PMG PETRO MANAGEMENT GROUP LTD.

Challenges of Reserves Estimate

(tight and unconventional reservoirs)

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For information:
www: petromgt.com
2015

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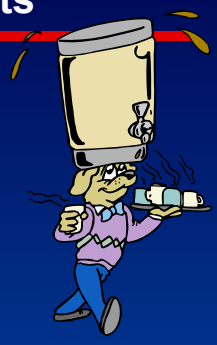
Quality Petroleum Engineering Consultants



- Reservoir Studies (Conventional/Simulation)
- Well Test Planning and Analysis
- Waterflood Design & Performance Monitoring
- Production Optimization
- Performance Evaluation of MFHW's (PTA, RTA, Numerical)
- Reserves and Economic Evaluations
- Complete frac design/optimization (Gohfer/KAPPA software)
- Government Submissions
- Customized course contents
- Expert Witness

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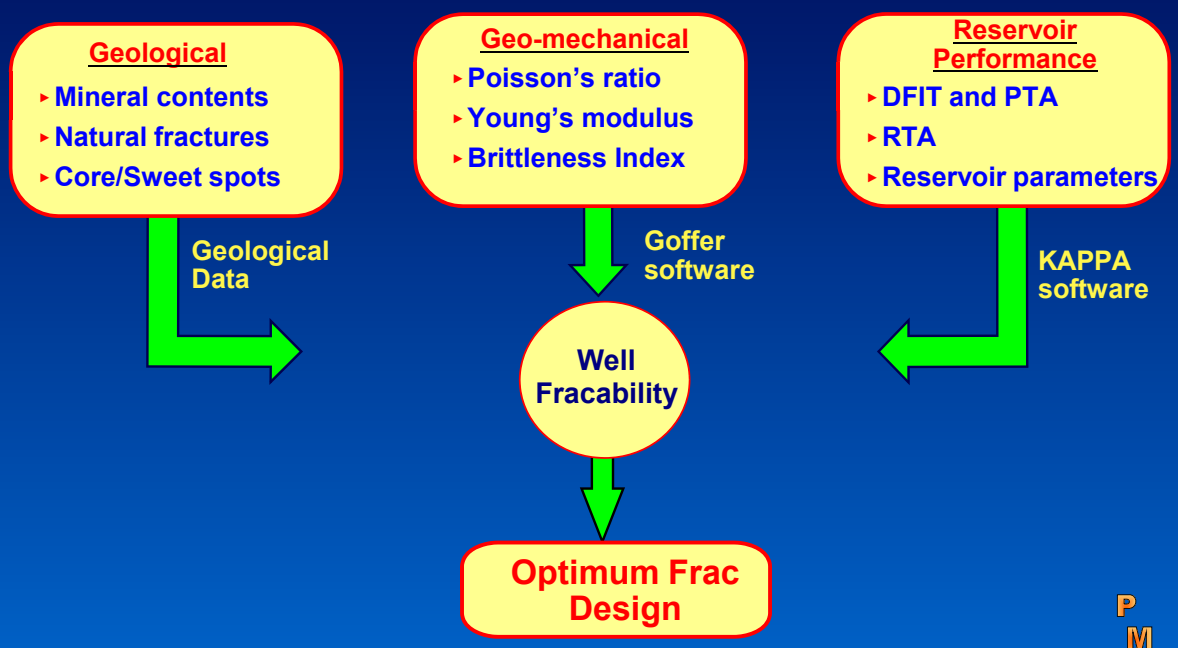
Petro Management Group - FracKnowledge

Full Well Frac Design and Optimization Services:



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Tight/Unconventional Oil and Gas

Agenda:

- Introduction
- Reservoir characteristics of conventional vs. tight/unconventional
- Conventional methods of estimating reserves
- Methods used for tight/unconventional reserves estimate
- Case study
- Closing comments

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Reserves Booking is Critical to E&P

- Share holders
- Managers/supervisors
- Even the employees...

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Why Reserves Estimate has been a Challenge?

Because....

- It relies on interpretations
- Reservoir engineering is not an accurate science
- Reserve's estimate is dependant on available technology
- Tight/unconventional reservoirs are more difficult to evaluate
- It depends on what the boss wants...(political)
- You need a good crystal ball !

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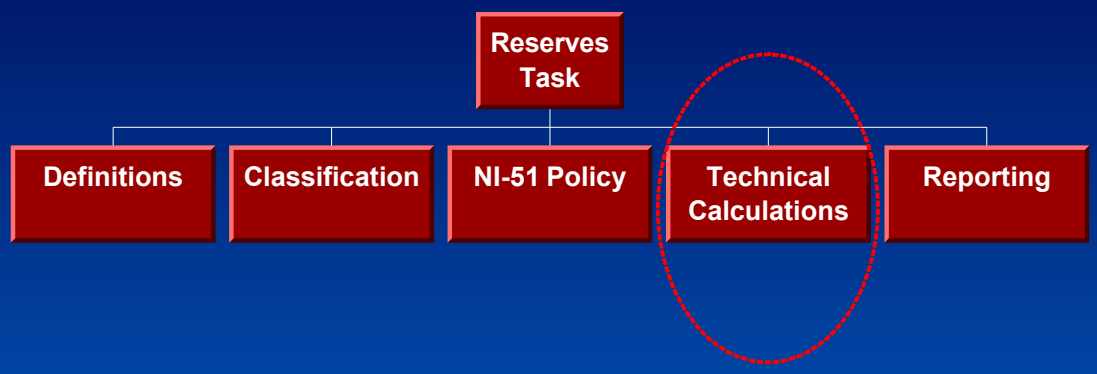
Task of Reserves Estimate



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Tight and Unconventional Oil and Gas

- Tight gas/oil sands
- Shale Gas
- shale oil and oil shale!!
- CBM

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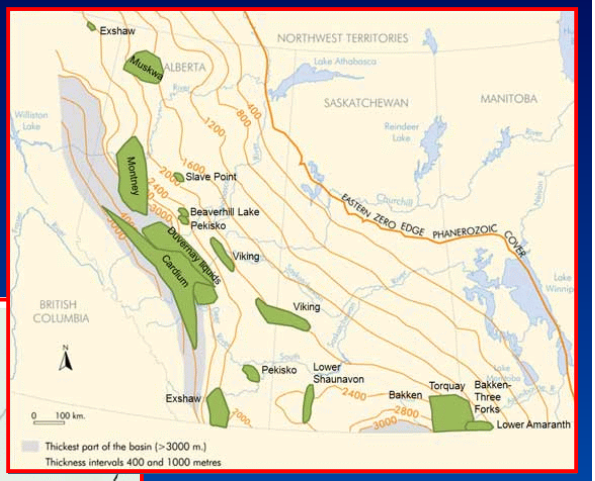
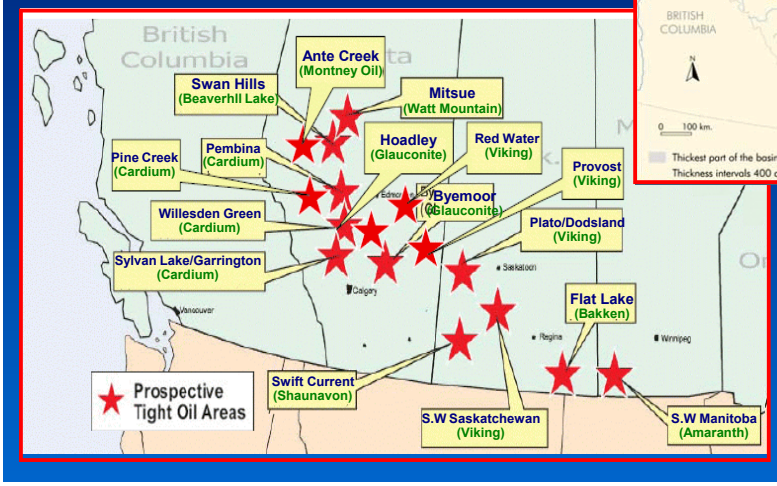
Tight Oil Plays in Western Canada

Hoadley (Glauconite) is a gas play but with high liquid yield





Source: Scotia Capital

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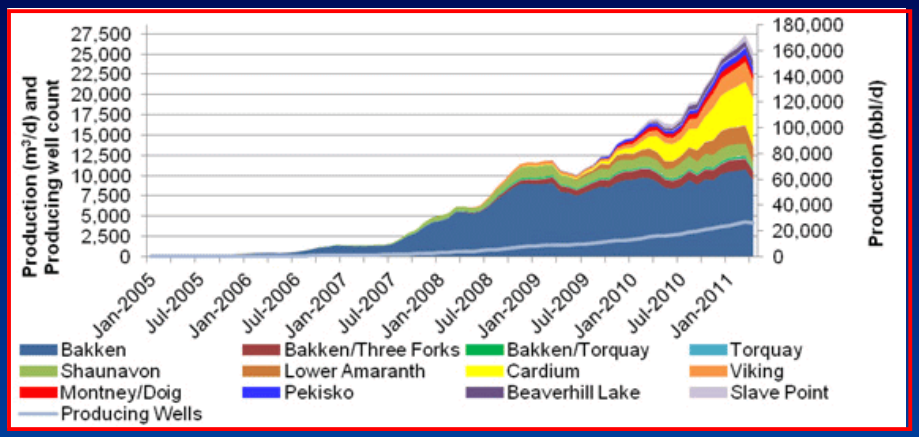
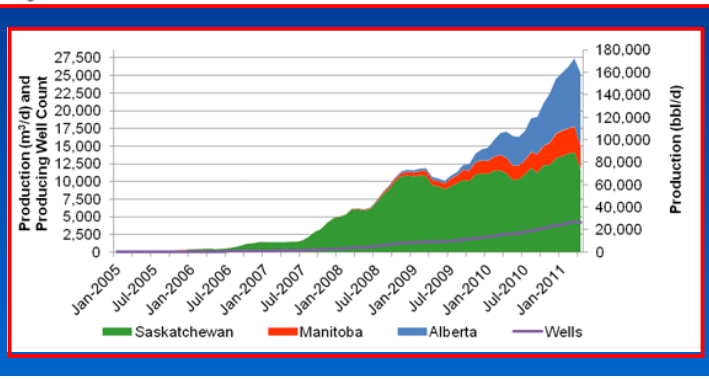
Canadian Tight Oil Production by Play





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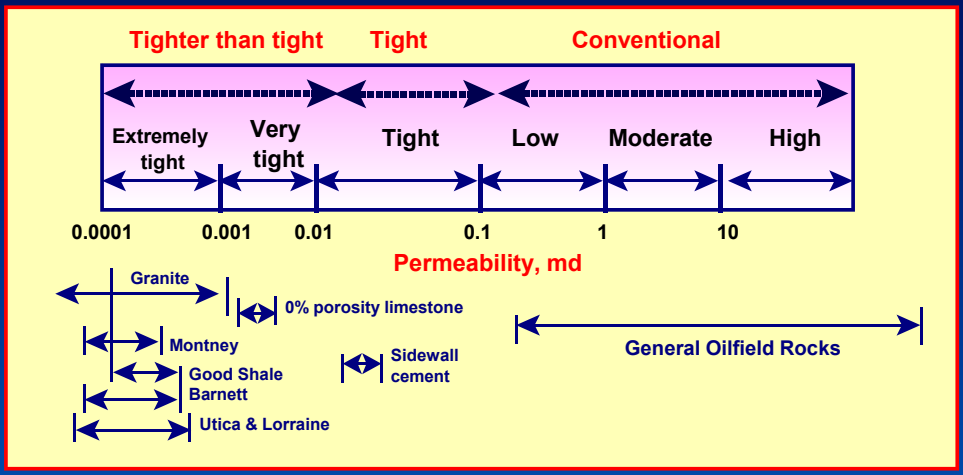
Permeability Terminology



Source: US Department of Energy Study

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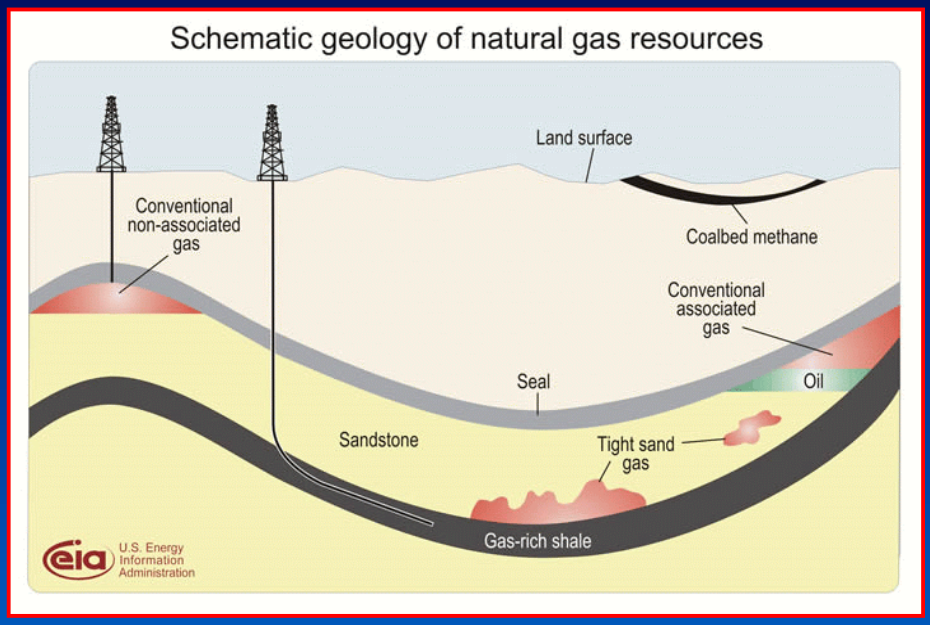
Conventional vs. Tight/unconventional



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Conventional vs. Tight/unconventional

Conventional:

- Localized structural trap
- Source rock separate from reservoir
- Permeability > 0.1 md
- Reservoir as a tank
- Hydrocarbons & rock are non-reactive
- Classic methods used to estimate reserves
  - Decline analysis and PTA
  - Static Material balance
  - Volumetric method
- Long history available
- Relatively homogeneous
- Boundary dominated (P.S.S)

Tight and unconventional:

- Large and continuos
- Hydrocarbons generated from within
- Permeability in micro & nano darcy
- Does not act as a tank
- Hydrocarbons & rock are reactive
- Reserves are estimated using:
  - Rate Transient Analysis (RTA)
  - Analogs fields
  - Advanced numerical methods
- Large number of wells required
- Short history available
- Heterogeneous and natural fractures
- Transient dominated

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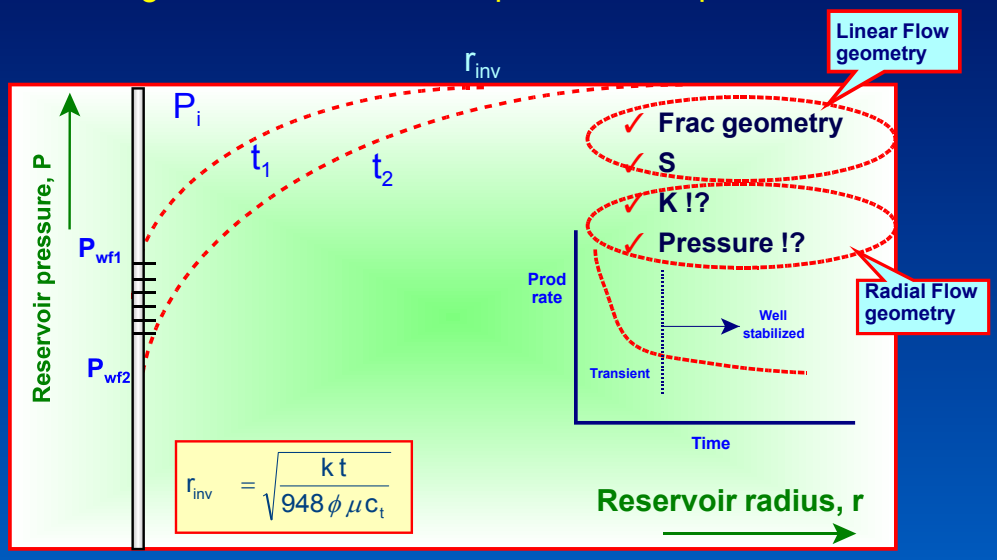
Infinite-acting (transient or non-stabilized)

- Pressure wave does not reach reservoir boundaries, it takes a long time:
  - Transient could be dominated by linear/bilinear flow regimes
  - Radial flow might not be observed, depends on the perm.



Where:

r_{inv}: Radius of investigation ft

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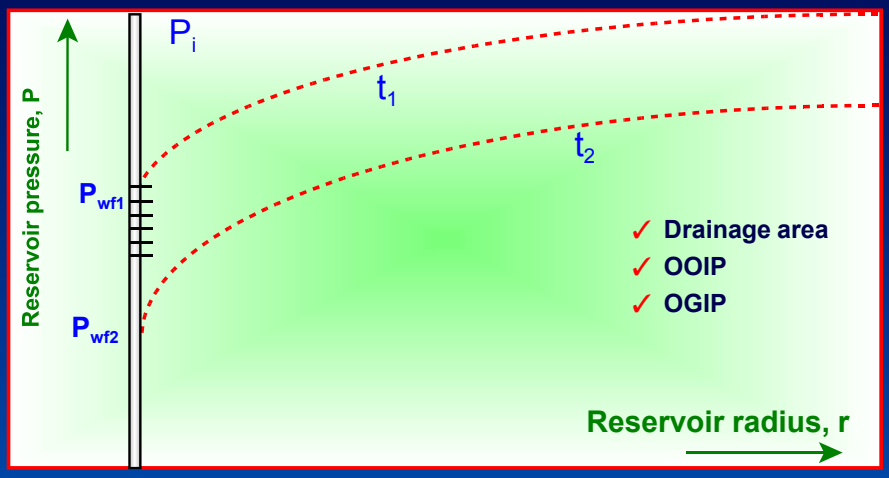
Pseudo Steady State (P.S.S.) - stabilization



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- Pressure wave reaches all reservoir boundaries (P.S.S); it could take a long time:
  - Montney (k = 0.01 md) - takes over 1 year
  - Shale gas (k=0.001 - 0.0001md) - takes at least 3 to 4 yrs

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Reserves Techniques for Conventional Reservoirs

- Volumetric calculations
- "Static" Material balance
- Decline analysis
- Pressure transient analysis (PTA) - well testing

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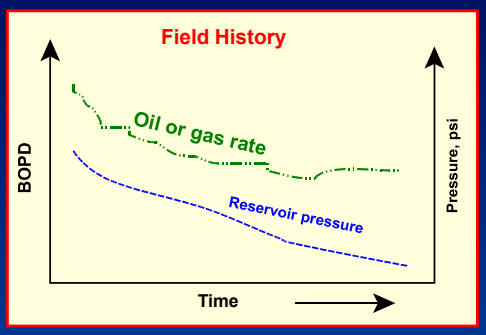
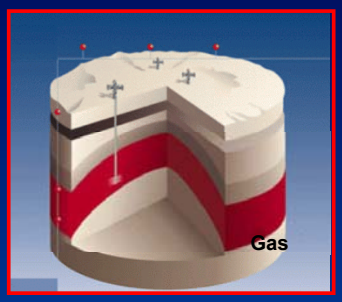
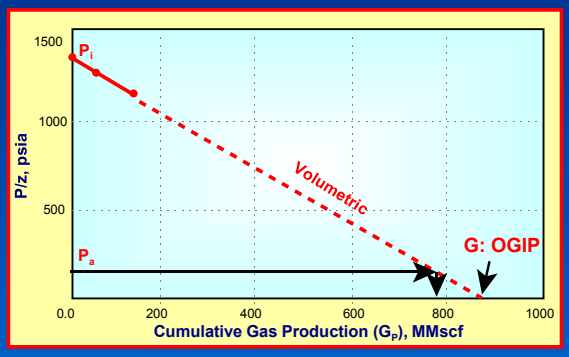
"Static" Material Balance





Requirements:

- Good "static" pressure history
- Reservoir acts like a tank
- Production of at least 10% of total reserves



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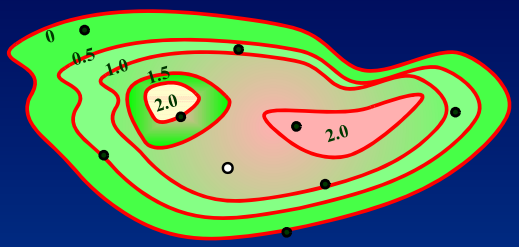
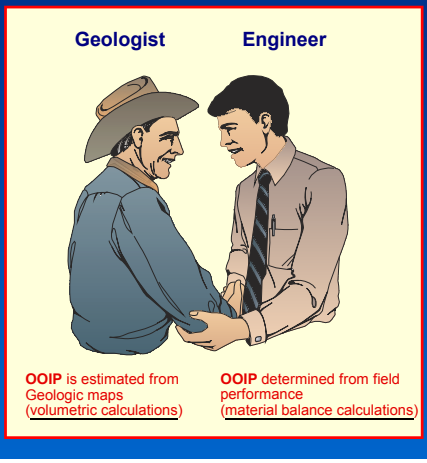
Consistency of Volumetric OOIP/OGIP



Net pay map

Volumetric (**Geology**) vs. Material Balance (**engineering**)



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Type Curve Analysis (DCA)

(by Arps in 1945)

General formula:

$$q_t = \frac{q_i}{(1 + bD_i t)^{1/b}}$$

Type		Rate	Remaining Reserves
Exponential	b=0	$q_t = q_i \cdot e^{-Dt}$	$Q_t = \frac{1}{D_i}(q_i - q_t)$
Hyperbolic	0 < b <1	$q_t = \frac{q_i}{(1 + bD_i t)^{1/b}}$	$Q_t = \left[\frac{q_i}{D_i(1-b)}\right] \cdot \left[1 - \left(\frac{q_t}{q_i}\right)^{1-b}\right]$
Harmonic	b=1	$q_t = \frac{q_i}{(1 + D_i t)}$	$Q_t = \left(\frac{q_i}{D_i}\right) \ln\left(\frac{q_i}{q_t}\right)$

Where:

- D_i: Initial decline constant
- q_i: Initial producing rate
- q_t: Producing rate at time "t"
- Q_t: Cumulative production at time "t"
- b: Exponent

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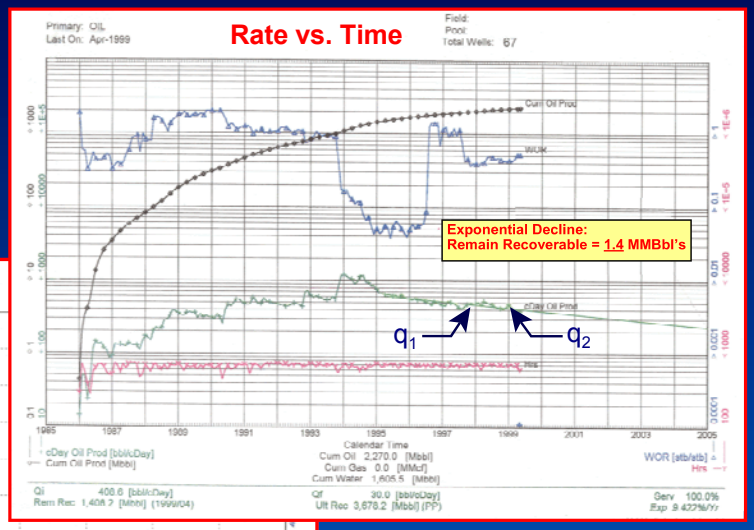
Use of Exponential Decline Curve

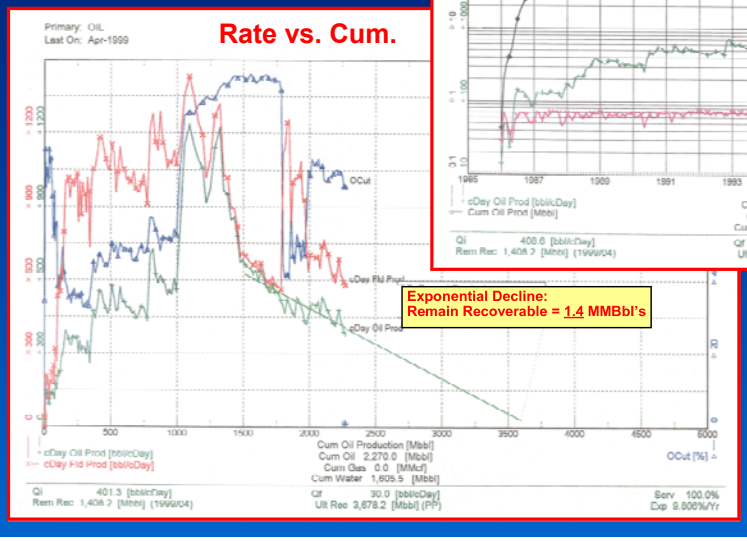
Decline Constant (D_i):

$D_i = \text{Ln}(q_1/q_2) / \text{time}$

Decline rate (P), %:

$$P = 1 - e^{-Dt}$$





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Main Assumptions in Decline Analysis

- Well is producing at or near capacity
- Well is producing at a constant BHFP
- Well is producing under boundary-dominated conditions (P.S.S)
- Reservoir acts like a tank model

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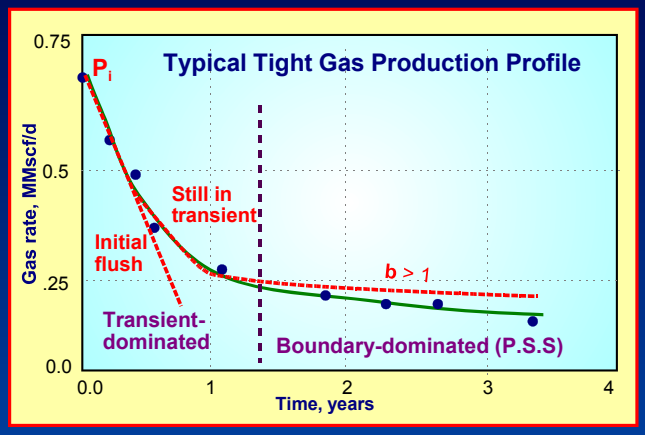
Abuse of Decline Curve Analysis!



Use of transient data will yield errors:

- **Early transient flush production** data will yield limited reserves (low)
- Use of **transient after flush production** data will yield optimistic reserves, as "b" could higher than a value of 1.

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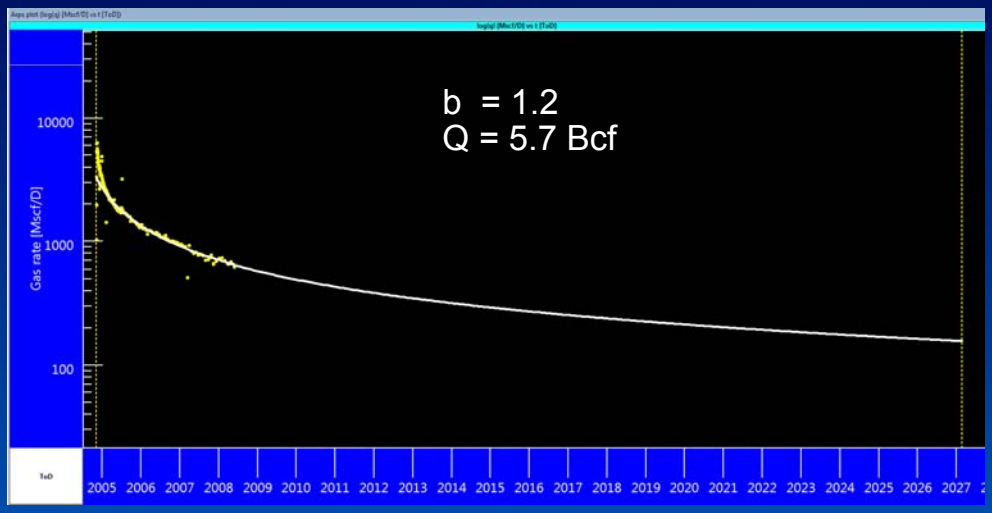
Hyperbolic Decline Curve Analysis During Transient (b>1.0)



- Non-unique solution, with reserves varying from 5.7 Bcf (b =1.2) to 12.5 Bcf (b = 1.4), during transient dominated flow.
- Use of well types could be appropriate in the presence of long production history, reaching P.S.S (boundary dominated flow)

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Reserves Techniques for Tight/unconventional Reservoirs

- Improved decline curve analysis techniques
- Rate Transient Analysis (RTA)
  - Fetkovich Type Curve
  - Blasingame Type Curves
  - Flowing material balance
  - Normalized rate (Agrawal)
- Analog fields - well types
- Modelling (history matching of production/pressure history)
- Numerical techniques

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Performance Evaluation Tools Besides RTA

Facts:

RTA tools are reliable, but it take a longs time to perform and requires pressure data.....

Reality:

My boss wants me to finish my reserves evaluation for 200 wells in one week, how about decline curve analysis (DCA)?

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Evolution of Decline Analysis

- Initially introduced by Johnson and Bollens [1928]
- Improved by Arps in 1945 (fixed decline constant)
- More improvements of decline curve analysis.....

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Why Need to Use Newer DCA Methods?

- The decline analysis by Arps, should only be applied when production is stabilized; when **P.S.S** is reached
- Arps assumes that the values **"b" and "D" are constants** for the full production history, which might not be appropriate for tight formations, as transient flow can last for months if not years .
- For instance, for shale gas, initial decline in the 1st year is usually 60% to 80%. Subsequent decline rate could be 5% to 10%/yr
- Transient flow regime could last for several years, during which hyperbolic decline analysis will yield a value of "b" over 1
- Fetkovich (1990) indicated that a value of **b > 1** should not be used for reserves determination (SPE 116731)
- New decline curve analysis techniques to allow the analysis of transient data

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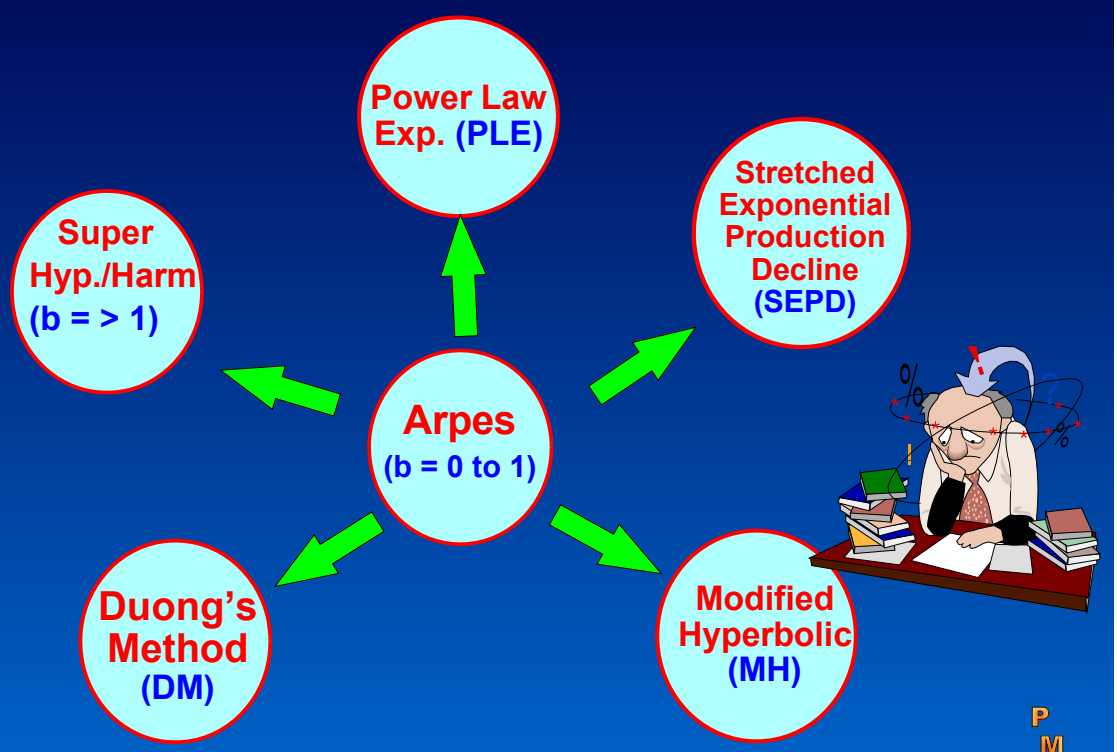
Evolution of Decline Curve Analysis



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Power Law Loss-Ratio (ILK et al - 2008) or Power Law Exponential (PLE)

Since the Contacted Reservoir Volume, is believed to increase with time, Ilk introduced a non-hyperbolic decline, where the values the of the decline constant **"D"** and **"b"** (Arps) change with time and were replaced by the parameters **D_i** , **D_∞**, and **n**, as follow:

$$D = D_\infty + D_i t^{-(1-n)} \qquad R = \frac{D_\infty}{D_i . t^{(n-1)}}$$

Where:

D_i: Decline constant at initial time
D_∞: Decline constant at infinite time
n: Time exponent
R: Power law loss-ratio (D_∞ /D_i)

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Stretched Exponential Production Decline (SEPD)

The stretched exponential decline was introduced by Valko (SPE 134231). The "SEPD" method is similar to the PLE method but without the constraining variable D_∞.

$$q = q_i \exp\left[-D_\infty t - D_i t^n\right]$$

Valko (2008) defined D_i as (1/ζ):

$$q(t) = q_i \exp\left[-(t/\tau)^n\right]$$

Where:

ζ : Characteristic time function for SEPD model

The "SEPD" method seems to yield reasonable results for **production history longer than 3 years**

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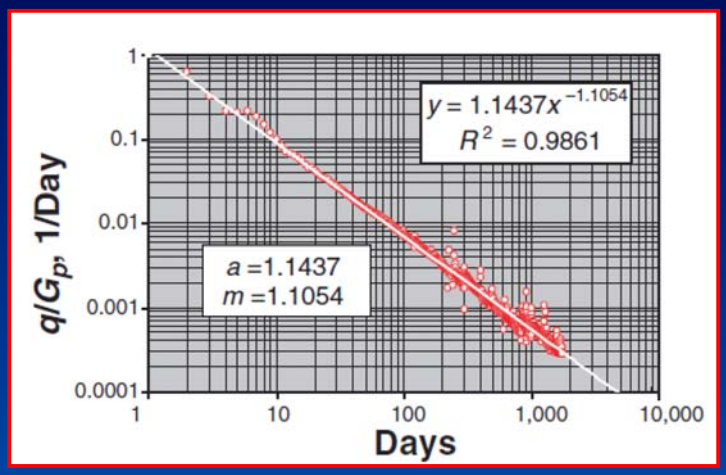
Duong Decline Method



$$\frac{q}{G_P} = a.t^{-m}$$

Graph production rate normalized to cumulative production (q/G_P) vs time on a Log-Log graph, will yield a linear trend

- m: slope of the line (m>1 for unconventional - m<1 for conventional)
- a: Intercept of the line at time value of 1
- Target for R>0.95 for good results

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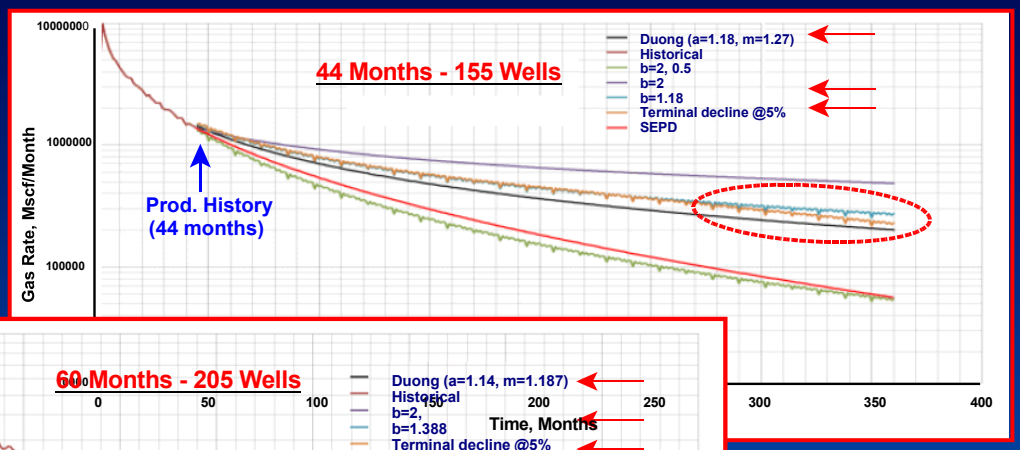
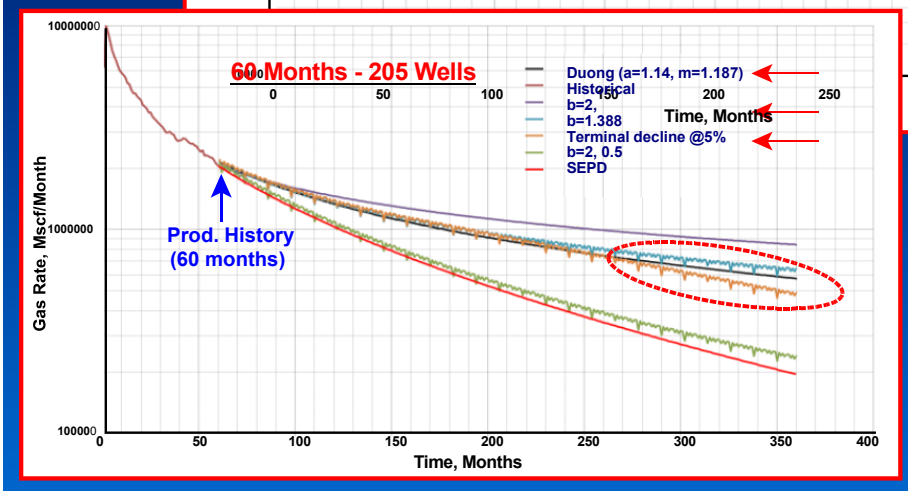
Barnett Shale – Johnson County





Middle profiles:

- b = 1.18 -1.3
- Duong
- Terminal decline @5%

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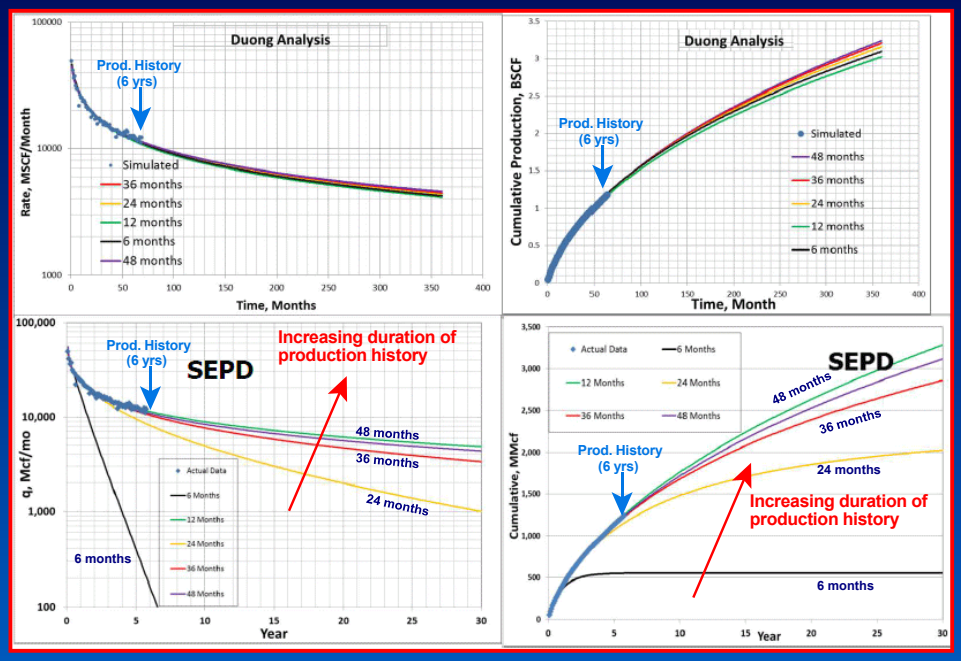
Ref: john Lee - U of H

Forecast Comparison of Duong vs. SEPD Methods At Different Production Durations



- Forecast by **Duong** is reasonable even at only **6 months** of production history
- Forecast by **SEPD** becomes reasonable after **3 yrs** of production history

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Summary of DCA Techniques

- The **Exponential decline** (constant % decline) has been traditionally used when PSS is reached; i.e for short transient flow experienced in relatively good formation permeabilities (Arps)
- **Hyperbolic** (b value up 1) and **Harmonic** (b=1) tools can be used if decline rate is not constant. However, **super Hyperbolic/Harmonic** (b>1), can be used to match transient data, but **should not be used for reserve determination** or unrealistically high reserves will result
- Newer DCA tools seem to yield reasonable reserves for tight/unconventional reservoirs, even when PSS is not reached:
  - **Power Law Exponential** Decline (PLE)
  - **Stretched Exponential Production Decline** (SEPD). Both PLE, SEPD are good for production history over 3 years, for tight/unconventional wells.
  - **Modified hyperbolic** (switch from hyperbolic to Arps when annual decline rate is approx. 5%), yields good results using "segmented decline tool"
  - **Duong's** Method yields reasonable results for short production history < 1 year

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Case Study

Arps vs Power Law Loss-Ratio

Sources: Canadian International Petroleum Conference - Paper 2009 -159

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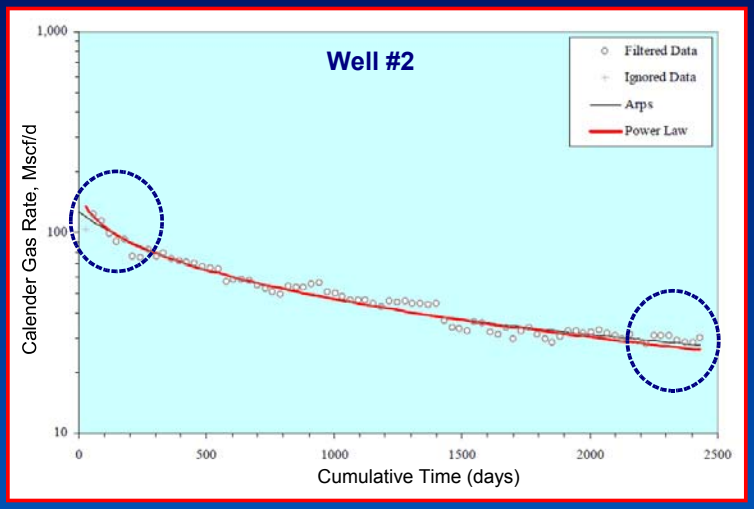
Comparison of Arps vs Power Law Loss-Ratio

A study was performed to compare analysis results of Arps vs. Power Law techniques, for 4 wells



- Power Law tends to yield a slightly better match of both early and late-time data, but let's compare the results.....

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Results Comparison of Arps vs. Power Law

Well	Arps Method			Power Law Method				
	b	q_i (Mscfd)	q_i (10^3 m^3/d)	n	$\hat{q}_i$ (Mscfd)	$\hat{q}_i$ (10^3 m^3/d)	$\hat{D}_i$	D_∞
1	0.488	309.6	8.8	0.5278	375	10.6	0.0109	7.4E-05
2	1.4	127.0	3.6	0.3442	200	5.7	0.1176	3.6E-05
3	1.2	50.3	1.4	0.2184	120	3.4	0.3136	3.3E-05
4	1.6	25.6	0.7	0.3552	50	1.4	0.2624	1.2E-05

Well	Arps Decline EUR (MMscf)	Arps Decline EUR (10^6 m^3)	Power Law EUR (MMscf)	Power Law EUR (10^6 m^3)	Discrepancy of EUR Arps vs. Power Law
1	1546	43.8	1489	42.2	+3.8%
2	380	10.8	231	6.5	+64.5
3	389	11.0	339	9.6	+14.7%
4	215	6.1	113	3.2	+90.3%

Note:

The higher the value of "b" over 1, the higher the discrepancy of the EUR between Arps and the Power Law techniques.

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Reserves Techniques for Tight/unconventional Reservoirs

- Improved decline curve analysis techniques
- Rate Transient Analysis (RTA)
  - Fetkovich Type Curve
  - Blasingame Type Curves
  - Flowing material balance
  - Normalized rate (Agrawal)
- Analog fields - well types
- Modelling (history matching of production/pressure history)
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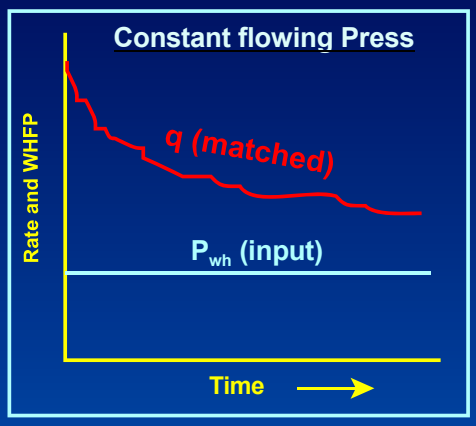
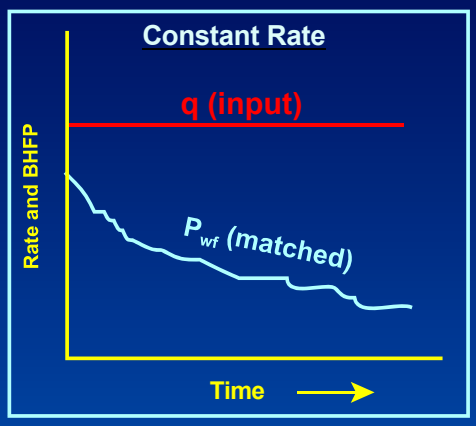
Techniques of Analysis

Rate Transient Analysis (RTA)



- Constant BHFP
- Declining production rate
- Sparse and inaccurate/noisy pressure data; usually WHFP
- Long period of production data

Pressure Transient Analysis (PTA) or Well Testing



- Constant production rate
- Declining BHFP
- Accurate and frequent measurements
- Short test duration

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Fetkovich Type Curve (Rate vs. Time)

One of the first generation of type curve matching of production history, which is based on decline analysis technique.

Limitations:

- It is based only on production data; pressure history is excluded
- It assume the BHFP is constant during the production life of the well, which is unrealistic
- Usually yield optimistic value of OOIP/OGIP

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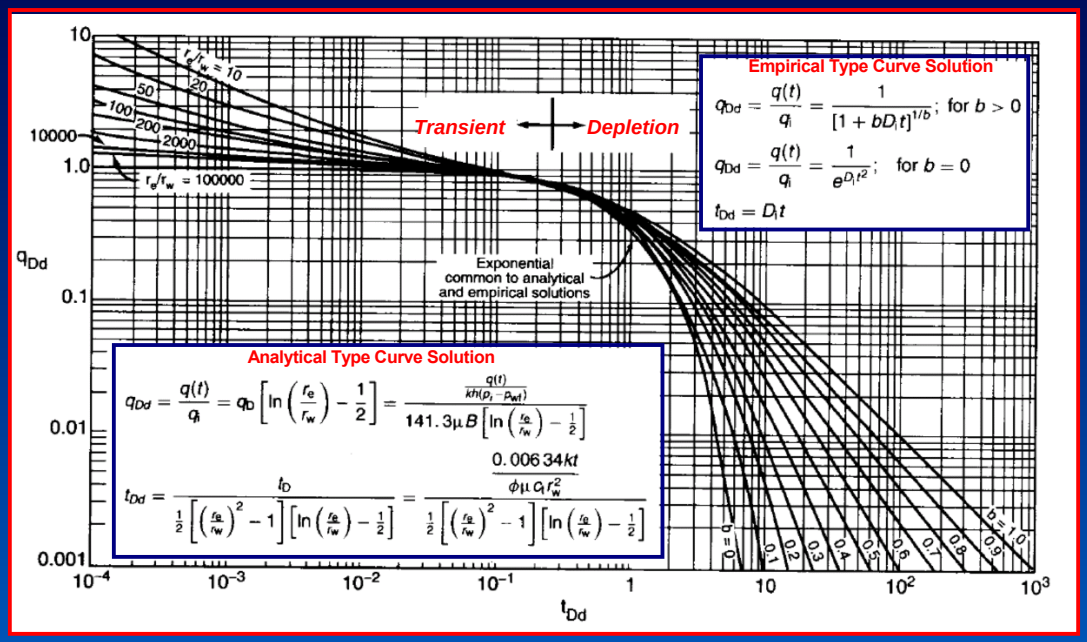
Fetkovich Type Curve (Rate vs. Time)



Transient data will yield:

- K
- S

Depletion data (P.S.S) will yield:

- Drainage area or
- Reservoir radius (r_e)

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Blasingame Type Curves

Concept:

- Analyze both **BHFP** and **production data**
- Producing rates are normalized to the draw down **$q/(P_i - P_{wf})$**, which represents the well initial productivity index, **P.I**
- Normalized production rate history is plotted against Normalized cumulative production/production rate **(N_p/q)***
- Boundary-dominated regime (P.S.S) is confirmed when the data shows a linear trend with a negative unit slope (slope = -1)
- Drainage area is then determined from the matching of production data during P.S.S regime

* Material balance pseudo time - **N_p/q** = Bbl/(Bbl/day) = time

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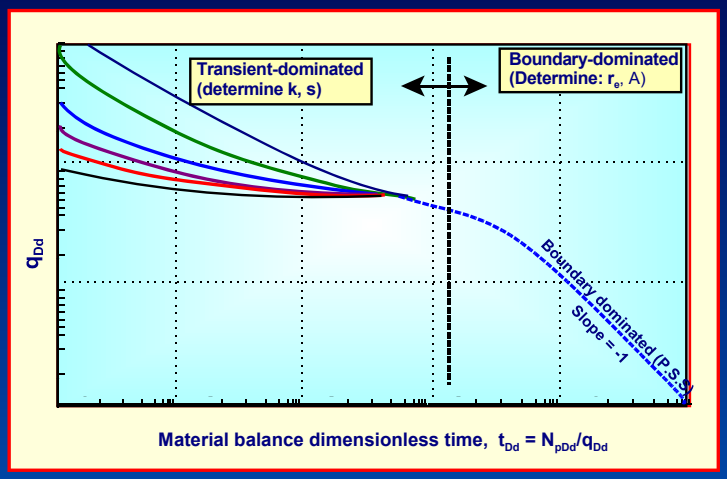
Use of Blasingame Type Curves



Method:

- WHFP's are converted to BHFP's
- Well P.I's are plotted against producing time on a log-log plot
- Overlay production data on Blasingame type-curve and obtain a match
- Determine k, s from transient data and the drainage area from the P.S.S data

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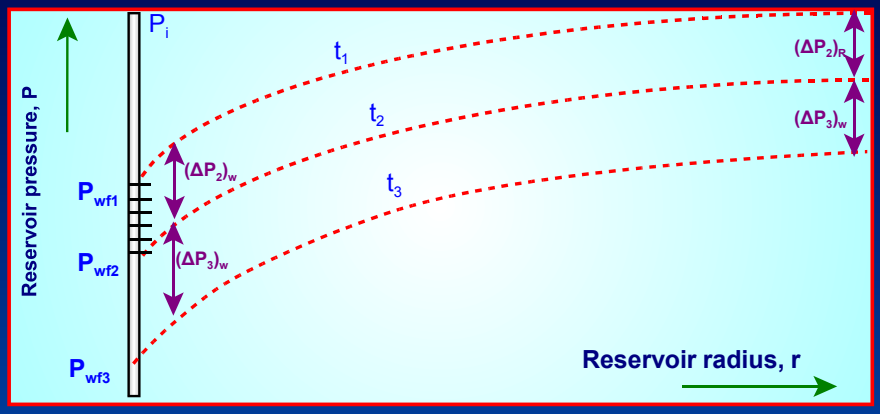
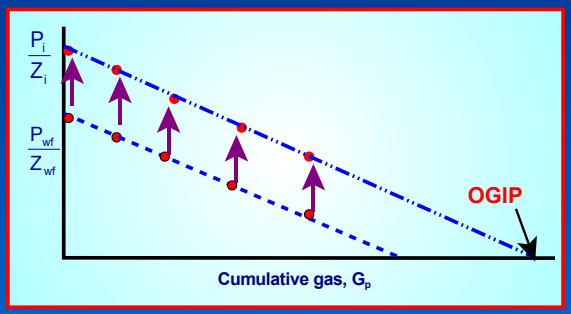
Concept of Flowing Material Balance (Gas)



PA

During P.S.S:

- Decline in BHFP and static reservoir pressure are equal
- BHFP are converted into static pressure to estimate OGIP from the P/z plot



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Reserves Techniques for Tight/unconventional Reservoirs

- Improved decline curve analysis techniques
- **R**ate **T**ransient **A**nalysis (RTA)
  - Fetkovich Type Curve
  - Blasingame Type Curves
  - Flowing material balance
  - Normalized rate (Agrawal)
- Analog fields - well types
- Modelling (history matching of production/pressure history)
- Numerical techniques

P
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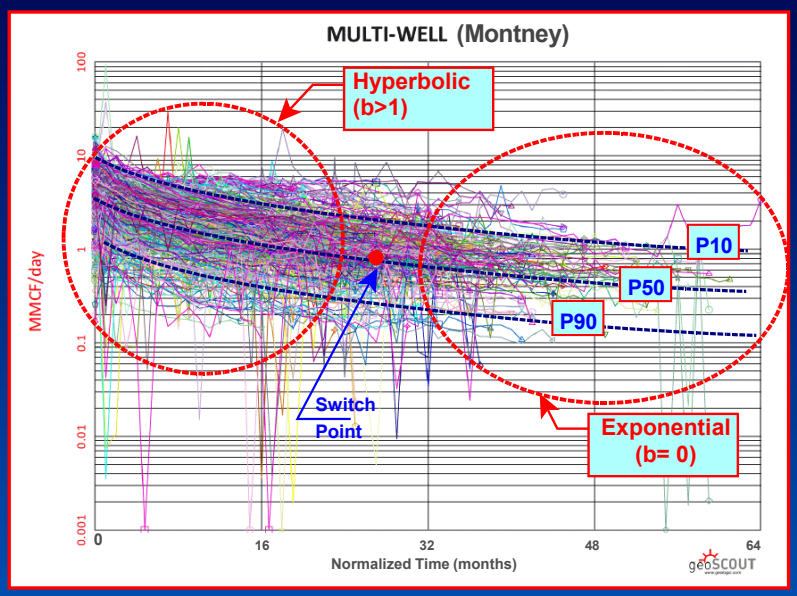
Reserve Estimates by Well Type

Commercial software:

- Harmony (Fekete)
- Citrine (KAPPA)



Literature suggests the early hyperbolic decline (b>1) be switch, when the annual decline rate reaches ≈ 5%, to the following:

- Exponential decline (b=0) - **Modified exponential**
- Hyperbolic decline (b ≈0.4 to 0.5 gas and 0.3 for oil) - **Modified hyperbolic**

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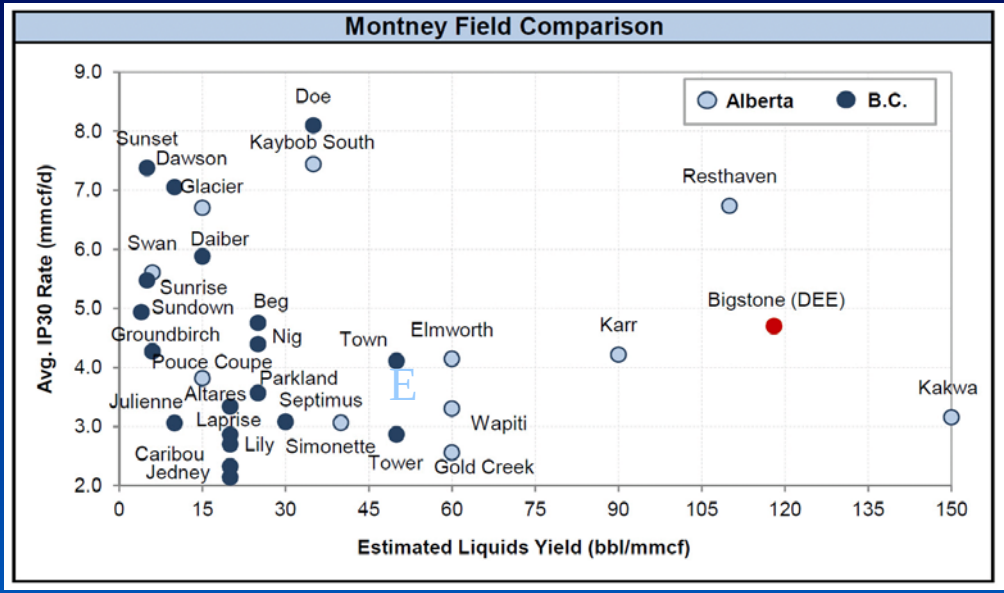
Liquid Yield - Montney



Source: National Bank from various company's presentations

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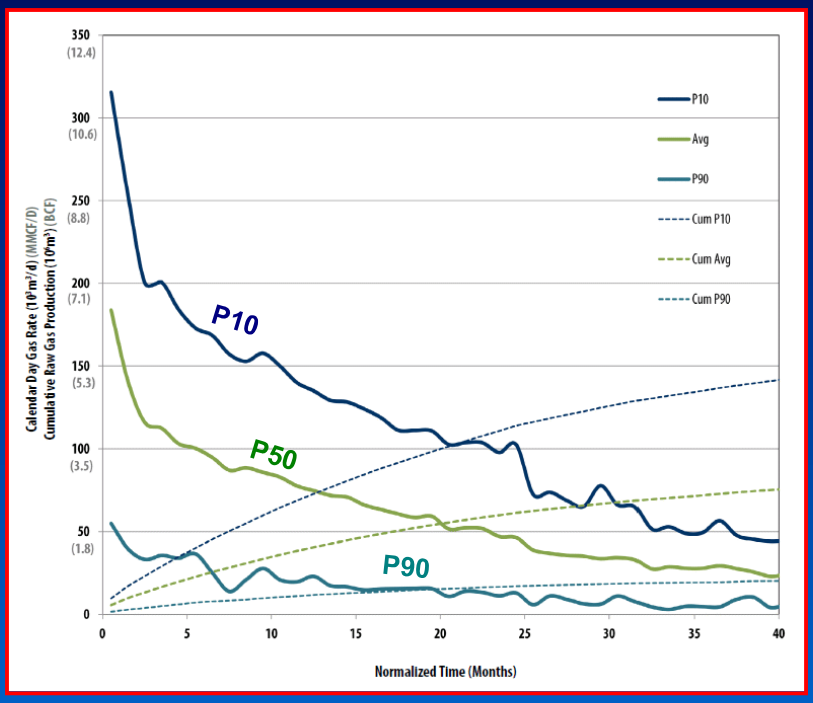
Probability of Reserves Estimated by Analogy (Horn River - B.C)



Source: AER

P
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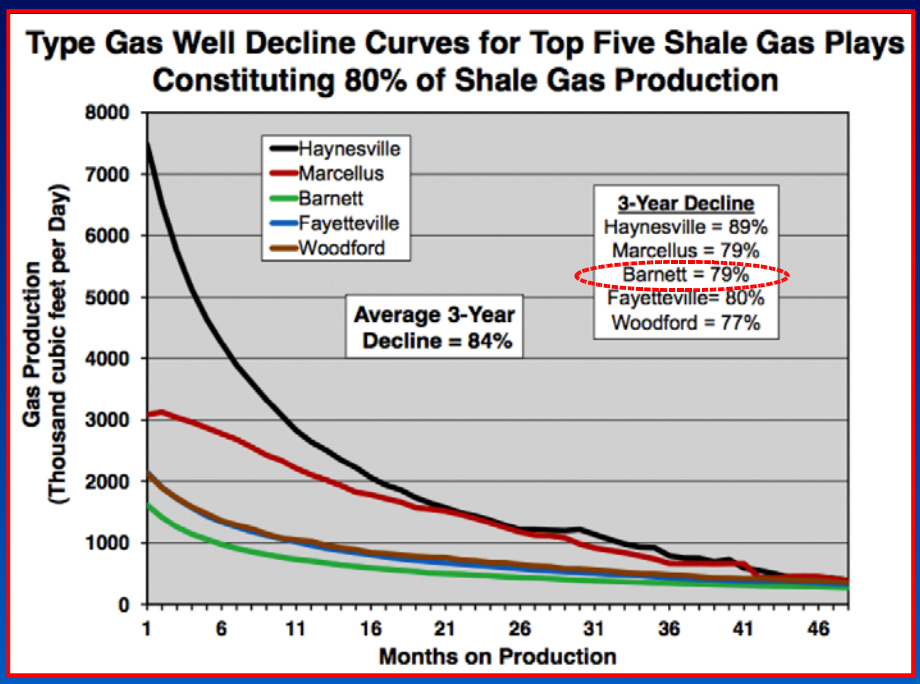
Type Wells - Shale Gas (USA)



Source: Drilling info, Dec. 2013, by Hughes GSR Inc.

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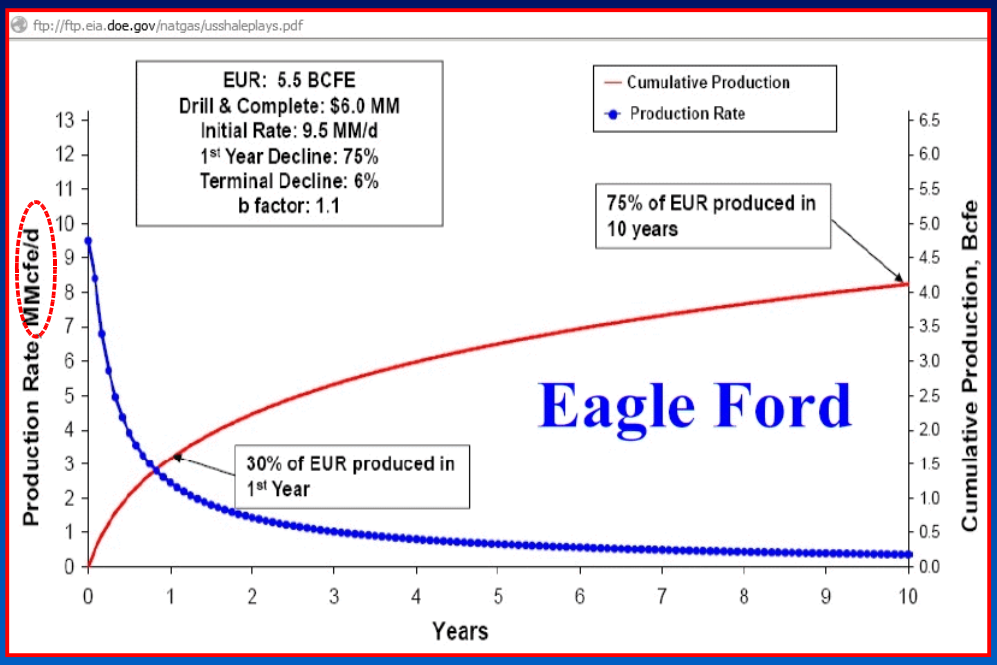
Typical Production Profile (shale gas)
(Eagle Ford - USA)



Source: DOE - USA

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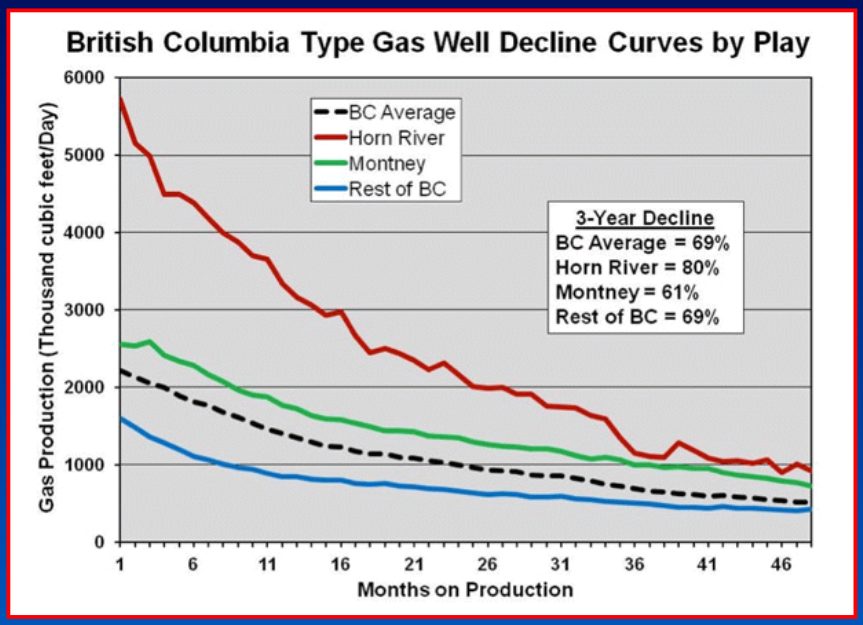
Comparison of Type Gas Wells - B.C



Source: Drilling info - Dec. 2013, by Hughes GSR Inc.

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How to Identify Flow Regimes?

- **Production history**

  Log-log graph of production vs material balance time

- **Pressure history**

  Diagnostic derivative plot

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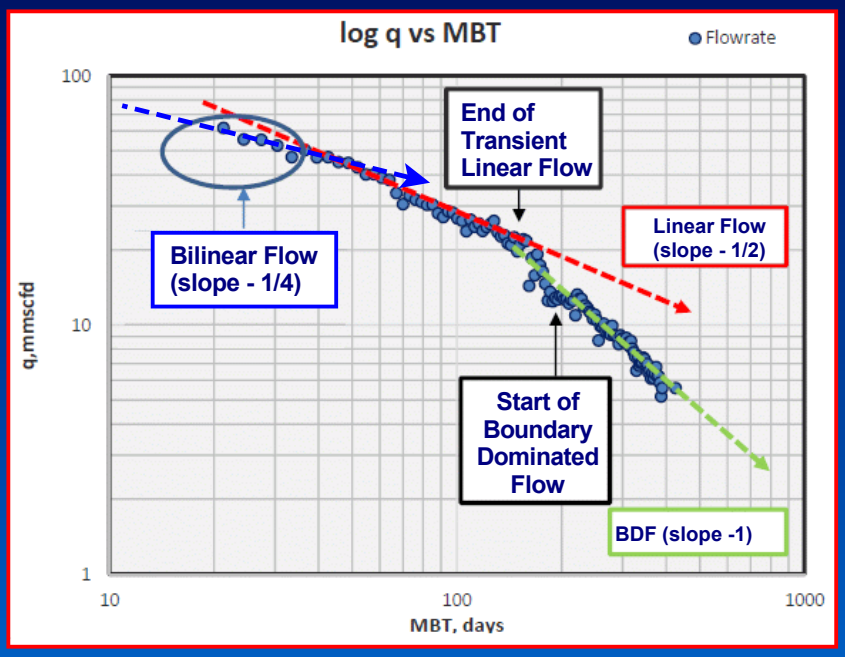
Identification of Flow Regimes
(production data only)

Source: John Lee



MBT: Material balance time - N_p/q = Bbl/(Bbl/day) = time

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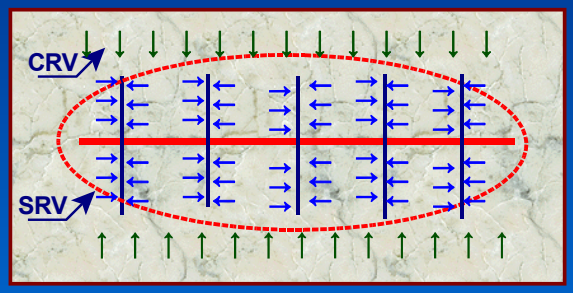
Flow Regimes for MFHW's

- Inner zone or Stimulated Reservoir Volume (**SRV**):
  - Bilinear flow
  - Main Linear
- Transition
- Outer zone (non-simulated reservoir volume or Contacted Reservoir Volume **CRV**):
  - Compound Linear
  - Transition
- Reservoir dominated (boundaries)



Play Source: Dr. Blasingame	Time of START of "Linear" flow (months)	Time of END of "Linear" flow (months)
Barnett	6	36
Fayetteville	4	16
Haynesville - LA	3	9
Haynesville - TX	4	8
Marcellus	5	20
Woodford	4	16

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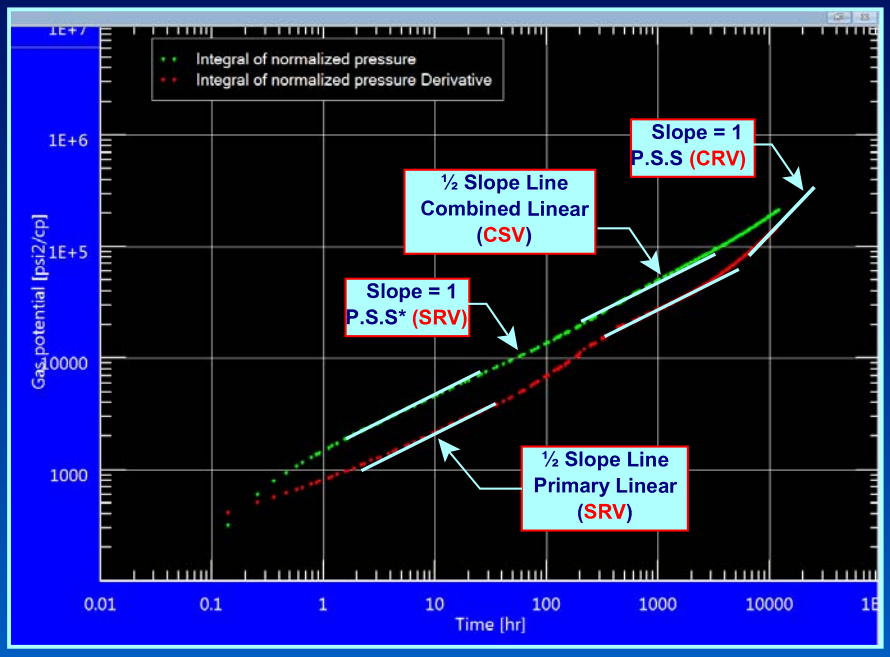
Identification of Flow Regimes
(pressure derivative plot)

1.3 yrs flow period (12,000 hrs) - k = 1.0 md



P.S.S* of only the **SRV**

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Case Study

Barnett Gas Shale (Denton)

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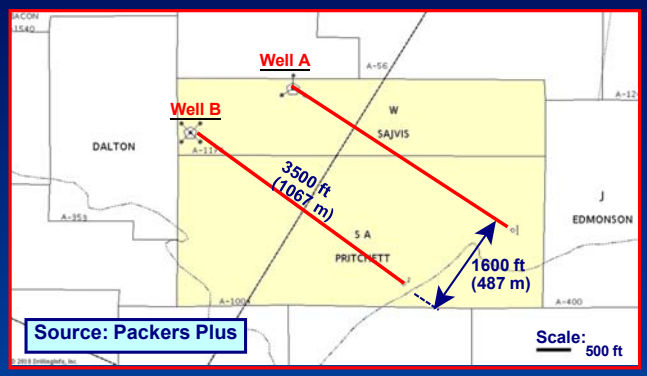
Multi-stage Frac Horizontal Wells



Start of production:

- **Well "A":** Nov. 9, 2004 open hole completion
- **Well "B"**: March 25, 2007 cased hole completion

Objectives of study:

- **Reserves estimate**
- Optimize Hz well spacing
- Determine formation parameters
- Compare well performance: frac techniques of open hole vs cased

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Analysis Step-by-Step

Procedures:

- **Flow regime diagnoses**
  - Pressure Derivative plot
  - Rate vs time (log-log plot)
  - Square Root of time vs pressure plot
- **Rate Transient Analysis (RTA)**
  - Fetkovich, Blasingame, and Agarwal type curves
  - Flowing material balance
- **Decline analysis**
  - Arps
  - Power Law Loss-ratio
- History matching of production/pressure data (**analytical**)
- Numerical output

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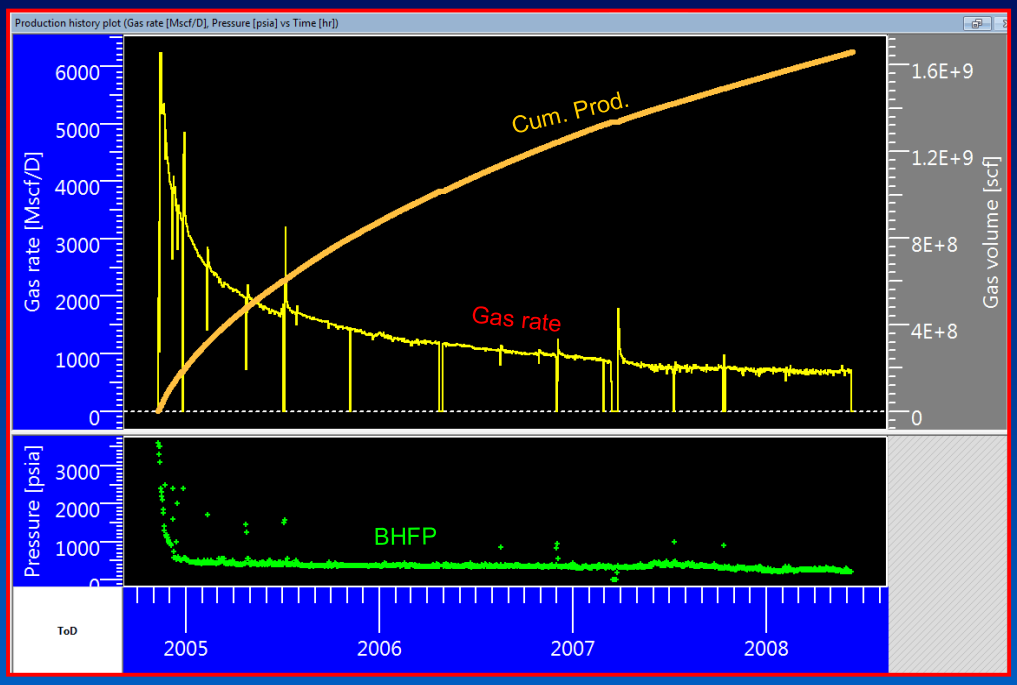
Production/Pressure History

Well "A"



Decline rate during 1st year = 76%

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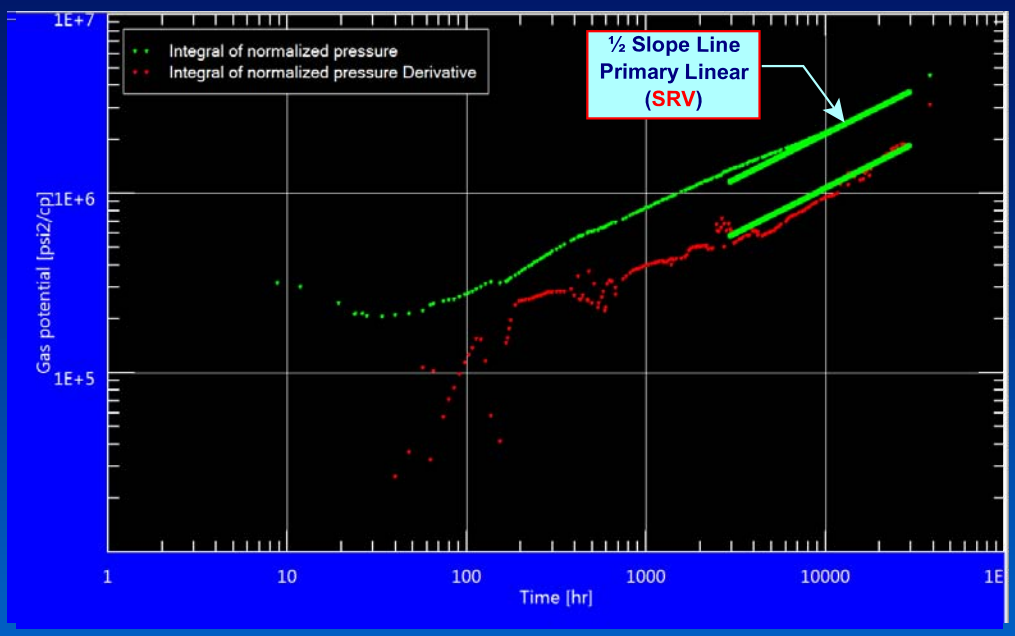
Identification of Flow Regimes

(Pressure Derivative/Diagnostic Plot)

Well "A"



Pressure history is dominated by "Linear flow geometry"

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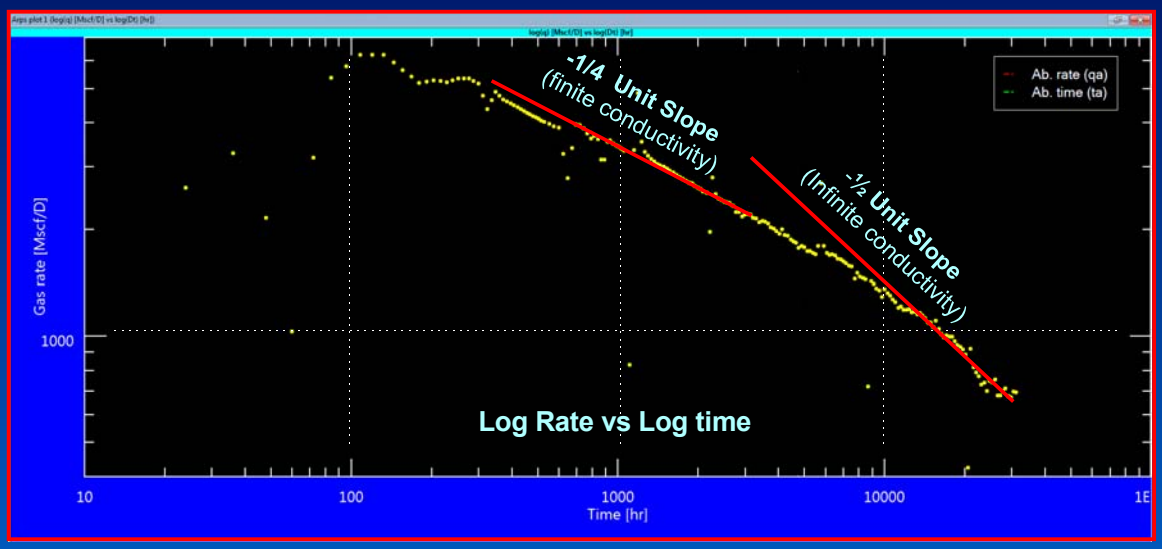
Identification of Flow Regimes
(Use of Production History)

Well "A"



Mixed fracture conductivity is evident (finite and infinite)

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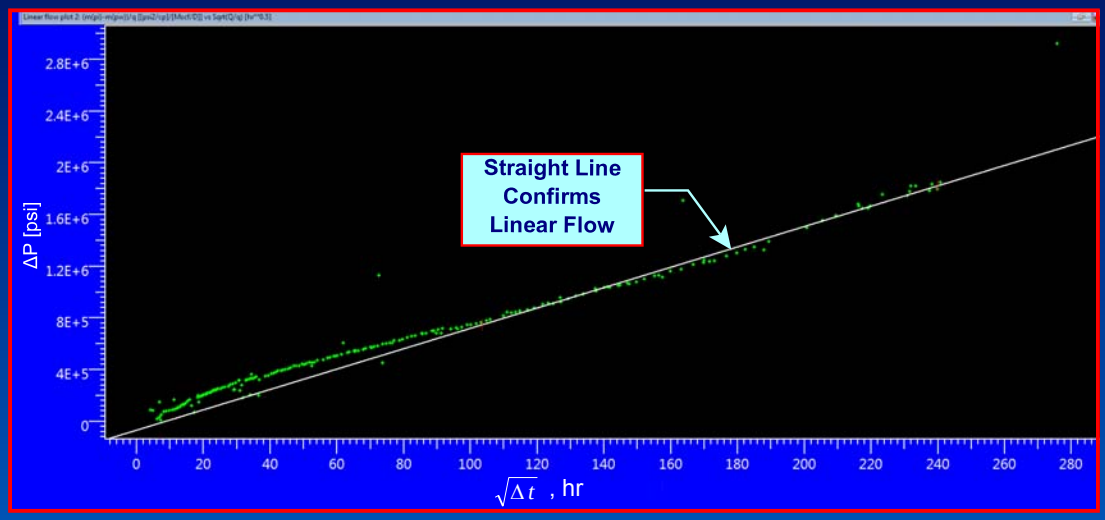
Identification of Flow Regimes
(Pressure vs $\sqrt{\Delta t}$ time)

Well "A"



Average fracture half-length (X_f) could be estimated from slope of the line, during linear flow

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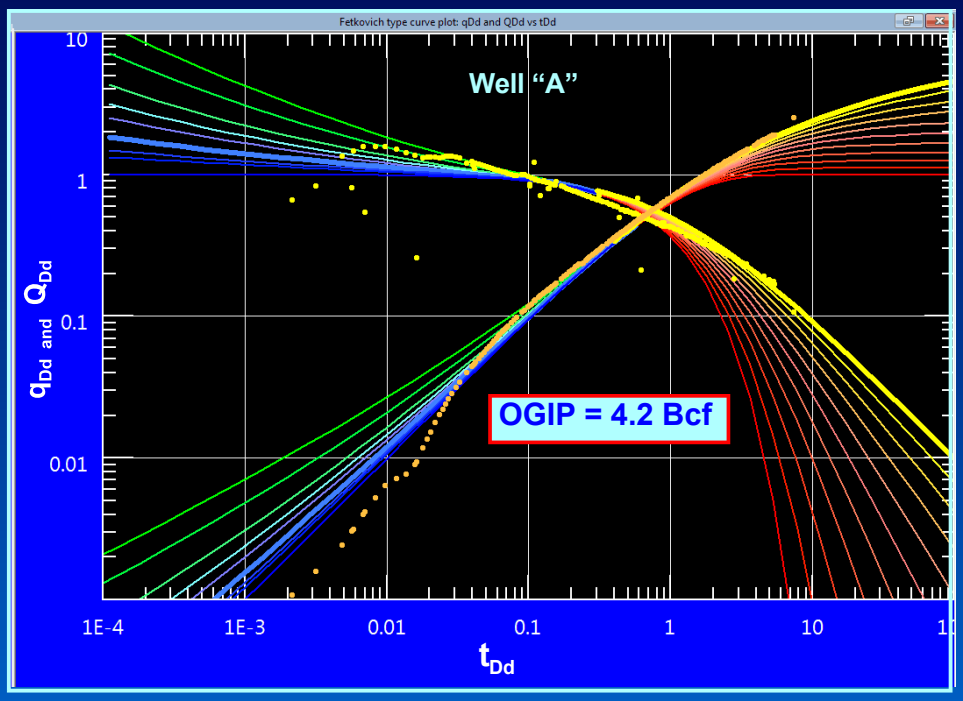
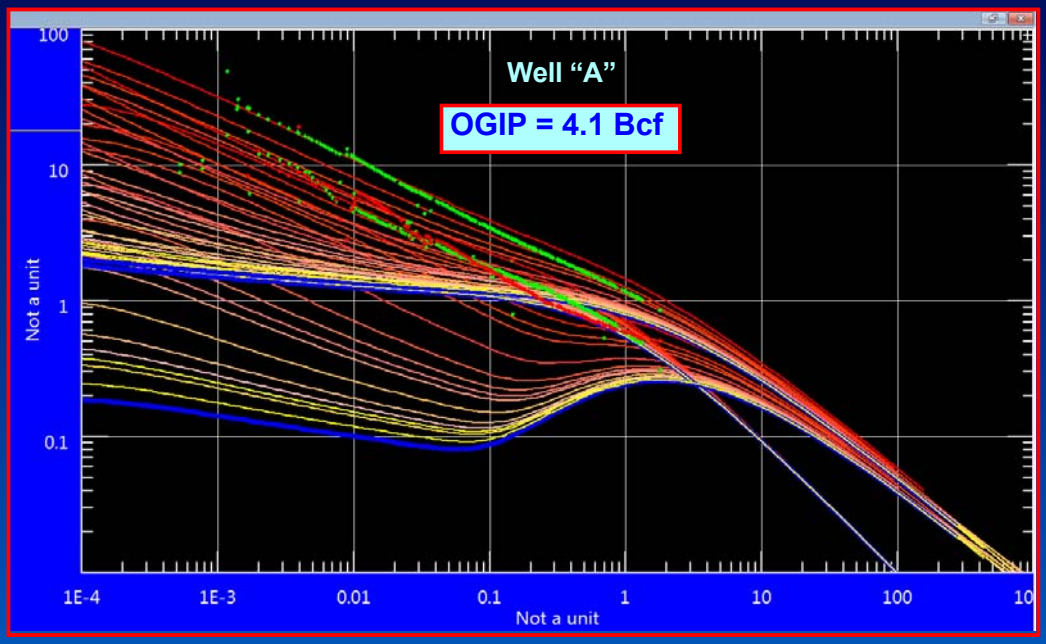
Fetkovich Type Curve Matching



Blasingame Type Curve



- Est. of drainage area from production history (SRV)
- Use estimated OGIP to improve the match of the production/pressure history

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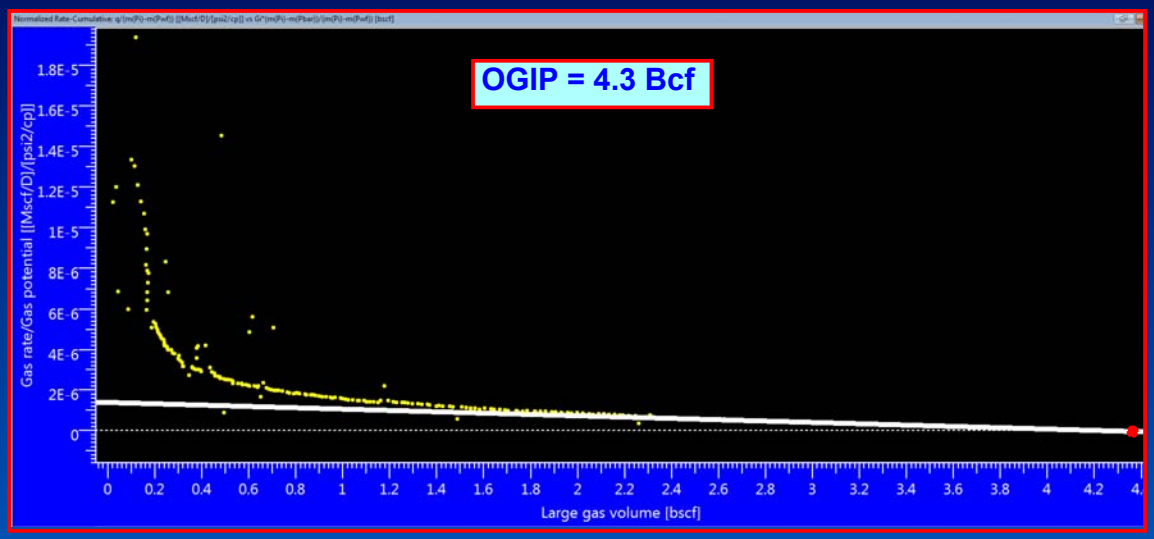
Normalized Rate-Cumulative (Agarwal)

Well "A"



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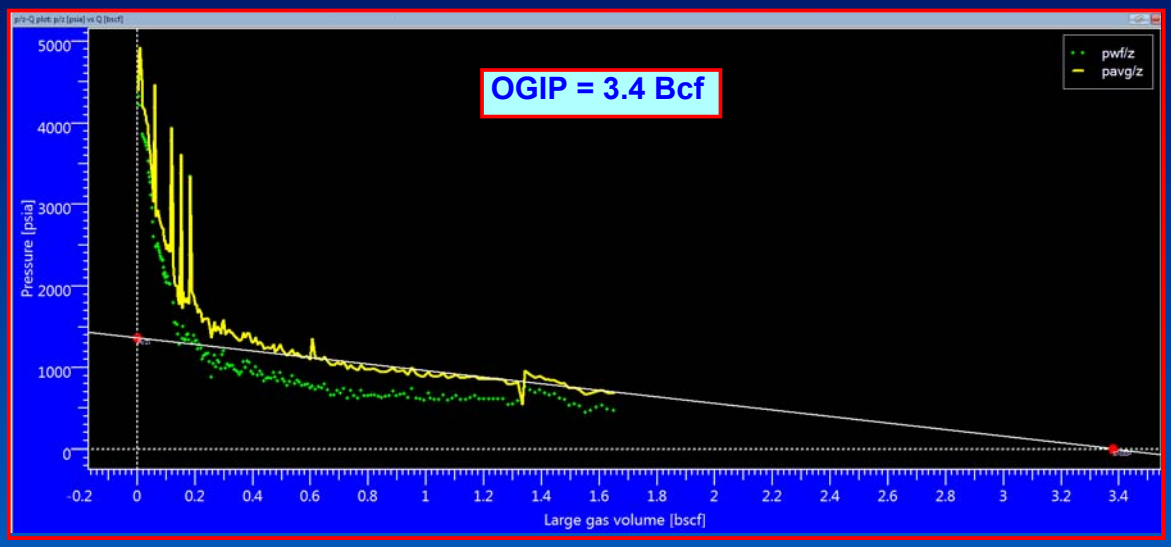
Flowing Material Balance
(Excluding Desorption)

Well "A"



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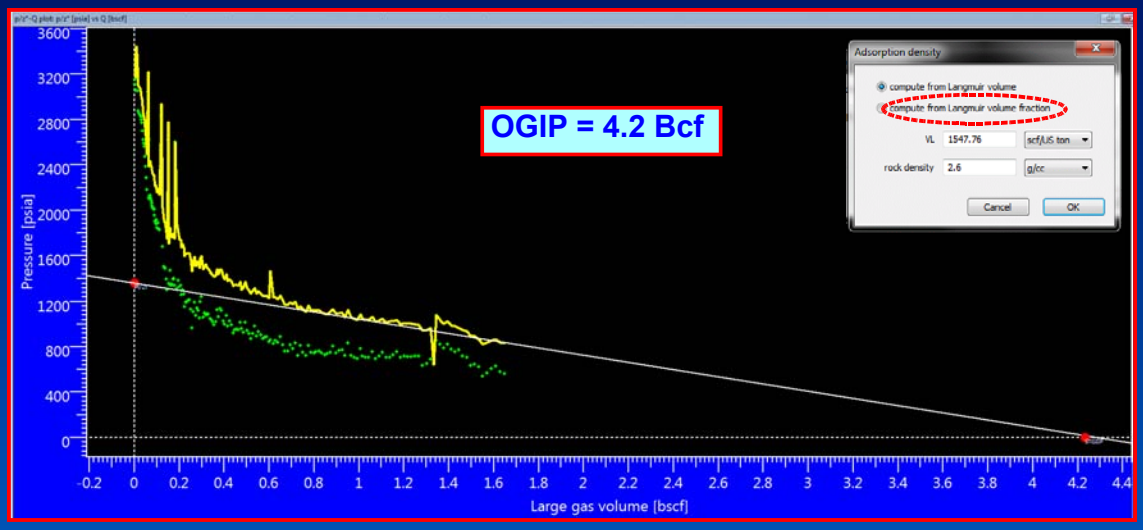
Flowing Material Balance
(including Desorption)

Well "A"



Include shale properties; Langmuir volume constant and density

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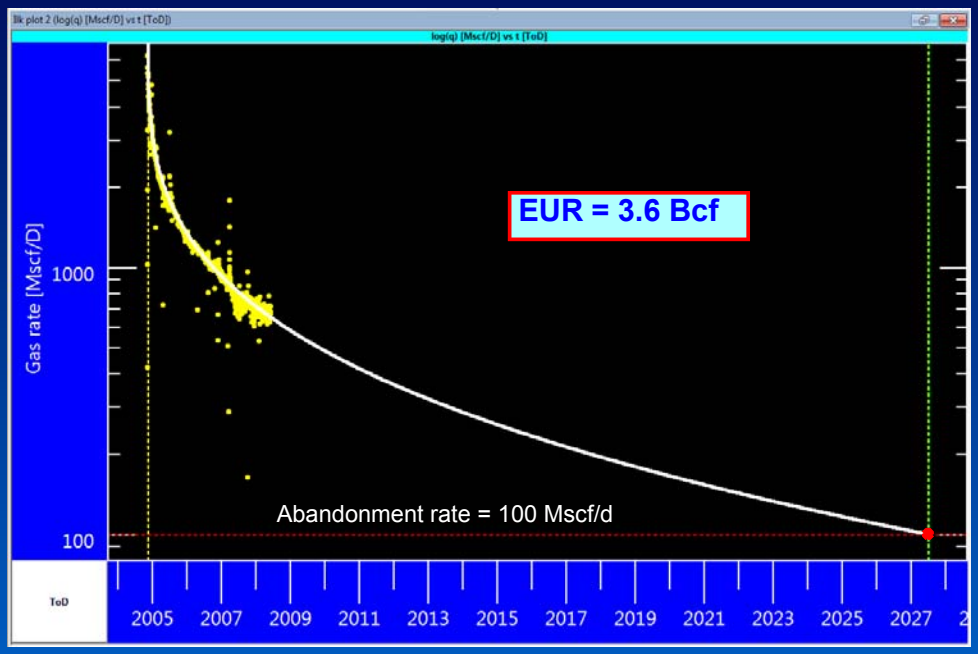
Power Law Exponential (PLE)

Well "A"



Remaining production life = 22.7 years

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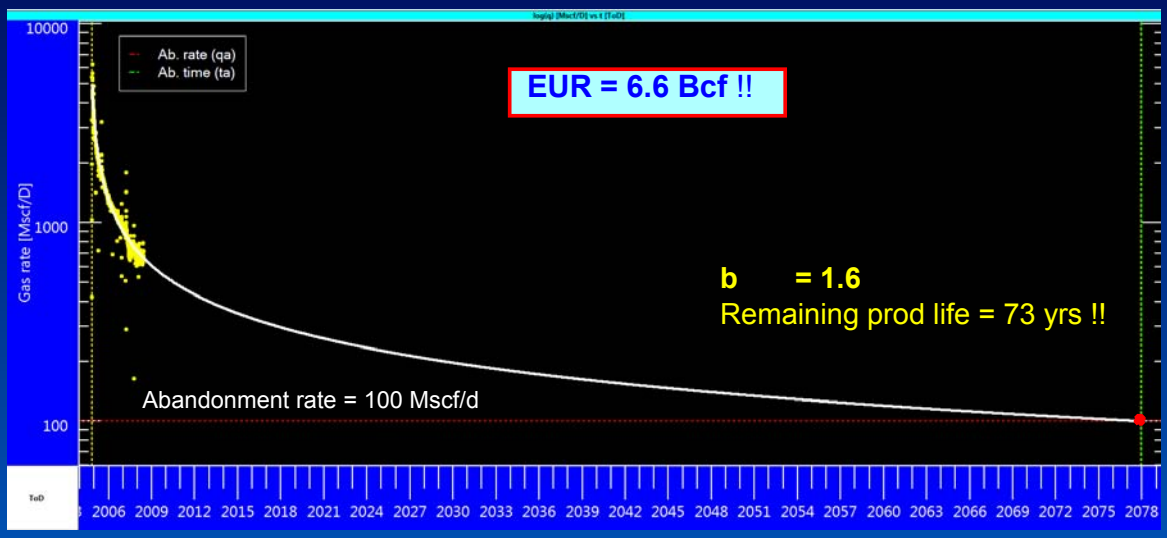
Decline Analysis (hyperbolic)

Well "A"



Excessive EUR is obtained from decline analysis;
Nearly **83.3%** higher than the Power Law Exponential (PLE)

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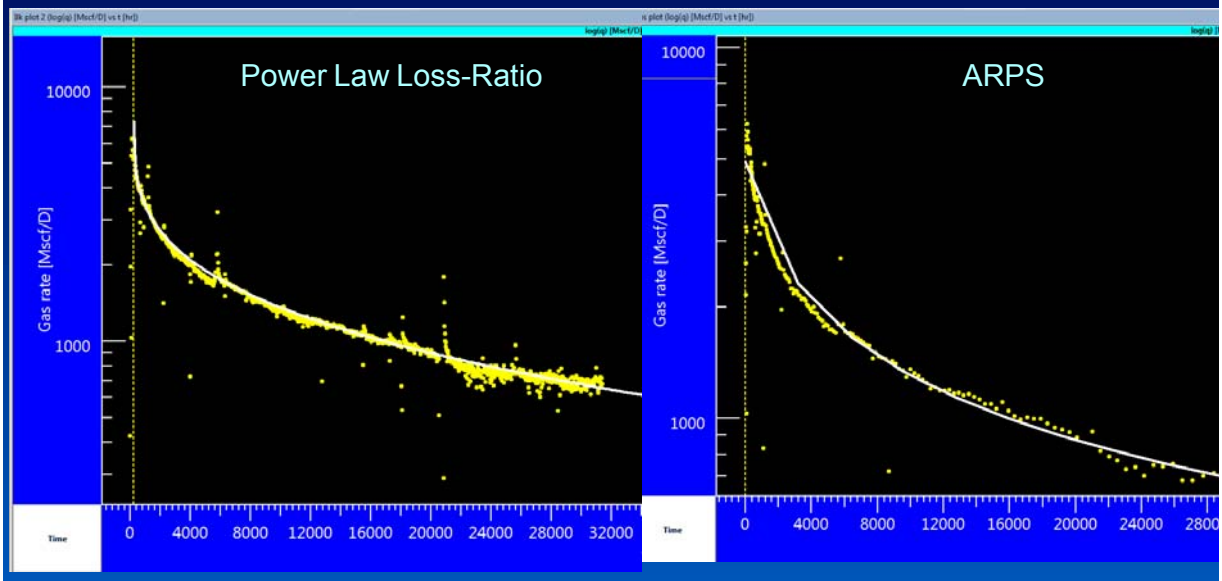
Match Comparison
(Power Law vs. ARPS)



Better match is obtained by the Power Law of both early and late time rate data

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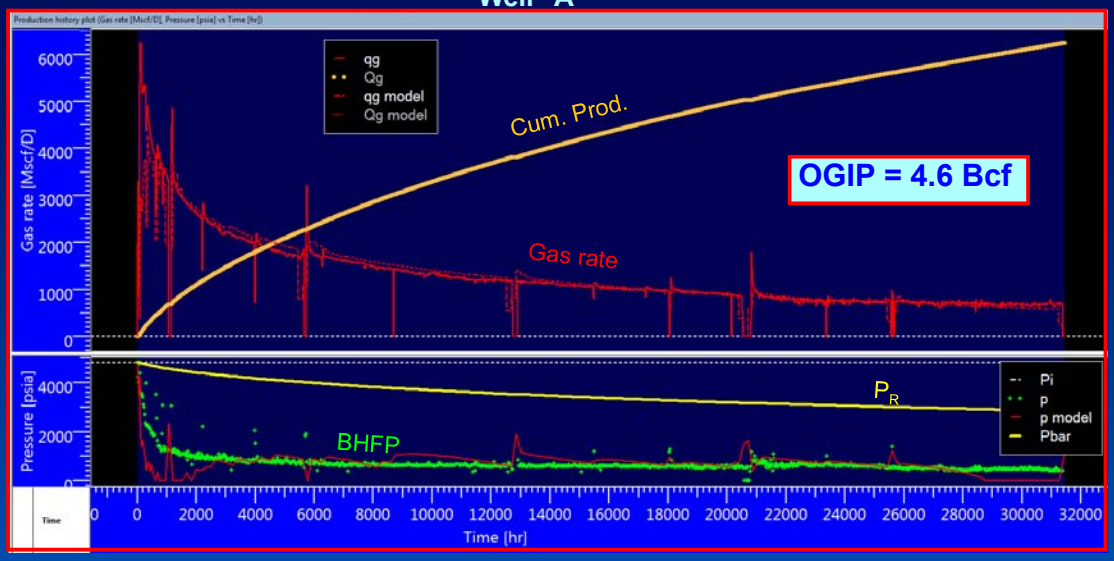
Production/Pressure History Match

Well "A"



Excellent match is achieved, placing confidence in results

Barnett "A" Well

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Summary of Results

Method	OGIP	EUR (Bcf)
Fetkovitch Type Curve	4.2	n/a
Blasingame Type Curve	4.1	n/a
Normalized Rate-cumulative (Agarwal)	4.3	n/a
Flowing Material Balance (no desorption)	~~3~~	n/a
Flowing Material Balance (with desorption)	4.2	n/a
History Matching (analytical)	4.6	n/a
Power Law Loss-Ratio	n/a	3.6
Decline Analysis (hyperbolic b = 1.6)	n/a	6.6

- Average OGIP (excluding the case with no desorption) = 4.28 Bcf
- Gas EUR: Power Law = 84.1 % - Decline analysis = 154% !!

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Why Numerical Modelling?

Benefits:

- Can account for reservoir heterogeneity (variable values of porosity, permeability and pay thickness)
- Can account for odd reservoir geometry; use actual contour maps instead of a square/rectangular shape
- Account for both transient and P.S.S flow regimes
- Visually can recognize the drainage area from isobaric animation of SRV and CRV

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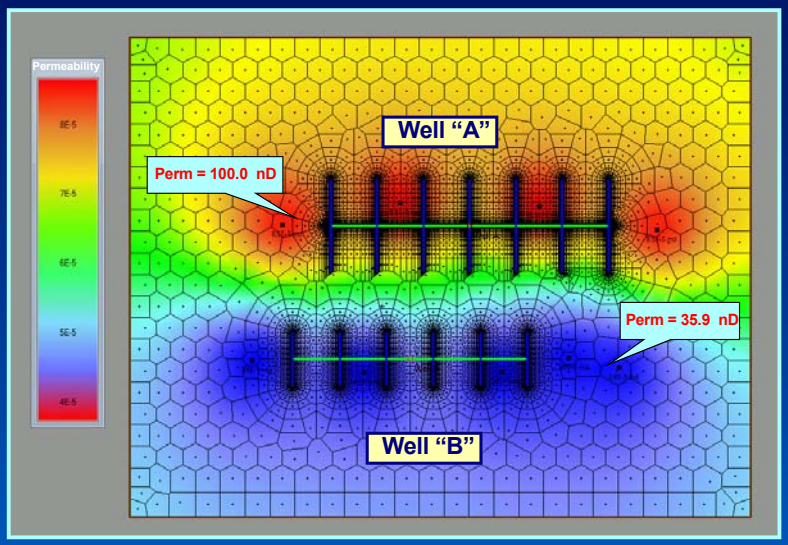
Numerical Modelling of Well's "A" and "B" (Permeability Distribution)



The pressure drop; after 4 yrs of production, has only affected the area of the reservoir that has been fraced

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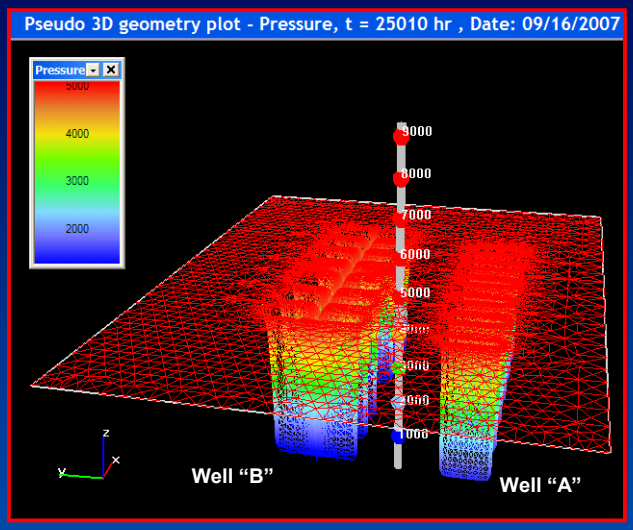
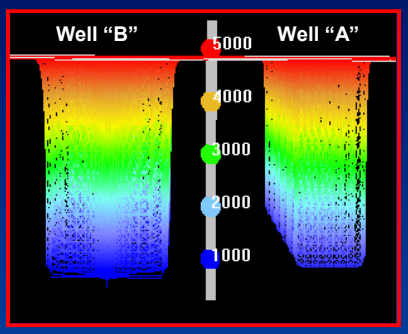
Pressure Profile (after 4 yrs of Production)





No pressure depletion between wells "A" and "B"

- Hz well spacing of 487 m is too large to allow efficient depletion of the Barnett shale.
- This conclusion is consistent with the well spacing commonly used in the Horn River (Canada), between 200 m to 300 m.

Source: Topaze software

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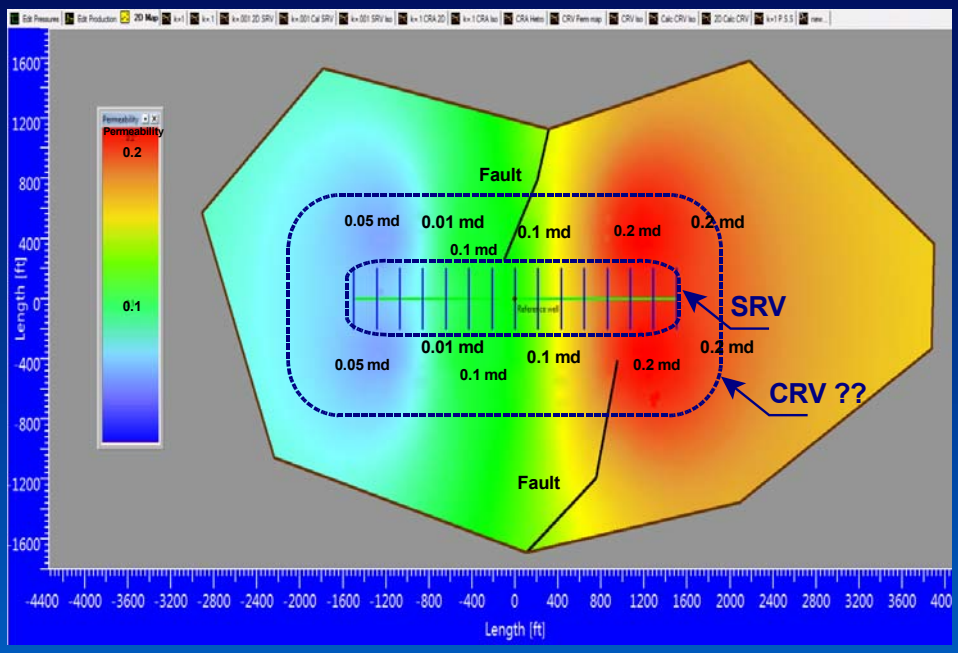
Modelling a Heterogeneous Formation



How to estimate CRV for heterogeneous reservoir?

Iso Video

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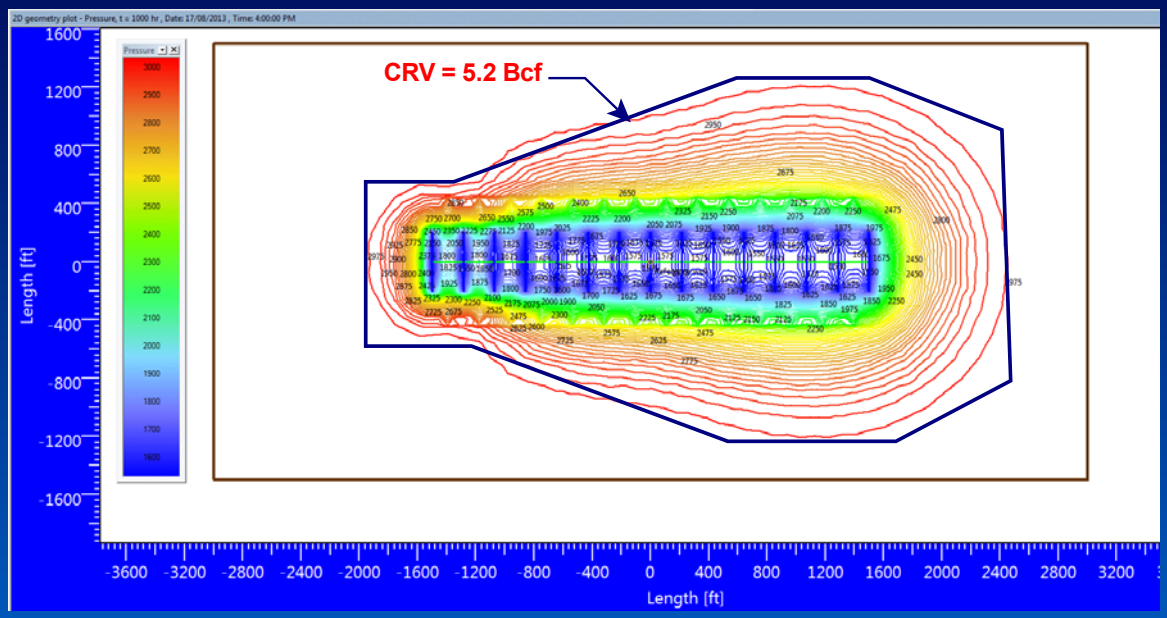
Contacted Reservoir Volume (CRV)
(Use of Iso-baric Contour Map)



CRV Topaz

Iso Video

P M G

Summary of Reserves Definitions

1. **Stimulated reservoir volume (SRV):**

   For short production periods and tight formations; production is restricted to the stimulated zone

2. **Contacted reservoir volume (CRV):**

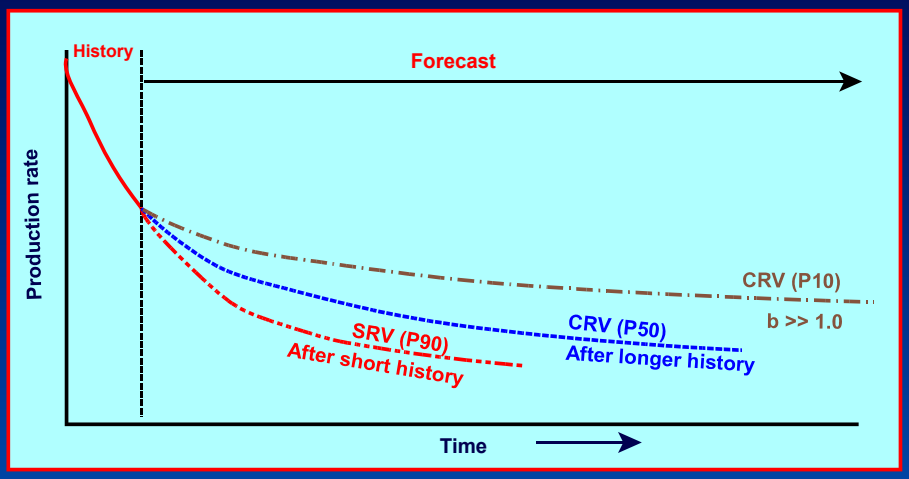
   For long production periods and relatively better formation permeability. Production contribution is from a portion of the reservoir larger than the SRV

3. **P90 .....P50.....P10**: Proved, Probable and Possible reserves

   - **P90**: the larger of SRV and CRV
   - **P50**: Based on reasonable well spacing to produce economic reserves
   - **P10**: Based on optimistic well spacing to produce economic reserves

P M G

Production Forecasts/Reserves



- **SRV (P90)**: reflects the most conservative reserves estimate
- **CRV (P50):** reflects the most likely recoverable reserves, based on a reasonable production period and a reasonable drainage area
- **CRV (P10)**: reflects an optimistic recoverable reserves, assuming an optimistic drainage area (use b>>1.0)

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Closing Comments

- The tighter the formation is, the longer it takes to confirm the EUR (SRV vs CRV)
- Production profile prediction could be generated based on analogous wells, but with caution...
- Decline curve analysis should be used with caution during transient, or unrealistically high reserves will be the outcome
- The combination of various evaluation techniques; PTA and RTA, DFIT, and numerical combined with micro-seismic/tracer survey can improve reserves estimate

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Thank You

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