Modern Production Analysis for CBM (and other Unconventional Gas)

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Presented at

Canadian Society for Unconventional Gas, June 7, 2006

Rapid Solutions Corp. (TSX-V: RPD)

Agenda

- ***Company Profile***
- ***Objective of Presentation***
- ***Case Studies***
  - Conventional Gas
  - Single & Two Phase CBM
  - Shale
  - Tight Gas
  - Non-linear Perm
  - Matrix Shrinkage

Rapid Solutions Corp.

- ***Engineering Services:***
  - Pressure Transient Analysis,
  - Production Data Analysis,
  - AEUB PAS Compliance,
  - Engineering Software Development

- ***Engineering Software***
  - Prodesy™: Production Data Analysis
  - ProdMatrix™: MultiWell Pressure/Rate Modeling
  - PAS Author: PAS Generation
  - Suite of Calculators for Wellbore, P/z, and more!

- ***Data Access and Management***
  - RapiData™: Online PTA & Completion Database
  - Centrix™: Well Life Cycle Management
  - Qdox™: Online Well File Access

Hot Topics in Industry

Modern Production Analysis:

P/z,
Reserves/ IGIP,
Transient Analysis,
w/o Shut-in

Unconventional Gas:

Single / Two Phase CBM
Shale Gas, Tight Gas, Layered

Advanced Production Data Analysis For Unconventional Gas

Objective of Presentation

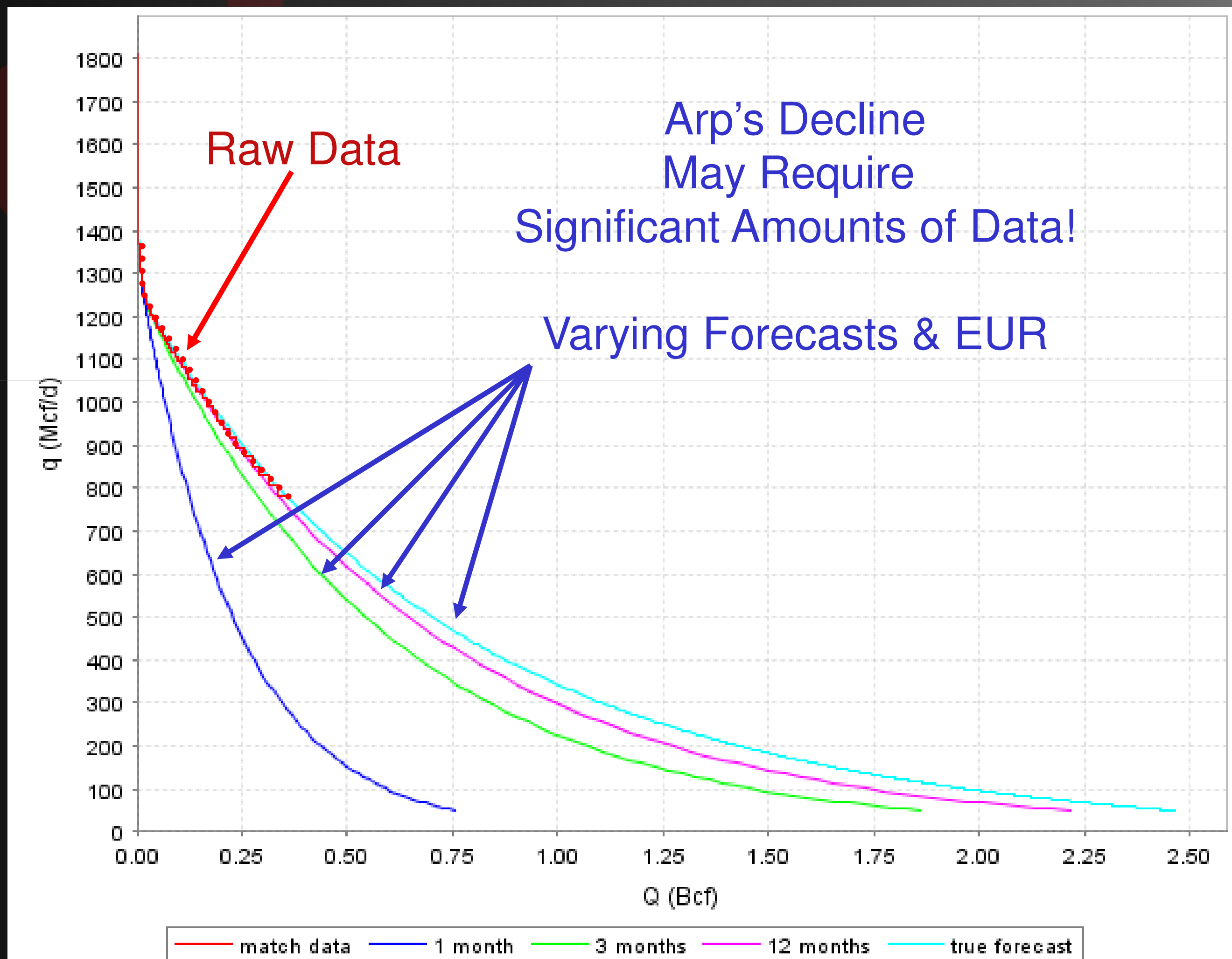
- ***We acknowledge numerical simulation***
- ***Demonstrate Simplicity***
  - Visually and computationally effective
  - Minimal inputs
  - Applies to heterogeneity, complex wells & more!
  - Comparable to conventional decline in terms of ease
- ***Demonstrate Accuracy***
  - Correct OGIP
  - Reliable forecasts etc.

Let's Start With Conventional Decline

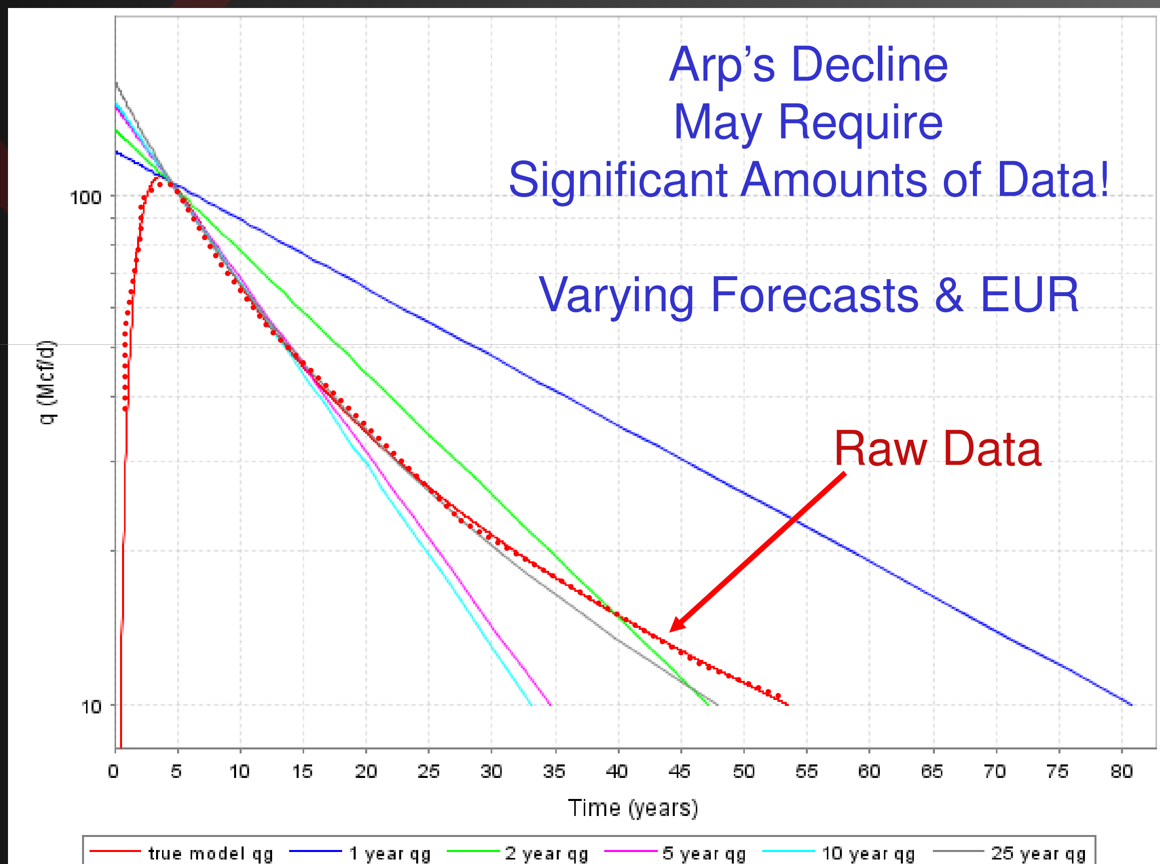
- Trend Extrapolation
- Provides EUR
- OGIP From Recovery Factor
- Used When There is Lack Of Flowing Pressure Data

$$OGIP = \frac{EUR}{RF}$$

CBM Decline Example: Single Phase



CBM Decline Example: 2 Phase



Improved Decline Analysis

- ***We Want More!***
  - Reservoir Engineers
    - Reservoir Characterization
    - Permeability
  - Reserves
    - OGIP
    - Expected Ultimate Recovery
  - Production
    - Deliverability Profile
    - Incremental vs. Accelerated Recovery

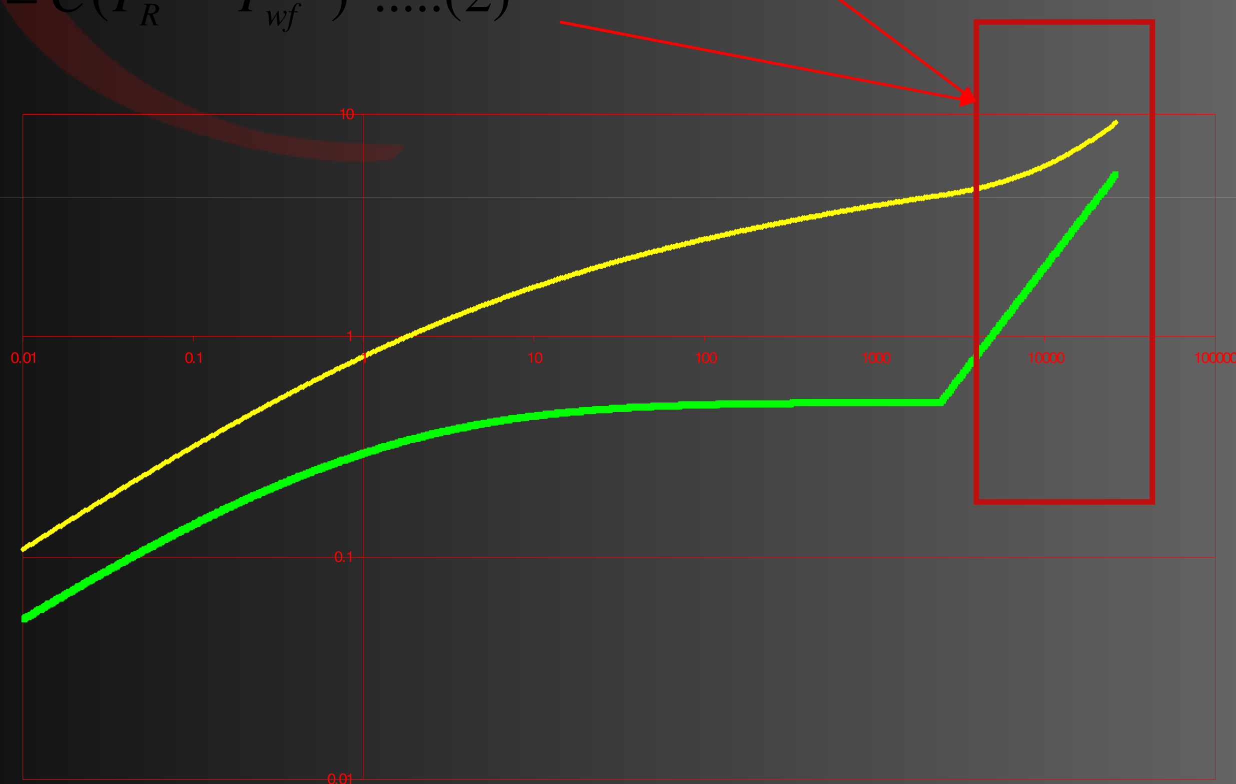
Introduce Normalized Decline

- ***Linearization of the PSS Equation***
  - Linearize the back-pressure equation!
- ***Why:***
  - Visually appealing
  - Can extract OGIP and effective flow parameters (kh)
  - Works for complex reservoirs
  - Suitable for conventional & unconventional gas, 2-phase flow, and even non-linear perm.

What is Stabilized Production? Or PSS?

$$p_D = 2\pi \cdot t_{AD} + \frac{1}{2}\ln\left[\frac{4A}{e^{\gamma} C_A r_w^{\,2}}\right] ......(1)$$

$$q_g = C(P_R^{\,2} - P_{wf}^{\,2})^n .....(2)$$



Back Pressure Equation

$$q_g = C(P_R^{\,2} - P_{wf}^{\,2})^n \;.....(2a)$$

$$q_g = C(\psi_R - \psi_{wf})^n \;.....(2b)$$

Contains
r_e, k, h, skin, C_A, etc

$$C = \frac{kh}{1.417 \cdot 10^6 T_f \left[\ln\left(\frac{re}{rw}\right) - \frac{3}{4} + s + Dq_{sc} \right]}$$

After Some Algebra: Generalized Equation

$$\frac{q_{sc}}{(\psi_i - \psi_{wf})} = \frac{kh}{1.417 \cdot 10^6 \frac{1}{2} \ln\left[\frac{4A}{e^{\gamma} C_A r_w^{\,2}}\right] T_f} + \frac{k \cdot x}{1.417 \cdot 10^6 \frac{1}{2} \ln\left[\frac{4A}{e^{\gamma} C_A r_w^{\,2}}\right] T_f} \frac{(\psi_i - \psi_R)}{(\psi_i - \psi_{wf})} OGIP \ldots\ldots(3)$$

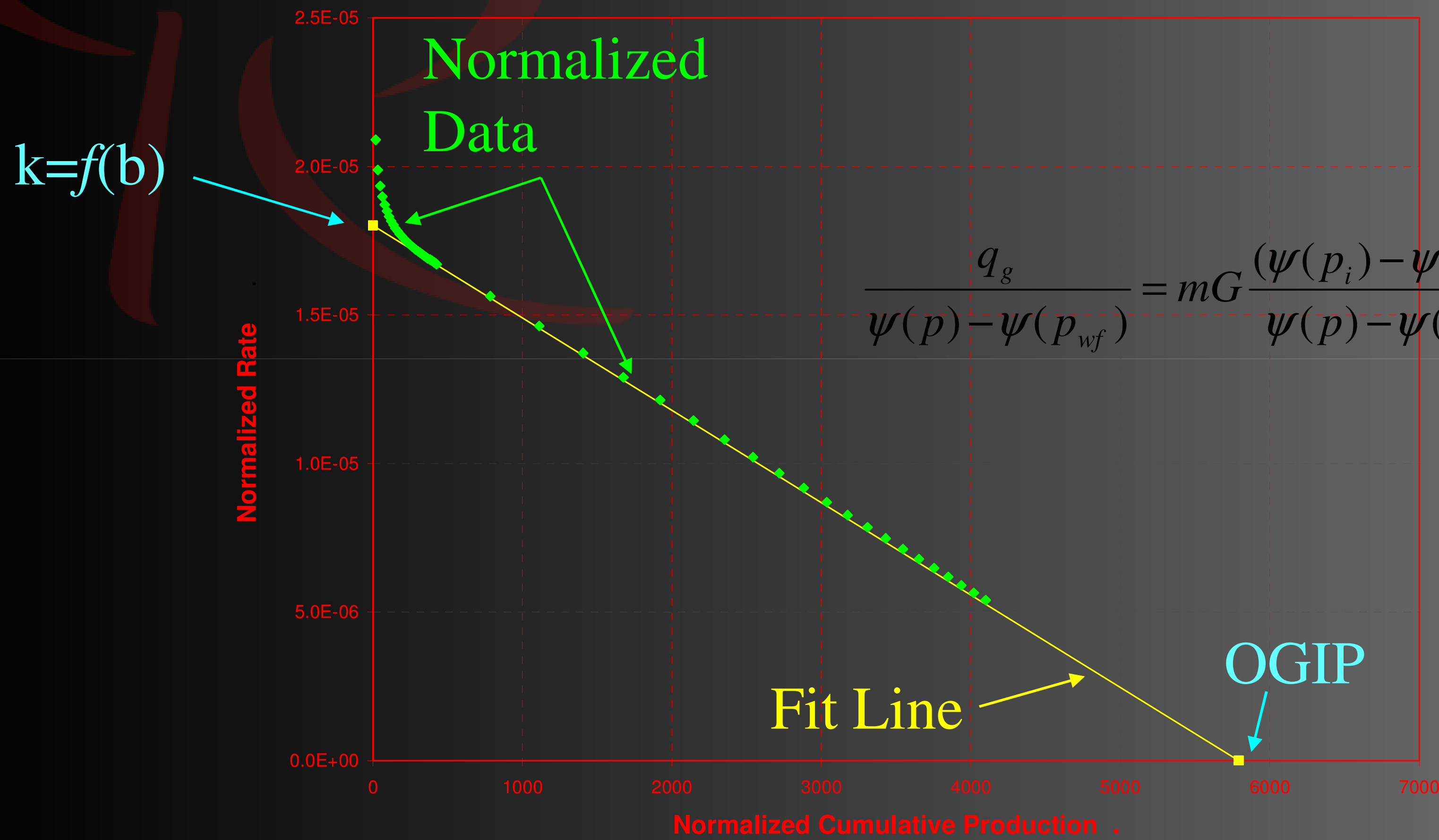
$$\frac{q_{sc}}{(\psi_i - \psi_{wf})} = b + m \frac{(\psi_i - \psi_R)}{(\psi_i - \psi_{wf})} OGIP \ldots\ldots(4)$$

$$b = f(k)$$

$$\frac{q_{sc}}{(\psi_i - \psi_{wf})} = 0; x = OGIP$$

*Note: Turbulence Ignored

Schematic of Normalized Decline



$$\frac{q_g}{\psi(p)-\psi(p_{wf})} = mG\frac{(\psi(p_i)-\psi(p_R))}{\psi(p)-\psi(p_{wf})} + b$$

Agarwal / Gardner / Mattar

Implications of General Equation

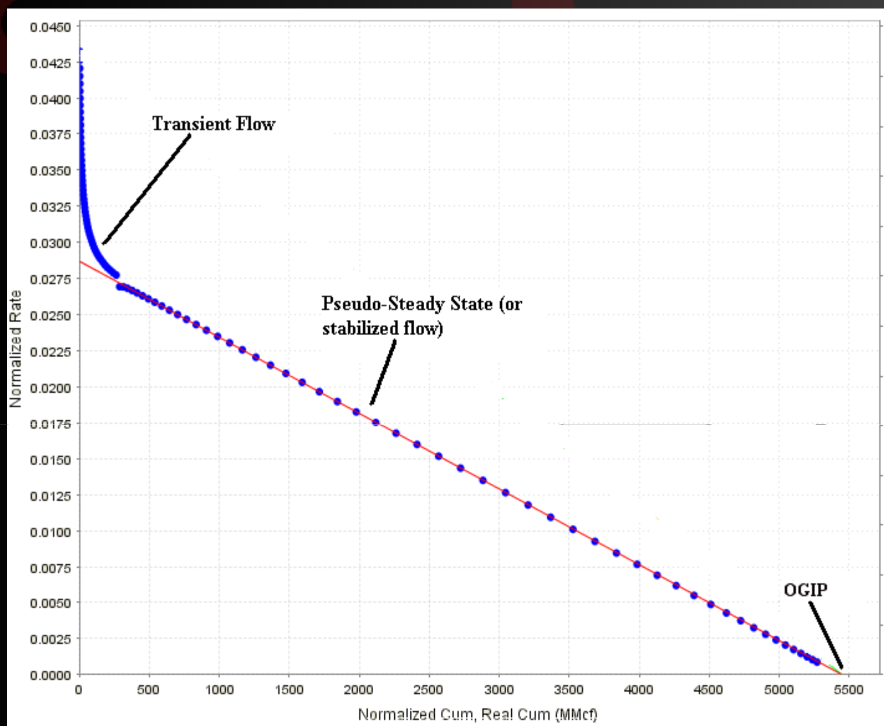
$$\frac{q_{sc}}{(\psi_i - \psi_{wf})} = \frac{k \cdot h}{1.417 \cdot 10^6 \frac{1}{2} \ln\left[\frac{4A}{e^{\gamma} C_A r_w^{\,2}}\right] T_f} + m \frac{(\psi_i - \psi_R)}{(\psi_i - \psi_{wf})} OGIP$$

Y-Intercept is Constant:
Interchange k, A, h, C_A, r_{wa}

Result:
Equivalent Reservoir Perm.
Assume C_A =31.62, s =0

Non-Volumetric Res:
Aquifer Support
Single Phase CBM
Shale Gas & More!

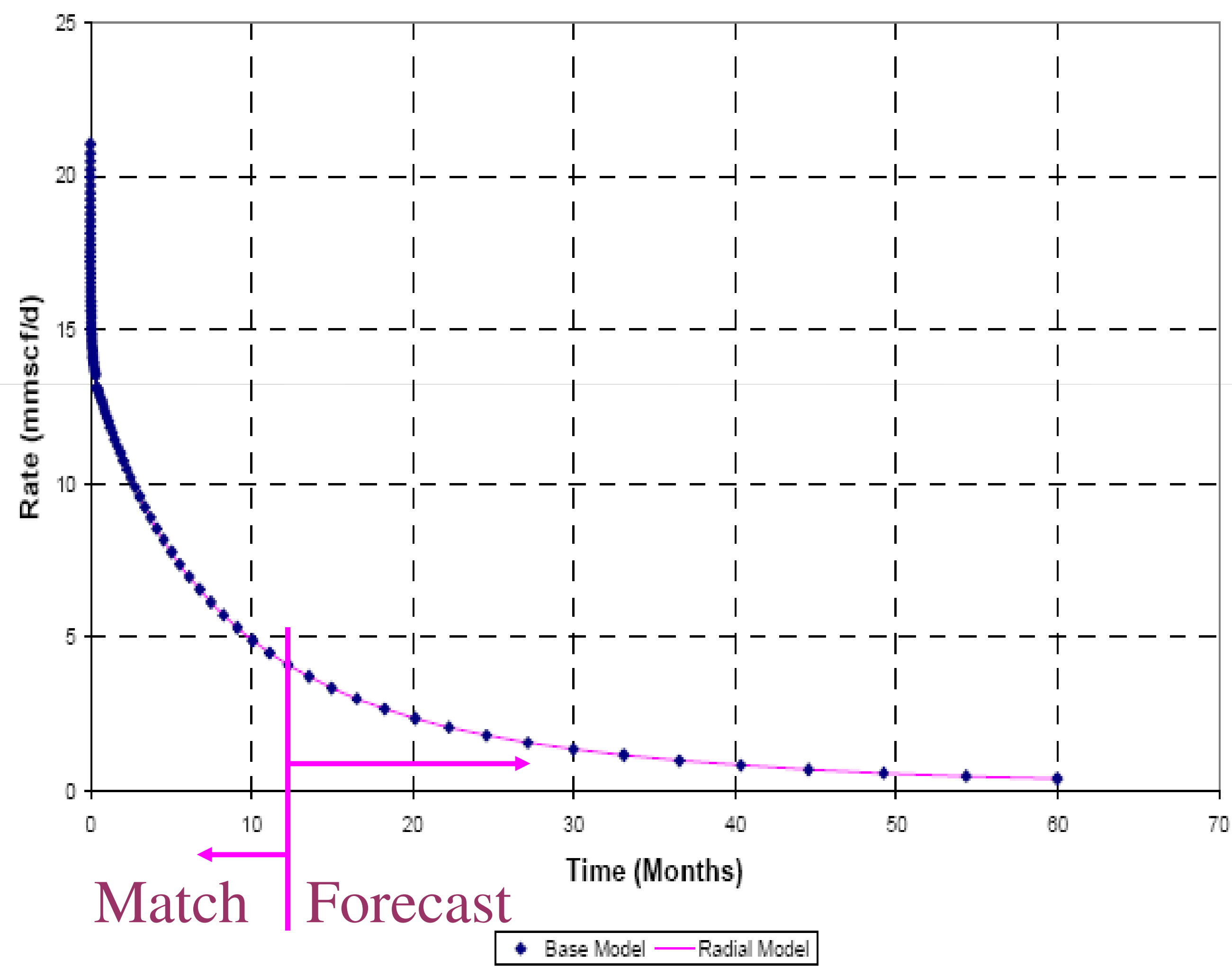
Simulated Example



Base IGIP	5.4 Bcf
Base Drainage Area	640 Acres (72 Acre Hole)
Base Perm.	20 md
Calc. IGIP	5.4 Bcf
Calc. Area	570 Acres (≈640-72)
Calc. Perm	16 md

$$\frac{q_{sc}}{(\psi_i-\psi_{wf})}=\frac{k\cdot h}{1.417\cdot 10^6\frac{1}{2}\ln\left[\frac{4A}{e^{\gamma}C_A r_w^{\ 2}}\right]T_f}+m\frac{(\psi_i-\psi_R)}{(\psi_i-\psi_{wf})}OGIP$$

Rate Forecast Comparison



Additional Simulated Cases!(CIM 2005-030)

	Property	Max Error in OGIP (%)	PSS Prod Match
Composite	Mobility	<2.5%	☺
Natural Fractures	λ, ω	<2.5%	☺
Homo. Variable Skin	skin	<0.5%	☺
Horizontal Well	L_w	< 2 %	☺
Hydraulic Frac	x_f finite / Infinite	<1%	☺

Results Thus Far!

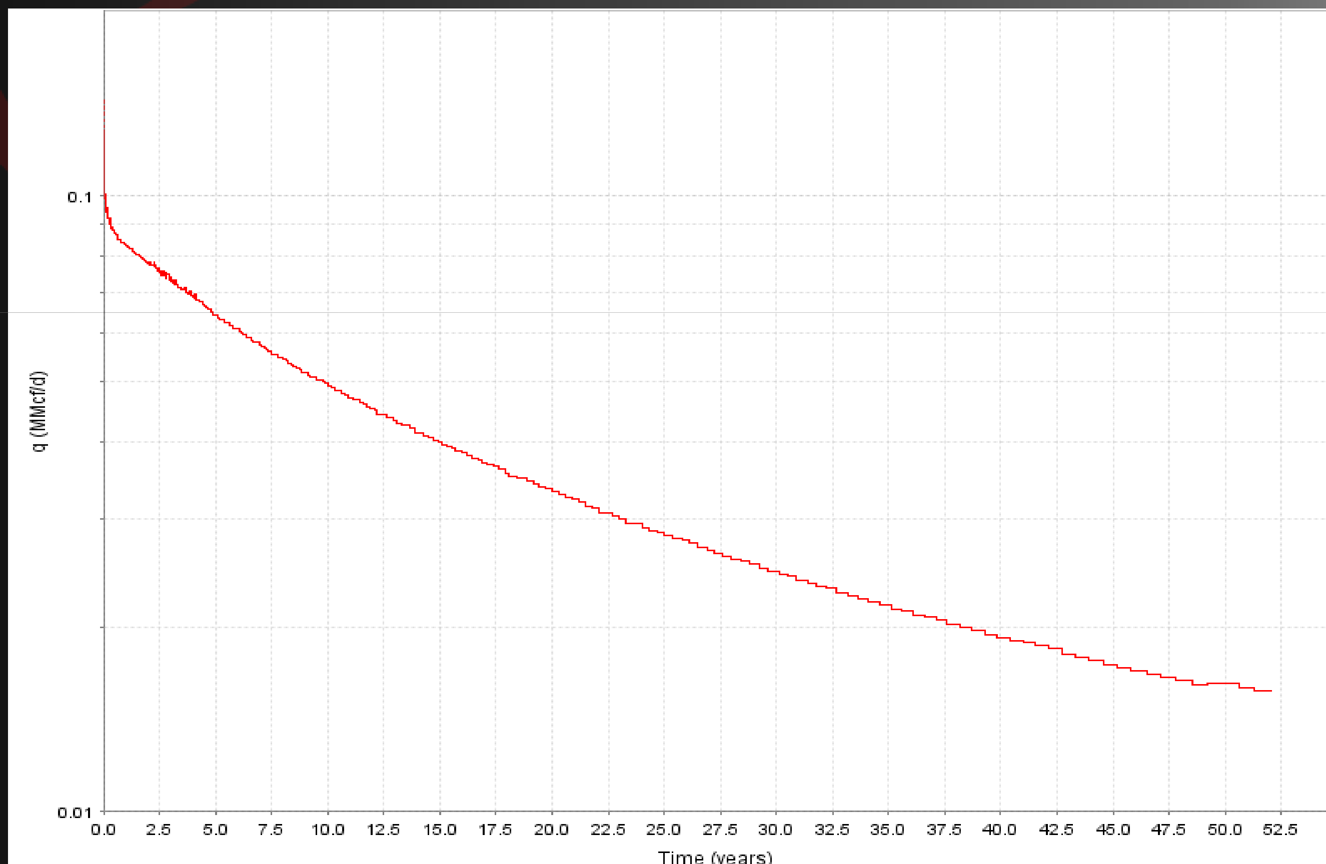
- ***Using Normalized Decline***
  - OGIP can be extracted easily
  - Average effective permeability is calculated
  - Complex reservoirs reduced to simpler ones
  - Long-term deliverability forecasts are accurate
- ***What About CBM? Shale? Etc.***
- ***Let's look At Some Case Studies***

Single Phase CBM

- ***Simulated Example***
  - V_L = 250 scf/ton
  - P_L = 661 psia
  - OGIP = 1.6 Bcf
  - Perm = 0.5 md

- ***Clarkson & McGovern "A New Tool for Unconventional Reservoir Exploration & Development Applications"***

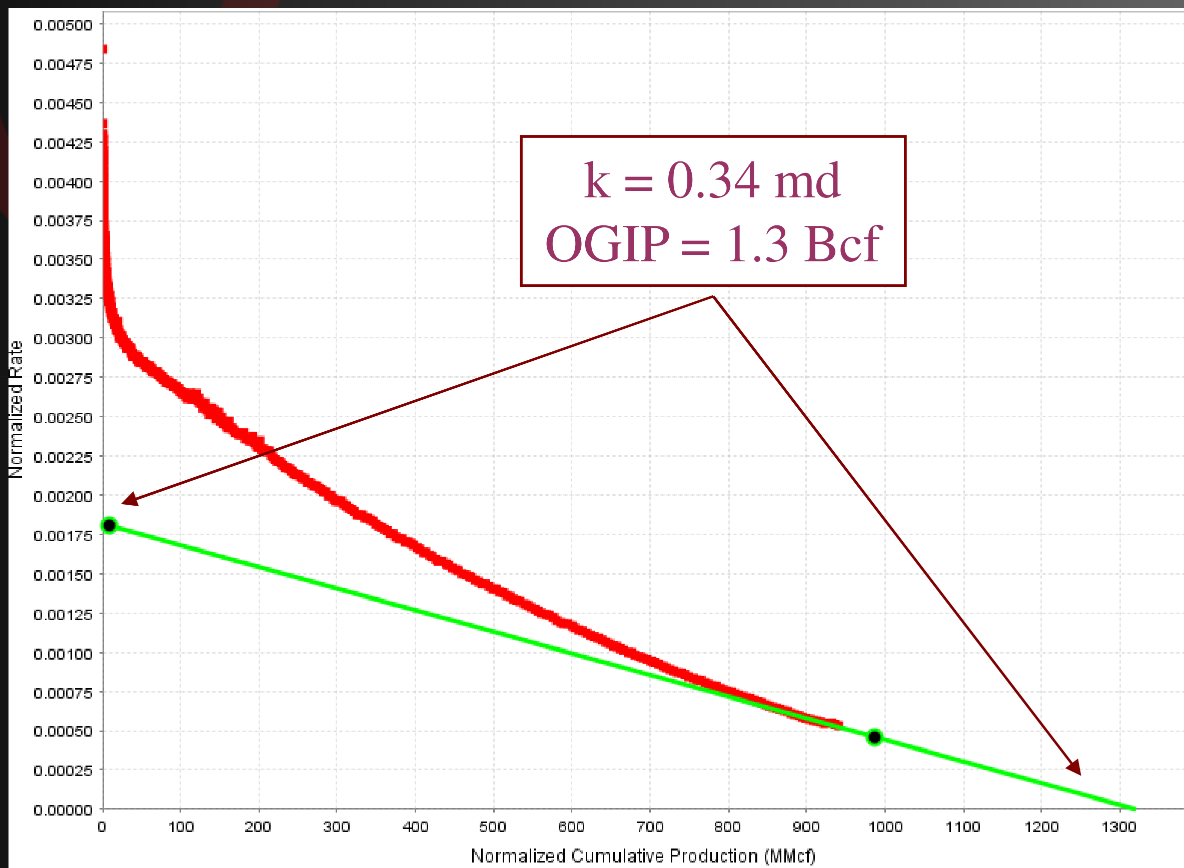
Raw Data for Clarkson Example



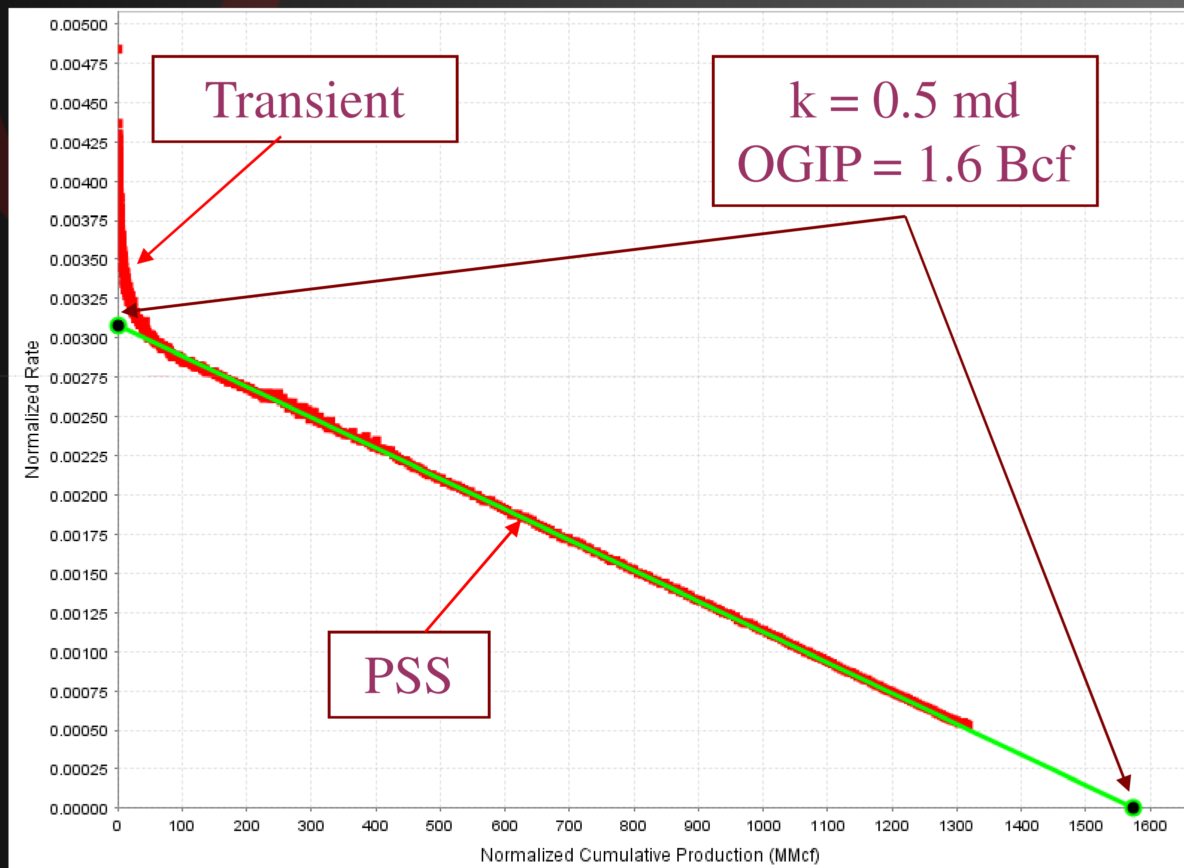
Review The Problem

- ***What Do We Want?***
  - Reserves
  - Future Deliverability
- ***What Do We Do?***
  - Numerical Simulation?
  - Decline?
  - Pressure Transient Analysis?
- ***Conditions***
  - Quick & Reliable

Simulated CBM Example



Simulated CBM Example



How Did We Get This to Work?

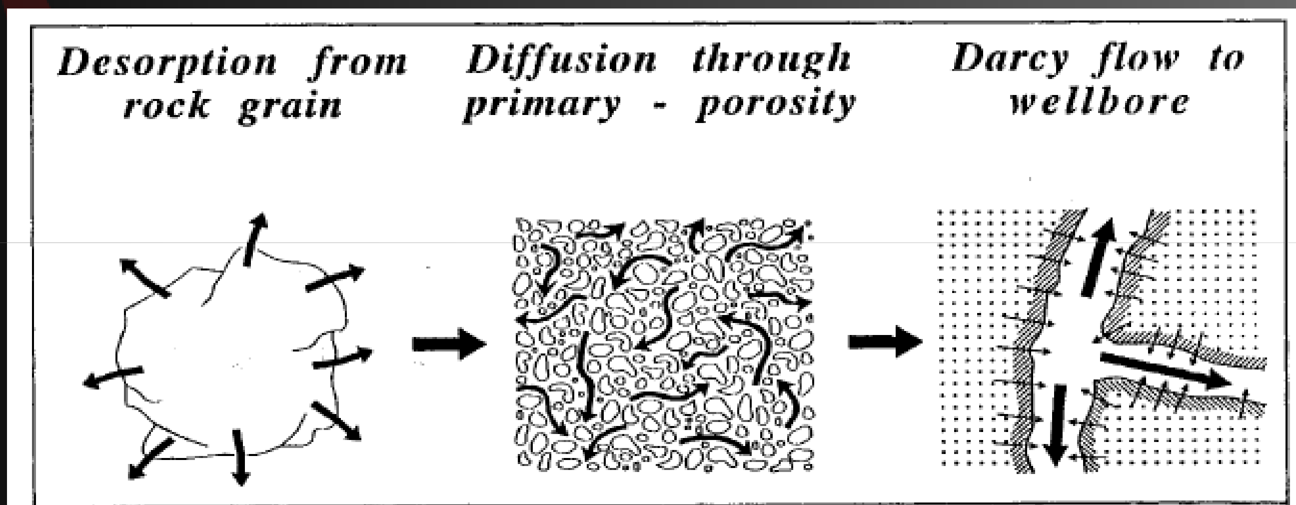
Adjusting for Single Phase Coal

$$\frac{q_{sc}}{(\psi_i - \psi_{wf})} = \frac{k \cdot h}{1.417 \cdot 10^6 \frac{1}{2} \ln\left[\frac{4A}{e^{\gamma} C_A r_w^{\ 2}}\right] T_f} + m \frac{(\psi_i - \psi_R)}{(\psi_i - \psi_{wf})} OGIP$$

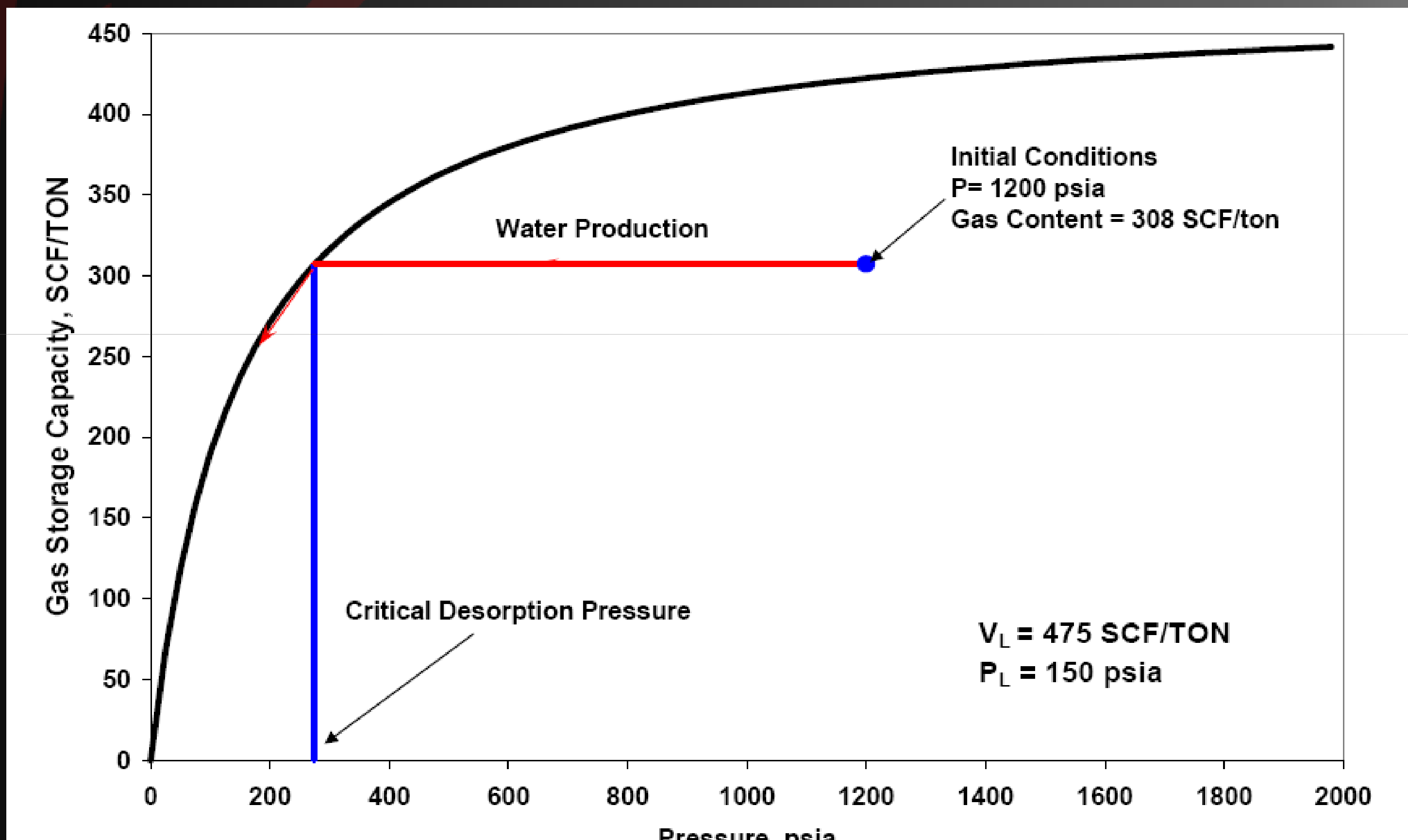
Modify Material Balance to Account for Absorbed Gas in Coal/Shale

King/Seidle/Cooper/Others

CBM Material Balance



Typical Isotherm!



Answers Provided

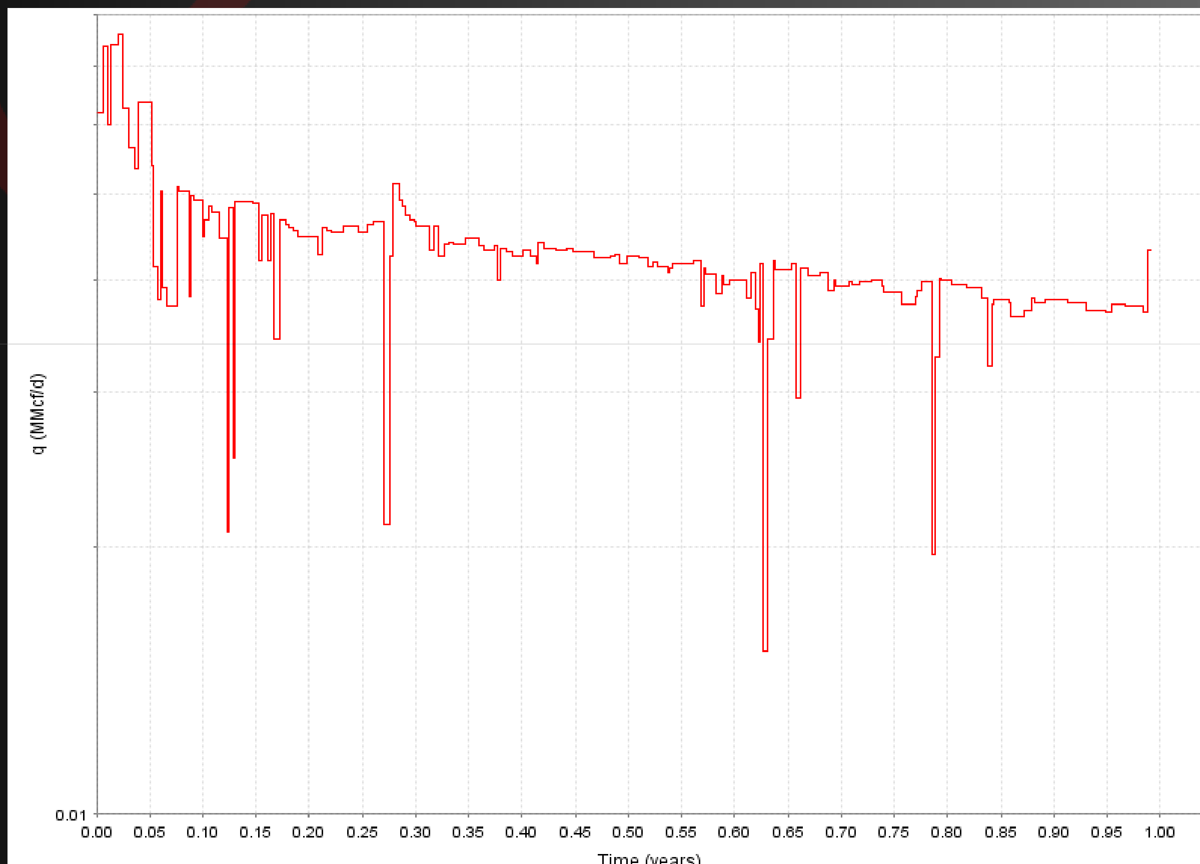
- ***Reservoir Characterization***
  - Average Effective Perm & Drainage Area
- ***Reserves Analysis***
  - OGIP vs Cum. Production (Current Recovery)
- ***Future Deliverability***
  - Expected Rates, Stimulation vs. Compression

1P HSC Coals

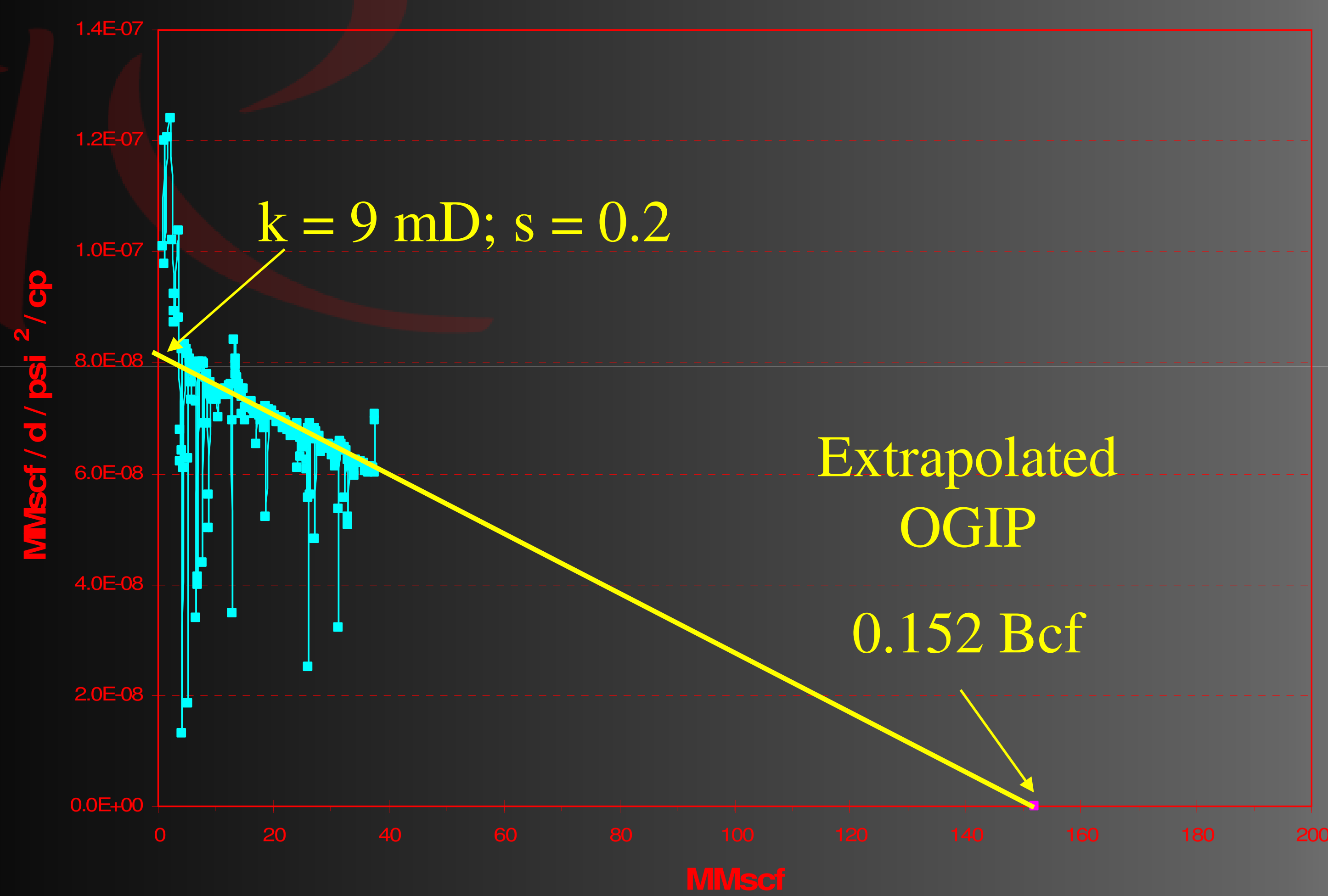
Clarkson / Seidle / Bustin (SPE 100313)

- Drainage Area: 80 Ac
- Net Pay: 50 ft
- Φ: 0.1 %
- Langmuir: 155 scf/ton, 547 psia
- Bulk Density: 1.33 g/cc
- P_{wf} = 20 – 25 psia; Pi = 86
- IGIP (Volumetric): 152 MMscf
- k: 9 mD

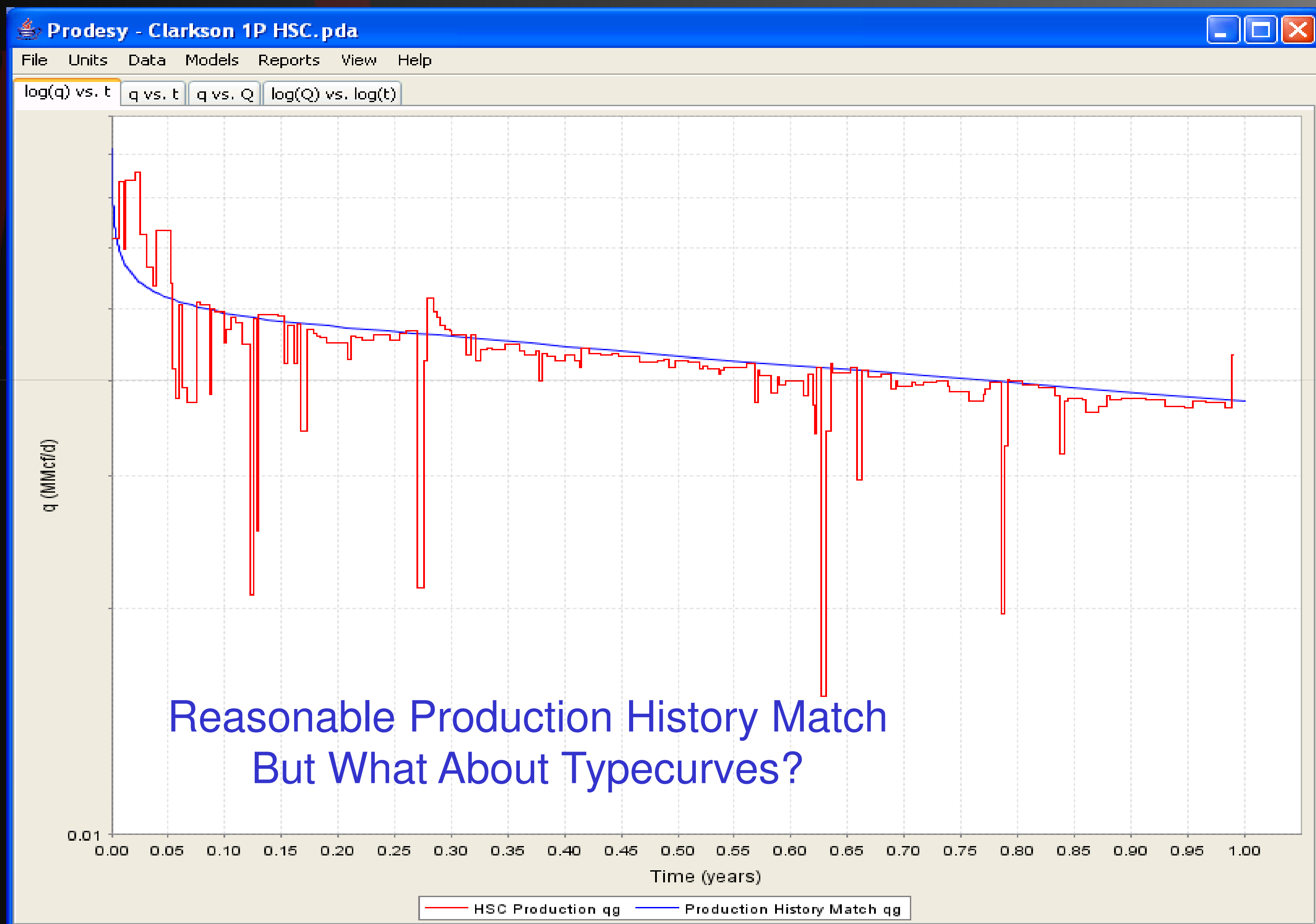
Raw Data for Clarkson et al



1P HSC Coals: Normalized Decline



1P HSC Coal: Production Match



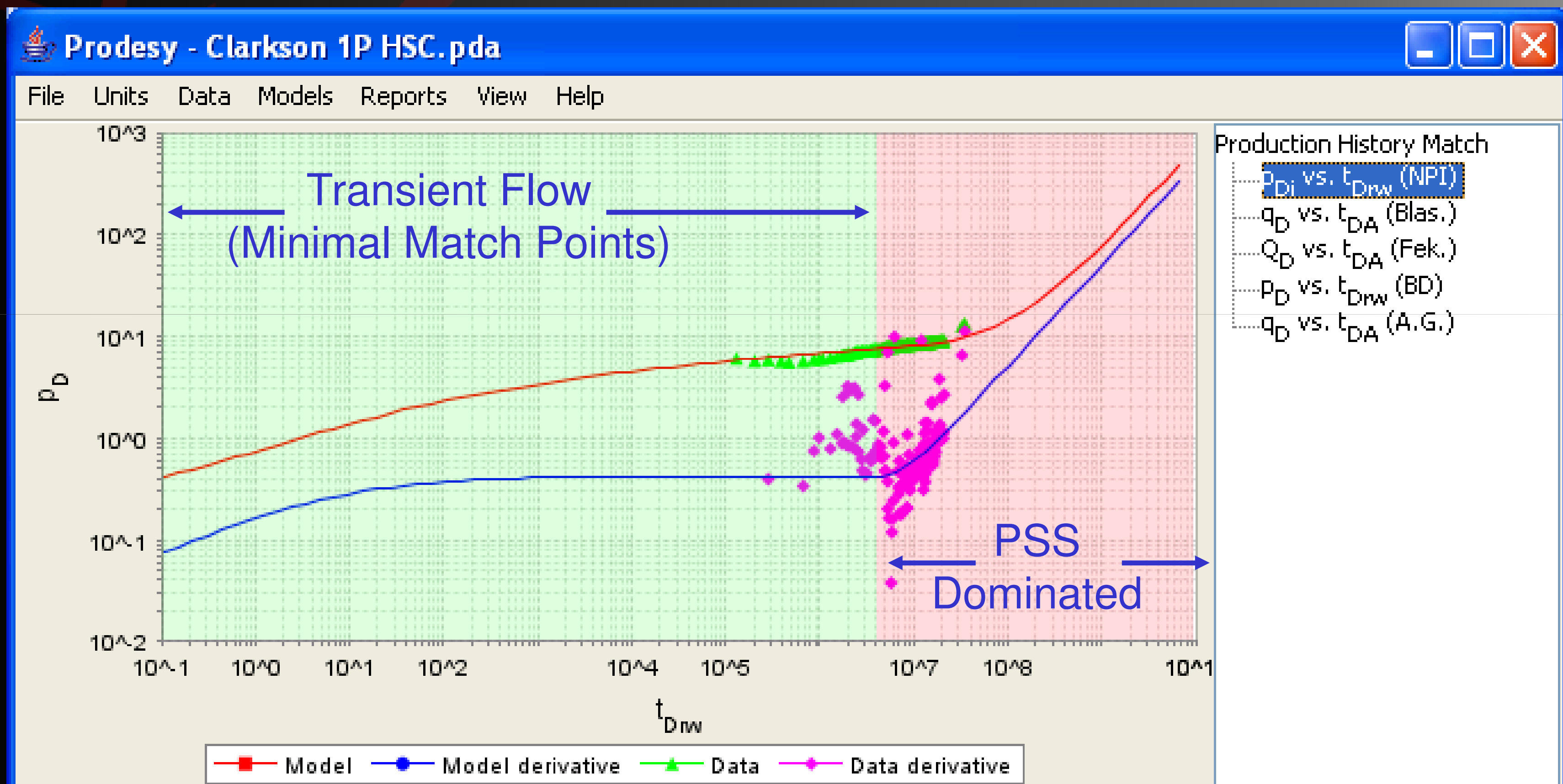
Using Conventional Typecurves

- *Modify "Pseudo Time" To Account for Absorbed Gas*
- *Use "Material Balance Time" For Variable Rate*

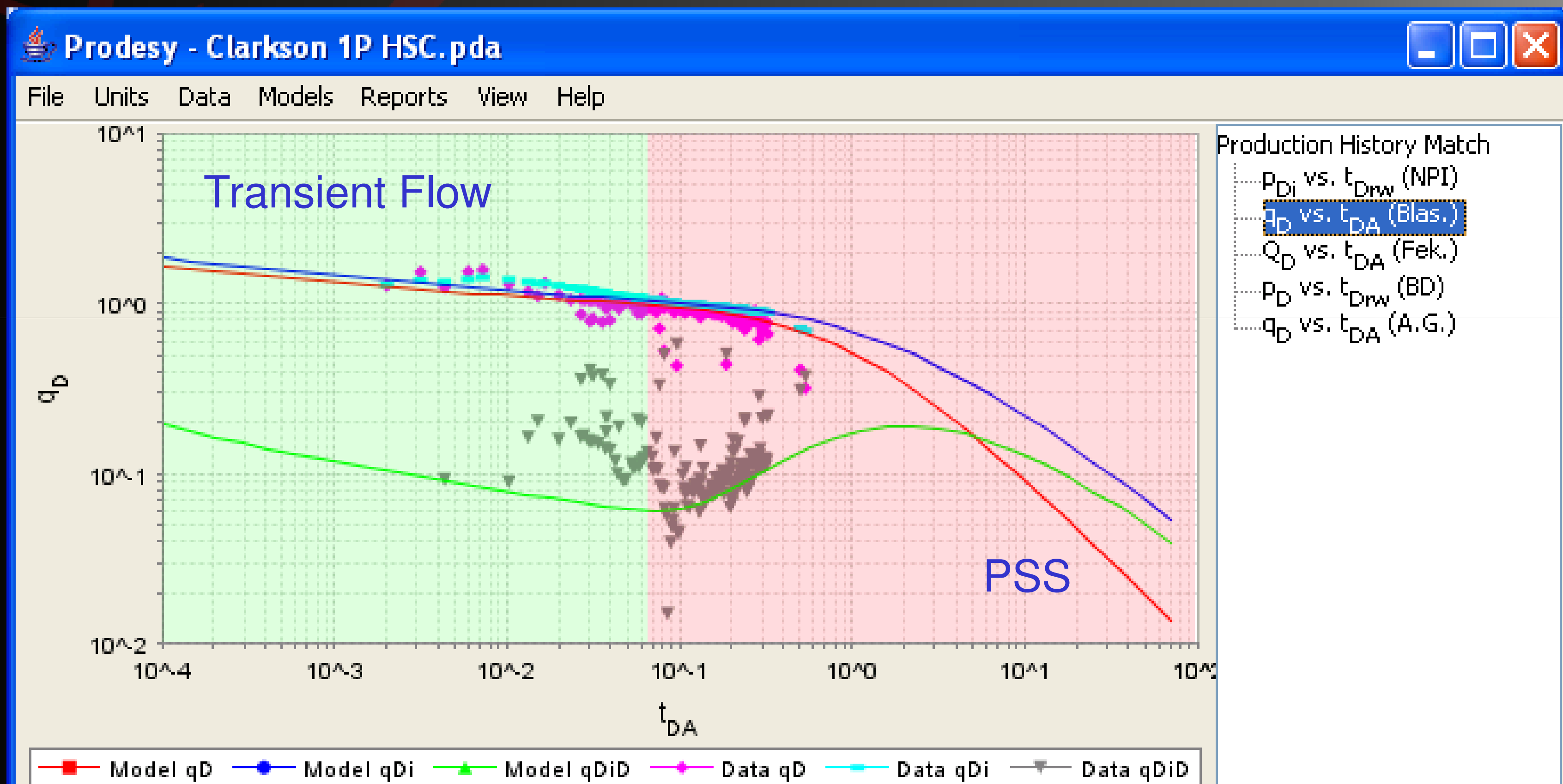
$$t_a = \int_0^t \frac{\dfrac{1}{\overline{u}\left(\overline{c_g} + \overline{c_f} + \overline{c_d}\right)}}{q(t)} \partial t$$

$$c_d = \frac{B_g \rho_c V_L P_L}{32.0368 (P_L + P)^2 \phi}$$

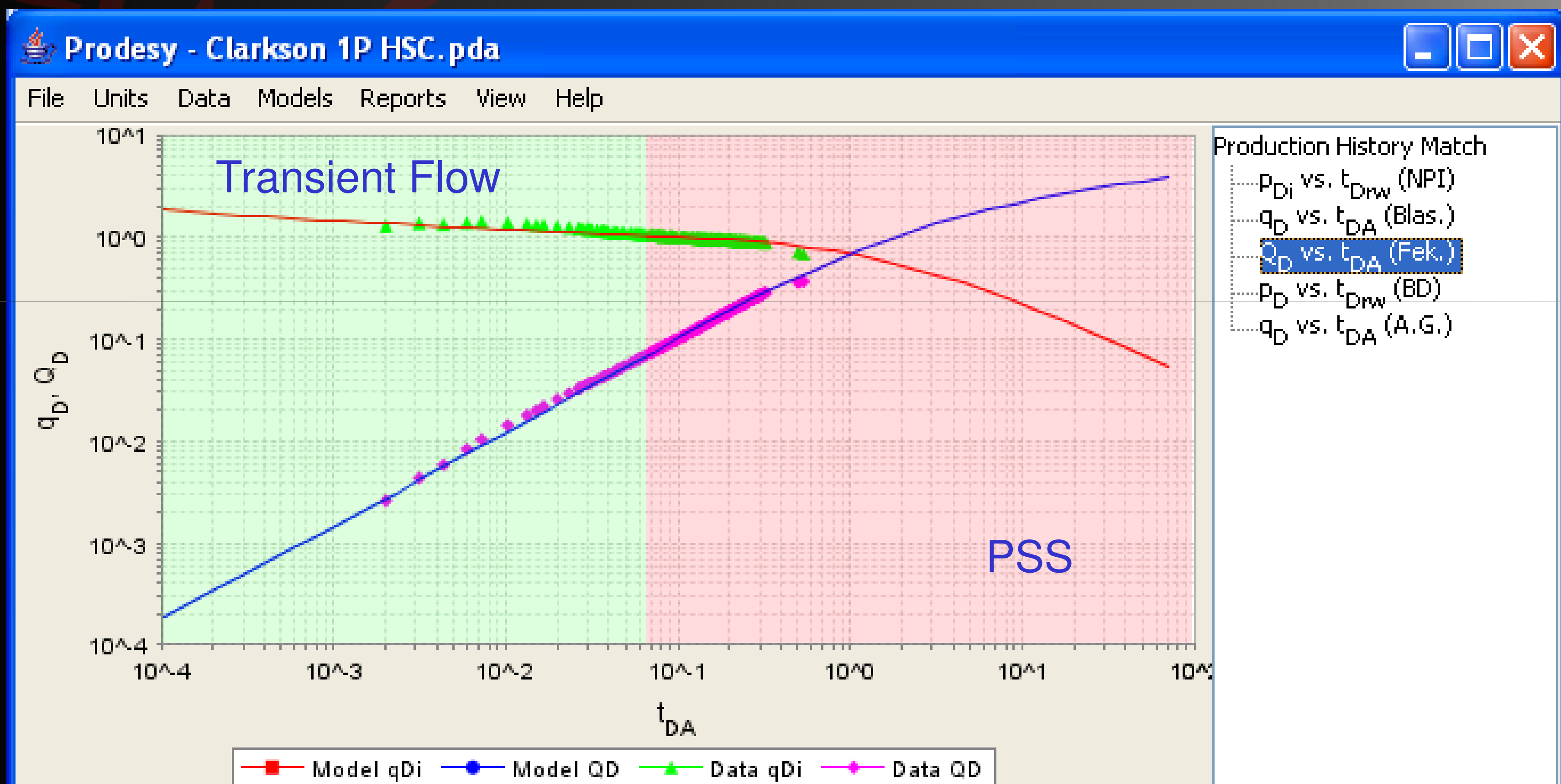
1P HSC Coals: NPI Derivative



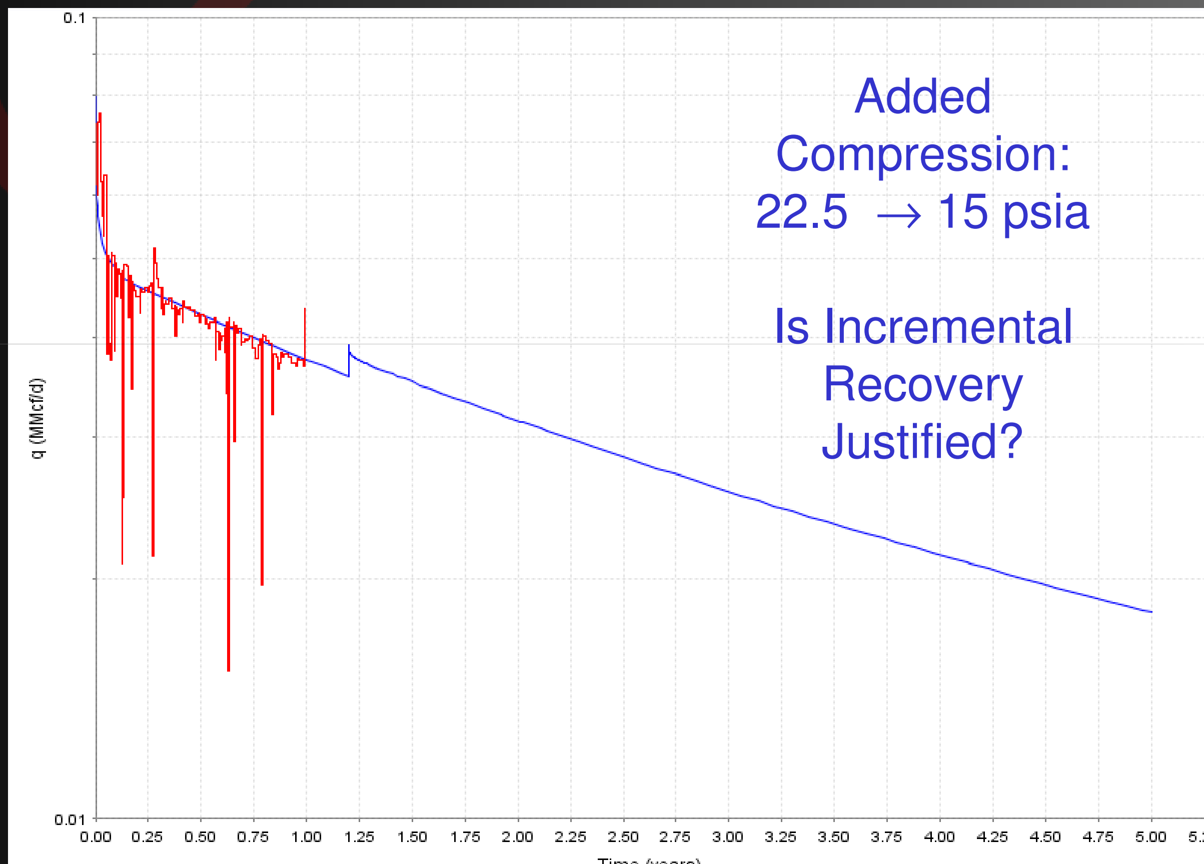
1P HSC Coals: Blasingame Typecurve



1P HSC Coals: Fetkovich Typecurve



Modeling Compression



What About More Complex Cases?

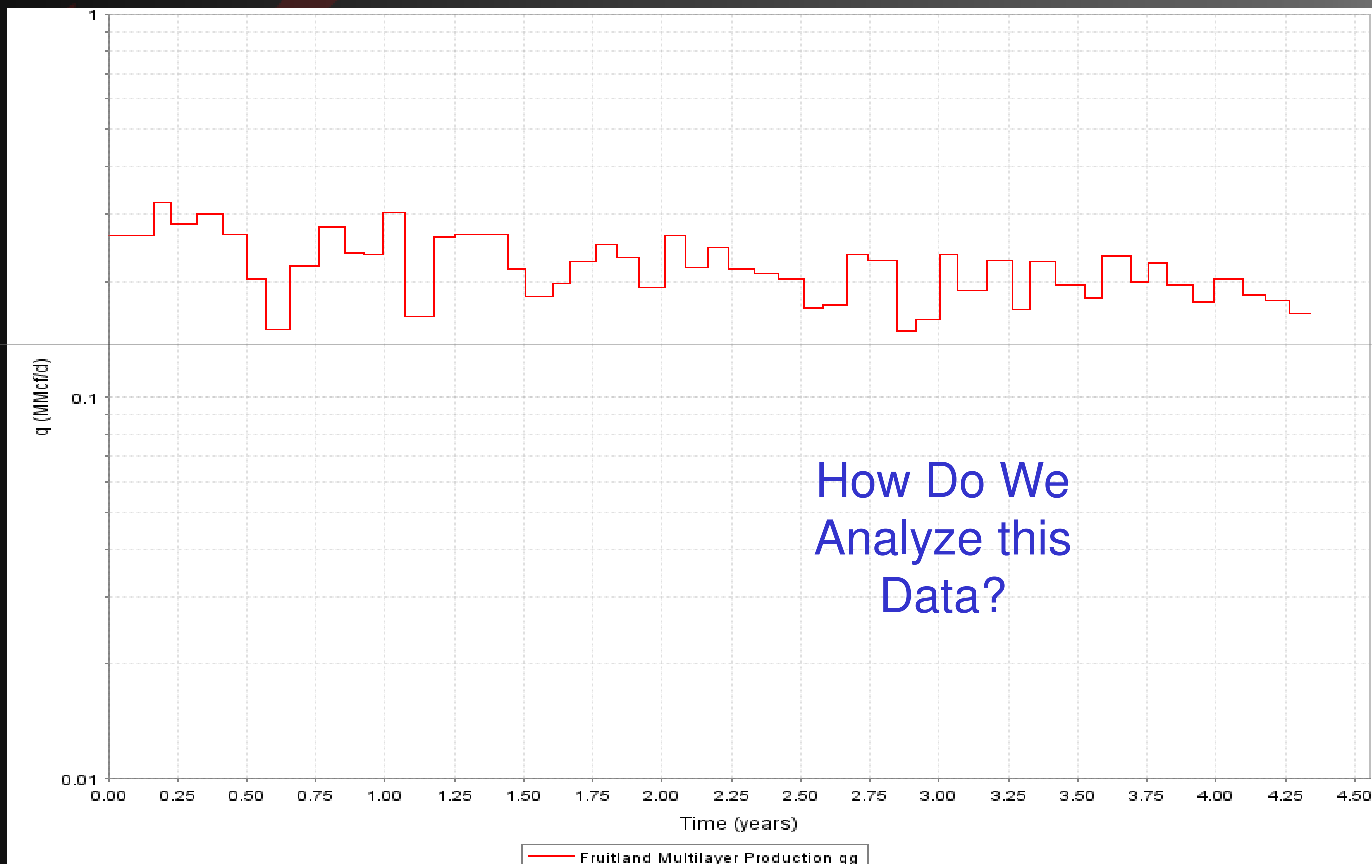
- ***Layered Reservoirs?***
- ***Commingled Reservoirs?***
- ***Lots of Industry Activity:***
  - Horseshoe Canyon / Ardley Coals
- ***Will our Technology Work?***

1P Multilayered Fruitland Coals

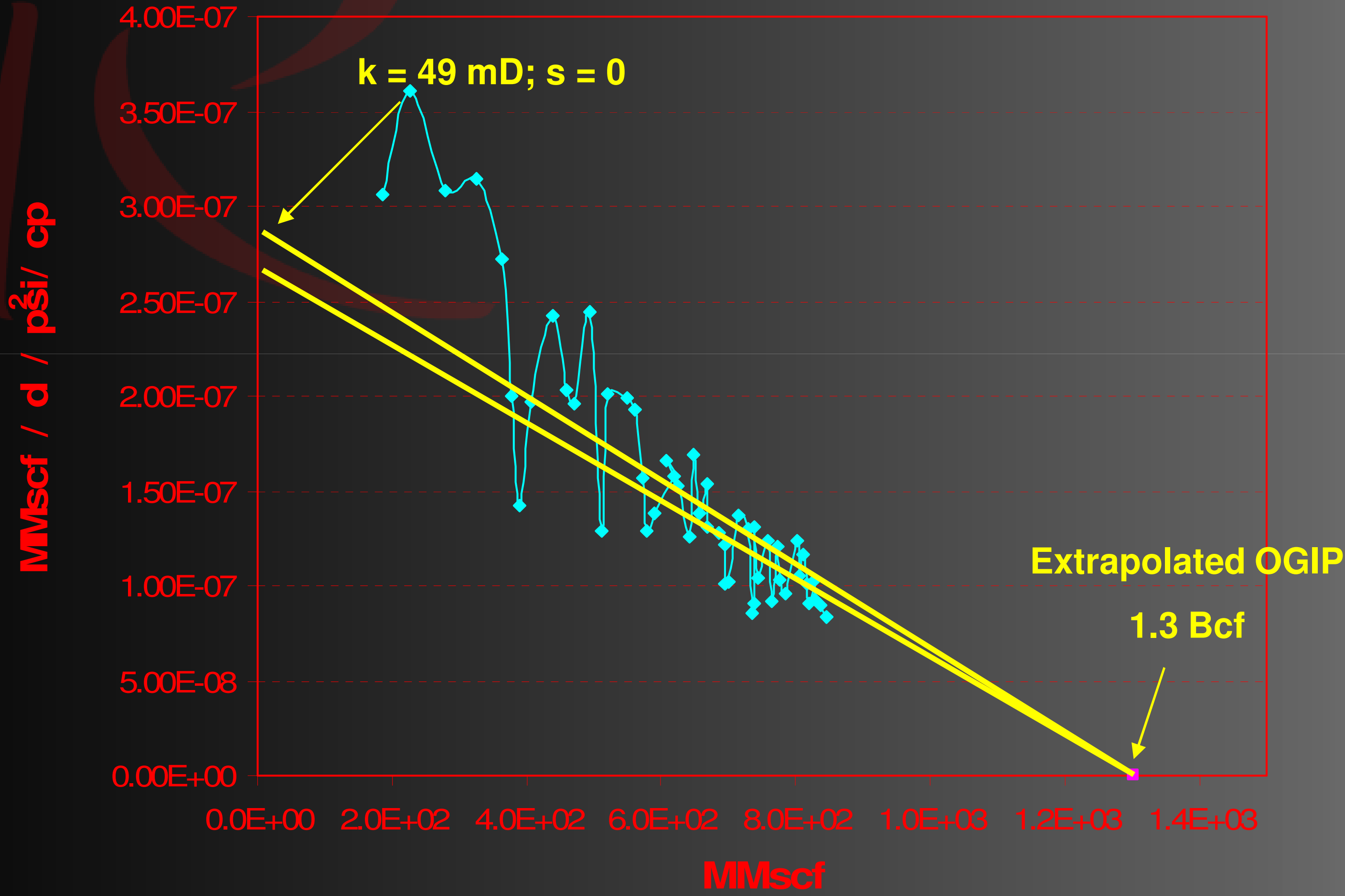
Clarkson / Bustin / Seidle (SPE 100313)

- ***Drainage Area: 320 Ac***
- ***2 Coal Layers***
- ***Net Pay: 35 ft (18 ft, 17 ft)***
- ***Φ: 1 %***
- ***Langmuir: 334 scf/ton, 823 psia***
- ***Bulk Density: 1.44 g/cc***
- ***IGIP (Volumetric): 1.3 Bscf***
- ***k: 48 mD (55 mD, 41 mD)***

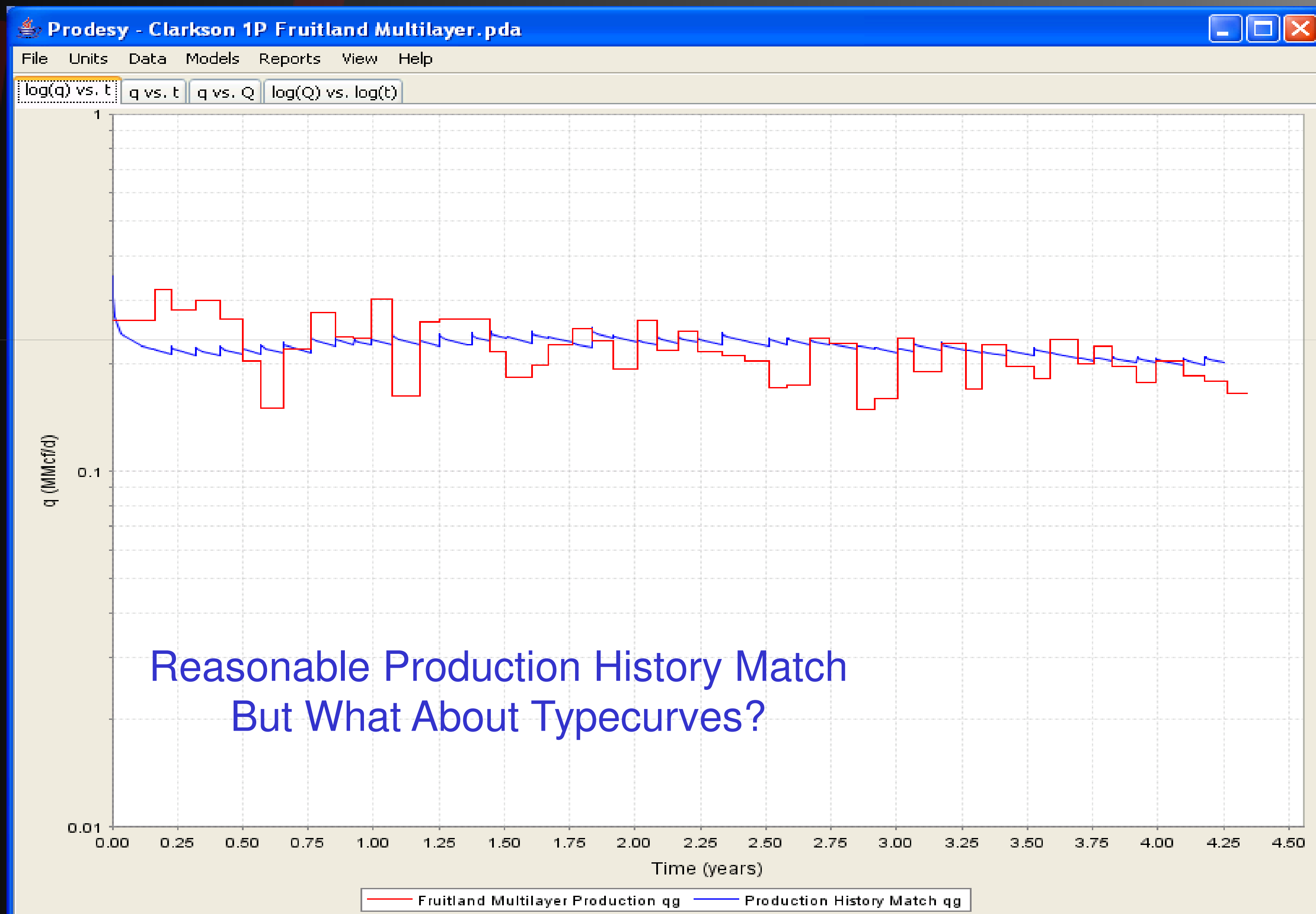
Raw Data for Clarkson et al



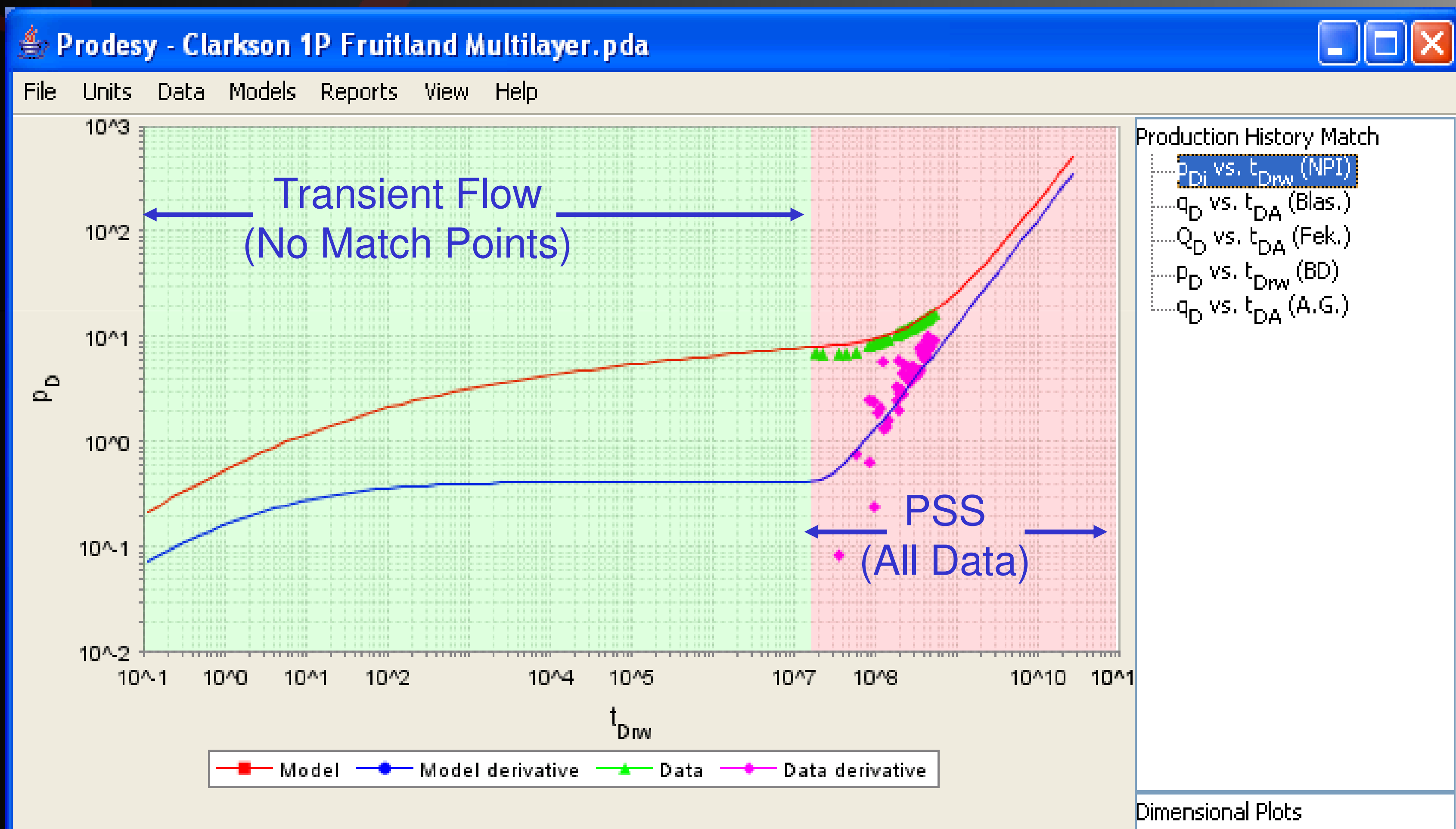
Layered Fruitland Coal: Normalized Decline



1P Multilayered Fruitland Coals



1P Multilayered Fruitland Coals: NPI Derivative

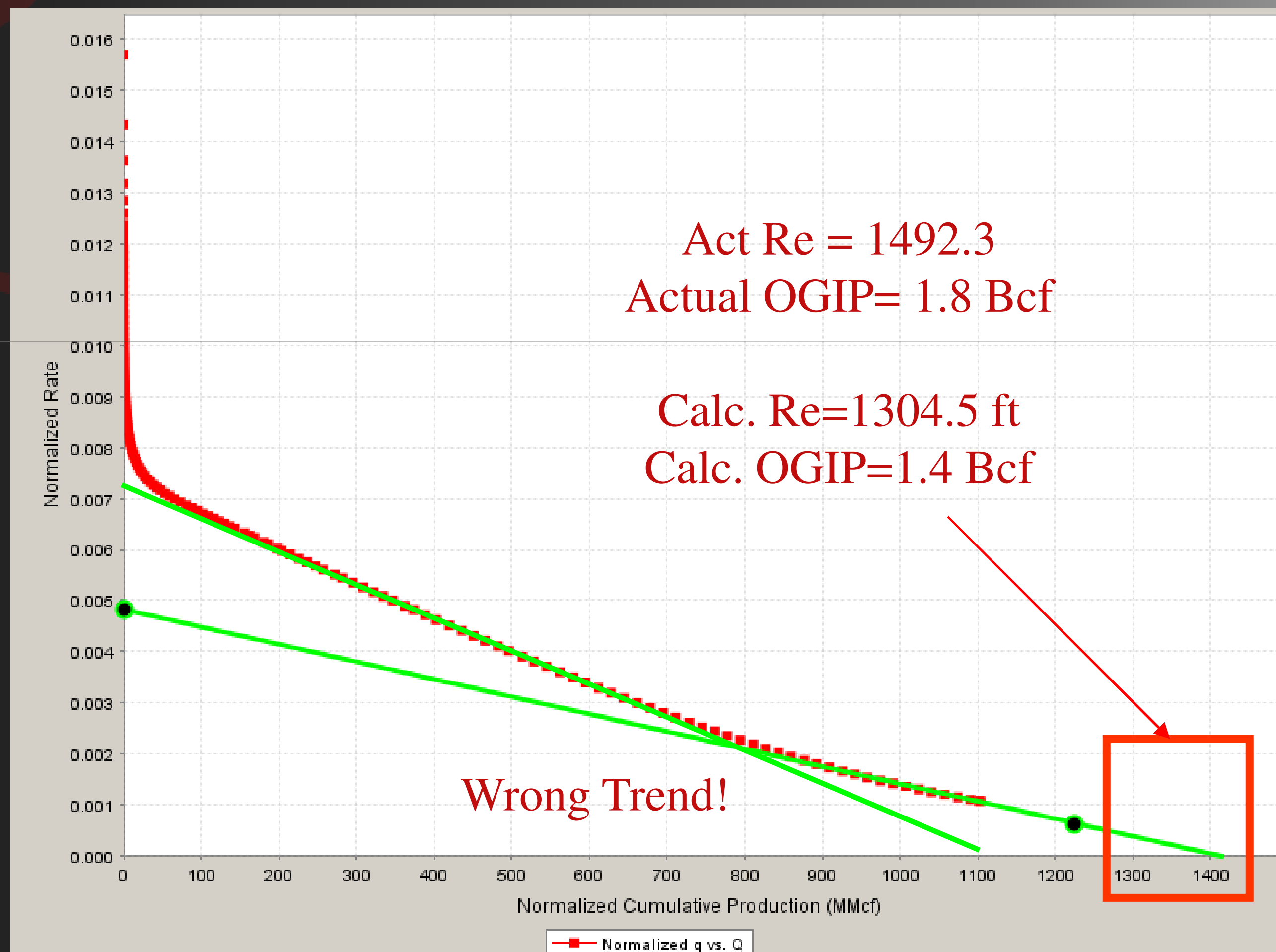


Speaking of Layered Reservoirs

- ***Study Has Some Limitations***
  - It appears that this method can be mis-leading in some layered scenarios

2 Layer Model: Normalized Decline

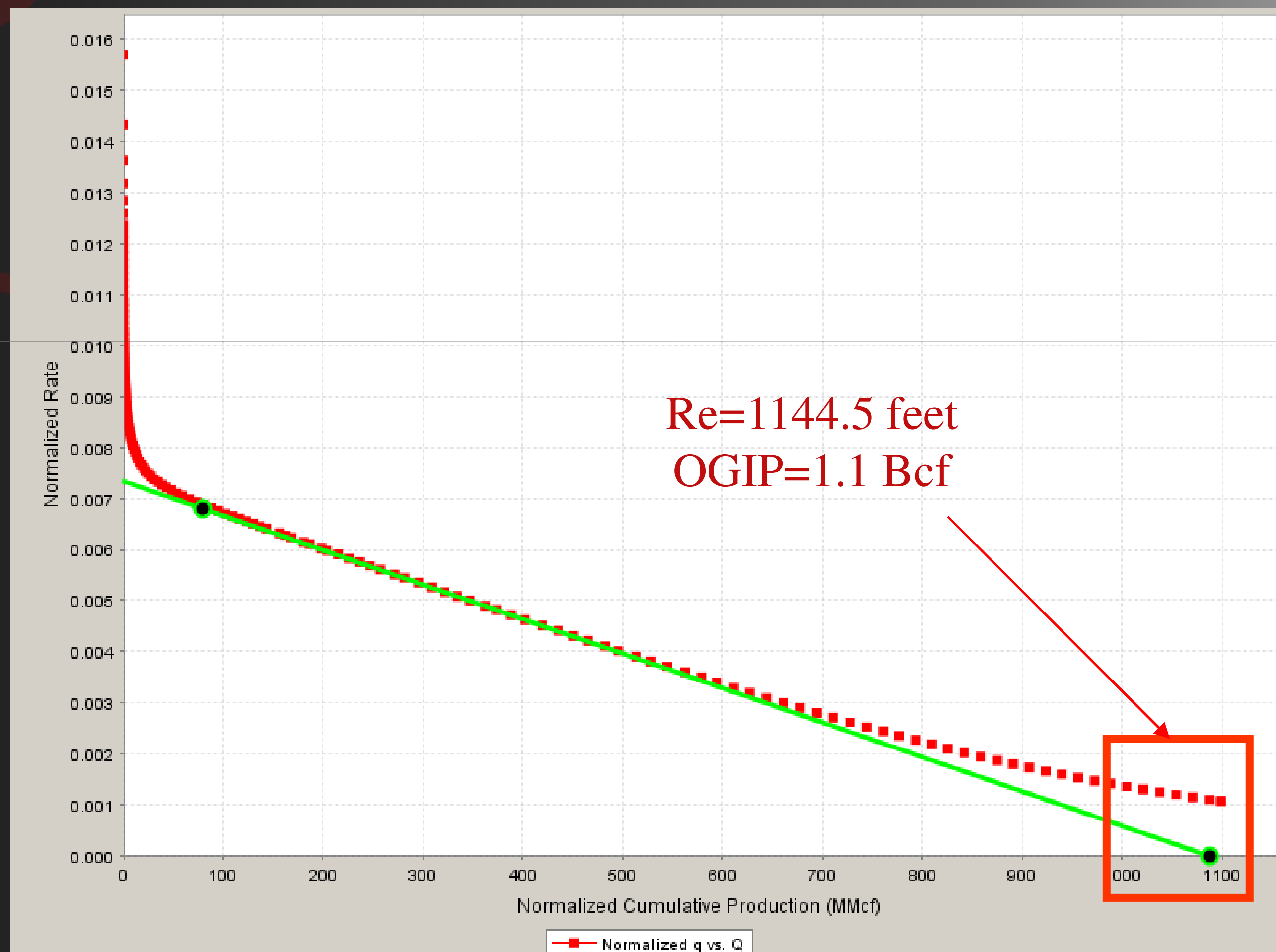
k1=10 md
k2=1 md
h1=5 ft
h2=5 ft



2 Layer Model: Normalized Decline

k1=10 md
k2=1 md
h1=5 ft
h2=5 ft

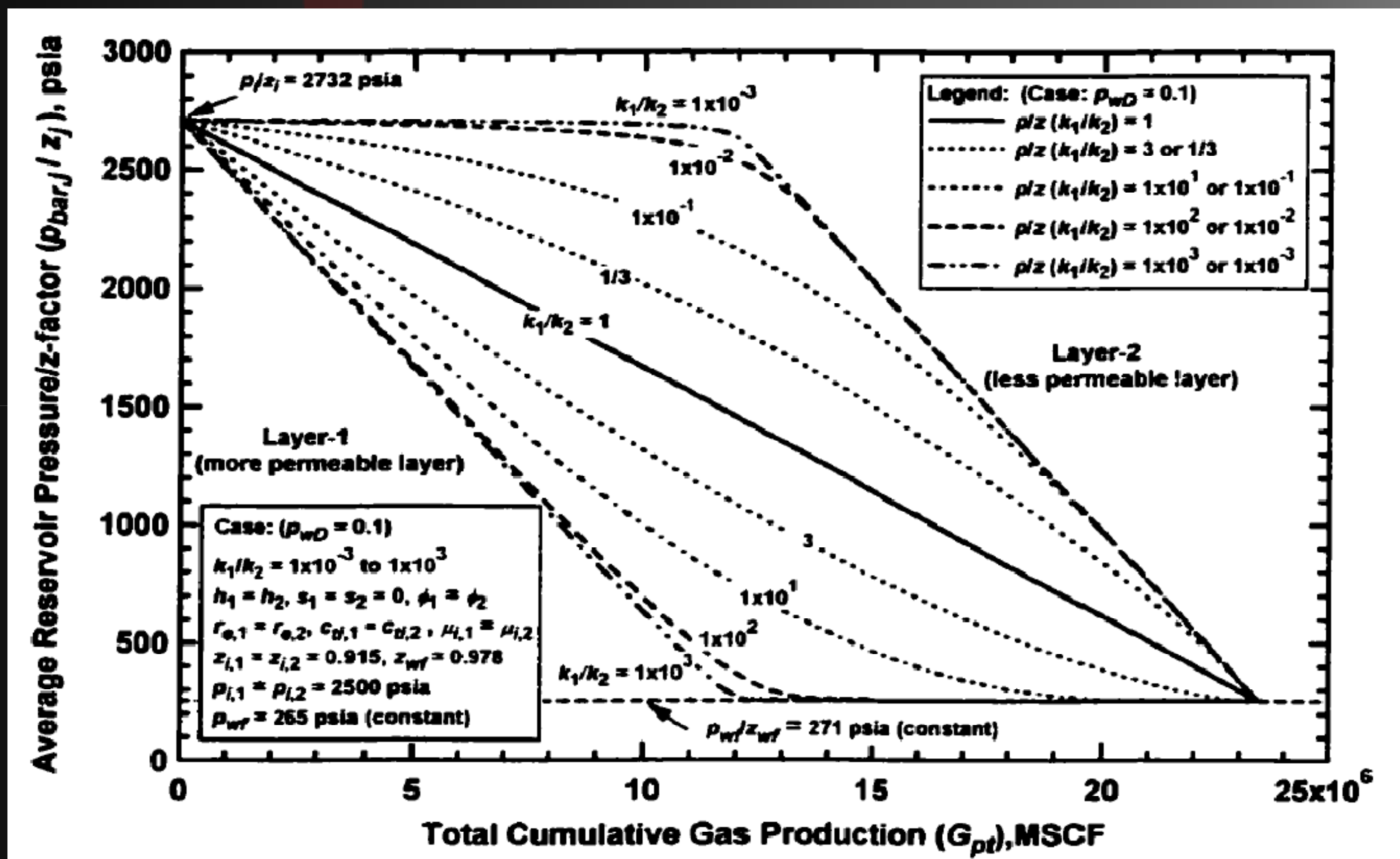
Layer 1 = 0.9 Bcf
Layer 2 = 0.9 Bcf



What Could Possibly Be The Problem?

- ***Differential Depletion***
  - P_{avg} in Norm. Decline is based on OGIP for both zones
  - However, each zone depletes at a different rate
  - During different stages of the well's life, it may be more appropriate to use individual layer P_{avg}, not the global P_{avg}

P/z: 2 Layer System



Source: "Analysis of Layered Gas Reservoir Performance Using a Semi-Analytical Solution for Rate and Pressure Behavior". Ph. Thesis, I. Nengah Suabdi

Basic Reservoir Parameters (Layered Simulation)

Permeability K1 (mD)	Permeability K2 (mD)	Net Pay 1 (Feet)	Net Pay 2 (Feet)
5	5	5	5
10*	***1****	***5***	***5***
10	1	10	1
10*	***1****	***1***	***10***
5	5	1	10
5	4	5	5
5	4	5	4
5	4	4	5
5	5	5	4
0.1*	***0.001****	***1***	***10***
0.1*	***0.001****	***10***	***1***

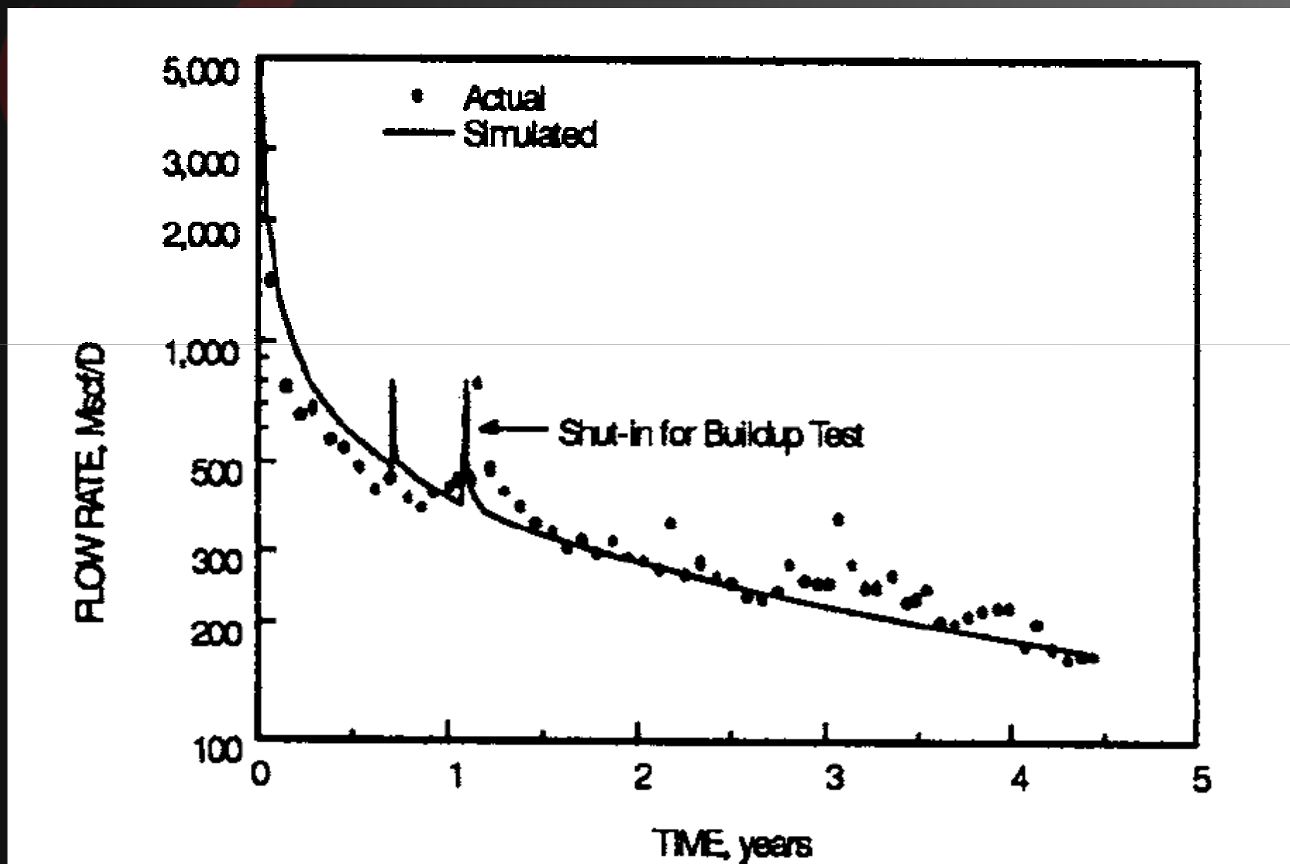
* Indicates Problems with Normalized Decline Approach

Barnett Shale Gas Example

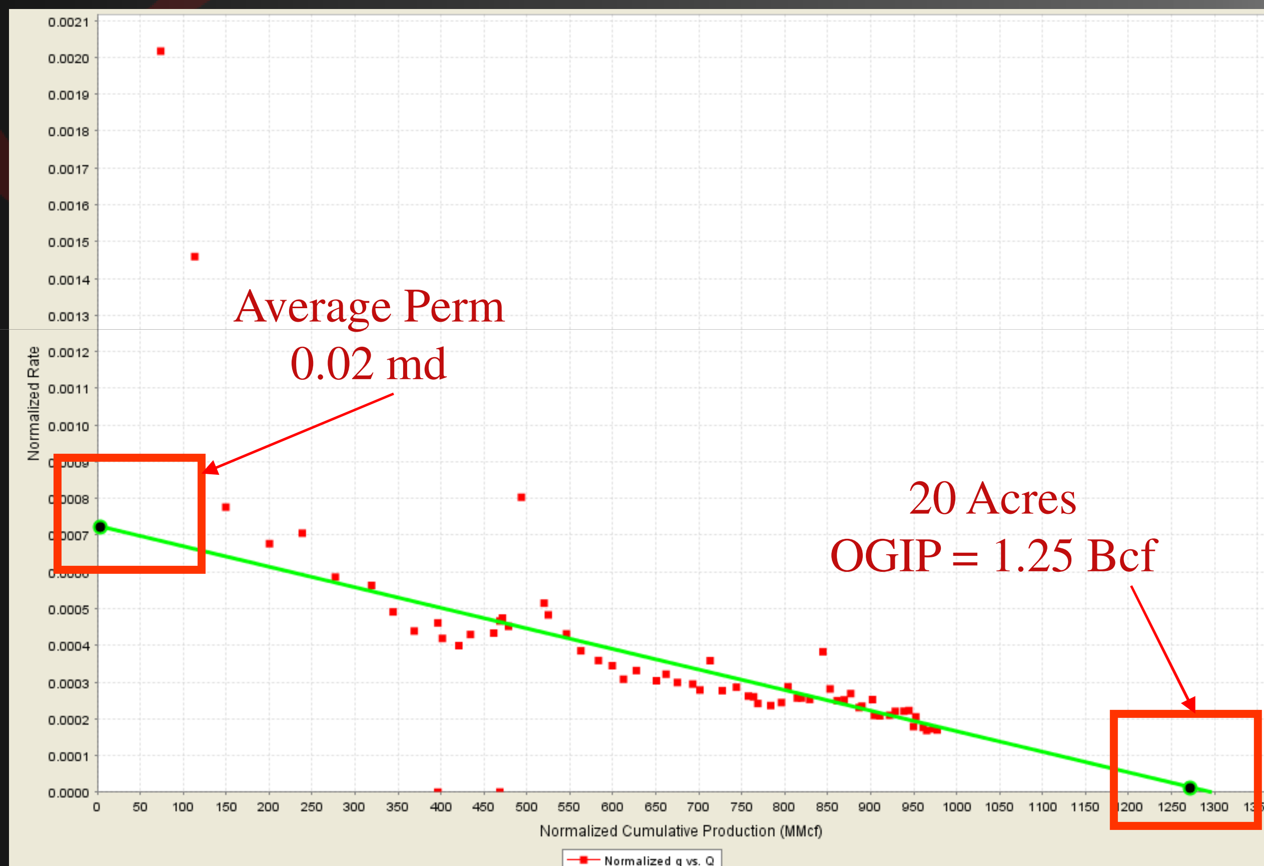
- Stella Young #4
- IGIP: 1.0 Bcf
- Drainage Area: 25 – 60 Acres
- Hydraulically Fractured
- Completed in 1985
- k: Less than 0.1 md

- Source: "Analysis of Production & Well Test Data from Barnett Shale Wells Operated by Mitchell Energy Corporation", GRI Contract No. 5086-213-1446

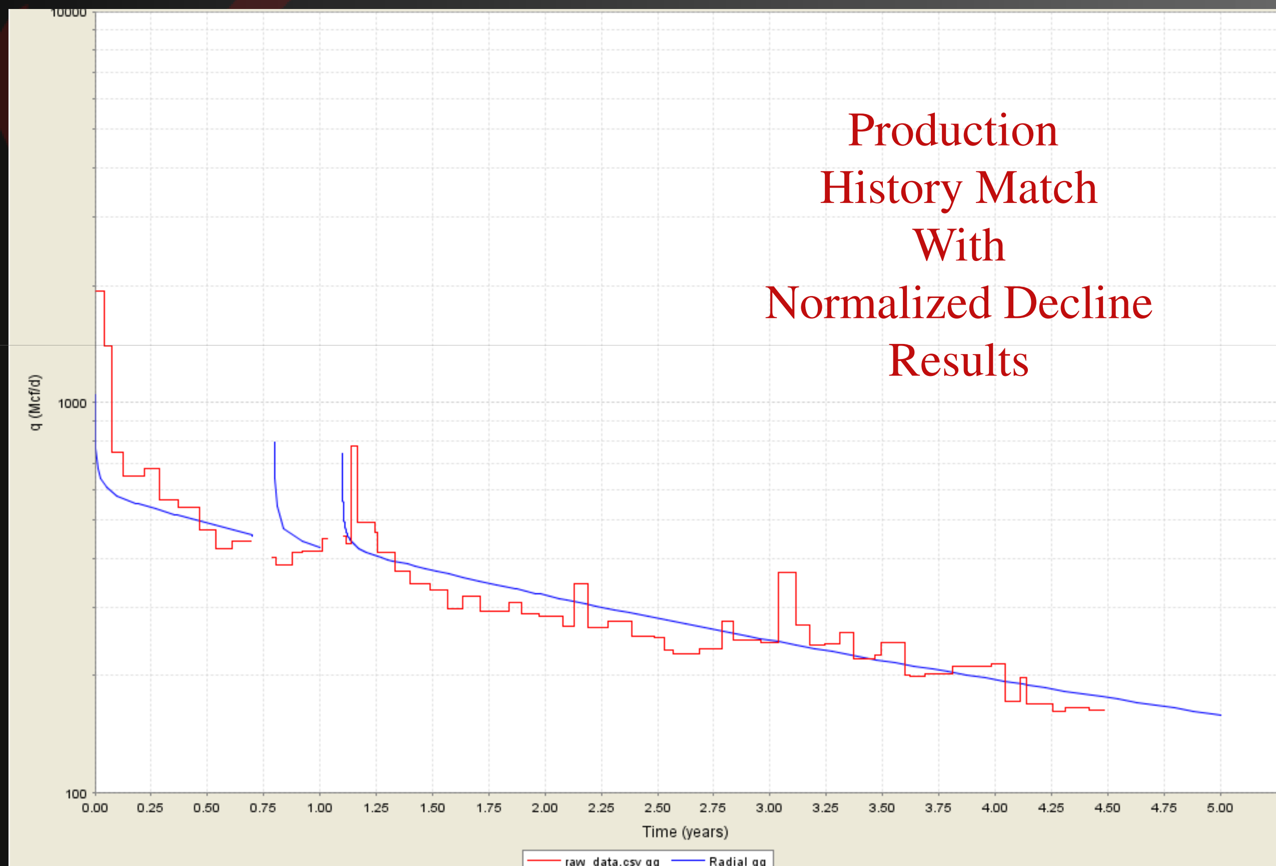
Original Analysis by GRI



Barnett Shale: Normalized Decline



Barnett Shale: Normalized Decline



Two-Phase Coals

- ***Generally considered to be numerical exercise***
  - Requires knowledge of relative perm curves
  - Could require multiple iterations
  - Significant overhead/time in building models
- ***In Alberta***
  - This may include Mannville Coals etc.

Let's Add for 2-Phase Flow

$$\frac{\dfrac{q_{sc}}{k_{rg}(p_R)}}{(\psi_i - \psi_{wf})} = \frac{k_a \cdot h}{1.417 \cdot 10^6 \dfrac{1}{2} \ln\left[\dfrac{4A}{e^{\gamma} C_A r_w^{\,2}}\right] T_f} + m \frac{(\psi_i - \psi_R)}{(\psi_i - \psi_{wf})} OGIP$$

Re-derive
Using
$k = k_a * k_{rg}(P_r)$

Y-intercept
Provides
Absolute permeability

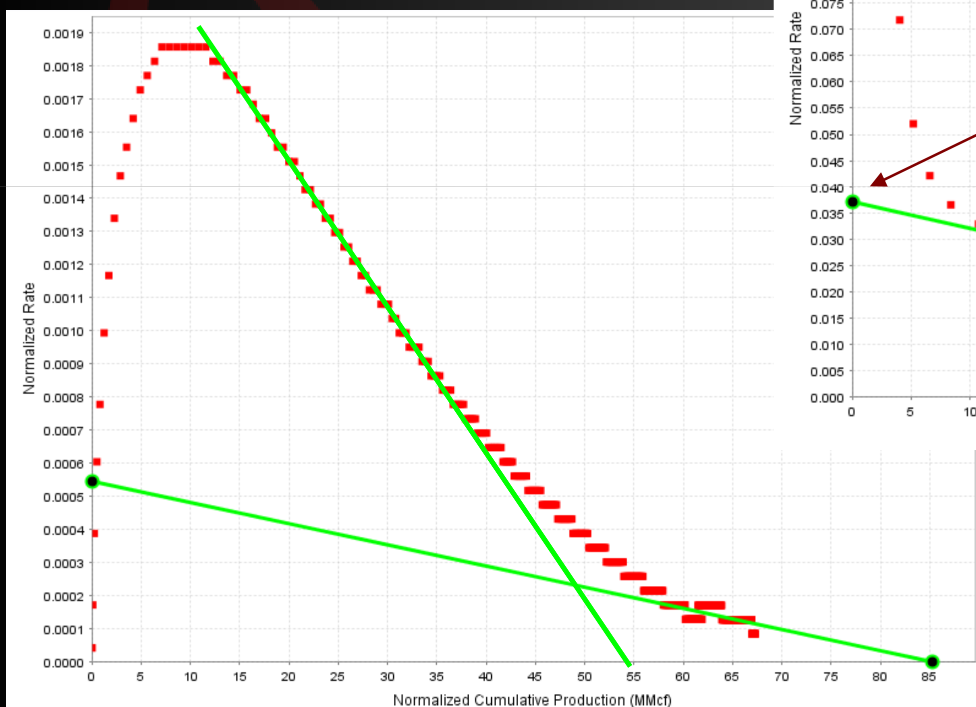
CBM Material
Balance

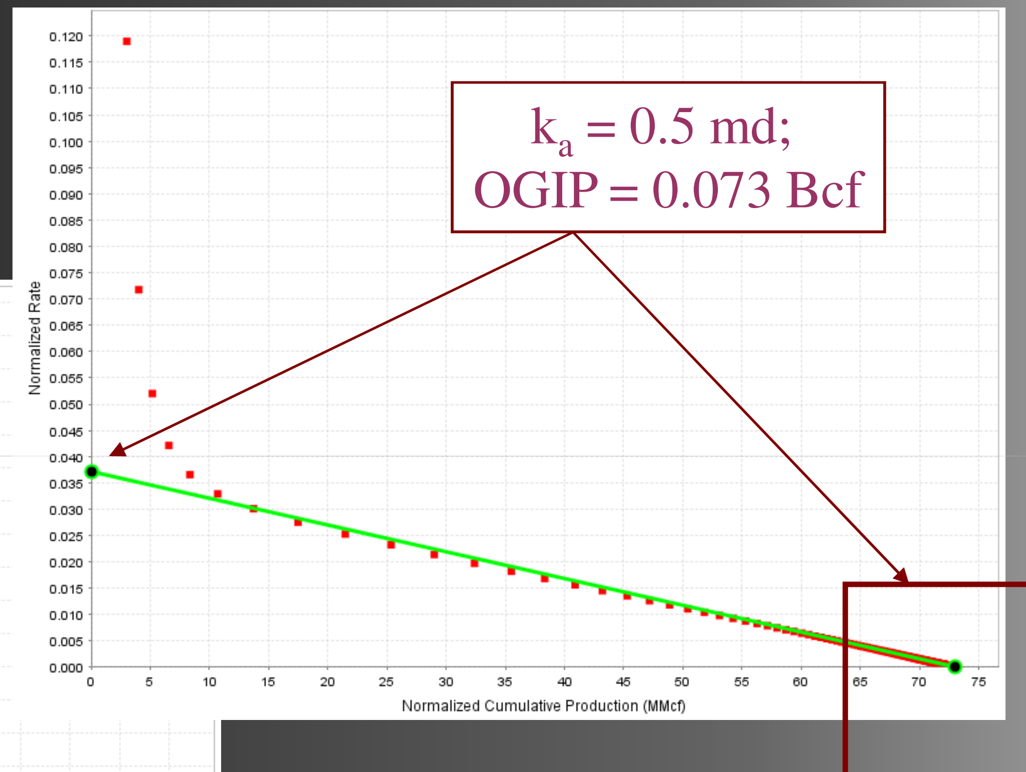
This approach is also suitable
matrix shrinkage &
other cases
where $k \propto P_R$

2-Phase CBM Case

- Absolute Perm =0.5 md
- OGIP = 0.073 Bcf
- V_L = 310 scf/ton
- P_L = 167 psia
- Simulated Data

2-Phase CBM Case: Normalized Decline

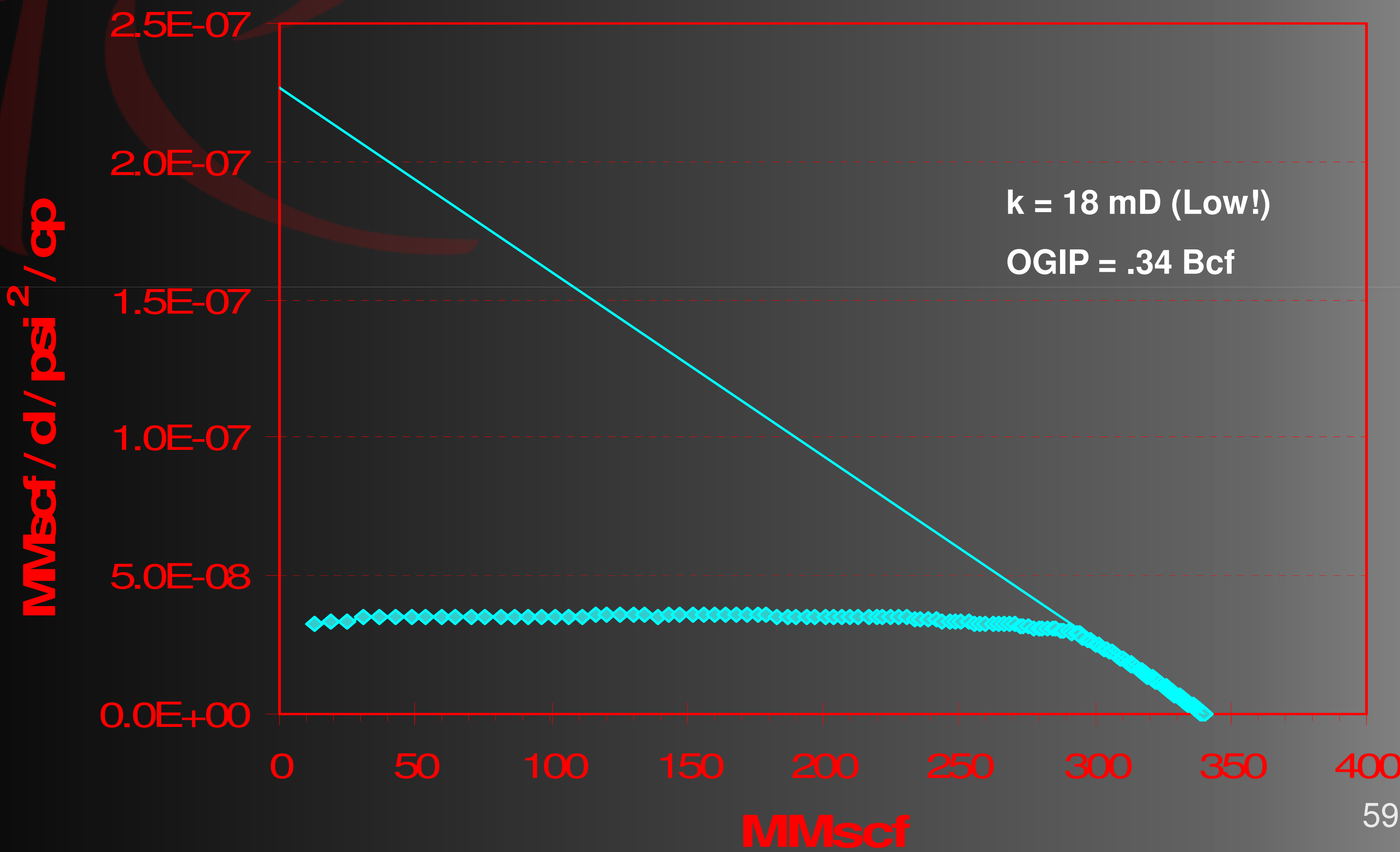




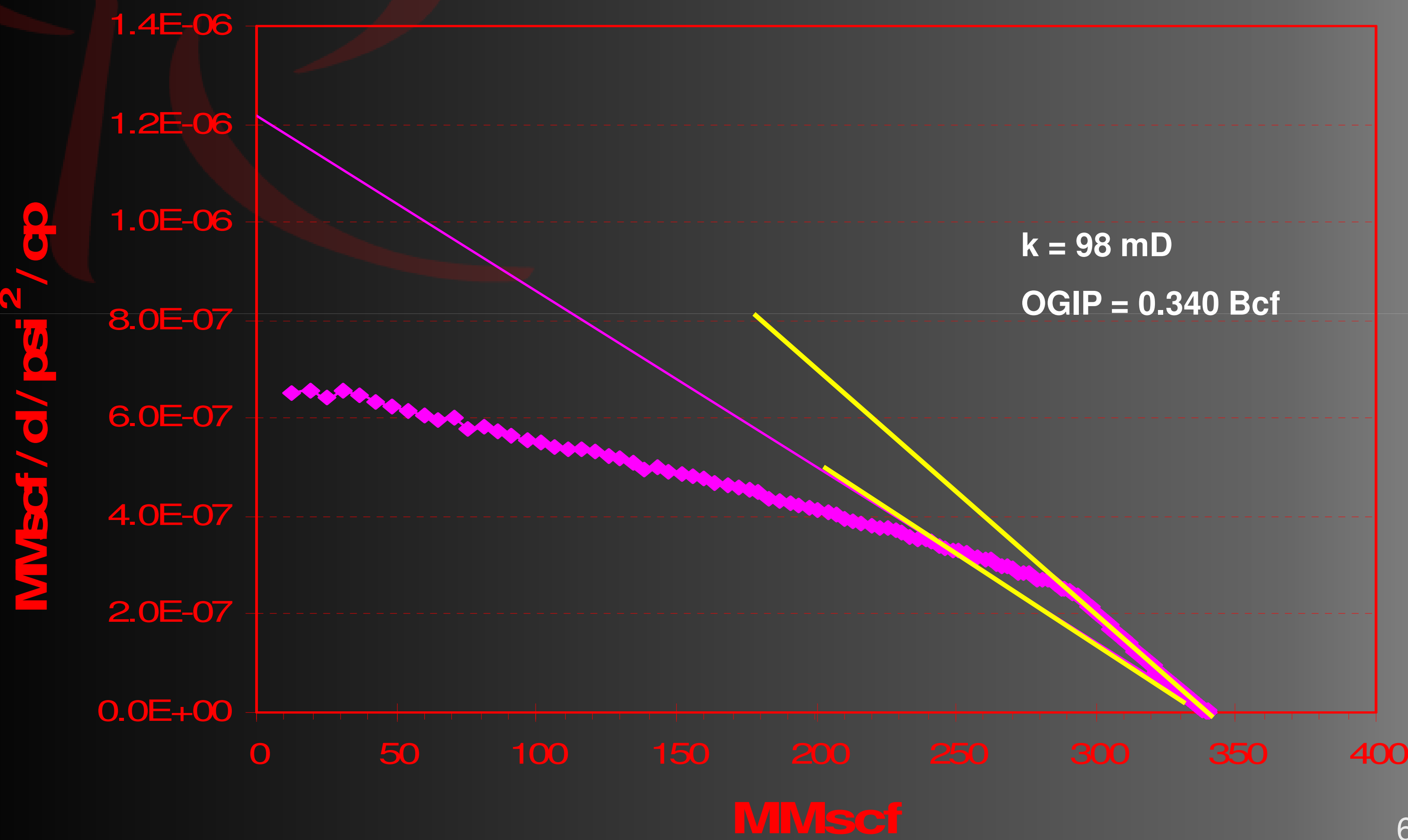
Powder River Basin 2P Coals
Seidle (SPE 75519)

- Drainage Area: 80 Ac
- Net Pay: 64 ft
- Sw: 95 %
- Φ: 13 %
- Langmuir: 218.4 scf/ton, 1355 psia
- Bulk Density: 1.33 g/cc
- IGIP (Volumetric): 340.6 MMcf
- k: 100 mD / Proxy Relative Perm

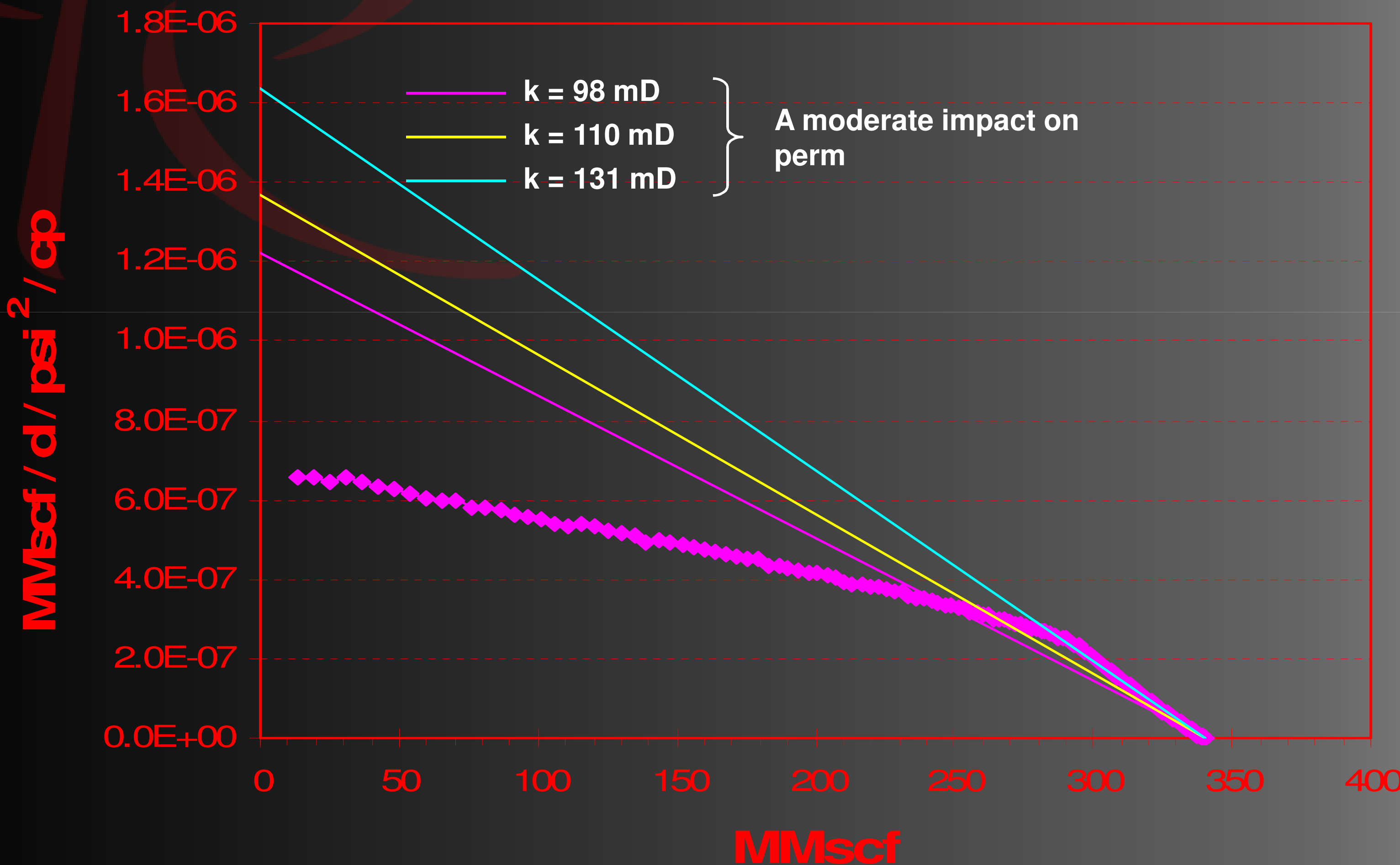
Powder River Basin:
Norm. Decline w/o Rel. Perm.



Powder River Basin 2P Coals
Normalized Decline with Rel. Perm.



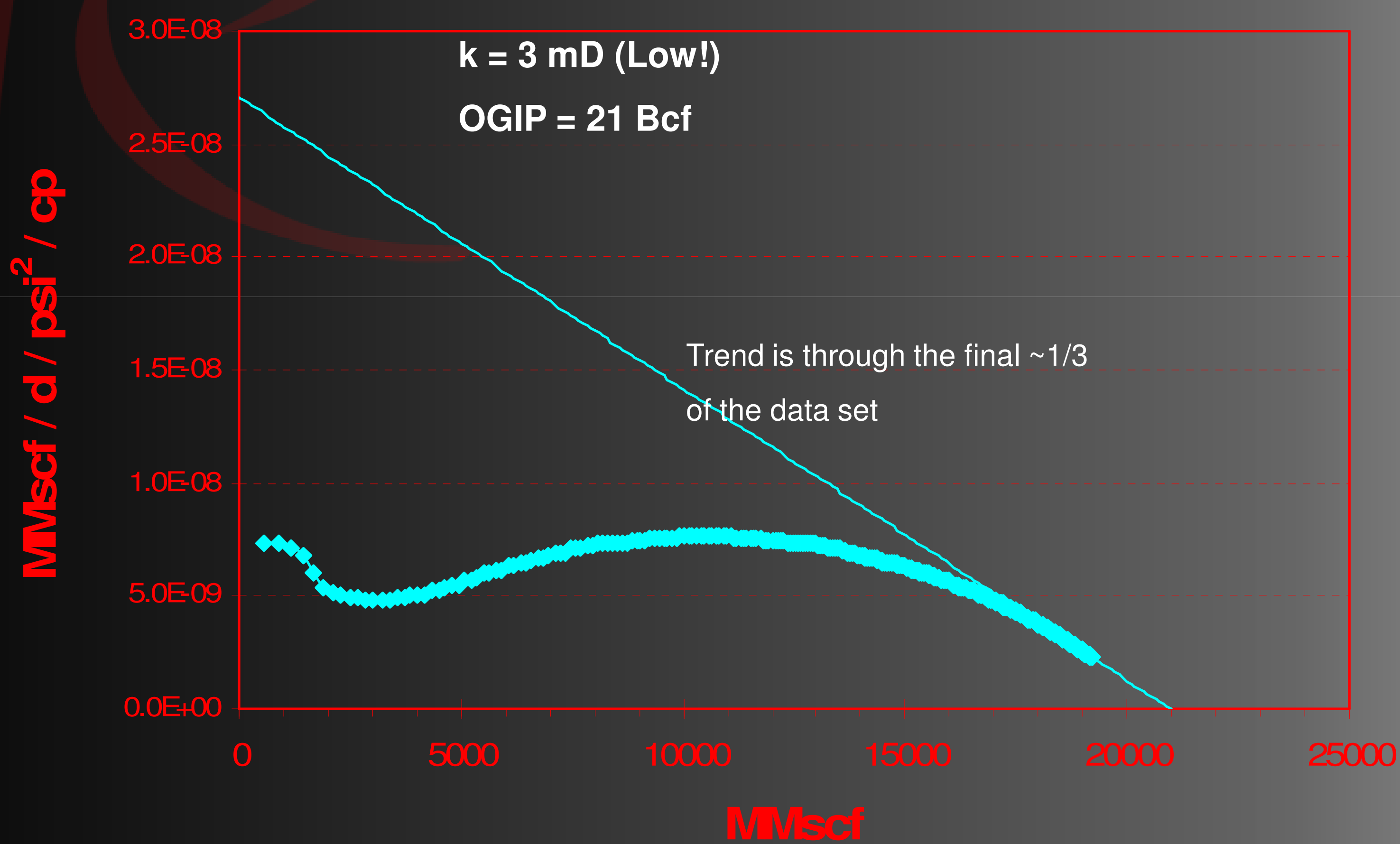
Powder River Basin 2P Coals
Permeability Sensitivity



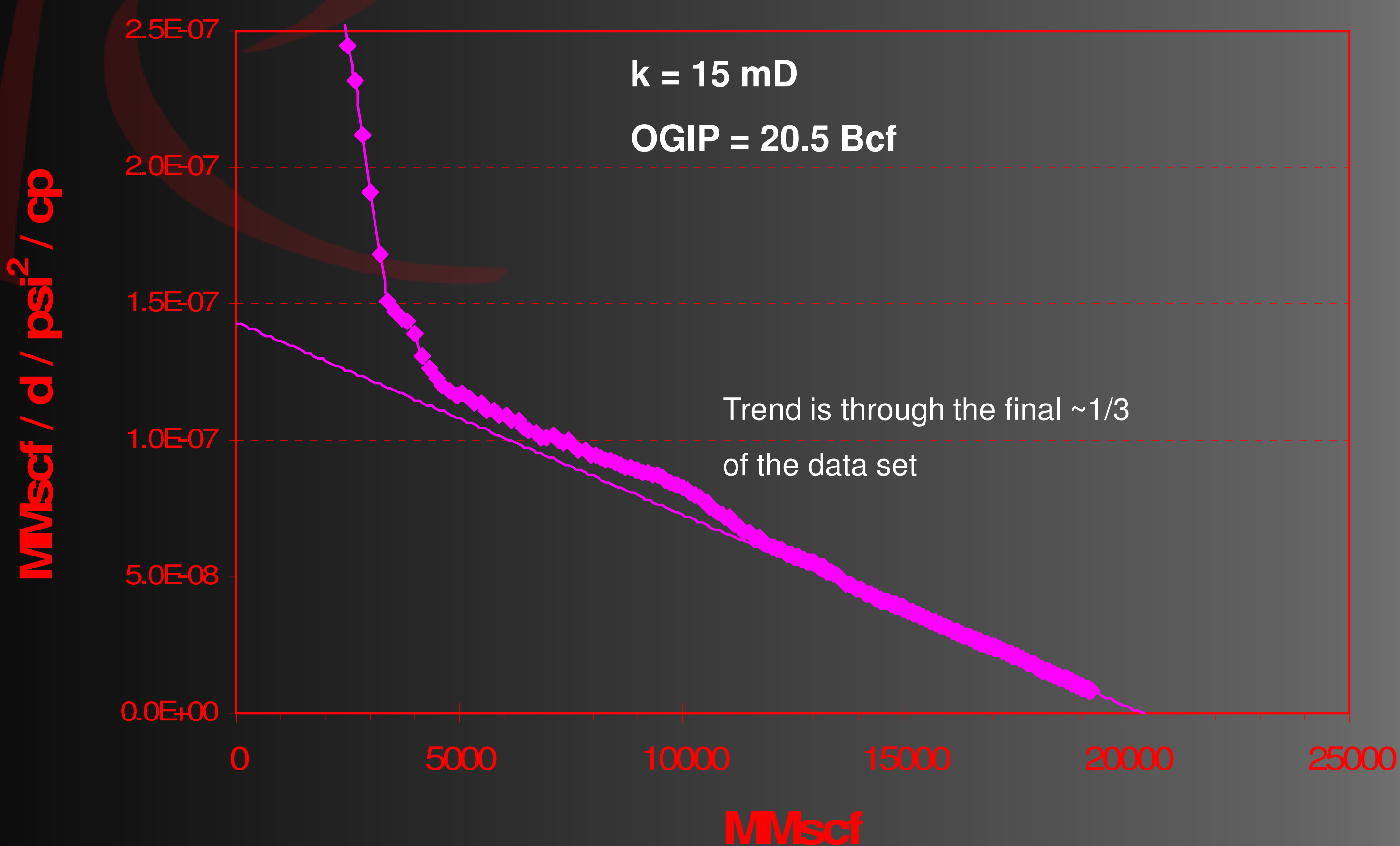
San Juan Basin 2P Coals
Seidle (SPE 75519)

- Drainage Area: 320 Ac
- Net Pay: 50 ft
- Sw: 95 %
- Φ: 1 %
- Langmuir: 640.1 scf/ton, 310 psia
- Bulk Density: 1.75 g/cc
- IGIP (Volumetric): 20.5 Bcf
- k: 20 mD

San Juan Basin 2P Coals
Normalized Decline: Non-Corrected



San Juan Basin 2P Coals Normalized Decline: Corrected



What About Tight Gas?

- ***Will this method work for tight gas?***
  - Reservoirs with $k \ll 0.1$ mD or less
- ***We admit the method is focused on stabilized production***
- ***Models are not accurate during transient flow***
- ***This could have a big impact on tight gas reservoirs***

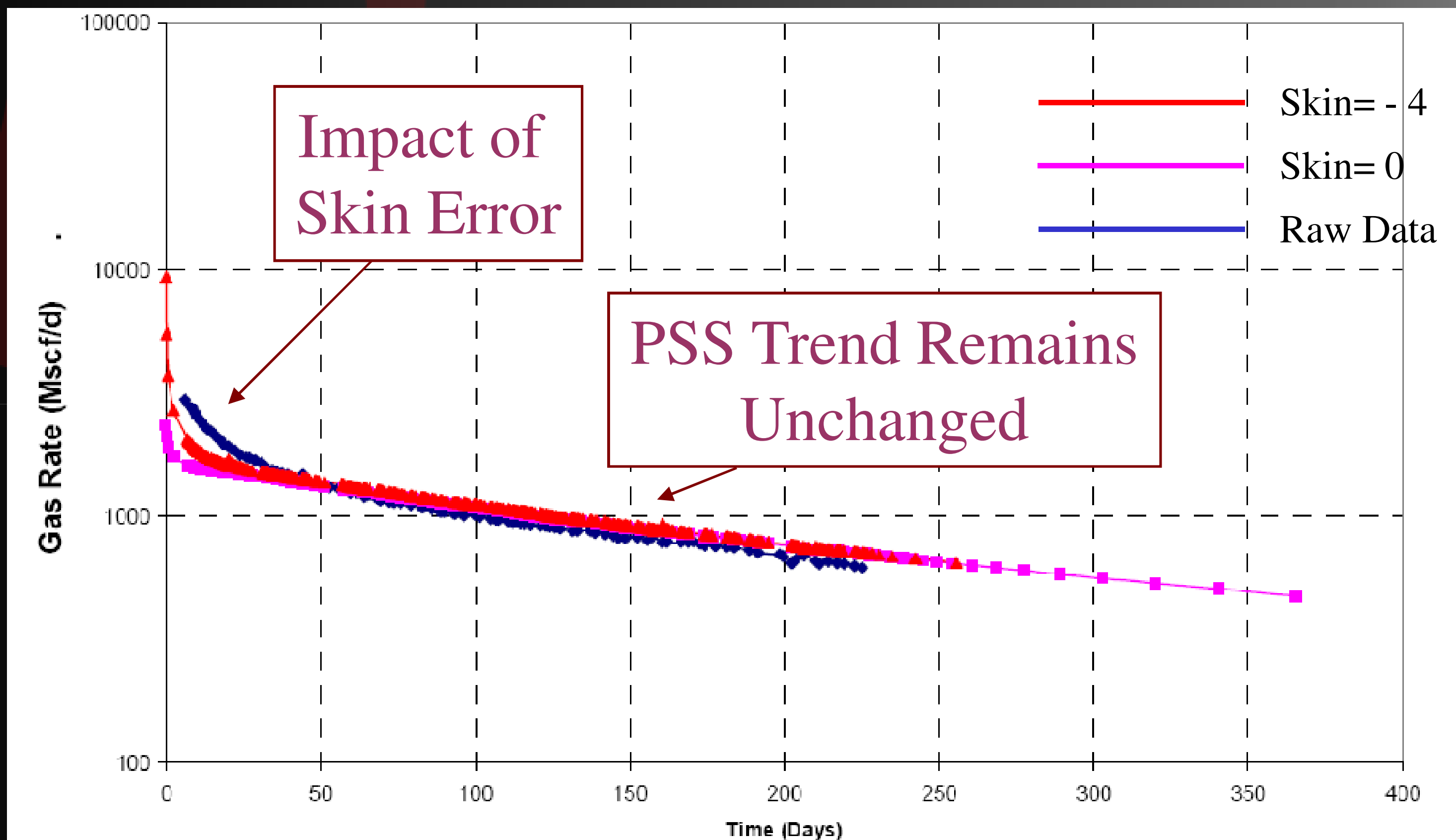
Tight Gas Well: C231

- ***Castlegate Tight Gas Wells, Utah***
- ***Original Drainage Area: 51-54 Acres***

Numerical	***Norm. Decline***
OGIP: 0.9-1.0 Bcf	0.7 Bcf
Perm: 0.04 md	0.17 md
Skin: -4.79	0.0
Xf = 65 ft	N/A
Area = 54 Acres	

- ***Source: "Analysis of Long-Term Behavior in Tight Gas Reservoirs", Arevalo-Villigran, SPE 95117***

Tight Gas Well 231: SPE 99351

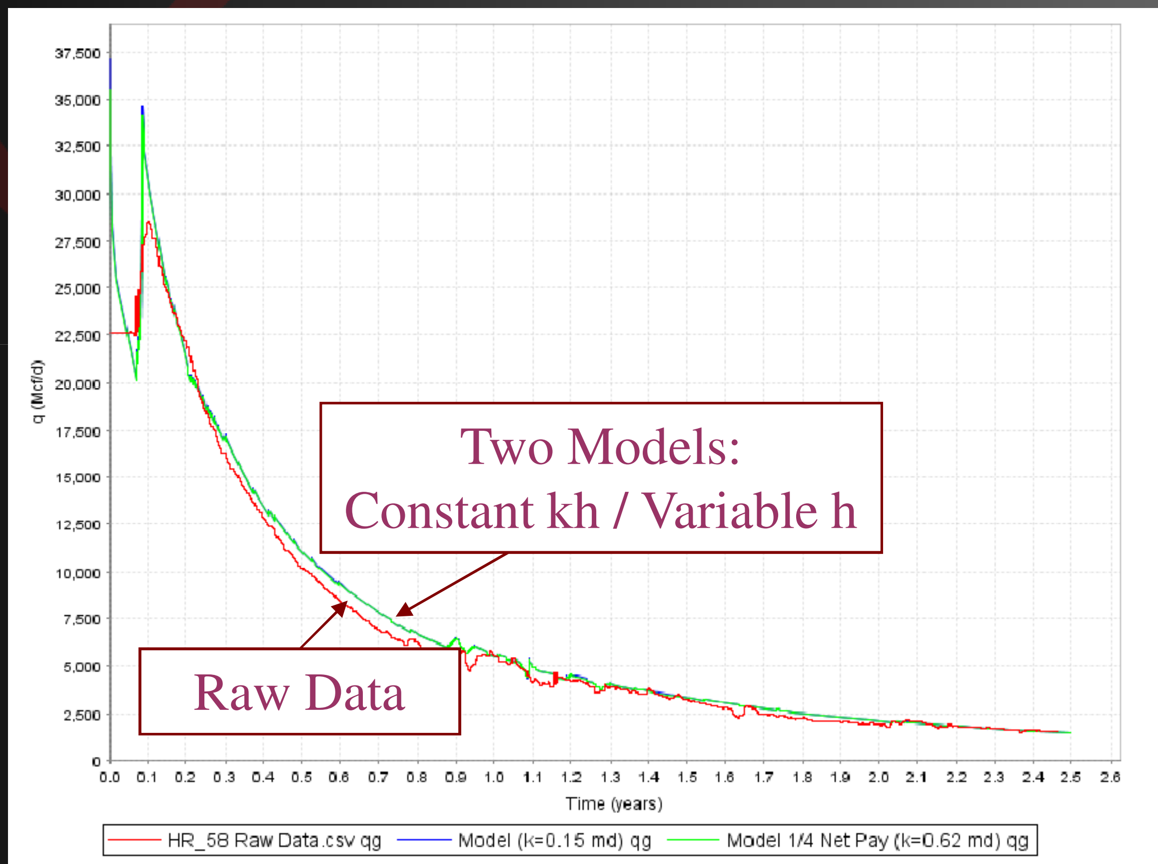


$$\frac{q_{sc}}{(\psi_i - \psi_{wf})} = \frac{k \cdot h}{1.417 \cdot 10^6 \frac{1}{2} \ln\left[\frac{4A}{e^{\gamma} C_A r_{wa}^{2}}\right] T_f} + m \frac{(\psi_i - \psi_R)}{(\psi_i - \psi_{wf})} OGIP$$

Tight Gas Well: HR-58

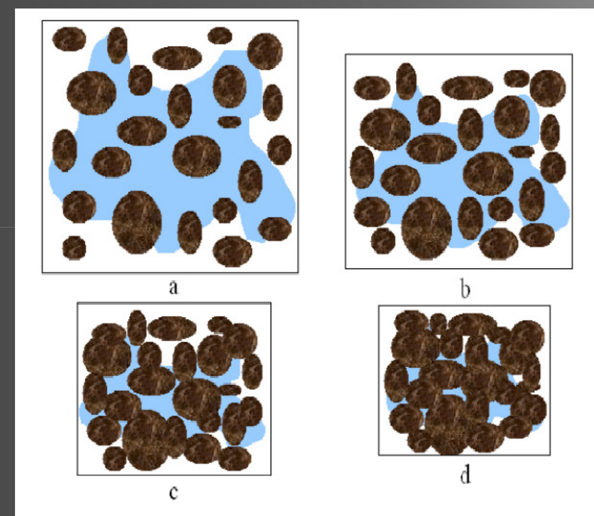
- ***HR-58***
  - High Pressure, Tight Gas
  - OGIP 9.8 Bcf; Perm = 0.038 md
- ***Stimulated***
- ***Numerical Simulation / PTA***
- ***Source: Ibrahim, M. et al, "Determination of OGIP for Tight Gas Wells – New Methods", CIPC No. 2003-12***

Tight Gas Well: HR-58 SPE 99351



Non-Linear Perm

- ***Permeability is a function of P_R***
  - Initial Perm = 0.0025 md (Tight)
  - OGIP = 259 Bcf
  - Numerical Simulation (GasSim™)
  - γ => Non-Linear Term



- ***Rodriquez "Stress-Dependent Permeability on Tight Gas Reservoirs" , 2004***

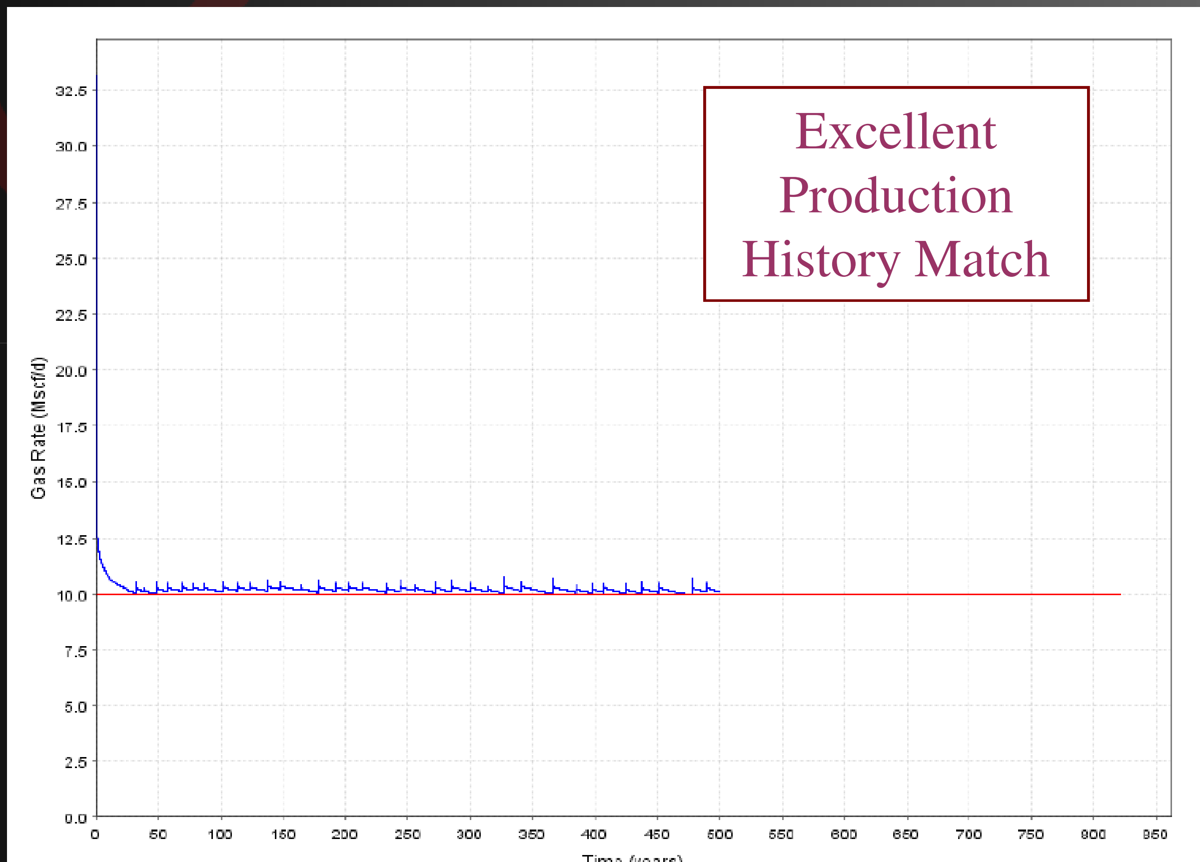
Recall Non-Linear Modification

$$\frac{\dfrac{q_{sc}}{k_{rg}(p_R)}}{(\psi_i - \psi_{wf})} = \frac{k_i \cdot h}{1.417 \cdot 10^6 \dfrac{1}{2} \ln\left[\dfrac{4A}{e^{\gamma} C_A r_w^{\,2}}\right] T_f} + m \frac{(\psi_i - \psi_R)}{(\psi_i - \psi_{wf})} OGIP$$

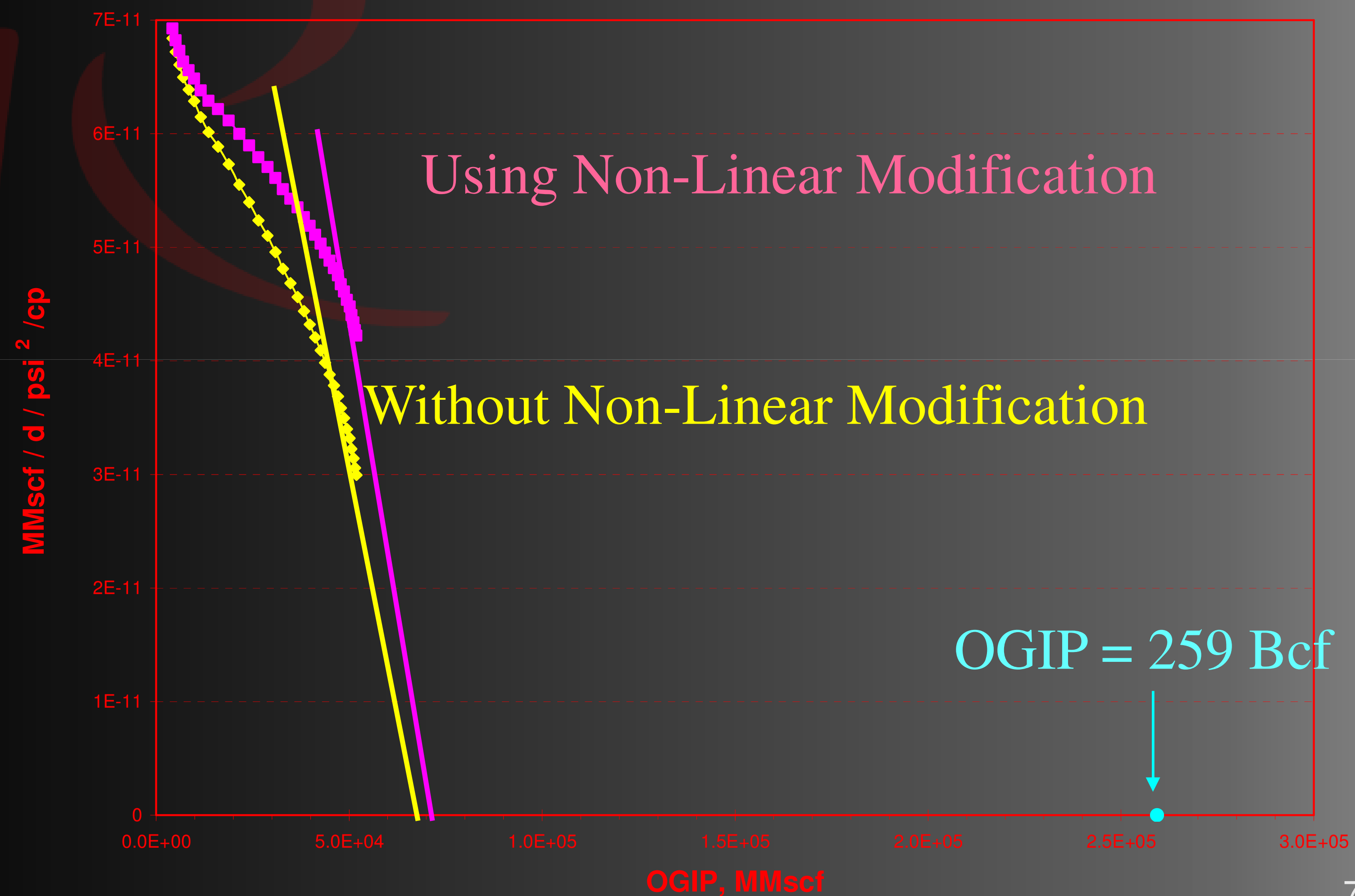
Re-derive
Using
$k = k_i * k_{rg}(P_r)$

Y-intercept
Provides
Initial Permeability

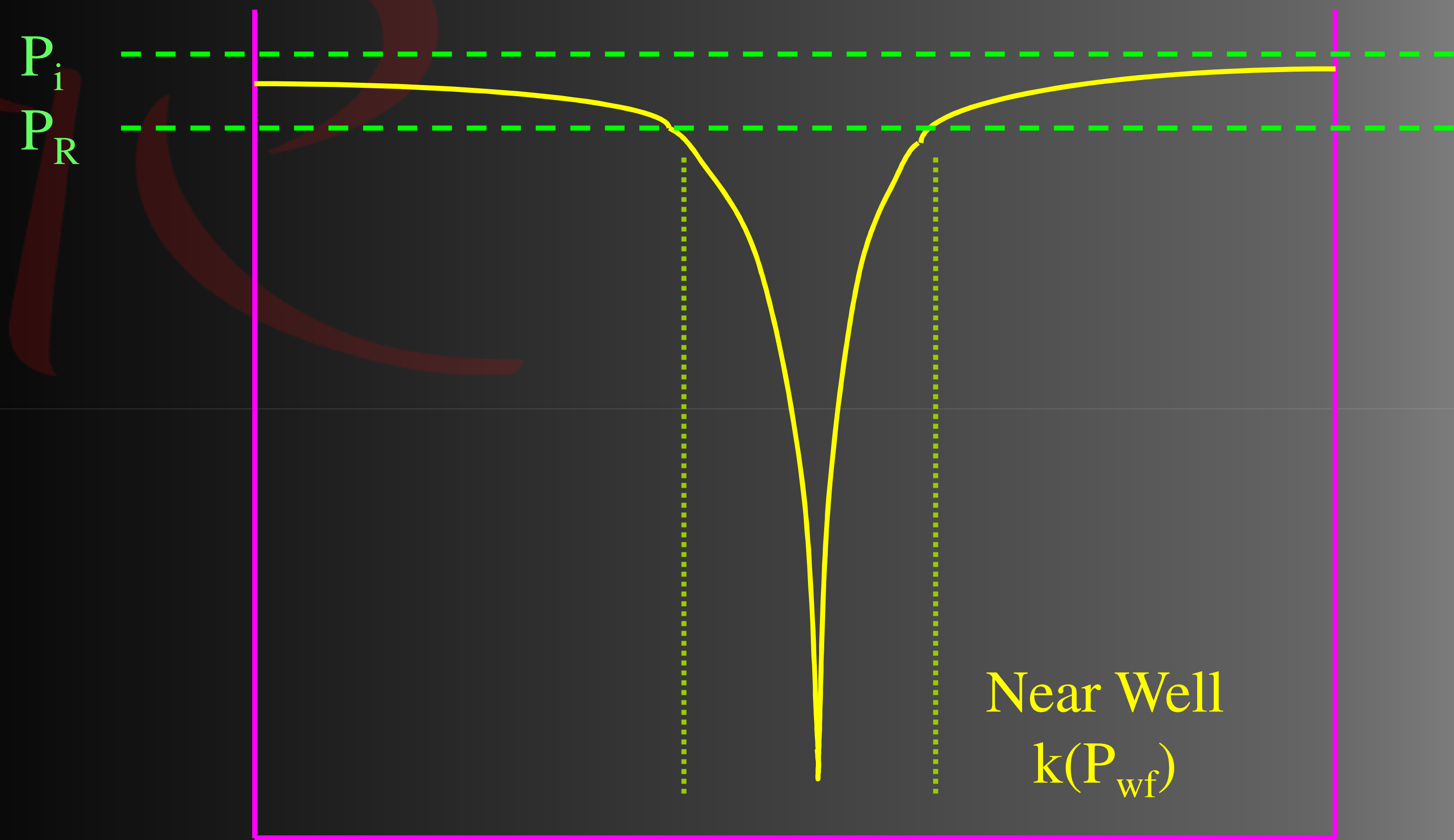
10 Mscf/d, $\gamma = 0.0008$



Additional Non-Linear Perm
20 Mscf/d, $\gamma = 0.0010$



Problems: Non-Linear Perm



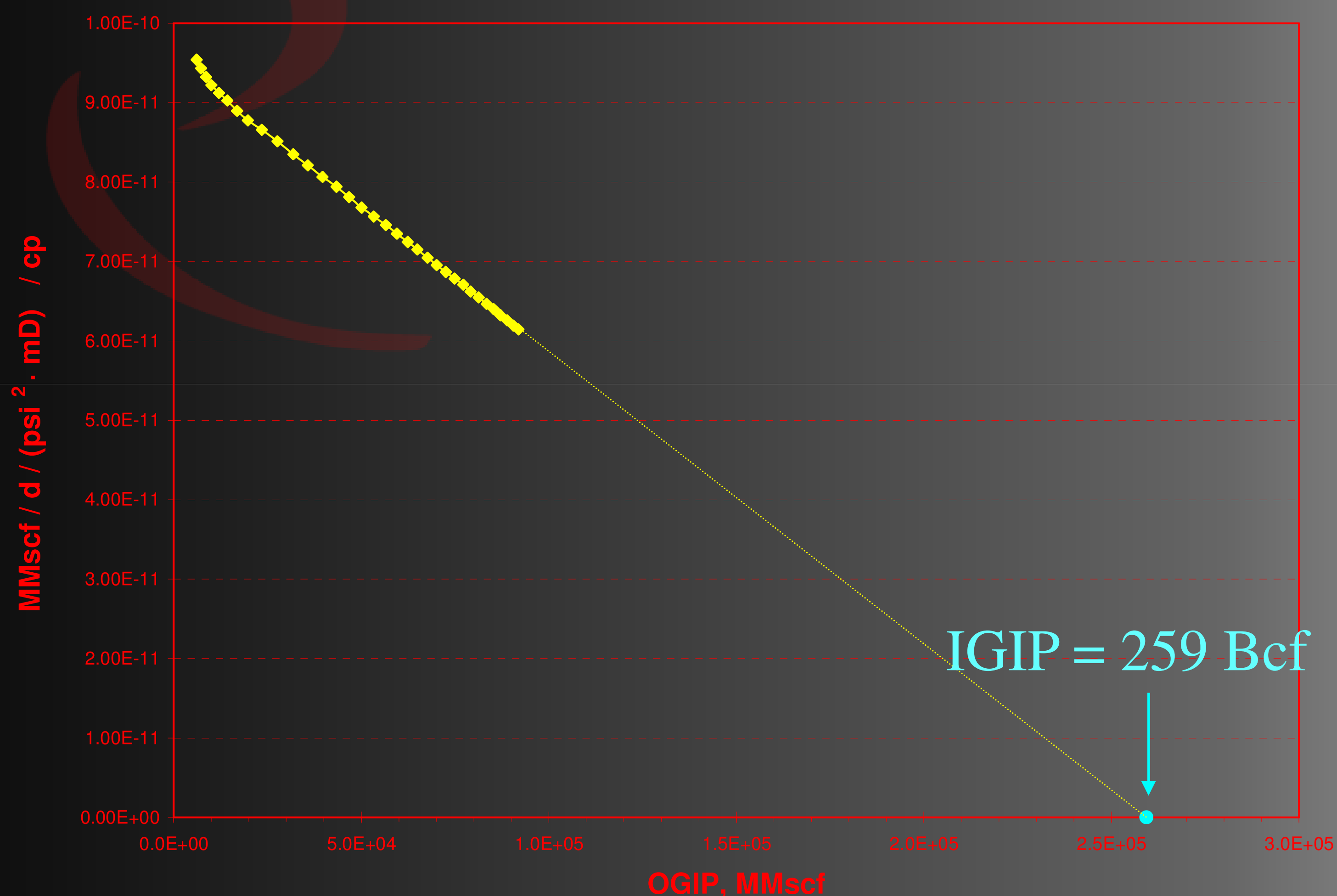
Modifications for Non-Linear Flow

$$\frac{\frac{q_{sc}}{k(p_R)}}{(\psi_i - \psi_{wf})} = \frac{k_i \cdot h}{1.417 \cdot 10^6 \frac{1}{2} \ln\left[\frac{4A}{e^{\gamma} C_A r_w^{\,2}}\right] T_f} + m \frac{(\psi_i - \psi_R)}{(\psi_i - \psi_{wf})} OGIP$$

$$\psi' = \frac{1}{2} \int_0^P \frac{P \cdot k(p)}{uz} \partial P$$

$$\frac{q_{sc}}{(\psi'_i - \psi'_{wf})} = \frac{k_i \cdot h}{1.417 \cdot 10^6 \frac{1}{2} \ln\left[\frac{4A}{e^{\gamma} C_A r_w^{\,2}}\right] T_f} + m \frac{(\psi'_i - \psi'_R)}{(\psi'_i - \psi'_{wf})} OGIP$$

20 Mscf/d, γ = 0.0010 Continued



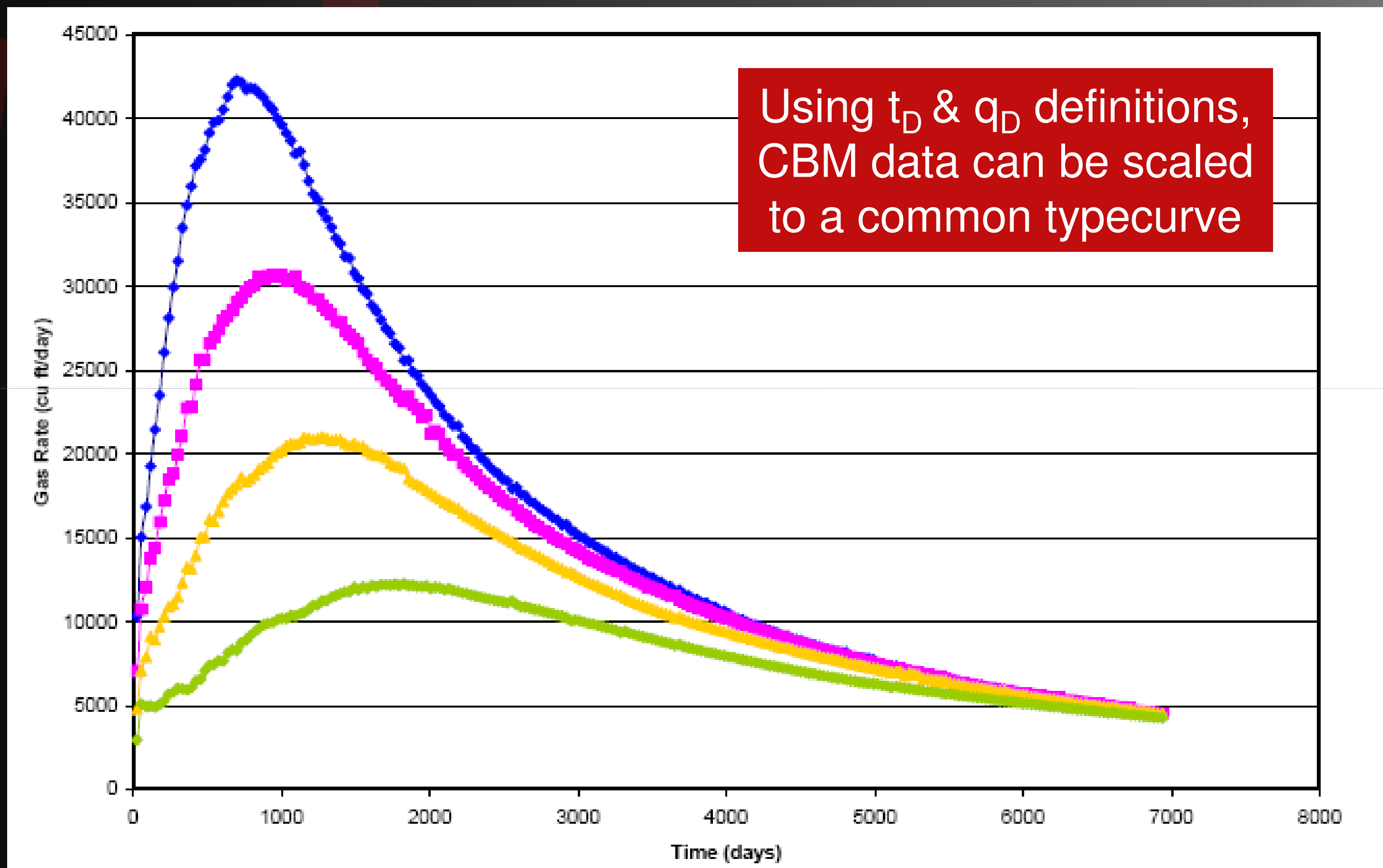
Typecurve Theory

- ***Simple, Reliable Tool to Analyze CBM Reserves***
  - No Relative Permeability Curves
  - No Isotherm Parameters
  - Just Production Data

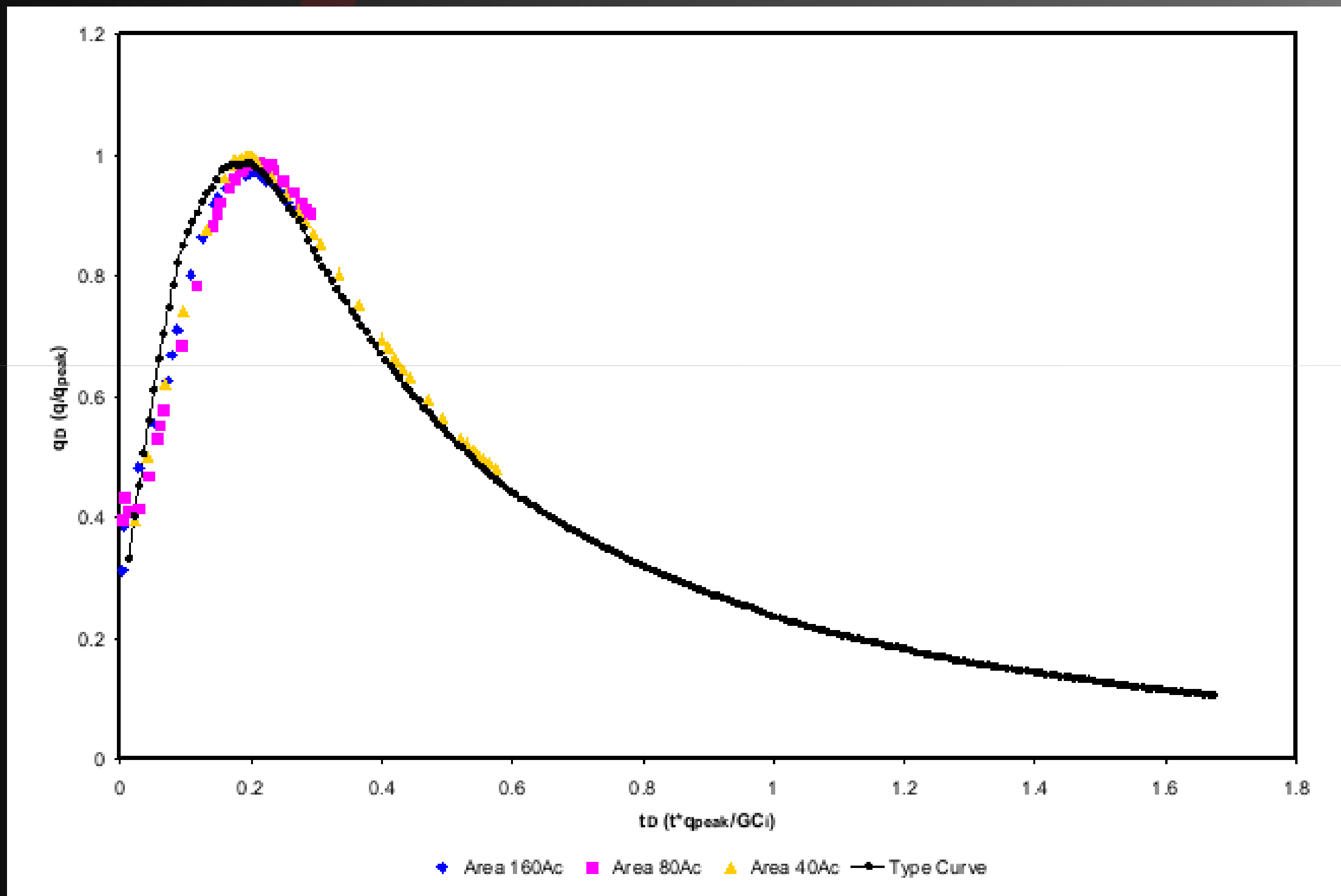
- ***West Virginia University***

$$q_D \propto C_1 \frac{q}{q_{\max}} \qquad t_D \propto C_2 \frac{t \cdot q_{\max}}{G_i}$$

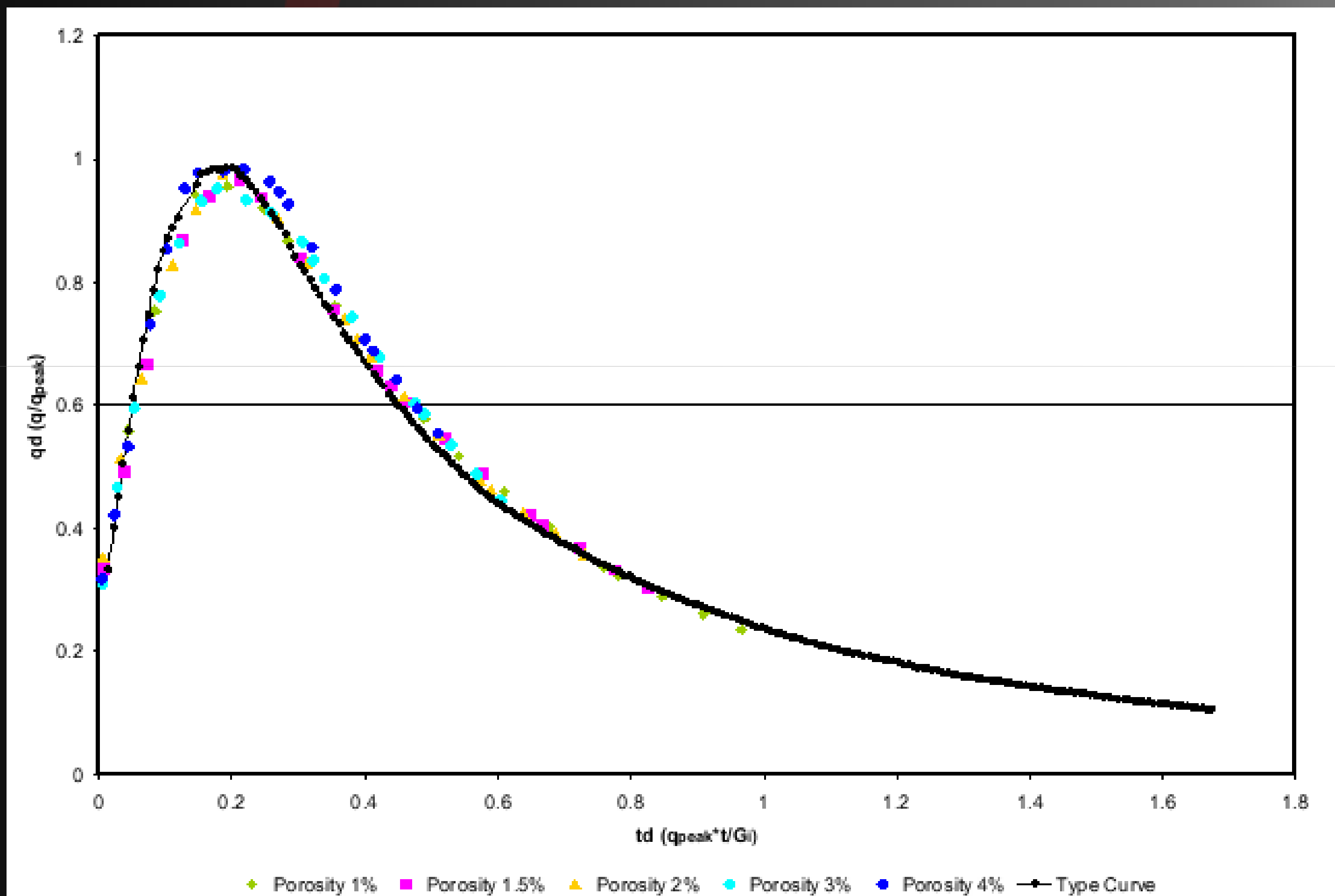
CBM Raw Data - Simulated



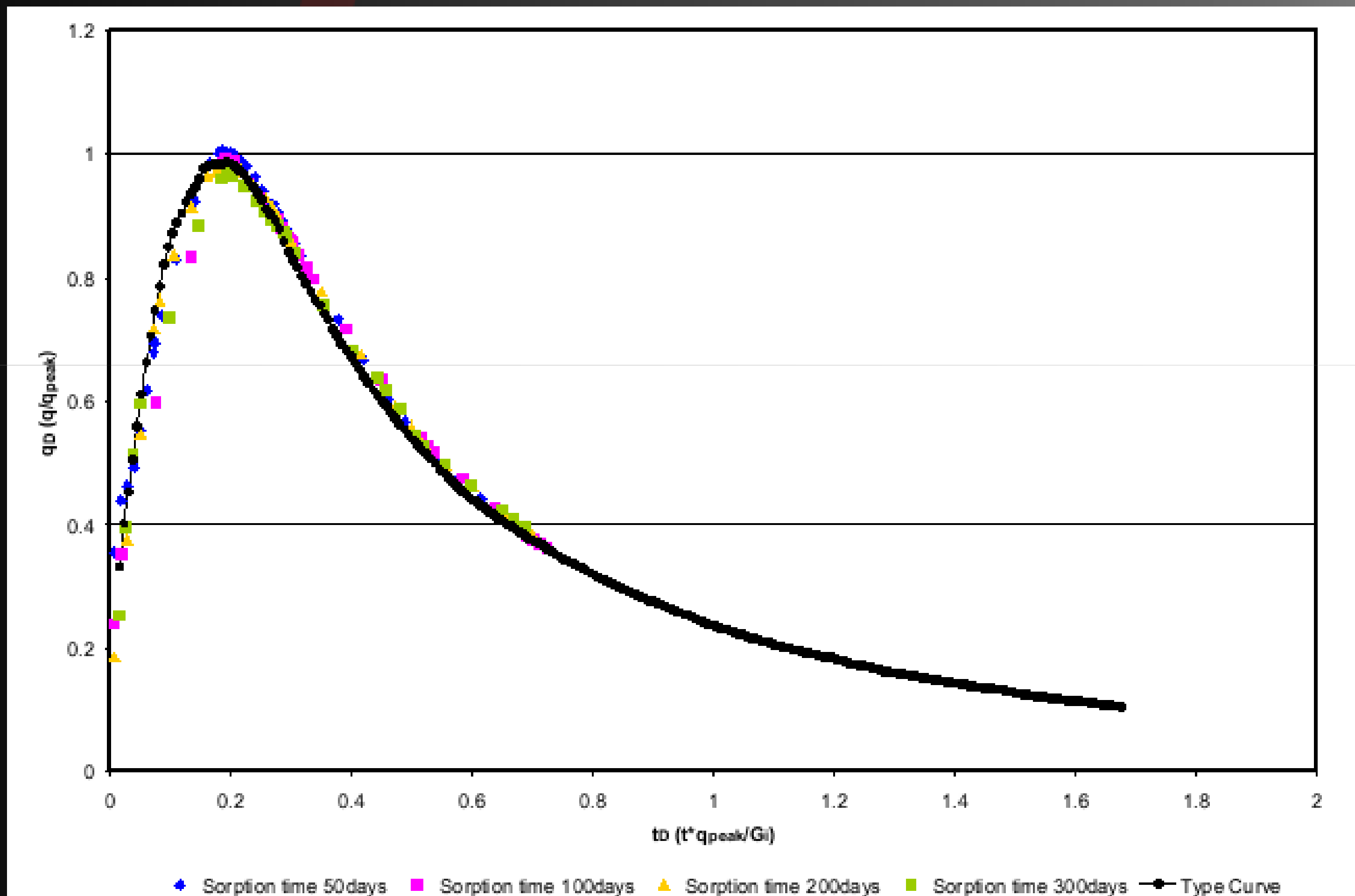
Typecurve Verification: Variable Drainage Area



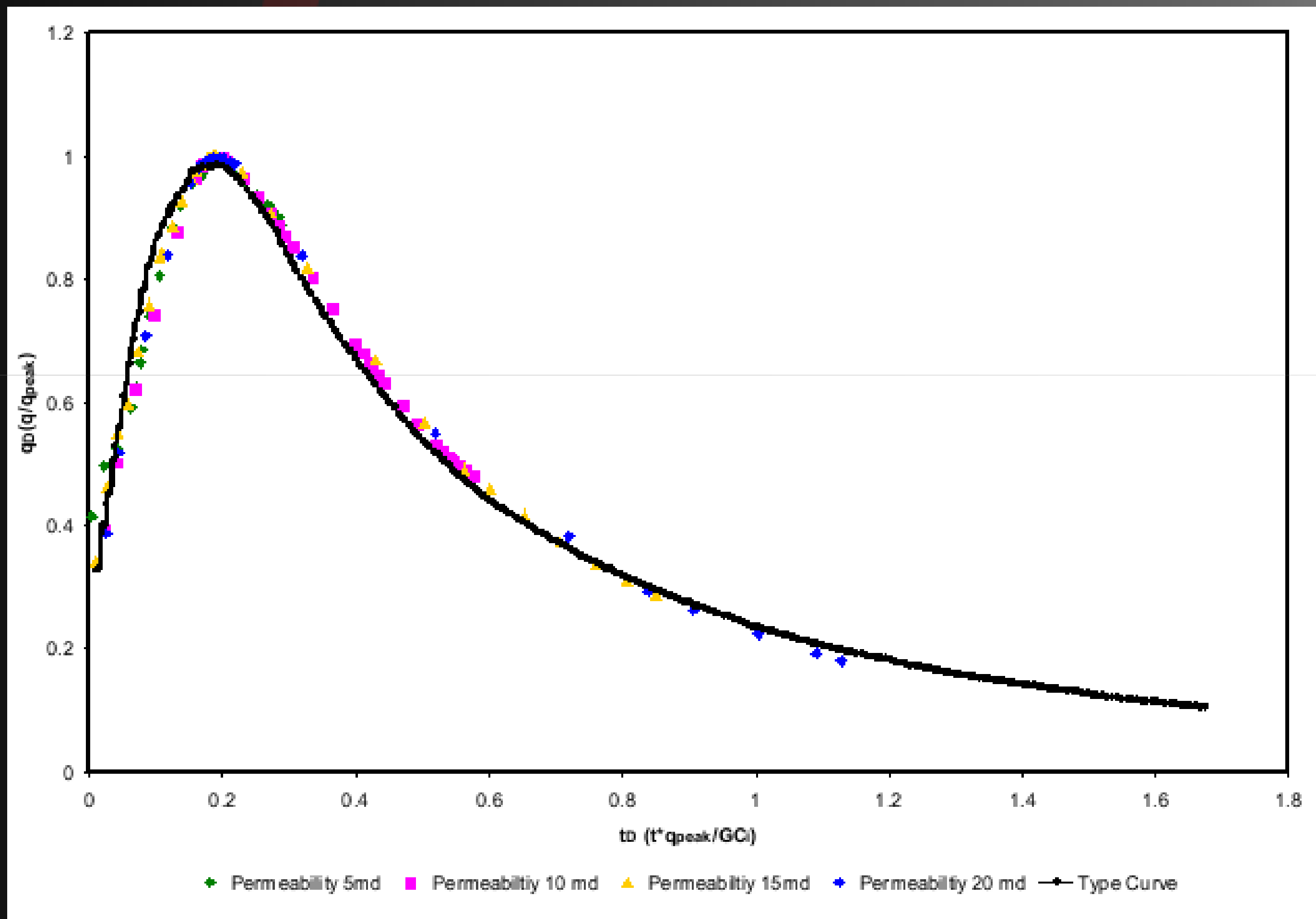
Typecurve Verification: Variable Porosity



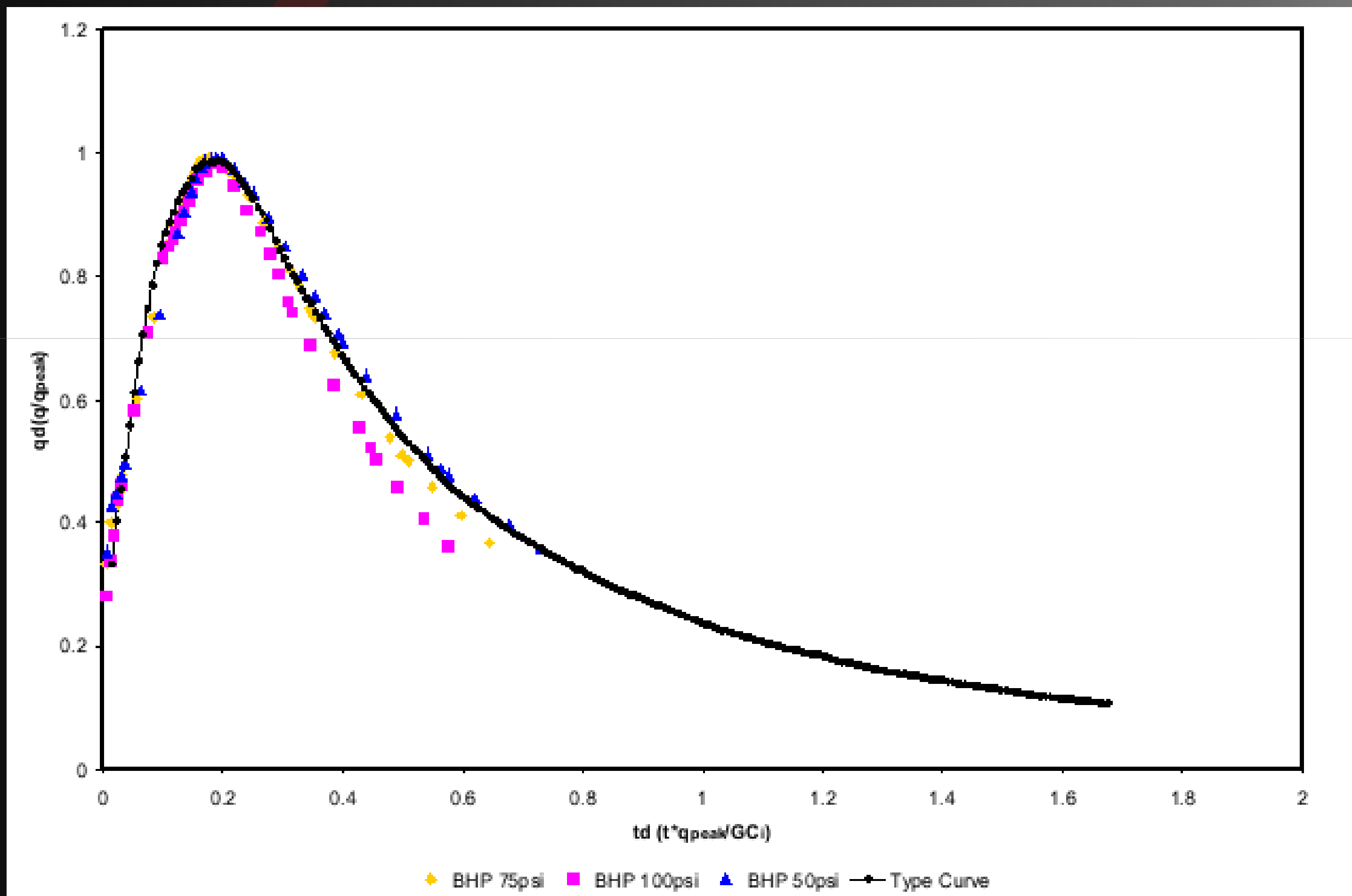
Typecurve Verification: Variable Sorption Time



Typecurve Verification: Variable Permeability

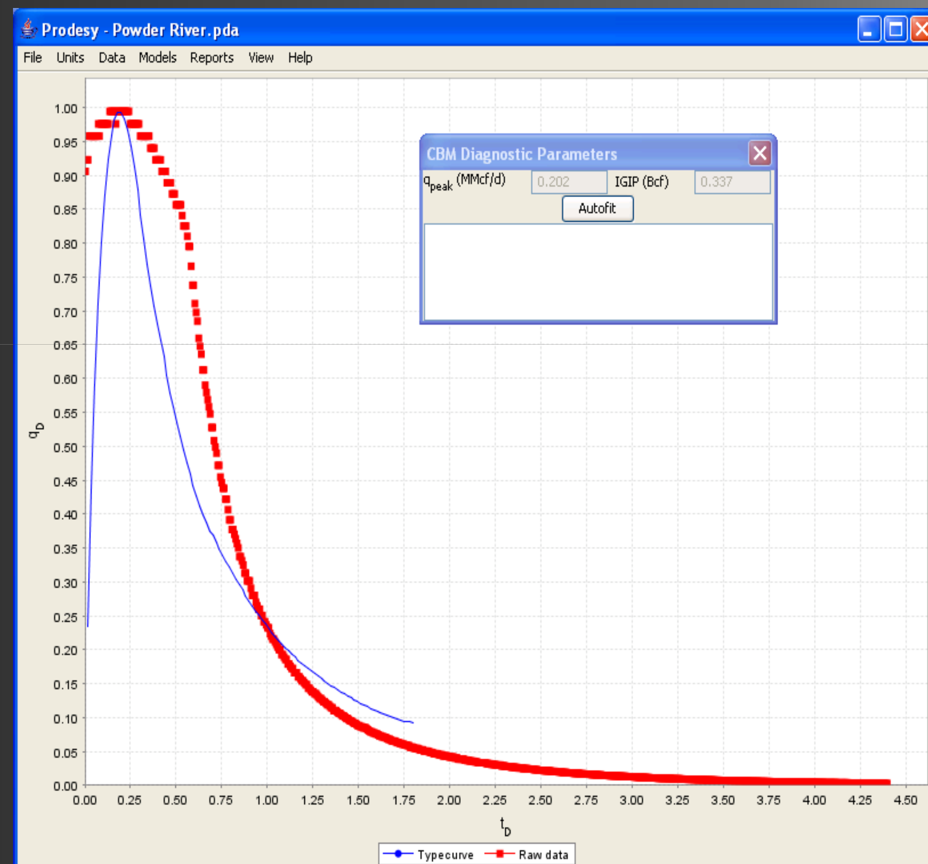


Typecurve Verification: Variable Flowing Pressure



Powder River Basin 2P Coals Typecurve Match?

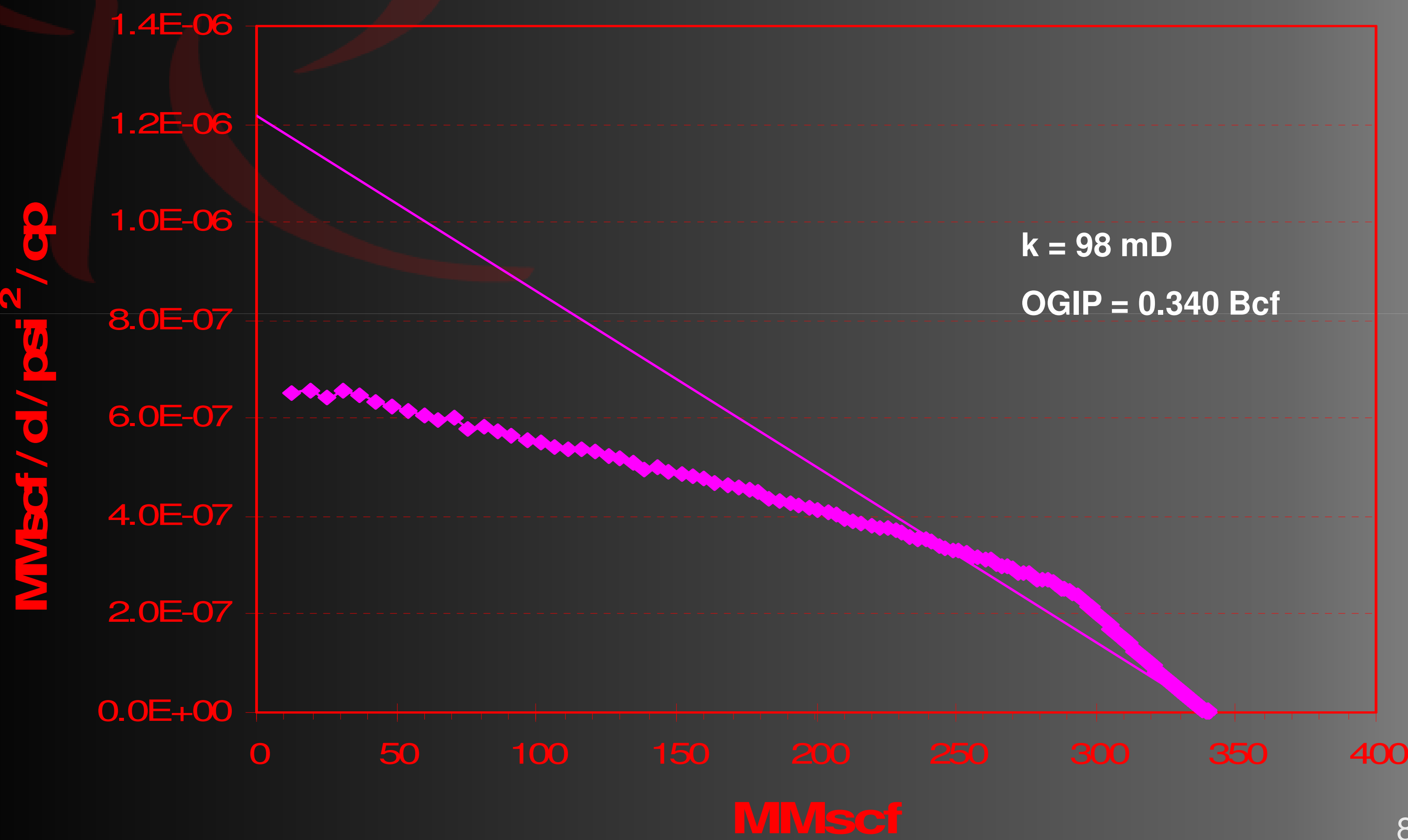
Match on peak



Calc OGIP: 0.337 Bcf

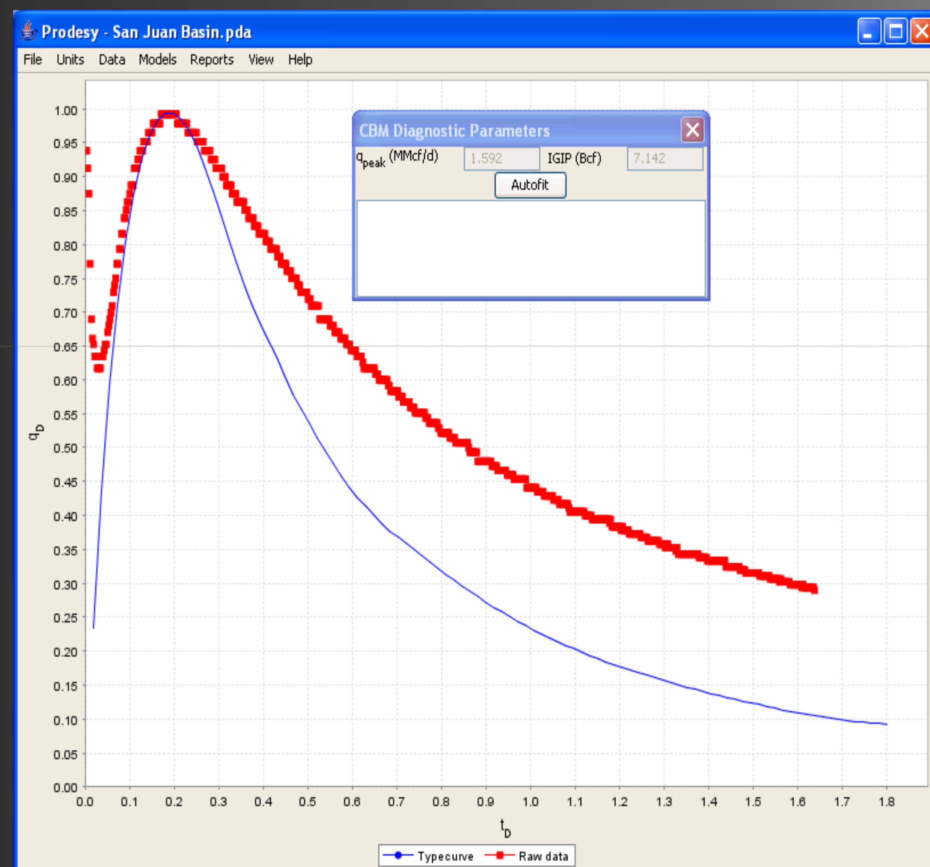
Act OGIP: 0.34 Bcf

Powder River Basin 2P Coals
Normalized Decline with Rel. Perm.



San Juan Basin 2P Coals Typecurve Match?

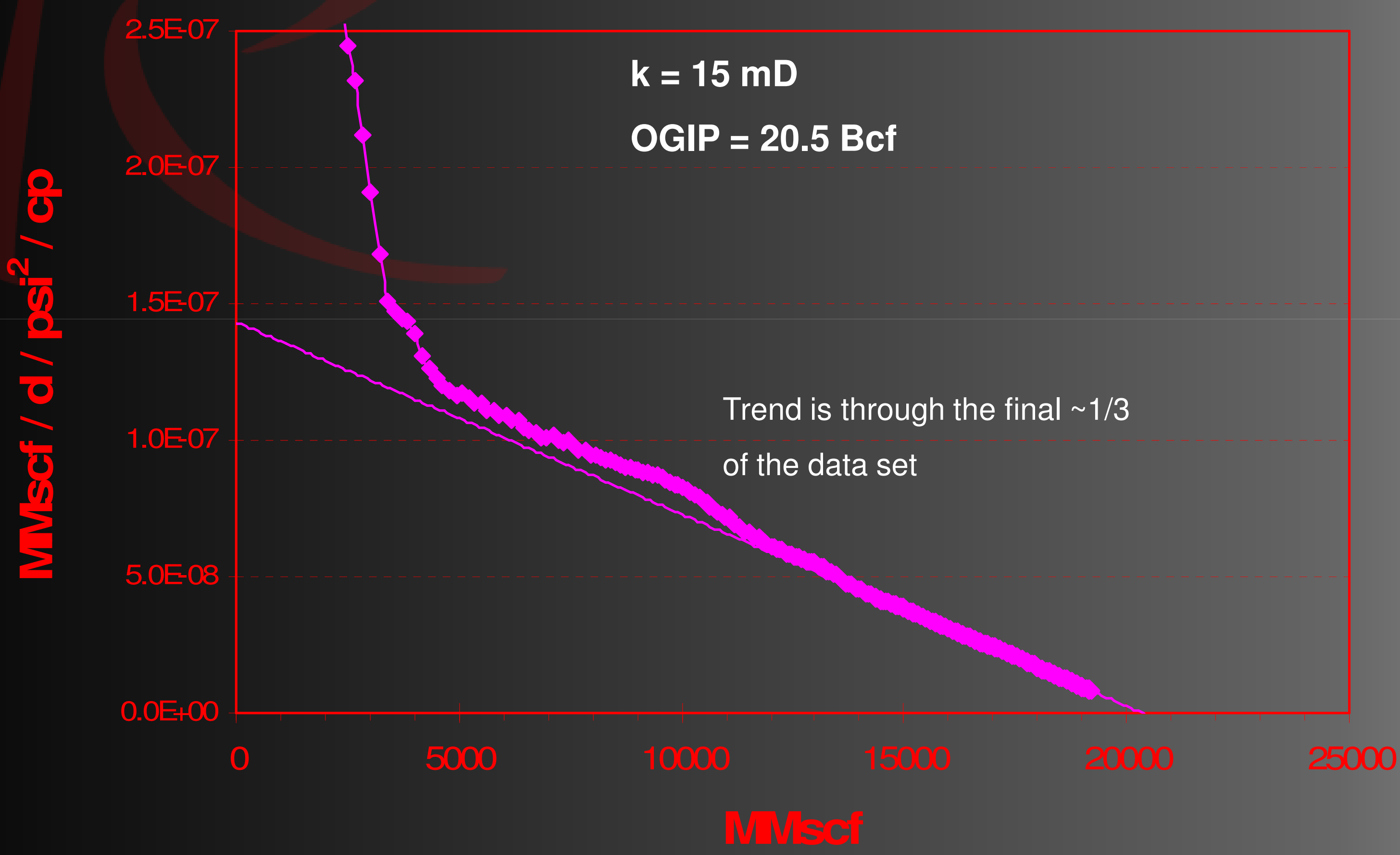
Match on peak →



Calc OGIP: 7.1 Bcf

Act OGIP: 20 Bcf

San Juan Basin 2P Coals
Normalized Decline: Corrected



Keeping it Simple

- ***We do need:***
  - Gas Specific Gravity
  - Formation Temperature
  - Water Saturation
  - Porosity
- ***Do these inputs need to be accurate?***

Additional Error Analysis

Property	Component	Error OGIP Calculation
Specific Grav	ψ, P_R*	3.8%
Porosity	P_R*	5%
Formation Temp	ψ, P_R*, z	6%
Water Saturation	ψ, P_R*	3.4%

*Ramagost & Farshad, SPE 10125

Keeping it Simple #2

- *Do we need Bottom-hole pressures?*
- *Can We Use Wellhead data?*
- *Generally Yes!*

Conclusions & Summary

- ***Simple "Visual Method" for GPA***
- ***Used to Extract;***
  - Average Effective Permeability
  - Average Effective Drainage Area
  - True or Actual OGIP
- ***Equivalent Model Can Be Used for Accurate Gas Rate Prediction***
- ***Applicable to Conventional and Unconventional Gas***

Key Contacts

- *Question / Sales / Technology Transfer*
- *Adrian Castellano*
- *713-996-7979*

  adrian.castellano@rapid.com