David S. Fulford

Staff Reservoir Engineer
Exploration Evaluation
Apache Corporation

David Fulford joined Apache Corporation in January 2013, working in the newly-formed Exploration Evaluation group with responsibility to support Apache's operating business units in the characterization of exploration and development opportunities for the purpose of strategic planning. He is actively involved with the mentoring of engineers progressing through the Apache Engineering Development program. Most recently, he has had Machine Learning as a Reliable Technology for Time/Rate Performance of Unconventional Wells published in *SPE Economics and Management*, and his manuscripts Unconventional Risk & Uncertainty: Show Me What Success Looks Like and People and Process: Integration of Technology and Organizational Alignment for Successful Implementation of a Strategic Capital Investment Portfolio selected by *Journal of Petroleum Technology* editorial staff for publication in the December 2016 and December 2017 issues, respectively. He is currently completing a Master of Science degree in petroleum engineering at Texas A&M, with an expected graduation date of August 2018.

Fulford graduated from Texas Tech University in 2006 with a Bachelor of Science degree in petroleum engineering, and entered the petroleum industry as a new-hire engineer with Devon Energy. He worked in several field- and office-based engineering roles spanning reservoir, drilling, and production engineering for Devon from 2006 to 2013. His most recent position was Senior Reservoir Engineer from 2011 to 2013 where his primary responsibility was to maintain an evergreen portfolio of cases that categorized exploration and exploitation investment opportunities.

During his time at Apache, Fulford has made considerable contributions to advancing the state-of-the-art of Apache's planning and budgeting processes, primarily through driving implementation of best practices and development of proprietary toolsets for the evaluation of investment opportunities for Apache's worldwide portfolio. His primary focus is on merging decision quality and reservoir engineering through improvements in the estimation of risk and uncertainty, and probabilistic evaluation of these within a decision framework that includes strategic alternatives. He maintains additional focus on reducing human bias in decision making through objective revision of prior beliefs via Bayesian methods, leading to original work in the estimation of ultimate recovery and production surveillance and forecasting of unconventional shale plays during the exploration phase. He has authored and presented numerous papers and spoken at many industry conferences on these topics.

Fulford has served on the program selection committee for the Unconventional Resources Technology Conference (URTeC) for the past 3 years, and as session chair for the Production Forecasting & Reserves and Advanced Data Analytics Session. He is a member of the Society of Petroleum Engineers (SPE), Society of Petroleum Evaluation Engineers (SPEE), and Society of Decision Professionals (SDP).

MULTI-PHASE PRODUCTION FORECASTING
"BUBBLE POINT DEATH?"

DAVID S. FULFORD

JANUARY 10, 2018

SOCIETY OF PETROLEUM EVALUATION ENGINEERS

MIDLAND CHAPTER

INTRODUCTION

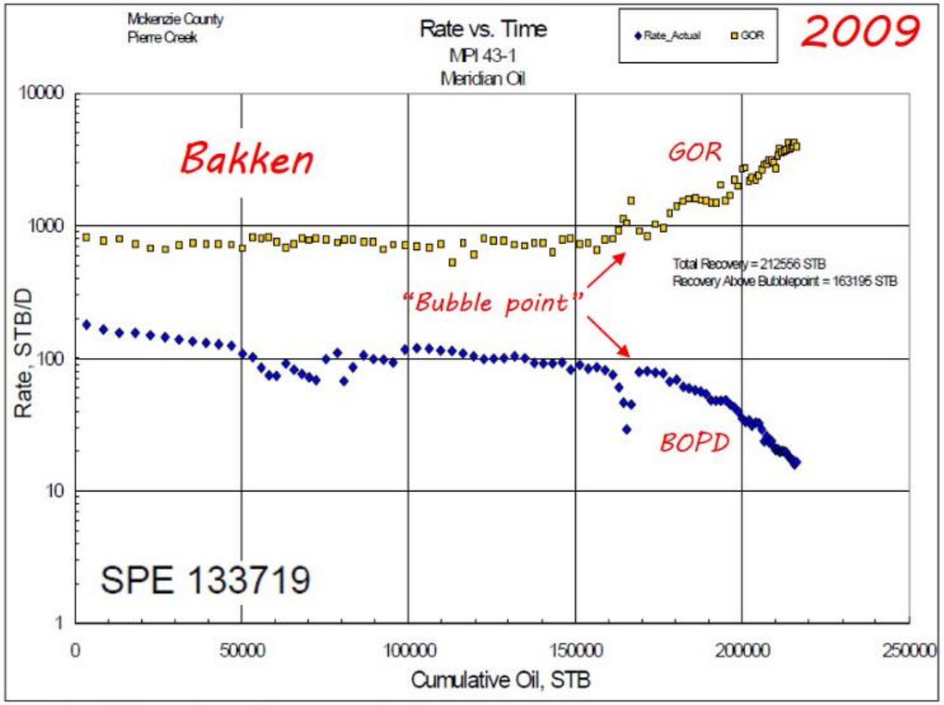
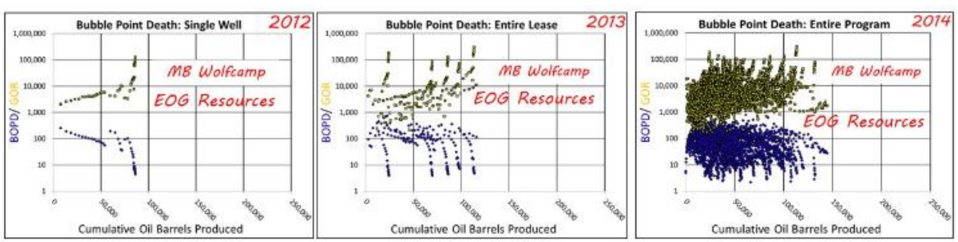


Fig. 5 – GOR vs. Cumulative production.



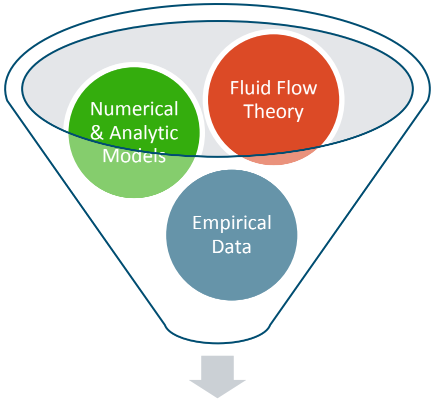
EOG's abandonment of its once grand Midland Basin Wolfcamp program

- Recently, doubts raised about reliability of **oil** forecasts given trend changes in *GOR* and *oil rate* that coincide with one another
- Shale "growth" stocks hit by investor doubts
- Analysts linking observed empirical data to recent miss by operators on **oil**

INTRODUCTION

- Is this:
  - a) expected behavior?
  - b) new and impactful to our ability to hit guidance?

- Second, if it is expected, have we properly *planned* for it?



TECHNICAL SUMMARY

- During infinite-acting linear flow and constant flowing pressure conditions, GOR is *<u>constant</u>* for a constant flowing pressure

- When the infinite-acting period ends, we observe two things:
  - 1) Change from -1/2 slope to negative unit slope or steeper on log-log rate-time plot
  - 2) GOR no longer constant but begins to increase

- These two together, we have a narrative of "bubble point death"
- Reality is that operation practices or lack of artificial lift more likely explanation for any "well death" after end of infinite-acting period or at bubble point pressure

LITERATURE REVIEW

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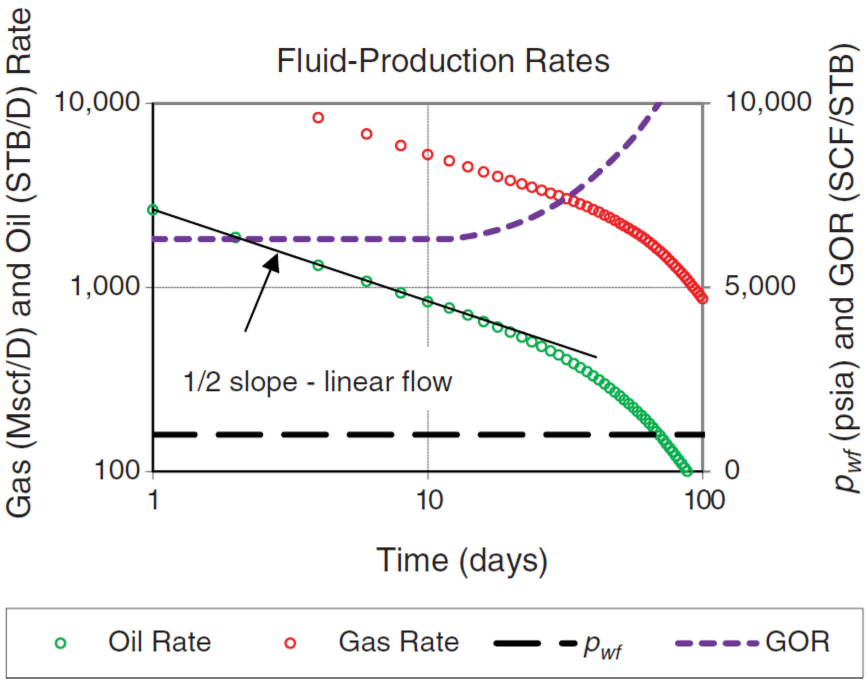
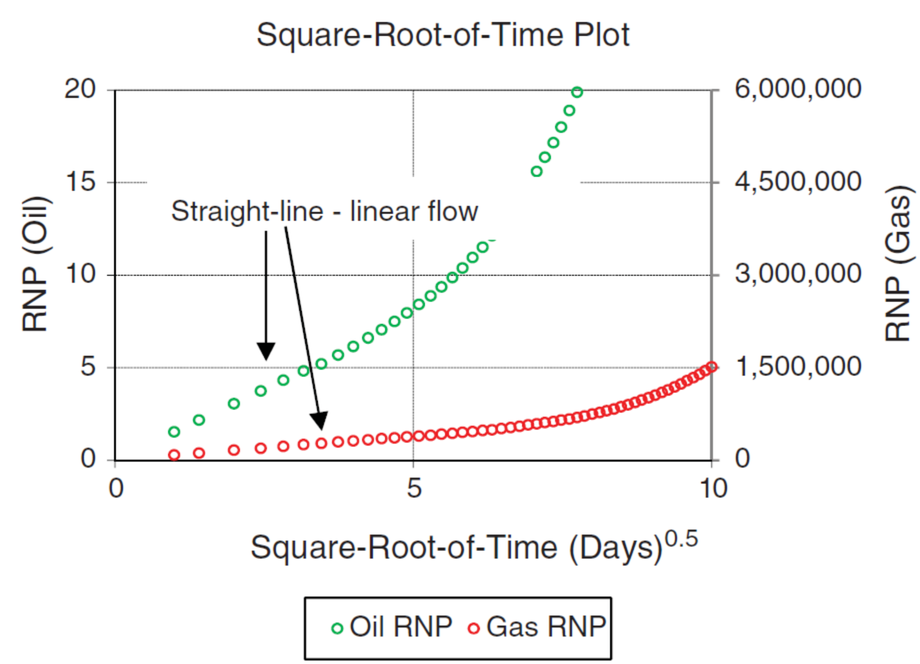




LITERATURE REVIEW

- From solution of PDE for infinite-acting case:
  - $\frac{q}{p_i - p_{wf}} = A\sqrt{\frac{k\phi c_t}{\mu}}\frac{1}{\sqrt{t}}$ $\rightarrow$ $q \propto \frac{1}{\sqrt{t}}$
- Combine time & space into similarity variable:
  - $\xi = \frac{x}{\sqrt{t}}$
- So, instead of
  - $GOR = f(x,t)$ $\rightarrow$ $GOR = f\left(\frac{x}{\sqrt{t}}\right)$

LITERATURE REVIEW

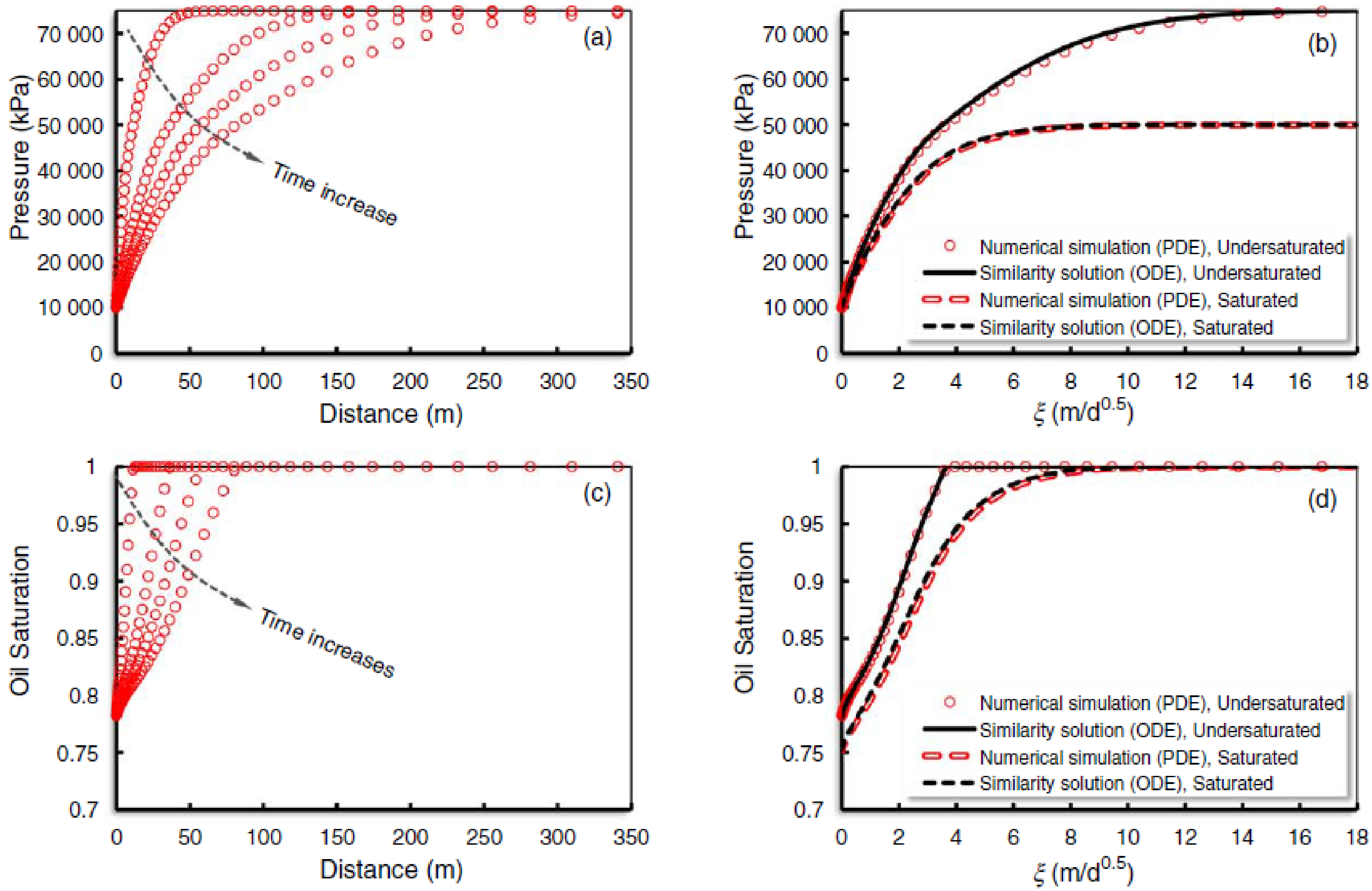


Fig. 9—Comparison of the performance of saturated ($p_i = p_{bp} = 50\,000$ kPa, $R_{si} = 219\ m^3/m^3$) and undersaturated ($p_i = 75\,000$ kPa, $p_{bp} = 50\,000$ kPa, $R_{si} = 219\ m^3/m^3$) tight oil reservoir.

LITERATURE REVIEW

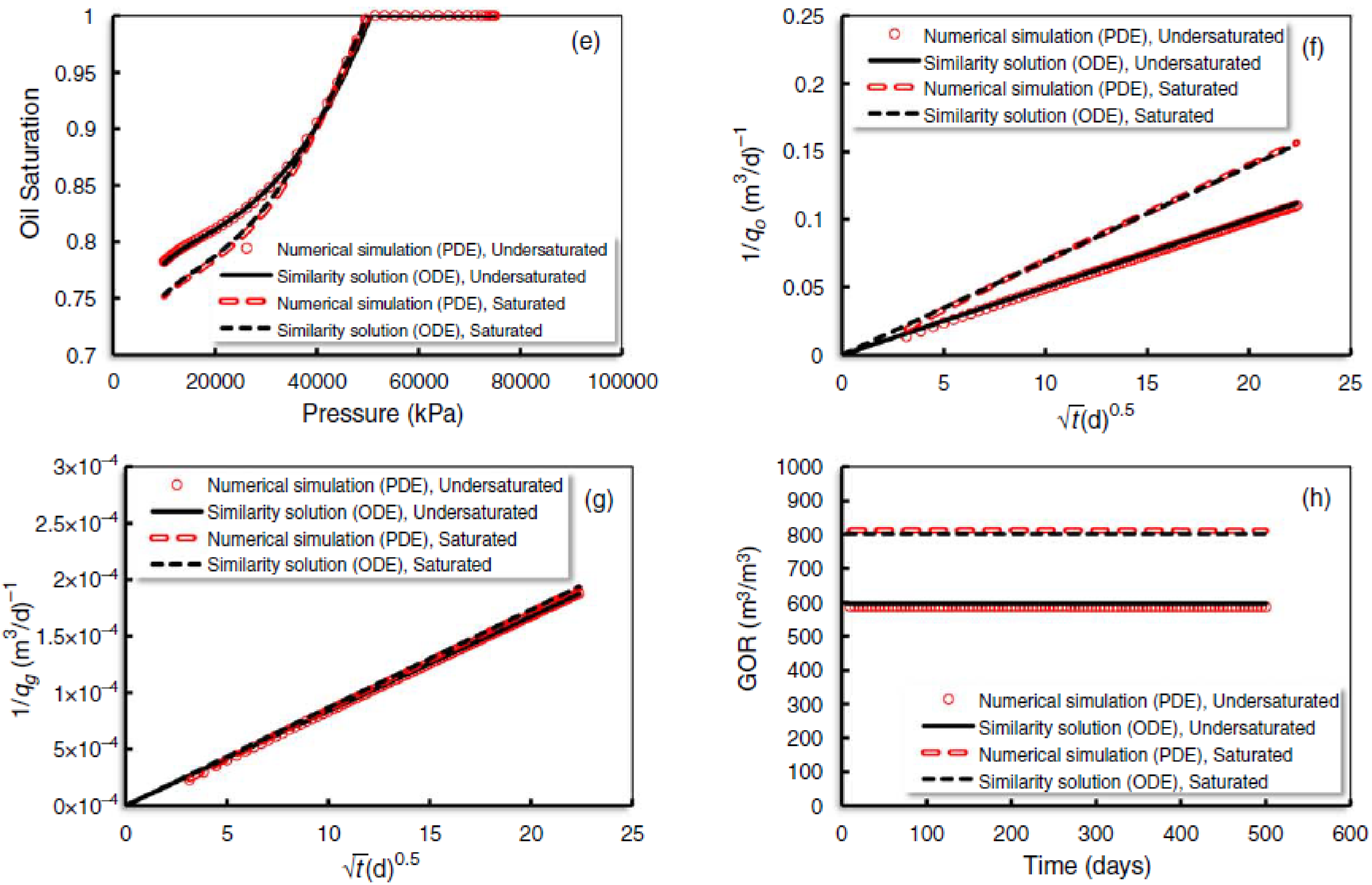


Fig. 9—Comparison of the performance of saturated ($p_i = p_{bp} = 50\,000$ kPa, $R_{si} = 219\,m^3/m^3$) and undersaturated ($p_i = 75\,000$ kPa, $p_{bp} = 50\,000$ kPa, $R_{si} = 219\,m^3/m^3$) tight oil reservoir.

LITERATURE REVIEW

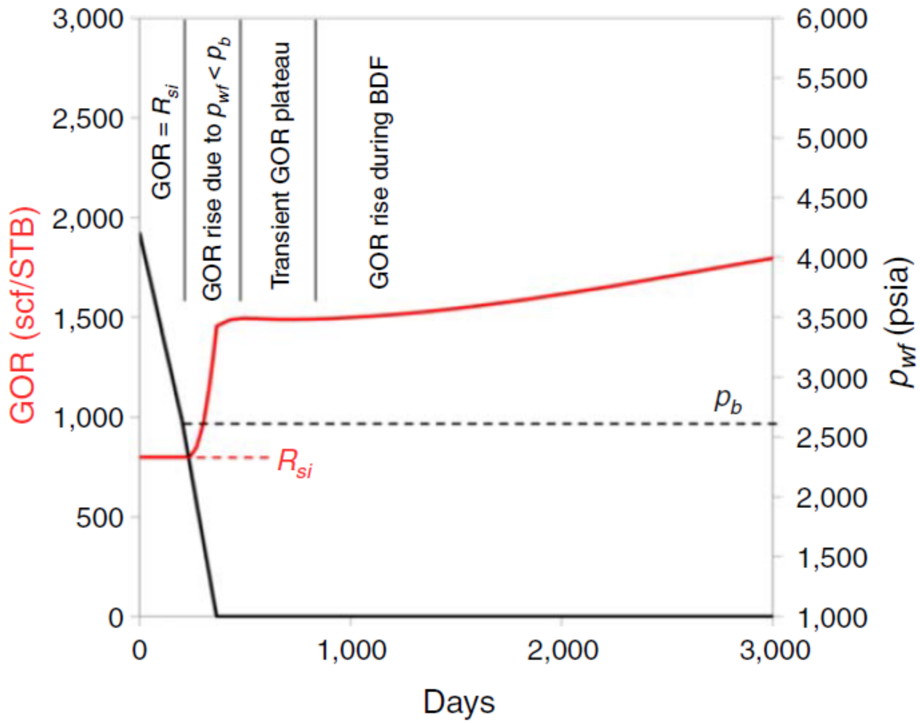
- $GOR = R_s + \frac{k_{rg}\mu_o B_o}{k_{ro}\mu_g B_g}$ evaluated at sandface
- If $\bar{p} = \underline{constant}$
- $\rightarrow \bar{B}_o \,\&\, \bar{S}_o \rightarrow k_{ro} \,\&\, \mu_o \rightarrow GOR = \underline{constant}$

- Implications:
  - "The production GOR is controlled by pressure and saturation at the sand face, not the average properties within the region of depletion.

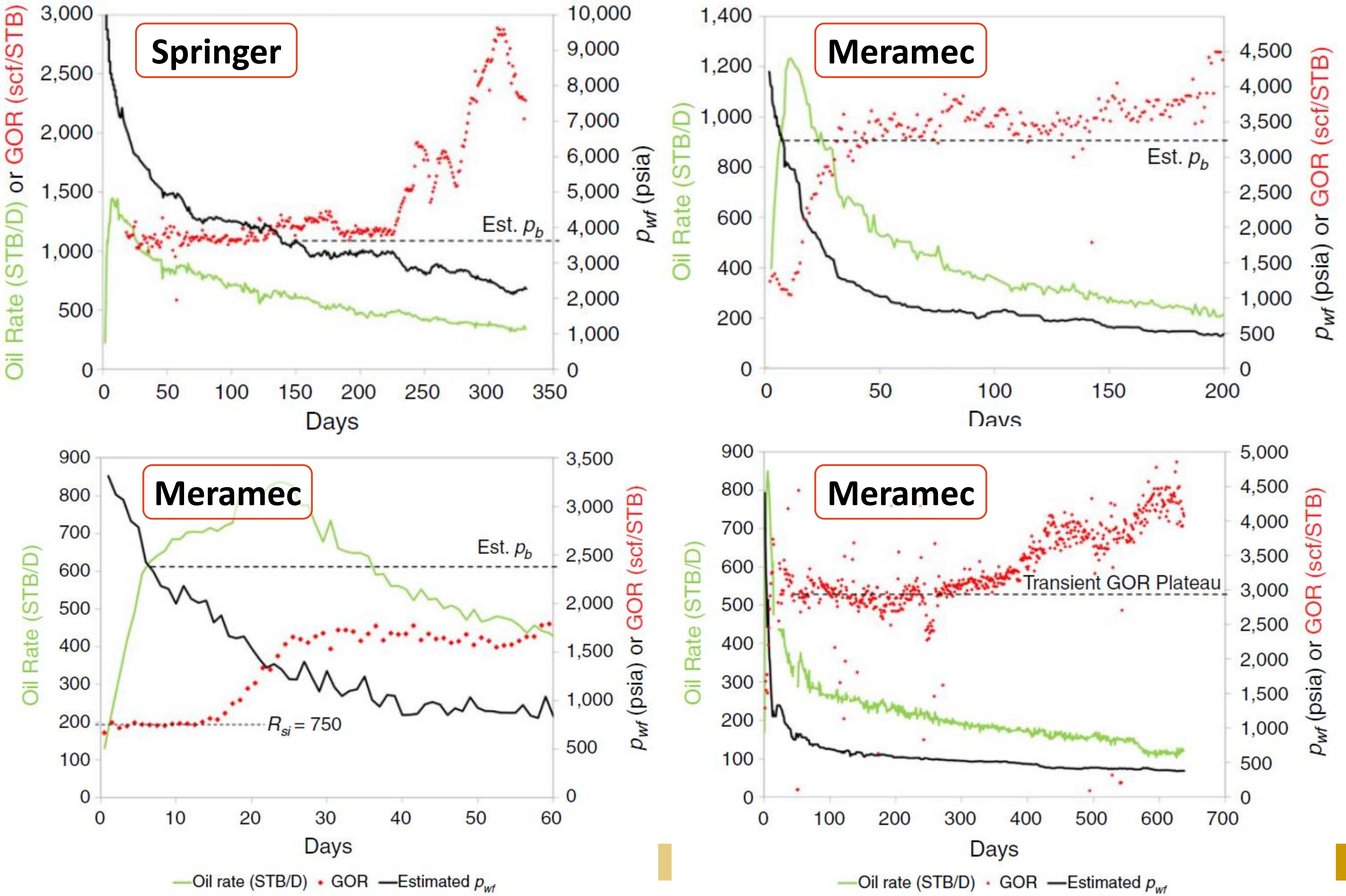
    The saturation/pressure relationship, and hence, the production GOR, is independent of absolute permeability."
  - "Recombination of fluid samples collected at the surface in the ratio of producing GOR does not represent the in-situ reservoir fluid"

LITERATURE REVIEW

- Early-time change in GOR due to p_{wf}:
  - 1) GOR = R_{si}
  - 2) GOR rise due to decreasing p_{wf}
  - 3) GOR plateau in linear flow
  - 4) GOR rise during BDF



LITERATURE REVIEW



LITERATURE REVIEW

- Additionally, bubble point is suppressed in nanopores

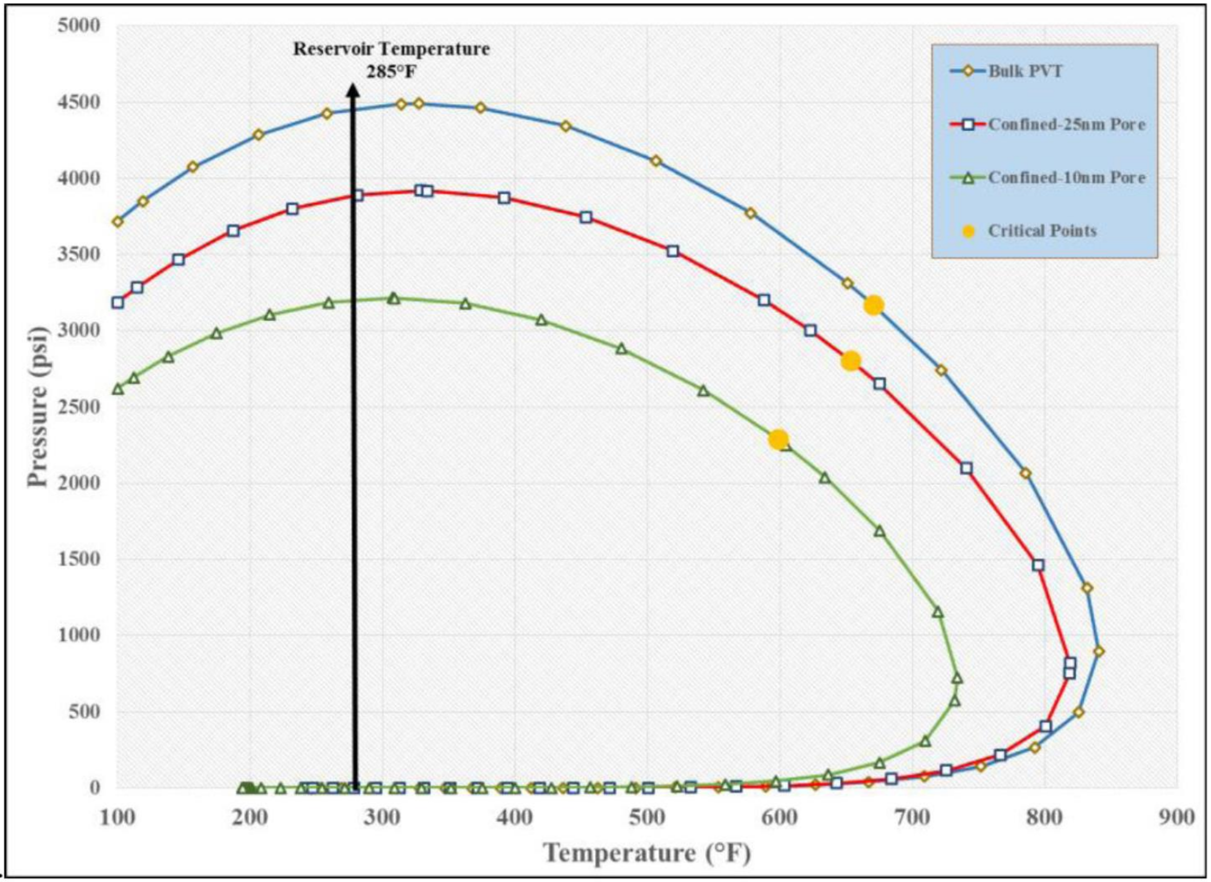


Figure 6—Confined and unconfined phase envelope

LITERATURE REVIEW

- Flow regimes dictate secondary phase yield *trends*

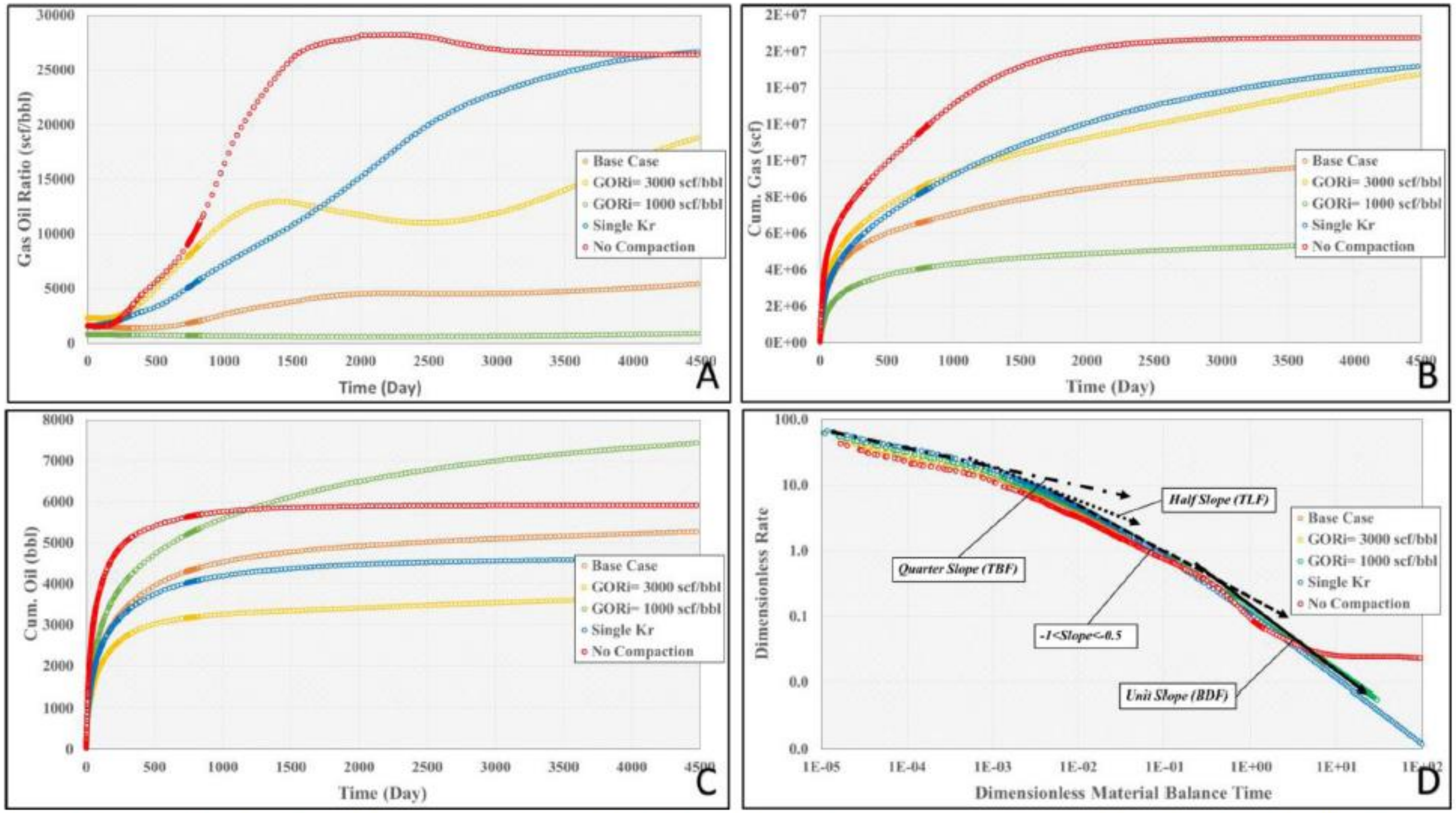
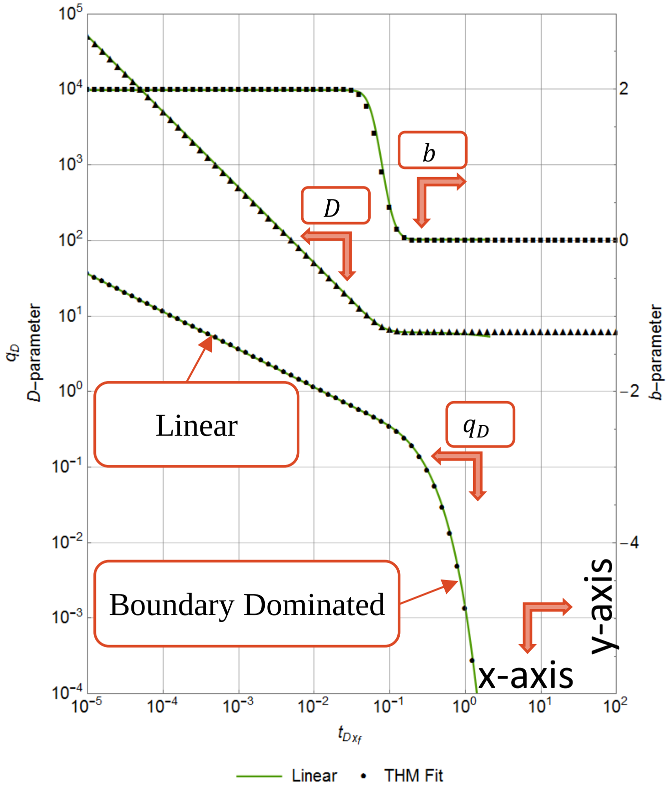


Figure 19—Simulation results of study's cases: A- GOR vs. time, B-Cumulative gas production vs. time, C-Cumulative oil production vs. time, D- log-log plot dimensioless rate vs. dimensionless MBT

MODEL APPROXIMATION

Tri-Diagnostic Plot



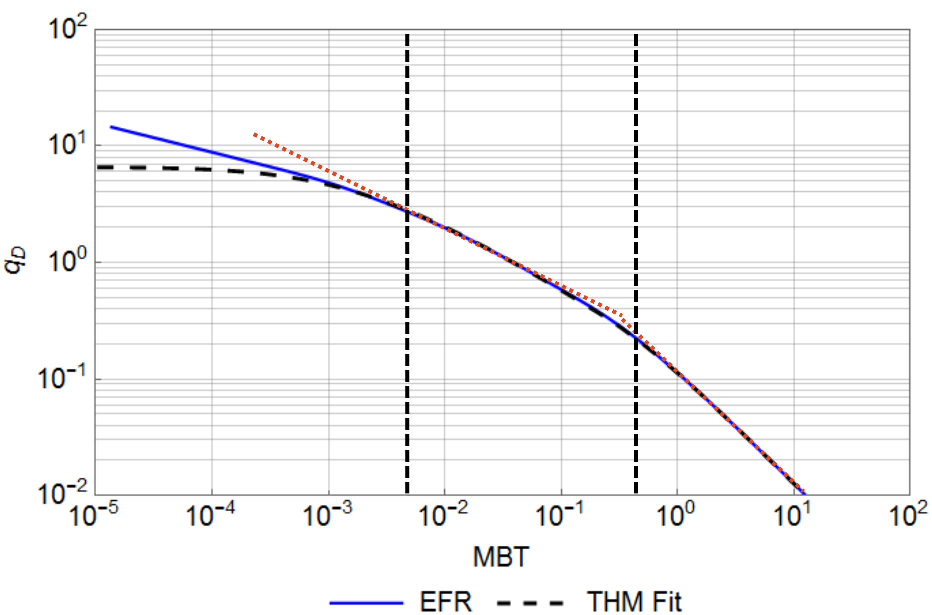
Transient Hyperbolic Model (THM) –

- Excellent approximation of Linear Flow Model
- $b(t) = b_i - (b_i - b_f)e^{-e^{-c(t-t_{elf})+e^{\gamma}}}$
- $D(t) = \frac{1}{\int b(t)dt}$ $\qquad c = \frac{e^{\gamma}}{1.5t_{elf}}$
- $q(t) = q_i e^{\int -D(t)dt}$
- *Used as basis*

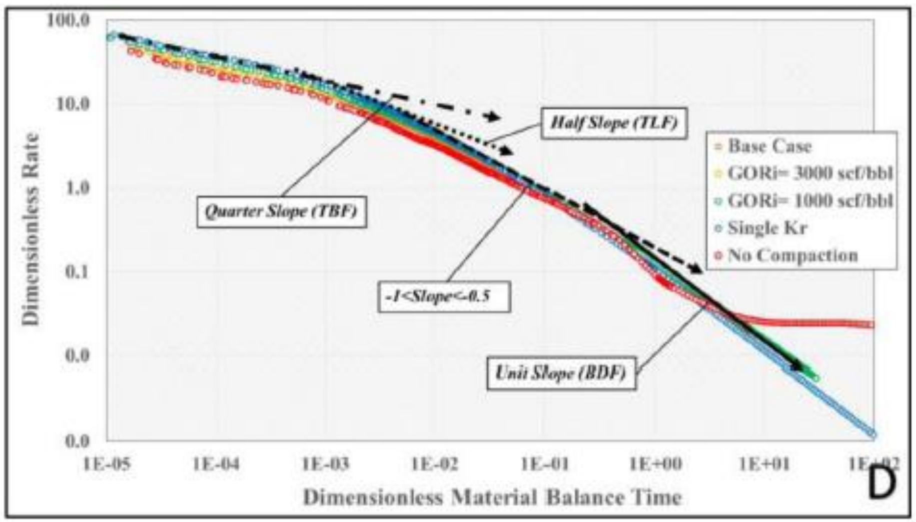
PRIMARY PHASE (OIL) FORECASTING

- Multi-Segment (Transient) Hyperbolic and Analytic solution on left
  - Fulford and Blasingame 2013, SPEE Monograph 4
- Compositional Simulation w/ nanophase behavior on right

Multi-Segment Hyperbolic

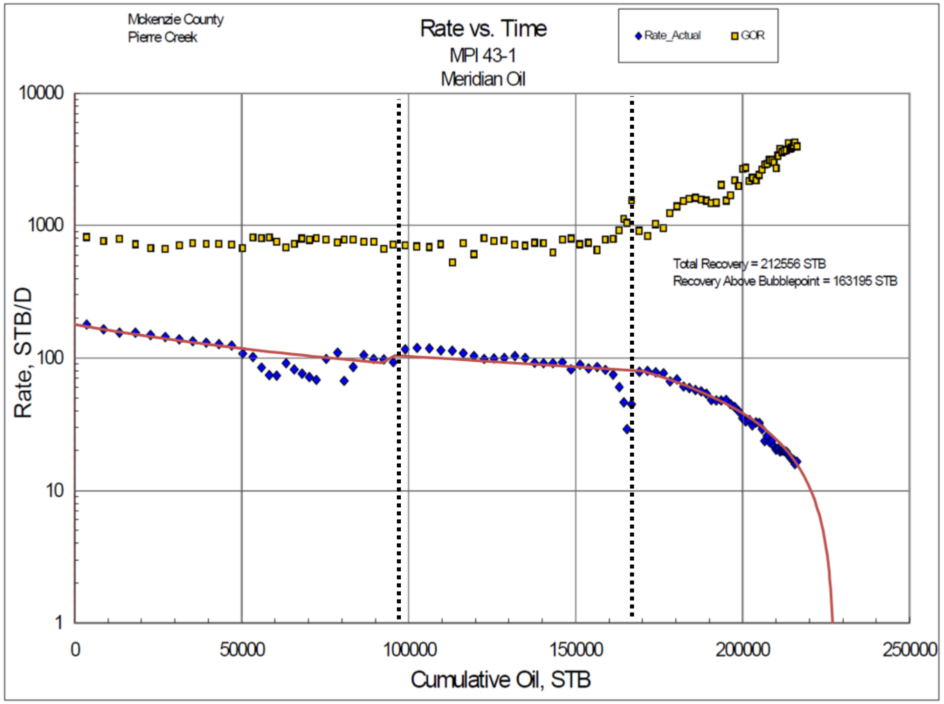


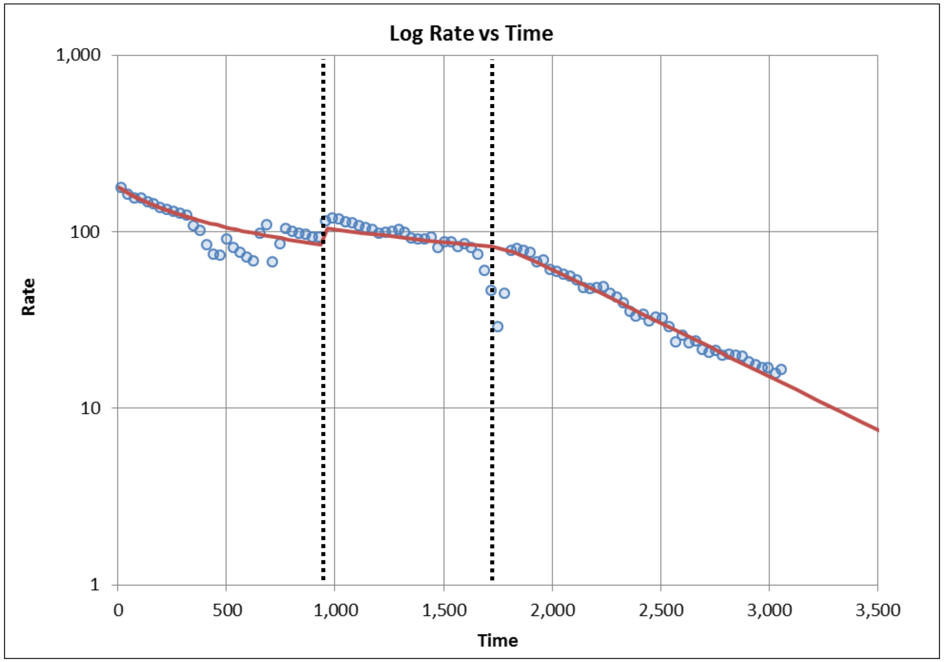
Compositional Sim.



BAKKEN WELL (SPE-133719-STU)

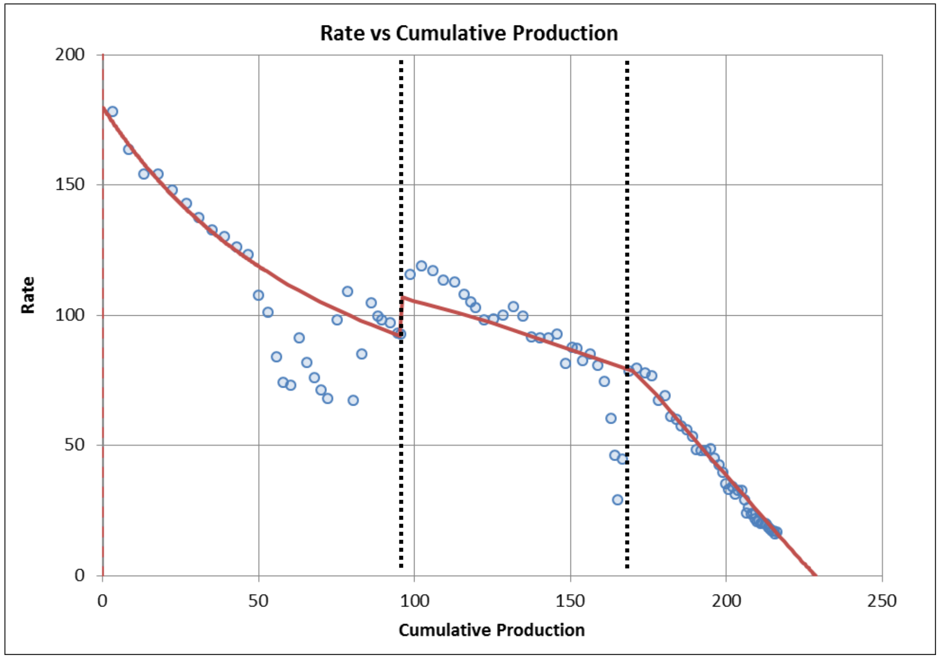
- 1st Segment: $b = 2$
- 2nd Segment: Rate shift; $b = 2$
- 3rd Segment: Rate continuous, $D = 0.11 \rightarrow 0.51$, $b = 0$

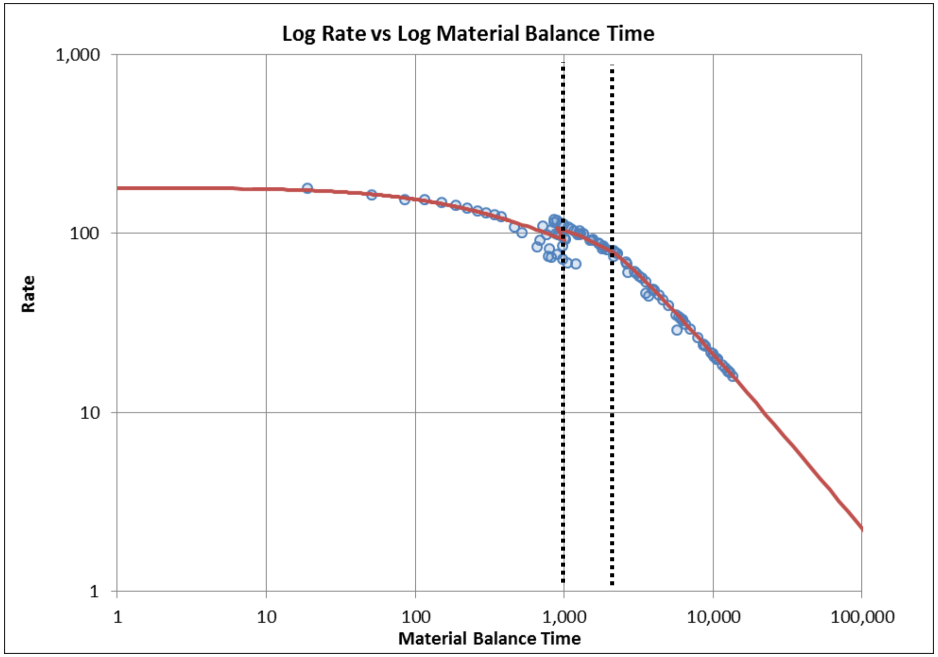




BAKKEN WELL (SPE-133719-STU)

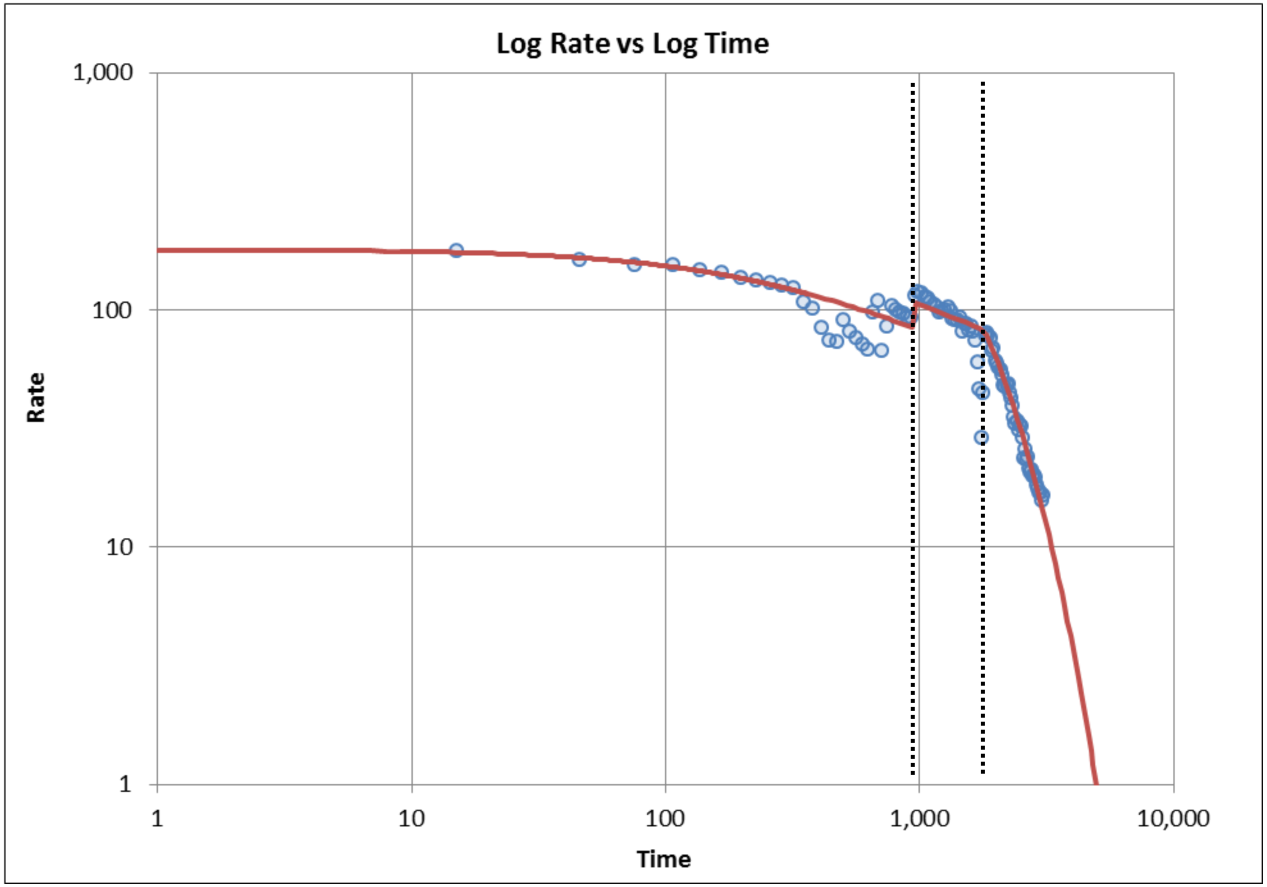
- Diagnostic plots only valid for specific flow regimes
  - If exponential, *Cartesian* Rate vs. Cum
- Rate vs. MBT follows same sequence



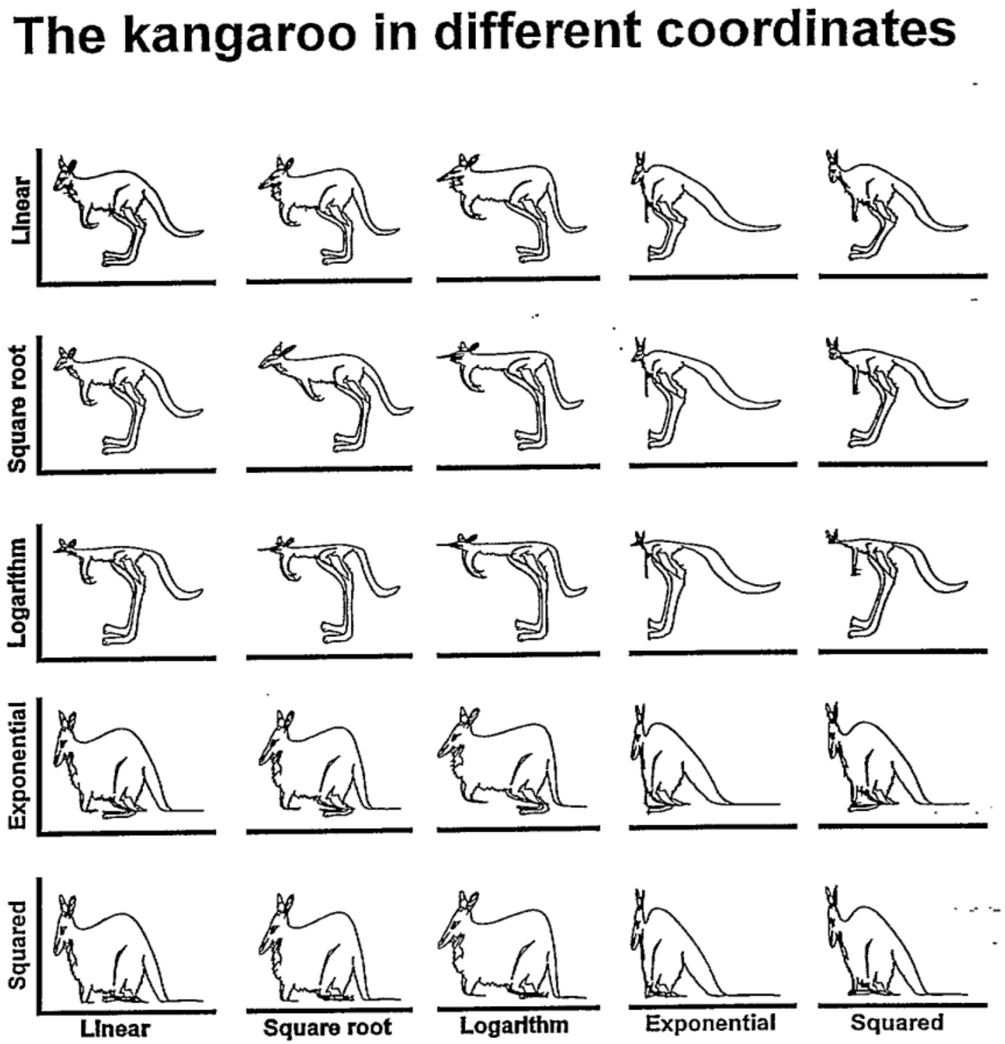


BAKKEN WELL (SPE-133719-STU)

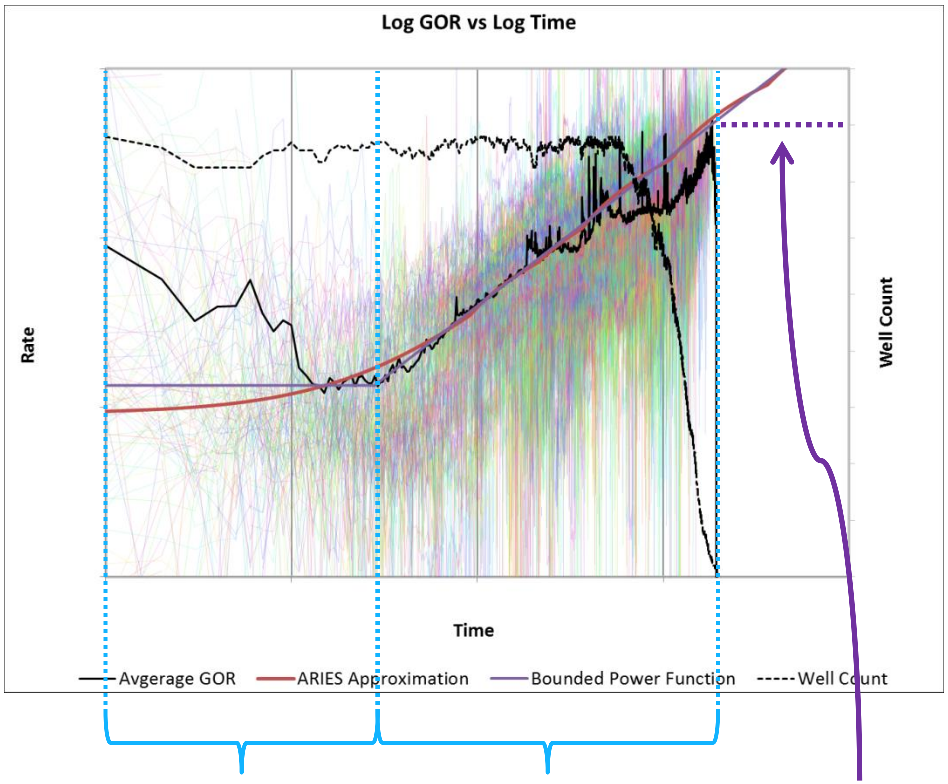
- *If it happens suddenly… it is not a reservoir effect.*
  - *Louis Matter, IHS Fekete*



AN ASIDE


The kangaroo in different coordinates
Linear
Square root
Logarithm
Exponential
Squared
Linear
Square root
Logarithm
Exponential
Squared

SECONDARY PHASE (GOR) FORECASTING



Infinite-acting Linear Flow

Boundary-*influenced* Flow

Use Maximum Limit for ***Reasonable Certainty***

- Literature sparse on empirical GOR forecasting… fit the “form” from data
  - $y = bt^m$
- Simple Power-Law function works well for GOR *or* CGR yield forecasts
- Couple to primary phase forecast by infinite-acting constant yield (y_{LF}) and diagnosed end of linear flow (t_{elf})
  - $b_{GOR} = y_{LF} t_{elf}^{-m_{GOR}}$

SECONDARY PHASE (GOR) FORECASTING

- All have similar *slope,* vertical shift is due to intercept

SECONDARY PHASE (GOR) FORECASTING

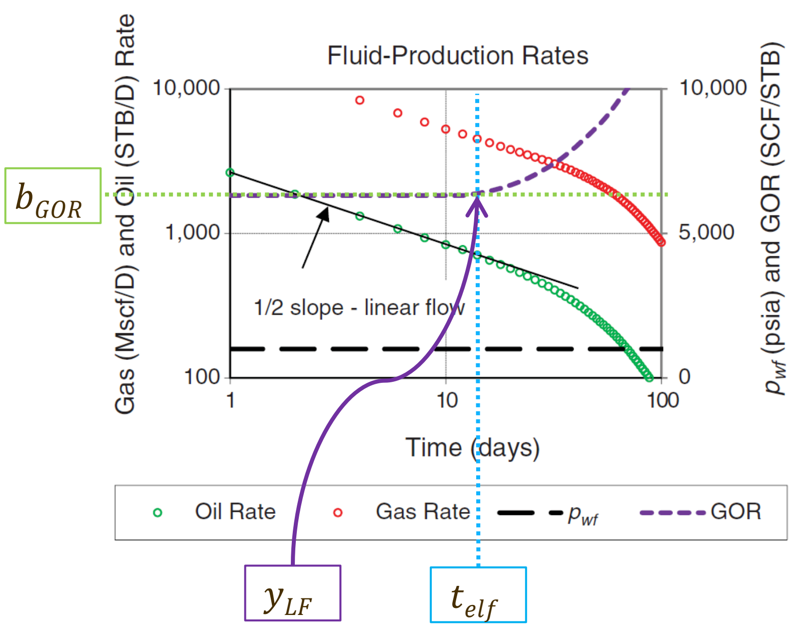
- Some considerations…
  - Wells in communication will establish similar GORs
  - Frac hits may change trend

- 2-parameter (Power-Law) model provides simplicity and ease-of-use for noisy production data
- Most wells fall within reasonable range of parameter values
  - Observed value in data shown –
    - m_{GOR}: 0.6 to 0.9

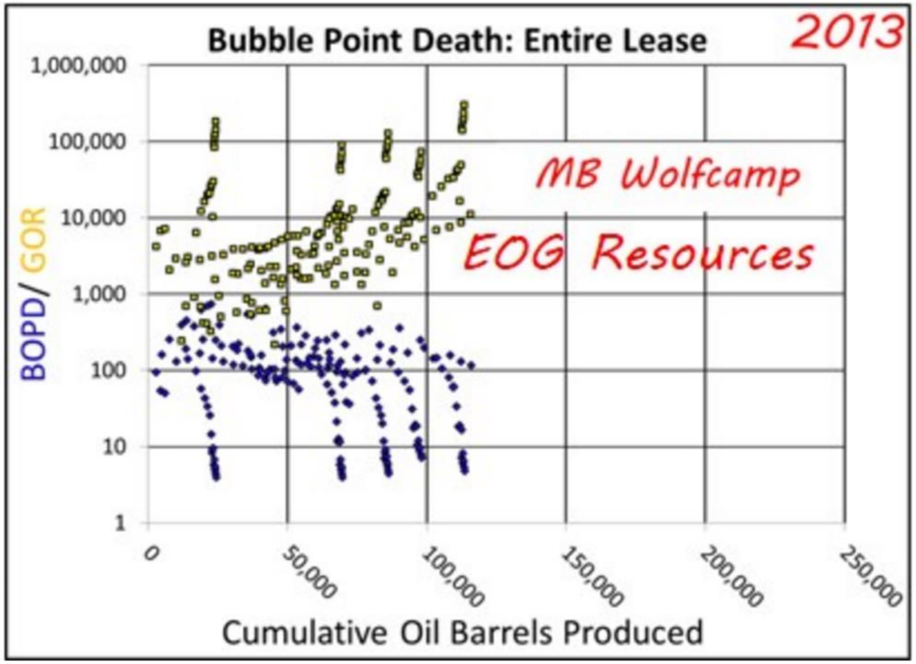
Apache

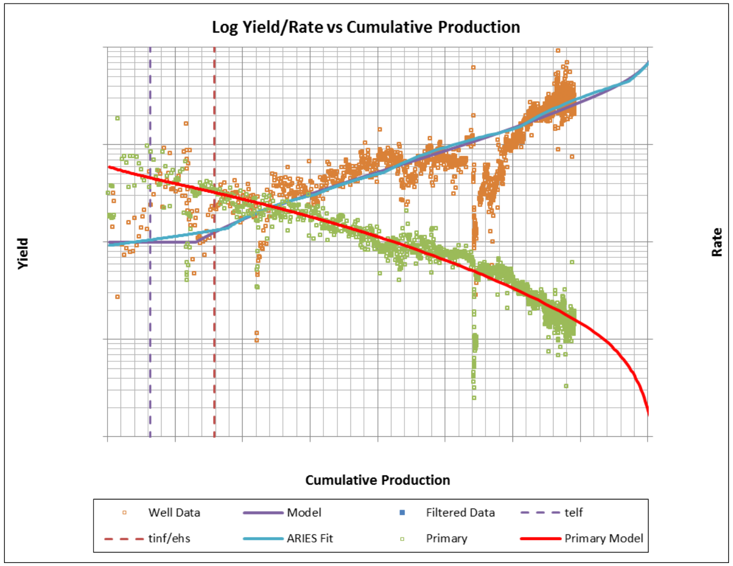
WORKFLOW

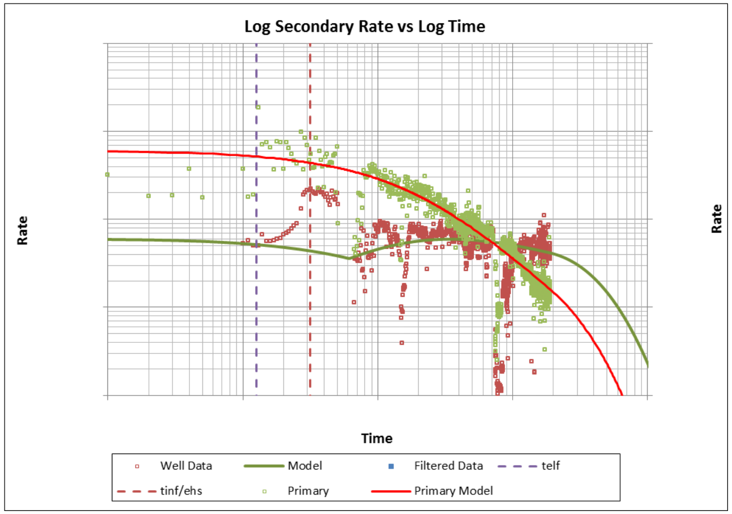
- 1) Forecast Oil phase, identify time to end of linear flow (t_{elf})
- 2) Specify slope (m_{GOR}) and GOR plateau (y_{LF}) during linear flow period from analog(s)
- 3) Calculate intercept (b_{GOR})
  - $b_{GOR} = y_{LF} {t_{elf}}^{-m_{GOR}}$
- 4) Forecast GOR
  - $GOR = b_{GOR} t^{m_{GOR}}$



DISCUSSION







- Rate-Cum not a useful diagnostic for well recovery
- "Bubble point death" not an issue in WC/LSS MFHWs as the entirety of production history appears to occur below bubble point (GOR increase coincides with end of infinite-acting period)

CONCLUSIONS

- GOR in tight oil can be approximated with a constant value during linear flow (for constant p_{wf})
- Primary phase flow regimes follow clear sequence even with more-complex physics (compaction, single/dual k, bubble point suppression) included in models
- GOR trends impacted by more-complex physics, but "trend" correlated with primary phase flow regimes
  - GOR increase may occur over years, but evidence is against "bubble point death" as a common phenomenon in tight oil
- Power-law slope (m_{GOR}) is a useful diagnostic, may be determined from analog(s) to forecast GOR trend

APPENDIX

DIAGNOSTICS

- Flow Rate proportional to square-root of time during infinite-acting flow
  - $q \propto \frac{1}{\sqrt{t}} \approx \frac{1}{\sqrt{1+2D_i t}} \approx \frac{1}{(1+D_i b t)^{\frac{1}{b}}}$
  - $\log q = -\frac{1}{b} \log t$
- Flow Rate trend change in *field data*
  - steeper slope
  - $b \rightarrow \approx 0.8 - 1.0$

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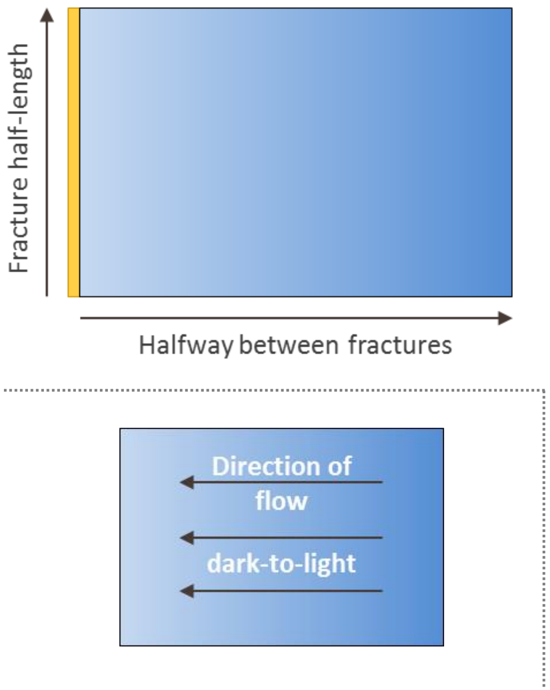
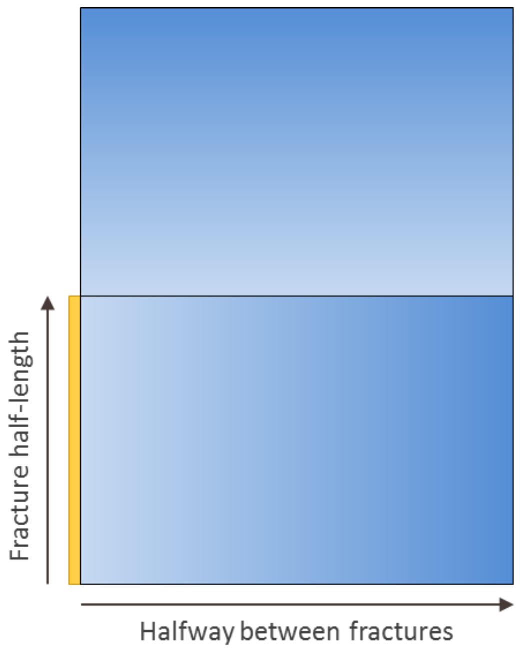
STATE-OF-THE-ART MODELS

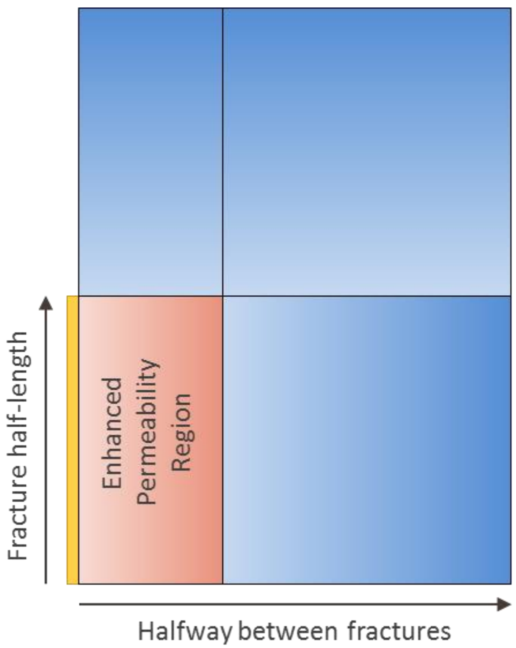
Linear



Trilinear

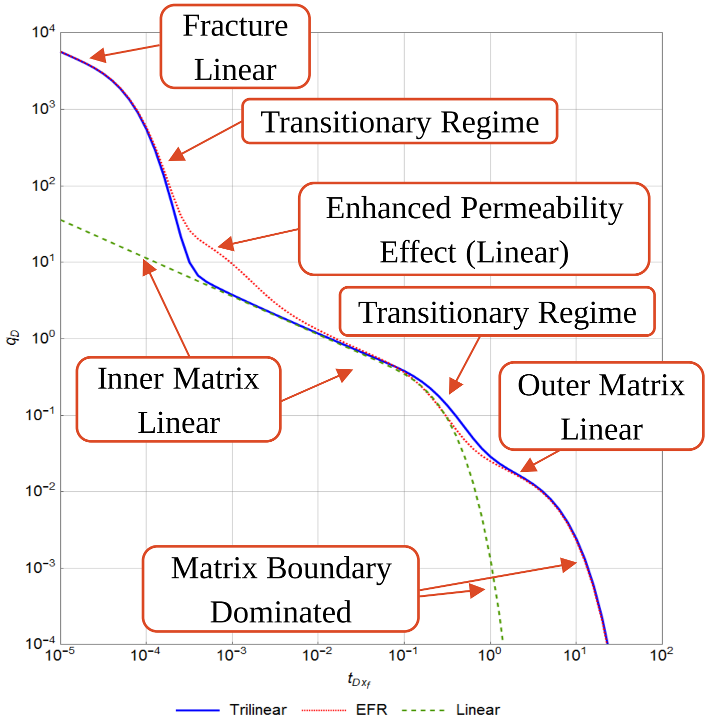


EFR

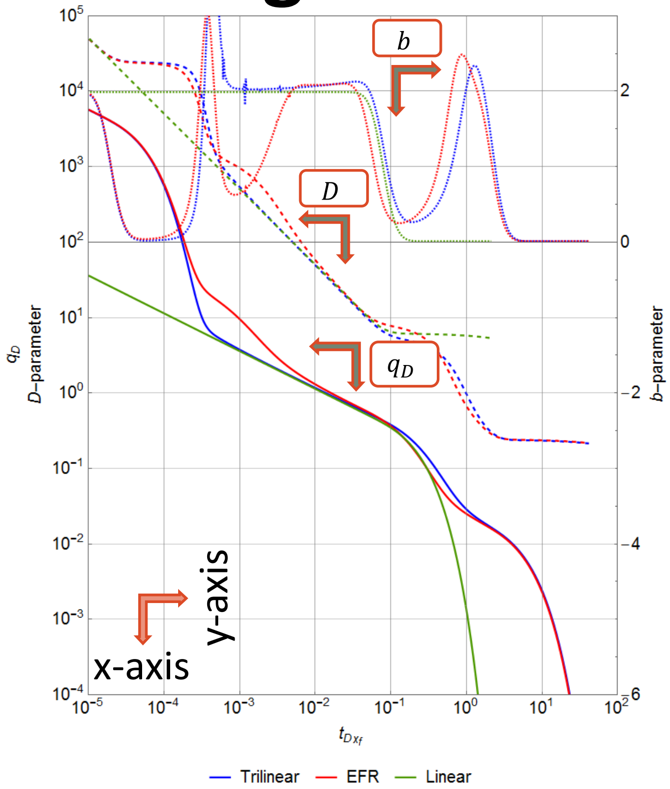


STATE-OF-THE-ART MODELS

Flow Behavior

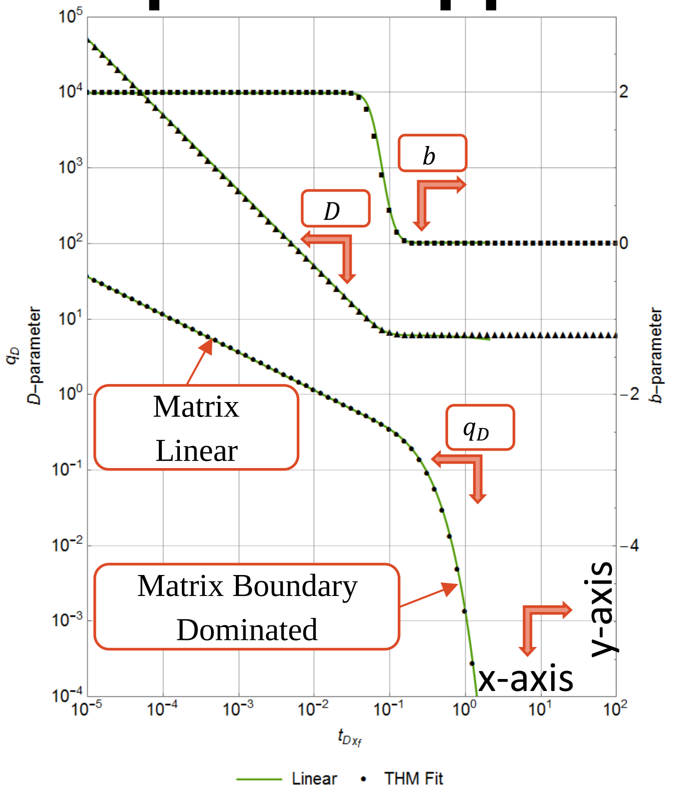


Diagnostics



MODEL APPROXIMATION

Empirical Approx.



Transient Hyperbolic Model (THM) –

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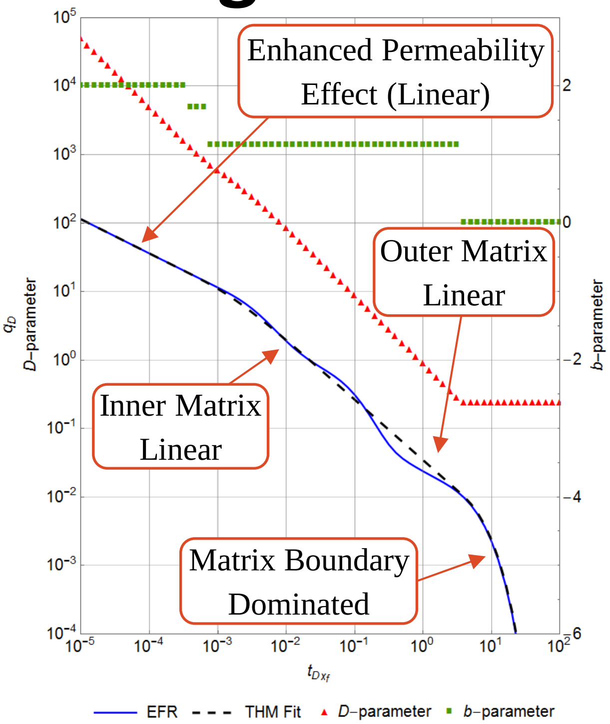
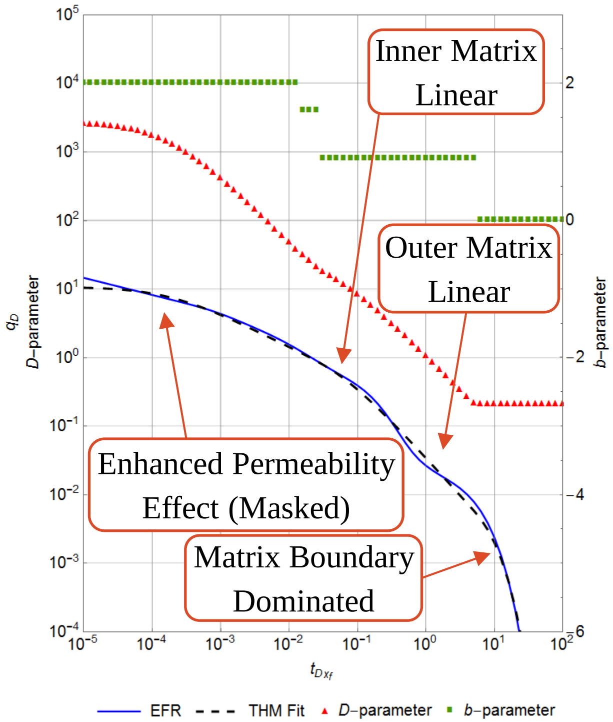
- *Used as basis*

MODEL APPROXIMATION

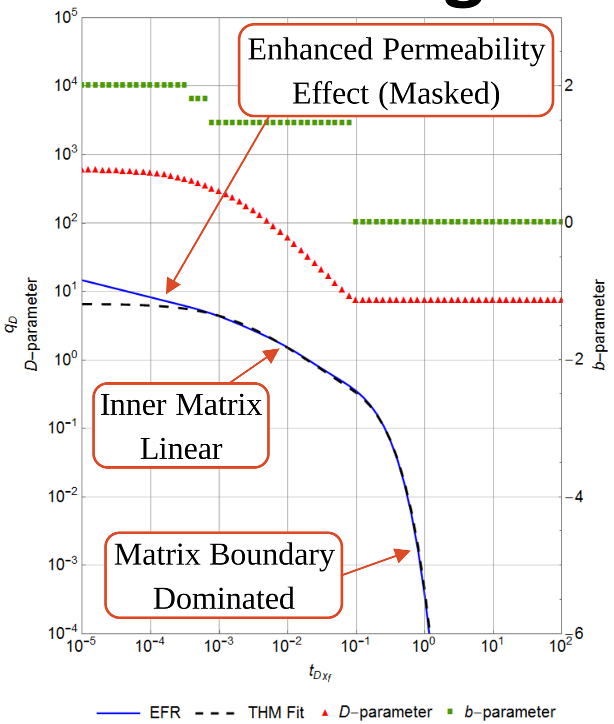
High FCD



Low FCD



No Outer Region



COMPOSITIONAL SIMULATION GRID

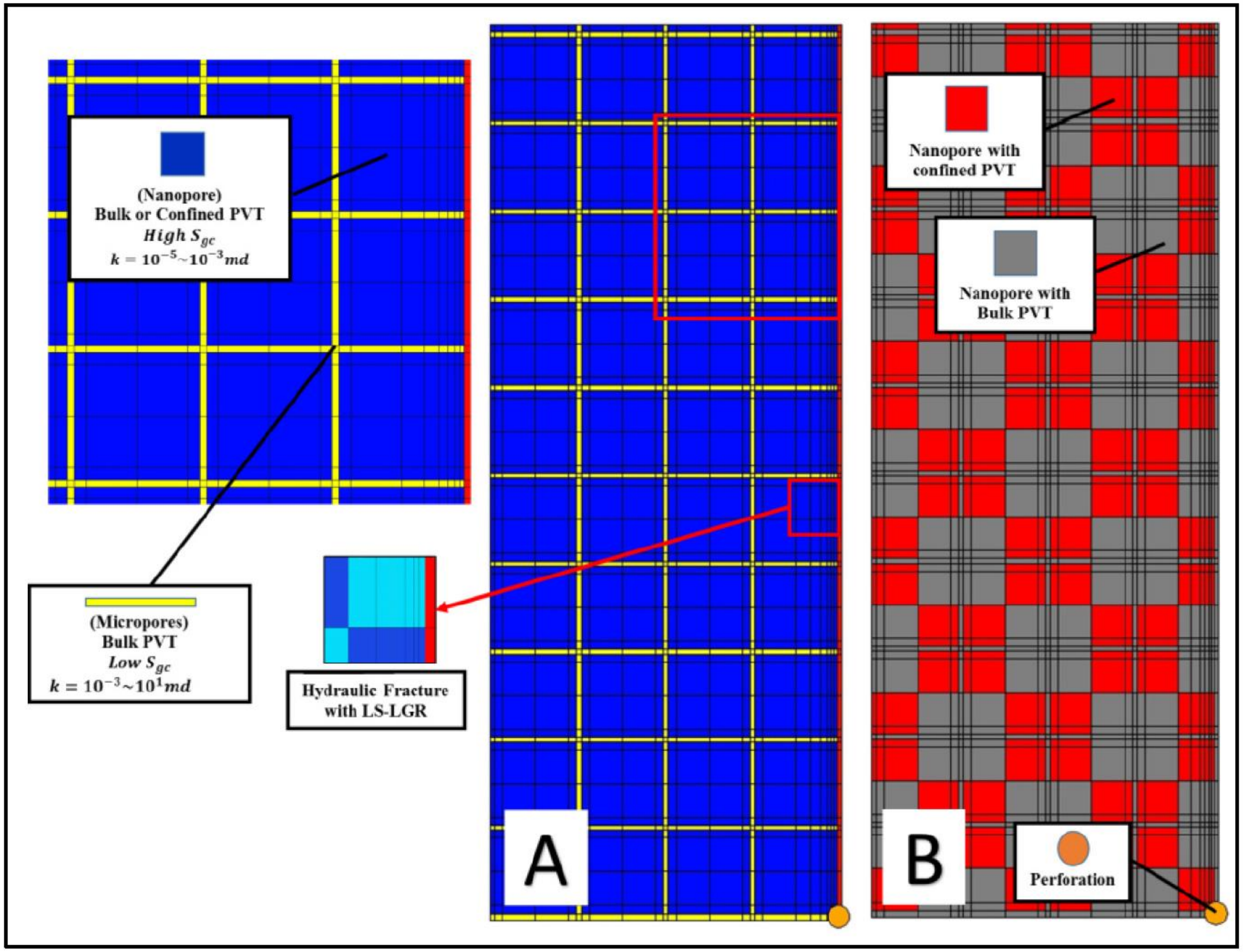


Figure 11—Numerical model geometry. A- Nanopores and micro pores distribution. B- PVT distribution.