MULTI-PHASE PRODUCTION FORECASTING
"BUBBLE POINT DEATH?"

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MAY 2, 2018
SOCIETY OF PETROLEUM EVALUATION ENGINEERS
HOUSTON CHAPTER

INTRODUCTION

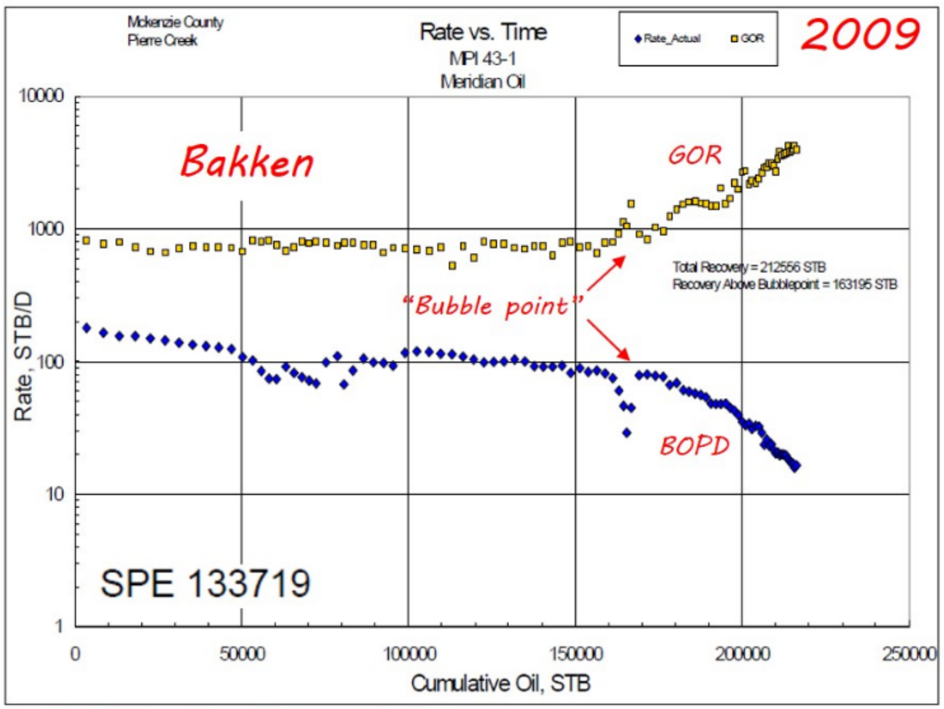
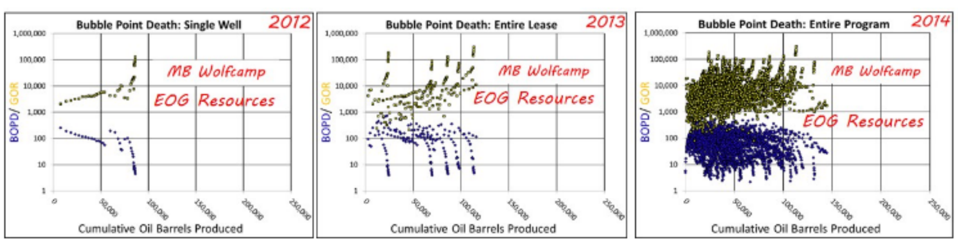


Fig. 5 – GOR vs. Cumulative production.



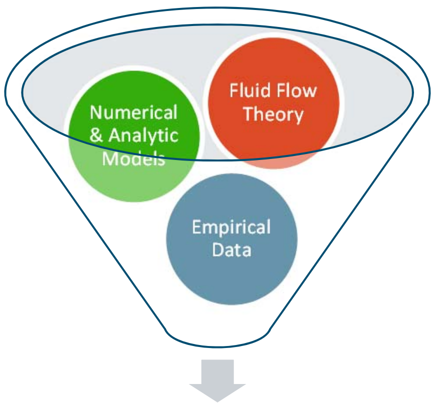
EOG's abandonment of its once grand Midland Basin Wolfcamp program

- In late 2017, 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?



Production Forecasting

TECHNICAL SUMMARY

- During infinite-acting linear flow and constant flowing pressure conditions, GOR is ***constant*** 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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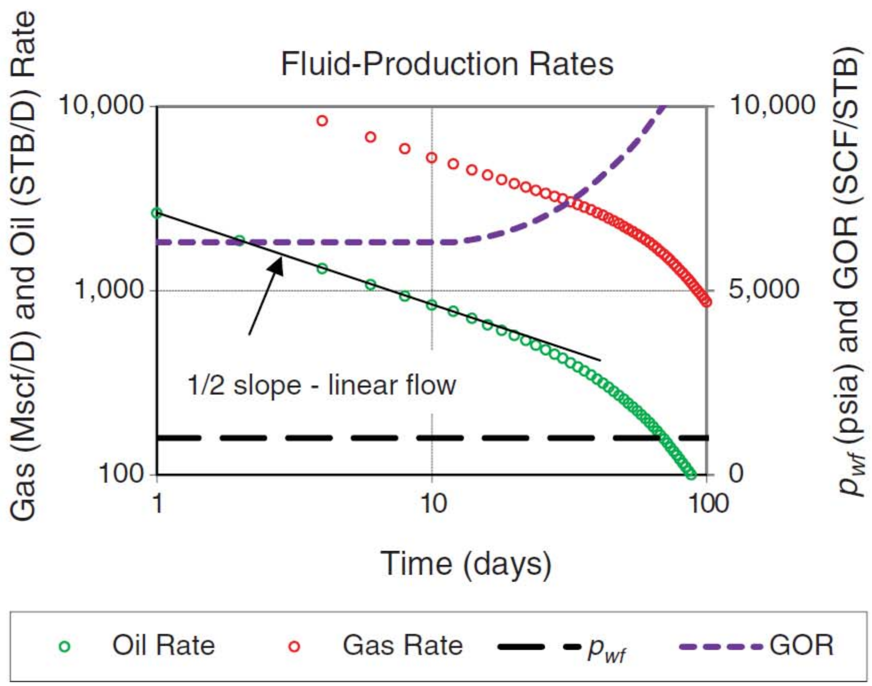
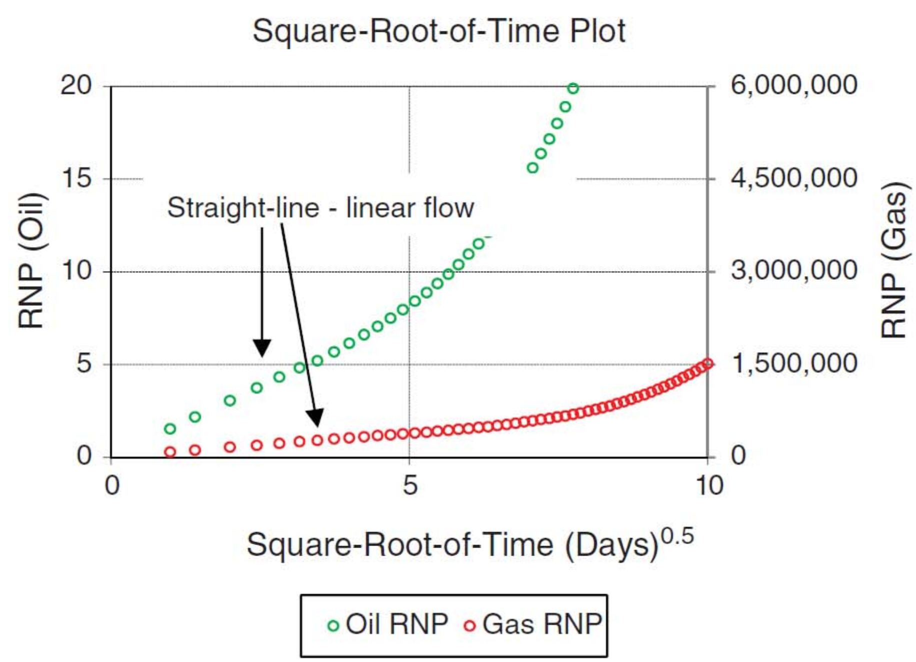




LITERATURE REVIEW

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

LITERATURE REVIEW

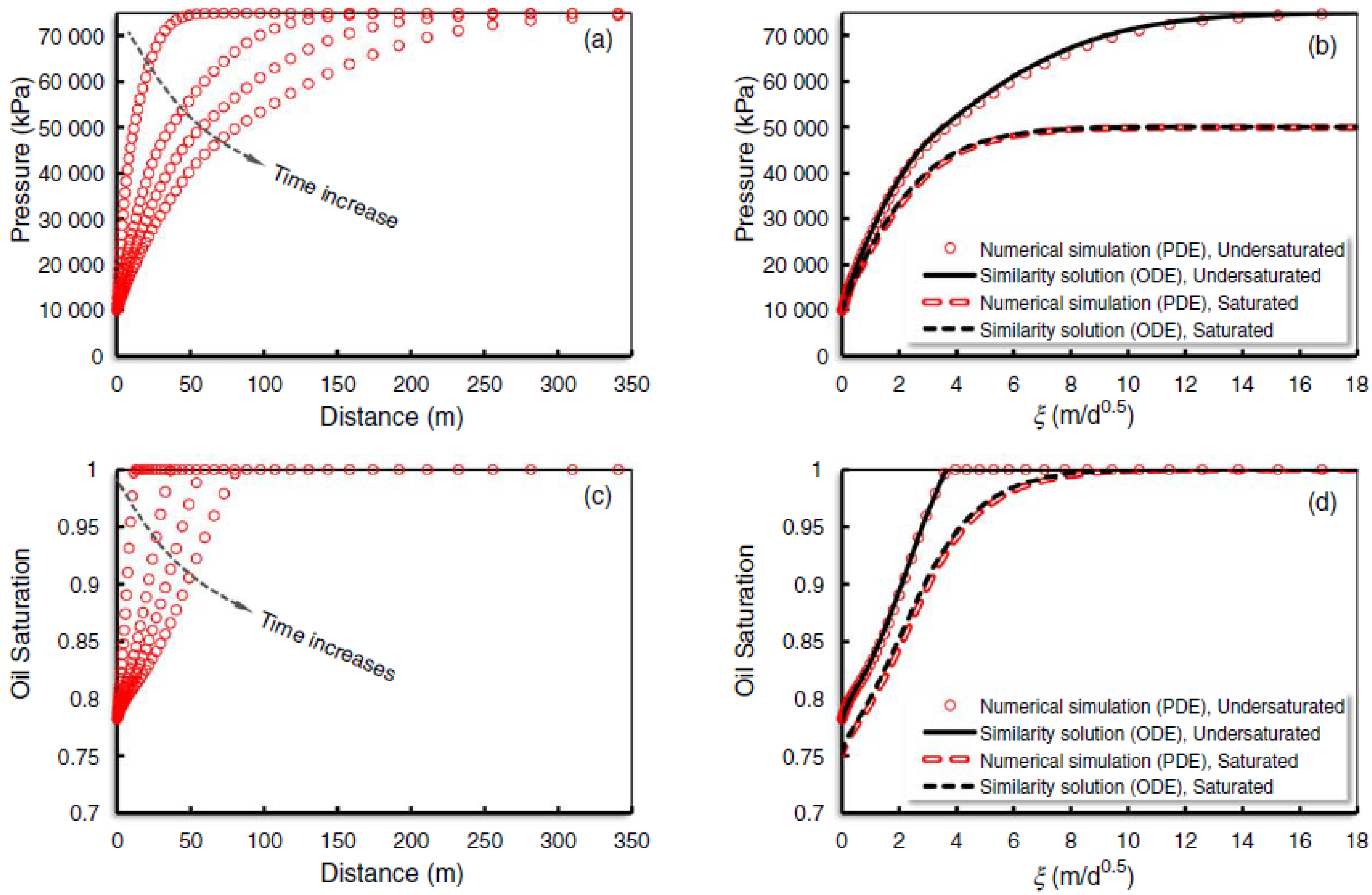
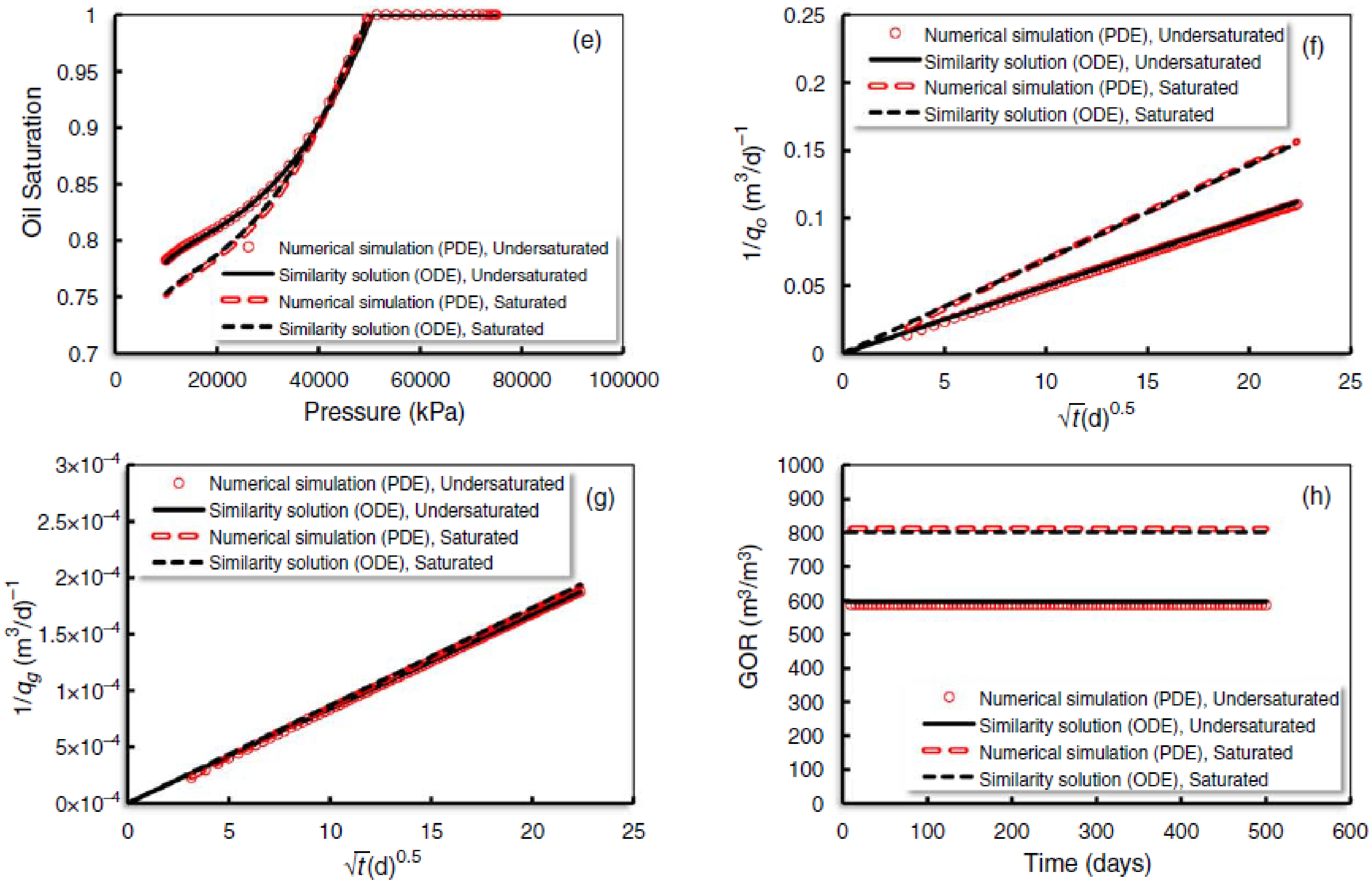


Fig. 9—Comparison of the performance of saturated ($p_i = p_{bp} = 50\,000$ kPa, $R_{si} = 219\ m^3/m^3$) and undersaturated ($p_i = 75\,000$ kPa, $p_{bp} = 50\,000$ kPa, $R_{si} = 219\ m^3/m^3$) tight oil reservoir.

LITERATURE REVIEW



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LITERATURE REVIEW

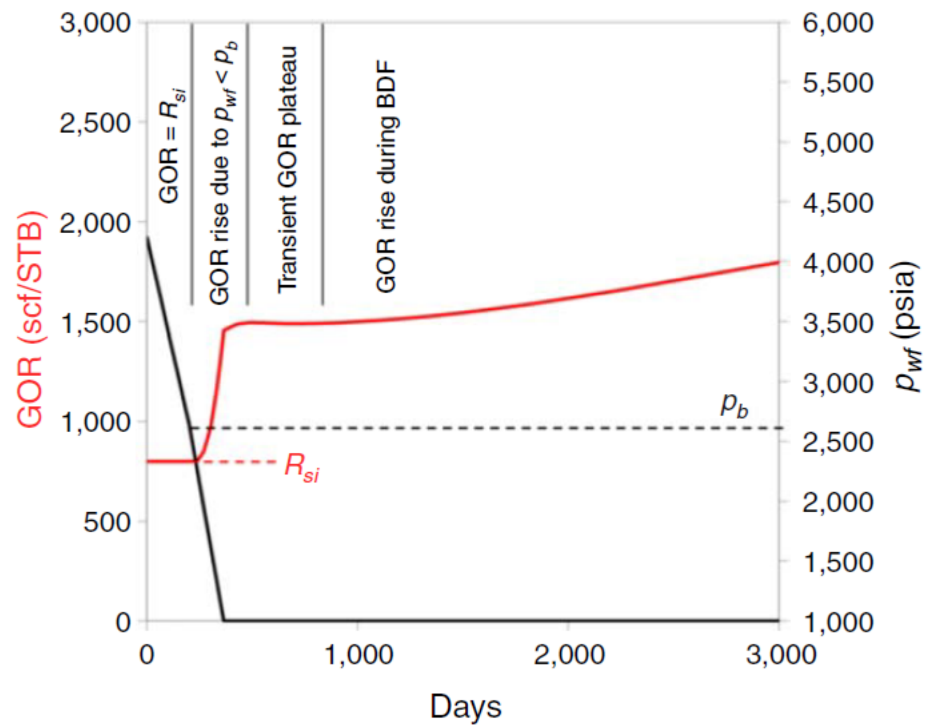
- $GOR = R_s + \frac{k_{rg}\mu_o B_o}{k_{ro}\mu_g B_g}$ evaluated at sandface
- If $\bar{p} = \underline{constant}$
- $\rightarrow \bar{B}_o \;\&\; \bar{S}_o \rightarrow k_{ro} \;\&\; \mu_o \rightarrow GOR = \underline{constant}$

- 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"

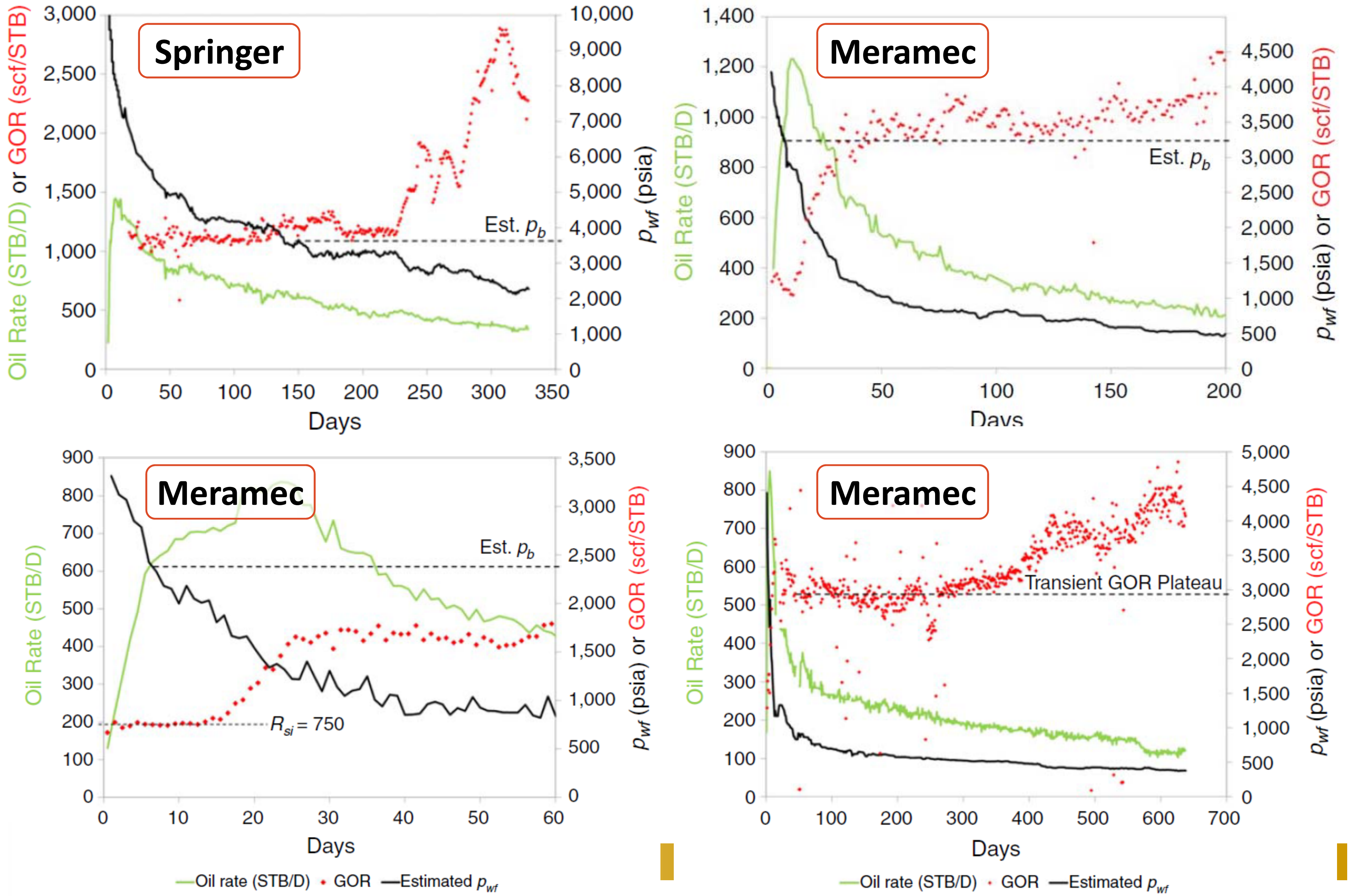
LITERATURE REVIEW

- 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



SPE-184397-PA (Jones 2017)

LITERATURE REVIEW



LITERATURE REVIEW

- Additionally, bubble point is suppressed in nanopores

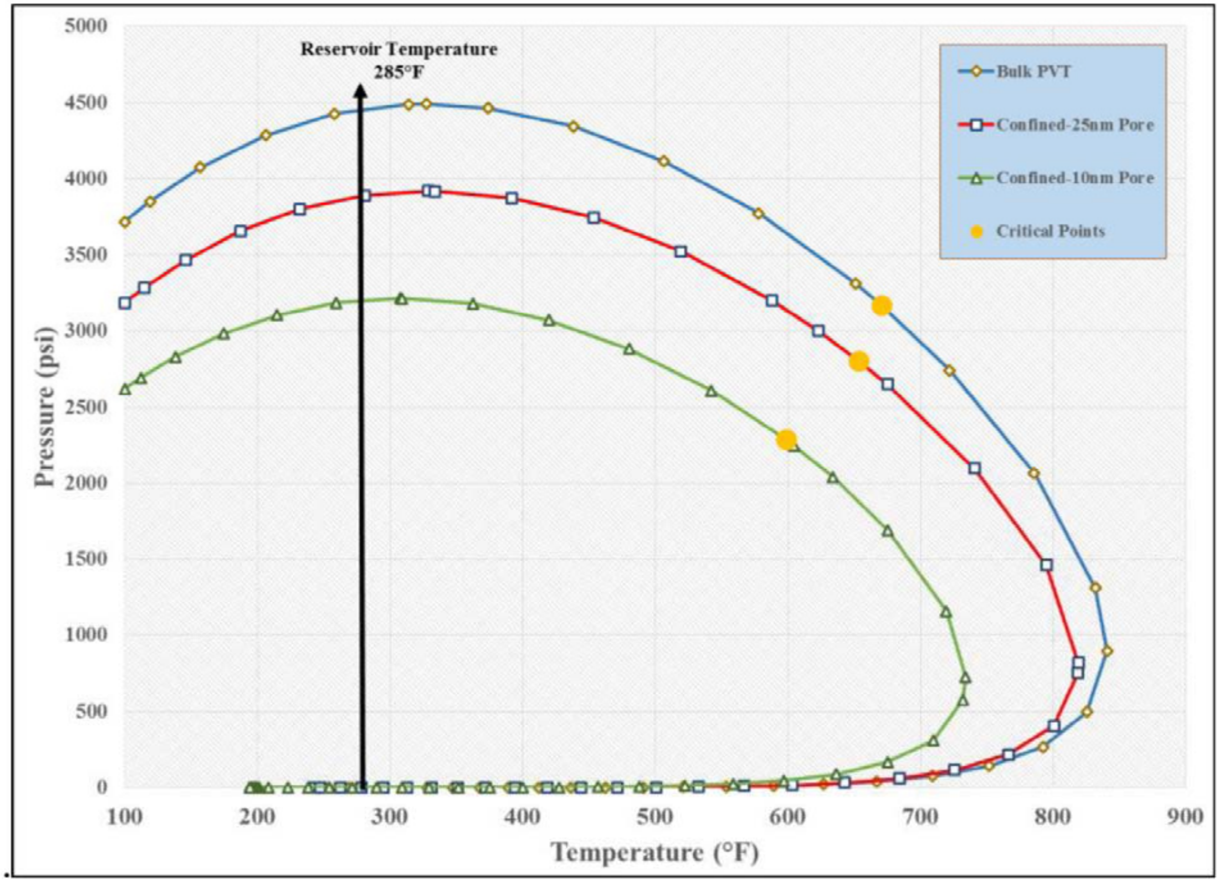


Figure 6—Confined and unconfined phase envelope

SPE-175137-MS (Khoshghadam et al 2015)

LITERATURE REVIEW

- Flow regimes dictate secondary phase yield *trends*

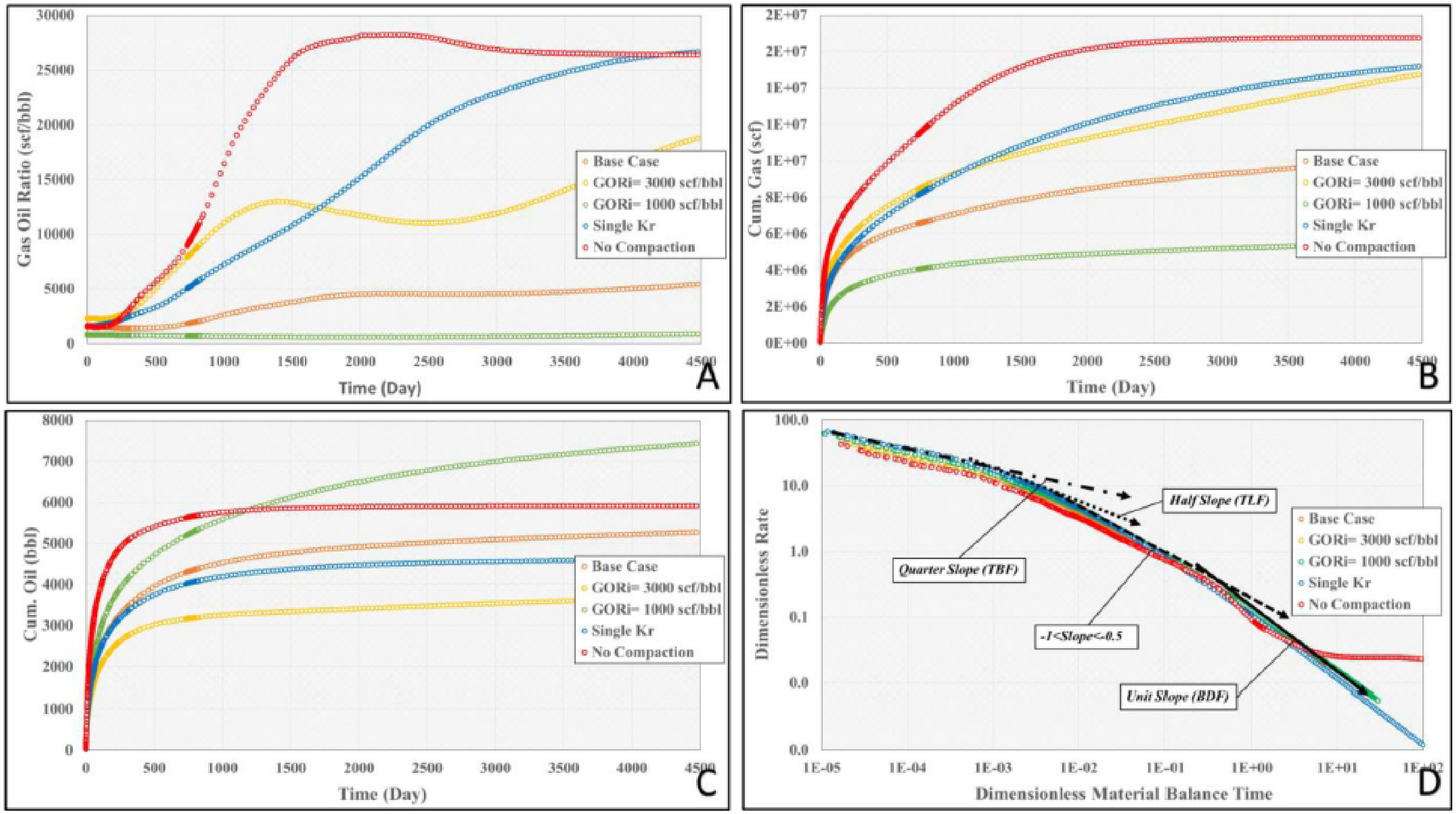
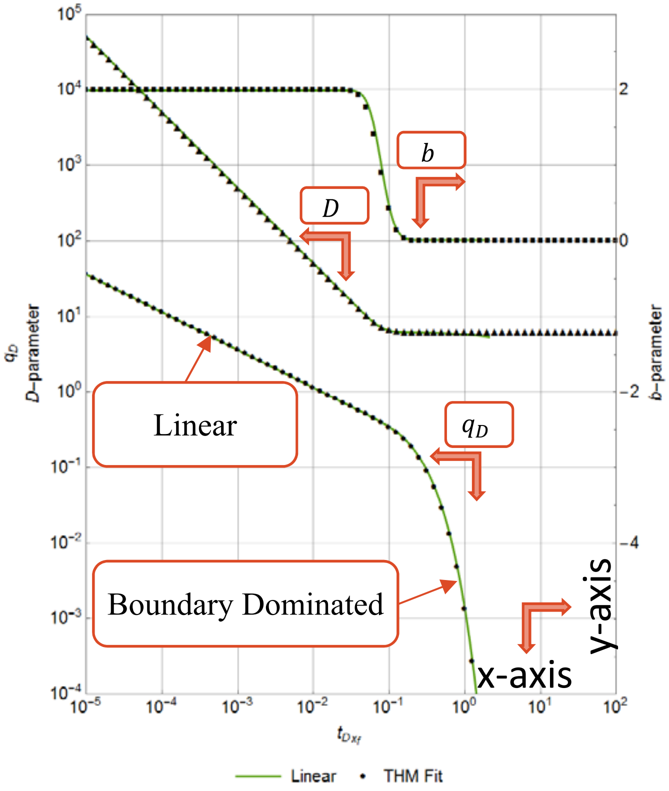


Figure 19—Simulation results of study's cases: A- GOR vs. time, B-Cumulative gas production vs. time, C-Cumulative oil production vs. time, D- log-log plot dimensioless rate vs. dimensionless MBT

MODEL APPROXIMATION

Tri-Diagnostic Plot



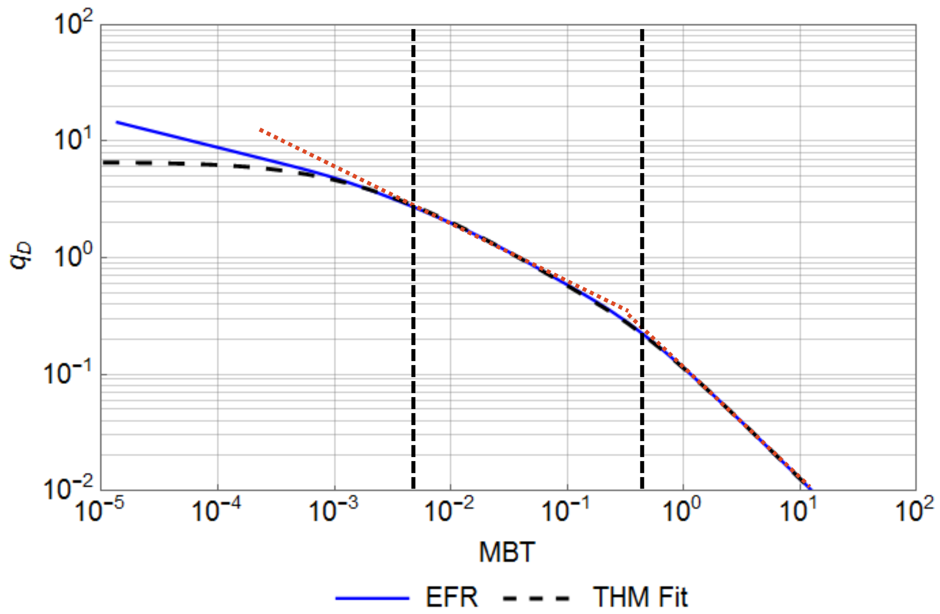
Transient Hyperbolic Model (THM) –

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

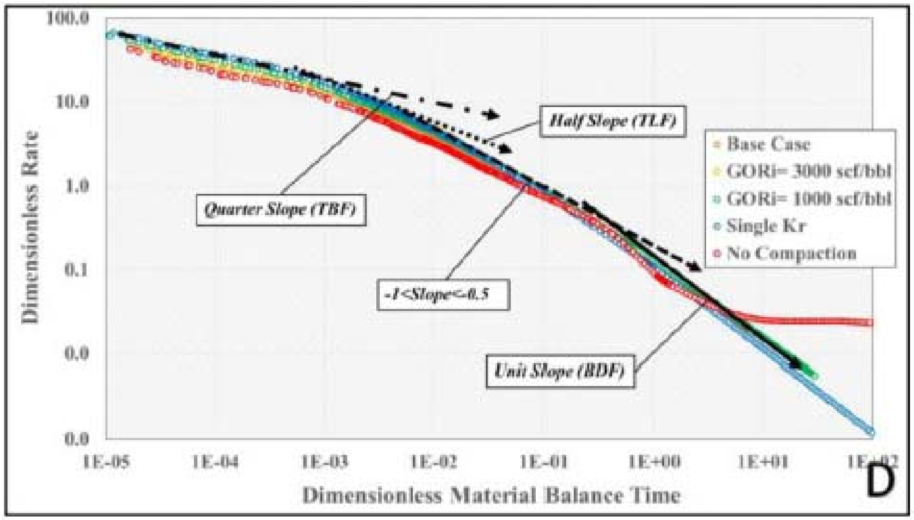
PRIMARY PHASE (OIL) FORECASTING

- 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

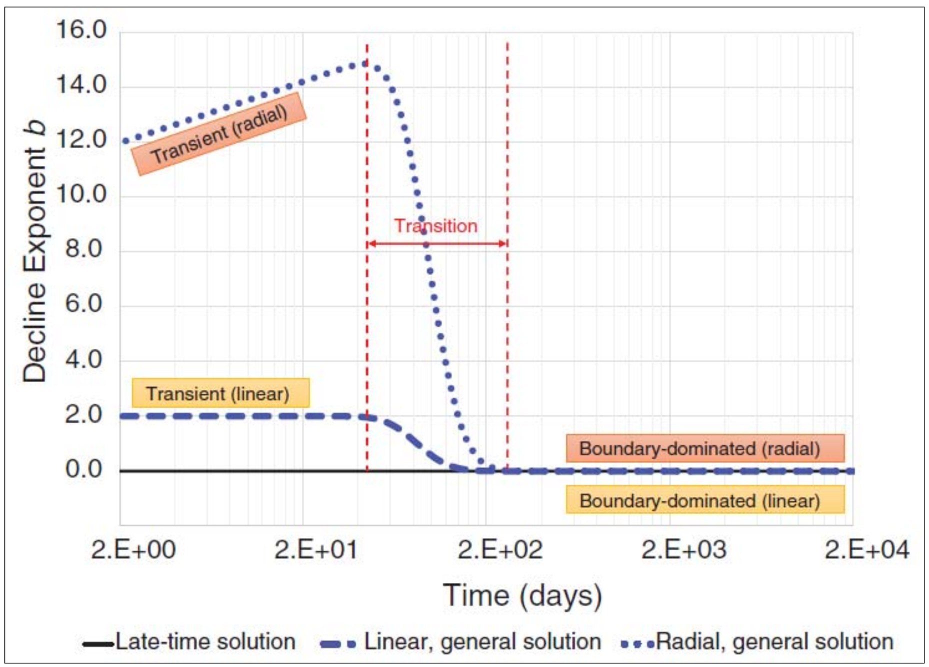


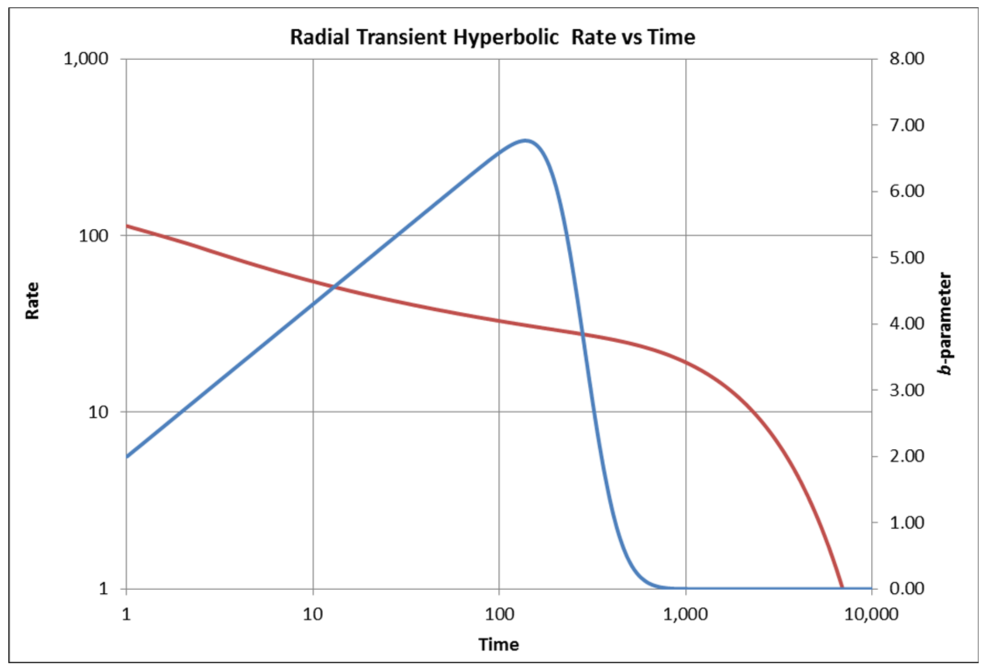
Compositional Sim.



RADIAL TRANSIENT HYPERBOLIC

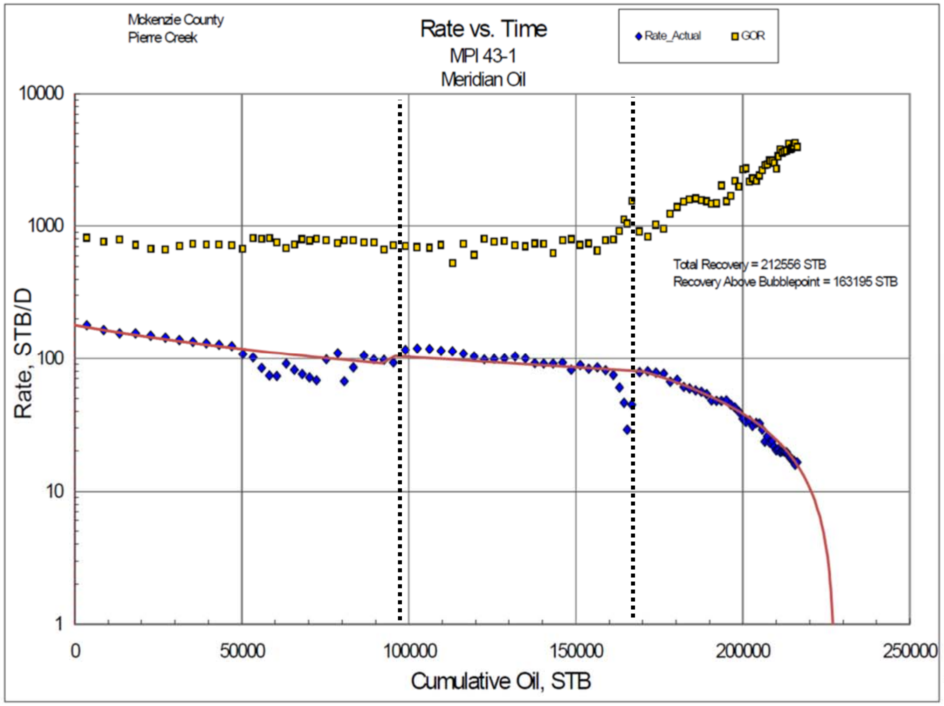
- Bakken well example is vertical well
  - Expect radial flow
  - Model radial flow as $b(t) = m \ln t + b'$

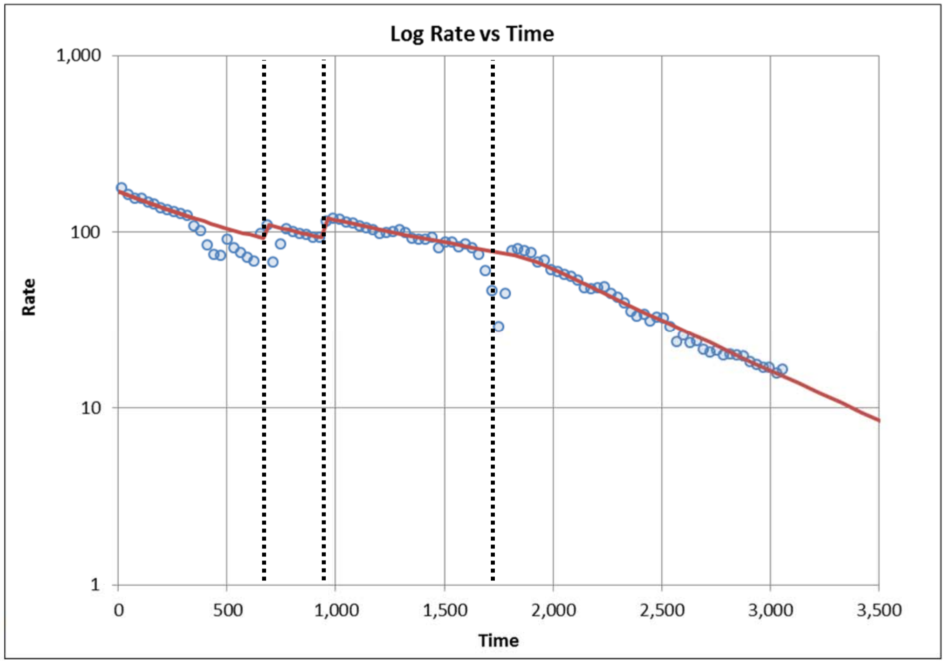




BAKKEN VERTICAL WELL (SPE-133719-STU)

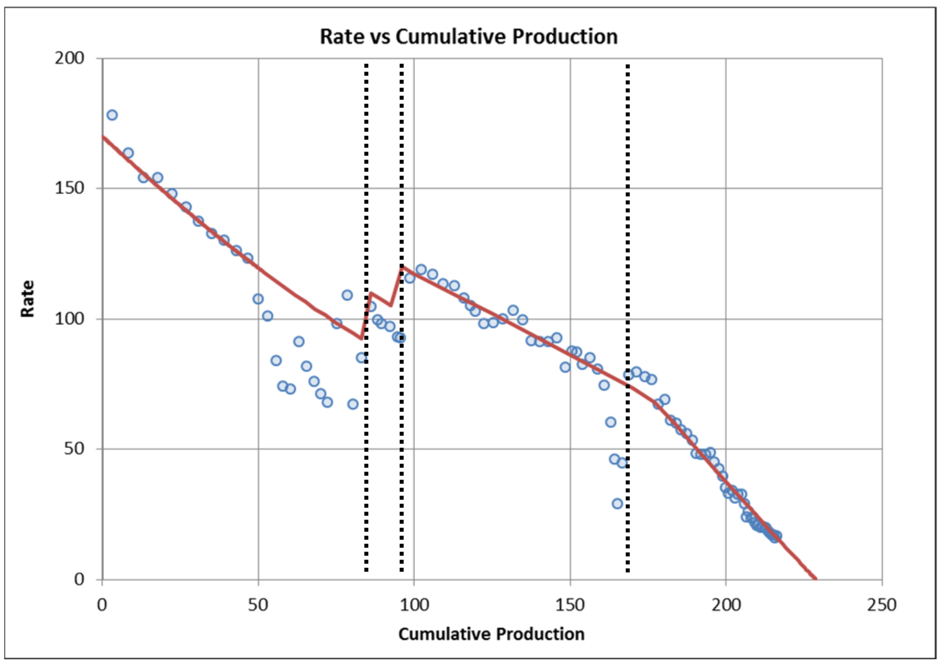
- 1st Segment: $b = m \ln(t) + b'$ (radial flow)
- 2nd/3rd Segment: Rate shift; $b = m \ln(t) + b'$
- 4th Segment: Rate continuous, $D = 0.19 \rightarrow 0.51$, $b = 0$

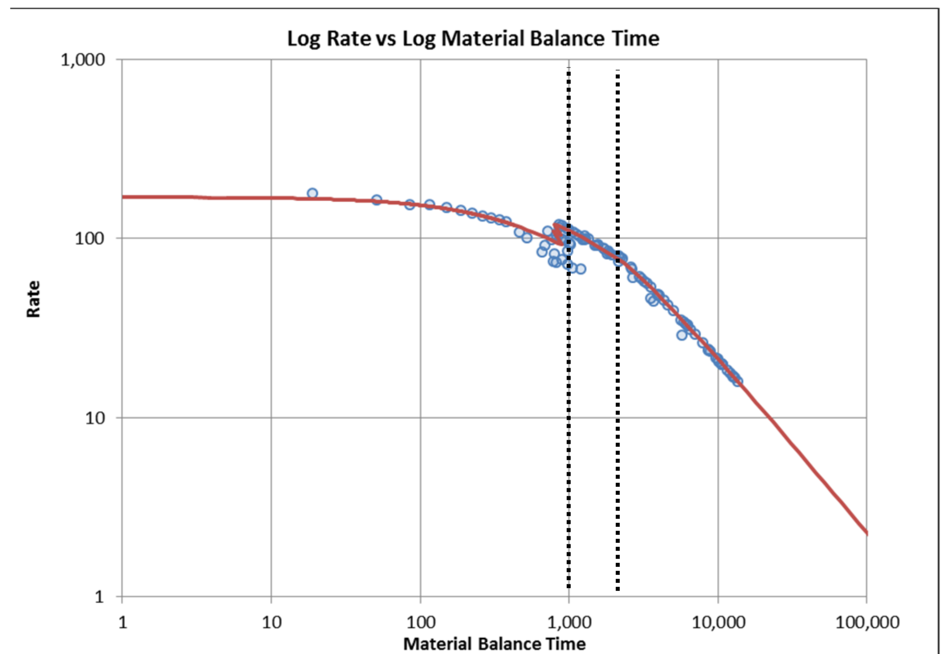




BAKKEN VERTICAL WELL (SPE-133719-STU)

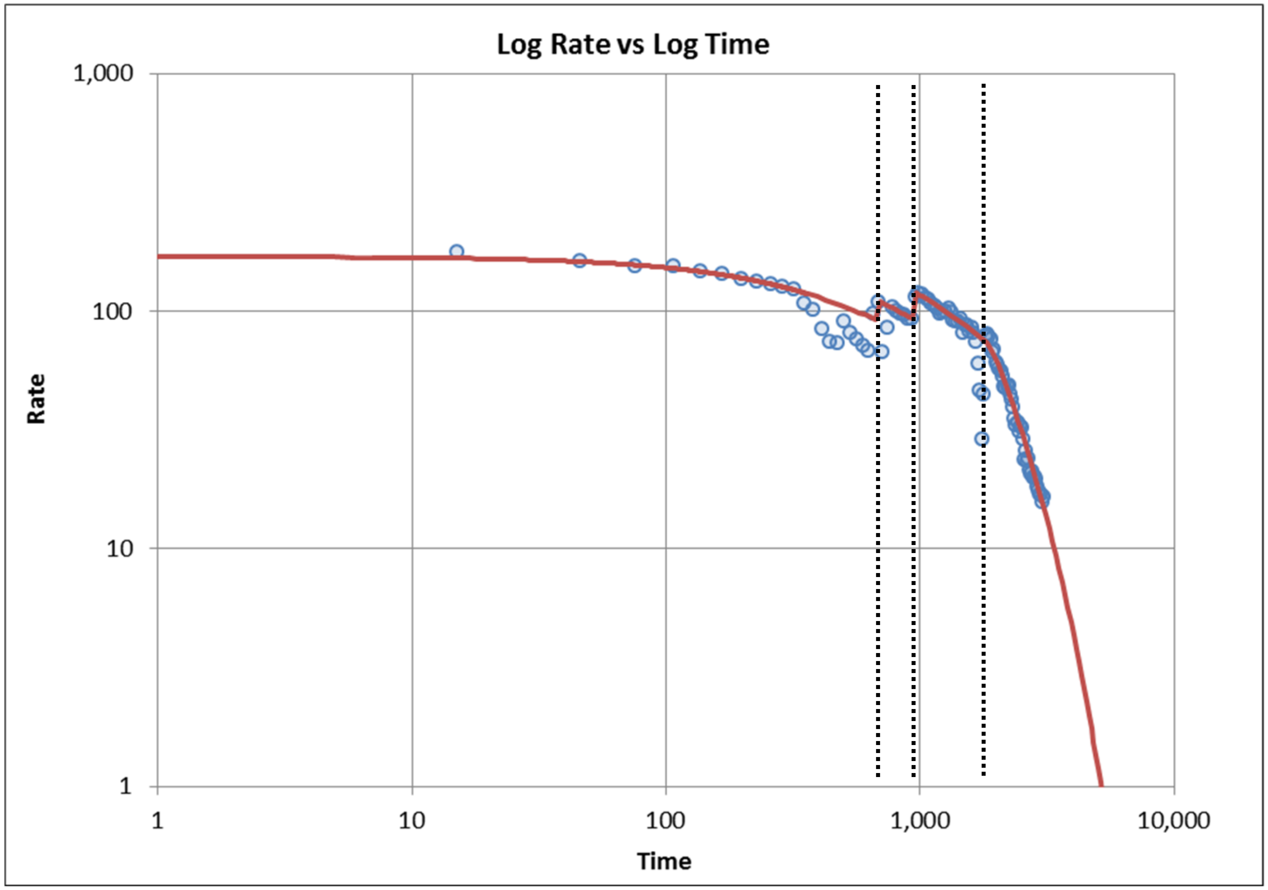
- Diagnostic plots only valid for specific flow regimes
  - If exponential, _Cartesian_ Rate vs. Cum
- Rate vs. MBT follows same sequence





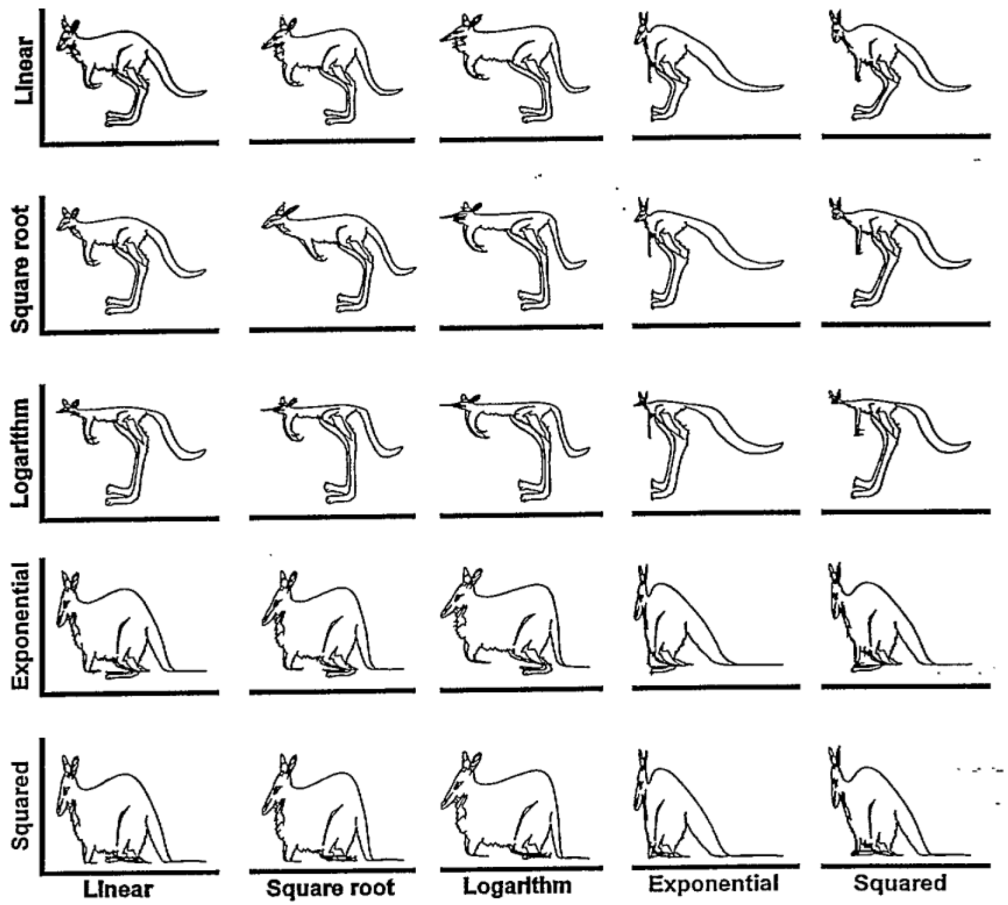
BAKKEN VERTICAL WELL (SPE-133719-STU)

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

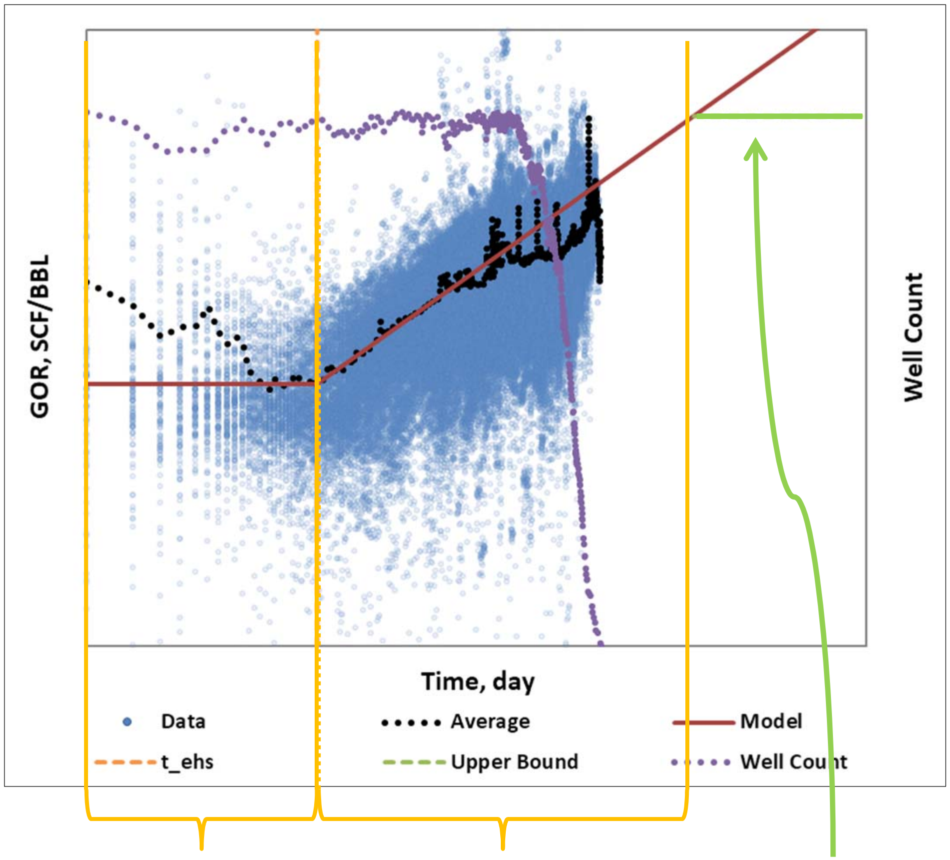


AN ASIDE

The kangaroo in different coordinates



SECONDARY PHASE (GOR) FORECASTING



Infinite-acting Linear Flow

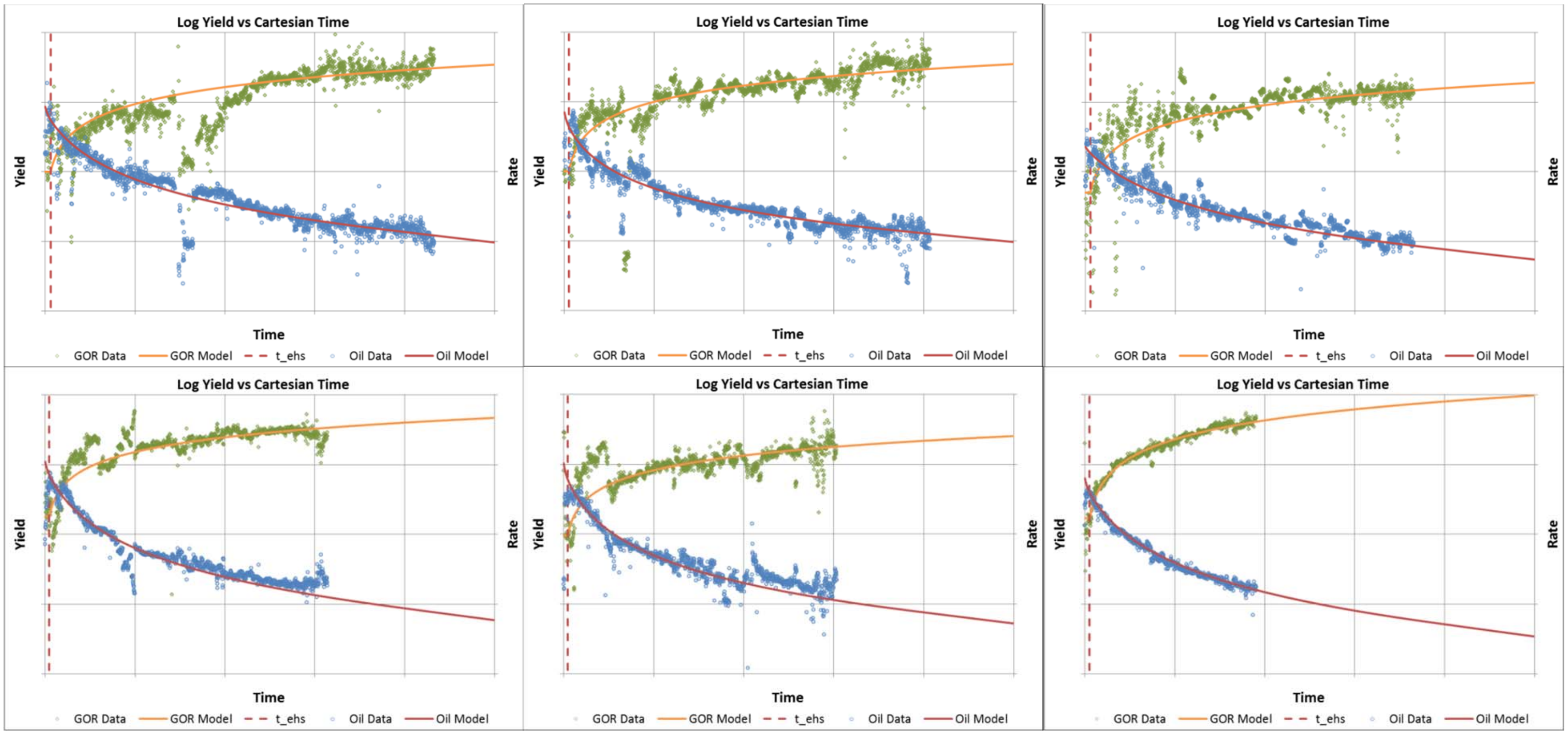
Boundary-*influenced* Flow

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 (GOR_{LF}) and diagnosed end of half slope (t_{ehs})
  - $b_{GOR} = GOR_{LF} t_{ehs}^{-m_{GOR}}$

SECONDARY PHASE (GOR) FORECASTING

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

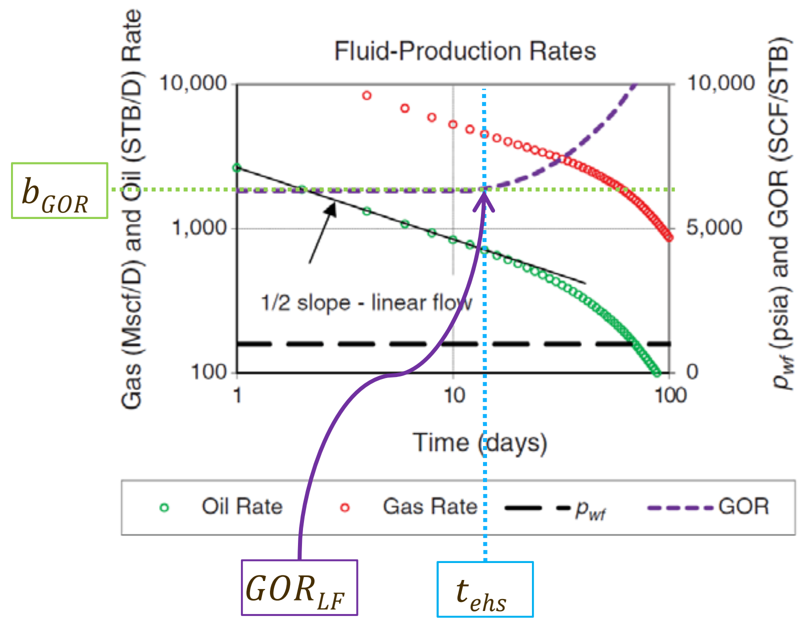


SECONDARY PHASE (GOR) FORECASTING

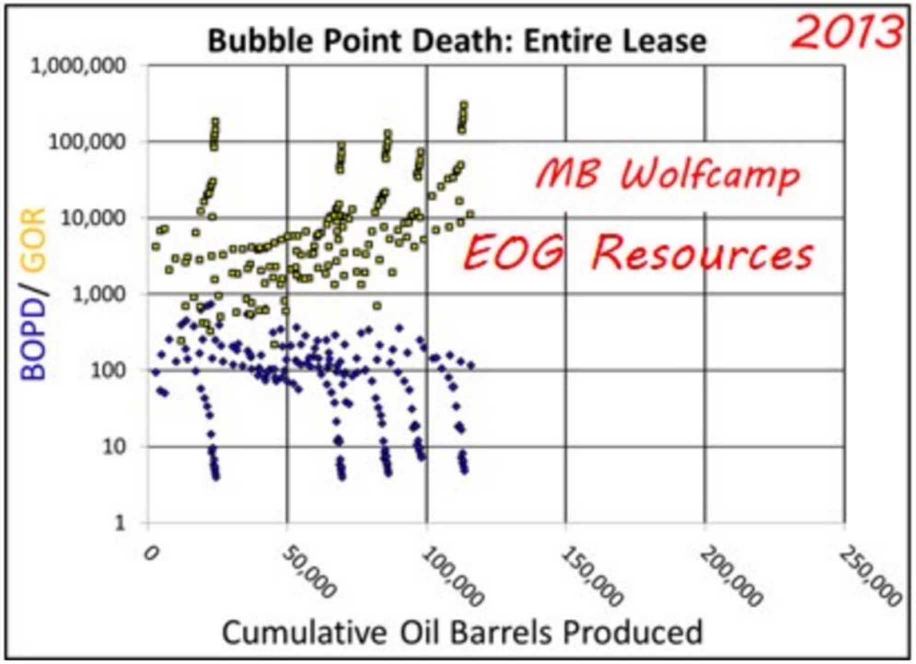
- Some considerations…
  - Wells in communication will establish similar GORs
  - Frac hits may change trend
- 2-parameter (Power-Law) model provides simplicity and ease-of-use for noisy production data
- Most wells fall within reasonable range of parameter values
  - Observed value in data shown –
    - m_{GOR}: 0.6 to 0.9

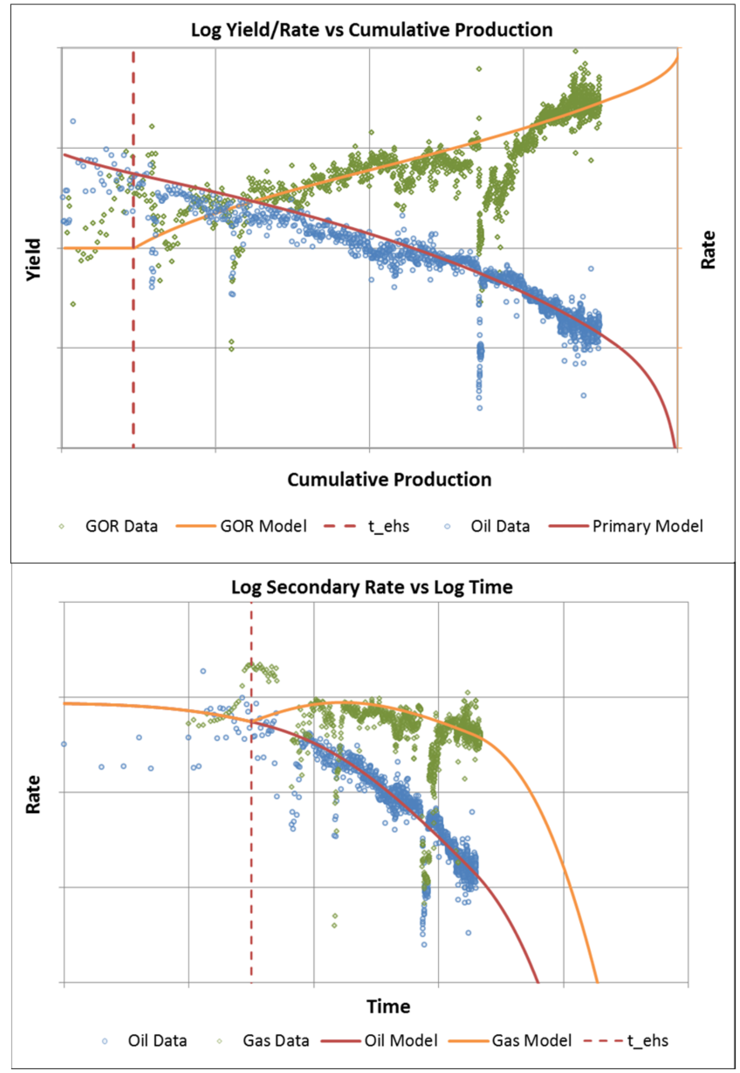
WORKFLOW

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



DISCUSSION





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

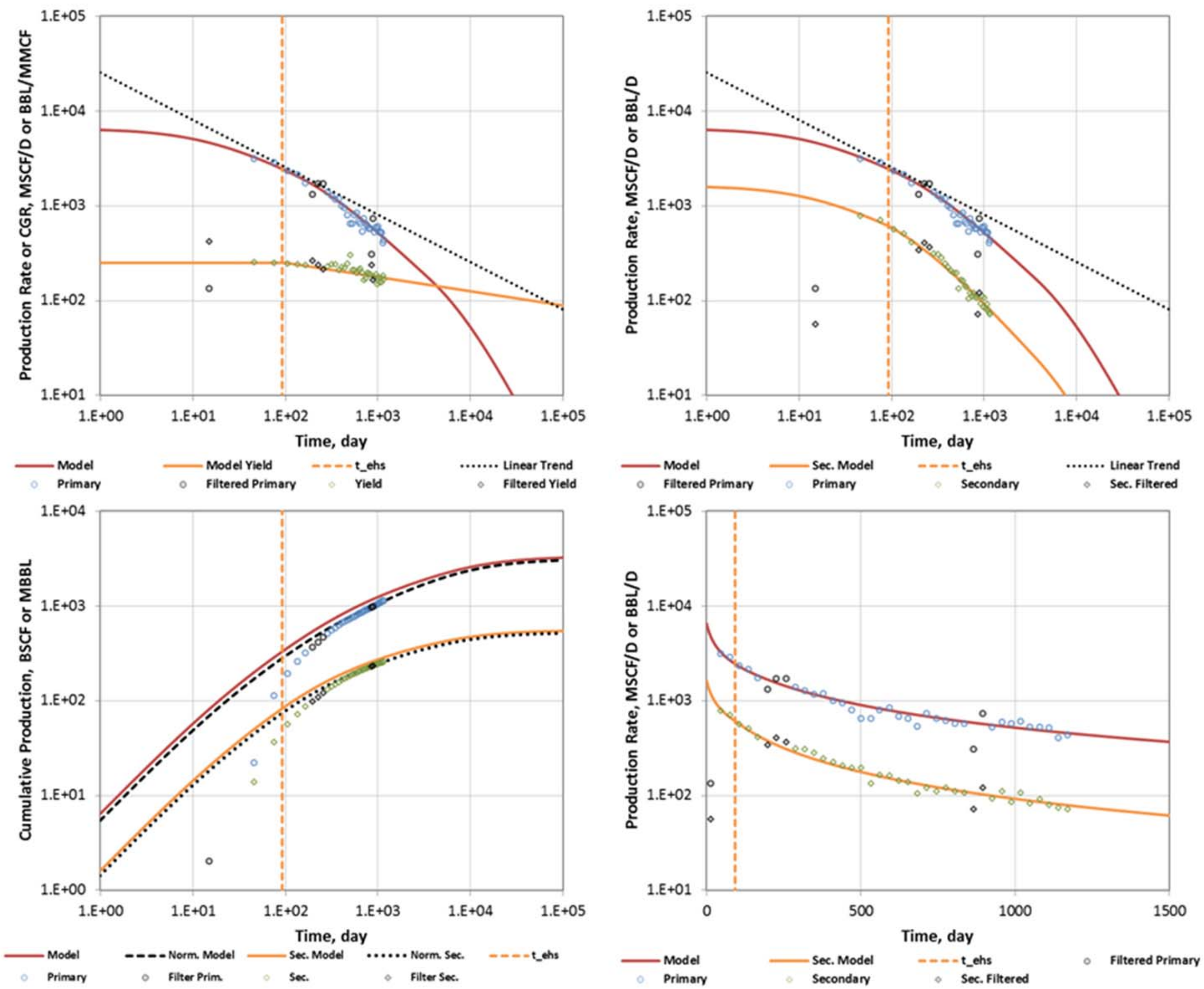
CONCLUSIONS

- 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

RETROGRADE CONDENSATE GAS EXAMPLE

EAGLE FORD

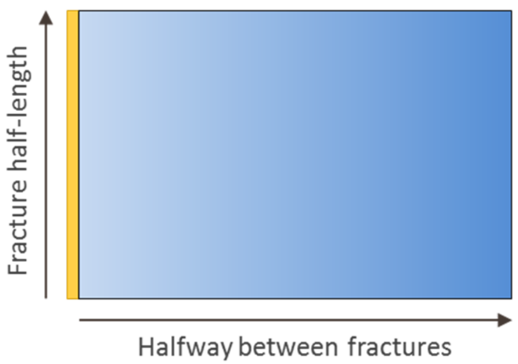


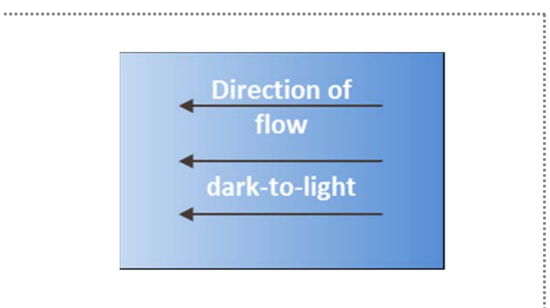
DIAGNOSTICS

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

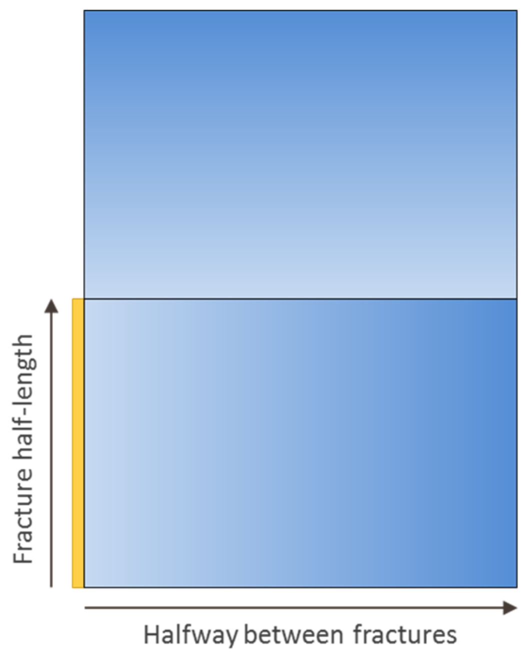
STATE-OF-THE-ART MODELS

Linear

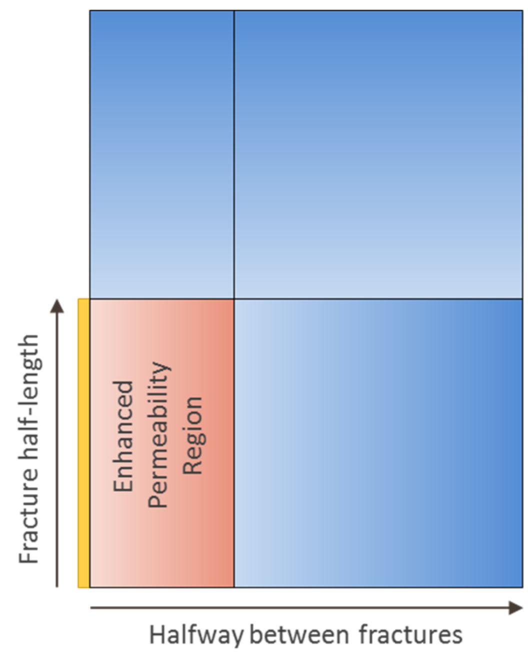




Trilinear

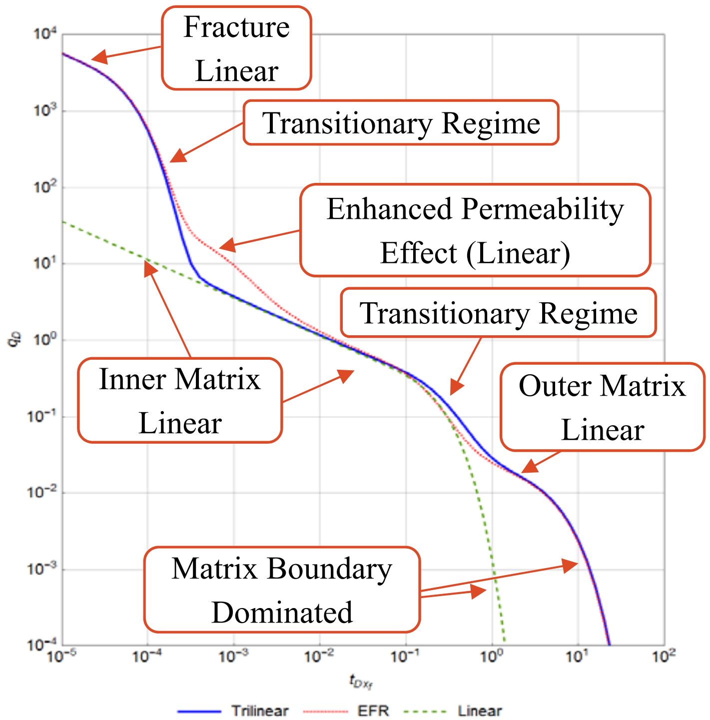


EFR

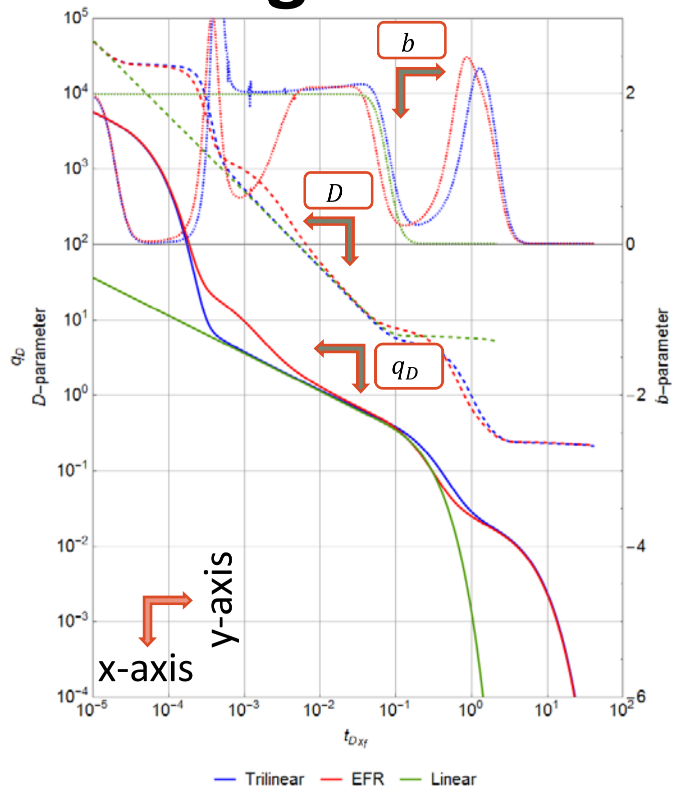


STATE-OF-THE-ART MODELS

Flow Behavior

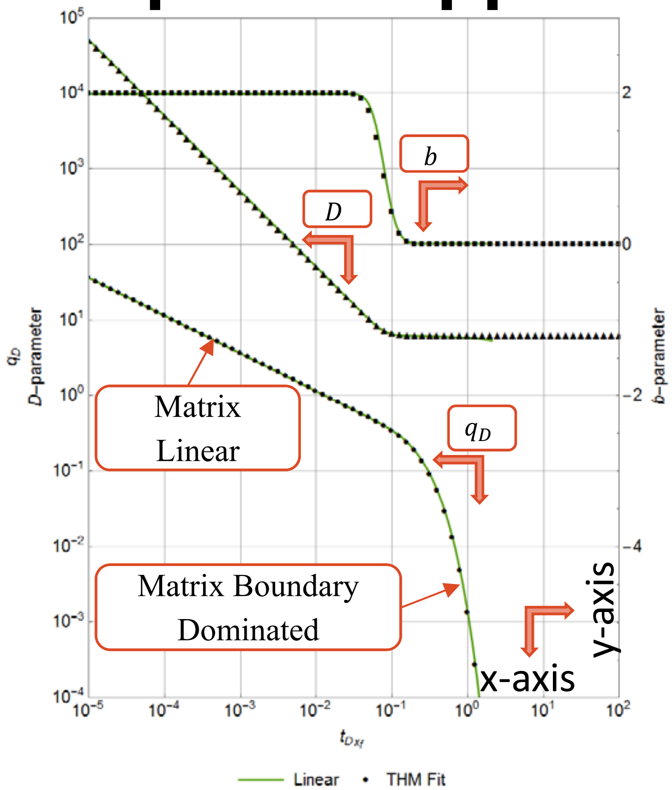


Diagnostics



MODEL APPROXIMATION

Empirical Approx.



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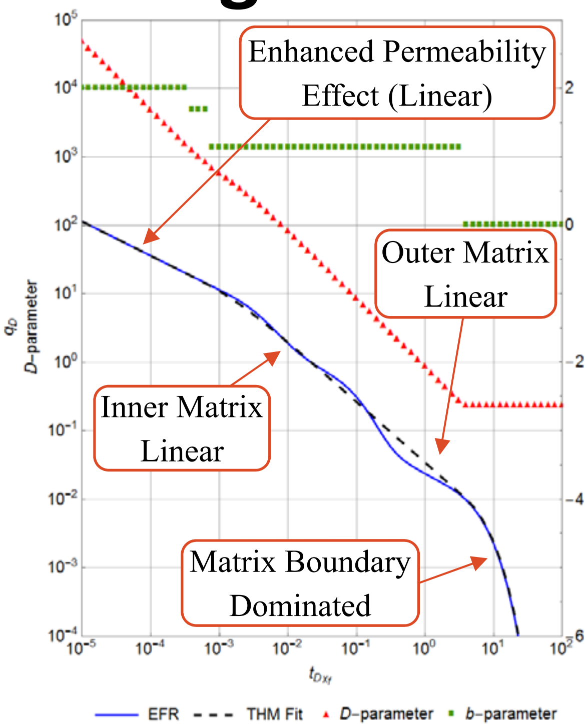
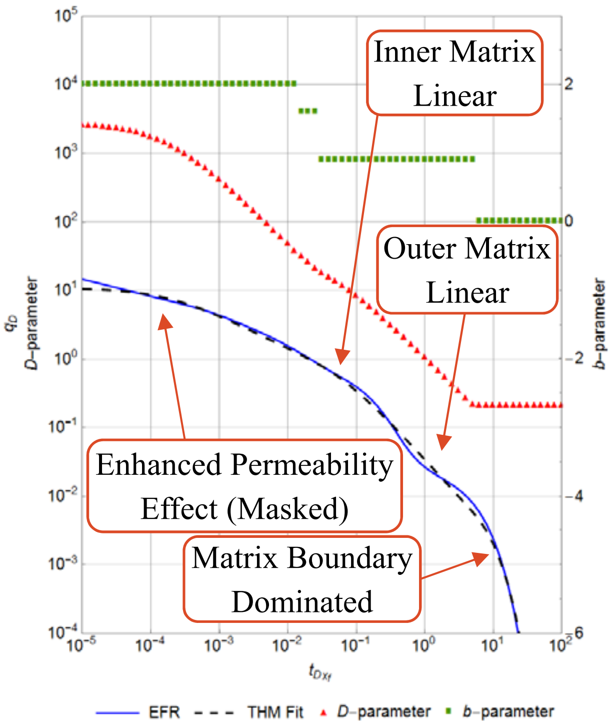
MODEL APPROXIMATION

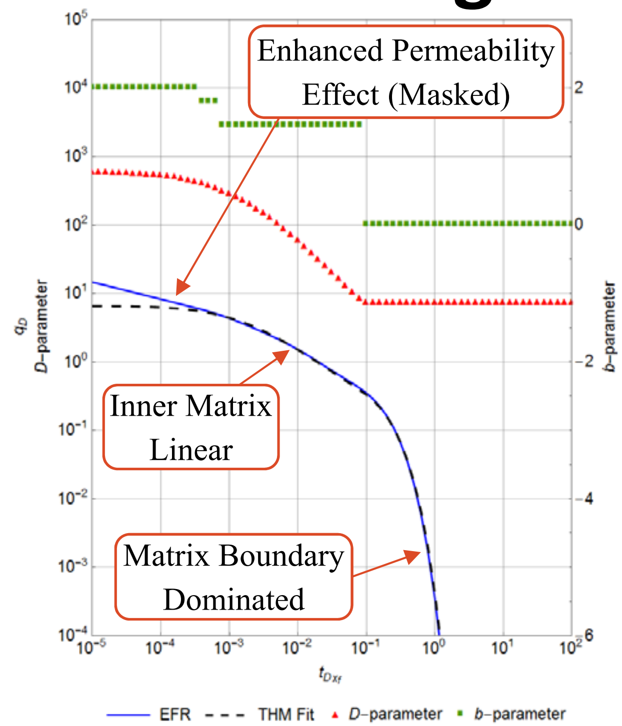
High FCD



Low FCD



No Outer Region



COMPOSITIONAL SIMULATION GRID

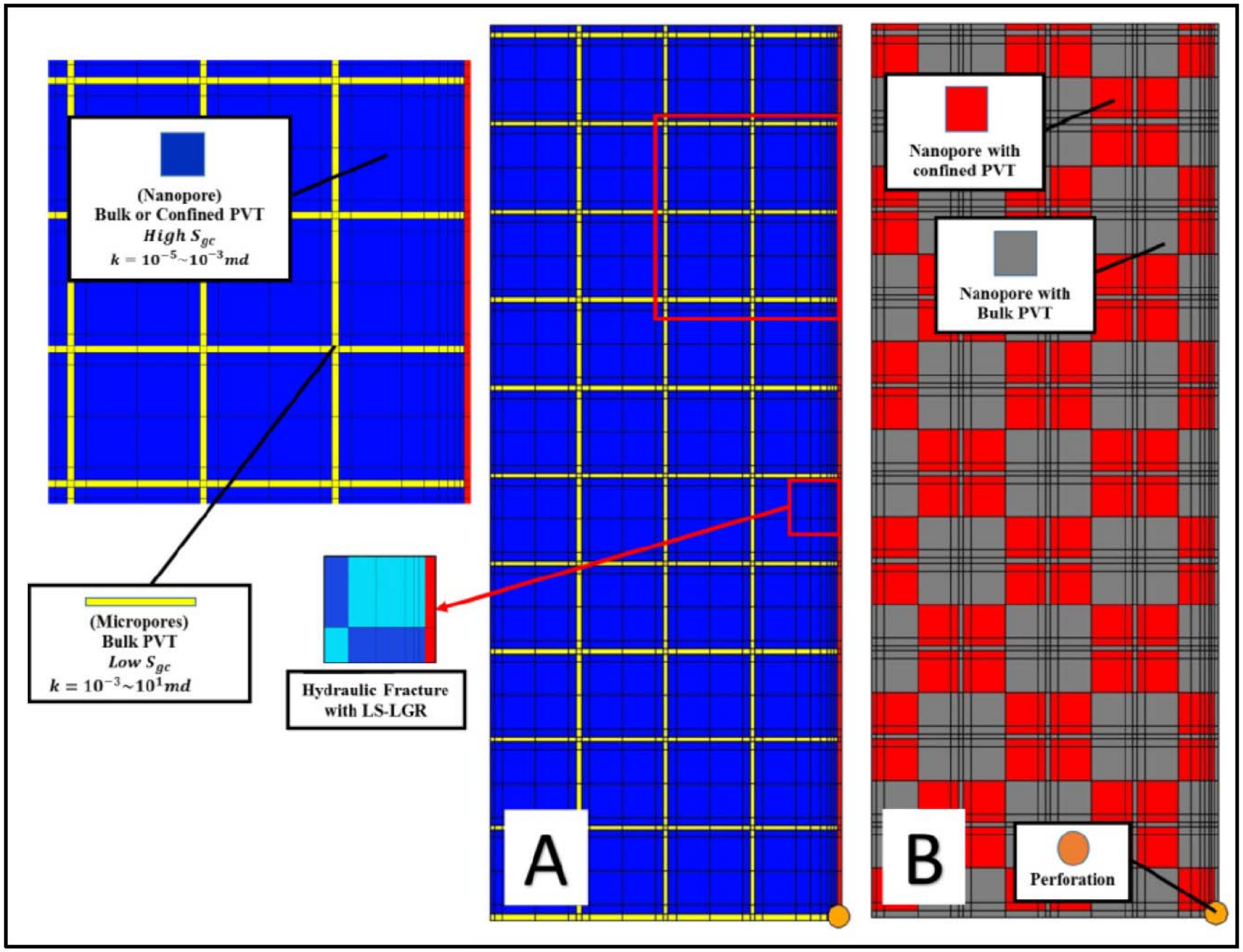


Figure 11—Numerical model geometry. A- Nanopores and micro pores distribution. B- PVT distribution.