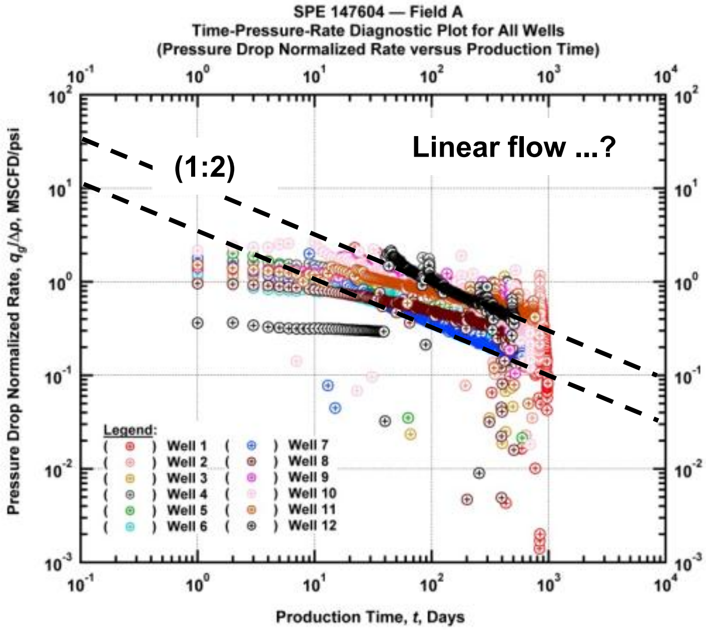
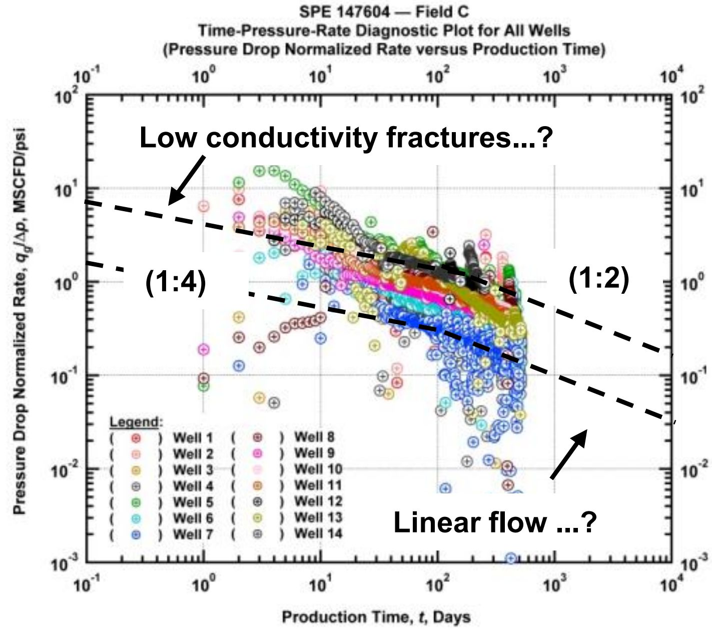
# Production Diagnostics: *Identifying Flow Regimes*

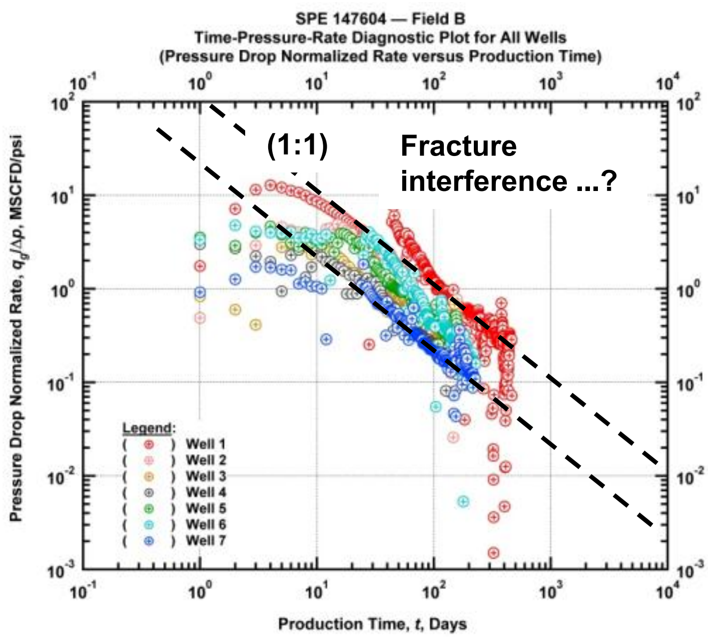



- **Flow Regimes**: **(Barnett Shale Example)**
  - Schematic illustrates possible flow regimes exhibited by time-rate-pressure data.
  - Duration/existence of flow regimes is DIFFERENT for each play.

# Production Diagnostics: *Identifying Flow Regimes*



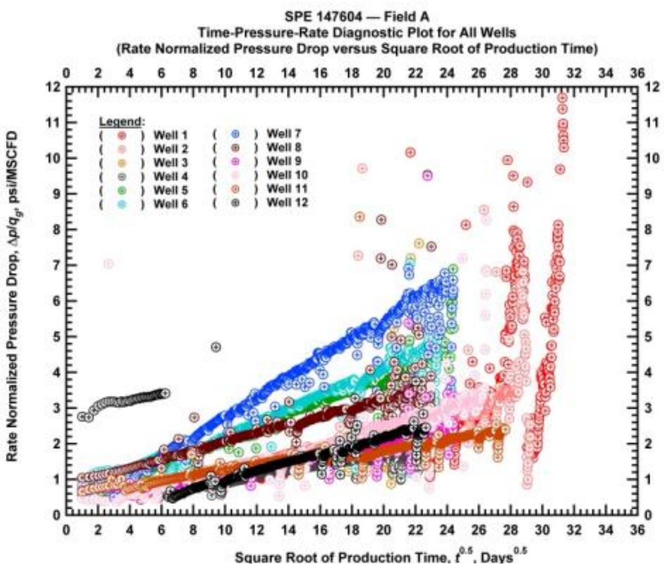



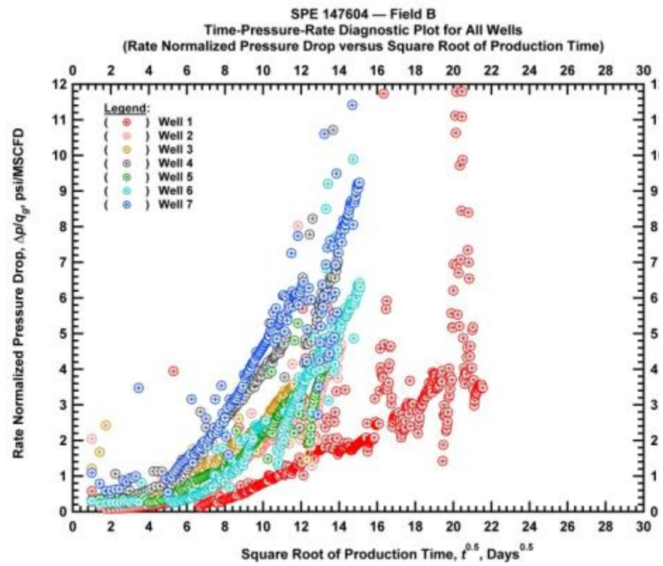

**Discussion:**

- Well clean-up effects (flowback) dominate early time behavior.
- Half-slope indicates linear flow regime is prevailing for Field A.
- Unit slope indicates fracture interference or depletion type signature (decreasing well productivity) for Field B.
- Long time well cleanup effects and operation issues prevent better diagnostics for Field C.
- Field C wells demonstrate linear and/or bilinear flow type signatures.

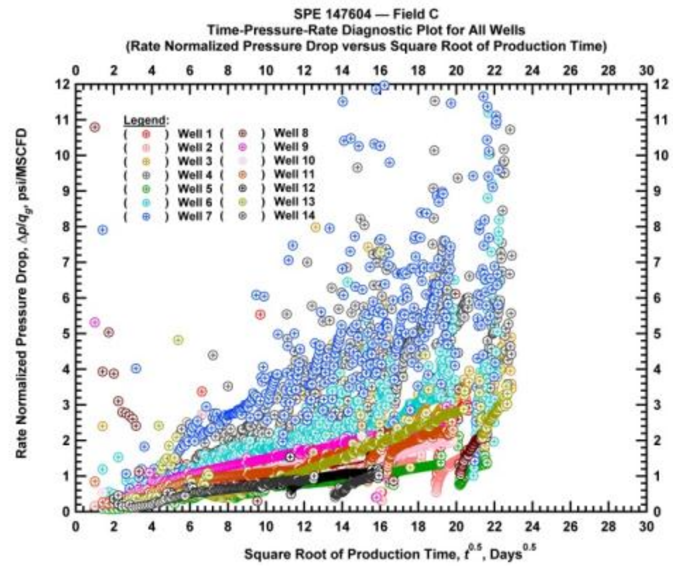
# Production Diagnostics: *Performance Comparison*



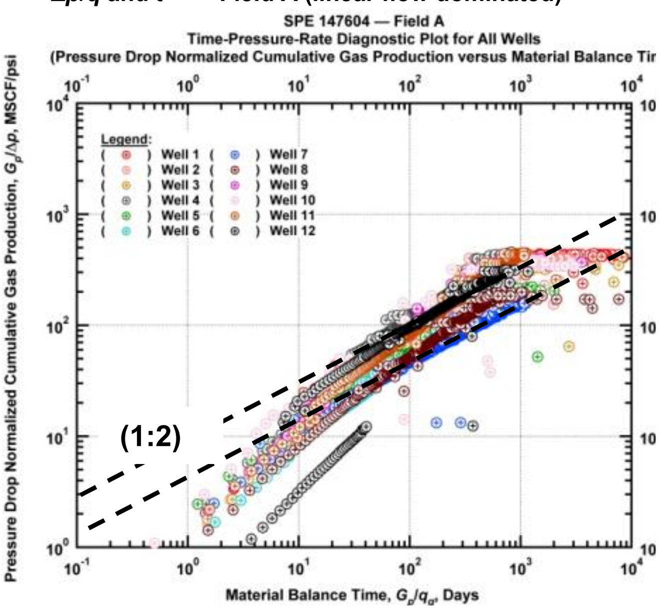

$\Delta p/q$ and $t^{0.5}$ — Field A (linear flow dominated)



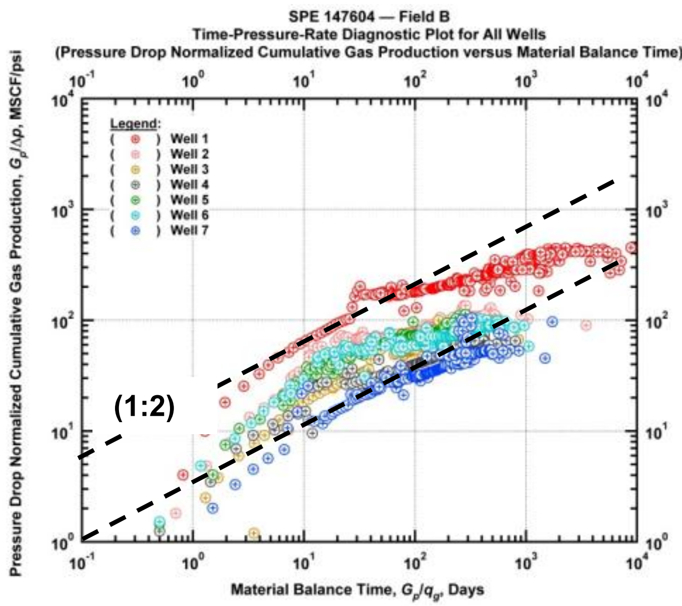

$\Delta p/q$ and $t^{0.5}$ — Field B (decreasing well productivity)



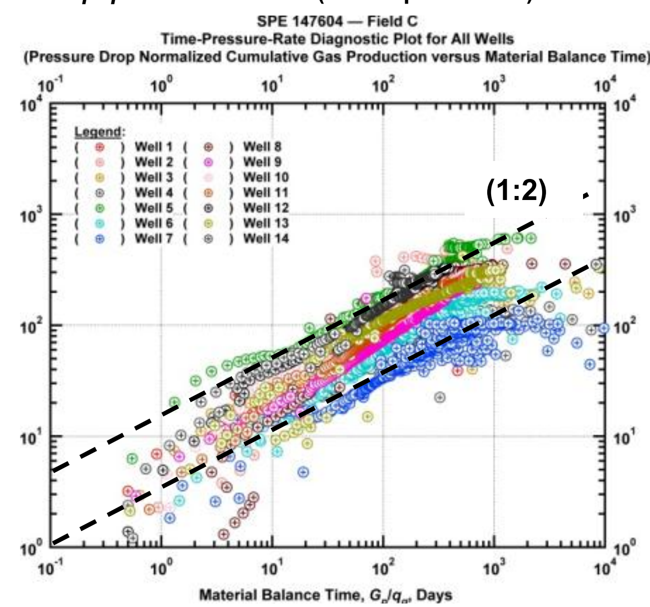

$\Delta p/q$ and $t^{0.5}$ — Field C (erratic production)




$G_p/\Delta p$ and $G_p/q$ — Field A (linear flow dominated)

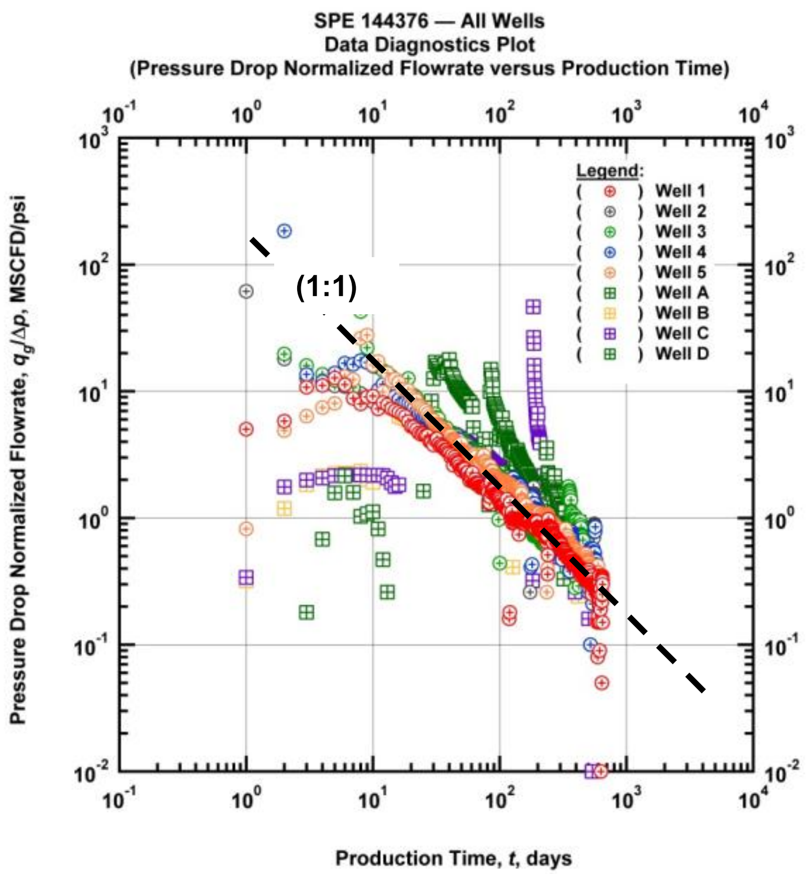


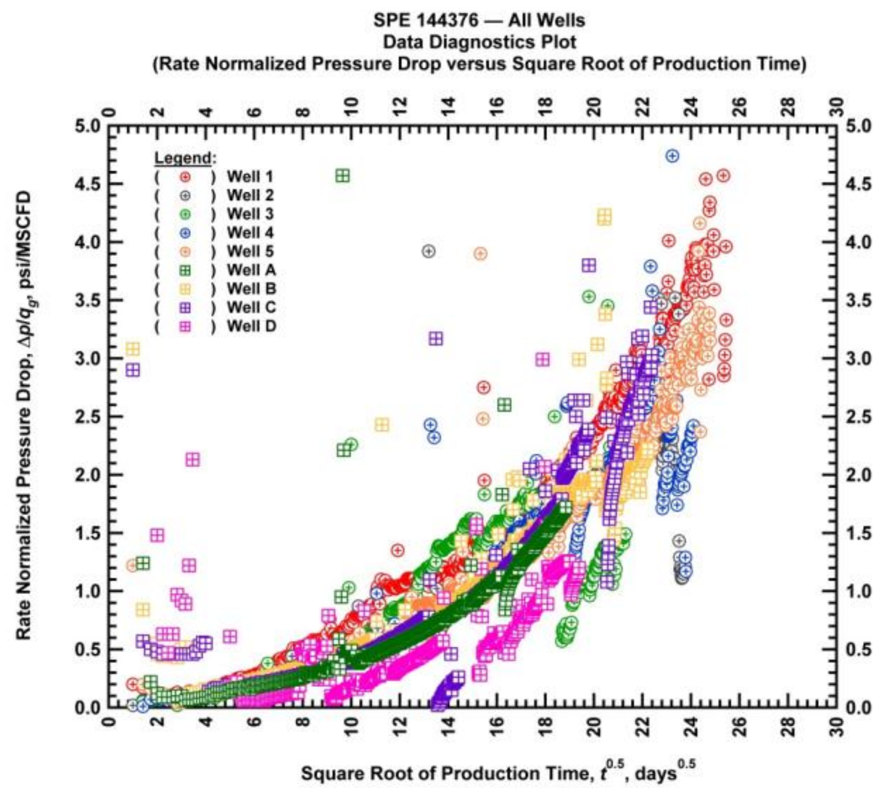

$G_p/\Delta p$ and $G_p/q$ — Field B (decreasing well productivity)




$G_p/\Delta p$ and $G_p/q$ — Field C (erratic production)

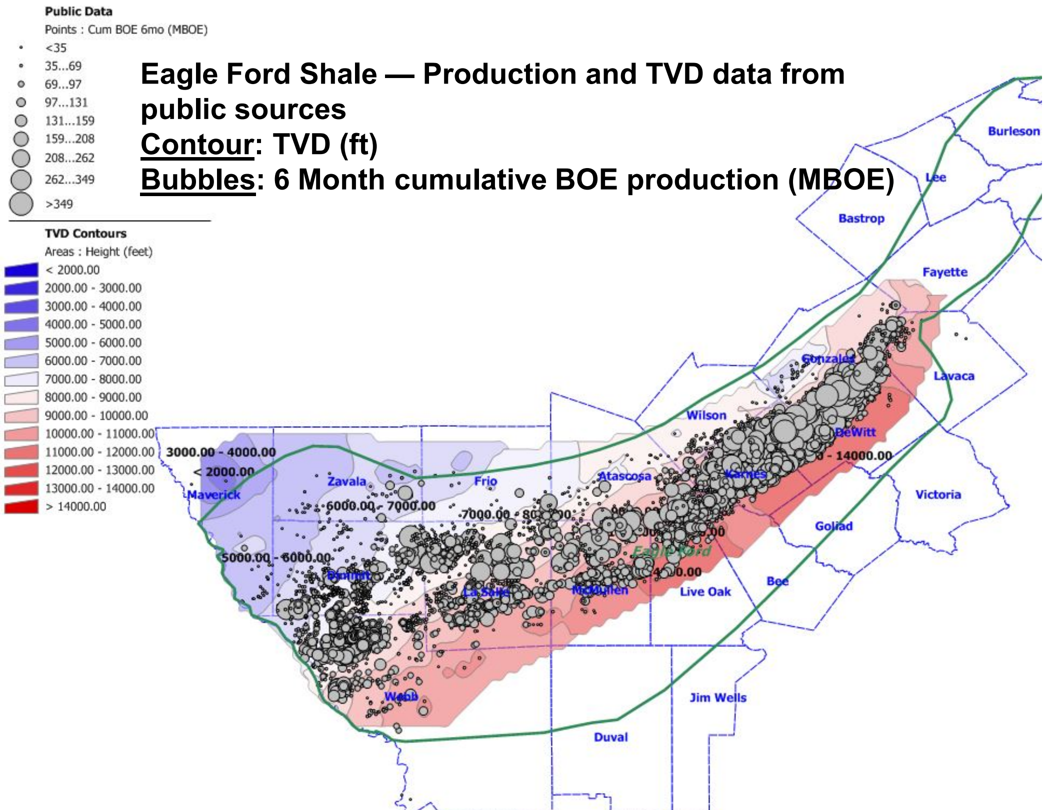
# Production Diagnostics: *Grouping Wells*



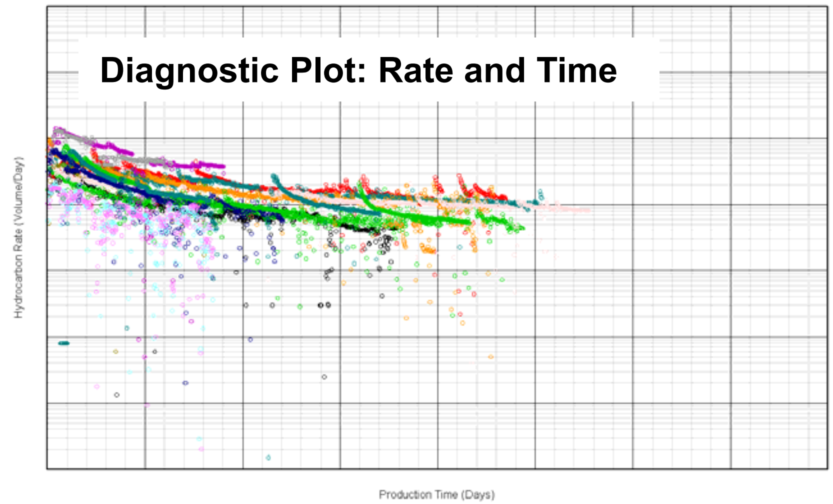



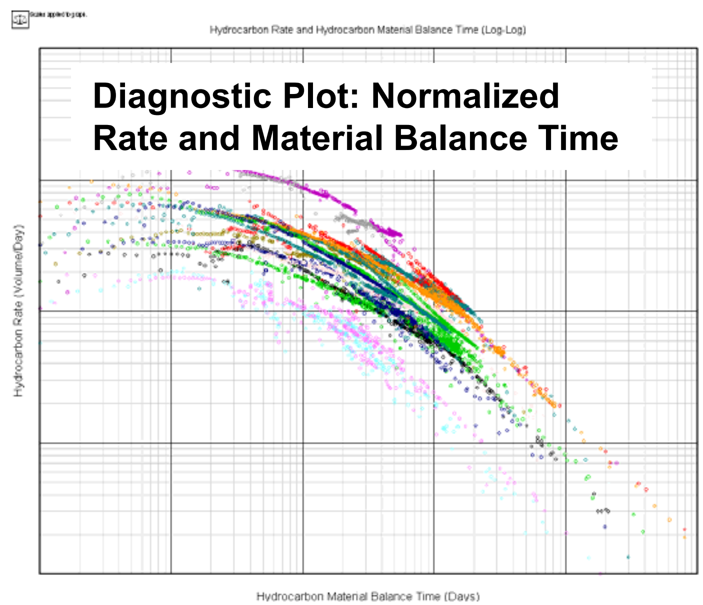

- **Discussion:**
  - Diagnosis of the performance of 9 wells producing in the same area (plot of productivity index).
  - Performance comparison of multiple wells to identify characteristics.
  - Differences in the productivity can be attributed to completion and operational issues.

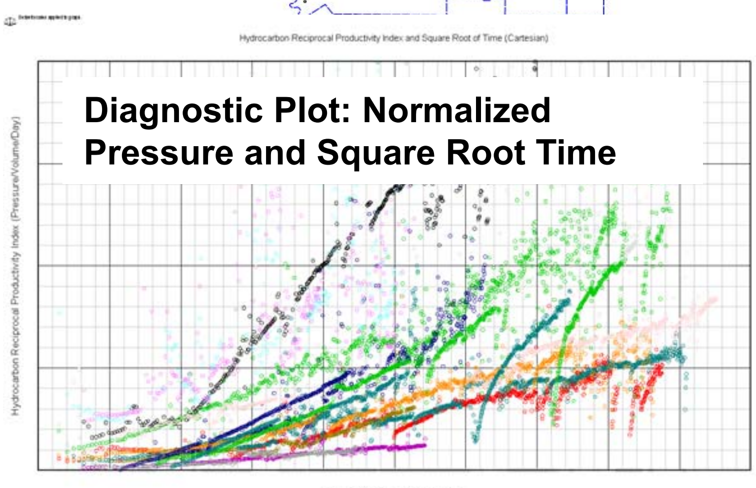
# Production Diagnostics: *Eagle Ford Example*



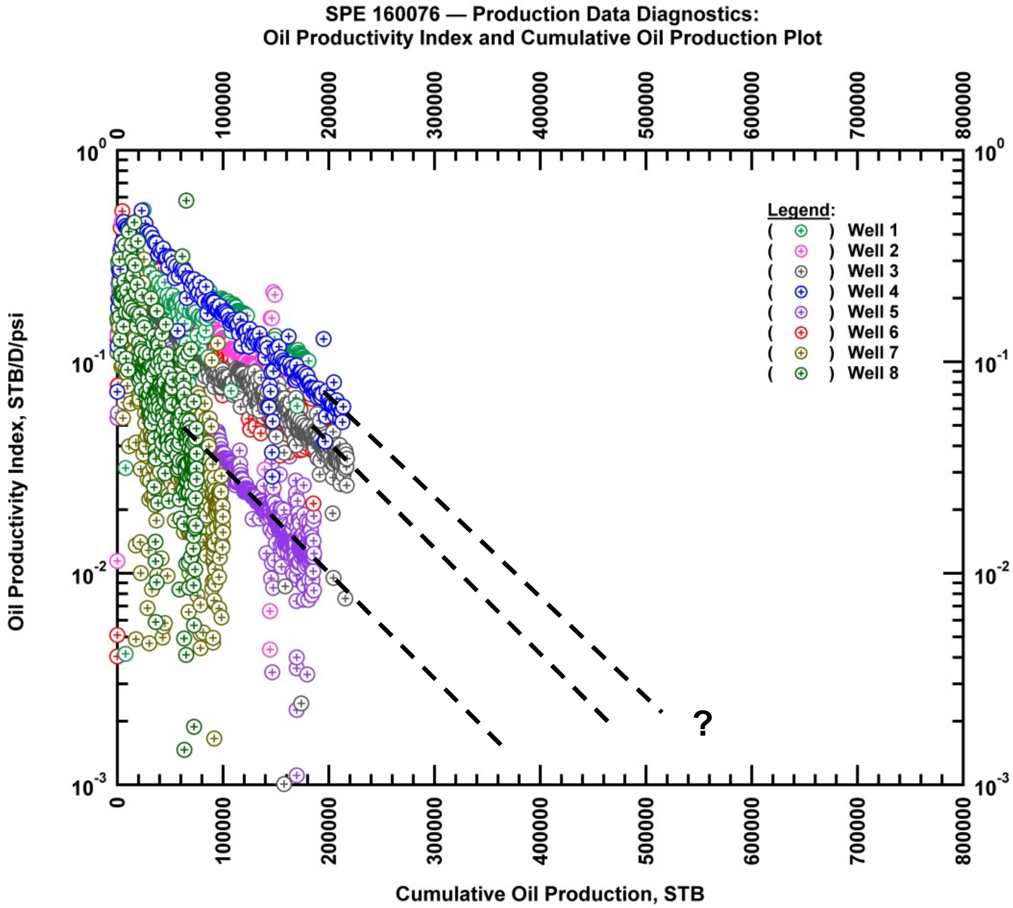

- Wells are grouped by specific characteristics (such as, geology/location, PVT behavior, completion, etc.).
- Representative wells are selected for analysis and modeling.



# Production Diagnostics: *Eagle Ford Example*




- **Diagnostics:**
  - **PLOT: Oil Productivity Index versus Cumulative Oil Production**
  - **OBJECTIVE: (Empirically) project recovery for a single well based on flow behavior**

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## *Analysis and Modeling*

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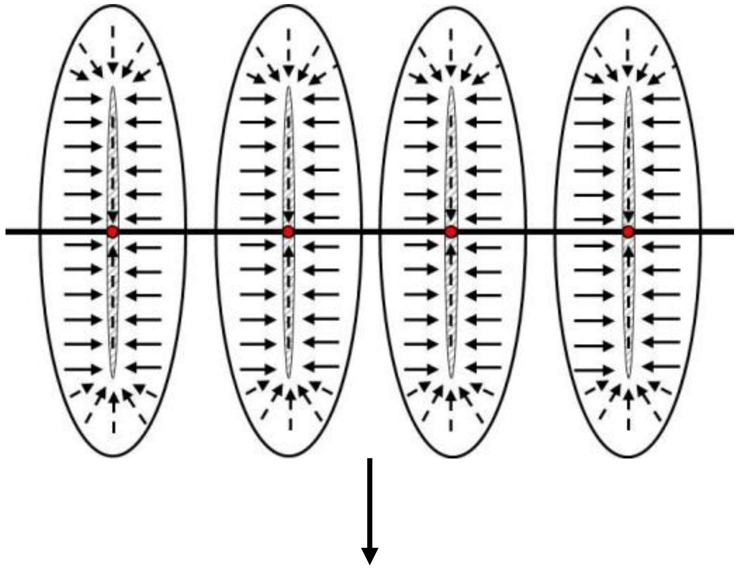
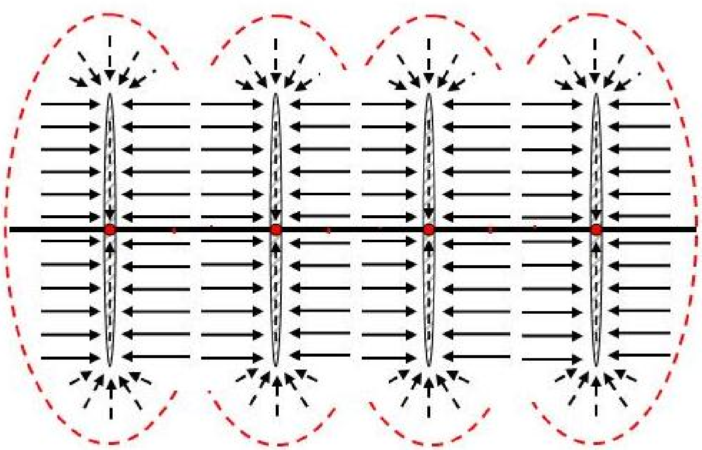
# Analysis and Modeling: *Model Configuration*

1

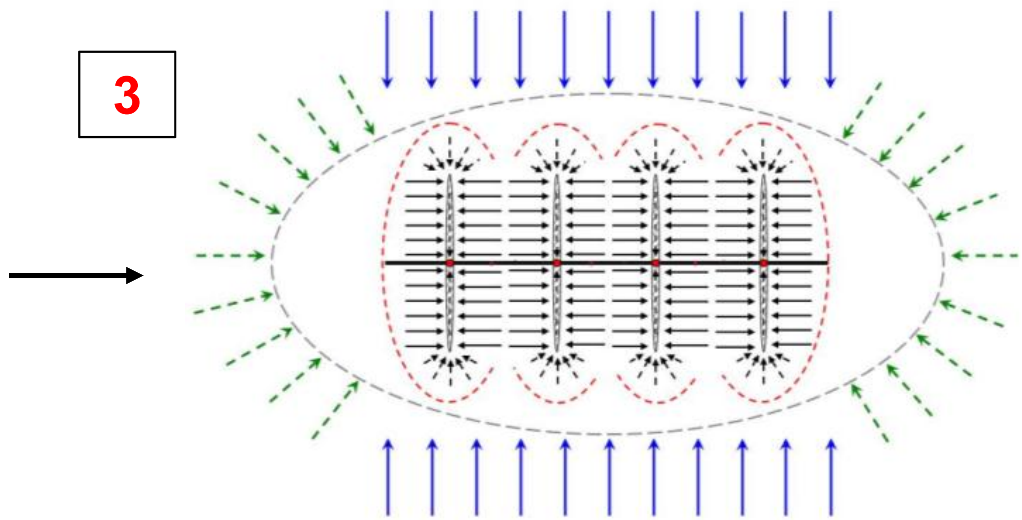


- **Model Parameters**:
  - Permeability ($k$)
  - Fracture half-length ($x_f$)
  - Fracture conductivity ($F_c$)
  - Drainage area ($A$)
  - Skin factor ($s$)
  - Well length ($L_w$)
  - Number of fractures ($n_f$)

2

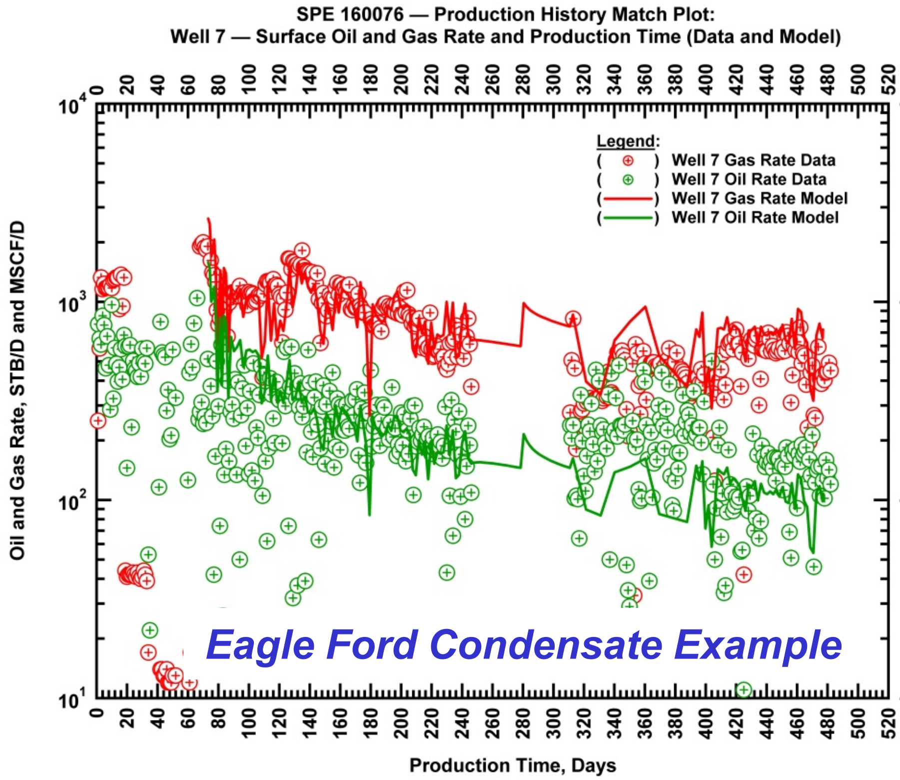


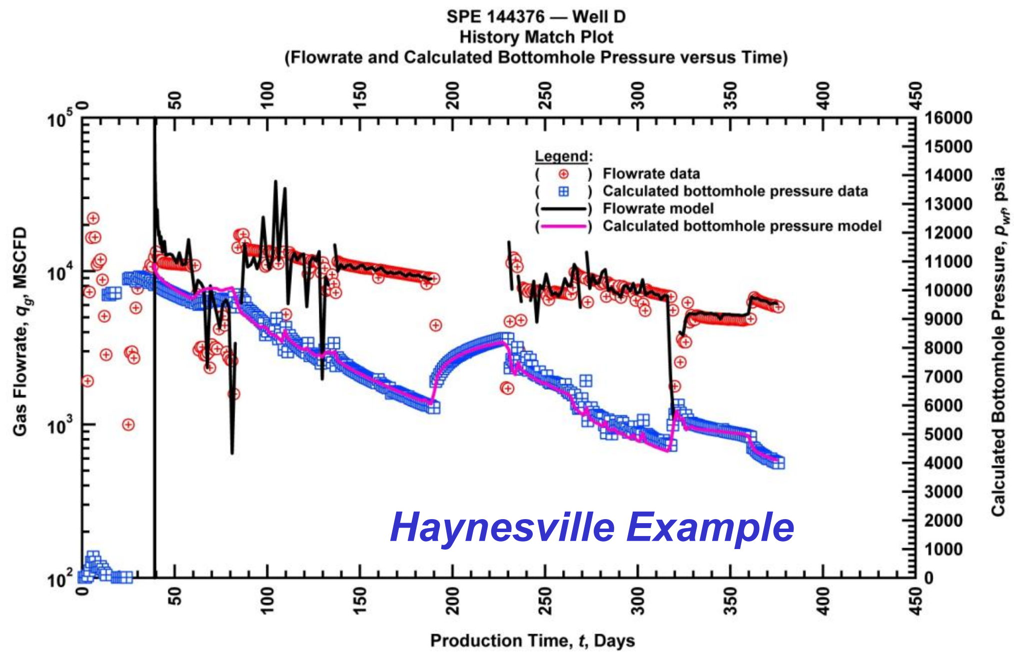
3



- **Discussion**: *Horizontal Well with Multiple Transverse Fractures*
  - This is the simplest model to represent multi-frac horizontal well production.

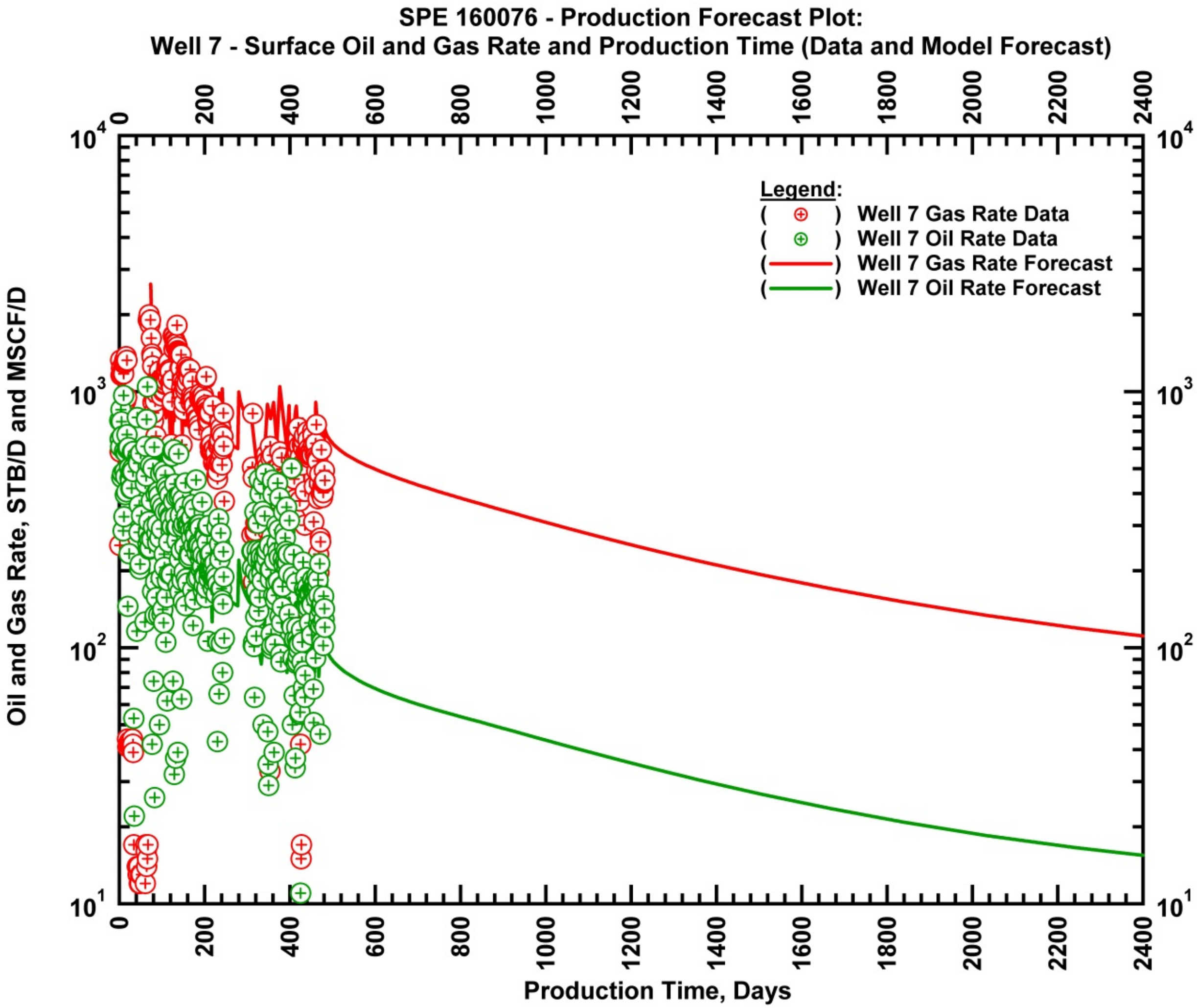
# **Analysis and Modeling**: *History Matching with Model*



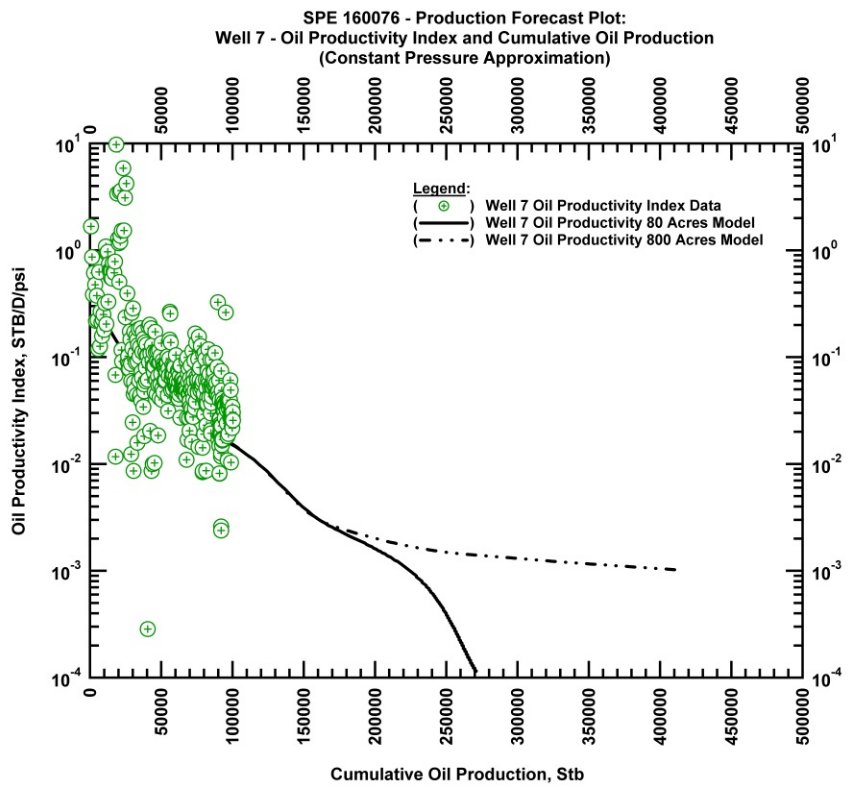

- **Analysis**:
  - *Model*: Horizontal well with multiple fractures, non-linear analysis accounting for multiphase flow and pressure-dependent reservoir properties.
  - *Multiphase Flow*: Rigorous fluid characterization (non-linear solution).
  - *Pressure-dependencies*: Approximate degradations in productivity.
  - Model-based analysis must be guided by production diagnostics.

# Analysis and Modeling: *Model Forecast*

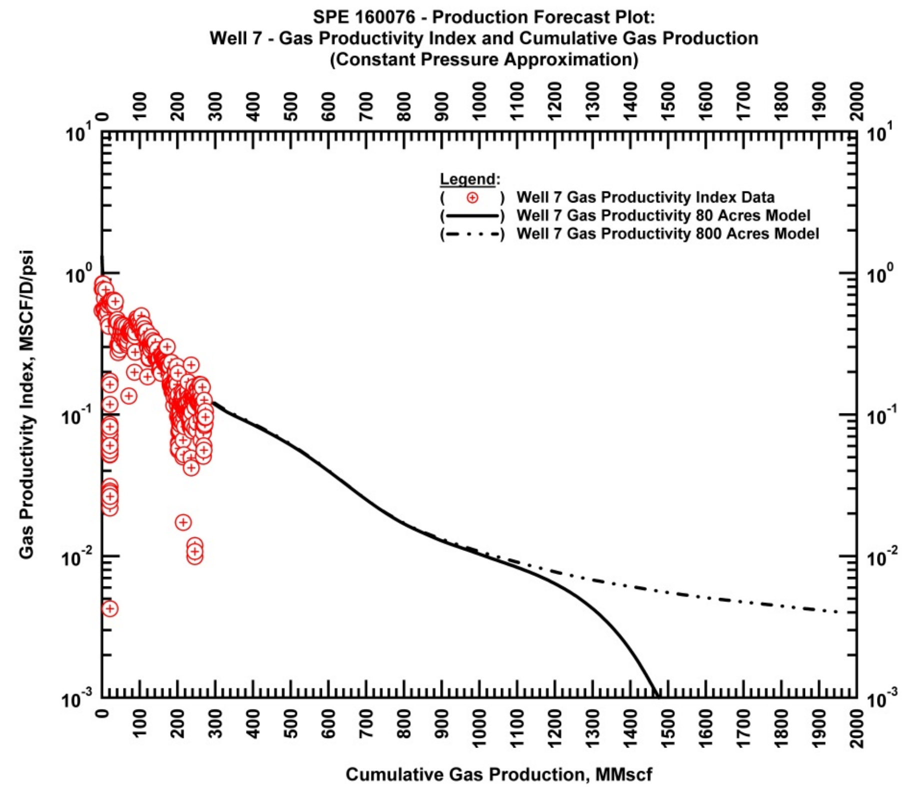



- **Forecast**:
  - Oil and gas rates are extrapolated using the model (80 acres)
  - $EUR_{OIL}$ = 0.23 MMSTB, $EUR_{GAS}$ = 1.05 BSCF

# Analysis and Modeling: *Model Forecast*



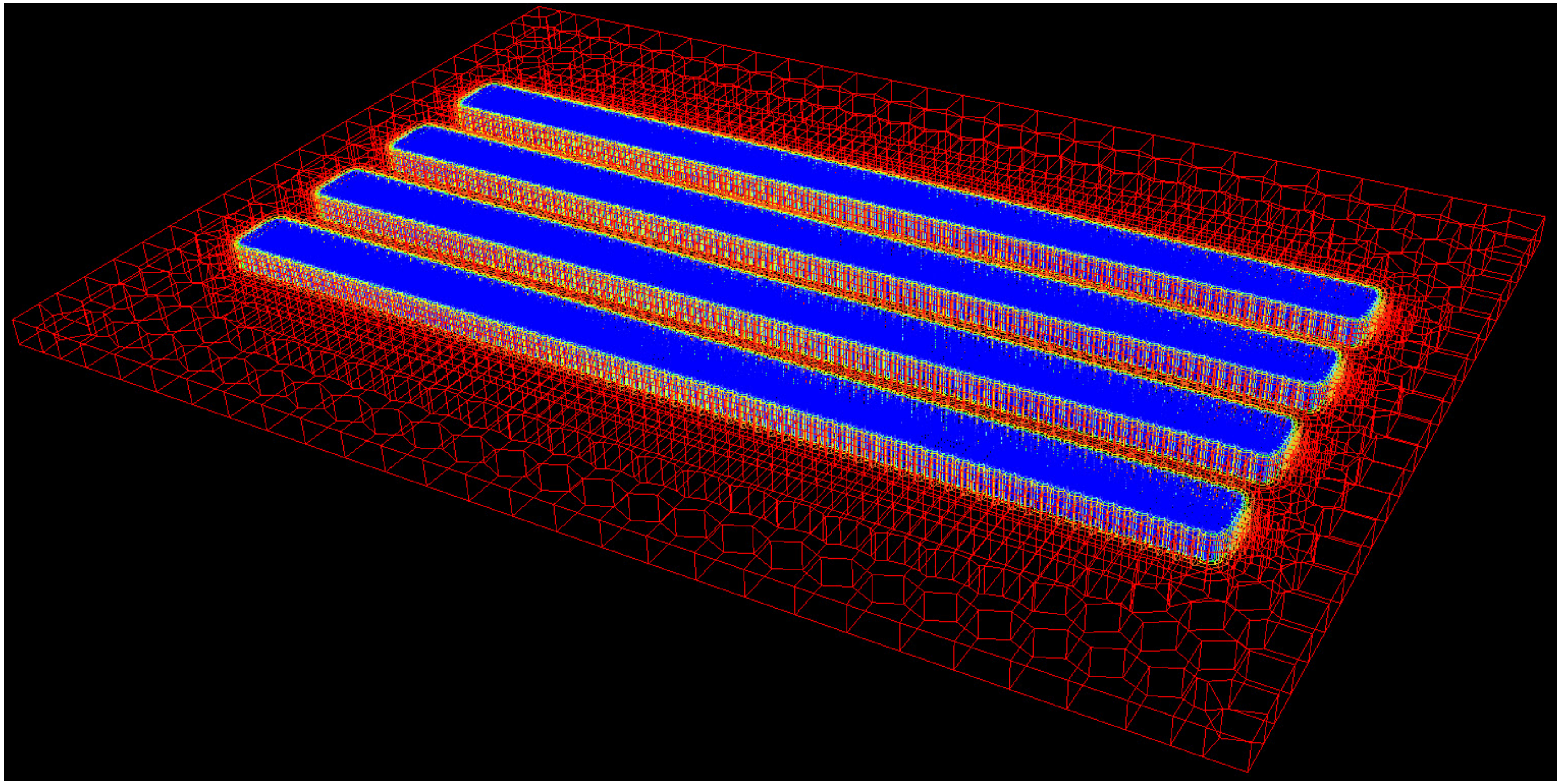

Oil productivity index and cumulative oil production plot




Gas productivity index and cumulative gas production plot

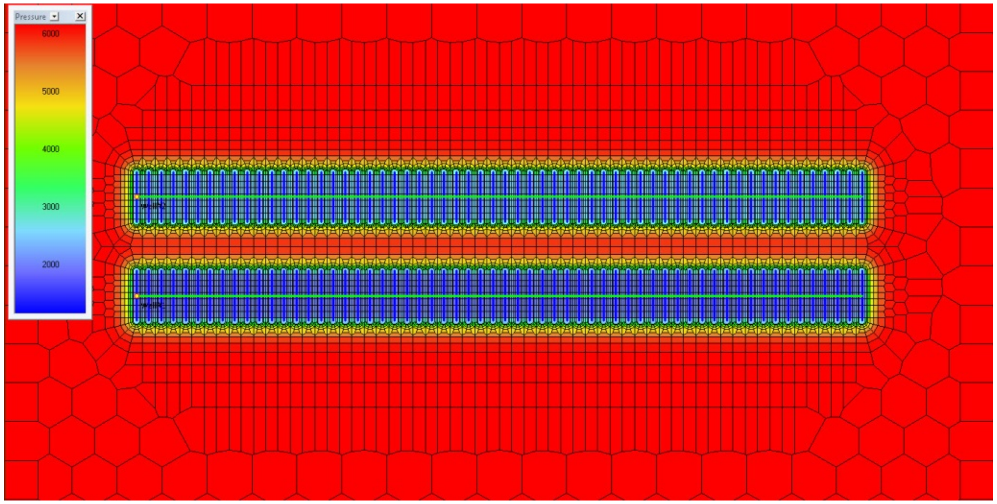
- **Forecast:**
  - Constant pressure simulation results are imposed on productivity index and cumulative production plots.
  - Forecast is different with respect to drainage area.

# Analysis and Modeling: *Effect of Well Spacing*

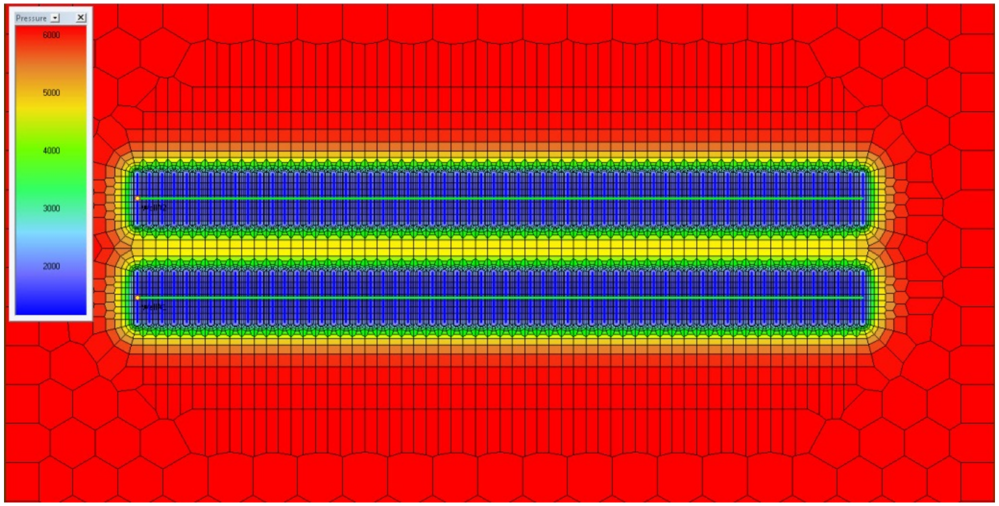


- **Modeling**: *Multi-well Modeling (Well Interference)*
  - Used model parameters obtained from the analyzed well(s).
  - Assumed development wells have the same well configuration
  - Assumed development wells have the same reservoir and fluid properties.
  - Vary distance between two wells to investigate the effect of spacing on EUR (Distance between wells corresponds to drainage area).

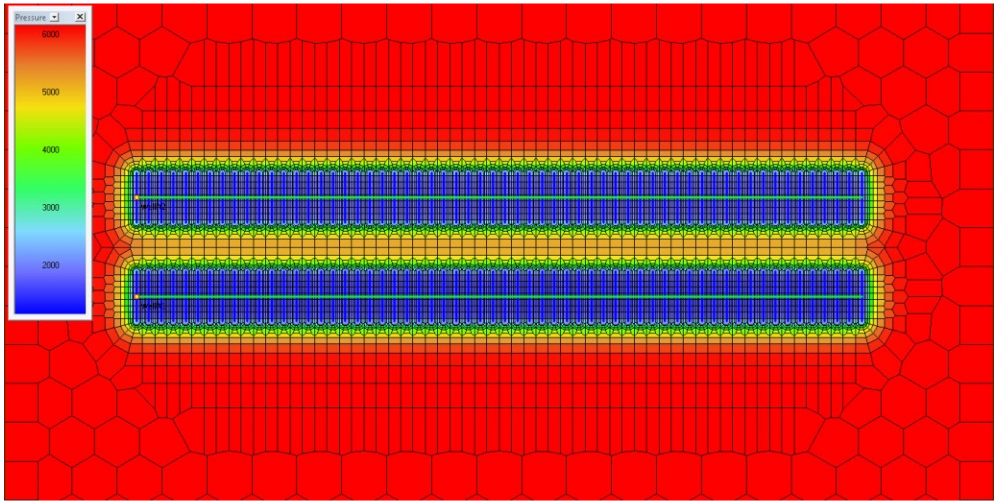
# <u>Analysis and Modeling</u>: *Multi-well Simulation*



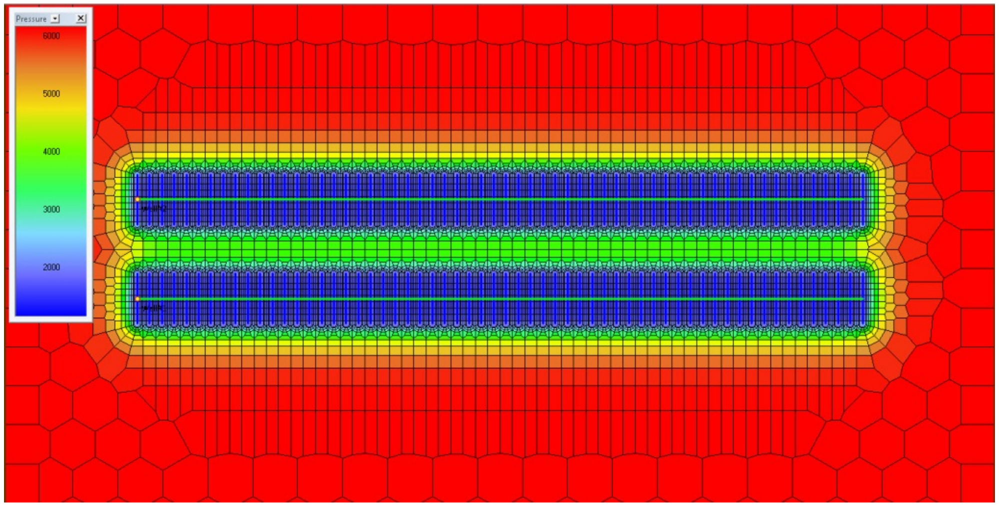

**Pressure Distribution — 1 Year**




**Pressure Distribution — 5 Years**



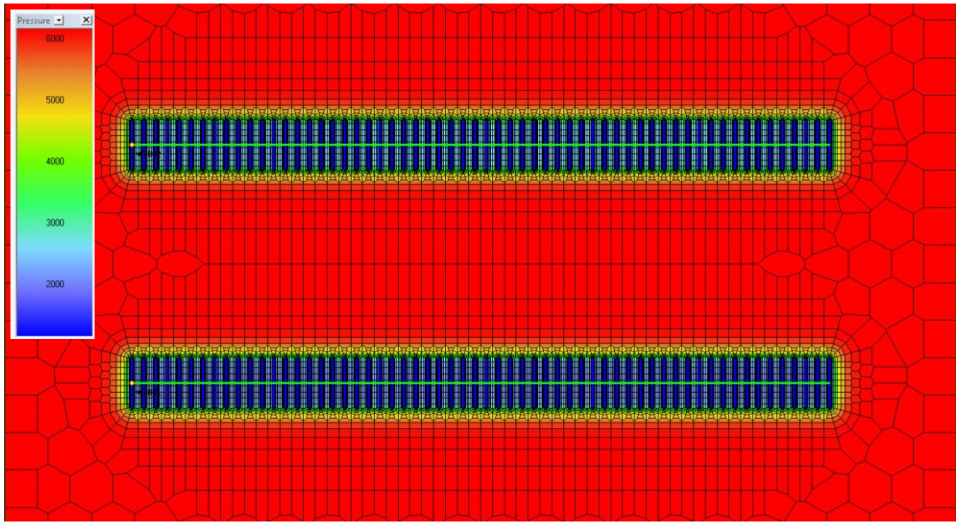

**Pressure Distribution — 3 Years**



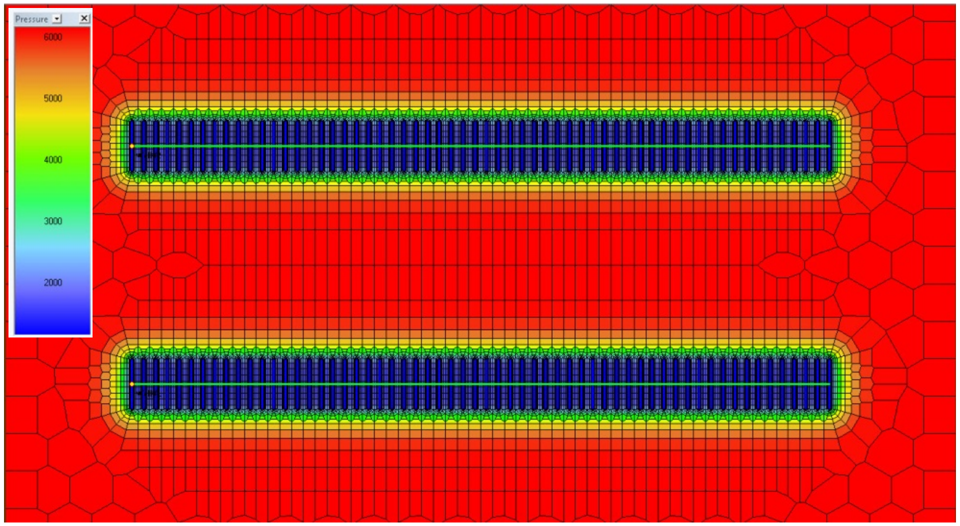

**Pressure Distribution — 8 Years**

- **80 acres well spacing is assumed for the multi-well simulation run.**

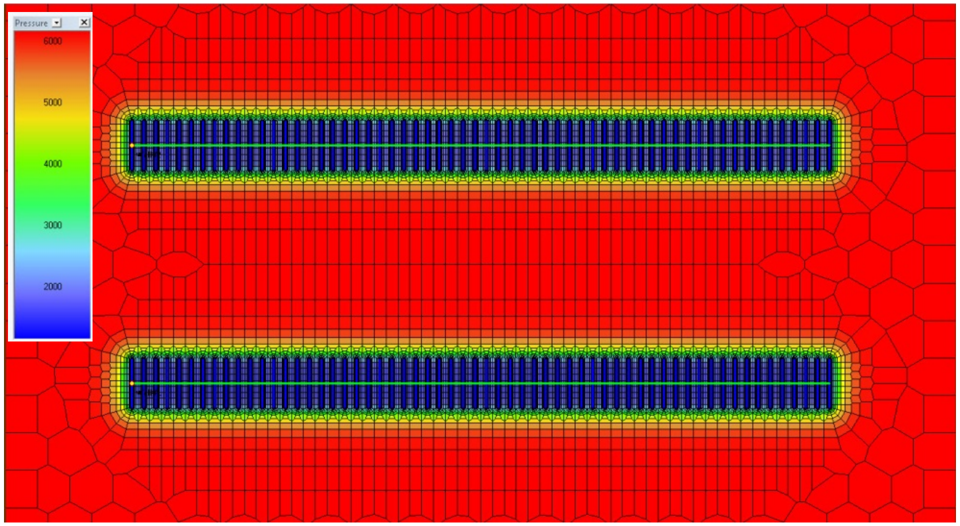
# Analysis and Modeling: *Multi-well Simulation*



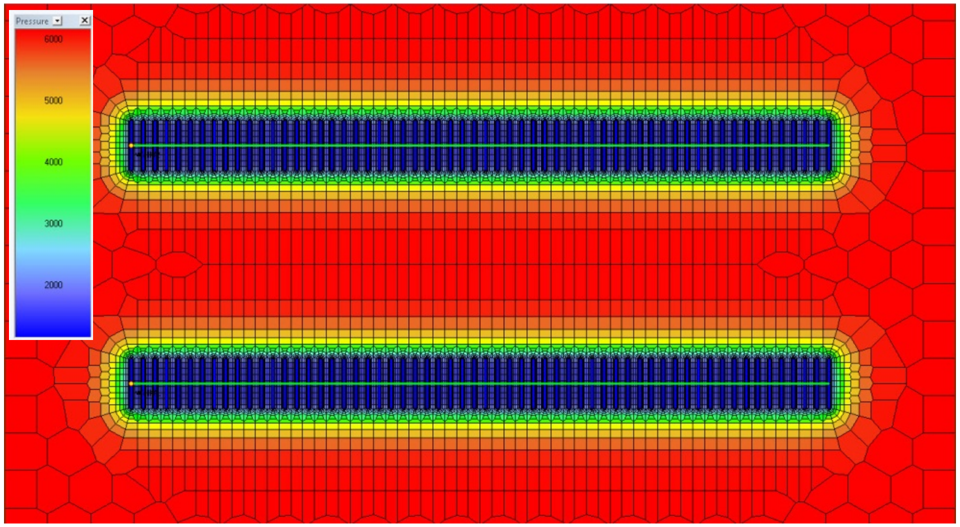
Pressure Distribution — 1 Year



Pressure Distribution — 5 Years



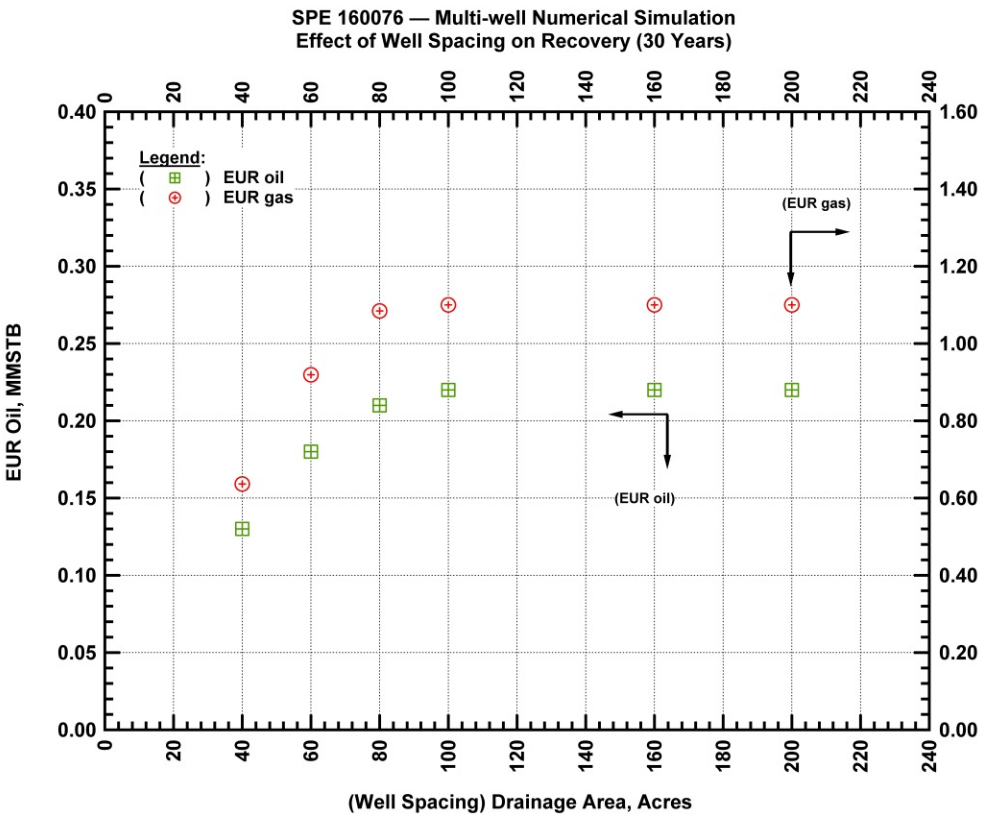
Pressure Distribution — 3 Years

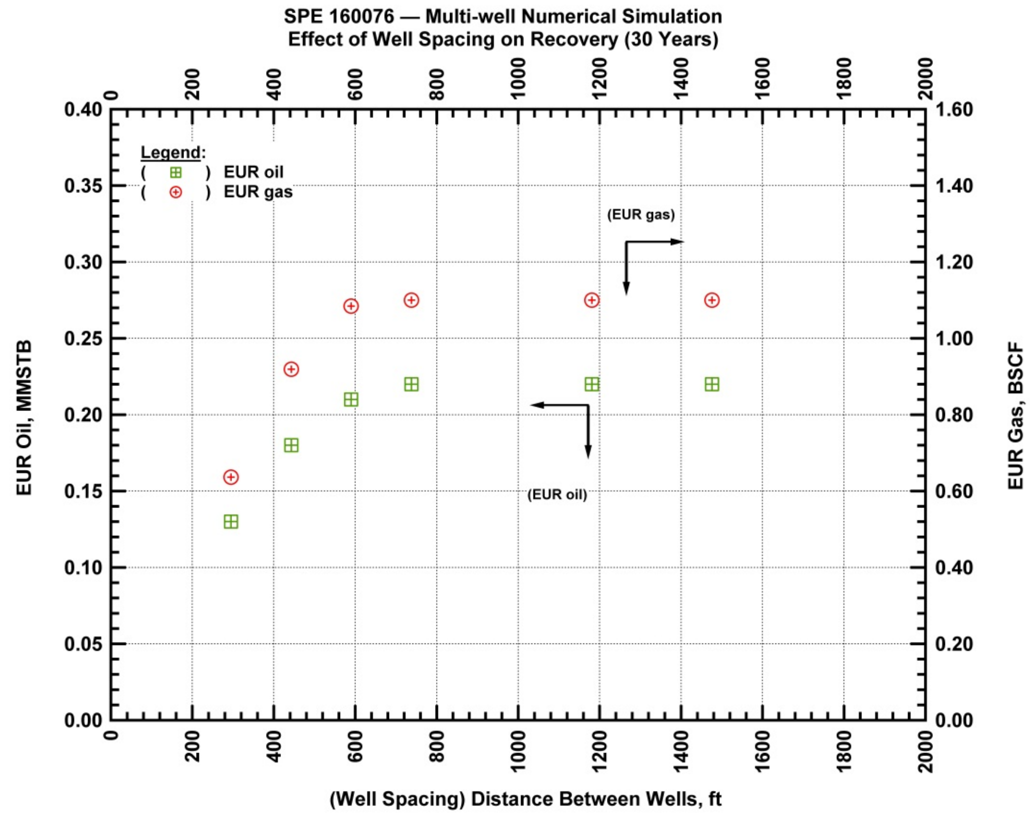


Pressure Distribution — 8 Years

- 200 acres well spacing is assumed for the multi-well simulation run.

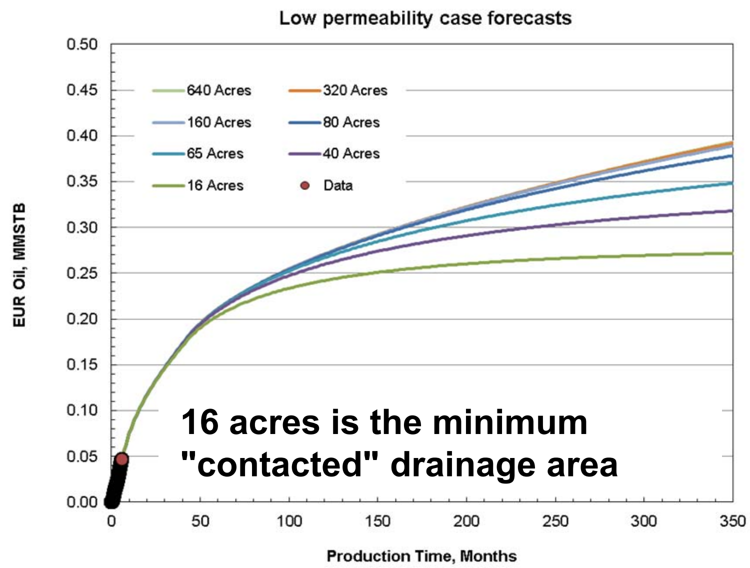
# **Analysis and Modeling**: *Effect of Well Spacing on EUR*

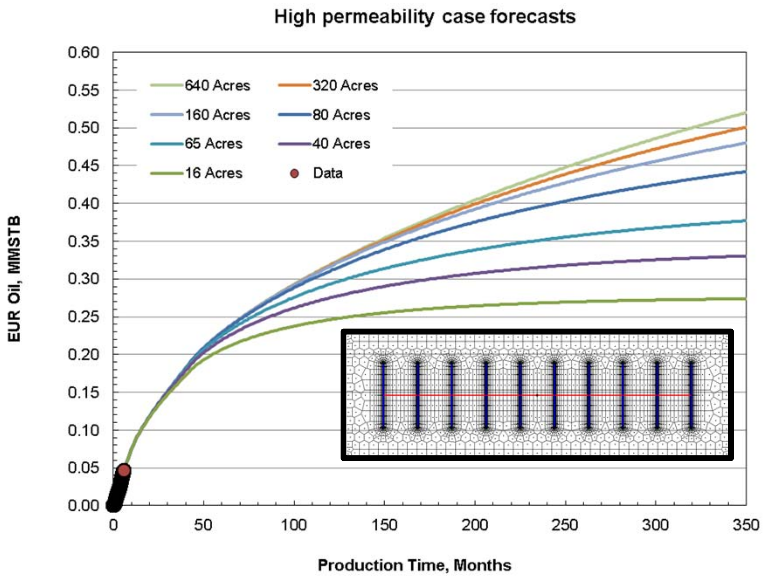


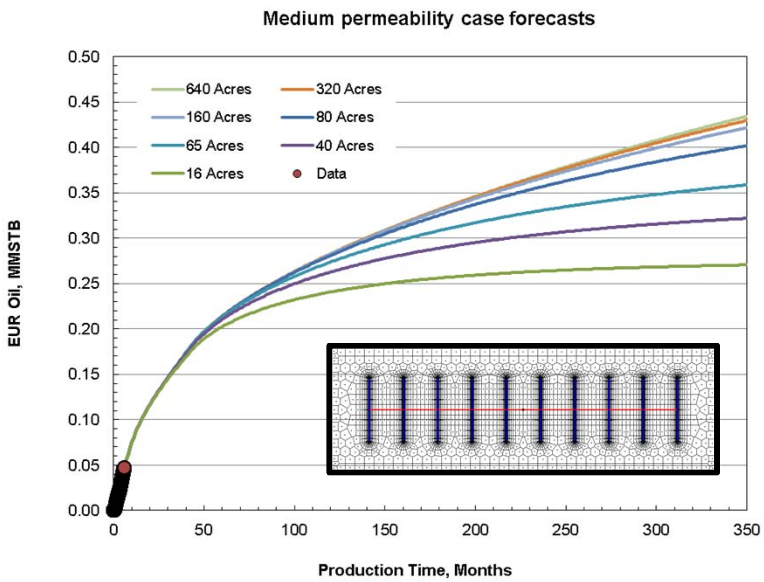



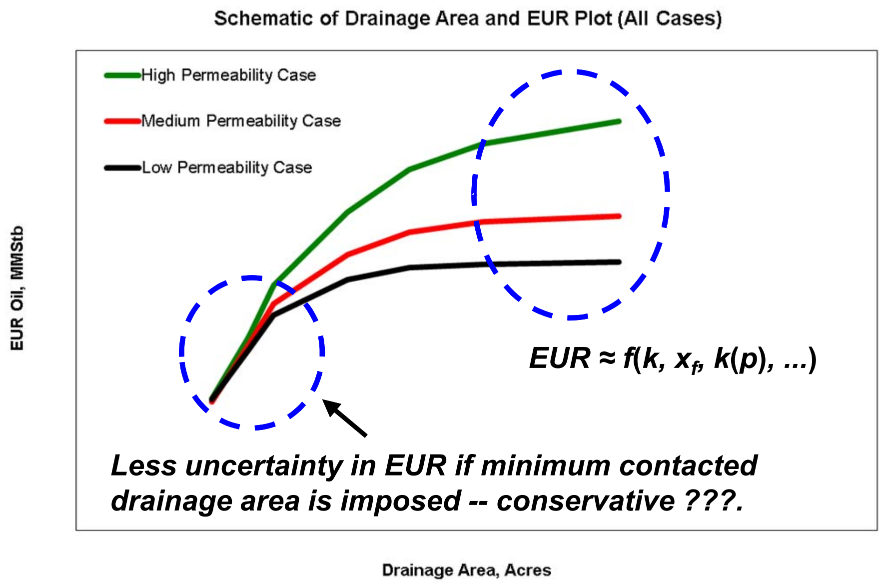

- **Discussion**:
  - EUR is a function of well spacing for less than 100 acres drainage area assumption (not affected over 100 acres).
  - EUR values are estimated at 30 years of production.
  - In our simulation runs, 100 acres drainage area corresponds to 738 ft distance between wells.

# **Analysis and Modeling**: *Uncertainty/Non-uniqueness*



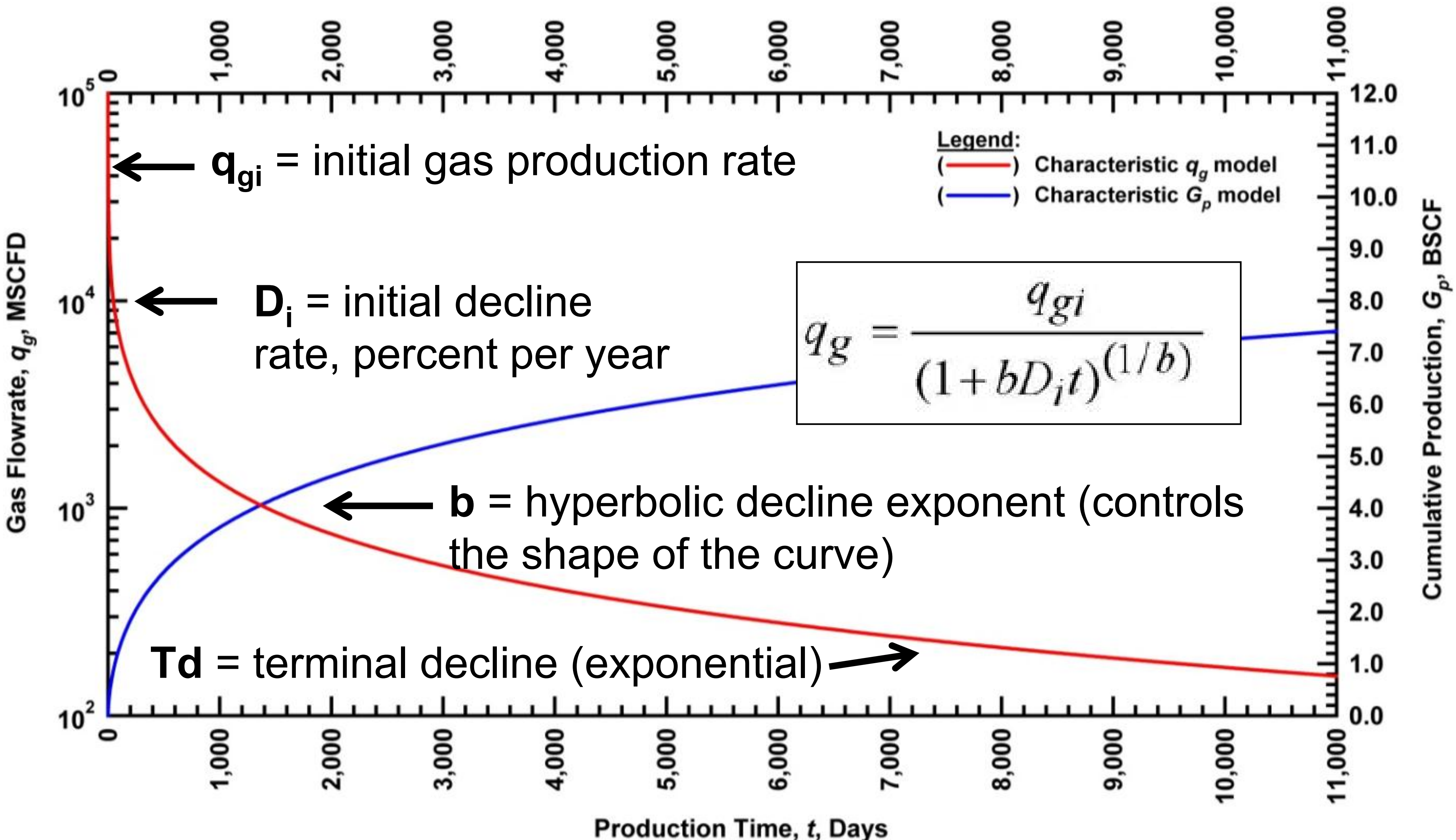




- **Different permeability values are utilized for history match and almost identical matches are obtained for each case. It is possible to obtain probabilistic forecasts.**

# **Analysis and Modeling**: *Time-Rate Profile*




- **Discussion**:
  - **Model-based analysis results can be converted into a time-rate (decline) profile.**

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## *Concluding Remarks*

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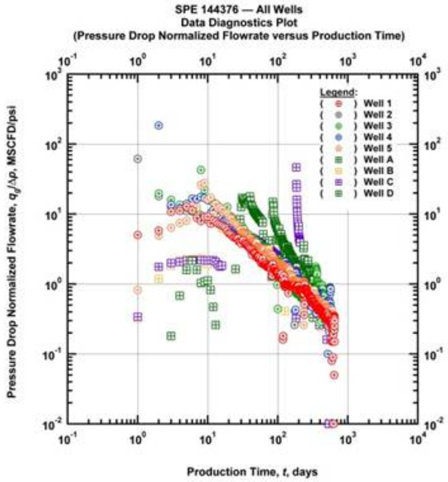
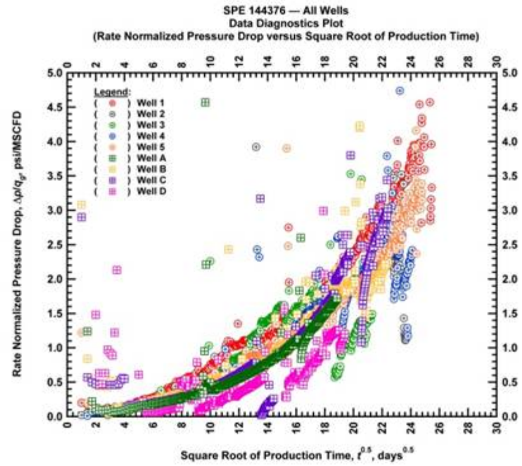
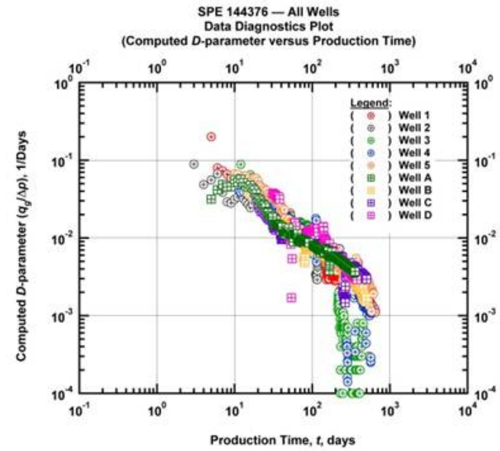
**+1.214.891.7381 — dilk@demac.com**

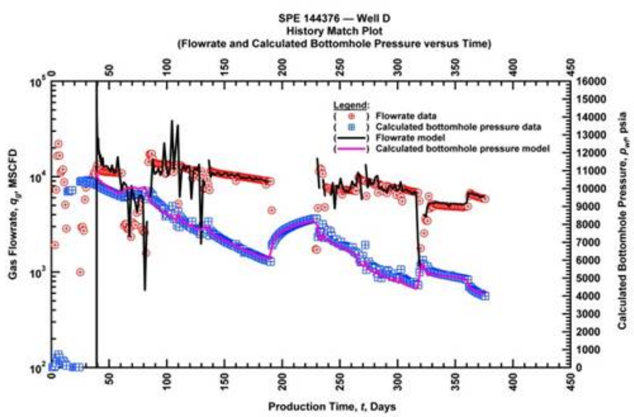
# **Concluding Remarks**: *Well Performance Analysis Procedure*

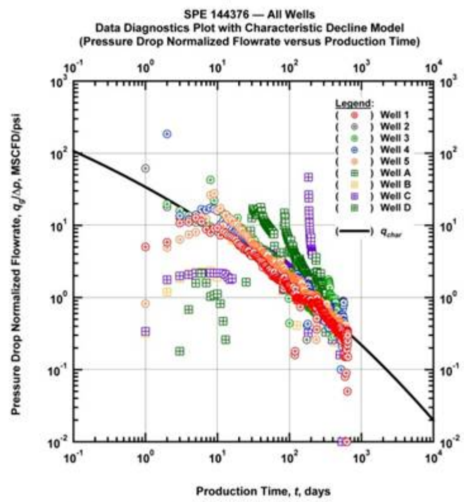


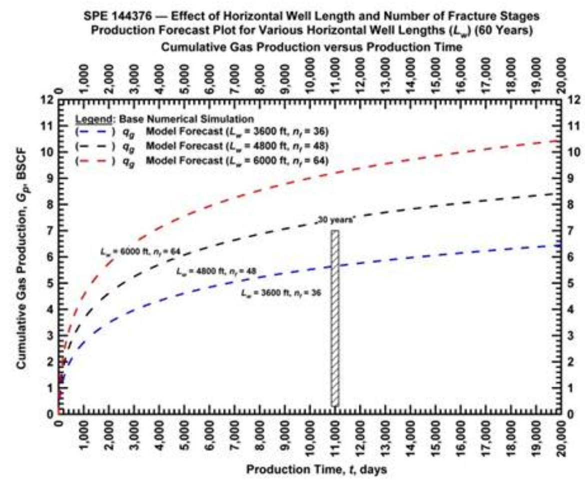




***DIAGNOSTICS***

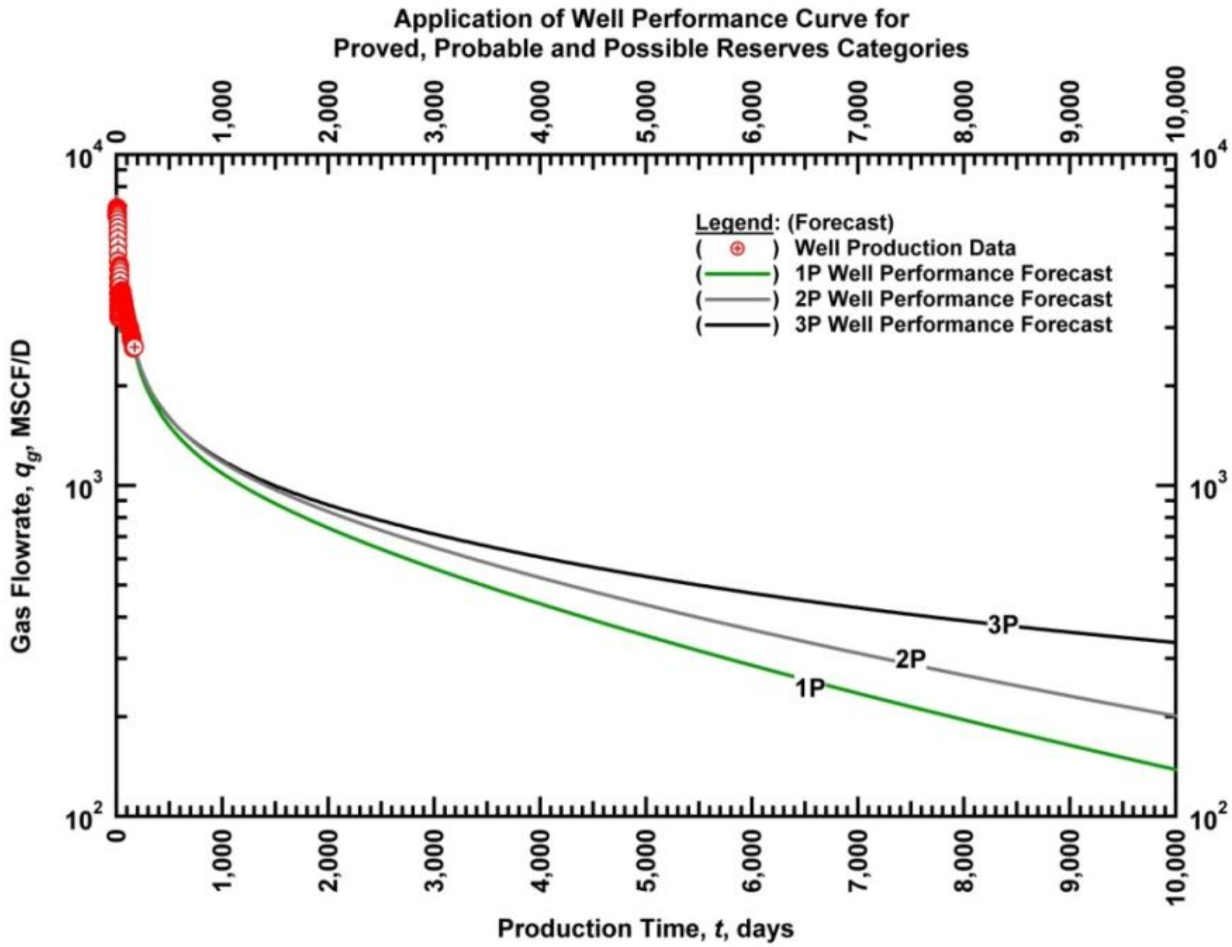



***ANALYSIS*** → ***VALIDATION*** → ***FORECAST***

# Concluding Remarks: *Proved Reserves Categories*




- **Proved reserves (1P)**: " ... *reasonable certainty* — to be recovered much more likely than not"
- **"Reasonably certain" *EUR* is much more likely to increase or remain constant with time**
- **Proved plus Probable reserves (2P)**: " ... as likely as not to be recovered" (50% prob.)
- **Proved plus Probable plus Possible reserves (3P)**: " ... possibly but not likely to be recovered" (10% probability)

# <u>Concluding Remarks</u>: *Well Performance in Unconventionals*

- **Decline curve analysis is currently the primary tool for forecasting, *although it may not be fully representative*.**
- **Time-rate-pressure data analyses need to become the dominant tool for evaluating completions and forecasting production.**
- **Diagnostic interpretation of production data is the key to understanding well performance behavior of a given well.**
- **Diagnostic analyses should be performed prior to model-based analyses to identify flow regimes and to assess the consistency of the data.**
- **We need to incorporate the fundamentals of flow mechanisms (e.g., near critical fluid behavior, geomechanics, formation characterization, hydraulic fracture growth, etc.) into analysis and modeling for improved analysis and forecasting.**
- **Numerical simulation gives insight into the evaluation of well spacing for future development.**

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# *Well Performance in Unconventional Reservoirs — State-of-the-art Analysis/Interpretation, and Models*

## *END OF PRESENTATION*

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