PTA/RTA/DCA Methods for the Evaluation of Well Performance in Unconventional Reservoirs — Vaca Muerta Field Examples

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A Quick Review of Where We Came From … (i.e., Ancient History)

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Production Analysis — Historical Context [*Rawlins/Schellhardt* (1935)]

A, Critical-flow prover
B, Prover vent
C, Spring gages to measure wellhead pressures
   P_c or P_w also prover pressures
D, Recording gage for observing behavior of
   well-head pressure
E, Connection below wellhead fitting to obtain
   wellhead pressure
F, Pressure gage manifold
x, y, z, x', y' and z', valves on pressure gage
   manifold
P_{c}, Pressure at wellhead under shut-in conditions
P_{w}, ... flowing
P_{s}, Back pressure at sand face in well bore
   under flowing conditions
P_{f}, Shut-in formation pressure

Gas Well Deliverability:

- The original well deliverability relation was derived from observations:

$$q_g = C(\overline{p}^2 - p_{wf}^2)^n$$

- The *"inflow performance relationship"* (or IPR) for this case is: (assuming *n*=1)

$$q_g = C(\overline{p}^2 - p_{wf}^2)$$

$$q_{g,max} = C(\overline{p}^2) \quad (p_{wf}=0)$$

$$\frac{q_g}{q_{g,max}} = 1 - \left[\frac{p_{wf}}{\overline{p}}\right]^2$$

Back-Pressure Data on Natural-Gas Wells and Their Application to Production Practices — Rawlins and Schellhardt (USBM Monograph, 1935).

Decline Curve Analysis — Historical Context [Johnson/Bollens (1927)]

Loss Ratio: (D-parameter)

$$\frac{1}{D} \equiv -\frac{q}{dq/dt} \equiv -\frac{dq}{dQ}$$

Assume

Constant $D(t) \ (= D_i)$ $\rightarrow q = q_i \exp[-D_i t]$

Derivative of Loss Ratio: (b-factor)

$$b \equiv \frac{d}{dt}\left[\frac{1}{D}\right] \equiv -\frac{d}{dt}\left[\frac{q}{dq/dt}\right] \equiv q\frac{d}{dQ}\left[\frac{1}{D}\right]$$

Assume

Constant $b(t) \ (= b)$ $\rightarrow q = \dfrac{q_i}{(1 + bD_i t)^{(1/b)}}$
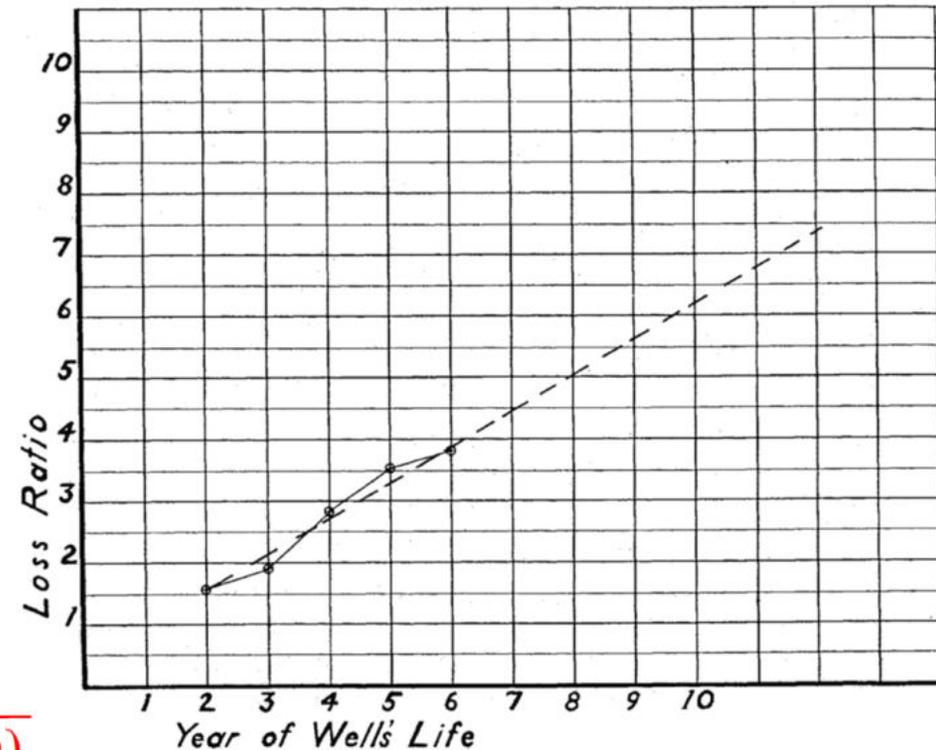
FIG. 1.—EXTRAPOLATION OF LOSS RATIO.

Early Example — Johnson/Bollens (1928)

Johnson, R.H. and Bollens, A.L.: "The Loss Ratio Method of Extrapolating Oil Well Decline Curves," Trans. AIME (1927) 77, 771.

Historical Analysis: Johnson/Bollens (1927)
- Johnson and Bollens proposed a plot of the *loss ratio* versus *time*.
- A linear plot of *loss ratio* versus *time* implies that $b(t)$ = constant (hyperbolic decline).
- A constant *loss ratio* versus *time* implies that $b(t)$ = 0 (exponential decline).

Decline Curve Analysis — Historical Context [Jones (1942)]

Jones, P.J.: "Estimating Oil Reserves from Production-Decline Rates," Oil and Gas Jour. (Aug. 20, 1942) 43.
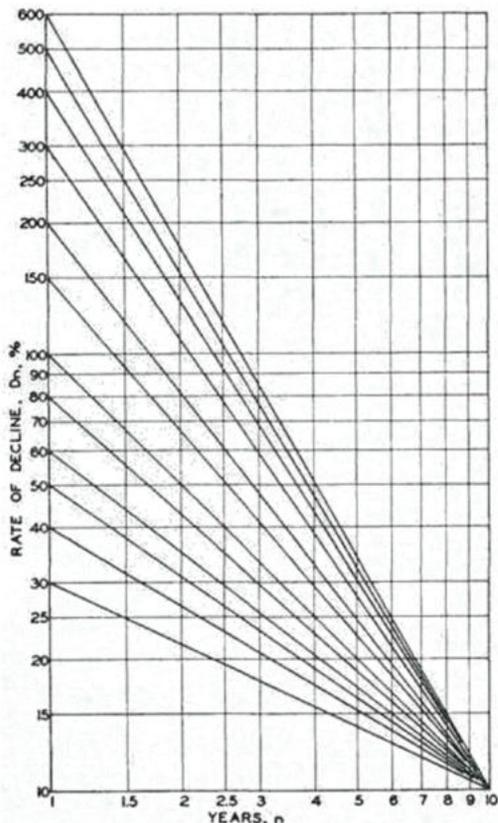
Fig. 37 — Variable rate of decline.

Analysis of Decline Curves

By J. J. ARPS,* MEMBER A.I.M.E.

(Houston Meeting, May 1944)

J. J. ARPS   231

P. J. Jones,[21] in 1942, suggested for wells declining at variable rates an approximation whereby the decline-time relationship follows a straight line on log-log paper. This corresponds to an equation:

$$\log D = \log D_0 - m \log t$$

in which D_o designates the initial decline and m is a positive constant. Integration of this relationship will lead to a rate-time equation of the general form:

$$P = P_o e^{\frac{D_o t^{1-m}}{100(m-1)}}$$

It may be noted that this relationship will not straighten out on semilog or log-log paper, but shows the interesting characteristic of straightening out when the log-log of the production rate is plotted against the log of the time.

$$D \equiv -\frac{1}{q_g}\frac{dq_g}{dt} \qquad b \equiv -\frac{d}{dt}\left[\frac{q_g}{dq_g/dt}\right]$$

Shale Gas Well (300 Days of Production)
D- and b-parameters versus Time Plot (Log-log Scale)

Power-Law Exponential: (2008)

$$q = \hat{q}_i \exp[-D_\infty\, t - \hat{D}_i\, t^n]$$
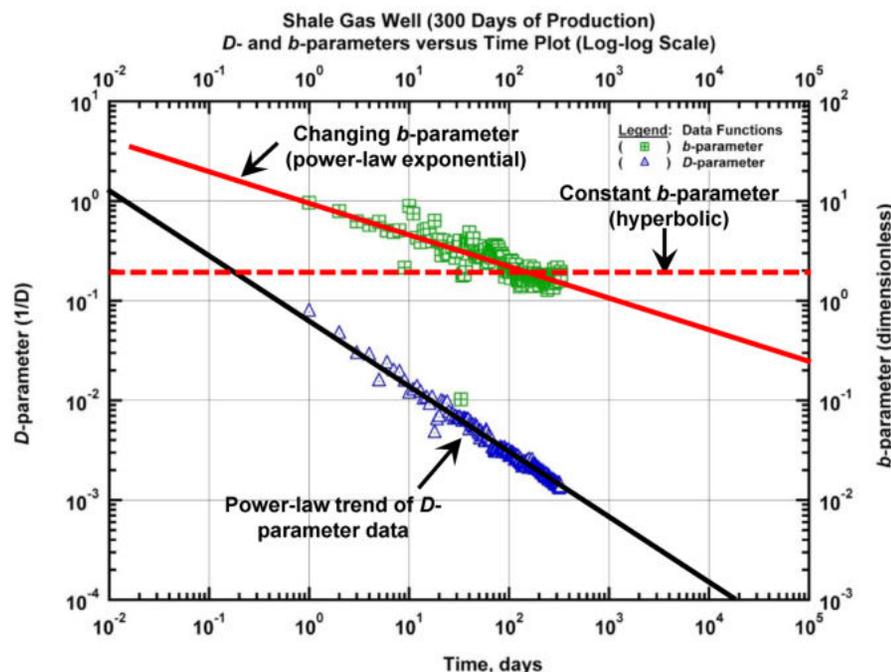
Historical Analysis: Jones (1942)
- Log[decline rate] versus log [time] validates the power-law exponential concept.
- Jones saw that this function had relevance, but he did not demonstrate the approach.
- Interesting that this was **66 years** before the PLE relation was observed.

Decline Curve Analysis — Modified-Hyperbolic Relation
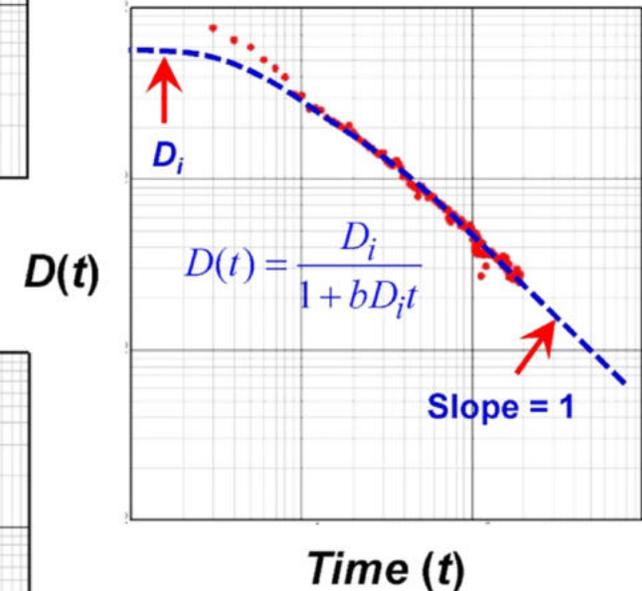## [Early Hyperbolic/Late Exponential]

Time-Rate Relation:

$$q(t) \equiv \begin{bmatrix} \text{For } t \le t_{\text{lim}}: \\[6pt] \dfrac{q_{i,\text{hyp}}}{(1+bD_i t)^{1/b}} \\[10pt] \text{For } t > t_{\text{lim}}: \\[6pt] q_{\text{lim}} \exp[-D_{\text{lim}}(t - t_{\text{lim}})] \end{bmatrix}$$
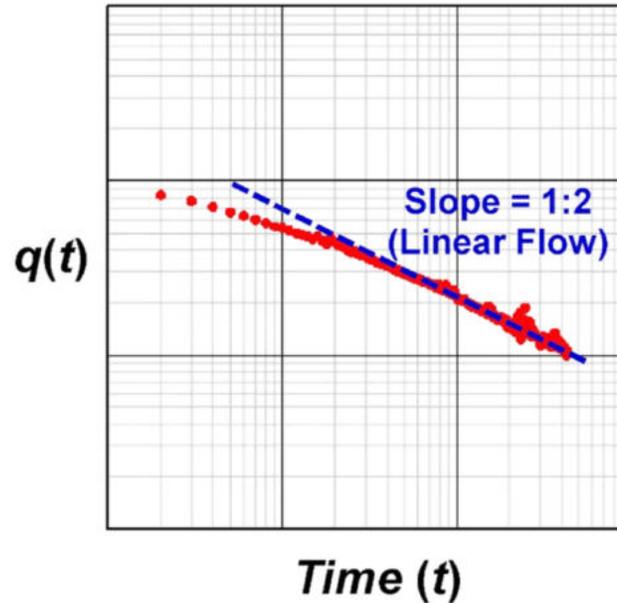
Terminal Decline "Switch:"

$$q_{\text{lim}} = q_{i,\text{hyp}}\left[\frac{D_{\text{lim}}}{D_i}\right]^{(1/b)}$$

$$t_{\text{lim}} = \frac{1}{bD_i}\left[\left[\frac{q_{i,\text{hyp}}}{q_{\text{lim}}}\right]^b - 1\right]$$

$D(t)$ Relation:

$$D(t) \equiv -\frac{1}{q}\frac{dq}{dt} = \frac{D_i}{1+bD_i t}$$
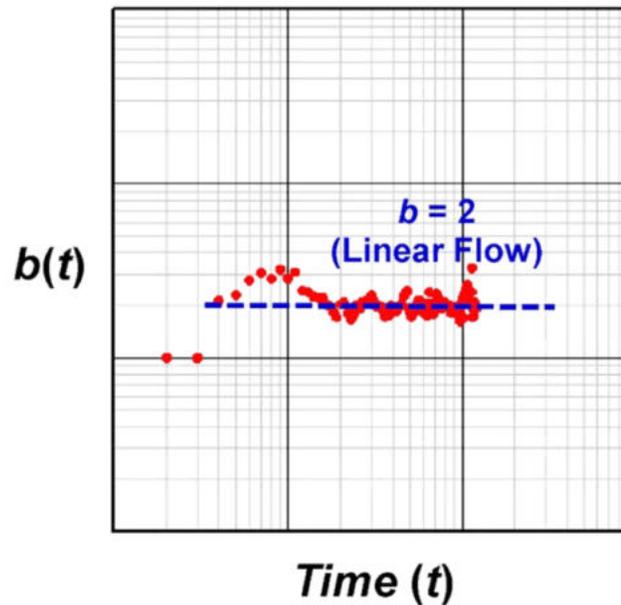
Arps "b-factor:"

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

$q(t)$ — Slope = 1:2 (Linear Flow) — Time (t)

$b(t)$ — $b = 2$ (Linear Flow) — Time (t)

$D(t)$ — D_i — $D(t) = \dfrac{D_i}{1+bD_i t}$ — Slope = 1 — Time (t)

Rate-Transient Analysis — Historical Context [*Fetkovich — (circa 1973)*]
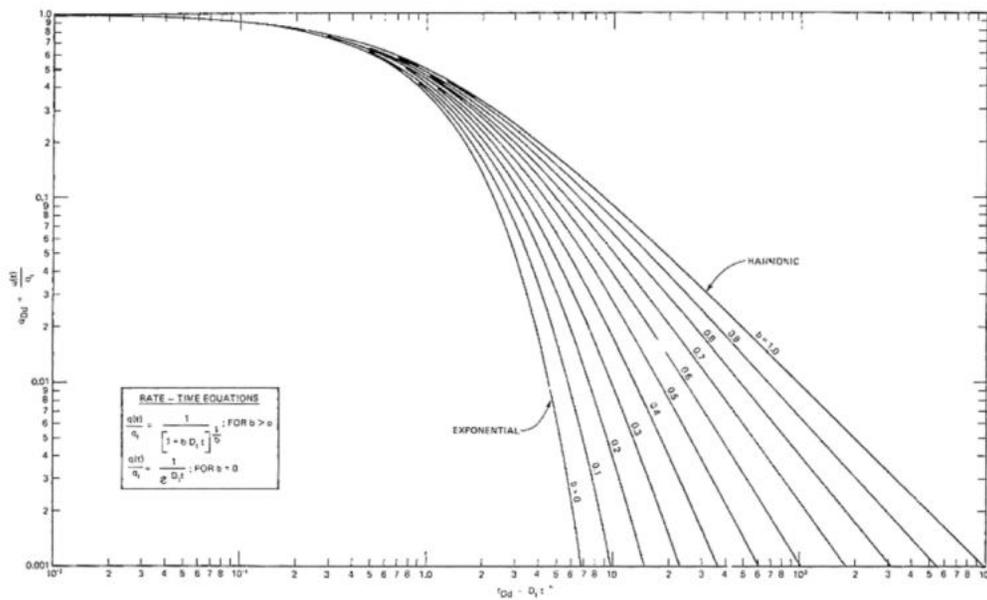
Fig. 1 - Type curves for Arps empirical rate-time decline equations, unit solution ($D_i \approx 1$).

Fetkovich Decline Type Curve — Arps Stems.
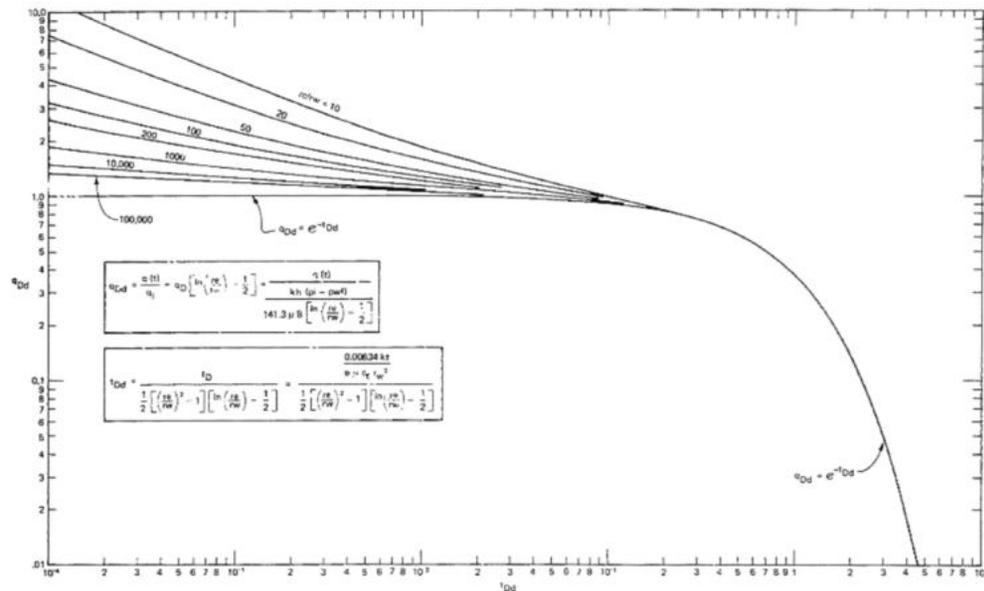
Fig. 3 - Dimensionless flow rate functions for plane radial system, infinite and finite outer boundary, constant pressure at inner boundary.
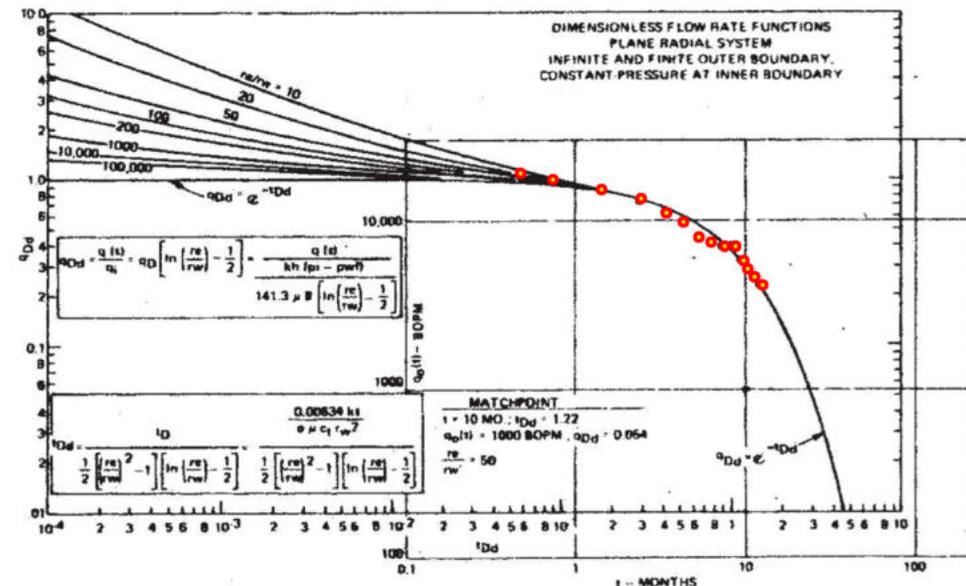
Fetkovich Decline Type Curve — Analytical Stems.
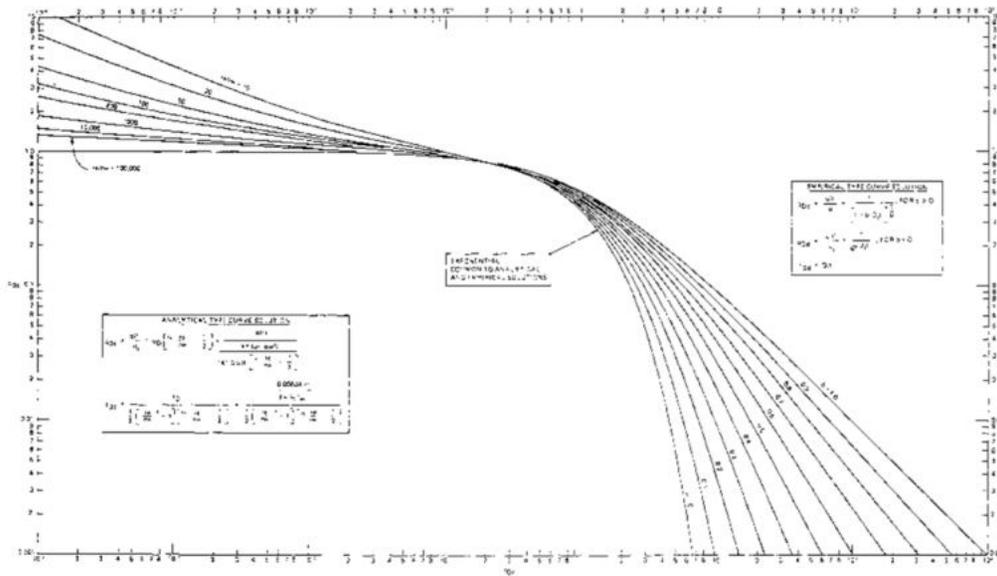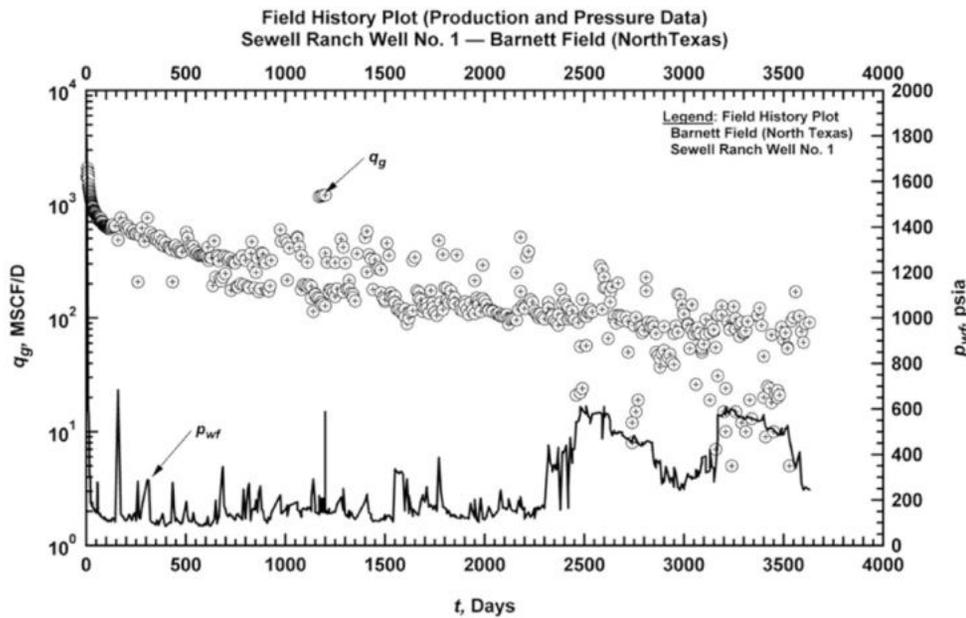

Composite of analytical and empirical type curves.

Fetkovich Decline Type Curve — Composite Curve (original curve).

Fetkovich Decline Type Curve — Example Data Case (SPE 004629).

Rate-Transient Analysis — Historical Context [*Blasingame — (circa* 1993)]

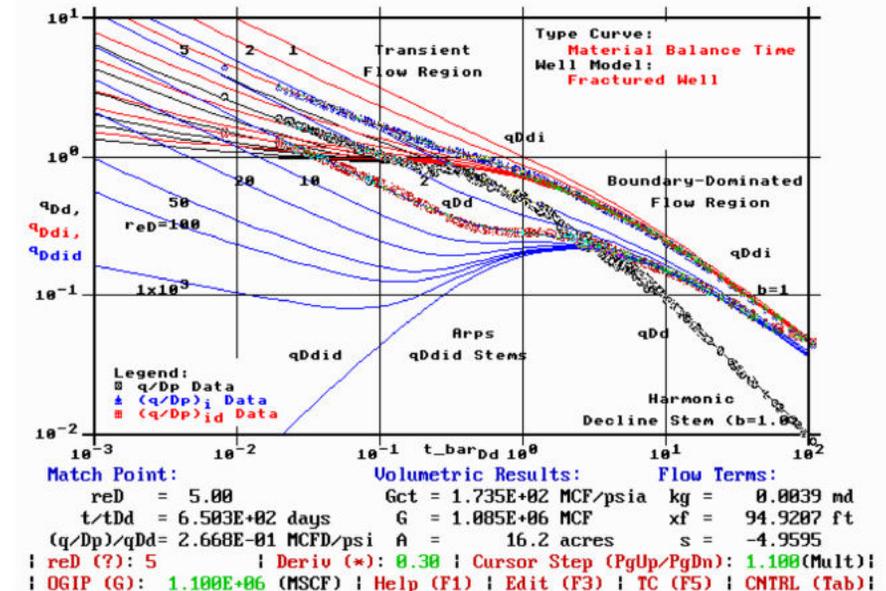"History Plot" — Gas rate and computed bottomhole pressures.
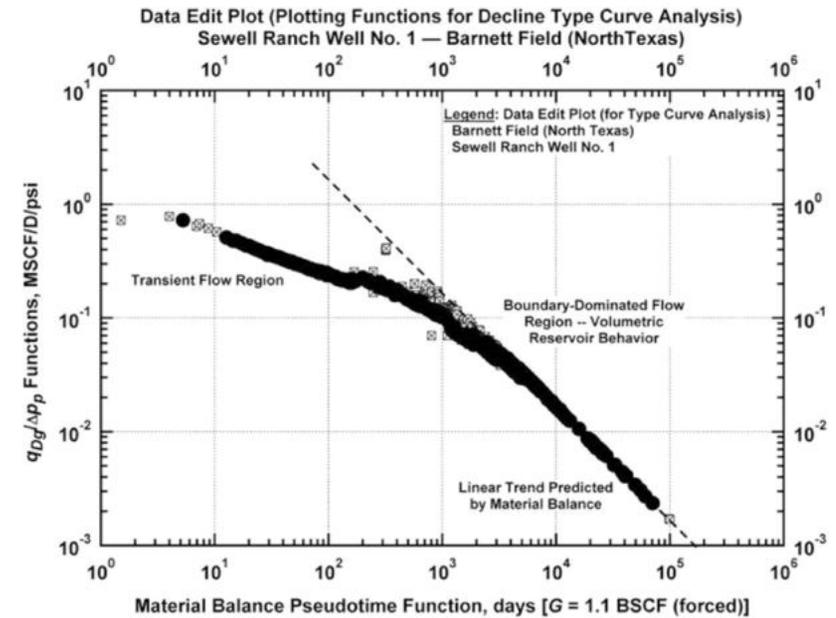
"Edit Plot" — Gas PI and gas material balance pseudotime.
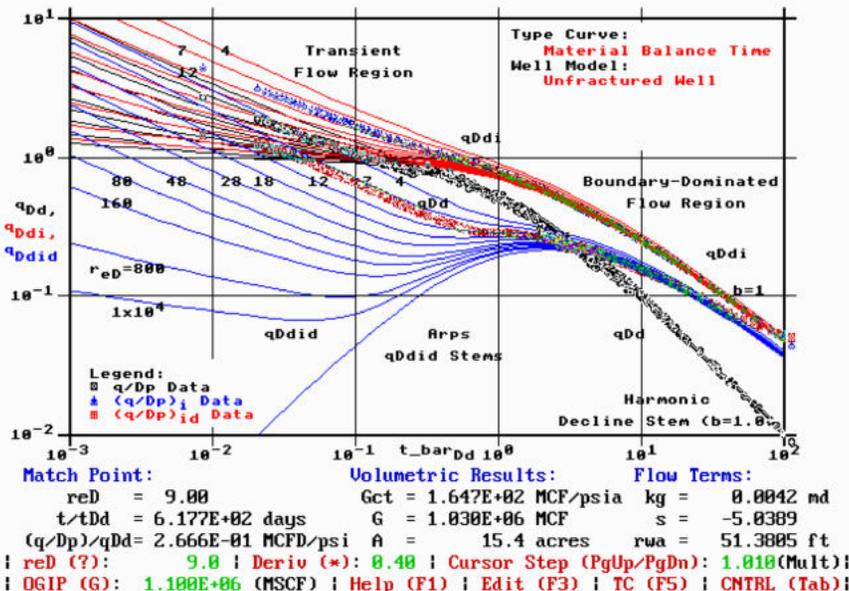
"WPA Plot" — (original RTA) Unfractured well model.

"WPA Plot" — (original RTA) Fractured well model (infinite conductivity).

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Last Thoughts —
Before We Go To the Vaca Muerta Examples

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# Rate-Transient Analysis — Data Considerations

Ideally:
- Instantaneous flowing bottomhole pressure $p_{wf}(t)$ (*i.e.*, real-time BHP)
- High resolution flowrates:
  —Every 5-10 min (preferred).
  —Every hour (we be good).
  —Daily average (reality).
- Bottomhole temperature:
  —Correlate with BHP for "frac-hits."
 —Correlate rate performance (maybe).

Reality:
- Surface pressure (hourly or higher frequency).
- Daily flowrates, with some speculation on accuracy of water rates (probably good enough).
- Completion data:
  —water pumped.
  —total proppant.
  —stage spacing.
  —number of stages, etc., etc.

Worst Case:
- No pressure ...
- Daily rates which may not accurately represent what was produced ...
- No completion records ...
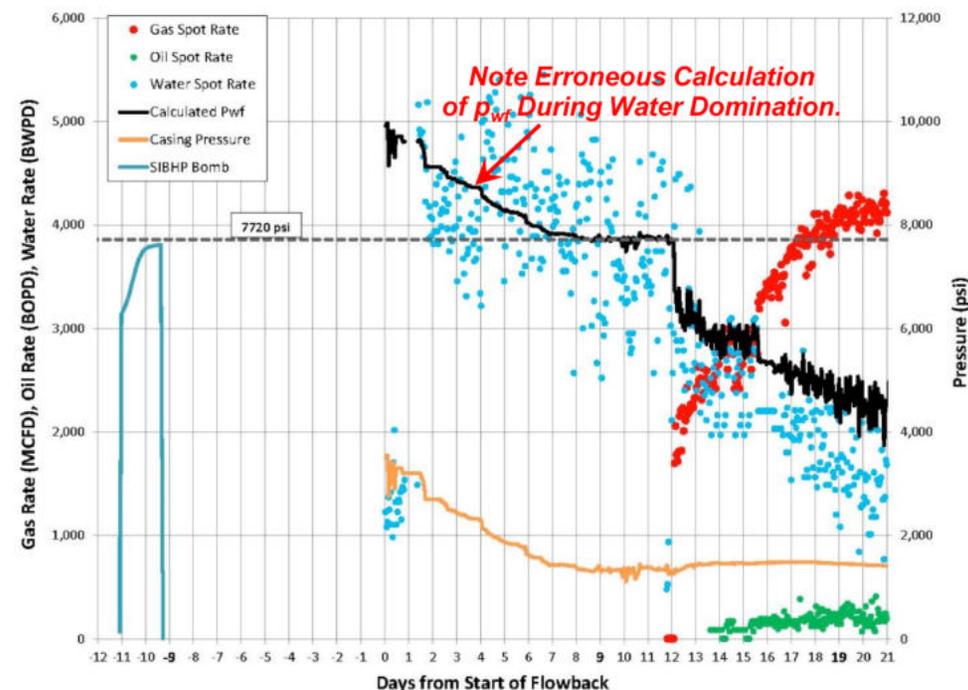
Rate and pressure functions vs. time.
(Source: URTeC 1934785)
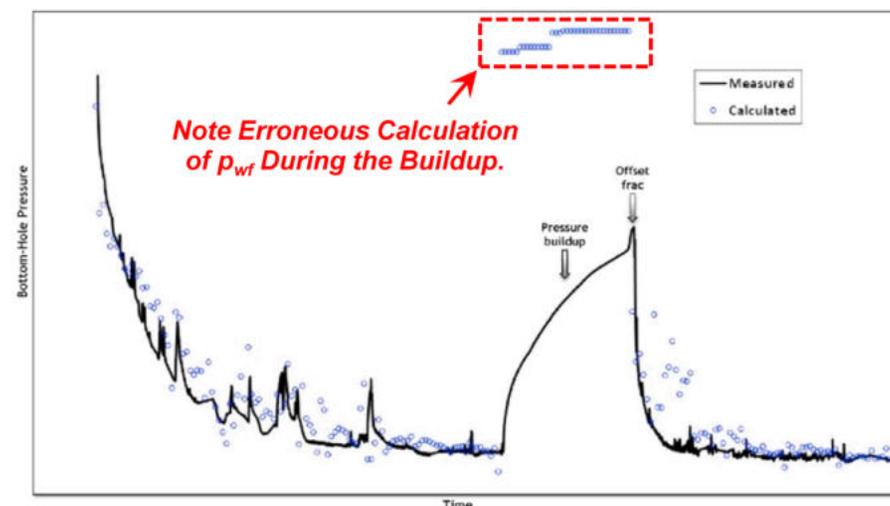
Comparison: $(p_{wf})_{meas}$ and $(p_{wf})_{calc}$ vs. time.
(Source: SPE 178608)

(*Formation*) *Linear Flow* — Δp/q versus SQRT[*t*] Plot (*This is NOT RTA!*)

- **Formation Linear Flow: (*t* = *t* or *t_{mb}* (material balance time))**
  - **Log-log diagnostic plot: log[Δp/q] versus log[*t*] (slope = -1:2)**
  - **"Traditional" plot: Δp/q versus SQRT[*t*] (straight-line portion)**
  - ***Extrapolation of rate using a linear flow model will over-predict EUR…***
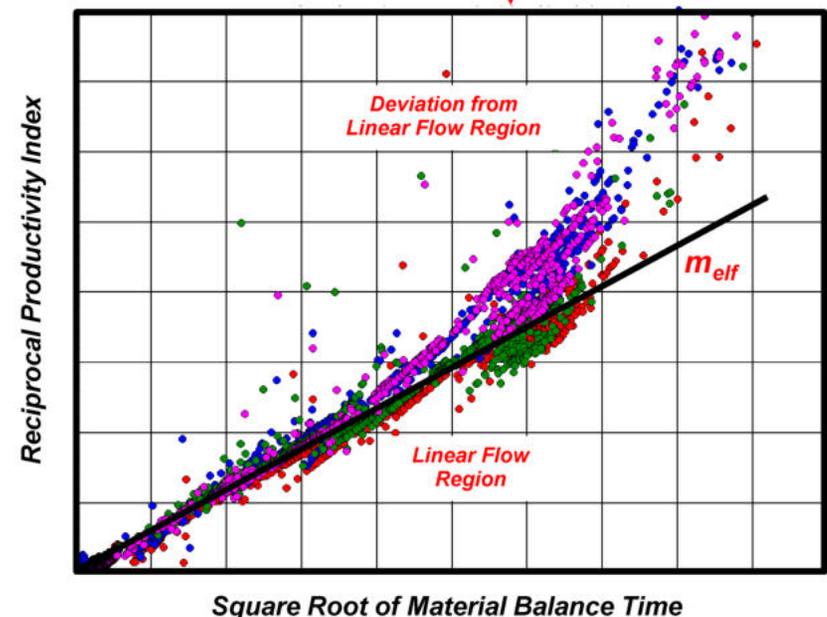
- **Governing Relation:**
$$\frac{(p_i - p_{wf})}{q_{\text{tot}}} = \frac{1}{\dfrac{1}{8.128494}\dfrac{1}{B}\sqrt{\dfrac{\phi c_t}{\mu}}\,[(A_{xf})_{\text{tot}}\sqrt{k}]}\sqrt{t} = m_{elf}\sqrt{t}$$

Where m_{elf} is the slope of the straight-line trend on a plot of $\dfrac{(p_i - p_{wf})}{q}$ vs $\sqrt{t}$.

Solving: $[A_{xf,\text{tot}}\sqrt{k}] = 8.128494\,B\sqrt{\dfrac{\mu}{\phi c_t}}\dfrac{1}{m_{elf}}$.
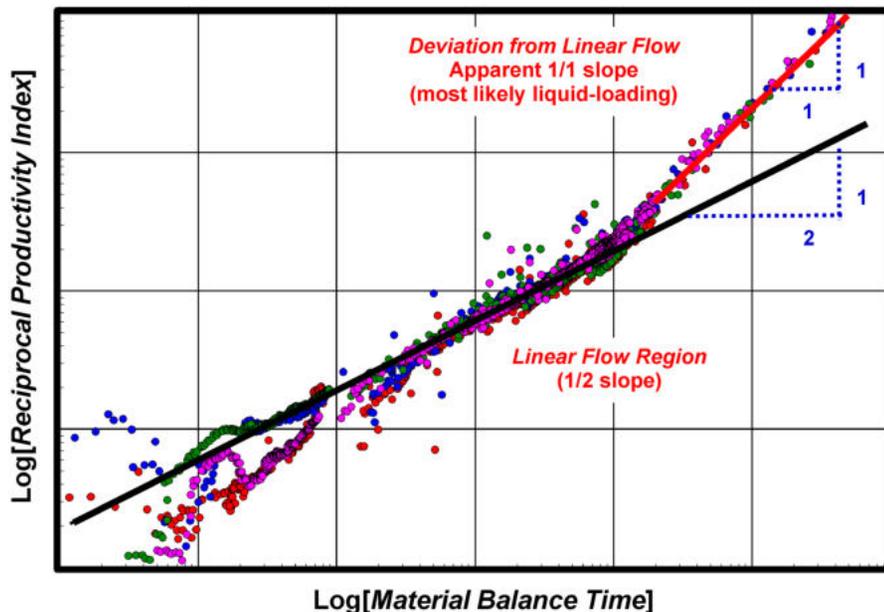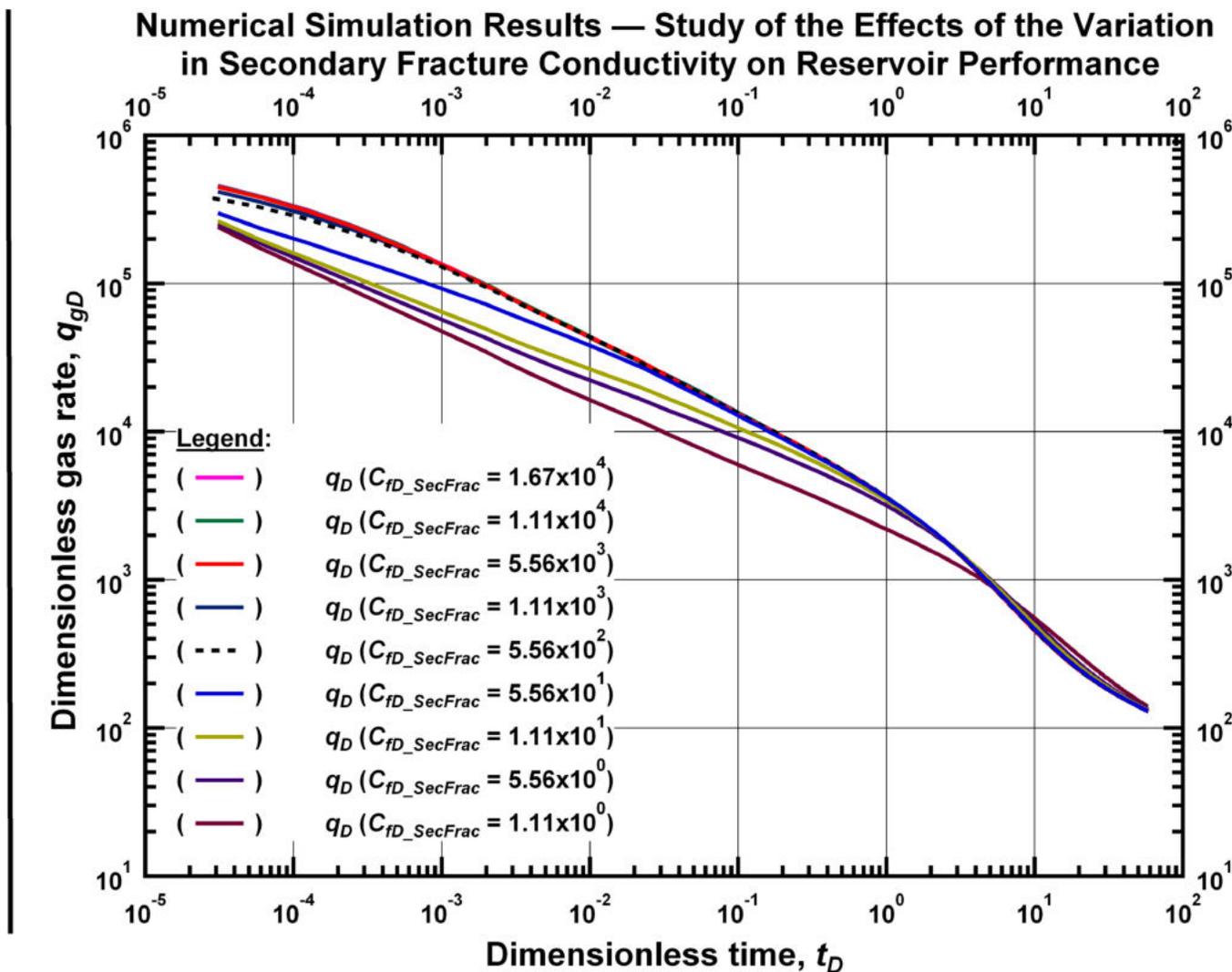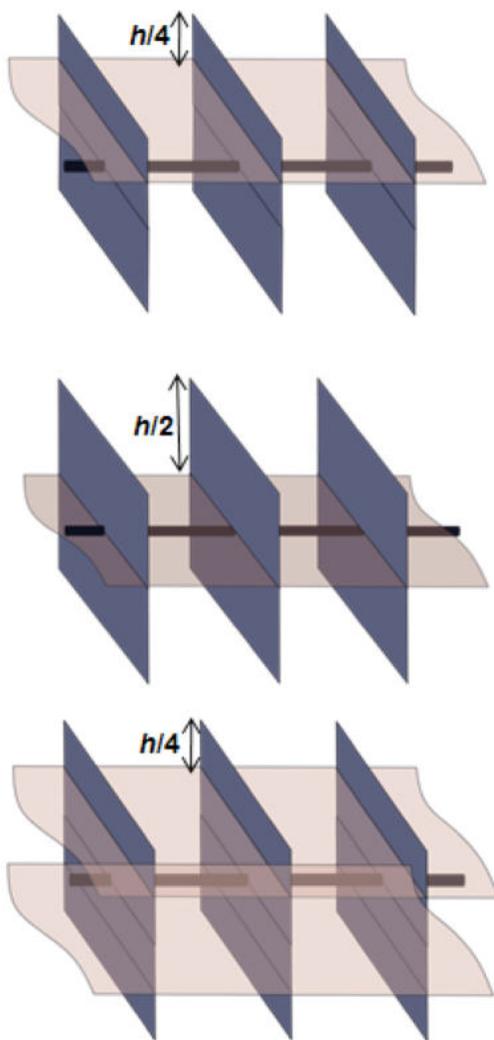

a. (Log-log plot): Reciprocal productivity index versus material balance time, multiple wells.

b. (Square root plot): Reciprocal productivity index versus square root of material balance time, multiple wells.

# RTA Signatures for Complex Fracture Case — Olorode (SPE 152482)

Numerical Simulation Results — Study of the Effects of the Variation in Secondary Fracture Conductivity on Reservoir Performance

Legend:
( ) q_D ($C_{fD\_SecFrac} = 1.67 \times 10^4$)
( ) q_D ($C_{fD\_SecFrac} = 1.11 \times 10^4$)
( ) q_D ($C_{fD\_SecFrac} = 5.56 \times 10^3$)
( ) q_D ($C_{fD\_SecFrac} = 1.11 \times 10^3$)
(- - -) q_D ($C_{fD\_SecFrac} = 5.56 \times 10^2$)
( ) q_D ($C_{fD\_SecFrac} = 5.56 \times 10^1$)
( ) q_D ($C_{fD\_SecFrac} = 1.11 \times 10^1$)
( ) q_D ($C_{fD\_SecFrac} = 5.56 \times 10^0$)
( ) q_D ($C_{fD\_SecFrac} = 1.11 \times 10^0$)

Dimensionless gas rate, q_{gD} (vertical axis)
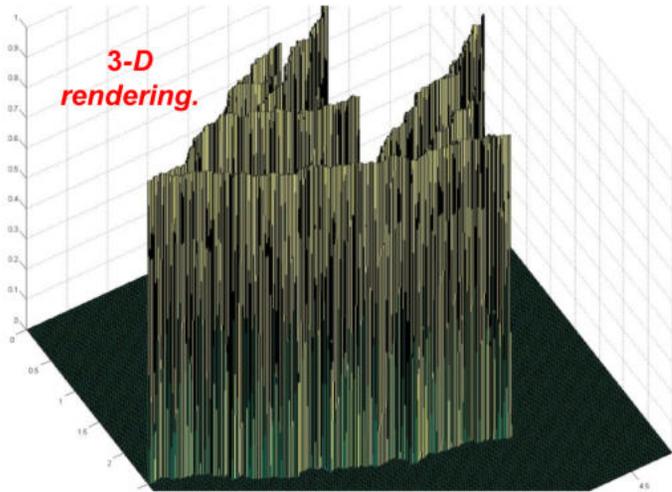Dimensionless time, t_D (horizontal axis)

Discussion:
- Reduction from linear flow (half-slope) for $C_{fD,SecFrac} < 10$.
- Model trends are also observed in field data.
- Secondary fracture concept may be useful in optimizing fracture design.
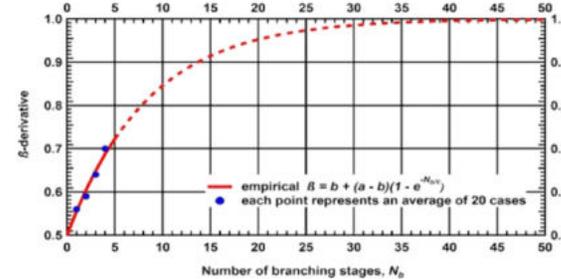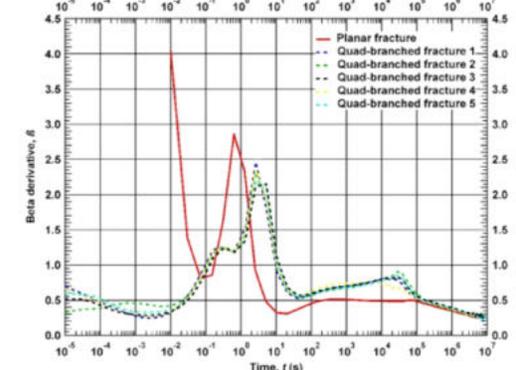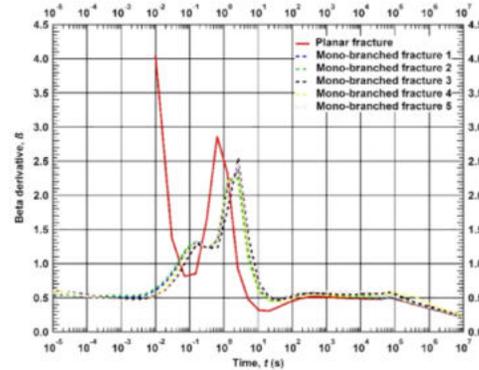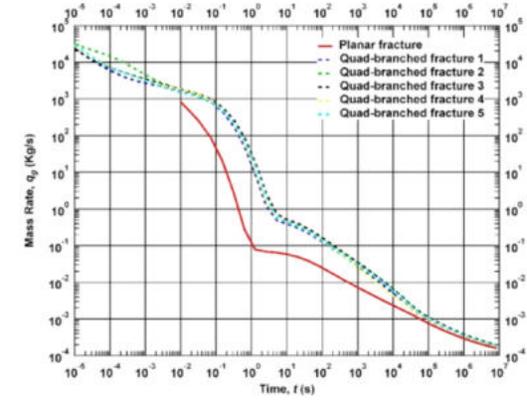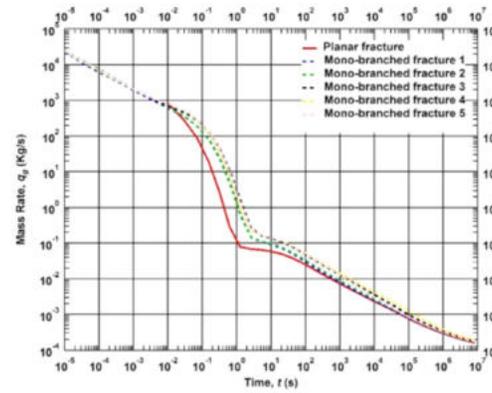
RTA Signatures for Random Fracture Case — Mhiri (SPE 175021)
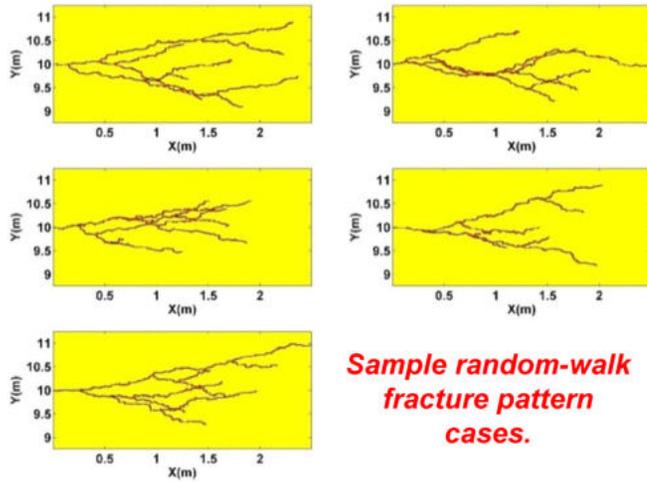
Sample random-walk fracture pattern cases.

3-D rendering.

Discussion:

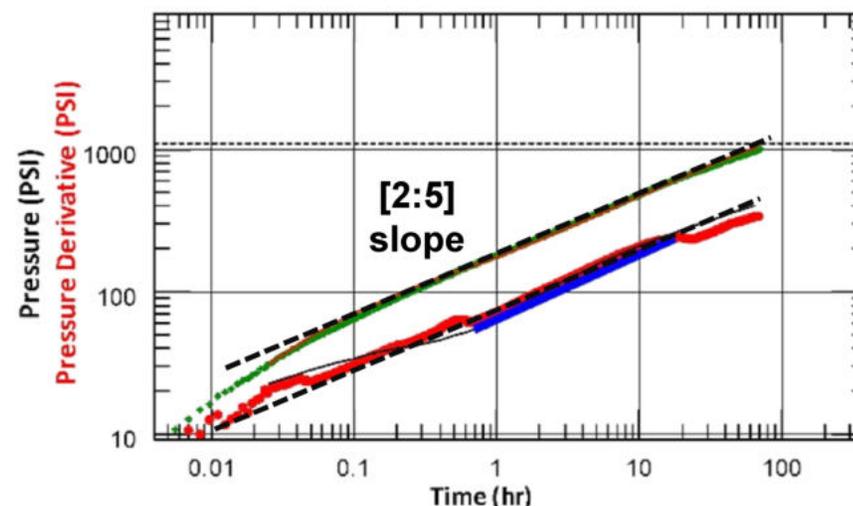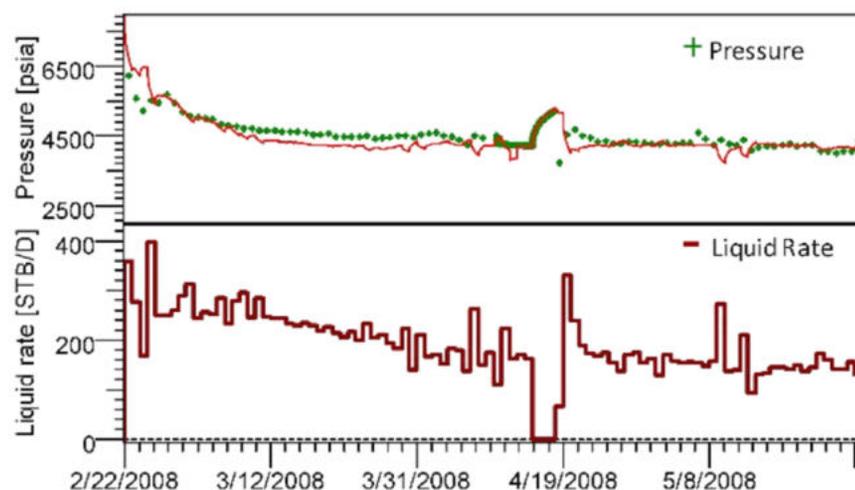- After a random number steps, the fractures may bifurcate (split).
- β-derivative of the mass flowrate is the diagnostic function.
- β-derivative is 0.55 (mono-branch) and 0.70 (quad-branch).

Pressure Transient Analysis in Shales — Recent Observations [*Kurtoglu* (2012)]
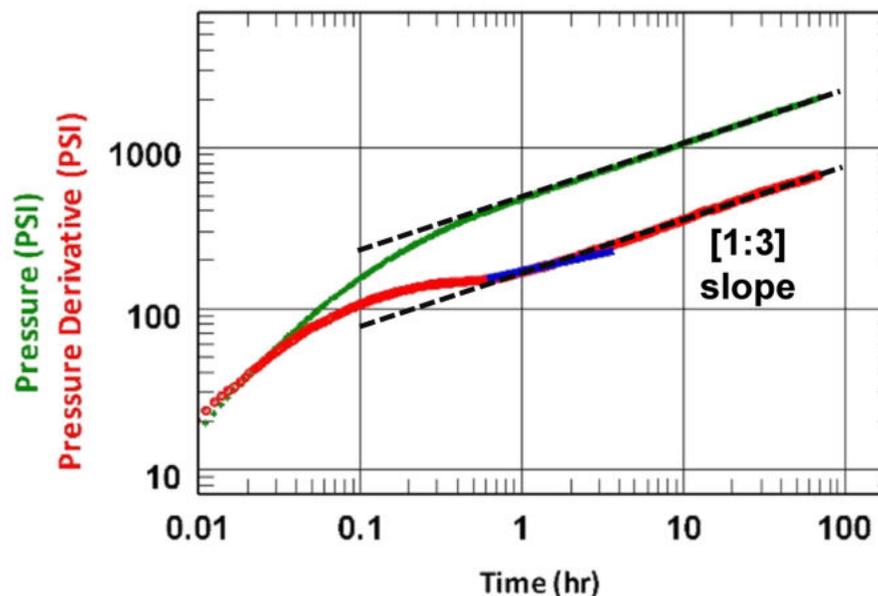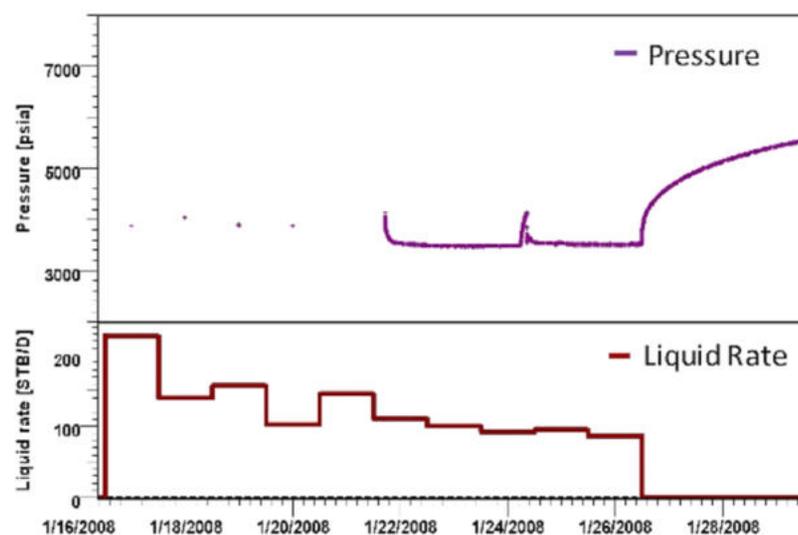
Discussion:
- **Unique signatures in the pressure drop and derivative functions.**
- **[1:3] slope could be due to natural fractures.**
- **[2:5] slope could also be due to natural fractures and/or multiphase flow effects.**
- **These signatures may be correlated with reservoir properties and/or well spacing.**

Pressure Transient Analysis in Shales — Recent Field Study [*Pradhan* (2021)]
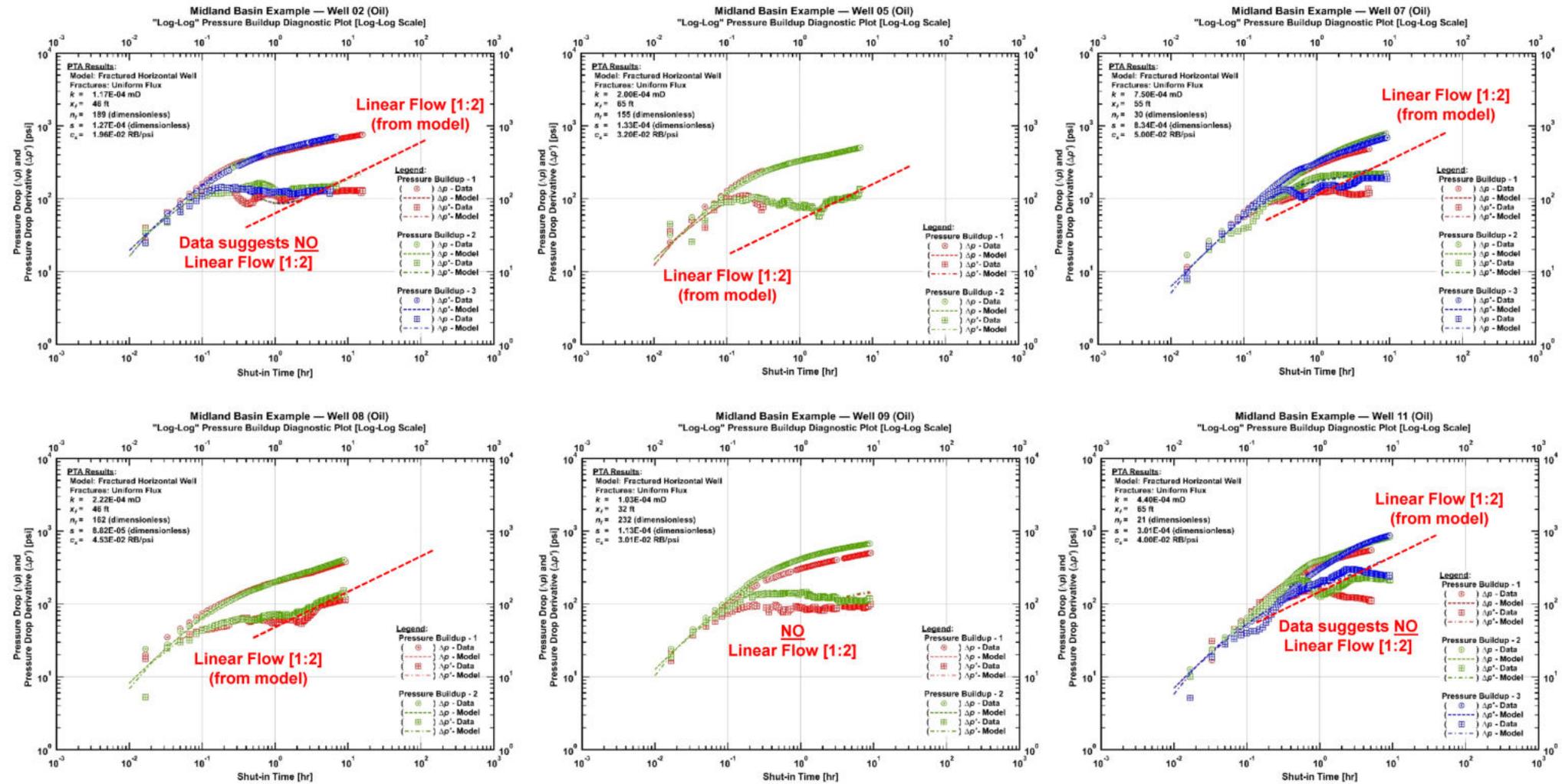
Pradhan, Y., Gildin, E., and Blasingame, T.A.: (2021) "Drawdown Management Strategies — Midland Basin Case Studies" paper Control ID: 5125 presented at the 2021 Unconventional Resources Technology Conference, Houston, TX, 25-27 July 2021. https://doi.org/10.15530/urtec-2021-5125

Discussion:
- All cases are "opportunity" shut-ins, performed to due operational needs.
- The multi-fracture horizontal well (MFHW) → "Linear Flow" signature (*i.e.*, a [1:2] slope).
- However; several cases do NOT indicate "Linear Flow" [1:2 slope].

Pressure Transient Analysis in Shales — Current Thoughts [*Chu* (2018)]
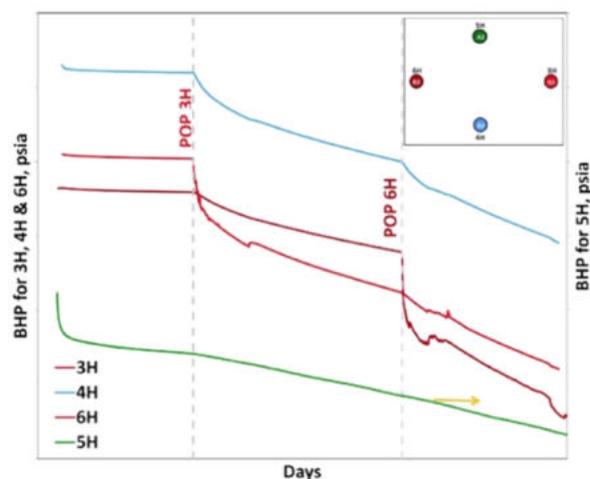
Pressure response due to Well 3H being "put-on-production" (or POP'd).
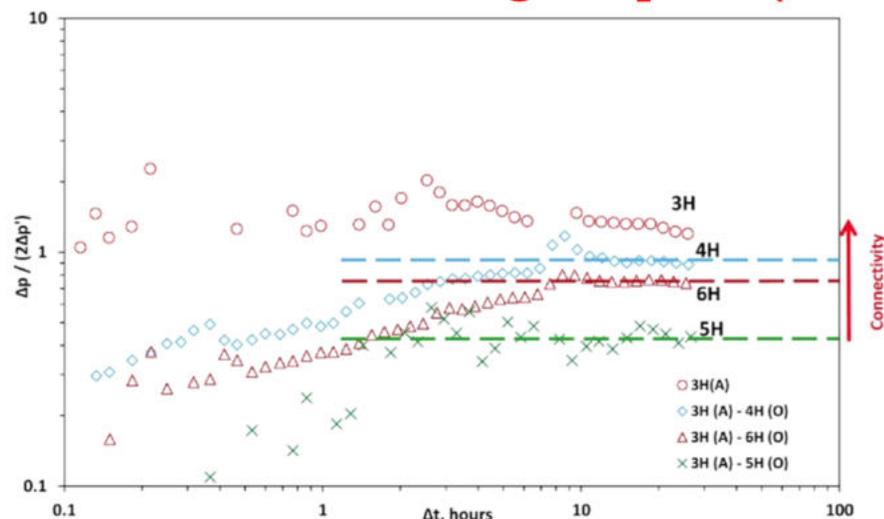
Chow Pressure Group (pressure derivative function) For all for 4 wells due to Well 3H being "POP'd."

Chu, W., Scott, K., Flumerfelt, R., & Chen, C.-C. (2018) A New Technique for Quantifying Pressure Interference in Fractured Horizontal Shale Wells. Society of Petroleum Engineers. doi:10.2118/191407-MS
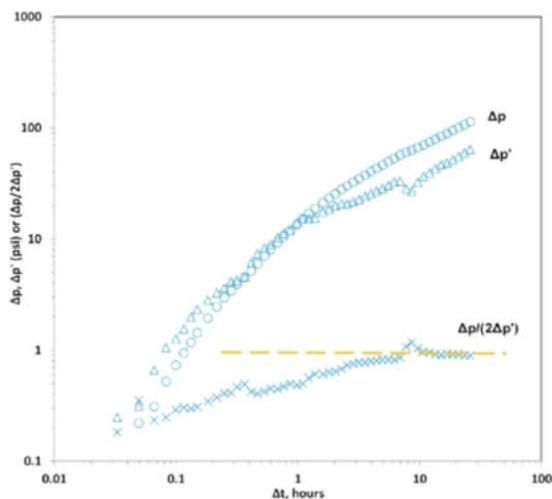
Pressure interference response in Well 4H. (due to Well 3H POP)
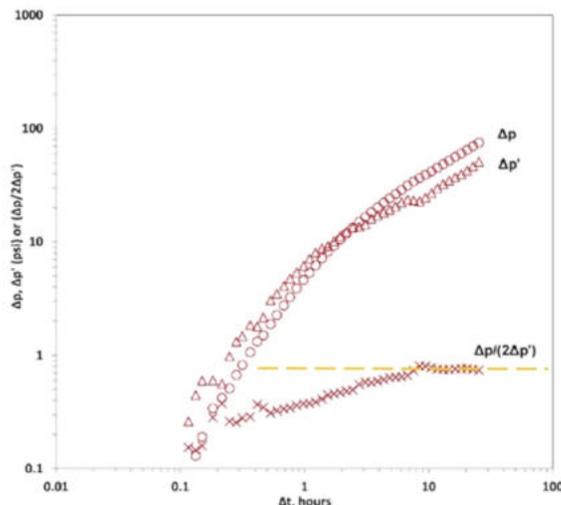
Pressure interference response in Well 6H. (due to Well 3H POP)
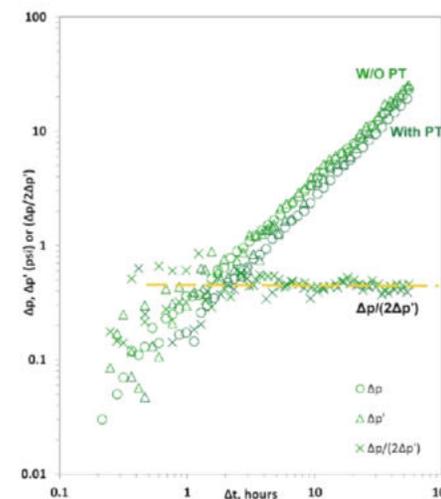
Pressure interference response in Well 5H. (due to Well 3H POP)

Discussion:
- Currently the most popular means of interpretation/analysis for induced PTA events.
- The "POP" (put-on-production) sends a pressure "signal" through the fracture system.
- Question: POP effect on long-term recovery? (*i.e.*, Can the POP effect be quantified?)

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Vaca Muerta Examples:
… before we start

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Vaca Muerta Examples: … *before we start*

A Few (Personal) Comments Before We Start:

- I was ASKED to perform this work as part of this webinar.
- I do NOT know the submitters, nor specific cases.   (*… this is a "blind test"*)
- I CANNOT share the data.   (*… it belongs to the operators who submitted it*)
- I DID NOT put results on the slides.   (*… its about process, not results*)
- I DID NOT consult anyone on any data case.   (*… all the work is my own*)

General Comments:

- Several cases were severely affected by operations.
- Operations-affected cases are very difficult to interpret using DCA methods.

PTA/RTA/DCA Methods for the Evaluation of Well Performance in Unconventional Reservoirs — Vaca Muerta Field Examples

Vaca Muerta Examples:
Well 01 (Oil)

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Production Summary Strip Plot — Vaca Muerta Example Well 01 (Oil)

Vaca Muerta Example Well 01 (Oil)
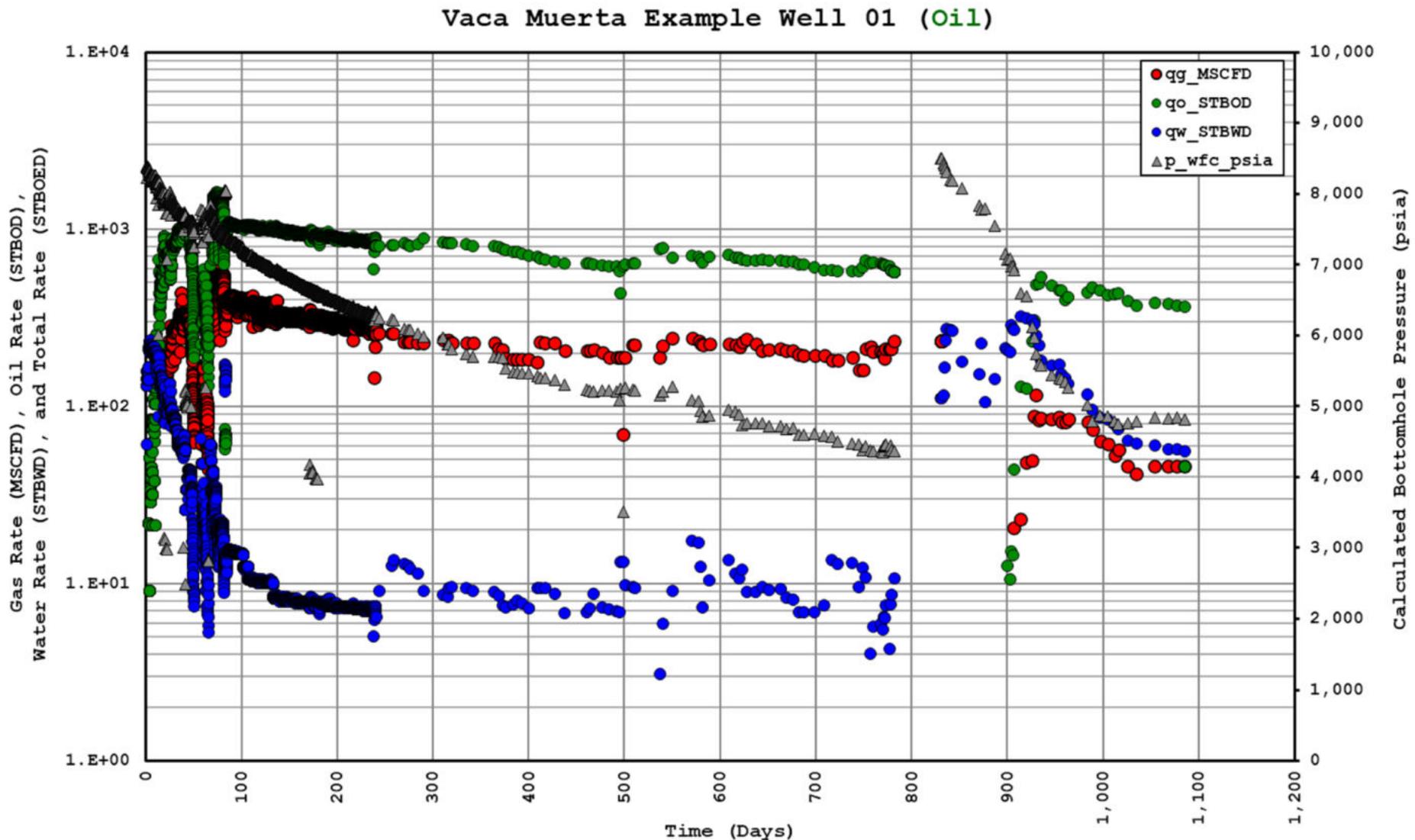
Discussion:
- All trends are reasonable (early trends are erratic, but typical).
- Oil rate trend seems quite robust (exponential?).
- Pressures seem quite reasonable, except during the shut-in (just don't know).

RTA Plot (*Kappa Topaze v*4) — Vaca Muerta Example Well 01 (Oil)
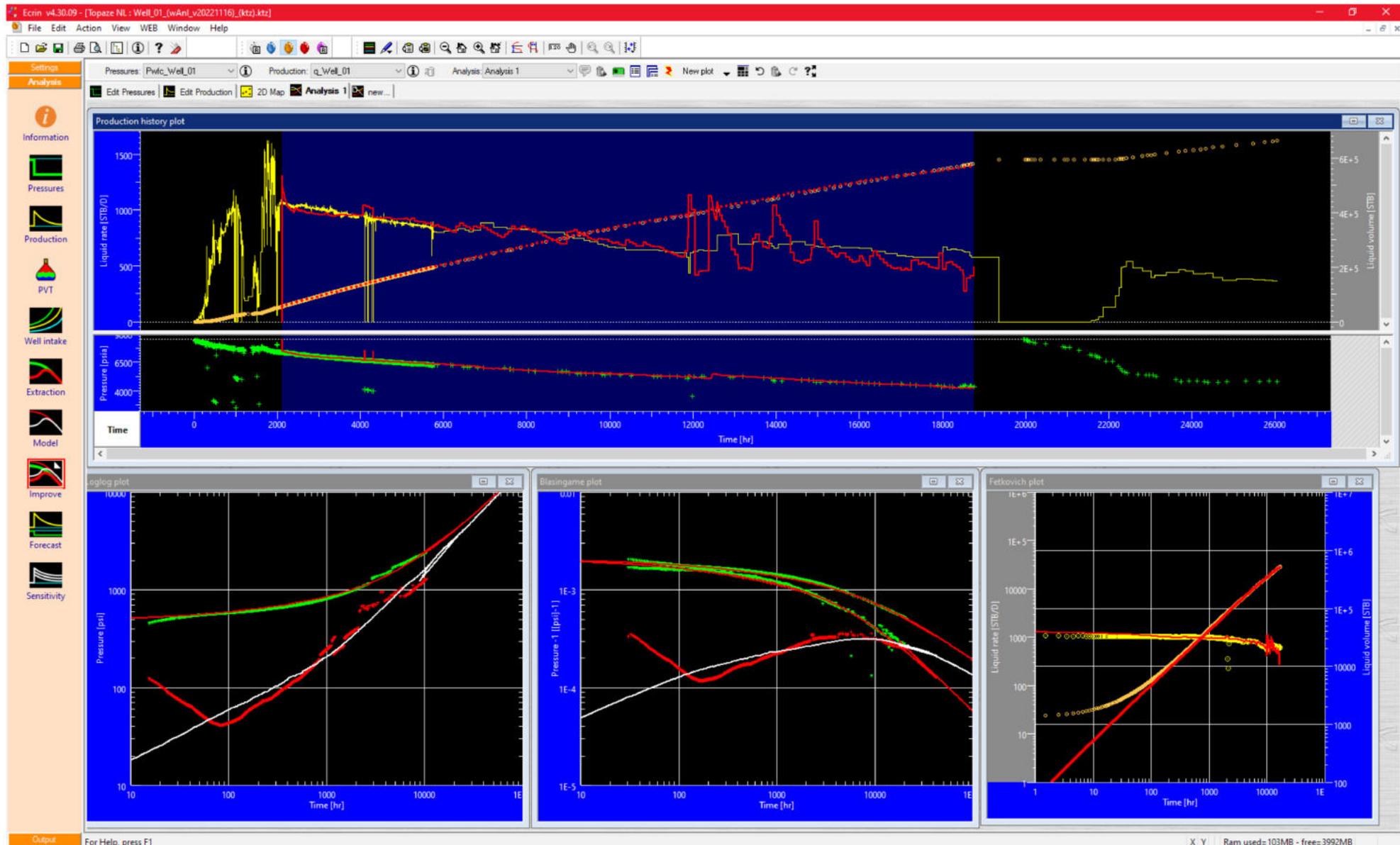
Discussion:

- Rate match is reasonable, pressure match is excellent / outstanding.
- Diagnostic plots have good / very good character.
- Post-shut-in production could not be matched (pretty common in unconventionals).

qQ Plot (*MH and PLE Models*) — Vaca Muerta Example Well 01 (Oil)

Discussion:

- **"Exponential" oil rate trend is evident (or at least we observe a "nearly" exponential trend).**
- **Difficult to match cumulative production due to early behavior (flowback).**

PTA/RTA/DCA Methods for the Evaluation of Well Performance in Unconventional Reservoirs — Vaca Muerta Field Examples

Vaca Muerta Examples:
Well 02 (Gas)

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Production Summary Strip Plot — Vaca Muerta Example Well 02 (Gas)

Vaca Muerta Example Well 02 (Gas)

Discussion:
- Gas rate trend is very robust (and is also "approximately" exponential).
- Water trend is erratic at times, but behavior is also reflected in pressure and gas rates.
- Pressure trend seems reasonable, some features may not be correlated with rates.

RTA Plot (*Kappa Topaze v*4) — Vaca Muerta Example Well 02 (Gas)
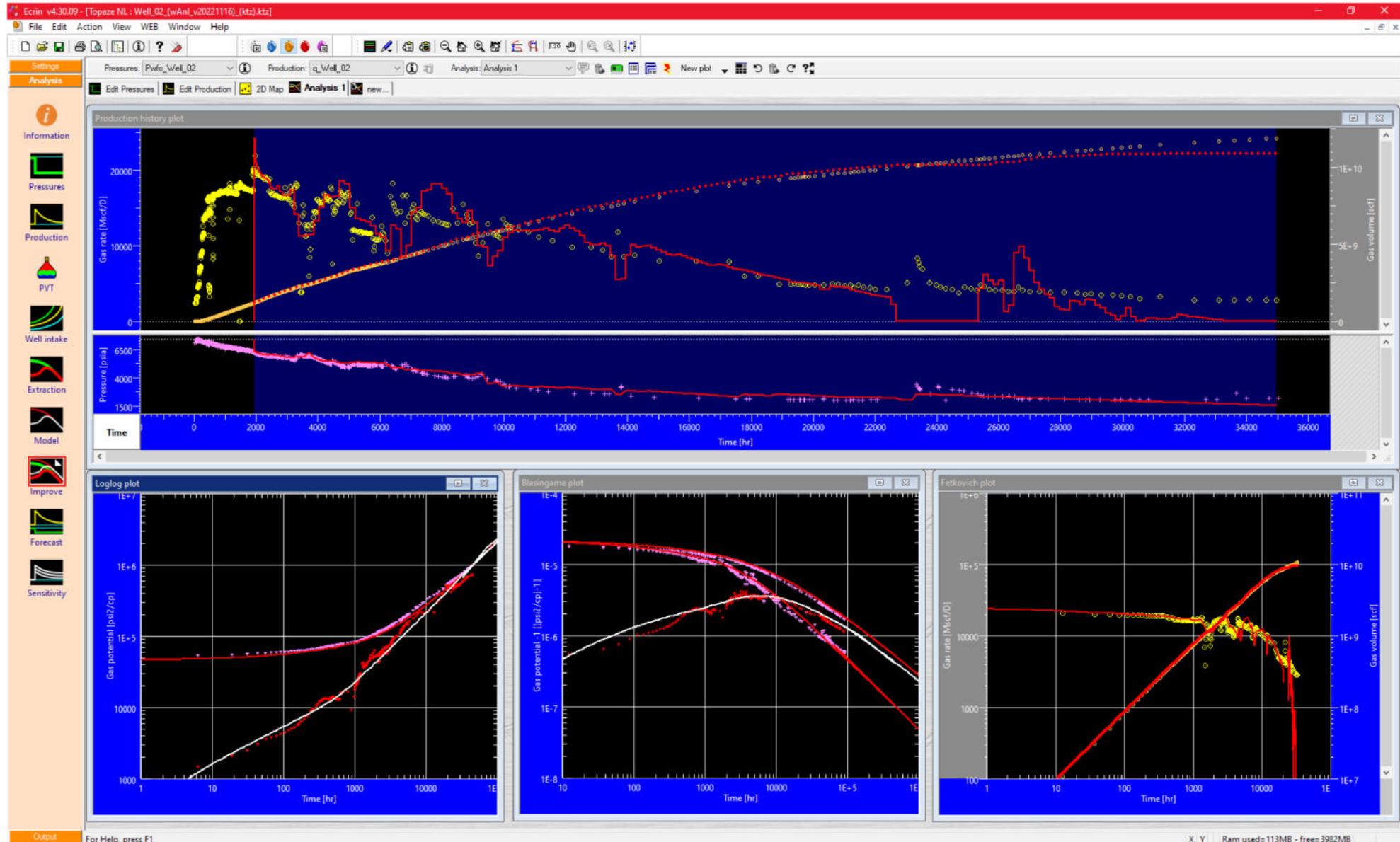
Discussion:

- **Very good pressure match and acceptable rate / cumulative matches.**
- **Diagnostic plots indicate strong skin effect.**
- **Diagnostic matches are excellent.**

qQ Plot (*MH and PLE Models*) — Vaca Muerta Example Well 02 (Gas)

Vaca Muerta Example Well 02 (Gas)
(Modified Hyperbolic and
Power-Law Exponential Rate Relations]
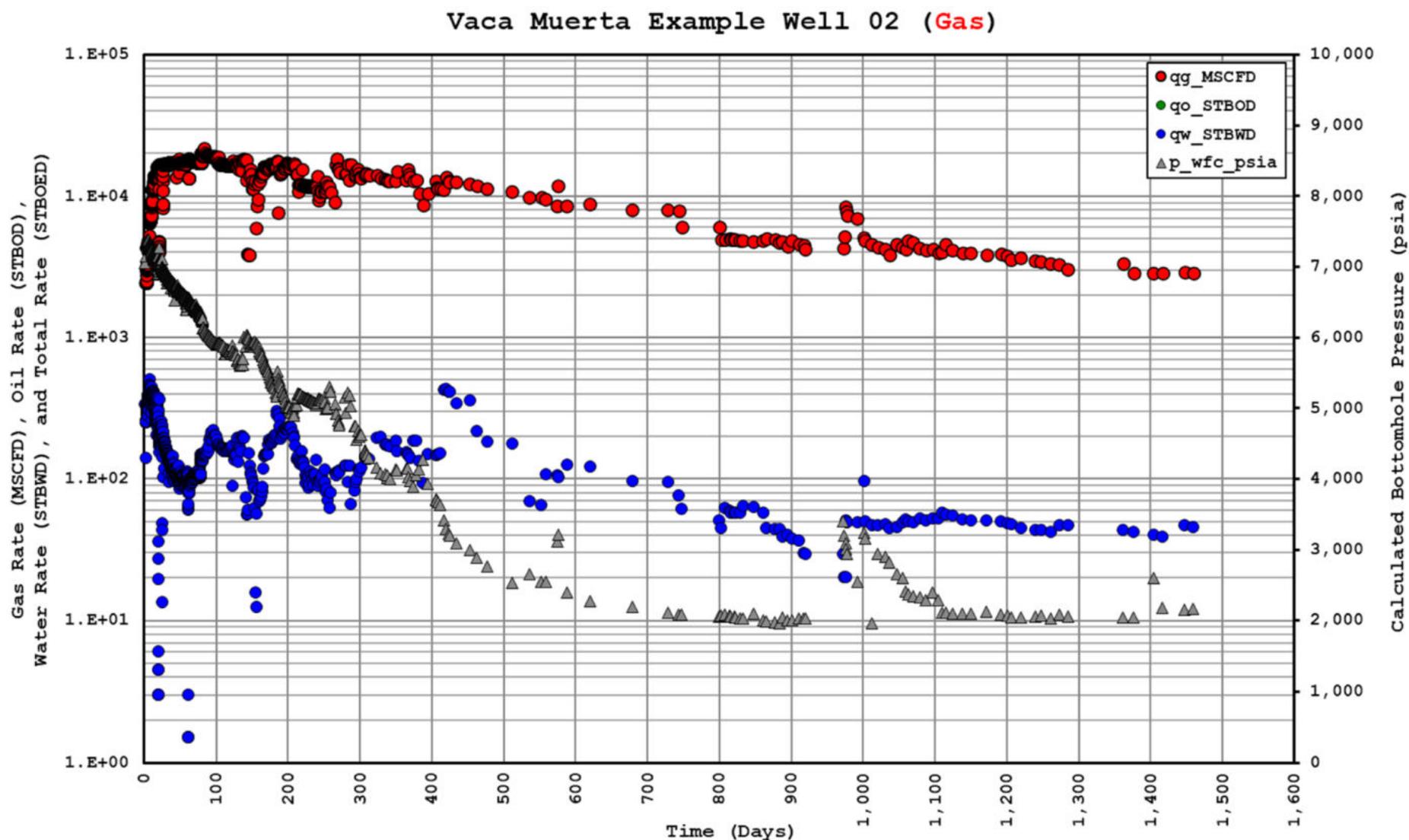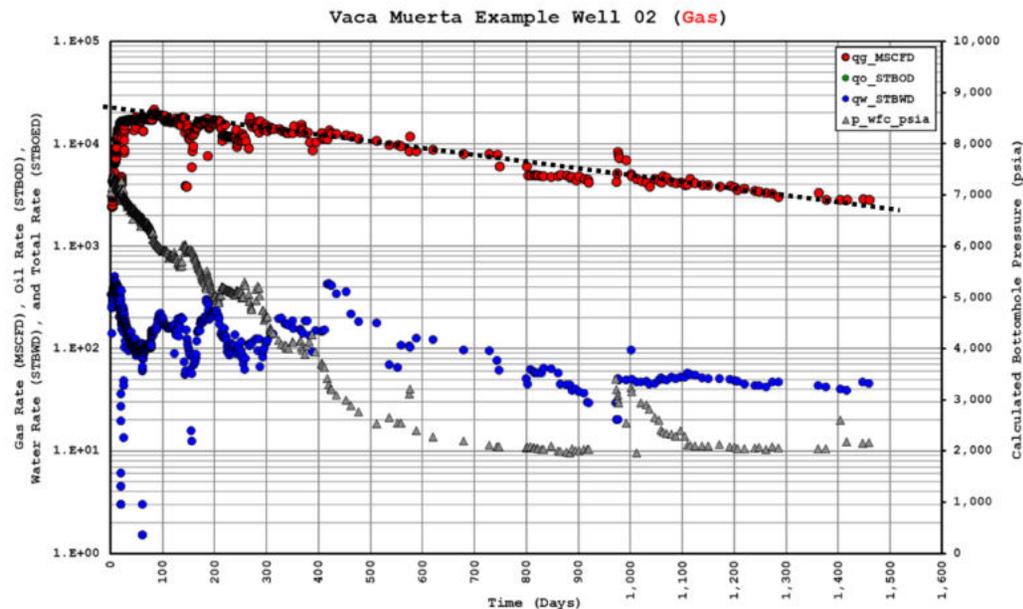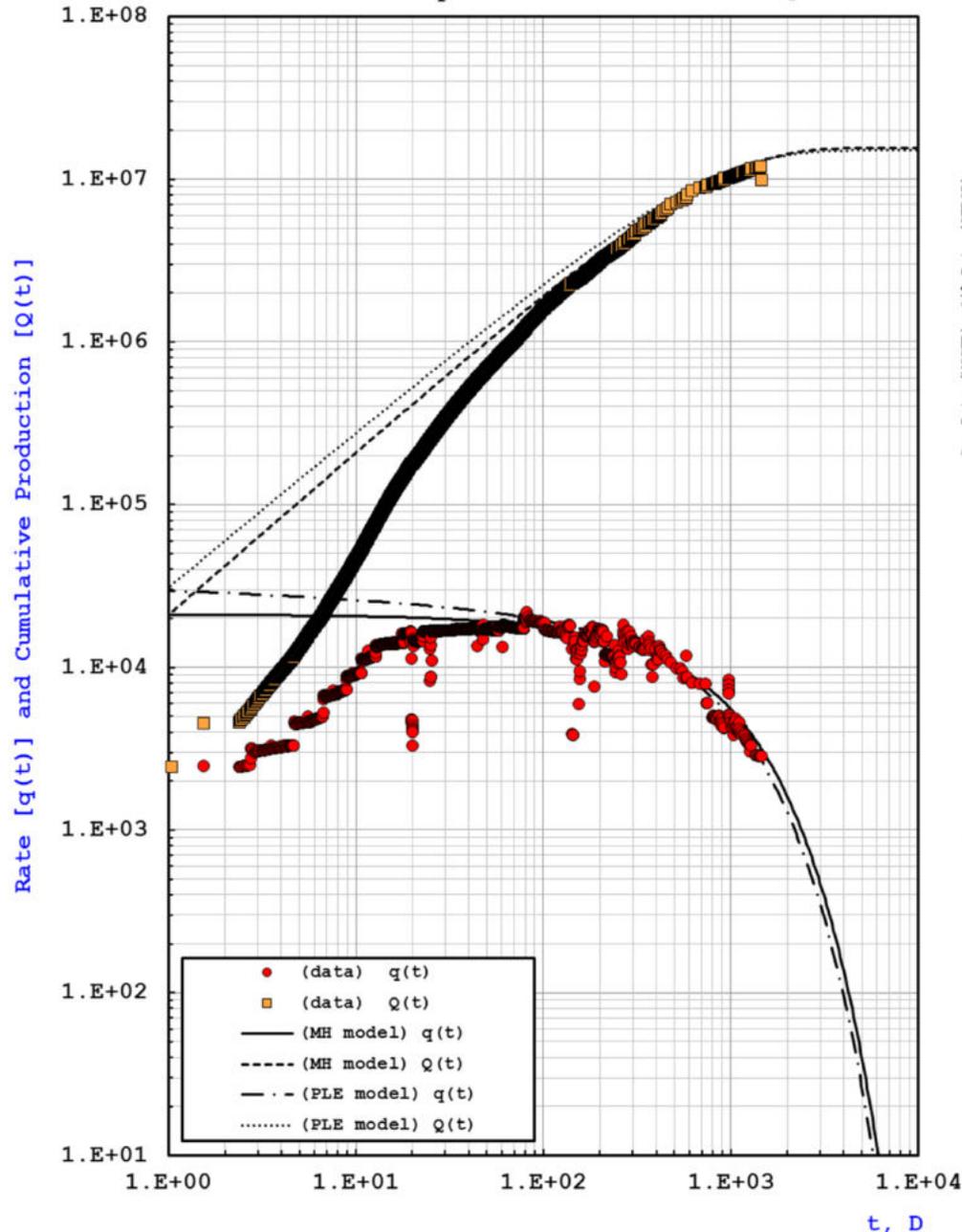
Discussion:

- **Gas rate trend is approximately exponential, as seen in semilog and log-log plots.**
- **Increasing gas rate during first months affects ability to interpret / match early-time rate data using DCA methods.**

PTA/RTA/DCA Methods for the Evaluation of Well Performance in Unconventional Reservoirs — Vaca Muerta Field Examples

Vaca Muerta Examples:
Well 03 (Oil)

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Production Summary Strip Plot — Vaca Muerta Example Well 03 (Oil)

Vaca Muerta Example Well 03 (Oil)
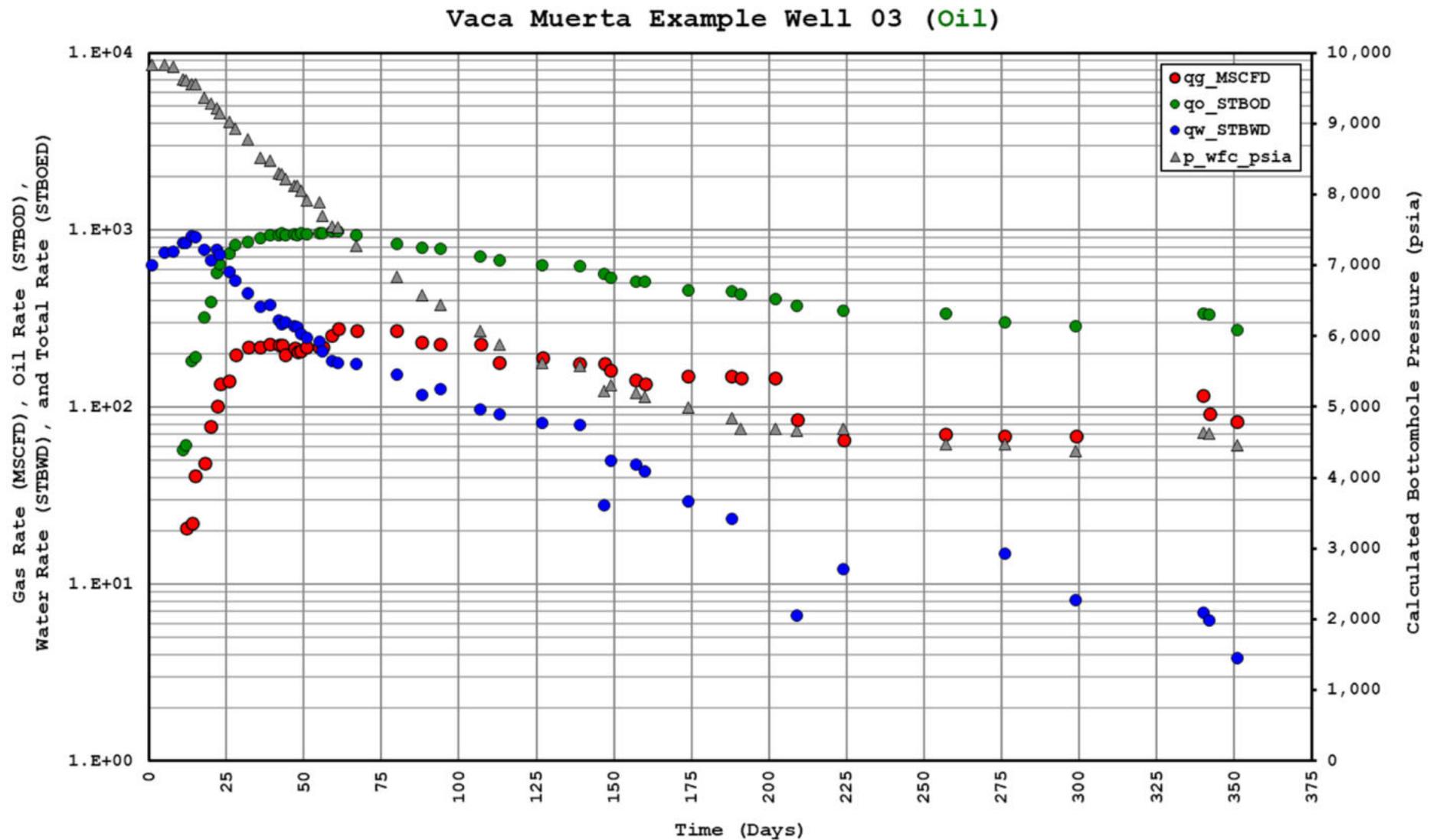
Discussion:

- Data trends are reasonable, early data are more frequent.
- Later oil and gas rate data do appear to have some bias.
- Pressure data appear to be quite robust (*i.e.*, well-behaved).

RTA Plot (Kappa Topaze v4) — Vaca Muerta Example Well 03 (Oil)
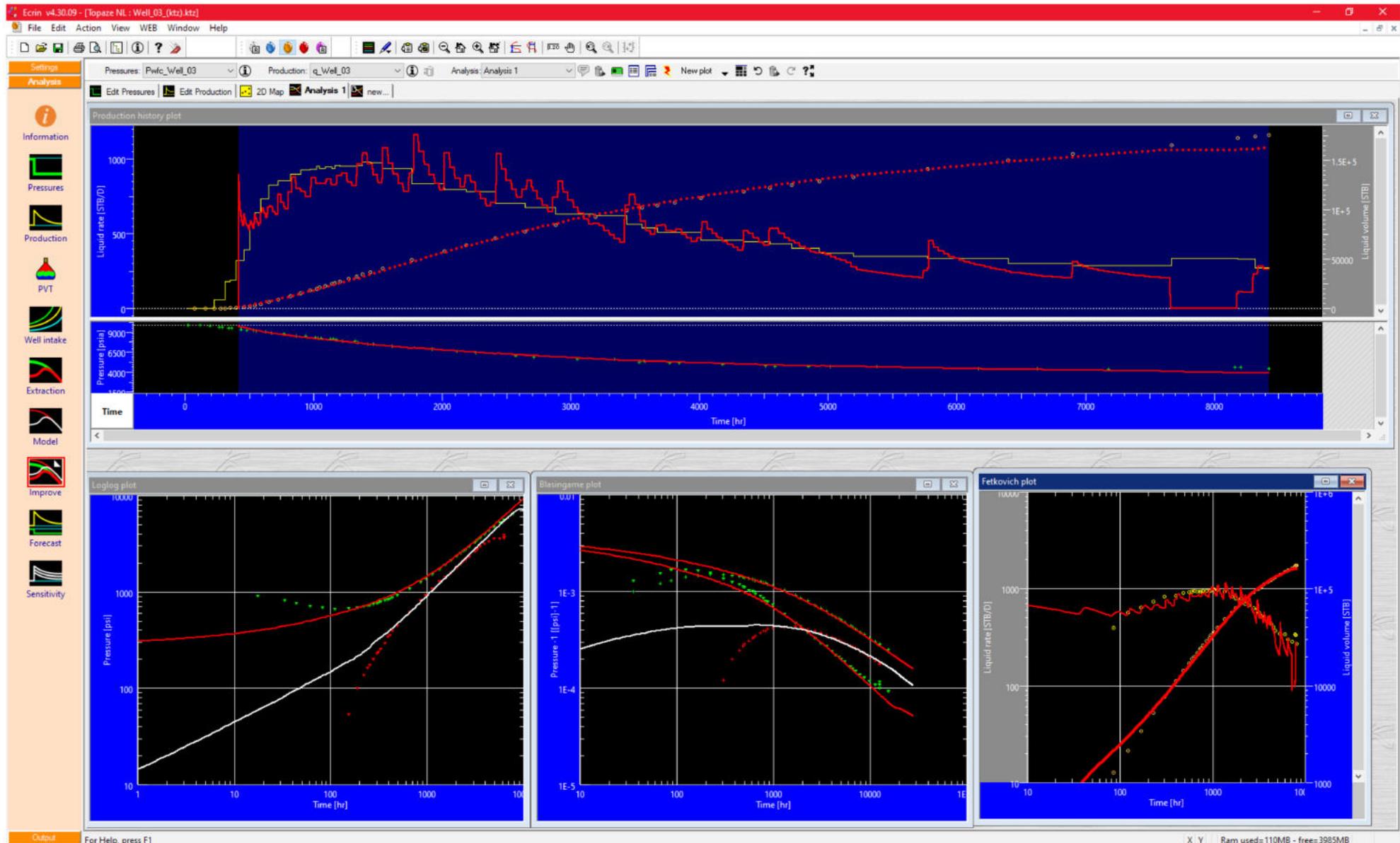
Discussion: (best fit of all data)
- All data are considered in the interpretations and analyses.
- Pressure match is excellent and rate data match is acceptable.
- Diagnostic plots show reasonable and representative trends.

RTA Plot (*Kappa Topaze v*4) — Vaca Muerta Example Well 03 (Oil)
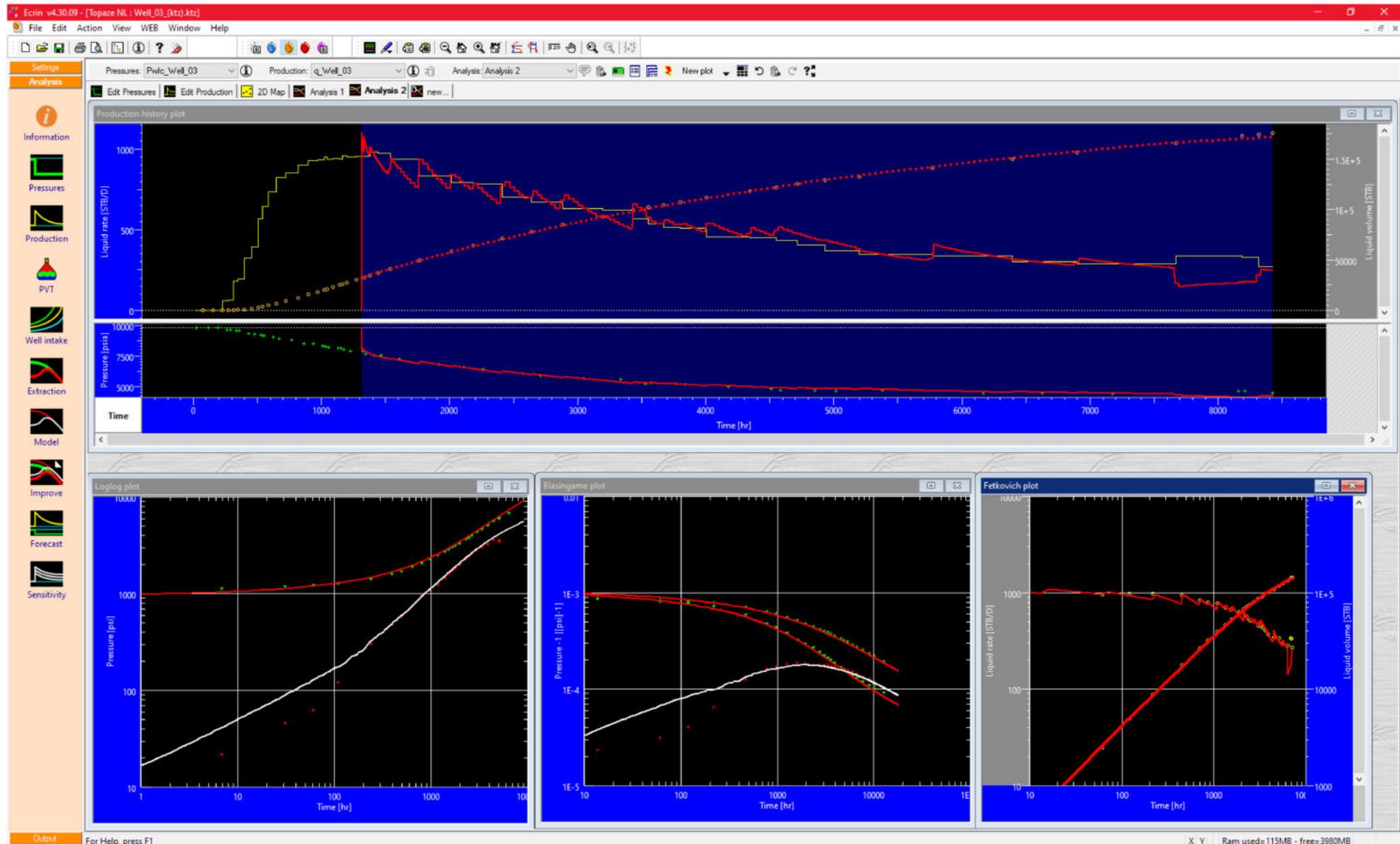
Discussion: (*better diagnostic trends*)
- Only declining rate data are used in this interpretation / analysis.
- Diagnostic plots are more robust when only declining rate data are used (for this case).
- (comment) This rendering may be better than trying to consider entire history.

qQ Plot (MH and PLE Models) — Vaca Muerta Example Well 03 (Oil)

Discussion:
- **The later-time oil rate profile in this case is also somewhat "exponential."**
- **Both DCA relations match the oil rate data equally well.**

PTA/RTA/DCA Methods for the Evaluation of Well Performance in Unconventional Reservoirs — Vaca Muerta Field Examples

Vaca Muerta Examples:
Well 04 (Oil)

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Production Summary Strip Plot — Vaca Muerta Example Well 04 (Oil)

Vaca Muerta Example Well 04 (Oil)
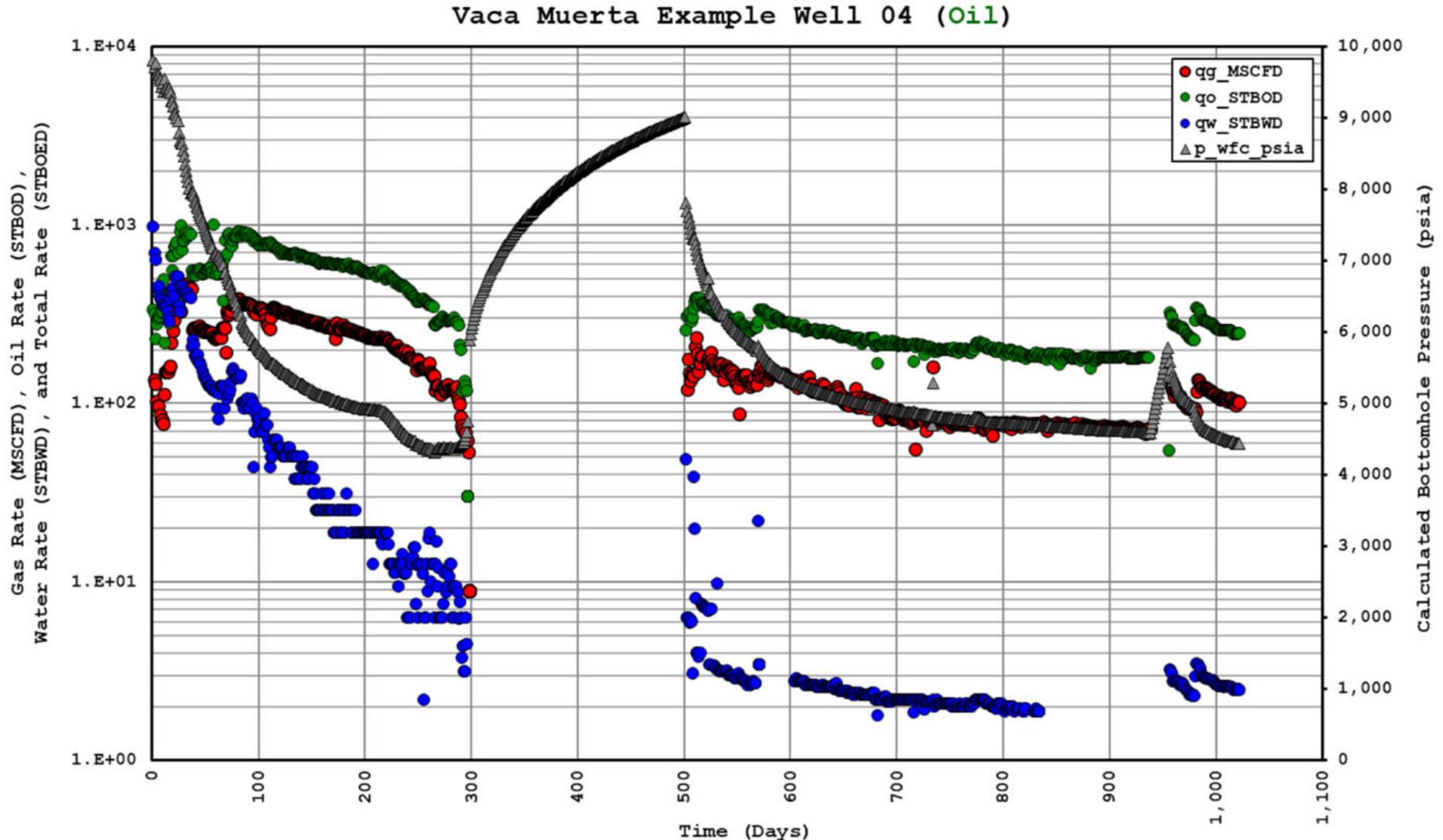
Discussion:
- All rate trends appear reasonable and relevant, the shut-in dominates the profile.
- Water rates show evidence of "allocation" in the 100-300 day timeframe.
- Interesting correlation of pressure with oil and gas rate data from 200-300 days.

RTA Plot (*Kappa Topaze v*4) — Vaca Muerta Example Well 04 (Oil)
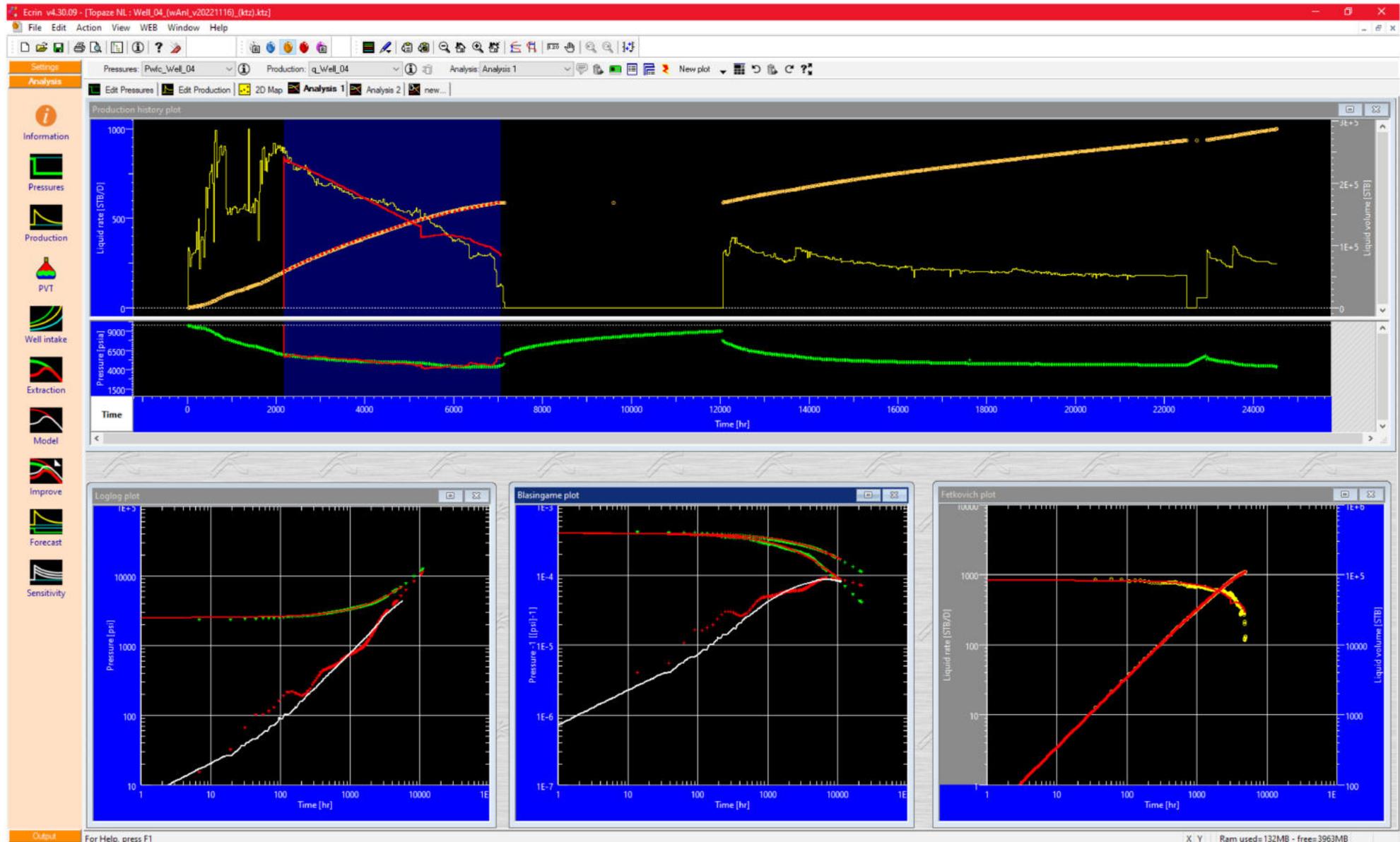
Discussion: (Fitting first sequence only)
- This analysis only considers the early portion of data (prior to the major shut-in).
- Diagnostic plots appear to be reasonable.
- Next slide will consider the interpretation and analysis of the entire production history.

RTA Plot (*Kappa Topaze v*4) — Vaca Muerta Example Well 04 (Oil)
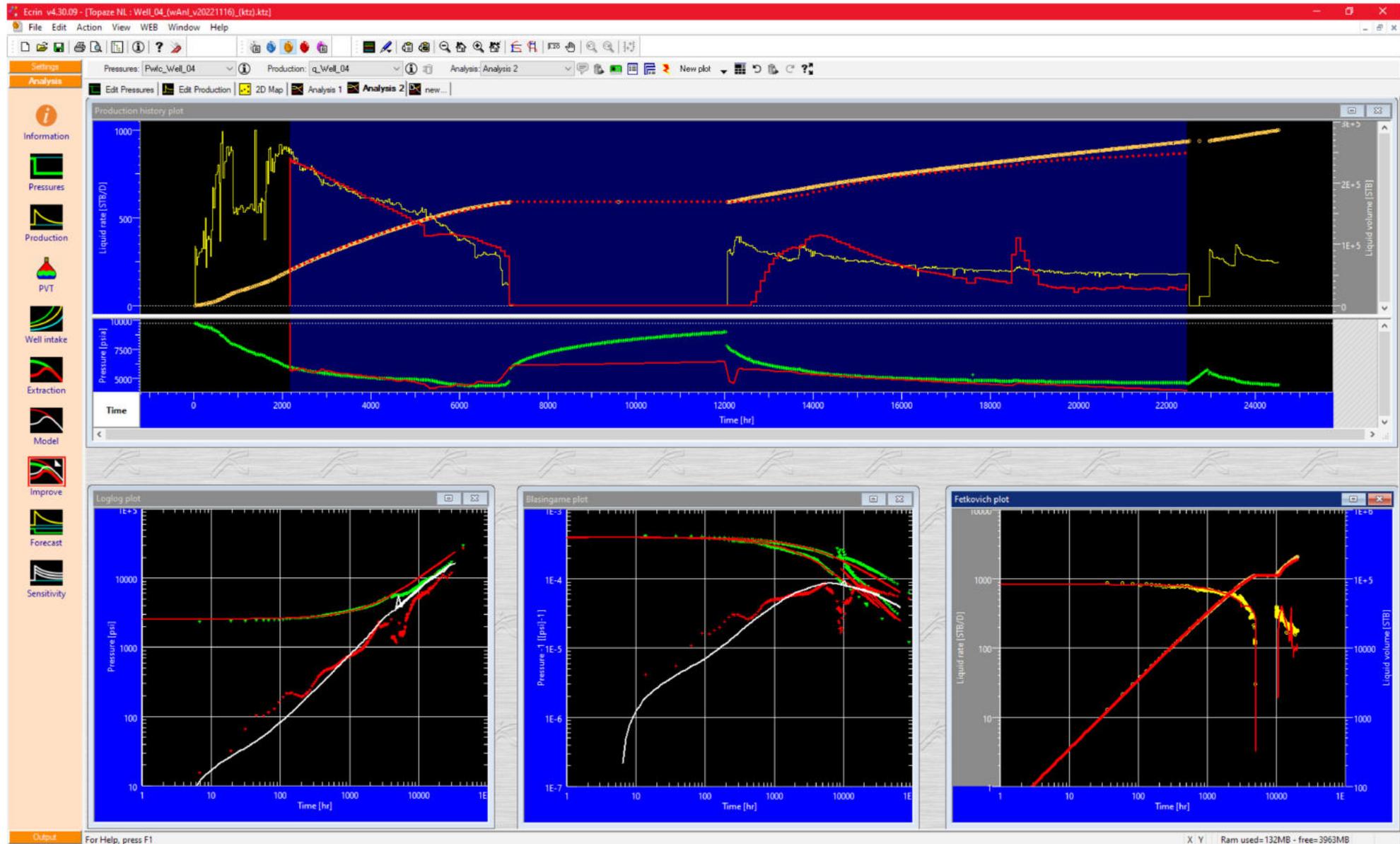
Discussion: (Expanding to all data)
- **This sequence considers the entire production history.**
- **The match of the later data essentially agrees with the earlier match, but is less robust.**
- **Trends evident on the diagnostic plots are reasonable (despite the shut-in).**

PTA Plot (*Kappa Sapphire v*4) — Vaca Muerta Example Well 04 (Oil)
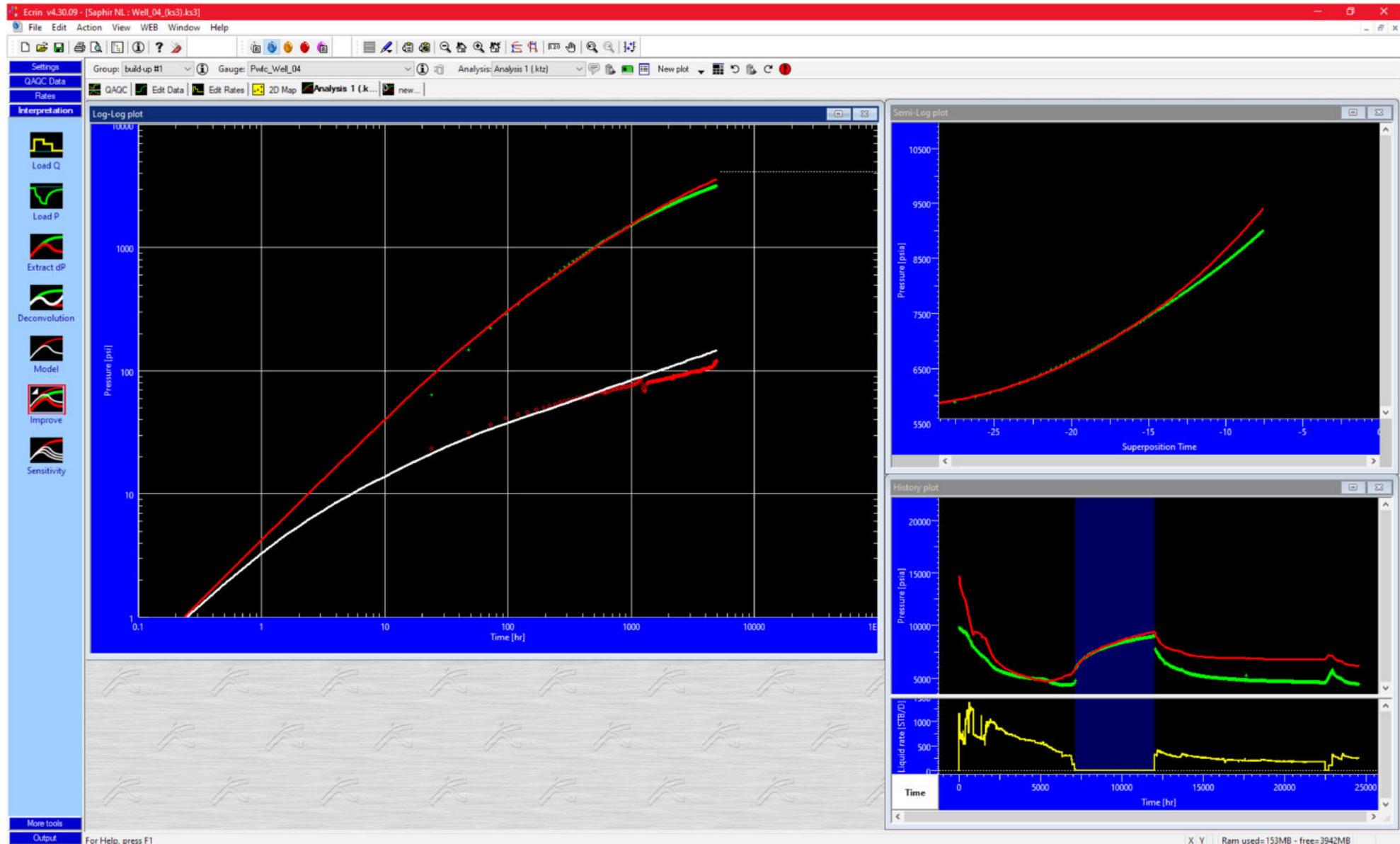
Discussion: (PTA is somewhat based on prior RTA, but also uses q_{tot})
- Match is NOT perfect, but it is much better than expected.
- Very little diagnostic character in pressure and pressure derivative functions.
- Used very low fracture conductivity to represent the behavior during shut-in.

qQ Plot (*MH and PLE Models*) — Vaca Muerta Example Well 04 (Oil)

Discussion:
- DCA (both relations) yields a reasonable match of the overall oil rate performance.
- Used actual time (as opposed to "time-on").

PTA/RTA/DCA Methods for the Evaluation of Well Performance in Unconventional Reservoirs — Vaca Muerta Field Examples

Vaca Muerta Examples:
Well 05 (Oil)

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Production Summary Strip Plot — Vaca Muerta Example Well 05 (Oil)

Vaca Muerta Example Well 05 (Oil)
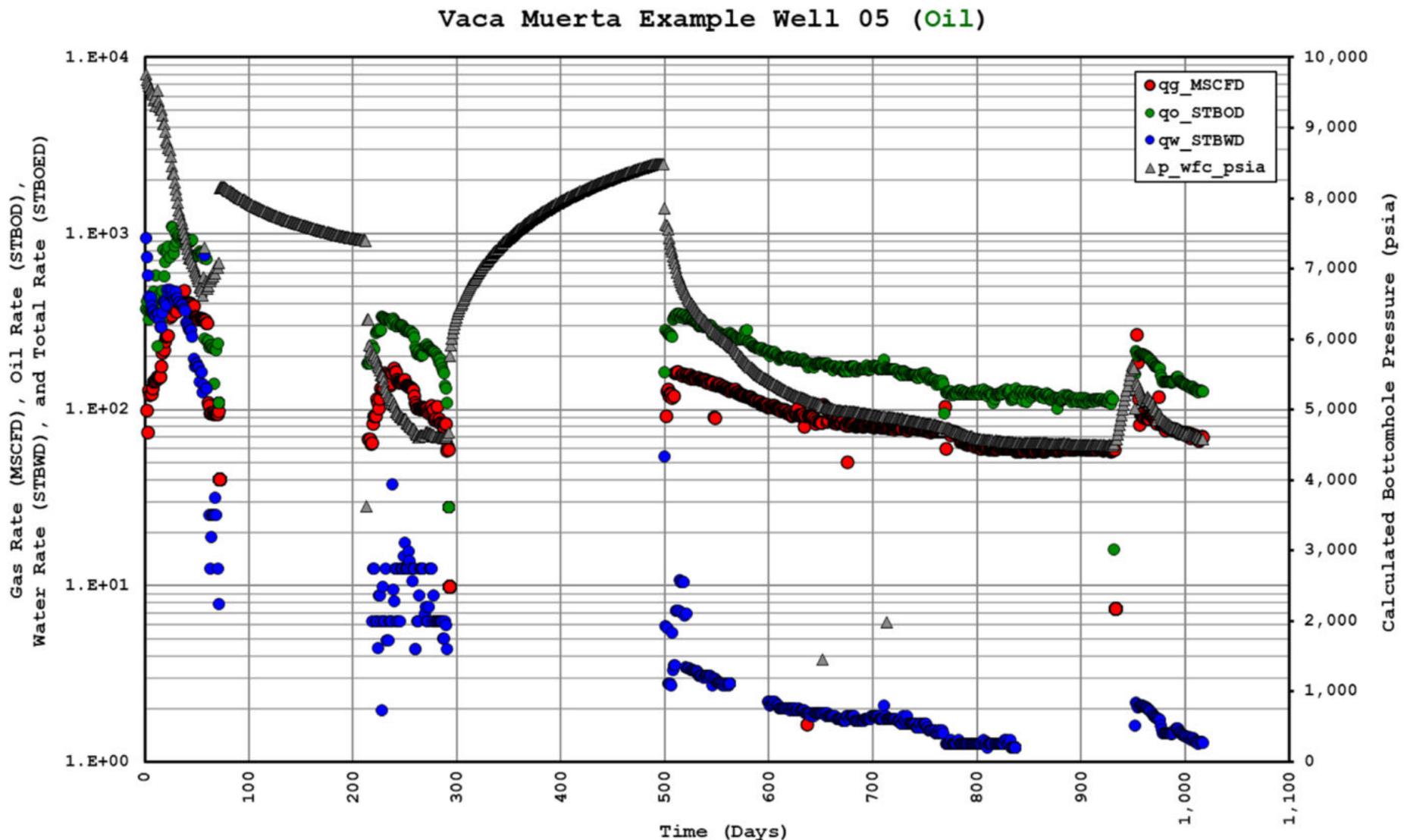
Discussion:
- Another case with major shut-ins, rates have a major improvement after 2nd shut-in.
- Rate and pressure trends seem reasonable, water rates after 1st shut-in are erratic.
- BHP data during the first shut-in are clearly erroneous (so were the surface pressures).

RTA Plot (*Kappa Topaze v*4) — Vaca Muerta Example Well 05 (Oil)
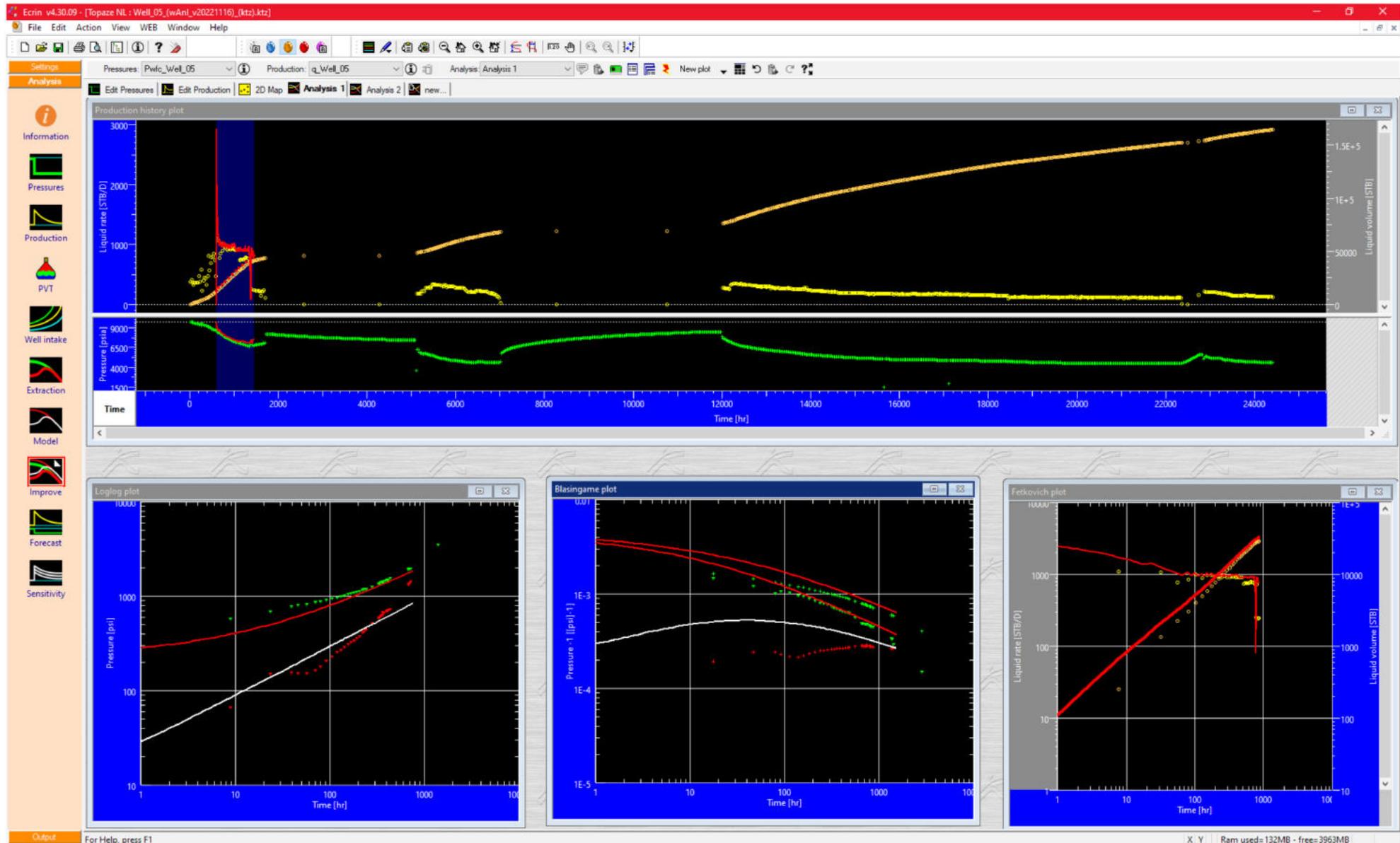
Discussion: (Fitting first sequence only)
- This is an attempt to use minimal data to characterize the production sequence.
- Diagnostic plots are reasonable (only about 50 days of data are used).
- Effort was made to match diagnostic behavior, but realistically, we need more history.

RTA Plot (*Kappa Topaze v*4) — Vaca Muerta Example Well 05 (Oil)
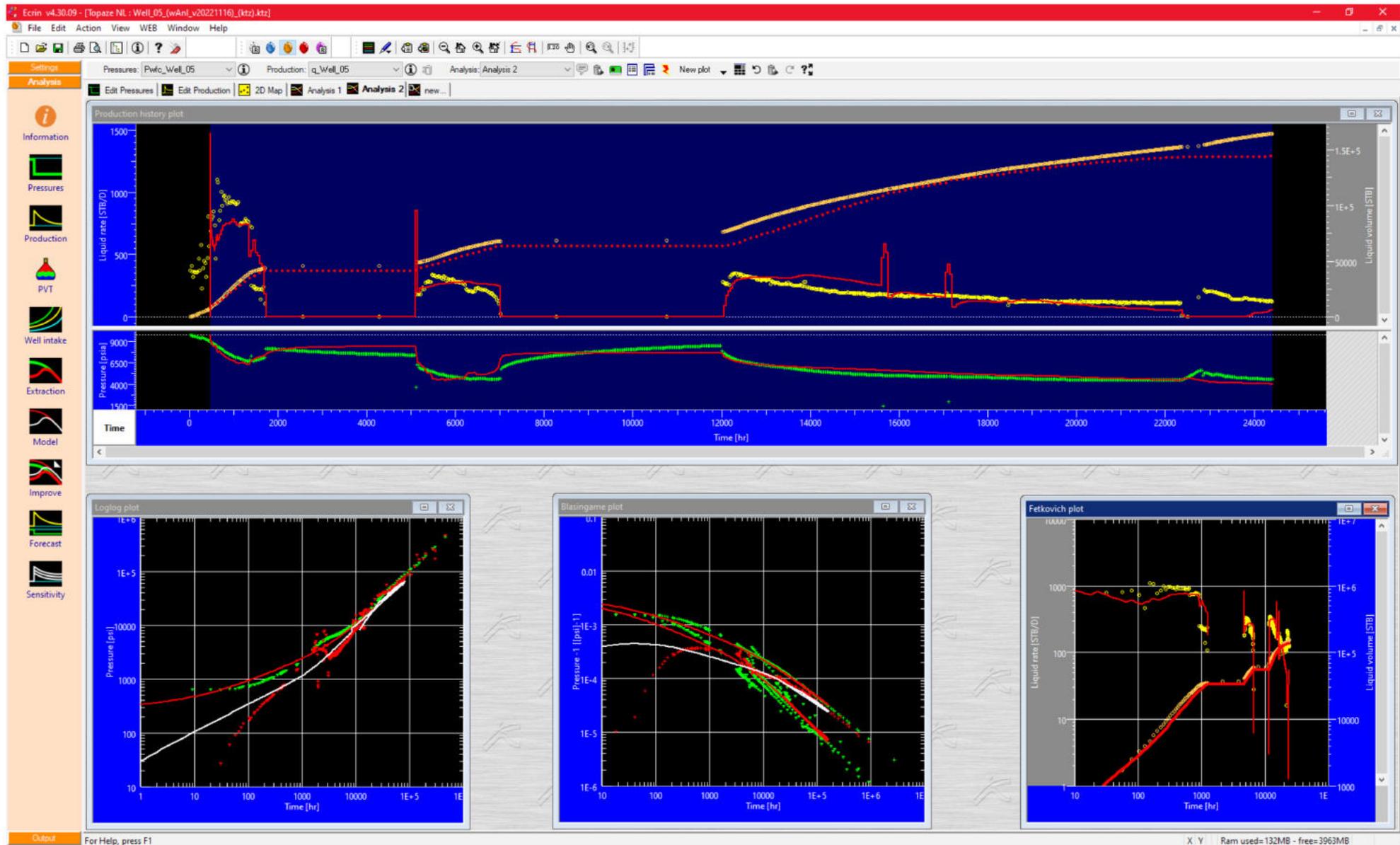
Discussion: (Expanding to all data)
- **Used initial (50-day) production match, extended to all data — acceptable match.**
- **Diagnostic functions are much better defined using the entire production history.**
- **Effect of shut-ins on diagnostic functions is substantial, but not overwhelming.**

PTA Plot (*Kappa Sapphire v*4) — Vaca Muerta Example Well 05 (Oil)
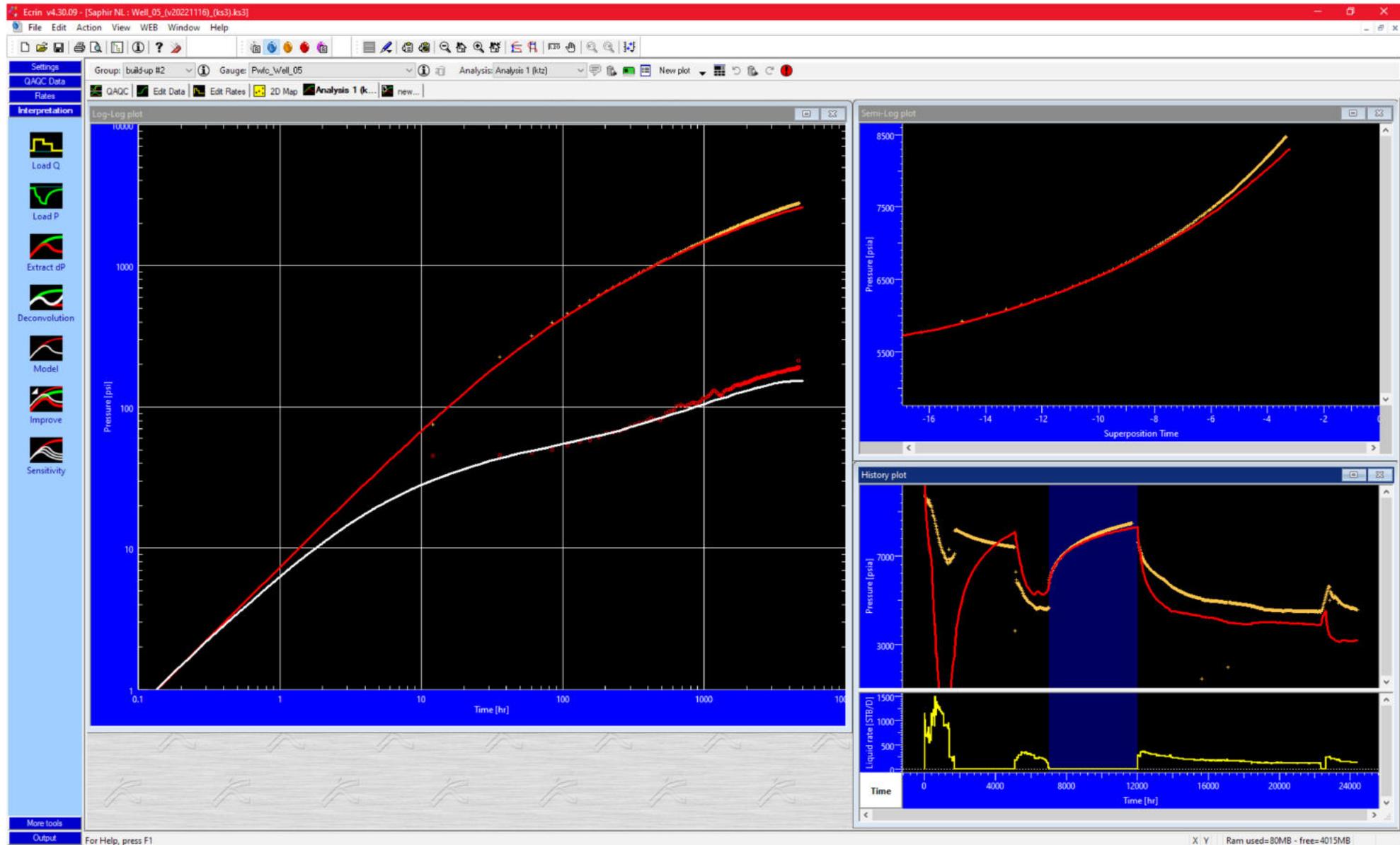
Discussion: (PTA is somewhat based on prior RTA, but also uses q_{tot})
- ● The PTA match of the 2nd shut-in is very good / excellent (log-log and summary plots).
- ● As noted earlier, the pressure history during the 1st shut-in is erroneous (wrong shape).
- ● Used the uniform flux (NOT the finite-conductivity) solution for the PTA history match.

qQ Plot (*MH and PLE Models*) — Vaca Muerta Example Well 05 (Oil)

Discussion:

- **About the best we can say is that the DCA proposed for the oil rates matches the early and late performance (we did not expect a match of the performance after the 1st shut-in given prior observations).**
- **Used actual time (not "time-on").**

PTA/RTA/DCA Methods for the Evaluation of Well Performance in Unconventional Reservoirs — Vaca Muerta Field Examples

Vaca Muerta Examples:
Well 06 (Oil)

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Production Summary Strip Plot — Vaca Muerta Example Well 06 (Oil)

Vaca Muerta Example Well 06 (Oil)
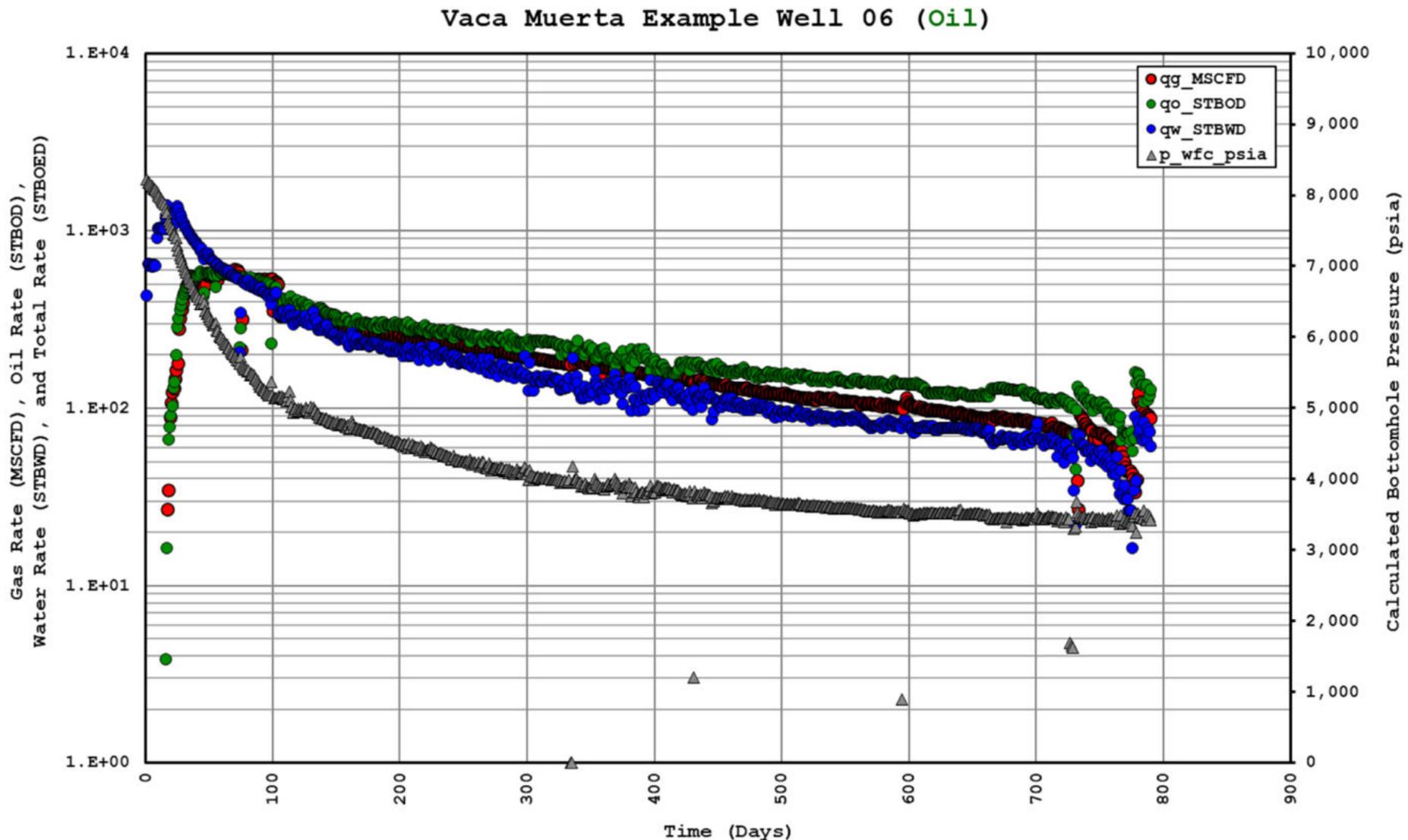
Discussion:
- Very good (of note excellent) well performance functions (rates and pressures).
- Early-time (choke-managed) performance will be challenging for DCA (as comment).
- Late-time performance appears to reflect operational considerations (artificial lift?).

RTA Plot (*Kappa Topaze v*4) — Vaca Muerta Example Well 06 (Oil)

Discussion:

- As expected, near-perfect matches of oil rate and BHP.
- Diagnostic plots were less well-defined when early-time performance was included.
- Only mis-match is a late times — again, most likely due to operational considerations.

qQ Plot (MH and PLE Models) — Vaca Muerta Example Well 06 (Oil)

Discussion:
- **As mentioned earlier, the choke-managed portion of the oil rate data at early-times is the only significant challenge for the DCA work.**
- **Both the Modified-Hyperbolic and the Power-Law Exponential DCA relations provide equiprobable interpretations and forecasts for this case.**

PTA/RTA/DCA Methods for the Evaluation of Well Performance in Unconventional Reservoirs — Vaca Muerta Field Examples

Vaca Muerta Examples:
Well 07 (Gas)

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Production Summary Strip Plot — Vaca Muerta Example Well 07 (Gas)

Vaca Muerta Example Well 07 (Gas)
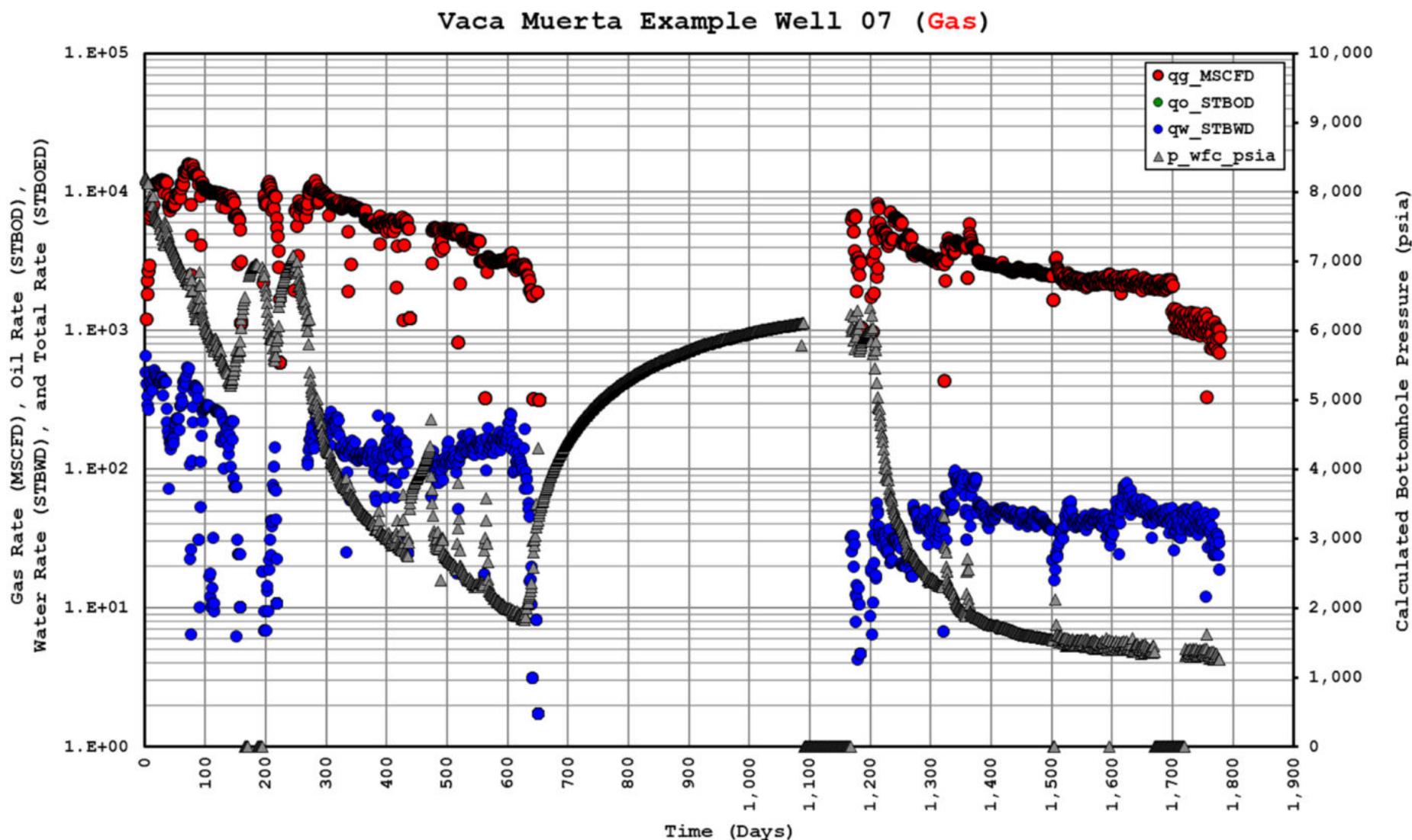
Discussion:
- Gas well case with single major shut-in (more than 450 days).
- Water and gas rates both suggest some liquid (water?) loading effects.
- Post-shut-in gas rate performance is much better, water rates do not recover.

RTA Plot (*Kappa Topaze v*4) — Vaca Muerta Example Well 07 (Gas)
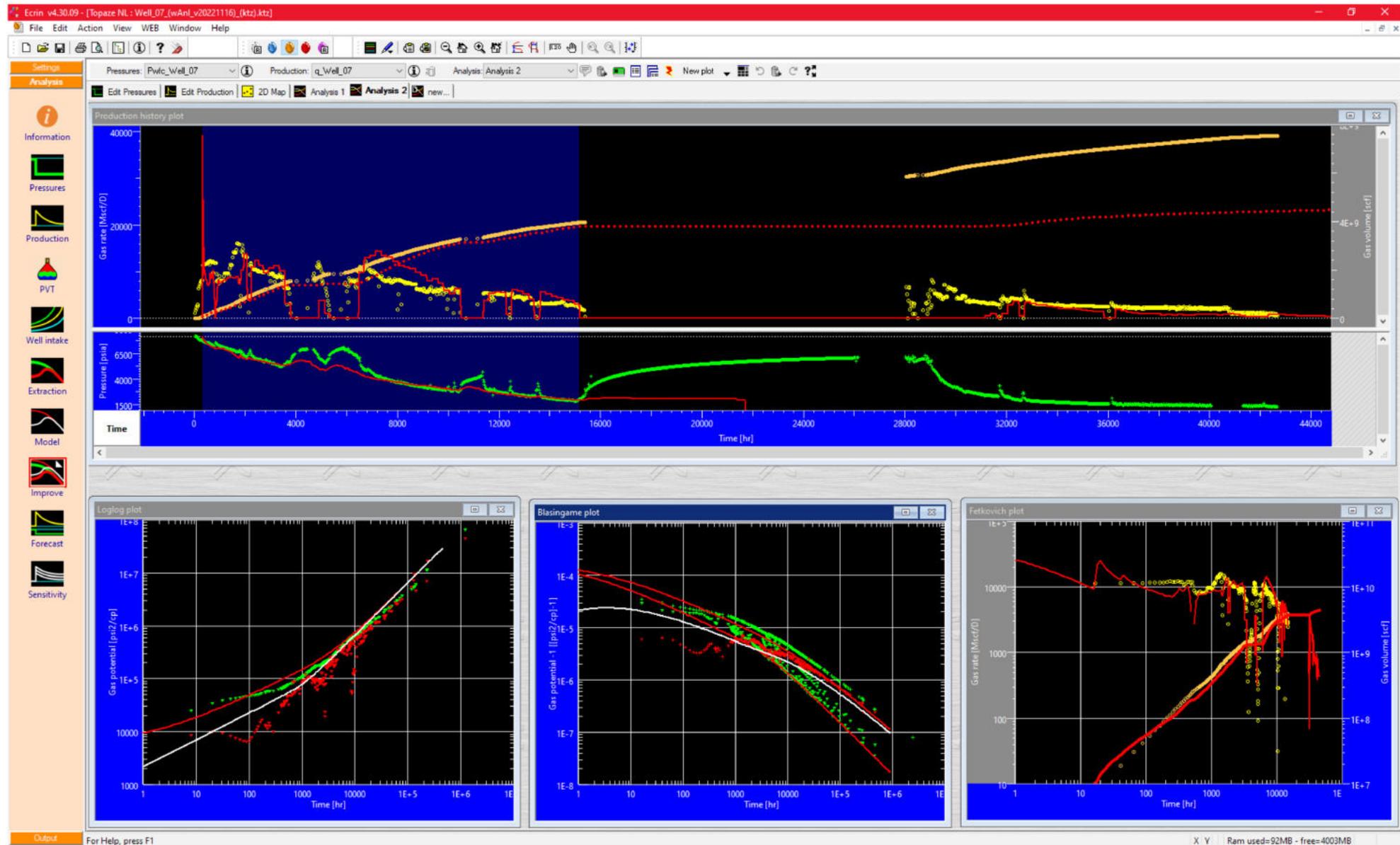
Discussion:
- **Focused on matching pre-shut-in performance (> 600 days of production).**
- **Did not match every feature (*e.g.*, short shut-ins), but good capture of most features.**
- **Extrapolation to post-shut-in performance is fair/acceptable (affected by water?).**

PTA Plot (*Kappa Sapphire v*4) — Vaca Muerta Example Well 07 (Gas)
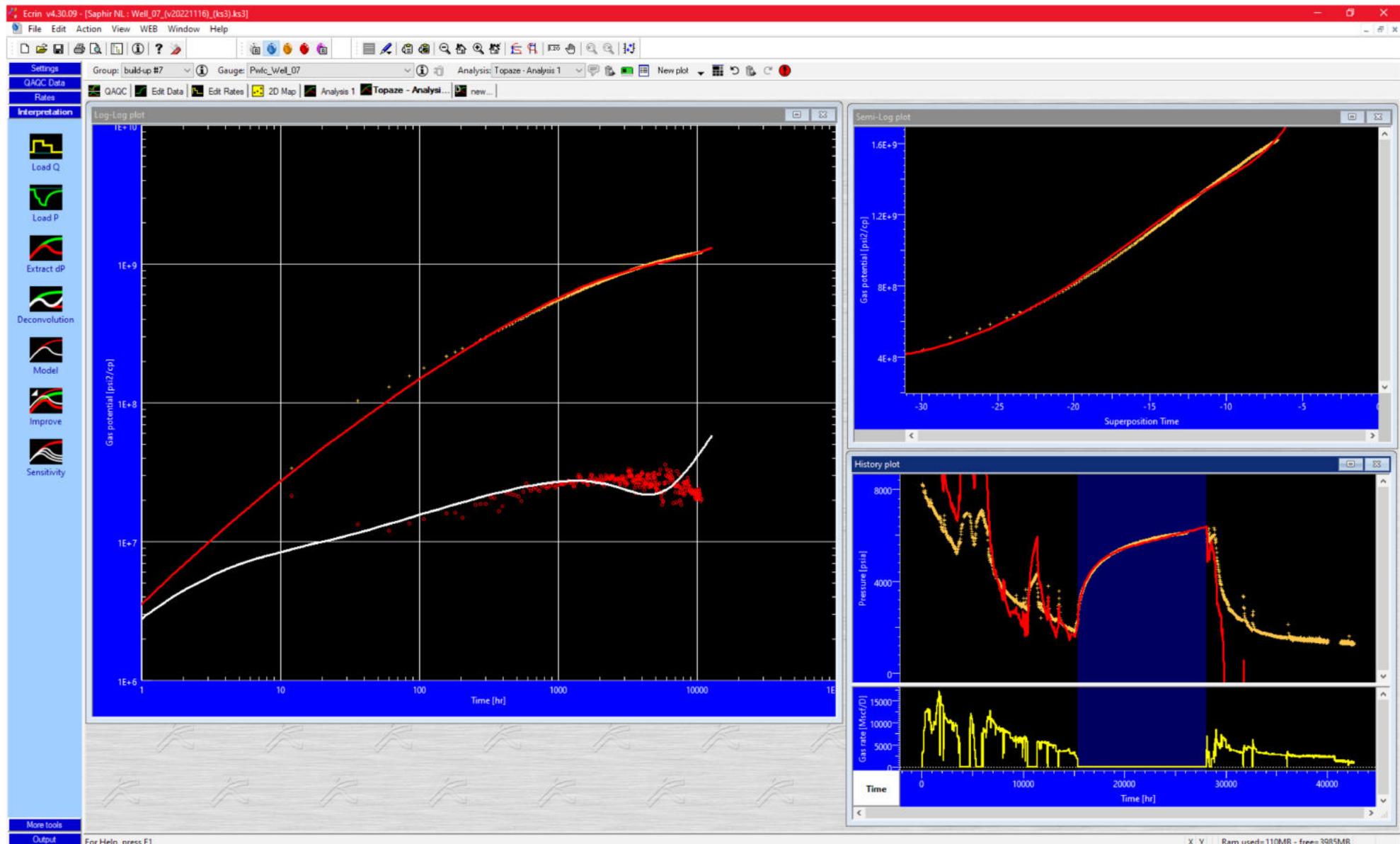
Discussion:

- **PTA match took considerable work, and we have a possible model artifact at late times.**
- **However … the matches of the shut-in (and pre-shut-in) pressures are excellent.**
- **Post-shut extrapolation of BHP is very poor (possible change in reservoir conditions).**

qQ Plot (*MH and PLE Models*) — Vaca Muerta Example Well 07 (Gas)

Discussion:

- **Given inspection of the semi-log rate plot (above), we should expect an exponential trend of pre-shut-in gas rate performance.**
- **Both DCA models yield an essentially exponential match of the pre-shut-in gas rate performance.**
- **Did not attempt a post-shut-in gas rate DCA match (not the purpose of this work).**

PTA/RTA/DCA Methods for the Evaluation of Well Performance in Unconventional Reservoirs — Vaca Muerta Field Examples

Vaca Muerta Examples:
Well 08 (Oil)

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Production Summary Strip Plot — Vaca Muerta Example Well 08 (Oil)

Vaca Muerta Example Well 08 (Oil)
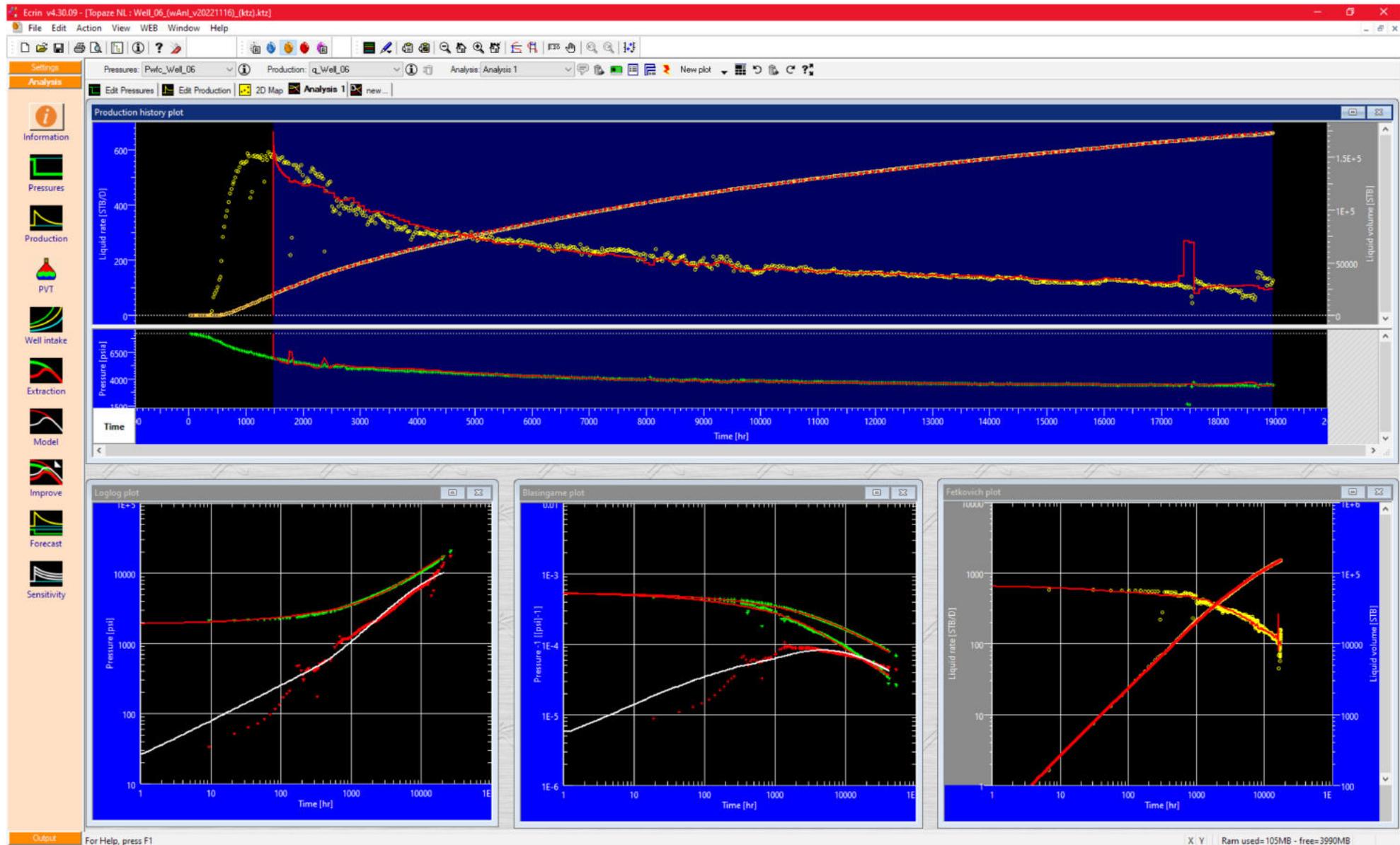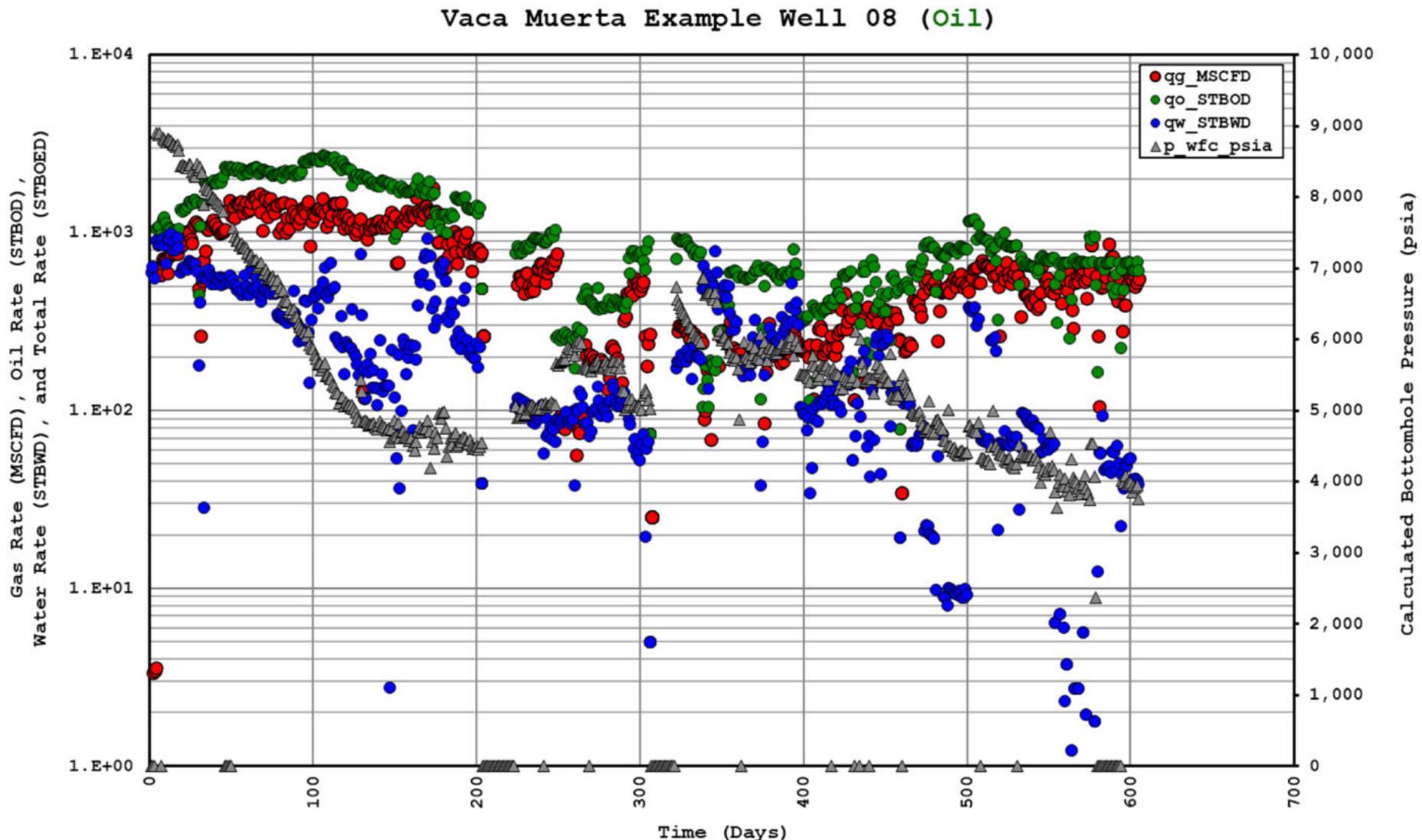
Discussion:
- Despite initial reaction, the oil, gas, and water trends are reasonably well-correlated.
- Water performance change for *t* > 330 days warrants more information (operations?).
- Pressure performance data seem reasonable / representative.

RTA Plot (*Kappa Topaze v*4) — Vaca Muerta Example Well 08 (Oil)
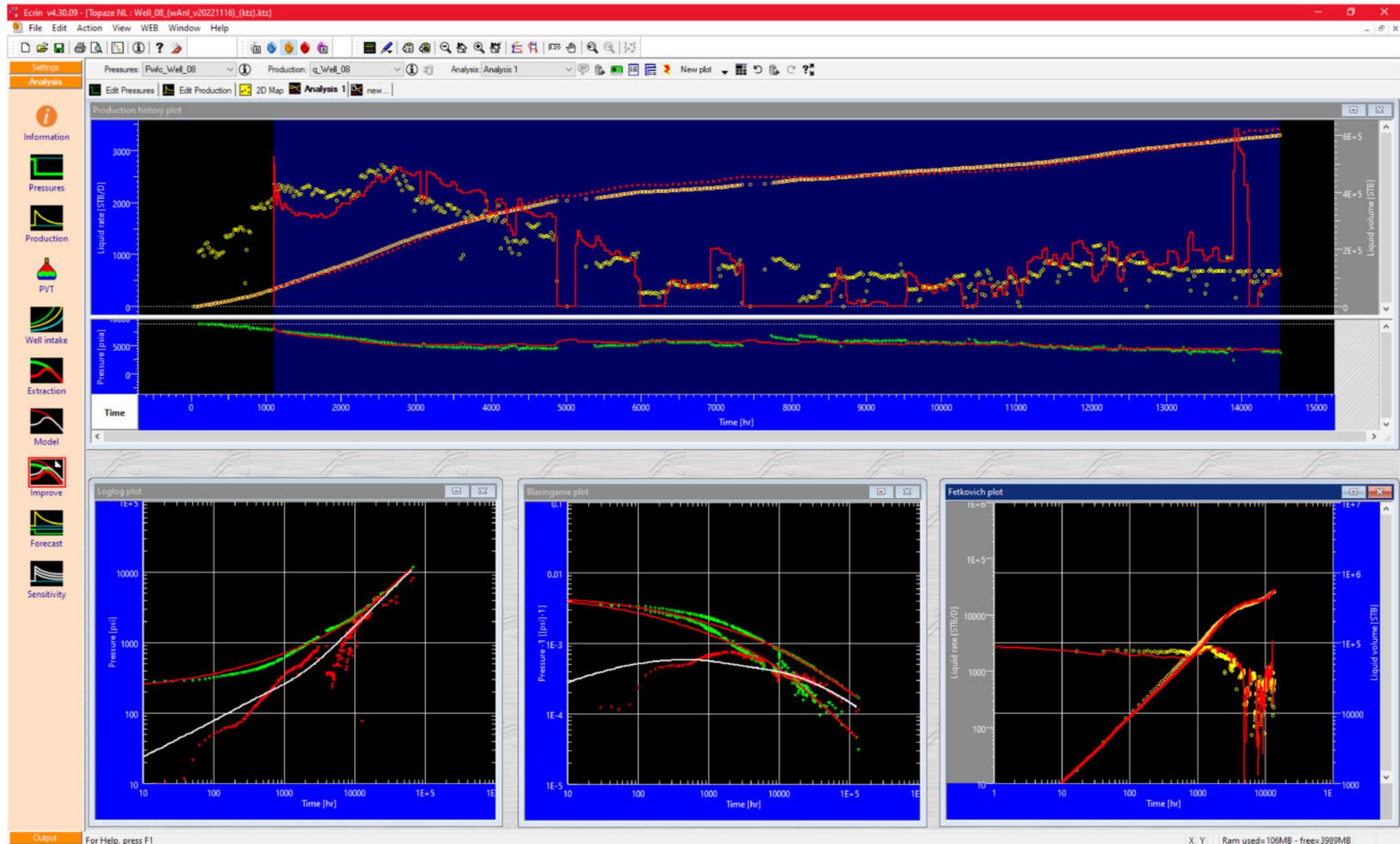
Discussion:

- Despite the apparent data noise and oscillations, diagnostic plots are very good.
- History match of oil rate and BHP is excellent (considering data noise / oscillations).
- This case illustrates value of RTA methodology.

qQ Plot (MH and PLE Models) — Vaca Muerta Example Well 08 (Oil)

Vaca Muerta Example Well 08 (Oil)
(Modified Hyperbolic and
Power-Law Exponential Rate Relations]

Vaca Muerta Example Well 08 (Oil)
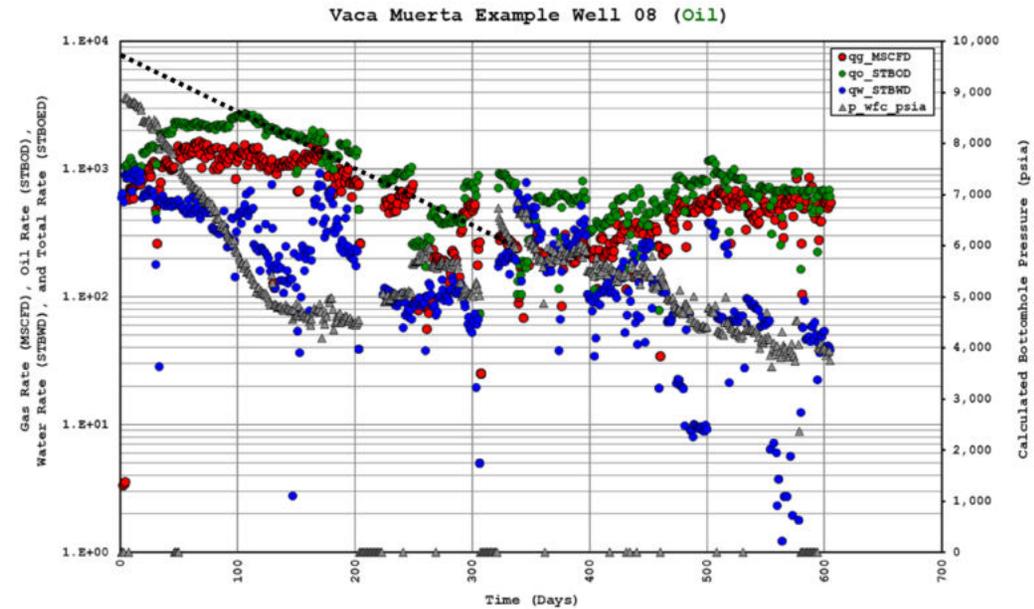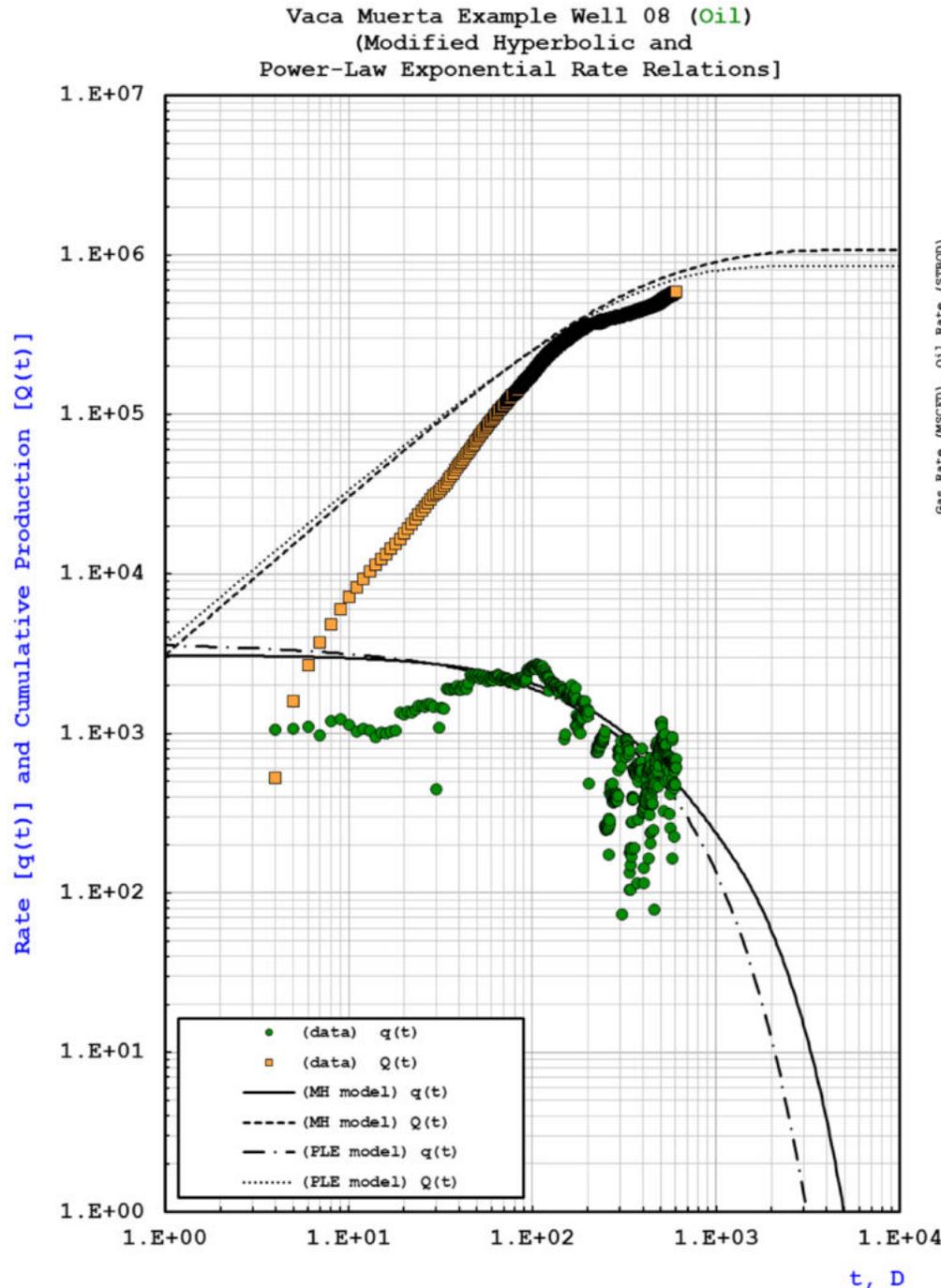
Discussion:
- **Given the observed nature of the oil rate and BHP performance, the DCA matches for this case were destined to be problematic (oscillations in pressure).**
- **From the semilog plot, oil rate is approximately exponential from 100-300 days — this is confirmed in the DCA work shown on the log-log plot.**

PTA/RTA/DCA Methods for the Evaluation of Well Performance in Unconventional Reservoirs — Vaca Muerta Field Examples

Have We "Hit a Wall" with PTA / RTA / DCA for Unconventional Reservoirs

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Have We "Hit a Wall" with PTA / RTA / DCA for Unconventional Reservoirs

Data:
- Rates $\qquad = f(t)$
- Pressures $\qquad = f(t)$
- Temperature $\qquad = f(t)$ **(?)**
- Other variables $\qquad = f(t)$ **(?)**

Diagnostics:
- *"Its just rate & pressure data…"*
- What we have tried so far:
  - Integration (cumulative)
  - 1st derivative
  - 2nd derivative
  - Laplace Transform
  - Splines
  - Averaging
  - Outlier rejection
  - Regularization, etc.
- What's Next?
  - Data proxies? (wavelets?)
  - Back to basics? (graphics?)

Data Analytics:
- "Exhaustive" data sets.
- "Selected" data sets.

Models:
- DCA: (*"more Arps than science"*)
  - $b(t)$ models $\qquad$ (*many*)
  - $D(t)$ models $\qquad$ (*several*)
  - Statistical models $\qquad$ (*several*)
  - Hybrid models $\qquad$ (*several*)
  - Semi-analytical models $\qquad$ (*a few*)
  - Analytical models $\qquad$ (*several*)
  - Ouija board models $\qquad$ (*a few*)
- PTA:
  - PTA in unconventionals $\qquad$ **(?)**
  - More proxy models $\qquad$ (power-law?)
  - Focus on well interference?
- RTA:
  - More focus on multiphase models?
  - Additional diagnostic concepts?
  - More "deconvolution" type efforts?
  - Multi-well analysis? (incl. interference)

What Does the Industry Want:
- A "simple" (and direct) RTA approach.
- Distinct diagnostics (flow regimes!).
- An RTA proxy that will "fit everything."
- Multi-well diagnostics / interpretations.

PTA/RTA/DCA Methods for the Evaluation of Well Performance in Unconventional Reservoirs — Vaca Muerta Field Examples

Questions I Might Ask if I Were in the Audience

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Questions I Might Ask if I Were in the Audience

Q-1. What does "linear flow" mean on an RTA or PTA diagnostic plot?

Q-2. Which DCA relation is "best" and why?

Q-3. Why don't we use RTA on every case where we perform DCA?

Q-4. Why is there often a "change" observed after a long-term shut-in?

Q-5. Can we create a "hybrid" DCA-RTA approach which would include BHP?

PTA/RTA/DCA Methods for the Evaluation of Well Performance in Unconventional Reservoirs — Vaca Muerta Field Examples

Brief Biography — Tom Blasingame

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Brief Biography — Tom Blasingame

Role:
- Professor, Texas A&M U.
- B.S., M.S., & Ph.D. from Texas A&M U.

Counts: (Since 1991)
- Over 190 Technical Articles
- 17 Ph.D. Graduates
- 78 M.S. (thesis)/37 M.Eng. (report) Graduates

[2019]
(removed overalls straps for photo)

[2019]
(China visa photo)

[self-image]
(2008)

[how others see me]

Historical Technical Contributions:
- (1980's) Material Balance DCA ("Rate Transient Analysis" (or RTA))
- (1990's) Analysis of Water-Oil-Ratio (WOR) Behavior
- (1990's) Direct Estimation of pavg from Pressure Buildup Tests
- (2000's) Pressure Integral and b-Derivative for PTA and RTA Methodologies
- (2000's) DCA and CEUR Relations for Unconventional Reservoirs
- (2010's) Diagnostic Analysis of Time-Rate Data (i.e., the qDb-plot)
- (career) Correlations for Rock and Fluid Properties
- (career) Deconvolution Methods (approximate, direct, and numerical)

Historical Professional Recognition:
- SPEi Distinguished Member (2000)
- SPEi Distinguished Service (2005)
- SPEi Uren Award (2006)
- SPEi Lucas Medal (2012)

- SPEi DeGolyer Service Medal (2013)
- SPEi Distinguished Faculty Award (2014)
- SPEi Honorary Member (2015)
- SPEi Director (Reservoir) (2015-2018)
- SPEi 2021 President (2019-2022)

Research Interests: (2022)
- Time-Rate (DCA) Decline Analysis
- Time-Rate-Pressure (RTA) Diagnostics
- Time-Pressure (PTA) Diagnostics

- Production/Completion Correlations
- Numerical Analysis/Interpretation of Data
- Analytical Solutions for Reservoir Behavior

PTA/RTA/DCA Methods for the Evaluation of Well Performance in Unconventional Reservoirs — Vaca Muerta Field Examples

Extra Materials

Miscellaneous Thoughts on Field Development Strategies

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Field Development Strategies
— Field-Derived Example of Well Performance Degradation (concept example)

EUR (30 Yr) versus Well Spacing

$$EUR_{30Yr} = EUR_{max}\left[1 - A_1 \exp\left[-\frac{1}{A_2}\,\text{WellSpacing}\right]\right]$$

EUR$_{max}$ for each geology.

Legend:
— Case 1 (best geology)
— Case 2 (to be used as reference case)
— Case 3 (poorest geology)

Dimensionless EUR versus Dimensionless Well Spacing

$$\frac{EUR_{30Yr}}{EUR_{max}} = 1 - A_1 \exp\left[-\frac{1}{A_2}\,\text{WellSpacing}\right]$$

Reference Curve
(all cases matched to this curve)

Dimensionless Well Spacing = Nominal Well Spacing/A_2

$$EUR_{30Yr} = EUR_{max}\left[1 - A_1 \exp\left[-\frac{1}{A_2}\,\text{WellSpacing}\right]\right]$$

$$\frac{EUR_{30Yr}}{EUR_{max}} = 1 - A_1 \exp\left[-\frac{1}{A_2}\,\text{WellSpacing}\right]$$

Discussion:
- Same concept as multi-well simulation study.   [*uses field "spacing tests"*]
- Degradation = *f*(completion, well placement/spacing, drawdown)[*geology = major factor*]
- Normalization is "conceptual." [*directionally supported by data from field spacing tests*]

Field Development Strategies
— Analysis of Well Performance
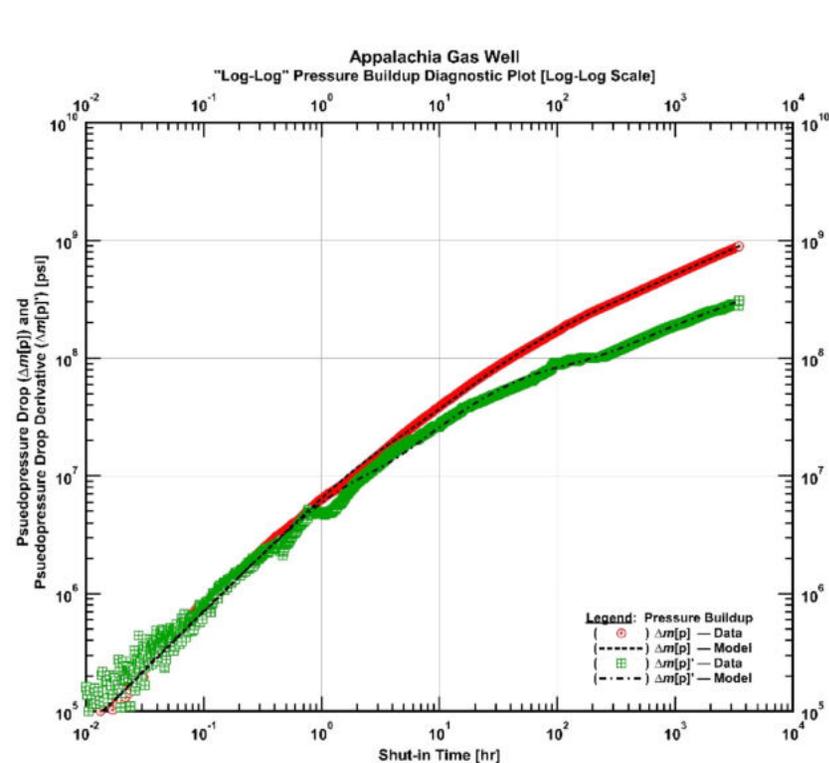
PTA Plot for Appalachia Gas Well (>5 months shut in).
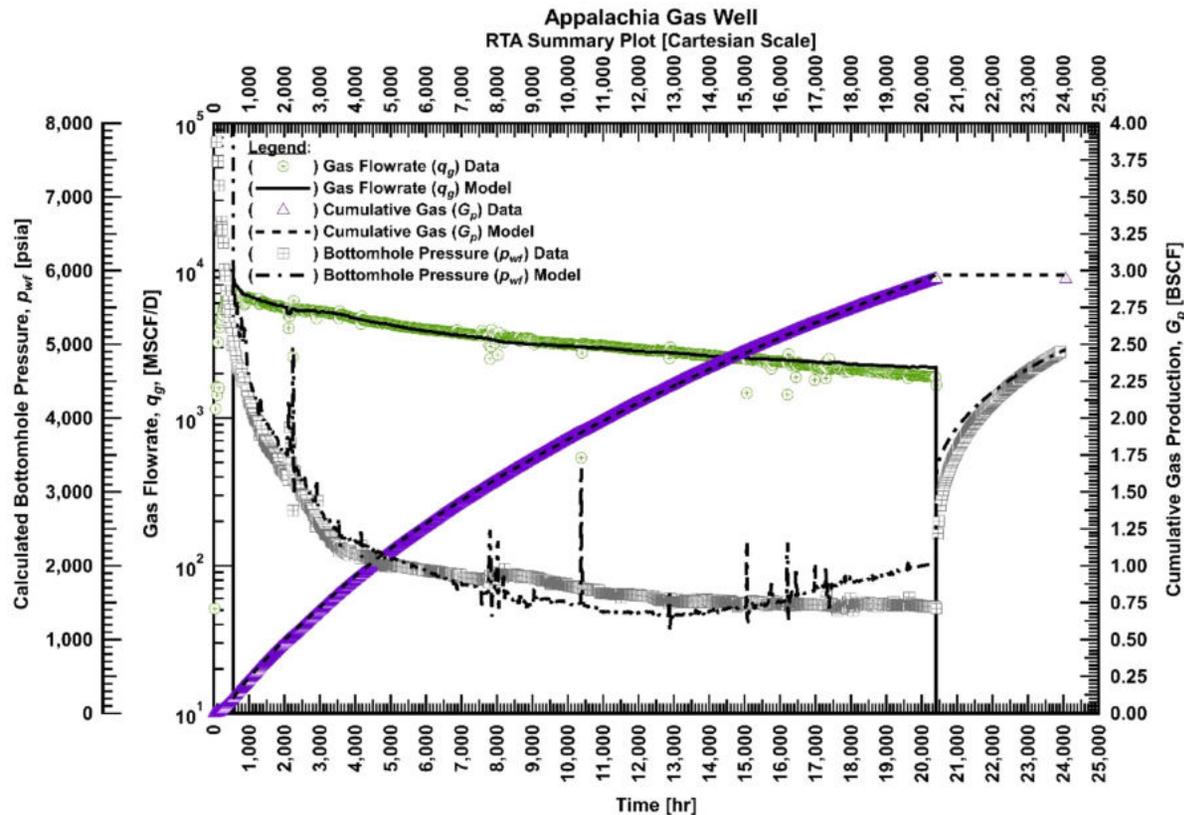
RTA Summary Plot for Appalachia Gas Well.
(production history-match plot)

Discussion:
- Unique PTA case, more than 5 months of high frequency/high resolution BHP data.
- Good RTA case, slight mismatch in BHP (less so in gas flowrate) at about 2 years.
- This case is an excellent "data quality" example.

Multi-Well RTA — A Few Good(?) Thoughts (2022)

1-, 2-, 3-Well Interference Cases

Base/Reservoir:

p_i	= 5000	psia
h	= 300	ft
ϕ	= 0.05	fraction
r_w	= 0.25	ft

PVT:

B_o	= 1.0	RB/STB
μ_o	= 0.5	cp
c_t	= 20×10^{-6}	psia-1

Model Properties:

k	= 5×10^{-5}	md
L_{well}	= 5000	ft
n_{frac}	= 50	
x_f	= 250	ft

Δp (psi)

Δp_d (psi)

Δp_{bd} (dimensionless)

Legend:
- Dp_1Well
- Dp_2Well
- Dp_3Well
- Dpd_1Well
- Dpd_2Well
- Dpd_3Well
- Beta_1Well
- Beta_2Well
- Beta_3Well

1-Well Case   2-Well Case   3-Well Case

Y-axis: Δp (psi), Δp_d (psi), and $\Delta p_{\beta d}$ (dimensionless)

X-axis: **Production Time (hr)**

β-Derivative: Definition

$$\Delta p_{\beta d}(t) = \frac{d\ln(\Delta p)}{d\ln(t)}$$

$$= \frac{1}{\Delta p} t \frac{d\Delta p}{dt}$$

$$= \frac{\Delta p_d(t)}{\Delta p}$$

Function: (power-law)

$$\Delta p(t) = at^b$$

Derivative: (power-law)

$$\Delta p_d(t) = t\left[b\ at^{(b-1)} \right]$$

$$= b\left[at^b \right]$$

$$= b\ \Delta p(t)$$

β-Derivative: (power-law)

$$\Delta p_{\beta d}(t) = \frac{\Delta p_d(t)}{\Delta p(t)} = b$$

(slope of power-law trend)

Necessary Components: Multi-Well Model
- Model must be robust (accurate and representative).
- Model must reproduce flow regimes. (diagnostics)
- Model must exhibit well interference effects.
- Model must be fast (for regression + modelling)

Likely Challenges: (feel free to add more)
- Interference features can be (very) subtle. (see figure)
- Multiphase flow effects.
- Dual porosity / naturally fractured reservoir effects.
- Faults and other heterogeneities.

Discussion:
- Need an RTA proxy model that will "match anything" (from an SPE ATW in 2022).
- Use for diagnostics, interpretation, analysis AND for forward modelling.
- High resolution flowrates and very accurate BHP measurements required.

PTA/RTA/DCA Methods for the Evaluation of Well Performance in Unconventional Reservoirs — Vaca Muerta Field Examples

Extra Materials

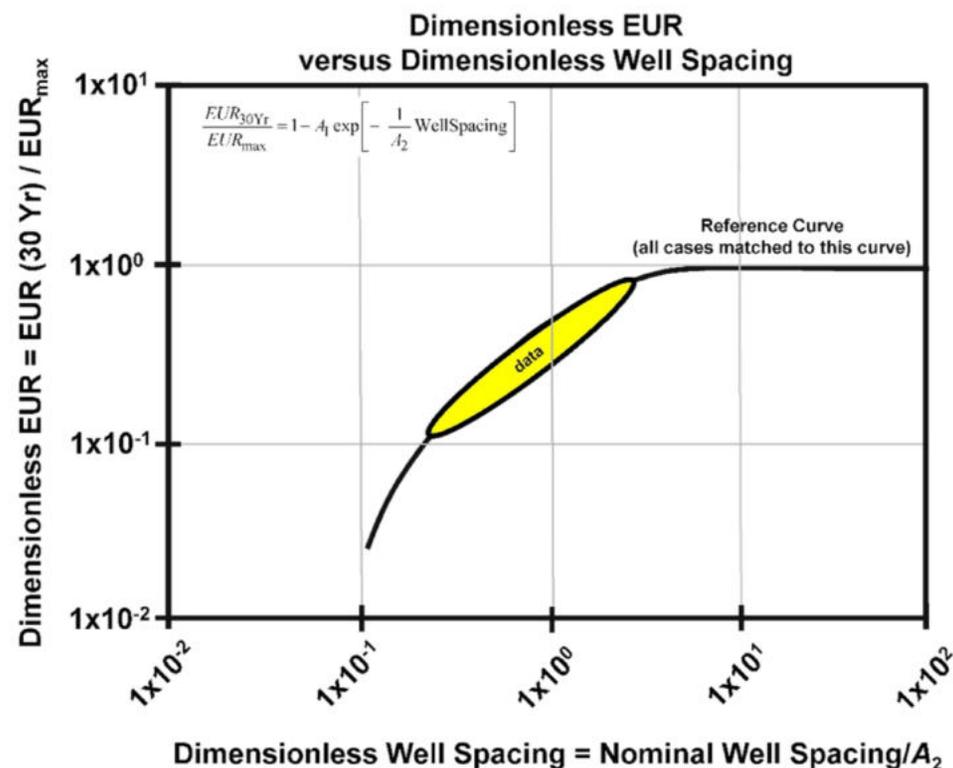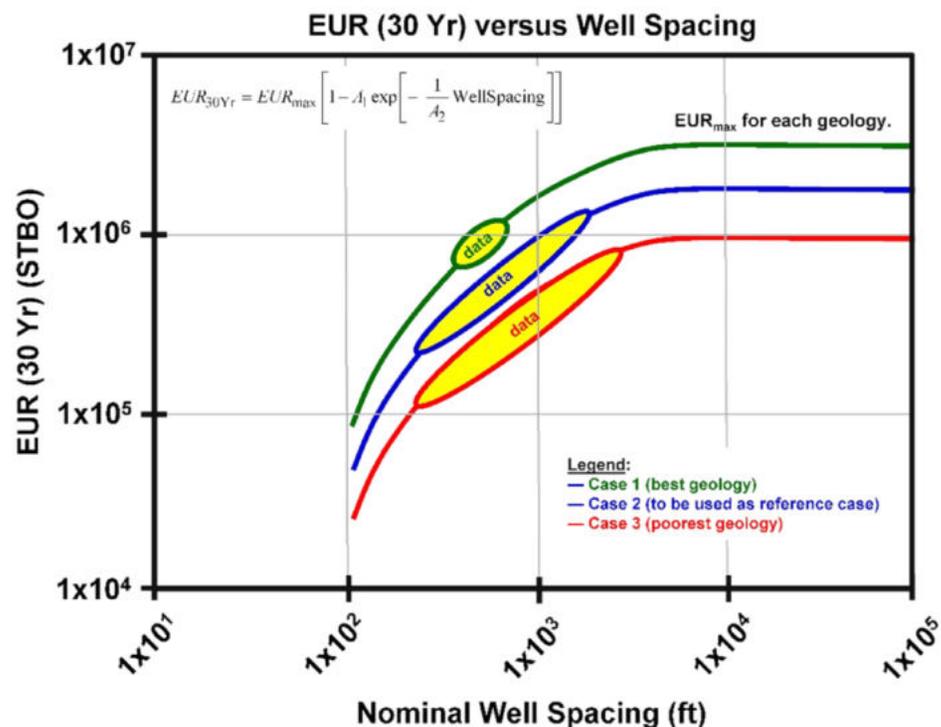## *Thoughts on Production Data Used for Reservoir Engineering in Unconventionals*

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Production Data Analysis — What can we do to our data?

Data Operations:

- **Auxiliary functions:**
  - — **Productivity Index**
  - — **Time root functions**
  - — **Other normalizations**
- **Smooth the Data:**
  - — **Averaging**
  - — **Wavelets**
  - — **Splines (probably a bad idea)**
- **Calculus:**
  - — **Integration (cumulative)**
  - — **1st derivative**
  - — **2nd derivative**
- **Mathematical Transforms:**
  - — **Laplace Transform**
  - — **Other transform(s)**
- **AI algorithms:**
  - — **Outlier rejection**
  - — **Training models**
  - — **…**

Discussion: What can we do to our data?
- **(advice) Do not "over-smooth" data.**
- **(advice) Do not "over-edit" data.**
- **There is a balance, must maintain data fidelity.**

Base Rate and Pressure Data
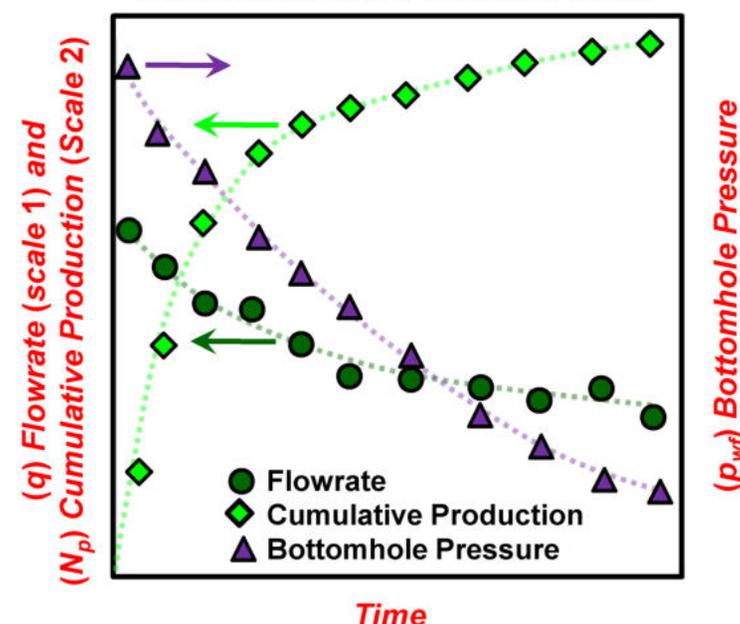
(*Simple*) RTA "Diagnostic" Plot
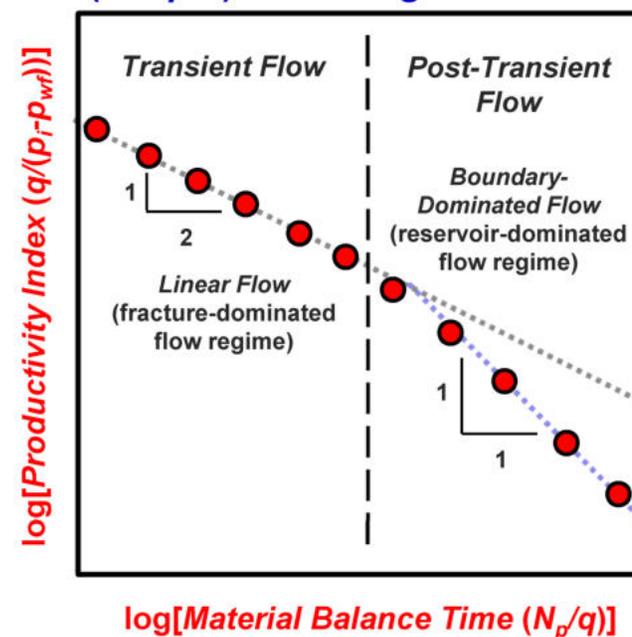
Production Data Analysis — Basic Data and Diagnostic Plots

Base Rate and Pressure Data

(q) Flowrate (scale 1) and (N_p) Cumulative Production (Scale 2)

Time

- ● Flowrate
- ◆ Cumulative Production
- ▲ Bottomhole Pressure

Data Editing Plot

(p_{wf}) Bottomhole Pressure

(q) Flowrate

Time

- ● Retained (*Unrejected*) Data
- ● Edited (*Rejected*) Data
- –·– Outlier Rejection Limits

Square Root Time Plot

Reciprocal Productivity Index $(p_i\text{-}p_{wf})/q$

Linear Flow | *Post-Linear Flow*

Linear Flow (fracture-dominated flow regime)
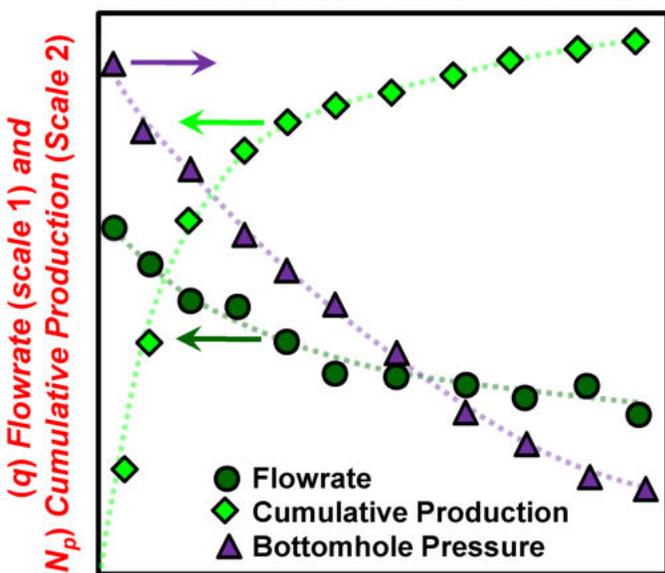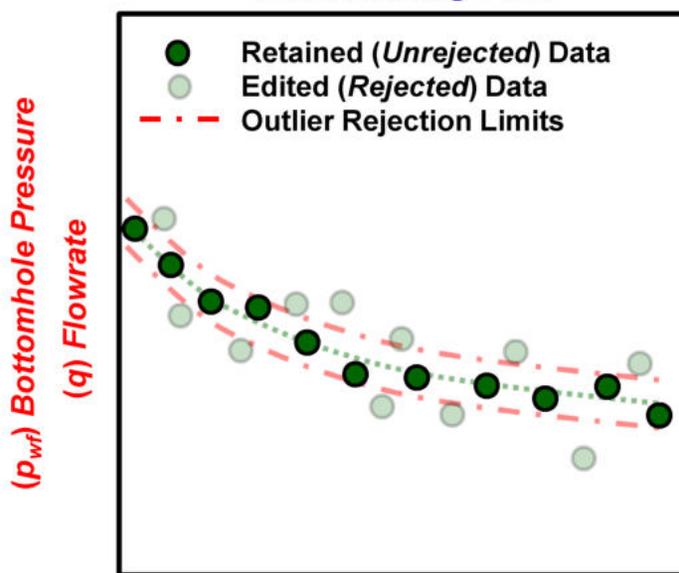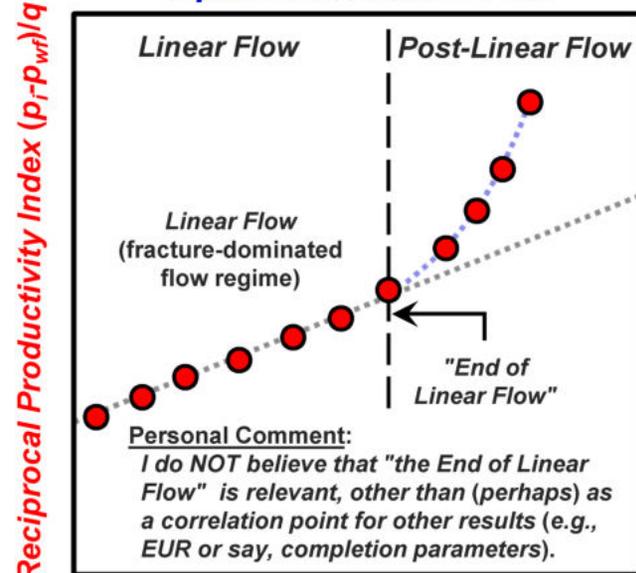
"End of Linear Flow"

Square Root[*Time*]

Personal Comment:
I do NOT believe that "the End of Linear Flow" is relevant, other than (perhaps) as a correlation point for other results (e.g., EUR or say, completion parameters).

RTA "Diagnostic" Plot

log[Productivity Index $(q/(p_i\text{-}p_{wf}))$ and Productivity Index Derivative]

Transient Flow
Linear Flow (fracture-dominated flow regime)

Post-Transient Flow
Boundary-Dominated Flow (reservoir-dominated flow regime)

2
1
1
1

log[*Material Balance Time* (N_p/q)]

- ● $q/(p_i\text{-}p_{wf})$
- ▲ $t_{mb} \times |d/dt_{mb} [q/(p_i\text{-}p_{wf})]|$

D(t) Diagnostic Plot

log[$D(t)$] [$1/D(t) = -q/(dq/dt)$]

$$D(t) \equiv -\frac{1}{q(t)}\frac{dq(t)}{dt} \approx At^{-B} + C$$

A = value of the trend at $t = 1$ *day.*

B = slope of the trend.

$t = 1$ *day*

C parameter (often 0 in practice - i.e., only a straight-line trend is observed)
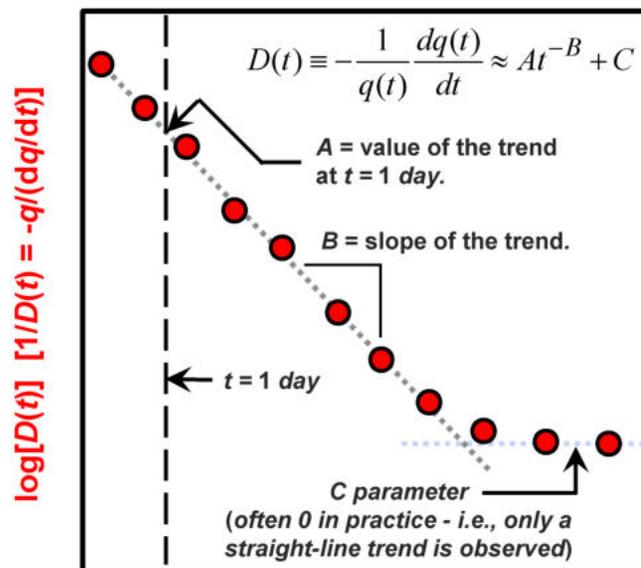
log[*Time*]

b(t) Diagnostic Plot

log[$b(t)$] [$b(t) = (d(1/D(t))/dt)$]

$C = 0$ Trend

$$b(t) \equiv \frac{d}{dt}\left[\frac{1}{D(t)}\right] \approx \frac{ABt^{-(B-1)}}{(A+Ct^B)^2}$$

b = constant assumption

$C \neq 0$ Trend
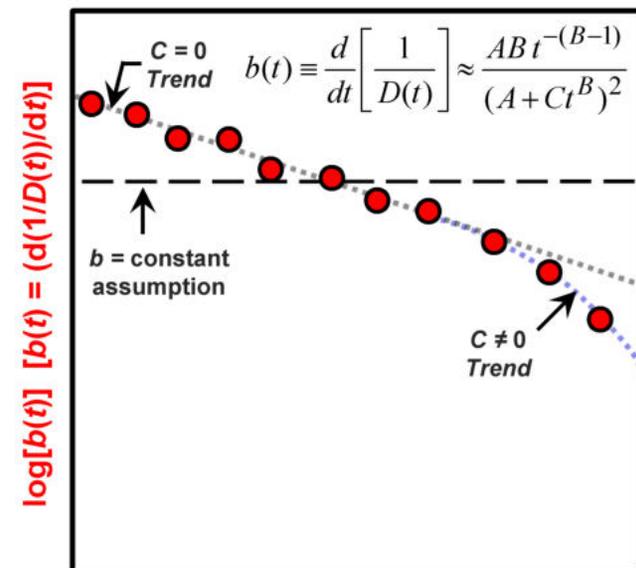
log[*Time*]

Production Data Analysis — Flowing Material Balance and … Friends

RTA Plot (*circa* 1985)

Reciprocal Productivity Index $(p_i\text{-}p_{wf})/q$

Transient Flow

N estimated from slope.

Boundary-Dominated Flow

$$\frac{\Delta p}{q} = \left[b_{pss}\right] + \left[\frac{1}{Nc_t}\frac{B_o}{B_{oi}}\right]\frac{N_p}{q}$$

[y-axis]   [intercept]   [slope] [x-axis]

Material Balance Time $(t_{mb} = N_p/q)$

Reciprocal Rate Plot (*circa* 2009)

Reciprocal Rate $1/q$

Transient Flow

Assuming p_{wf} = constant leads to erratic data signatures.

N estimated from (center) slope.

Boundary-Dominated Flow

$$\frac{1}{q} = \left[\frac{b_{pss}}{\Delta p}\right] + \left[\frac{1}{Nc_t\Delta p}\frac{B_o}{B_{oi}}\right]\frac{N_p}{q}$$

[y-axis] [intercept]   [slope]   [x-axis]

Material Balance Time $(t_{mb} = N_p/q)$

FMB Plot (*circa* 1998)

Productivity Index $(q/(p_i\text{-}p_{wf})$

$$\left[\frac{q}{(p_i - p_{wf})}\right] = \left[\frac{1}{b_{pss}}\right]$$

[y-axis]   [intercept]

$$- \left[\frac{1}{b_{pss}N}\right]\left[\frac{B_o}{B_{oi}}\frac{N_p}{(p_i - p_{wf})c_t}\right]$$

[slope]   [x-axis]

Boundary-Dominated Flow

N

Transient Flow

$x = (B_o/B_{oi}) \times (1/(\Delta pc_t)) \times N_p$

Rate-Cumulative Plot

(q) Flowrate

Transient Flow

EUR_{Exp} — Exponential Decline

EUR_{Hyp} — Hyperbolic Decline

EUR_{Exp} EUR_{Hyp}

Boundary-Dominated Flow

(N_p) Cumulative Production

β-Derivative Diagnostic Plot

$\log[\beta$-Derivative]

Cleanup

Linear Flow β = 1/2

$$\beta(t) = -\frac{d\ln[q(t)]}{d\ln[t]} = -\frac{t}{q(t)}\frac{dq(t)}{dt}$$

$\log[Time]$