SPEE Lunch Presentation | 08 July 2015
Society of Petroleum Evaluation Engineers (SPEE)

# *Reservoir Engineering Aspects of Unconventional Reservoirs*

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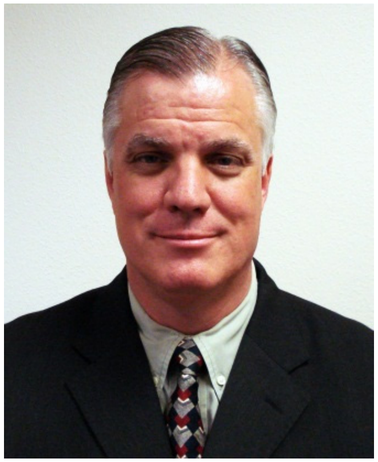
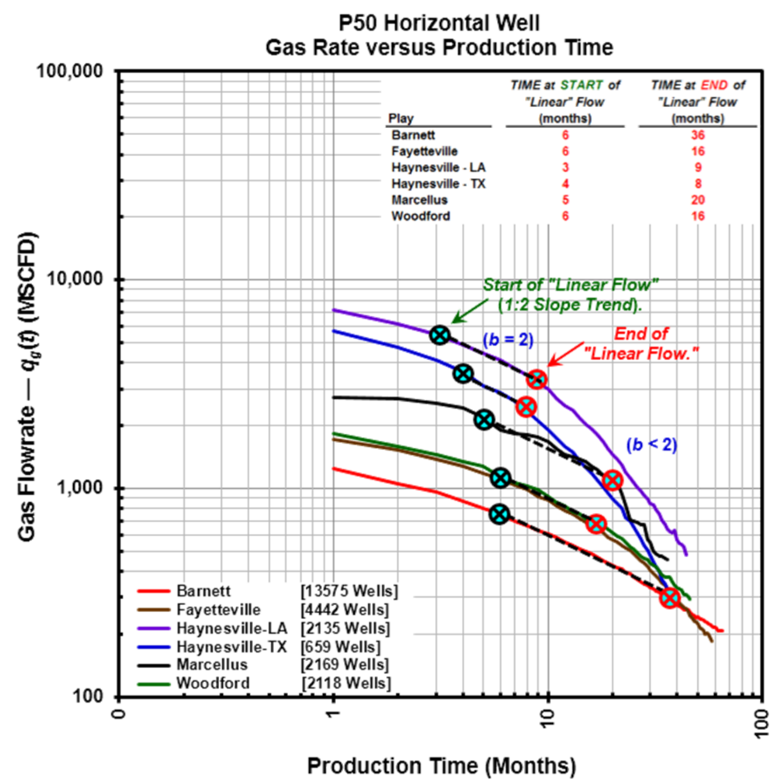
# Brief Biography: *Blasingame*



- **Role:**
  - Robert L. Whiting Professor, Texas A&M U.
  - B.S., M.S., and Ph.D. degrees from Texas A&M U. (PETE)
- **Counts: (July 2015)**
  - 55 M.S. (thesis) and 31 M.Eng. (report, non-thesis) Graduates
  - 13 Ph.D. Graduates
  - Over 140 Technical Articles
- **Recognition:**
  - SPE Distinguished Member (2000)
  - SPE Distinguished Service Award (2005)
  - SPE Distinguished Lecturer (2005-2006)
  - SPE Uren Award (2006)
  - SPE Lucas Medal (2012)
  - SPE DeGolyer Distinguished Service Medal (2013)
  - SPE Distinguished Achievement Award for PETE Faculty (2014)
  - SPE Honorary Member (2015)
  - SPE Tech. Director for Reservoir Description and Dynamics (2015-2018 )
- **Current Research Activities: (July 2015)**
  - Flow Phenomena in Ultra-Low Permeability Reservoir Systems
  - Production Performance Analysis for Shale Systems
  - Performance Behavior of Naturally Fractured Reservoir Systems
  - Numerical Modeling of Ultra-Low Permeability Reservoir Systems

- **Facts of life…**
  - Analogs (… need to understand uncertainty (very high))
  - EUR (… *minimum of* 18-24 *months*)
  - IP (… *may be uncorrelated with EUR*)
  - Early Productivity (… poor wells don't get better)
  - Time-Rate Analysis (… not representative? (chaotic operations))
  - Time-Rate-Pressure Analyses (… requires a reservoir model)
- **Comments on recovery…**
  - Early EUR? (… is this/can this be meaningful?)
  - EUR = *f*(*t*)? (… how do we incorporate this?)
  - Well Spacing? (… is this really the holy grail?)
- **Shale Well Performance is a function of …**
  - Porosity.
  - Permeability.
  - Reservoir thickness.
  - Well placement.
  - *Natural fractures.**
  - *(Over-) pressure.**
  - *Thermal maturity.**
  - *Well spacing.**
  - *Well stimulation.**

  * Defining factors (Blasingame)



- **Things that SHOULD help…**
  - Production Logs — (… but just a snapshot in time)
  - Optimal Proppant Design/Placement — (… obvious, but)
  - Stimulation Stages/Perforation Clusters — (… geology + logs)
- **Things that DEFINITELY WOULD help…**
  - Measured $p_{wf}$ — (… yes, this is my favorite song)
  - Downhole Fluid Sampling — (… sooner or later)
- **QUANTIFYING reservoir properties?**
  - Pressure Transient Analysis — (what does this give us in ultra-low *k* rock?)
  - Production Analysis — ($p_{tf}$ may not be sufficient, liquid-loading, etc.)
  - Petrophysical analysis — (theory ≠ application)

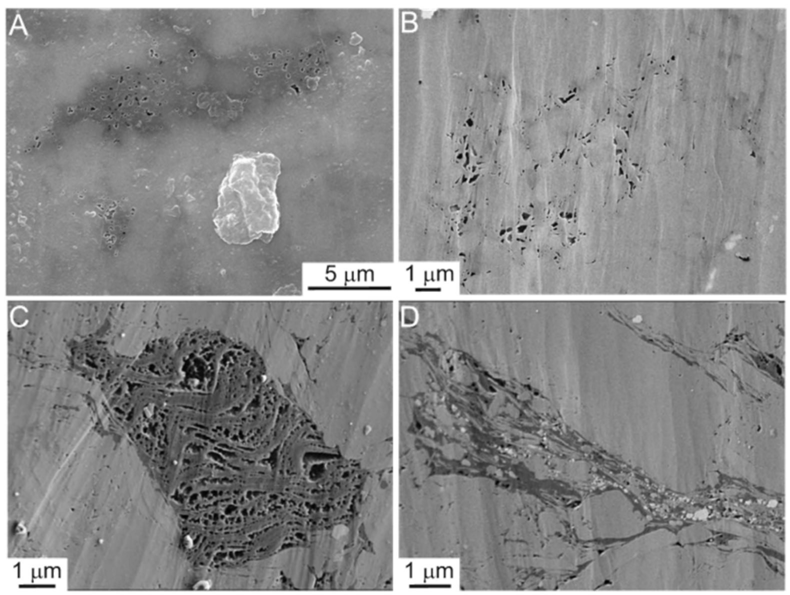
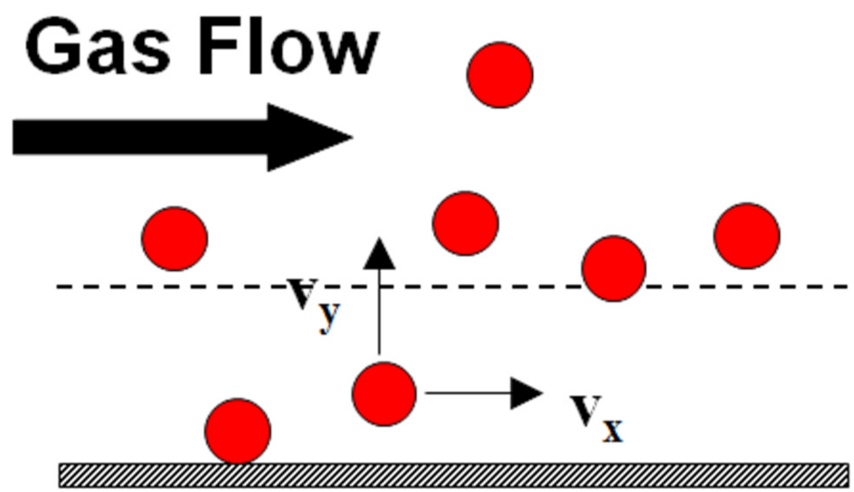



FIG. 5.—Nanopores associated with organic matter in the Barnett Shale. **A)** Elliptical to complexly rounded nanopores in an organic grain. Darker materials are organics. BSE image. Blakely #1, 2,167.4 m. **B)** Angular nanopores in a grain of organic matter. SE image. Blakely #1, 2,167.4 m. Accelerating voltage = 10 kV; working distance = 6 mm. **C)** Rectangular nanopores occurring in aligned convoluted structures. SE image. T.P. Sims #2, ~ 2,324 m. Accelerating voltage = 2 kV; working distance = 3 mm. **D)** Nanopores associated with disseminated organic matter. Carbon-rich grains are dark gray; nanopores are black. SE image. T.P. Sims #2, ~ 2,324 m. Accelerating voltage = 2 kV; working distance = 2 mm.

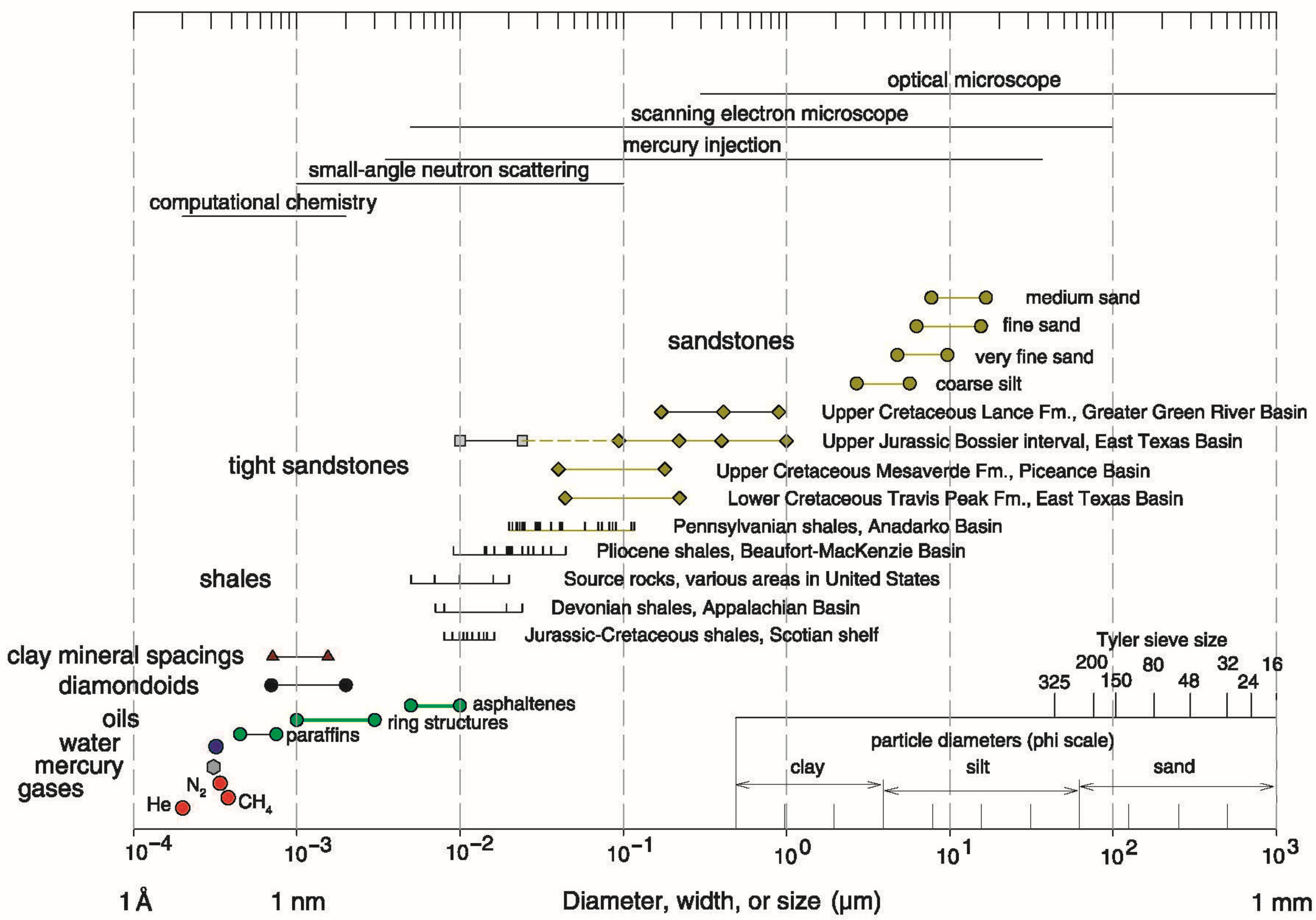
Loucks, R.G., R.M. Reed, S.C. Ruppel, and D.M. Jarvie: "*Morphology, Genesis, and Distribution of Nanometer-scale Pores in Siliceous Mudstones of the Mississippian Barnett Shale*," J. Sedimentary Research, v. 79/12 (2009).




*Gas Slippage* — Kundt, A. and Warburg, E.: "Über Reibung und Wärmeleitung verdünnter Gase, " Poggendorfs Annalen der Physik und Chemie (1875), 155, 337.

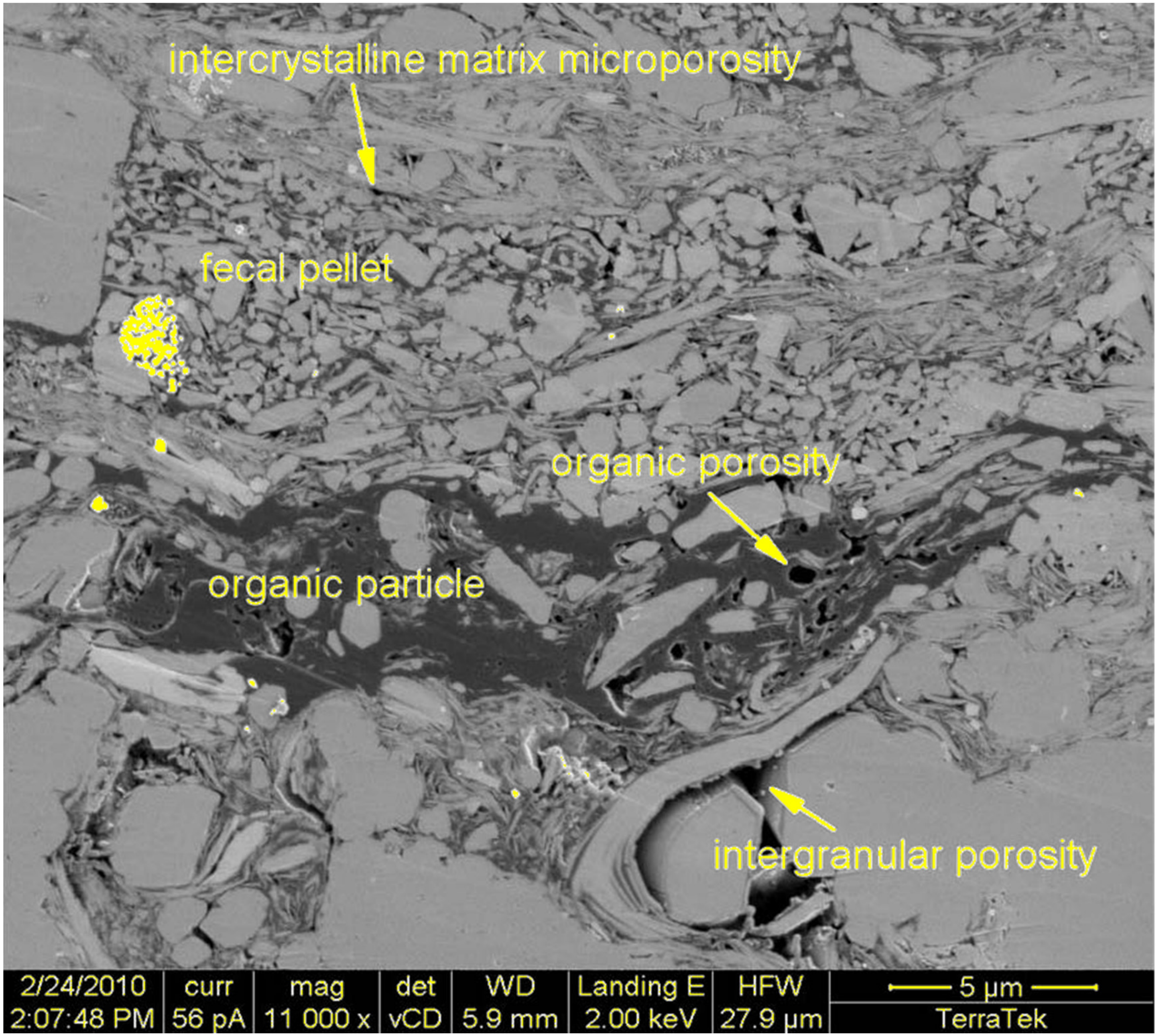
Florence, F.A., Rushing, J.A., Newsham, K.E., and Blasingame, T.A.: "*Improved Permeability-Prediction Relations for in Low Permeability Sands*," SPE 107954.

# **Pore Space**: *Very Small Spaces*



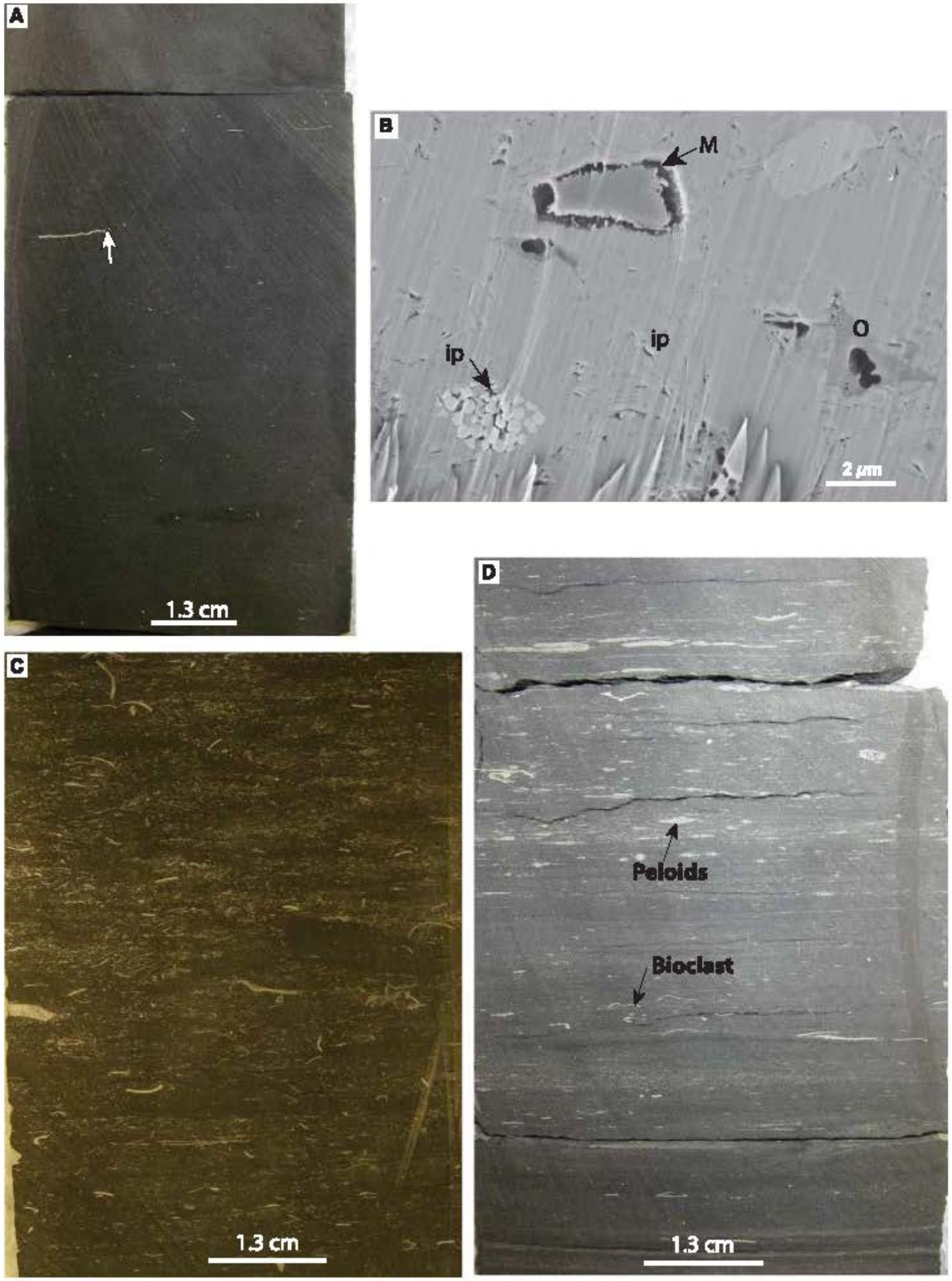

Nelson, P. H., 2009, Pore-throat sizes in sandstones, tight sandstones, and shales: AAPG Bulletin, v. 93, p. 329–430, doi:10.1306/10240808059.

# **Pore Space**: *Image of Shale Pore Space (Haynesville)*



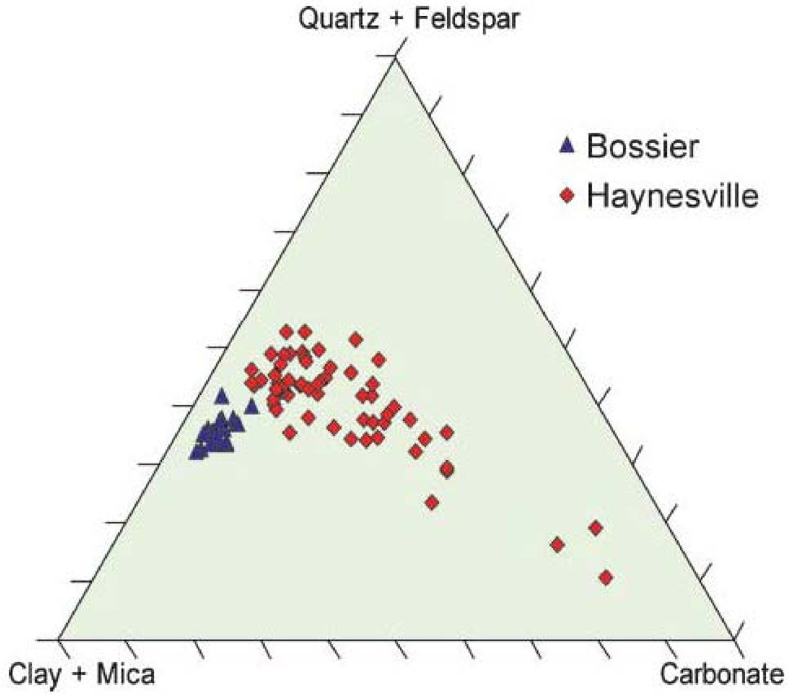

Spain, D. R., and G. A. Anderson, 2010, Controls on reservoir quality and productivity in the Haynesville Shale, northwestern Gulf of Mexico Basin: Gulf Coast Association of Geological Societies Transactions, v. 60, p. 657-668.

# Core Scale: *Core Images (Haynesville — Macro and SEM scales)*



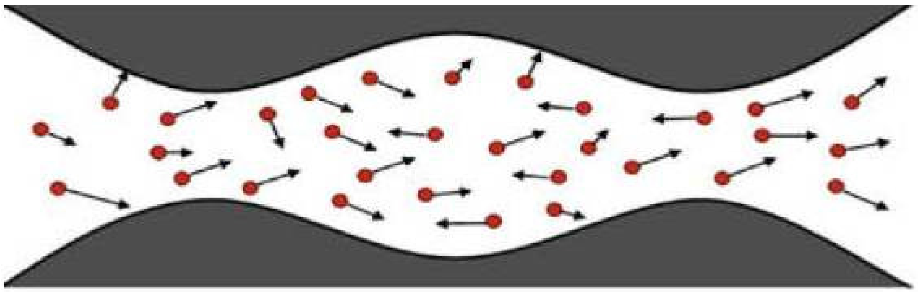

**Legend:**

A. Core slab of unlaminated mudstone facies showing homogeneous matrix with few thin-shelled filibranch bivalves (example at arrow).
B. (Ar-ionmilled SEM image showing different pore types of the Haynesville including organic (o), interparticle (ip), and moldic (M) micropores and nanopores.
C. Core slab of the bioturbated mudstone facies showing carbonate bioclasts and bioturbation.
D. Core slab of the laminated mudstone facies showing laminations of clay, organics, carbonate bioclasts (arrow), peloids (arrow), and mollusk shells.

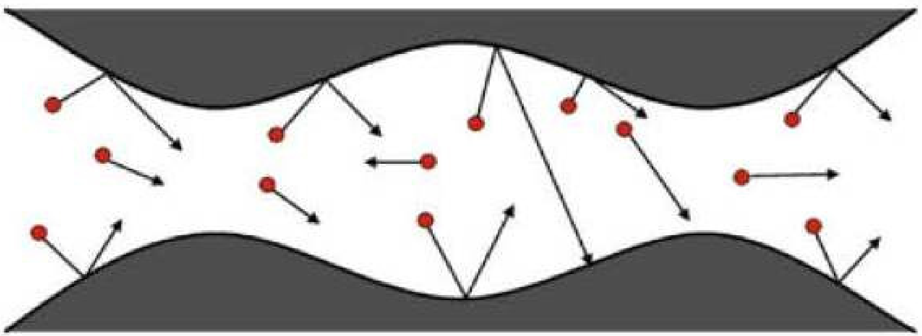



Hammes, U., Scott, H.H., and Ewing, T.E., 2011, Geologic analysis of the Upper Jurassic Haynesville Shale in east Texas and west Louisiana: American Association of Petroleum Geologists Bulletin, v. 95, no. 10, p. 1643-1666.

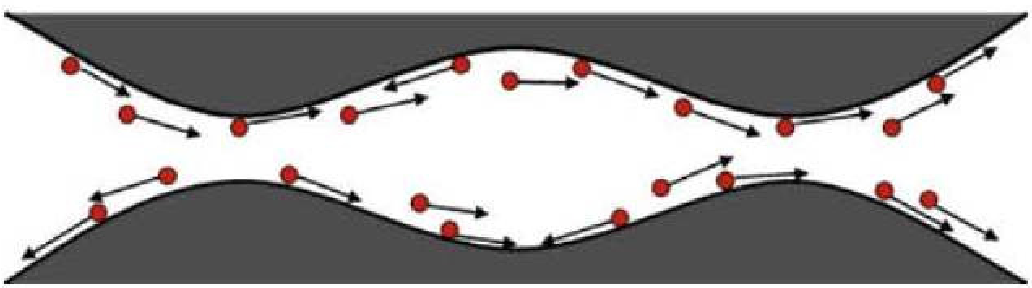
# <u>Flow Models</u>: *Flow in Small Conduits*



(a) Bulk Diffusion (Darcy's Law).



(b) Knudsen Diffusion.



(c) Surface Diffusion (Klinkenberg Flow).

## <u>Guidance</u>:

- Darcy's law → typical flow assumption.
- Knudsen diffusion → $k(p)$.
- Surface diffusion → slip (Klinkenberg).

| Flow regime | Knudsen Number | Flow Model | Comment |
|---|---|---|---|
| Continuum (Viscous) flow | Kn < 0.01 | Darcy's equation for laminar flow and Forchheimer's equation for turbulent flow. | Assumes immobile fluid at the pore wall. |
| Slip flow | 0.01 < Kn < 0.1 | Darcy's equation with Klinkenberg or Knudsen's correction. | Knudsen's correction is more accurate, but Klinkenberg's correction is easier. |
| Transition flow | 0.1 < Kn < 10 | Darcy's law with Knudsen's correction can be applied. | Knudsen's diffusion equation is the more reliable approach. |
| Knudsen's (Free Molecular) Flow | Kn > 10 | Knudsen's diffusion equation. | For very small pore-throat radii (shales). |

Ziarani, A. S., and Aguilera, R.: 2012, Knudsen's Permeability Correction for Tight Porous Media, Transport in Porous Media, Volume 91, Issue 1, pp 239-260

# Reserves: *Conventional Versus Unconventional*

## *Conventional Reservoirs*

- Localized structural trap
- External hydrocarbons sourcing
- Hydrodynamic influence
- Porosity important
- Permeability > 0.1 md
- Permeability ≠ *f*(*p*)
- Traditional phase behavior (PVT)
- Minimal extraction effort
- Significant production history
- Mid-late development life-cycle
- Few wells for commerciality
- Base reserves on volumetrics
- Assess entire prospect before drilling
- Boundary-dominated flow (months)

- *Traditional reserves methods*

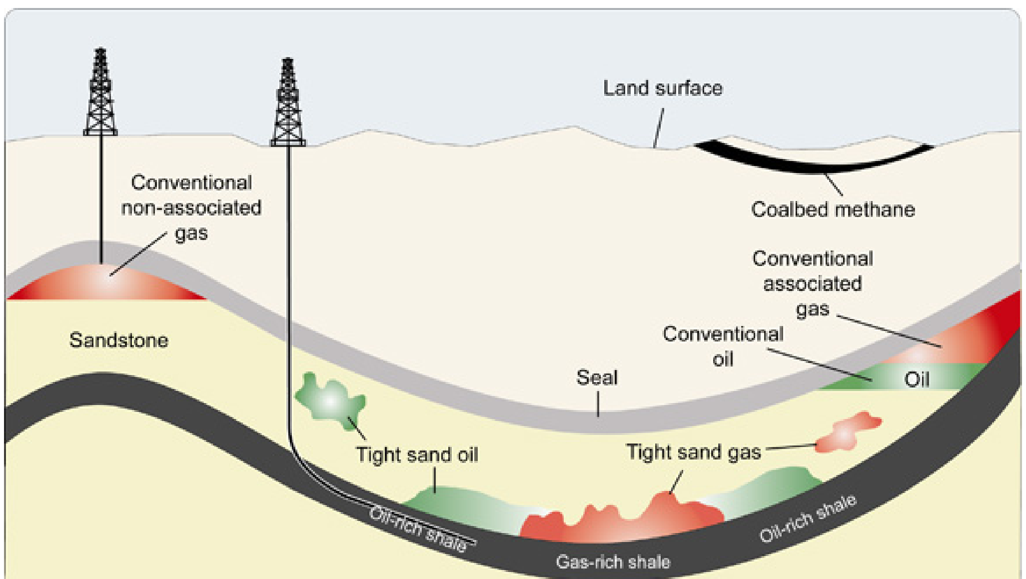
## *Unconventional Reservoirs (Shales)*

- "Continuous-type" deposit
- Self-sourced hydrocarbons
- Minimal hydrodynamic influence
- Porosity may not be important
- Permeability << 0.1 md
- Permeability = *f*(*p*)
- Complex (HP/HT) PVT
- Significant extraction effort
- Limited production history
- Early development life-cycle
- Many wells for commerciality
- Base reserves on analogs
- Prospect driven by drilling
- *No* boundary-dominated flow

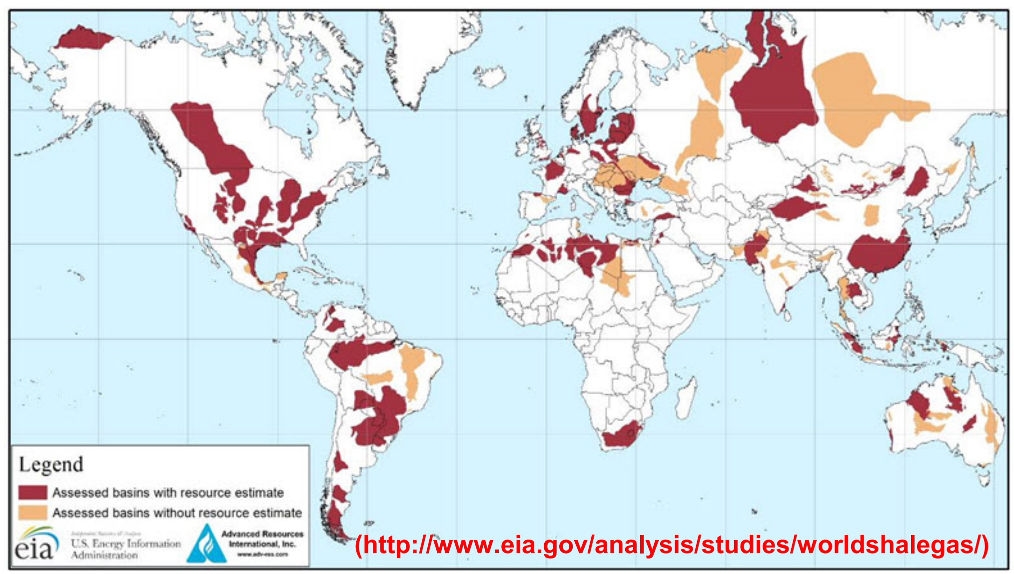
- *Traditional reserves methods*

?

Contributions From: Brad BERG, Anadarko

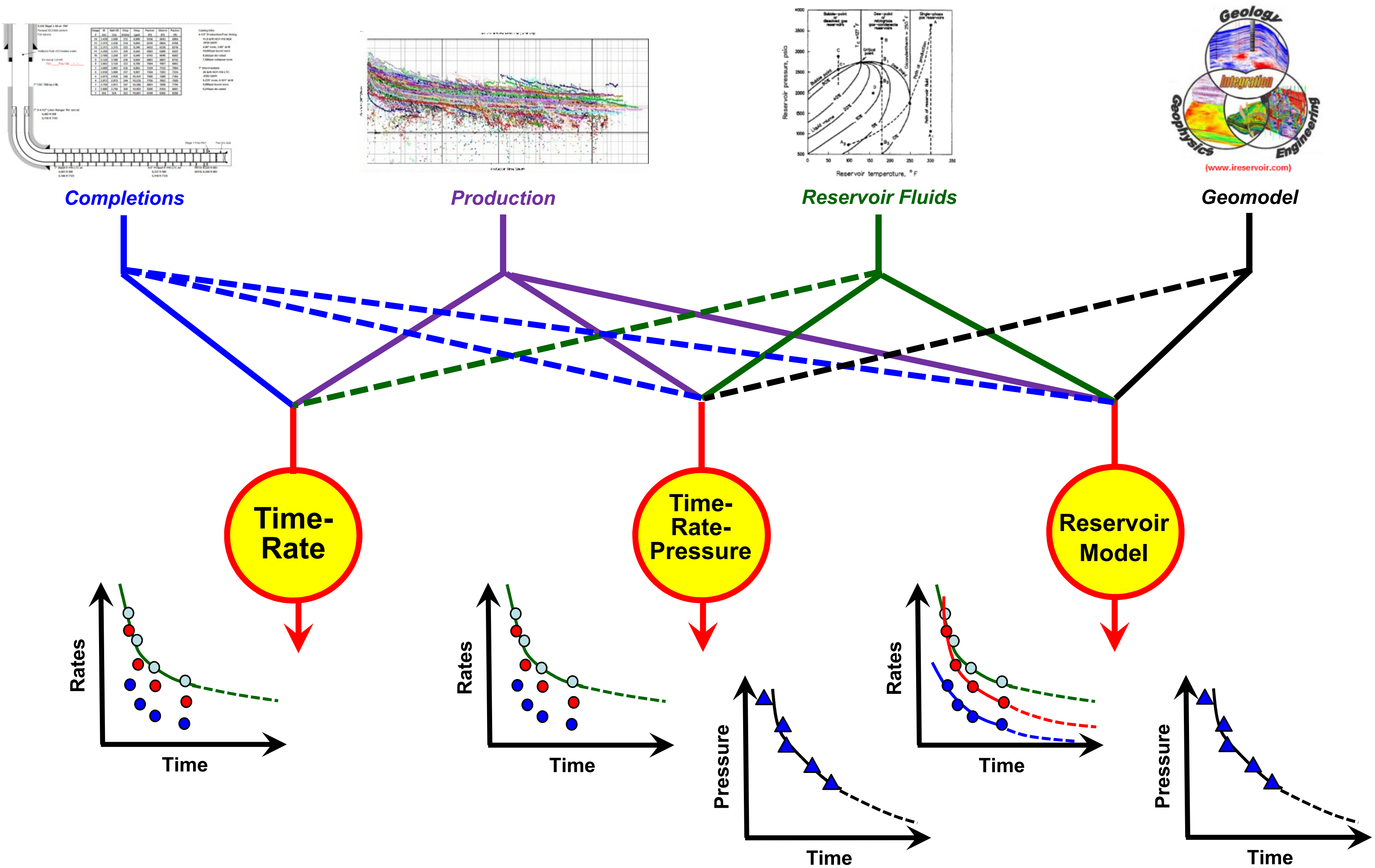



(http://www.neb-one.gc.ca/clf-nsi/rcmmn/hm-eng.html)




(http://www.eia.gov/analysis/studies/worldshalegas/)

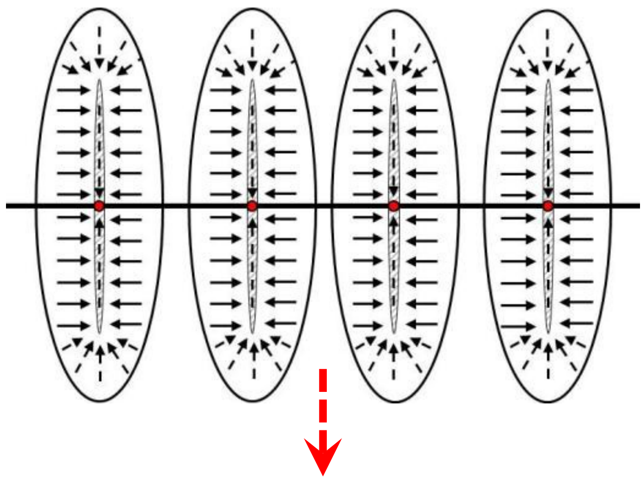
# **Work Path**: *Analysis of Well Performance*




| | | |
|---|---|---|
| **Model: Time-Rate**<br>**Basis: Proxy model**<br>● **Predictions**<br>● **EUR**<br>● ***Correlations*** | **Model: Time-Rate-Pressure**<br>**Basis: Analytical/Numerical**<br>● **Predictions**<br>● **EUR/SRV**<br>● ***Estimate Properties*** | **Model: Time-Rate-Pressure**<br>**Basis: Full Numerical**<br>● **Predictions**<br>● **EUR/SRV**<br>● ***Flow Mechanisms*** |

# Time-Rate Behavior: *Typical Flow Regimes in Unconventional Reservoir Systems*

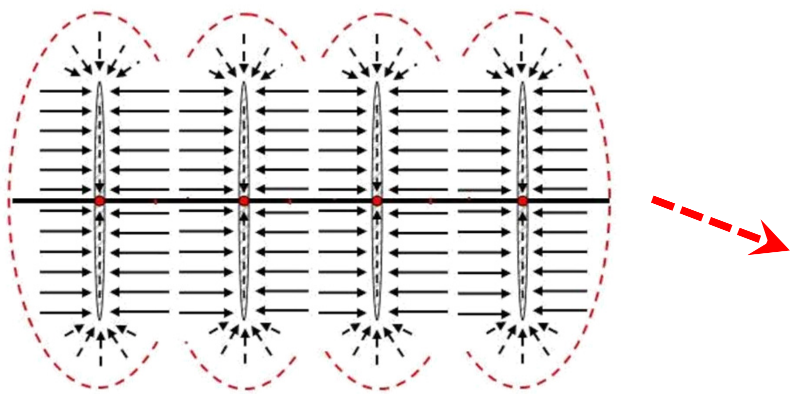
**Linear Flow:**
**(fracture flow does not interfere)**



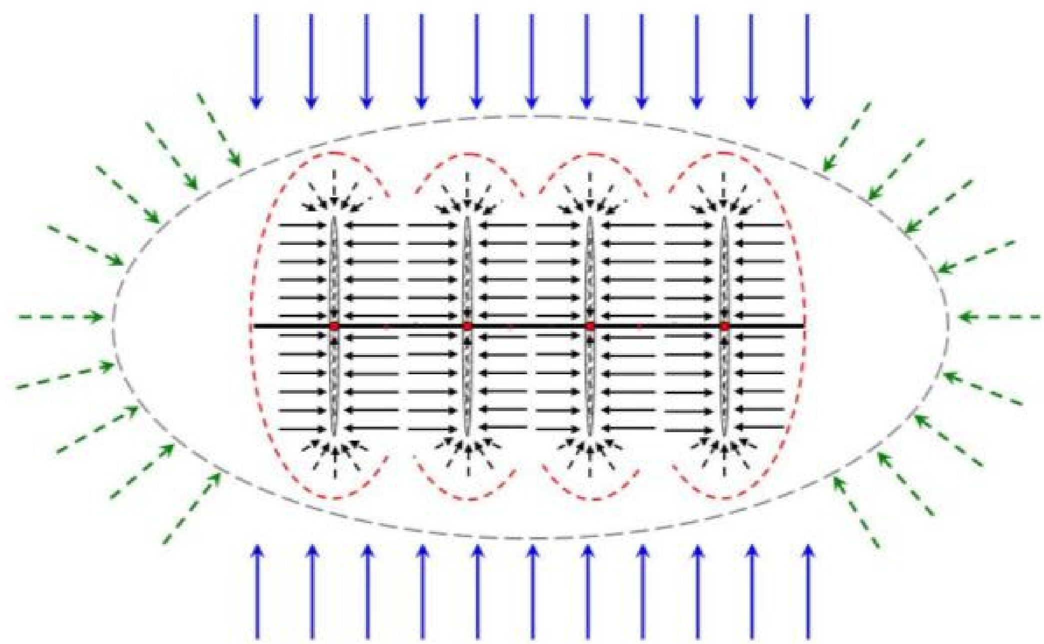
***Required* Model Parameters:**

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

**"SRV" Flow: ("depletion")**
**(fracture flow does interfere)**

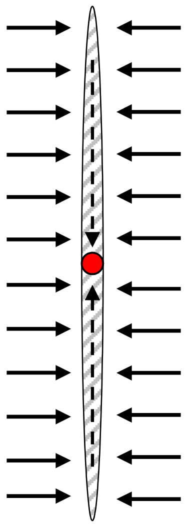


**"Post-SRV" Flow:**
**("Compound Linear Flow")**



# Time-Rate Behavior: (*Formation*) *Linear Flow — Theory*

## Solution for a Single Fracture: (transient linear flow)



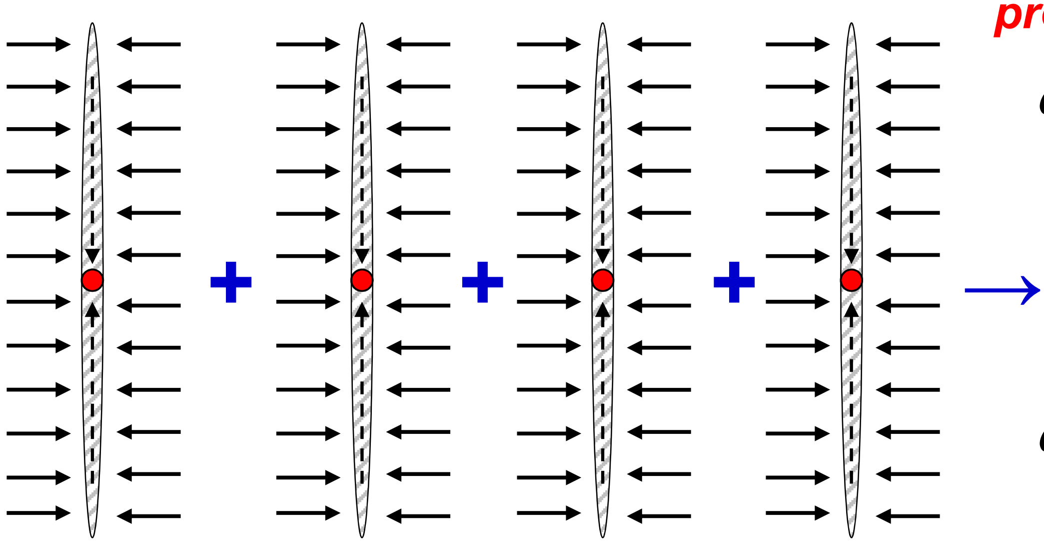
$$p_D = \sqrt{\pi \, t_{Dxf}}$$

$$q = \frac{1}{8.128494}(p_i - p_{wf})\frac{1}{B}\sqrt{\frac{\phi c_t}{\mu}}\sqrt{k}\,A_{xf}\,\frac{1}{\sqrt{t}}$$

$$q = C\,A_{xf}\,\frac{1}{\sqrt{t}} \qquad \left[ C = \frac{1}{8.128494}(p_i - p_{wf})\frac{1}{B}\sqrt{\frac{\phi c_t}{\mu}}\sqrt{k} \right]$$

**Note:**
***These solutions are only valid for transient linear flow [i.e., the case of non-interfering pressure distributions (due to the fractures)].***

## Additive Fractures: (transient linear flow)

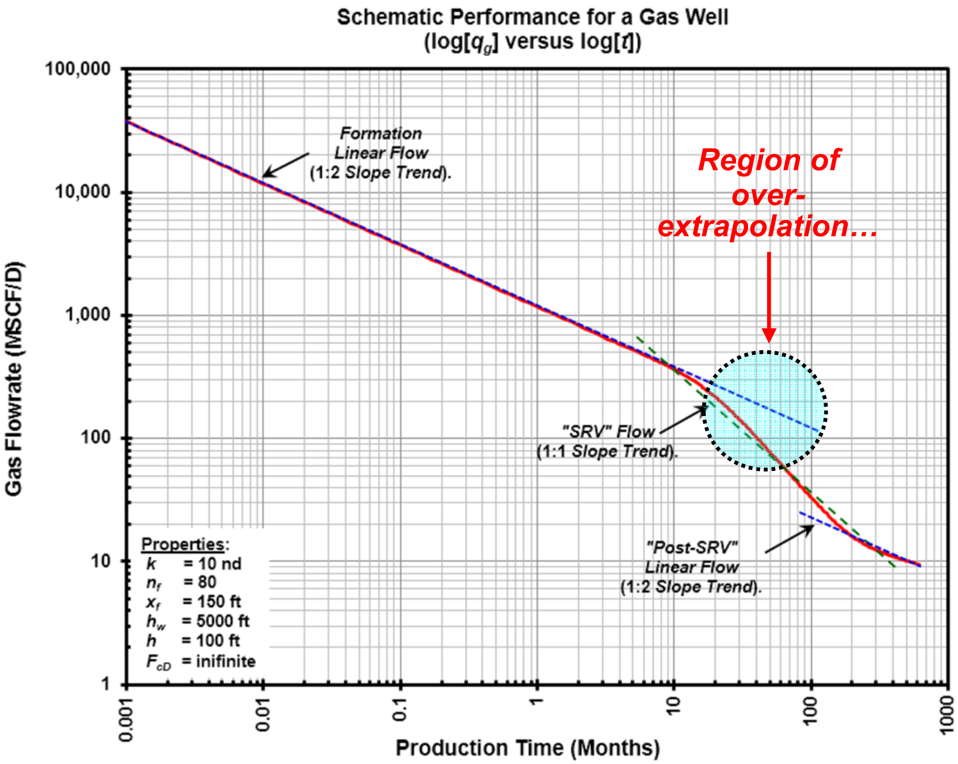


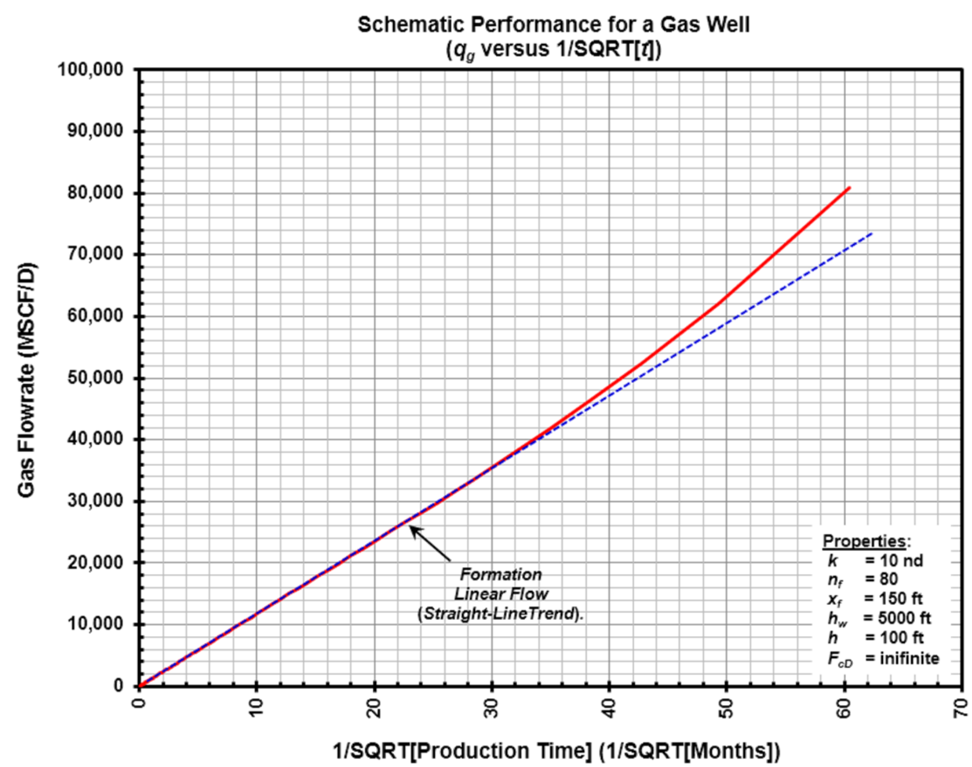
$$q_{\text{tot}} = C\,[A_{xf,1} + A_{xf,2} + A_{xf,3} + A_{xf,4} + \ldots + A_{xf,n}]\frac{1}{\sqrt{t}}$$

$$q_{\text{tot}} = C\,(A_{xf})_{\text{tot}}\,\frac{1}{\sqrt{t}}$$

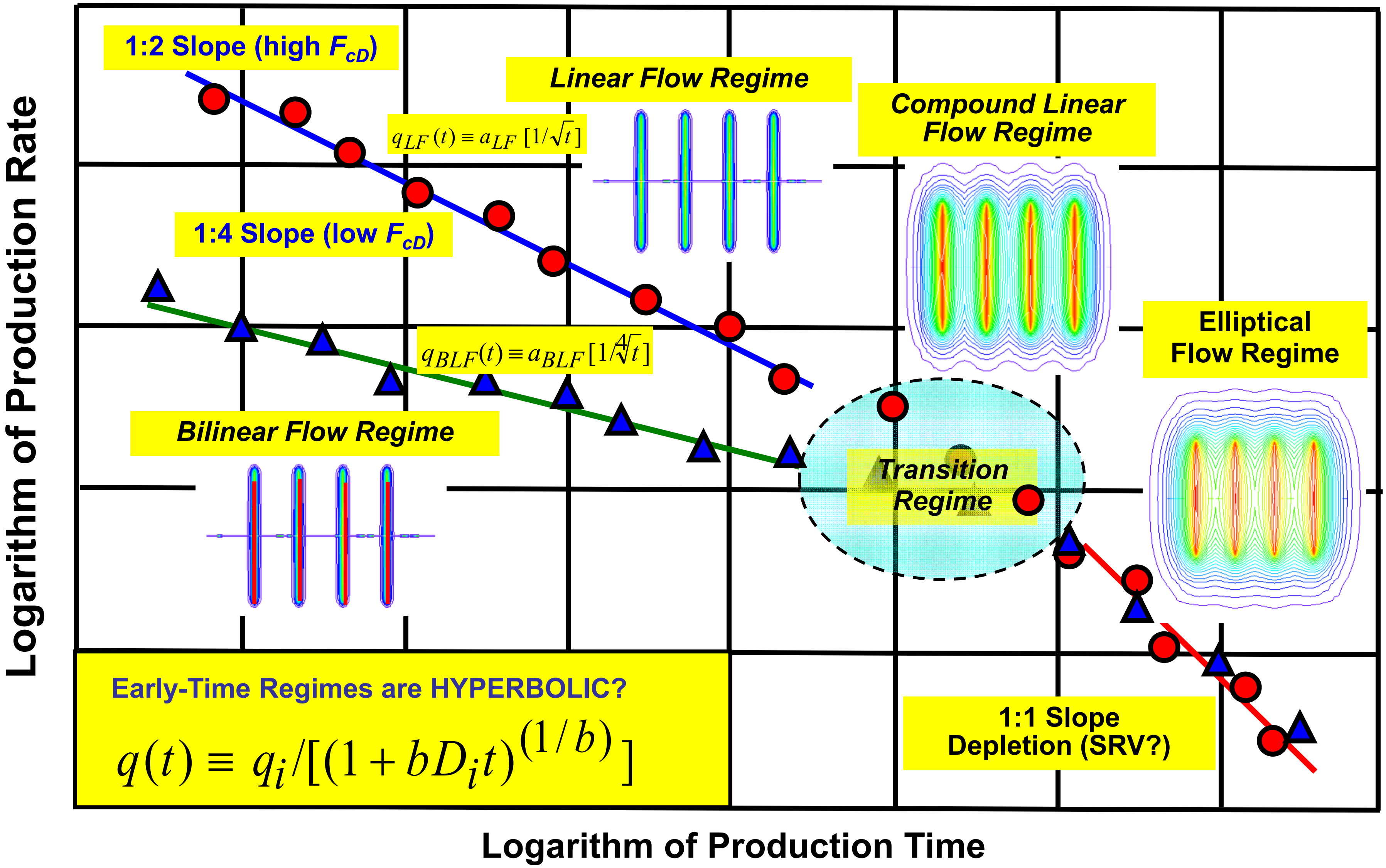
# Time-Rate Behavior: (*Formation*) *Linear Flow — Practice* (*Synthetic Example*)

- **Formation Linear Flow**
  - Log-log diagnostic plot: log[$q(t)$] versus log[$t$] (slope = -1:2)
  - *"qDb"* (time-rate) plot: log[$q(t)$] log[$D(t)$] log[$b(t)$] versus log[$t$]
  - "Traditional" plot: $q(t)$ versus 1/SQRT[$t$] (straight-line portion)
  - ***Extrapolation using a linear flow model will over-predict EUR…***



# **Time-Rate Behavior**: *Flow Regimes for a Multi-Fracture Horizontal Well* [1/2]

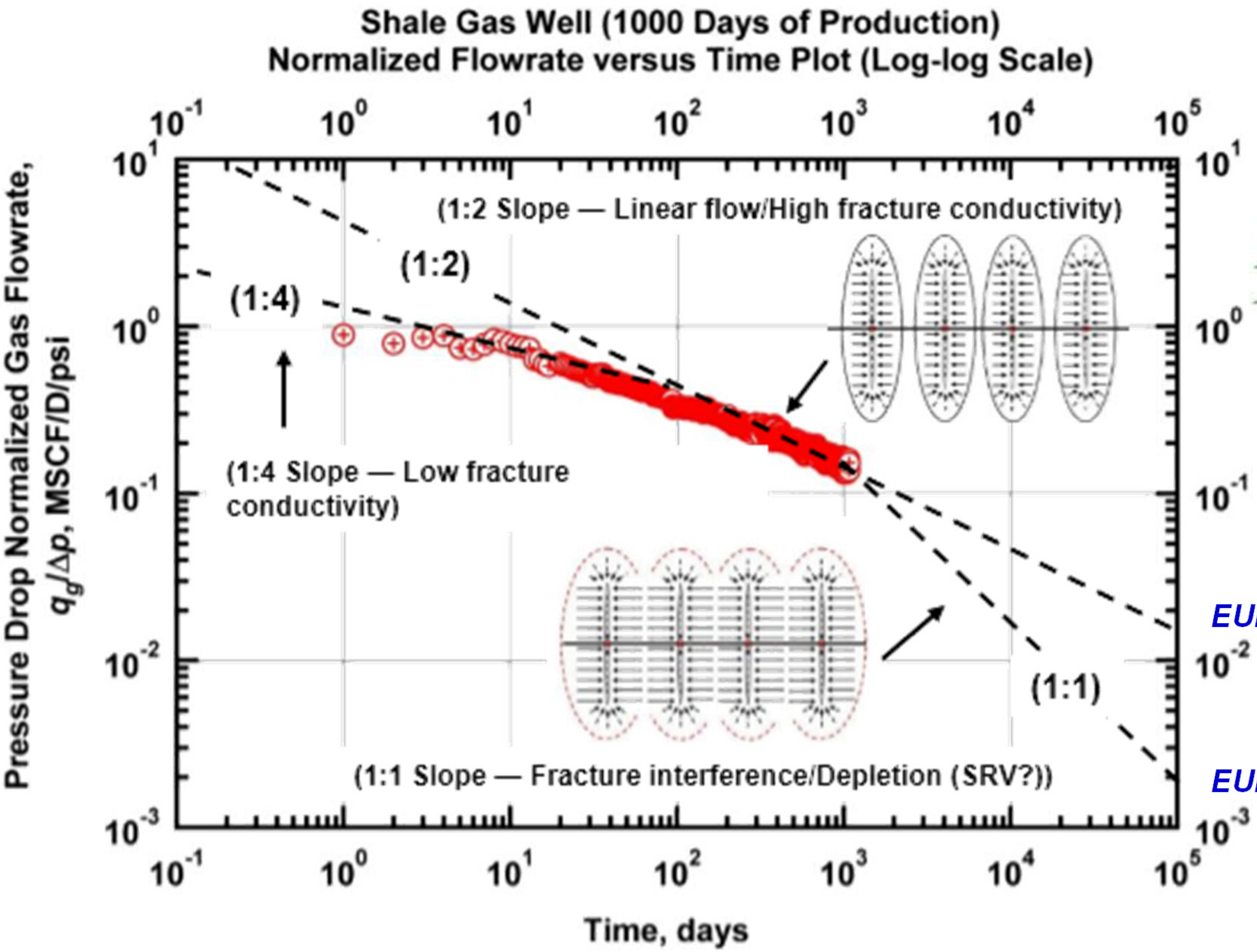


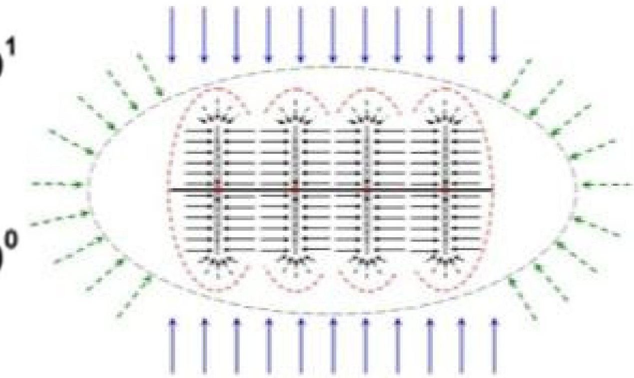

For Shales: | days | *weeks* | *months* | *years* | *decades* | … |

## Discussion:

- 1:2 Slope → b=2 (*HIGH* conductivity) — formation LINEAR flow regime.
- 1:4 Slope → b=4 (*LOW* conductivity) — BILINEAR flow regime.
- *Schematic is over-si*mplified to illustrate basic behavior.

# <u>Time-Rate Behavior</u>: *Flow Regimes for a Multi-Fracture Horizontal Well* [2/2]



**Pseudo-elliptical flow regime (flow from matrix to collection of fractures) might exist after fracture interference.**

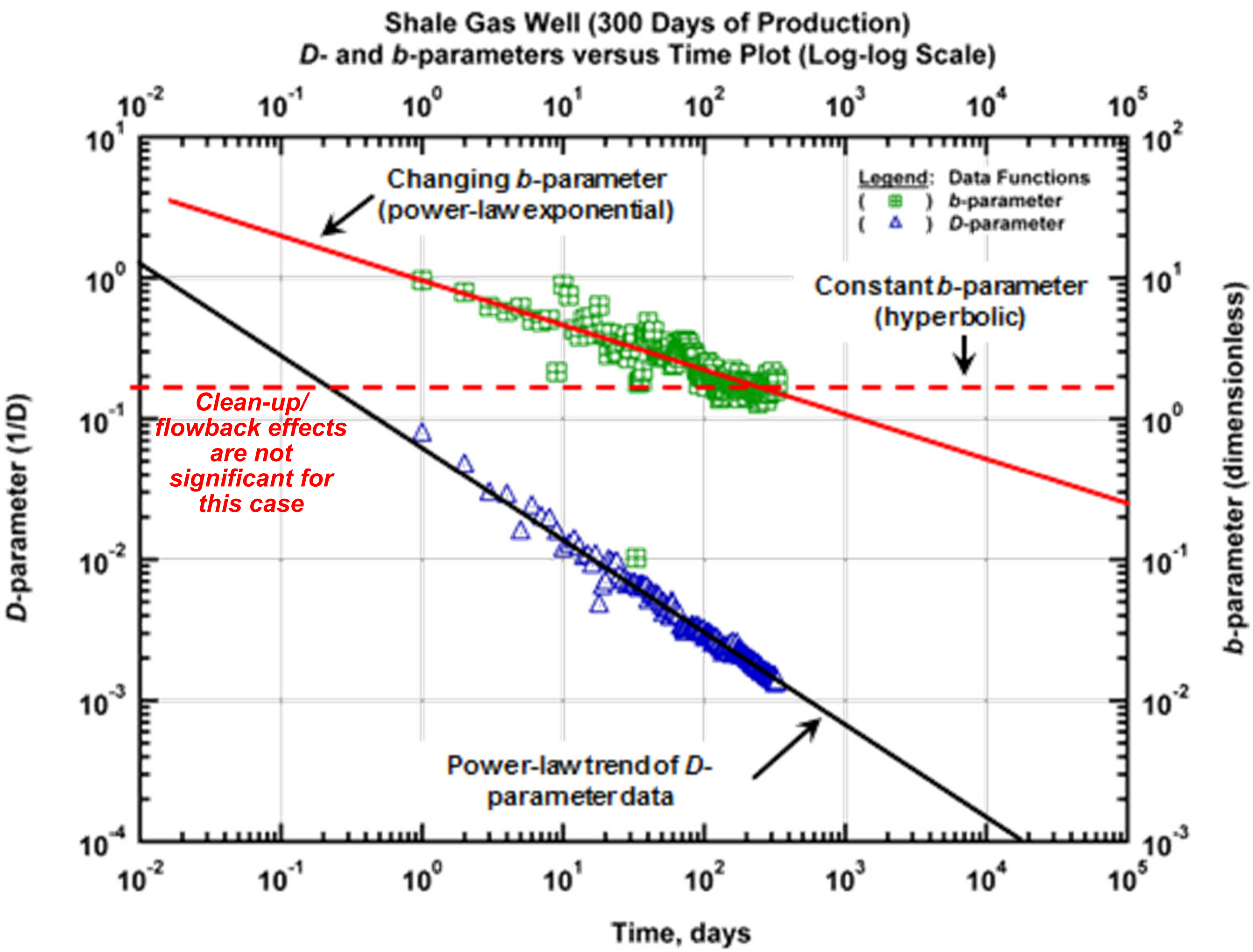
***EUR$_{LF}$* (VERY OPTIMISTIC)**

***EUR$_{Dep}$* (CONSERVATIVE ???)**

## <u>Flow Regimes</u>: (Barnett Shale Example)

- **Schematic illustrates flow regimes exhibited by time-rate-pressure data.**
- **Duration/existence of flow regimes is <u>DIFFERENT</u> for each play.**

# Time-Rate Behavior: *Power-Law Exponential Rate Relation*




Ilk, D., Rushing, J.A., Perego, A.D., and Blasingame, T.A.,: "Exponential vs. Hyperbolic Decline in Tight Gas Sands — Understanding the Origin and Implications for Reserve Estimates Using Arps' Decline Curves," paper SPE 116731 presented at the 2008 Annual SPE Technical Conference and Exhibition, Denver, CO, USA, 21–24 September 2008.

***PLE Rate Relation*:**

$$q(t) \equiv \hat{q}_i \exp[-D_\infty t - \hat{D}_i t^n]$$

**Decline Function: *D*(*t*)**

$$D(t) \equiv -\frac{1}{q}\frac{dq}{dt}$$

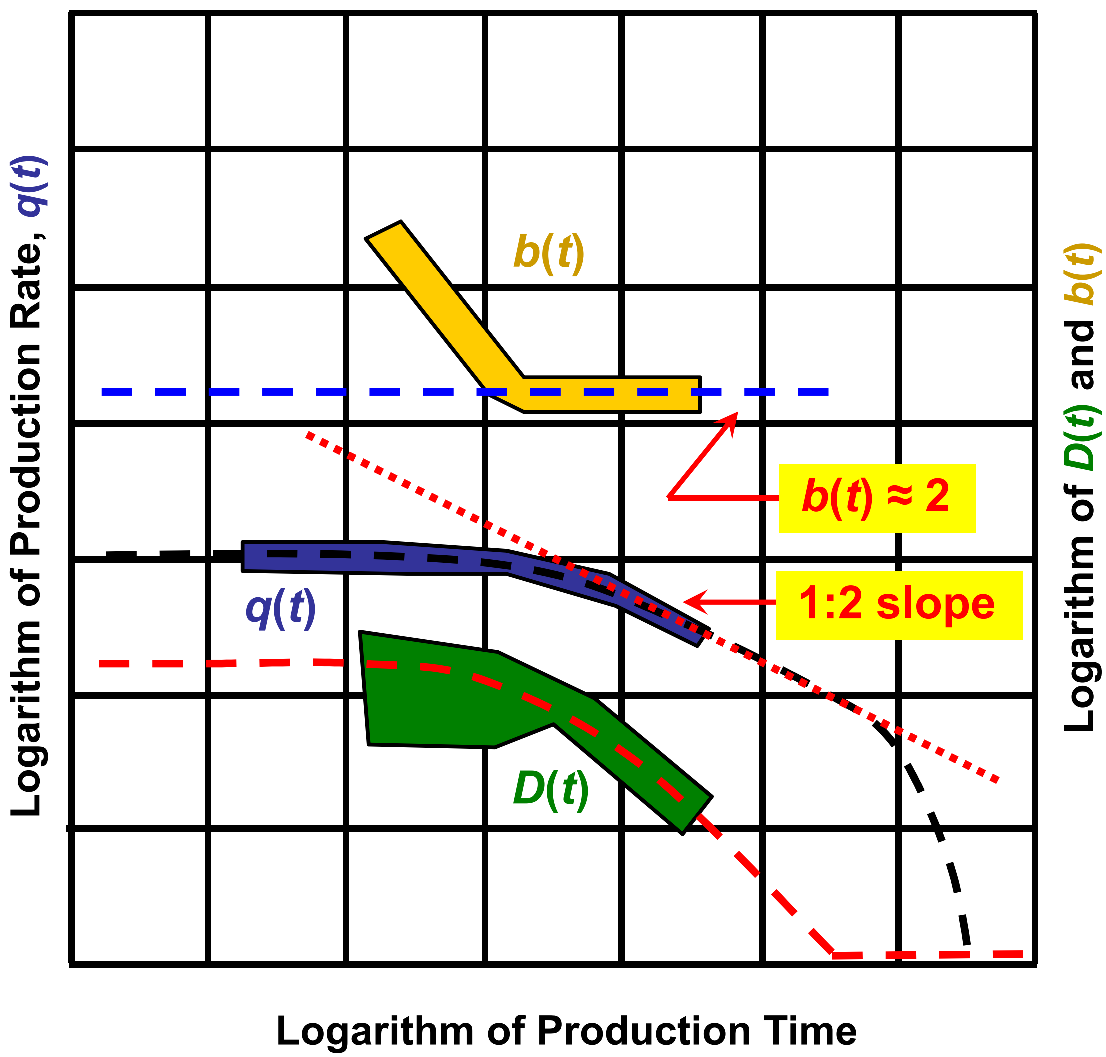
$$\approx D_\infty + n\hat{D}_i t^{-(1-n)}$$

**Hyperbolic Function: *b*(*t*)**

$$b(t) \equiv \frac{d}{dt}\left[\frac{1}{D(t)}\right]$$

$$\approx \frac{n\hat{D}_i(1-n)}{[n\hat{D}_i + D_\infty\, t^{(1-n)}]^2} t^{-n}$$

# Time-Rate: *Modified Hyperbolic Rate Relation*




***Rate Relation*:**

$$q(t) \equiv \begin{cases} \dfrac{q_{i,\text{hyp}}}{(1+bD_i t)^{1/b}} & (t < t^*) \\ q_{\lim} \exp[-D_{\lim}(t - t_{\lim})] & (t > t_{\lim}) \\ q_{\lim} = q_{i,\text{hyp}} \left[ \dfrac{D_{\lim}}{D_i} \right]^{(1/b)} & \\ t_{\lim} = \dfrac{1}{bD_i} \left[ \left[ \dfrac{q_{i,\text{hyp}}}{q_{\lim}} \right]^b - 1 \right] & \end{cases}$$

***D*(*t*) Function:**

$$D(t) \equiv -\frac{1}{q}\frac{dq}{dt}$$

***b*(*t*) Function:**

$$b(t) \equiv \frac{d}{dt}\left[\frac{1}{D(t)}\right] \equiv \text{constant}$$

**Discussion:**

- ***qDb*** **functions are DIAGNOSTIC.**
- ***D*(t) and *b*(t) evaluated from data.**
- ***b*=2 behavior = Linear Flow.**
- **Case appears to be "hyperbolic."**

## Time-Rate: *Power Law Exponential Rate Model*

### *Power-Law Exponential*: (PLE)

— Observed Behavior of *D*(*t*):

$$D(t) \equiv -\frac{1}{q(t)}\frac{dq(t)}{dt} \approx D_\infty + n\hat{D}_i t^{-(1-n)}$$

— Integrating to solve for *q*(*t*):

$$q(t) = \hat{q}_i \exp[-D_\infty\, t - \hat{D}_i\, t^n]$$

— Differentiating to solve for *b*(*t*):

$$b(t) = \frac{n\hat{D}_i(1-n)}{[n\hat{D}_i + D_\infty\, t^{(1-n)}]^2} t^{-n}$$

### *Stretched Exponential*: (SEM)

— Observed Behavior of *q*(*t*):

$$q(t) = \hat{q}_i \exp[-(t/\tau)^n]$$

— Differentiating to solve for *D*(*t*):

$$D(t) \equiv -\frac{1}{q(t)}\frac{dq(t)}{dt} \approx n\tau^{-n}t^{n-1}$$

— Differentiating to solve for *b*(*t*):

$$b(t) = \frac{1-n}{n}\tau^n t^{-n}$$

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Literature:

- Kohlrausch (1854).
- Phillips (1996).
- Kisslinger (1993)
- Decays in random, disordered, chaotic, heterogeneous systems (*e.g.*, relaxation, aftershock decay rates, *etc.*).

Valkó (2009)

$$q(t) = \hat{q}_i \exp[-(t/\tau)^n]$$

Jones (1942) and Arps (1945)

$$q(t) = q_o \exp\left[\frac{-D_o\, t^{m-1}}{100(m-1)}\right]$$

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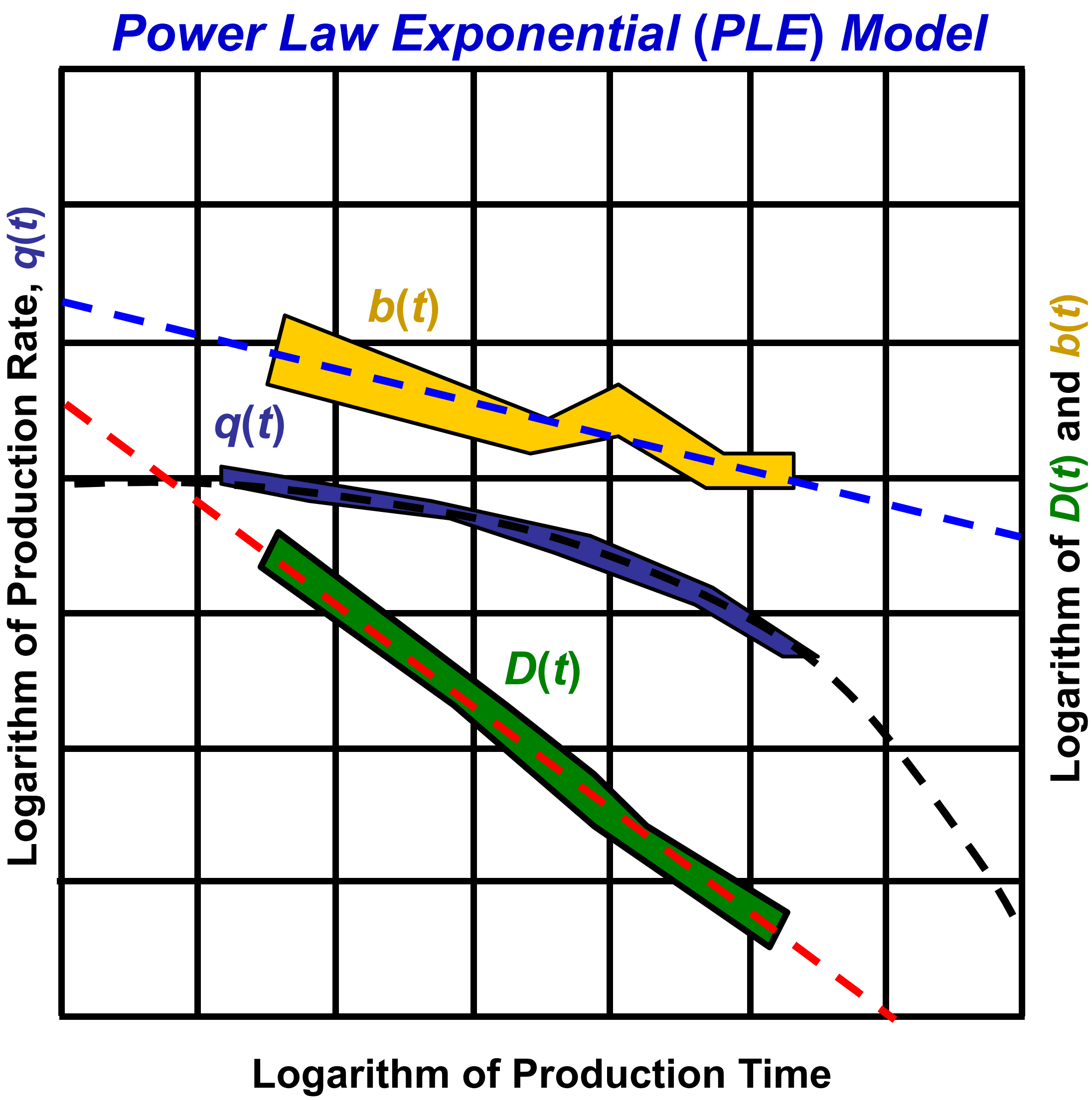
Discussion:

- Models are the same when $D_\infty = 0$.
- The Power-Law Exponential model was derived from observations (Blasingame/Ilk).
- The Stretched-Exponential model was taken from a statistics text (Valko).

# Time-Rate: *Power Law Exponential Rate Relation*




***Rate Relation*:**

$$q(t) \equiv \hat{q}_i \exp[-D_\infty t - \hat{D}_i t^n]$$

***D*(*t*) Function:**

$$D(t) \equiv -\frac{1}{q}\frac{dq}{dt}$$

$$\approx D_\infty + n\hat{D}_i t^{-(1-n)}$$

***b*(*t*) Function:**

$$b(t) \equiv \frac{d}{dt}\left[\frac{1}{D(t)}\right]$$

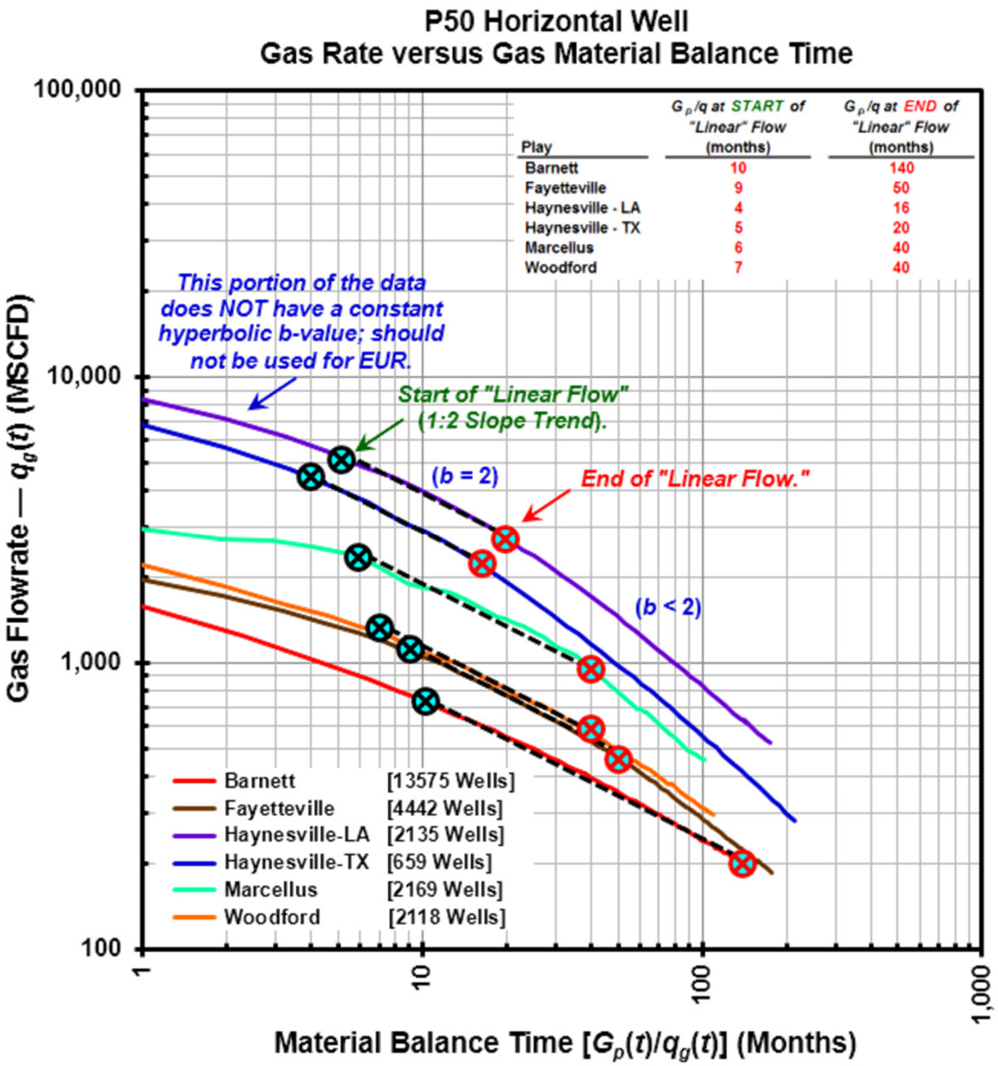
$$\approx \frac{n\hat{D}_i(1-n)}{[n\hat{D}_i + D_\infty t^{(1-n)}]^2} t^{-n}$$

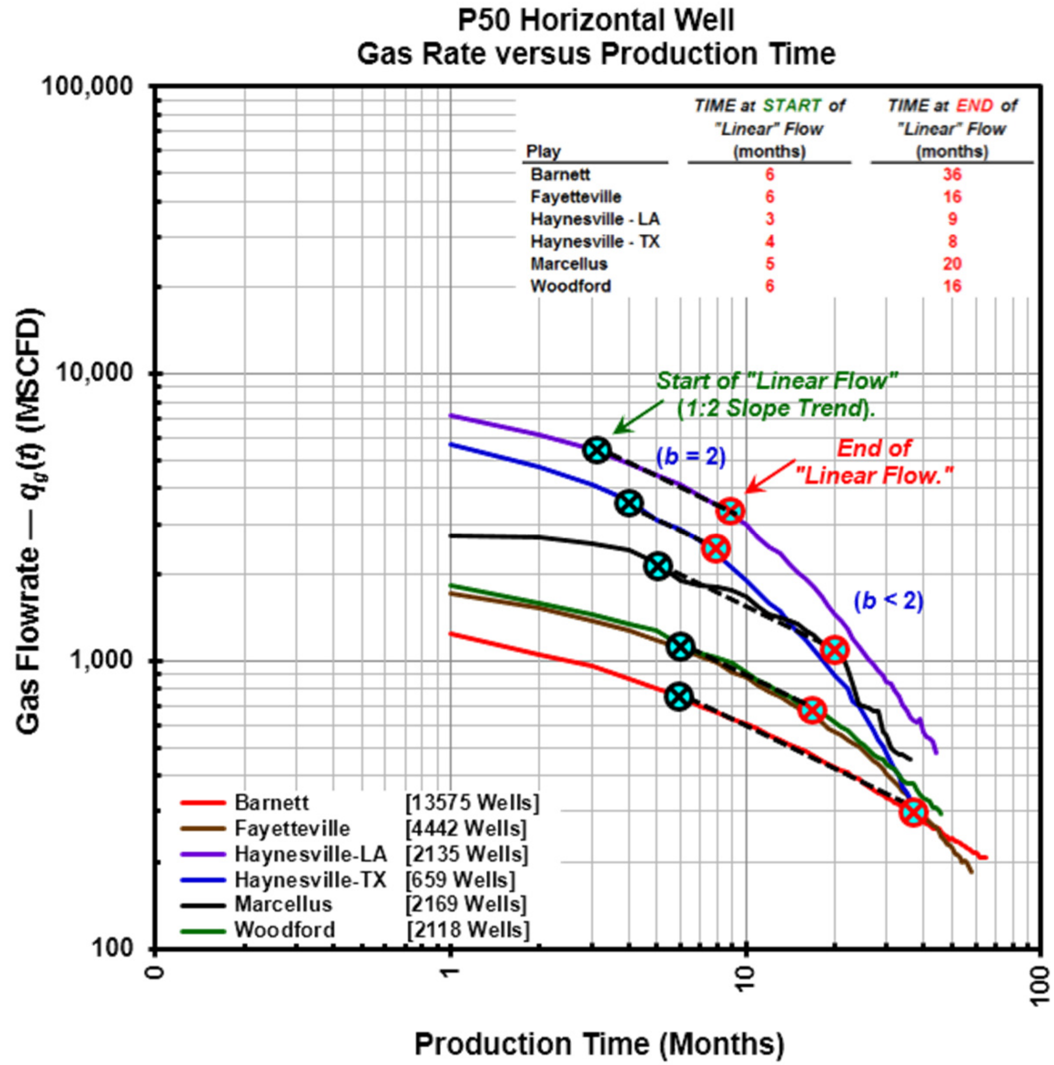
## Discussion:

- ***qDb*** **functions are DIAGNOSTIC.**
- **PLE derived from:** $D_\infty + n\hat{D}_i t^{-(1-n)}$
- **No direct analog to hyperbolic case.**
- **This is a "tight gas" reservoir case.**

# Rate-Time Analysis: *Calibration — Linear Flow (Gas Shales)* [1/2]

## *Data taken from publicly available sources — Horizontal Shale (Dry) Gas Wells ONLY*



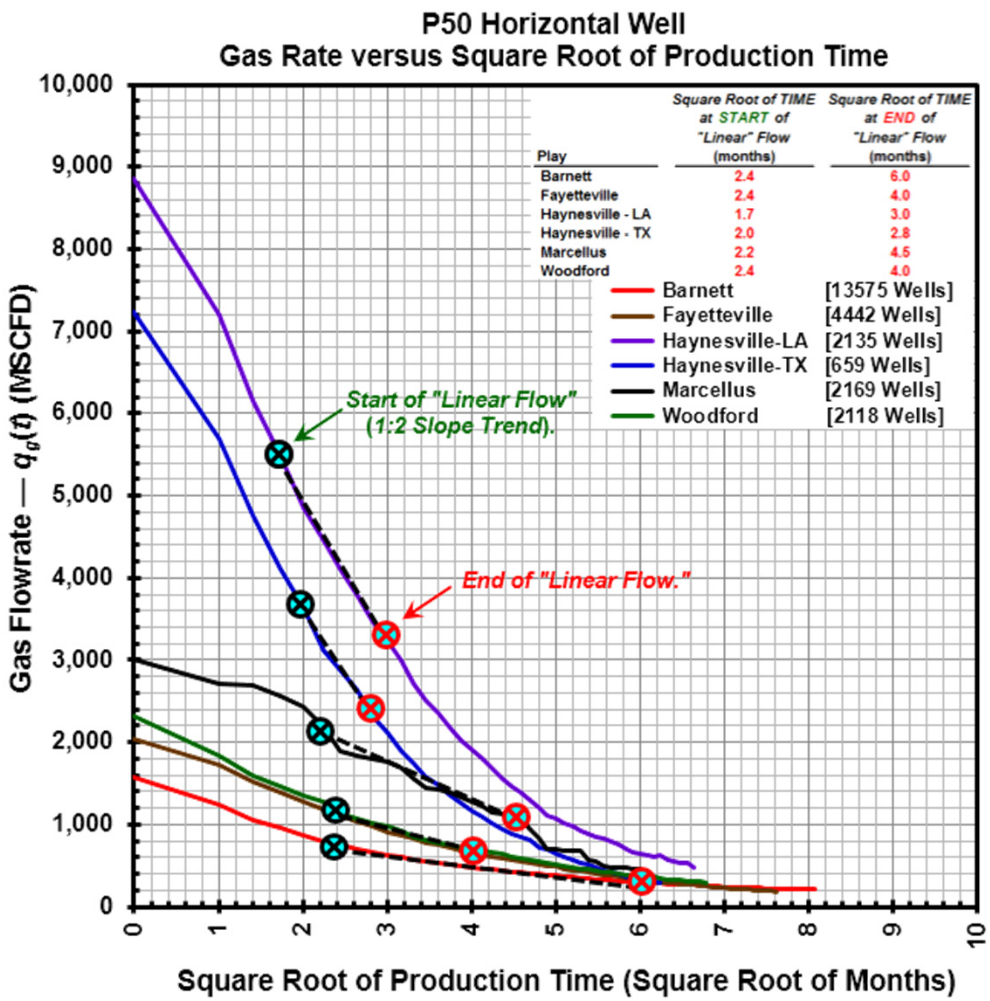

**Discussion:**

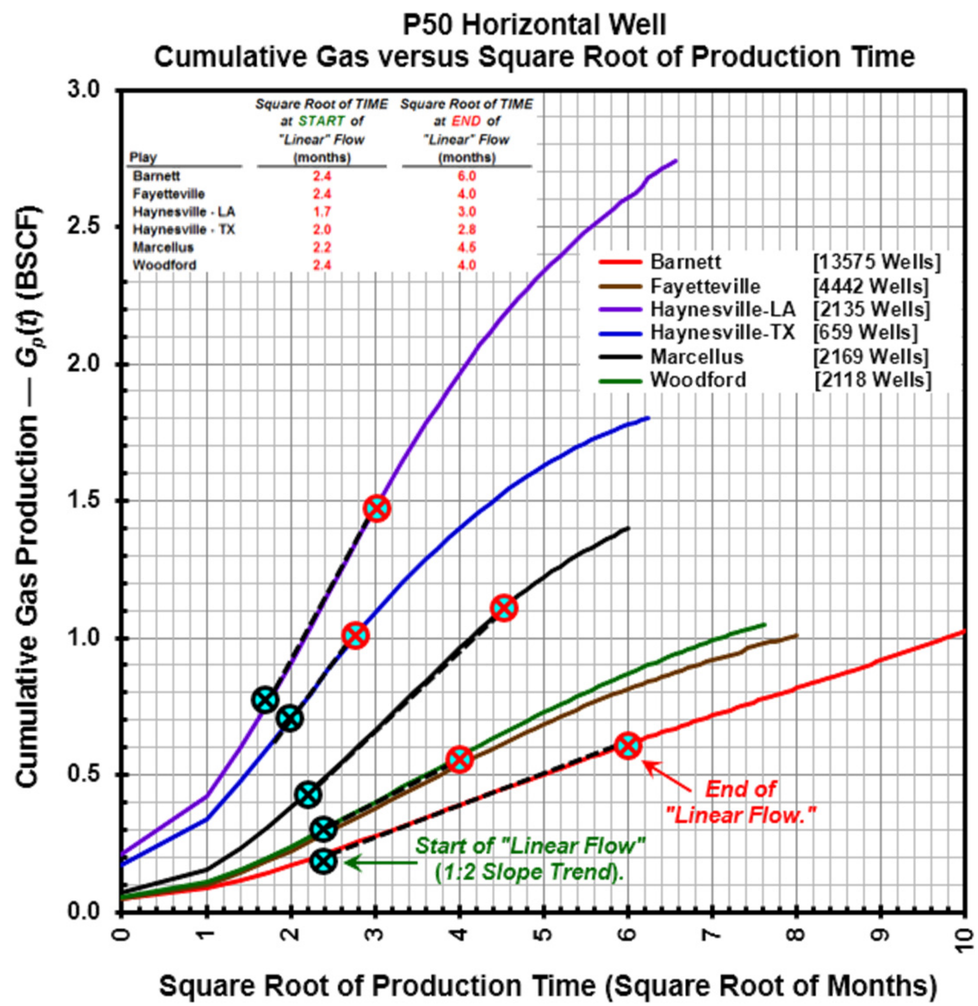
- **START of "Linear Flow" (~3-6 months).**
- **END of "Linear Flow" (~9-36 months).**
- **"Linear Flow" is represented by *b* = 2.**
- **EUR requires at least 20+ months (except Haynesville ~1 year; and Barnett ~3 years).**

**Heckman, T.L., et al (2013):** ***Best Practices for Reserves Estimation in Unconventional Reservoirs — Present and Future Considerations,*** **Keynote presentation presented at the 2013 SPE Unconventional Resources Conference, The Woodlands, TX (USA), 10-12 April 2013.**

# <u>Rate-Time Analysis</u>: *Calibration — Linear Flow (Gas Shales)* [2/2]

## *Data taken from publicly available sources — Horizontal Shale (Dry) Gas Wells ONLY*



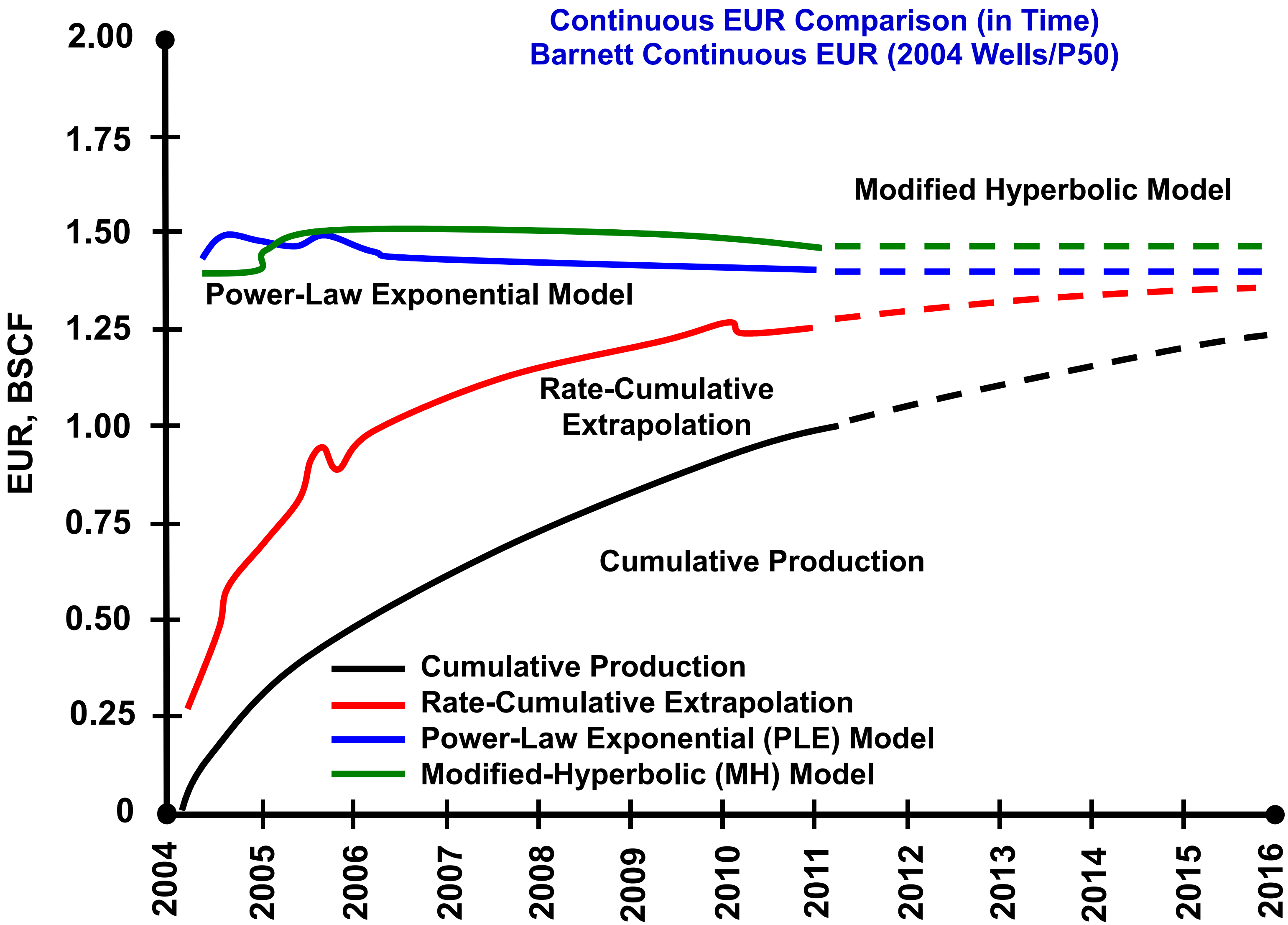


**Heckman, T.L., et al (2013): *Best Practices for Reserves Estimation in Unconventional Reservoirs — Present and Future Considerations*, Keynote presentation presented at the 2013 SPE Unconventional Resources Conference, The Woodlands, TX (USA), 10-12 April 2013.**


## <u>Discussion</u>:

- **START of "Linear Flow" (~3-6 months).**
- **END of "Linear Flow" (~9-36 months).**
- **"Linear Flow" is represented by linear trends on these plots.**
- **Square root time plot used to show linear portion of trend ($G_p(t)$ vs. SQRT($t$) is most clear).**

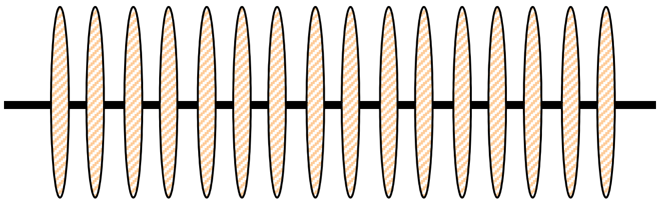
# <u>Continuous EUR</u>: *Barnett Shale Example*



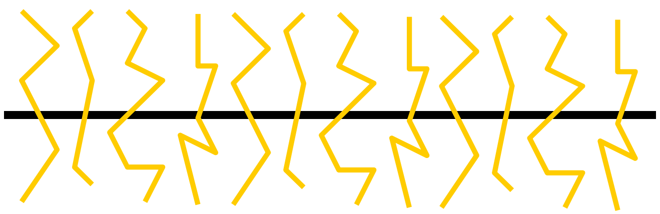

## <u>Discussion</u>:

- $G_p$ trend is well-established.
- $q_g$-$G_p$ extrapolation → EUR.
- PLE model is slightly conservative.
- MH model is the industry standard.

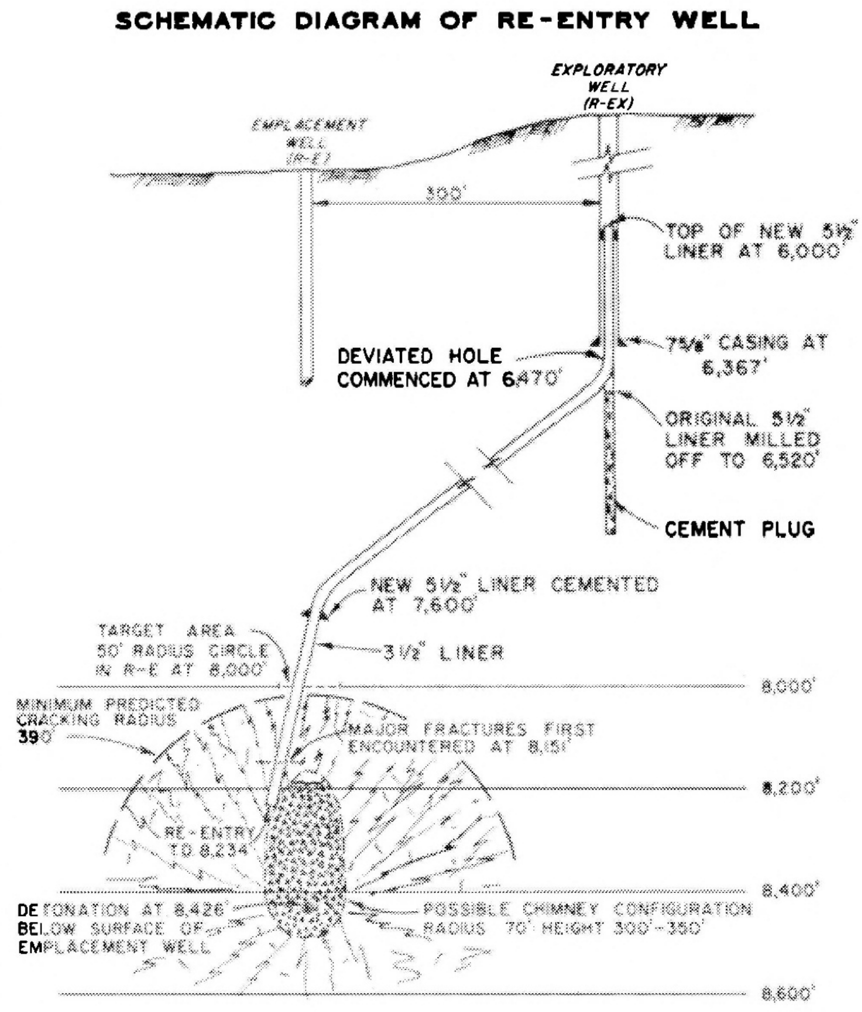
*"You only produce from what you frac …"*
Anonymous



Individual Fractures from
Individual Perforation Clusters



Complex Fractures from
Individual Perforation Clusters



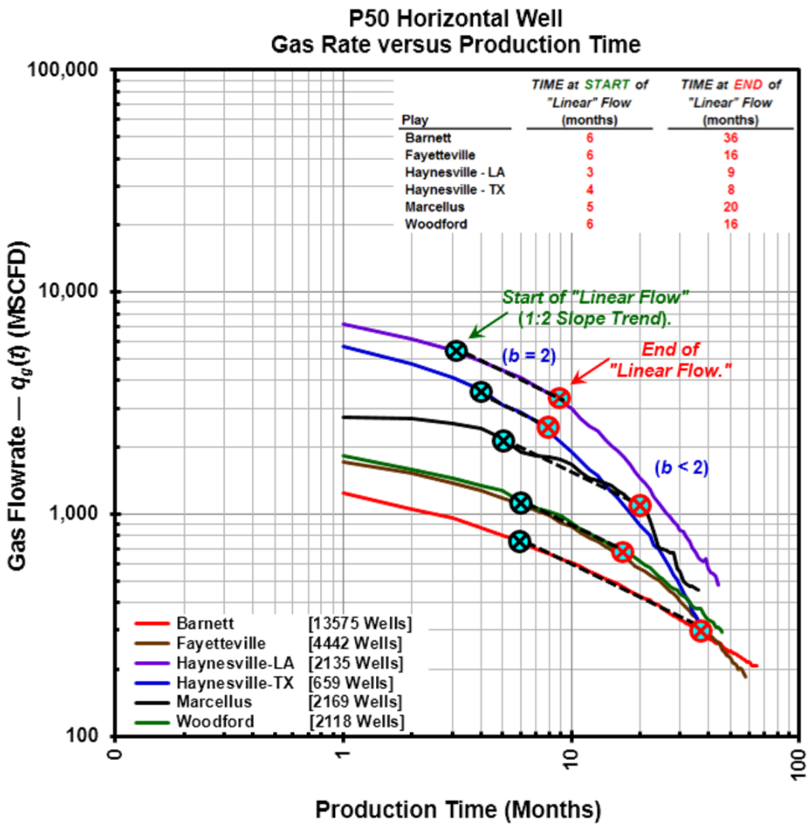

Project Rulison (1971)
Stimulation using Atomic Weapons

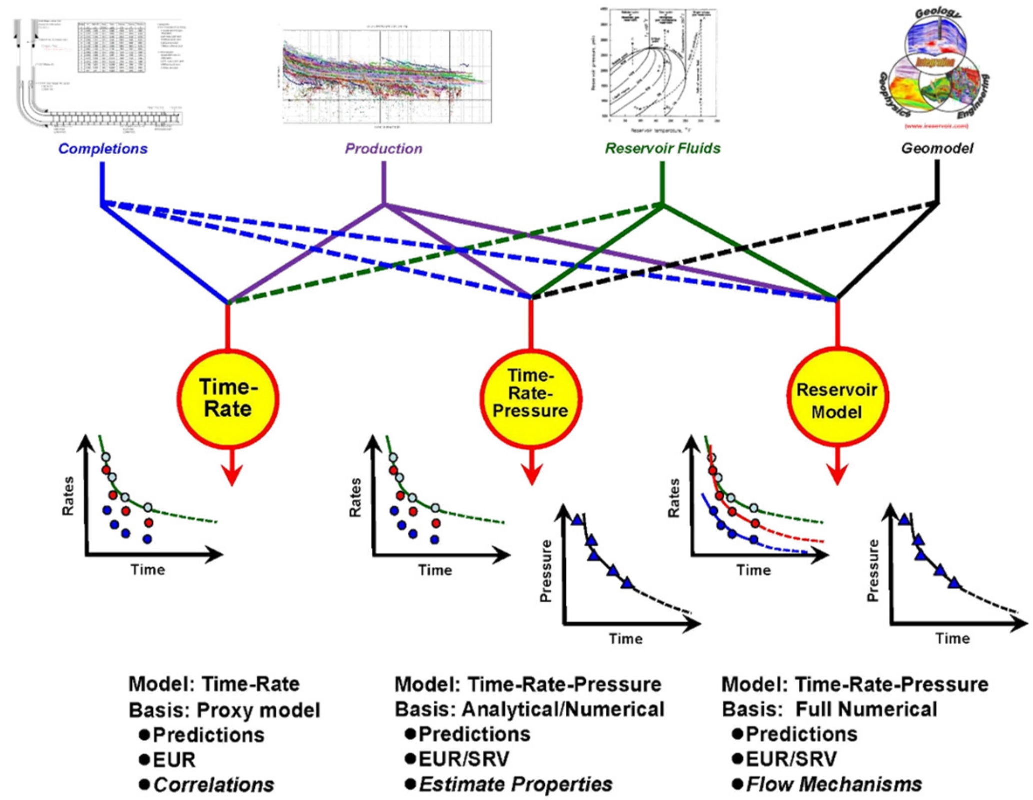
## Discussion:

- SRV (Stimulated Reservoir Volume)
  - Build Complexity → Slickwater
  - Build Conductivity → Hybrid/Gel
- Future Stimulation Challenges:
  - "Rubble-ize" the reservoir?
  - "Pulverize" the reservoir?
  - Do this with little or no water?

# Summary:

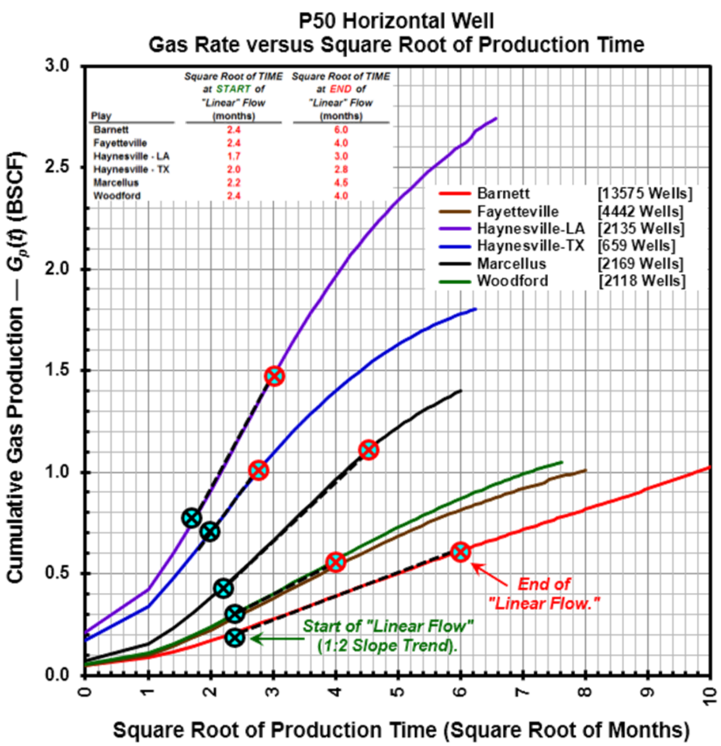
- **Where we want to be: (or so we think)**
  - Fit for purpose stimulation … (… oil/gas/condensate/geology)
  - More effective reservoir monitoring … (… this is important!)
  - Early EUR … (… prediction/correlation?)
  - Well spacing … (… geology + PVT + modeling)
- **How do we get there…**
  - Better understanding of flowback/dewatering … (… optimization)
  - Pressure-dependent properties … (… $k$, $F_{cD}$, desorption?)
  - Understanding of the pore-scale … (… what flows when/how)
  - Petrophysics … (… conventional petrophysics not adequate)
  - PVT … (… oil/gas/condensate/water — HP/HT)



# **Challenge Points**: *"What Keeps Me Up at Night…"*

- **What we *REALLY* know…**
  - Tight gas is relatively easy … (... vertical wells, HP/HT, PVT)
  - Gas shales are technically viable as a resource … (…a matter of economics)
  - Horizontal multi-fractured wells … (… (now) taken for granted)
- **What we *THINK* know…**
  - The fracture geometry is … (... planar? complex? who cares?)
  - The phase behavior is … (… extremely complex … *f*(Volume)???)
  - The $p_{tf}$ to $p_{wf}$ conversion(s) is/are … (... early-time heavy water load?)
  - Optimal well spacing/orientation/placement … (... do this early!)
- **What we may *NEVER* know…**
  - Distribution of natural fractures … (... impossible?)
  - Transport of gas/liquids in shales … (... via organic matter?)




- **Closure: Unconventional Reservoirs**
  - *EUR requires 18-36 months of production.*
  - *Significant reservoir heterogeneity.*
  - *Production requires stimulation.*
  - *Reservoir monitoring is essential.*
  - *Overpressure is important.*
  - *Pressure transient testing may help.*
  - *Tight-gas analogs are not perfect.*
  - *Performance management is essential.*
  - *Long-term production testing is critical.*

# *Reservoir Engineering Aspects of Unconventional Reservoirs*

## *End of Presentation*

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