10º Congreso de Exploración y Desarrollo de Hidrocarburos
Simposio de Recursos No Convencionales: Hacia una Nueva Convención

DIAGNOSTIC PLOTS FOR PRODUCTION OPTIMIZATION IN UNCONVENTIONAL RESERVOIRS

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RESUMEN

Diagramas Diagnósticos para Optimización de Producción en Reservorios No Convencionales
La formación Vaca Muerta esta llamada a ser, uno de los *plays* no convencionales más importantes del mundo, localizada en la Cuenca neuquina de la región Sur de la República Argentina. Como en todo nuevo *play*, solo unos pocos bloques están bajo la fase de desarrollo, mientras que el resto de los bloques, están en etapas de exploración con pocos o ningún pozo horizontal aun perforado. Puntos de aterrizaje, largos laterales, diseños de fractura hidráulica y procedimientos de gerenciamiento del orificio de producción son algunos de los puntos críticos a ser optimizados durante la etapa temprana del desarrollo de todo bloque, previo a migrar hacia la fase de perforación en modo "factoría". La actividad de perforación se está incrementando y respuestas rápidas son requeridas para la optimización del desarrollo de la formación Vaca Muerta.
La industria ha frecuente e incorrectamente aceptado, especialmente en reservorios no convencionales, que los primeros datos de producción están directamente relacionados a la futura performance de un pozo (ejemplo: caudal inicial de producción y volúmenes acumulados). Sin embardo, los primeros datos de producción son muchas veces función de prácticas operativas y no presentan relación directa con la futura performance del pozo. Información critica como datos de presión, diseño de fractura hidráulica y tipo de fluido son usualmente ignorados cuando se realiza un análisis de performance de producción.
Muchas herramientas heredadas de la ingeniería clásica de reservorios convencionales son usualmente usadas para entender la performance de producción de un pozo. Algunas de ellas son análisis de curvas de declino que no poseen sustento físico, modelos analíticos que son solo válidos bajo ciertas condiciones, y complejos modelos numéricos que requieren diversas fuentes de información para reducir sus incertidumbres. Una pieza de información común entre todas estas técnicas es disponer de suficiente historia de producción, pero las respuestas no pueden hacerse esperar mientras la actividad de perforación sigue en aumento.
Para mejorar los análisis de producción, gráficos de diagnóstico caudal-tiempo-presión son herramientas fundamentales en la ingeniería de reservorios para:

- Comparar *performance* entre pozos
- Entender los regímenes de flujo
- Detectar tempranamente perdidas de productividad
- Monitorear en el tiempo la conductividad de la fractura hidráulica
- Obtener información de entrada para modelos numéricos
- Control de calidad de los caudales alocados

Este trabajo expone los gráficos de diagnóstico más utilizados en reservorios no convencionales aplicados en ejemplos reales de campo.

INTRODUCTION

Unconventional Reservoirs are characterized to have an extremely low permeability in the range of a few hundred of nano-Darcies and Multi-Fractured Horizontal Wells (MFHW) are the most popular technique to economically develop these types of reservoirs. Since transmissibility is very low, wells are expected to be producing in a transient flow regime for several years. Kang *et al*. (2011) showed that a generalization of the "radius of investigation" concept for transient radial flow becomes, for transient linear flow:

$$t = \frac{1896 \cdot \phi \cdot \mu \cdot C_t \cdot d^2}{k} \qquad \text{(Eq. 1)}$$

From Figure I, it is noted the time difference between pressure propagation in Unconventional Reservoirs (a hundred of nano-Darcies permeabilities) and Conventional Reservoirs (permeabilities greater than 0.1 mD).

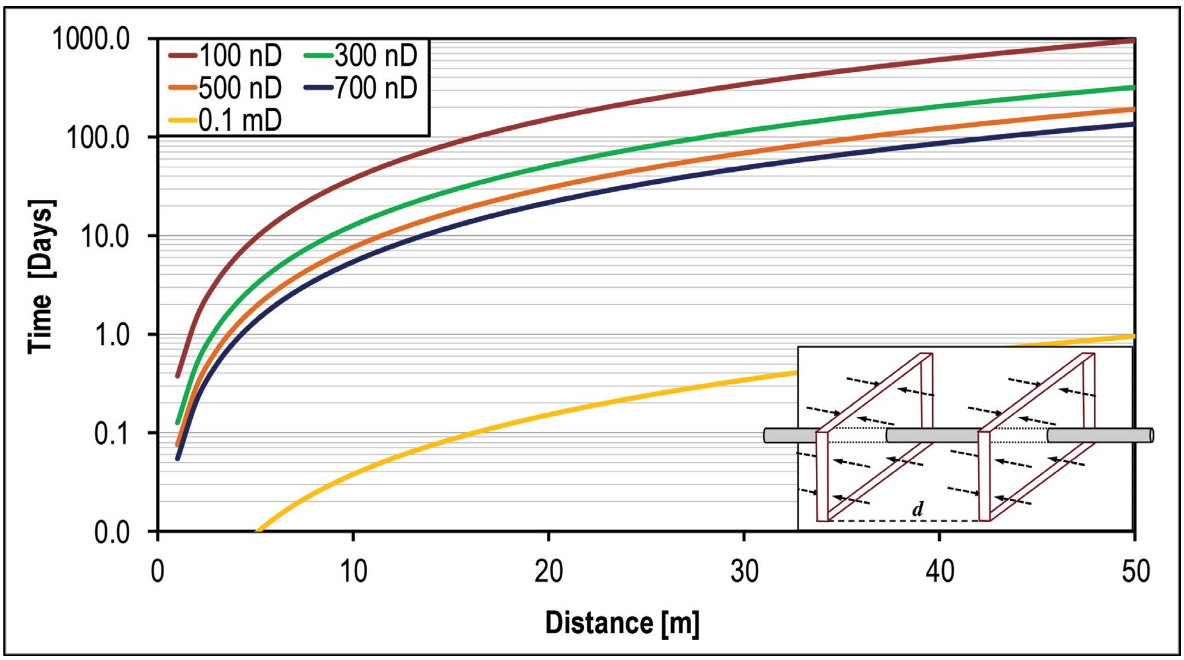

Figure I. Radius of Investigation vs. Time of a typical Shale Formation (Porosity 10% / Ct 8.10-6 psi-1 / Oil Viscosity 0.6 Cp).

Flow regime identification is critical to have a good understanding of well performance and extract key reservoir parameters; and Diagnostic Plots are a powerful tool that reservoir engineers should include in their toolkit.

Flow Regimes

The expected sequence of flow regimes for MFHW within a single-porosity reservoir has been described by Van Kruysdijk and Dullaert (1989). This flow regime sequence was later detailed and applied to analytical modeling by Chen and Raghavan (1997), who first presented an algorithm to calculate pressure distribution caused by multiple fractures (P. Liang *et al.* 2012). Six flow regimes can be identified from a Log-Log Diagnostic Plot (Figure II).

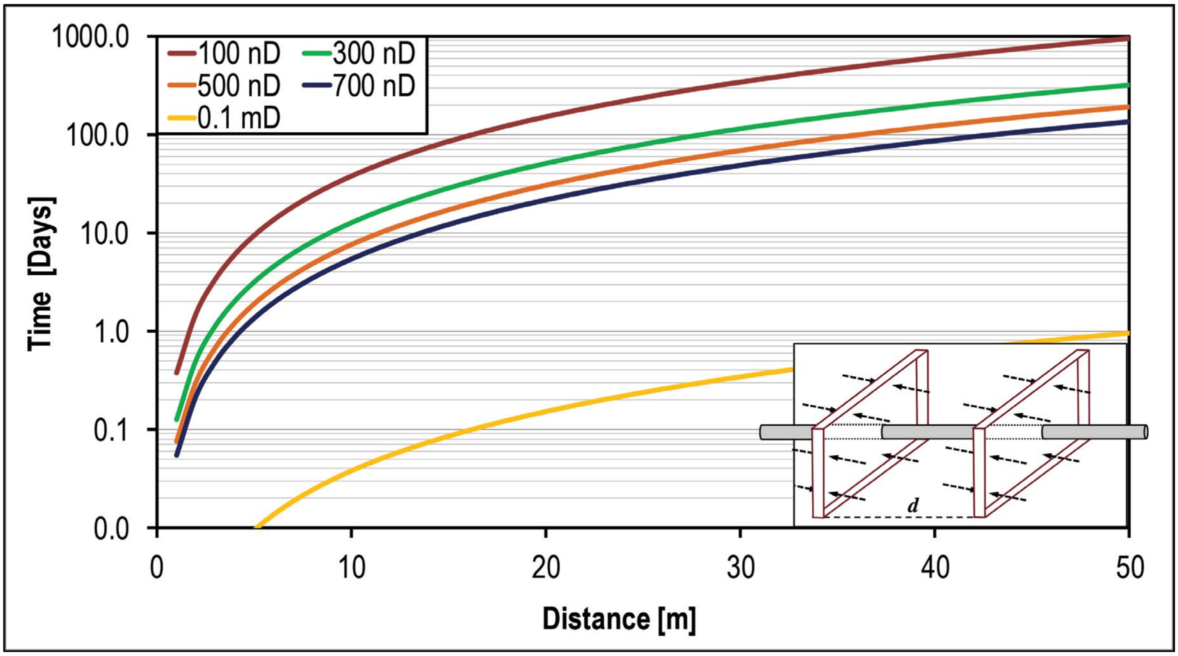

Figure II. Log ΔP/Qo vs. Log t Plot showing Flow Regimes in a MFHW (modified from Clarkson and Beierle, 2010).1-Bi-Linear Flow, 2-Formation Linear Flow, 3-Transition Time Compound Linear Flow, 4-Compound Linear Flow, 5-Transition time to Boundary Dominated Flow, 6-Boundary Dominated Flow (modified from P. Liang, *et al.*).

1. Bi-Linear Flow

This flow regime is only observed when the hydraulic fractureconductivity is finite and the pressure drop along the hydraulic fracture network is in the same magnitude order of the drawdown (Pr – BHFP). This type of flow regime is short-lived andrarely observed in Unconventional Reservoirs.

2. Formation Linear Flow

It is dominated by a flow perpendicular to the vicinity of the hydraulic fracture (Figure III). This is the main flow regime observed in reservoirs with extremely low permeability during several years (i.e.: Unconventional Reservoirs). Very useful data could be obtained from RTA.

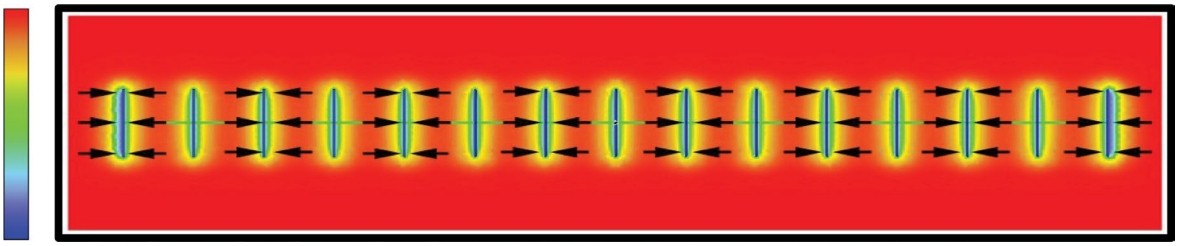

Figure III. Pressure 2D Map in a Linear Flow Regime from a Simulator Output

3. Transition time Compound Linear Flow

After the primary linear flow, there is a transition during which the fractures start to interfere with each other and the contribution to flow from the region beyond the fractures becomes significant (Chen and Raghavan, 1997).

4. Compound Linear Flow

Once hydraulic fractures have noticed interference and the SRV started to be depleted, a flow regime perpendicular to the primary linear flow could be potentially detected, depending upon the fractures geometries and dimensions (Figure IV).

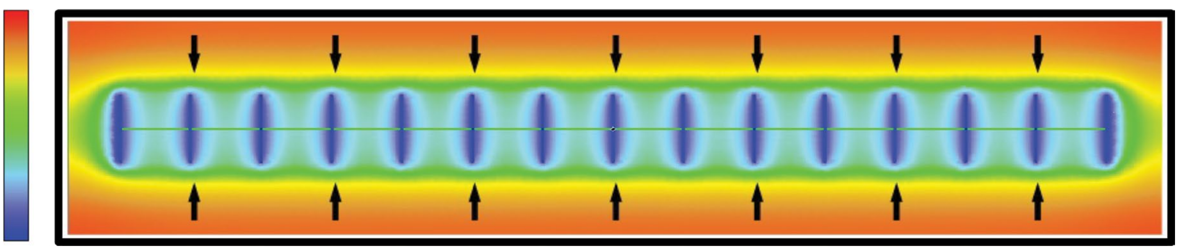

Figure IV. Pressure 2D Map in a Compound Flow Regime from a Simulator Output

5. Transition time to Boundary Dominated Flow

Compound Linear Flow is followed by a transition period toward the boundary dominated flow.

6. Boundary Dominated Flow

Once the boundaries have been reached, and the region outside the SRV starts to be depleted, a boundary dominated flow will govern the flow regime (Figure V).

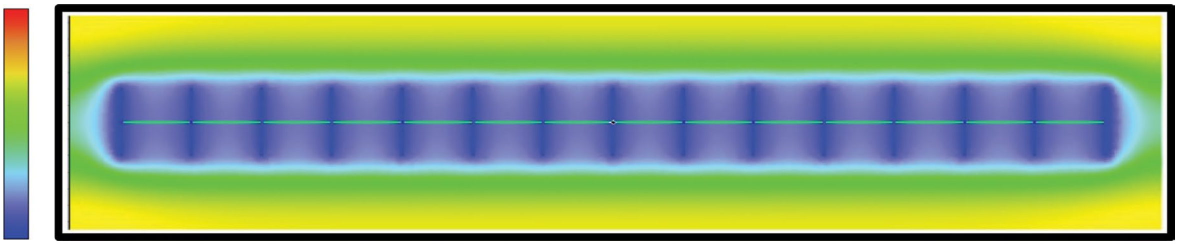

Figure V. Pressure 2D Map in a Boundary Dominated Flow Regime from a Simulator Output

Diagnostic Plots

Specialized plots are very important to get information from the reservoir and, depending on the type of flow regime, different properties could be extracted. This contribution is focused specifically in Rate Transient Analysis for Unconventional Reservoirs where Formation Linear Flow is the main regime.

The equation that mainly governs the Linear Flow regime is given by:

$$\frac{(Pi-Pwf)}{q} = 16.26 \cdot \frac{B}{Af} \cdot \left(\frac{\mu \cdot t}{k \cdot C_t \cdot \phi}\right)^{\frac{1}{2}} + 141.3 \cdot \frac{B \cdot \mu}{k \cdot h} \cdot s_f. \quad \text{(Eq. 2)}$$

The Diagnostic Plots used in this contribution are elaborated using rates, downhole flowing pressure (measured and calculated) and knowing the initial reservoir pressure.

Log-Log Plot

It can be easily demonstrated from the linear flow equation (Eq. 2) that, when the rate divided by drawdown is plotted in a Log-Log scale against thecorrespondent material balance time (i.e.: Np/qo), the slope should be -1/2 (Figure VI). Using material balance time converts the constant pressure solution into the constant rate solution, which is the solution widely used in the field of well testing. The same procedure can be done with the Bilinear Flow equation and the Boundary Dominated Flow equation to demonstrate that the slope observed under these flow regimes are -1/4 and -1 respectively.

Main Uses:

- Identify flow regimes
- Detect any productivity loss
- Compare performance between wells
- If BHFP is available (i.e. PDGs), a QA/QC of allocated rates could be done

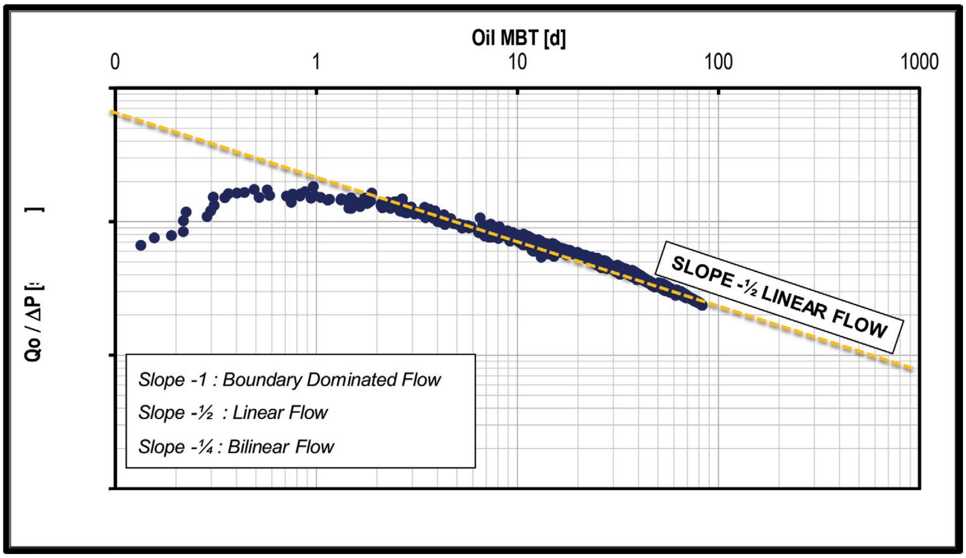

Figure VI. Log-Log Plot showing a Linear Flow regime (-1/2 Slope)

Linear Flow Plot

In the case that linear flow is identified, an additional useful Diagnostic Plot can be constructed by plotting Sqr(t) vs. the Reciprocal Productivity Index. In this plot, we should observe a straight line inversely proportional to the Linear Flow Parameter ($A_f x k^{1/2}$) while the well is producing under a Linear Flow Regime. This parameter is a valuable information to constrain Numerical Models andcan be extracted when B, μ C_t and ϕ are known.

Main Uses:

- Detect any productivity loss
- Monitor the hydraulic fracture conductivity with time
- Compare performance between wells
- Extract the linear flow parameter ($A_f x k^{1/2}$) to be used in a numerical model (assuming known B, μ, ϕ and C_t).

Field Examples

Productivity Loss

Productivity losses due to operational problems (i.e. paraffin issues) can be detected when a suddenly and unexpected slope change is observed in a Log-Log Plot. In the field example showed in the Figure VIII, it can be clearly seen how the slope has suddenly changed. Thereservoir engineers detected the productivity loss and, after cleaning the well using a slickline, it was determined that it was a paraffin issue. After removing the paraffins, the slope recovered to its original value.

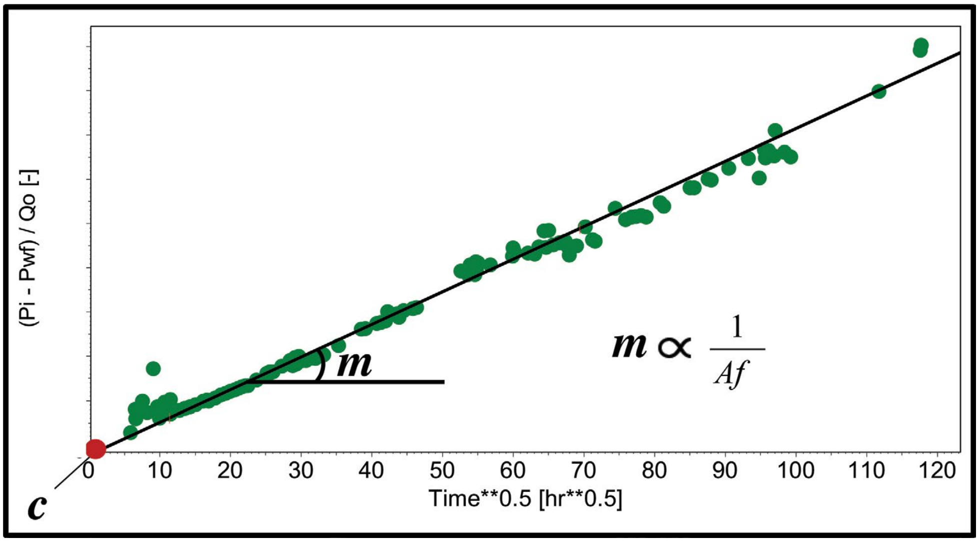

Figure VII. Linear Flow Plot showing a straight line from the origin

Understanding the real performance of a well is of particular importance in exploration and appraisal wells that would be used to evaluate future investments in the area.

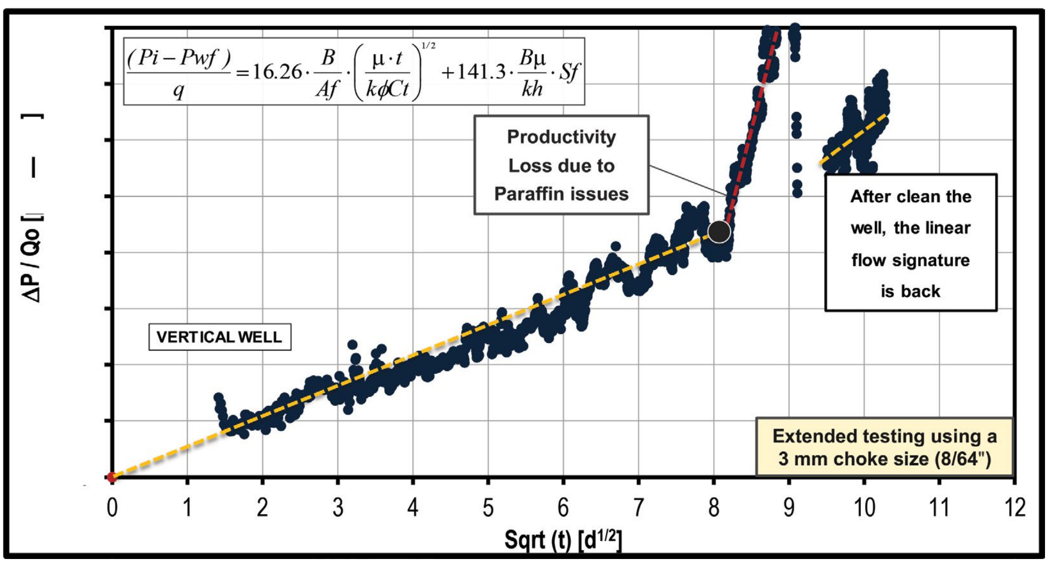

Figure VIII. A Productivity Loss identified using a Liner Flow Plot

Hydraulic Fracture Conductivity Monitoring

The hydraulic fracture conductivity is usually challenging to monitor in unconventional reservoirs. However, assuming constant fluid and rock properties, it is possible to observe a slope change in every choke change. Thislower productivity index could potentially be indicating a reduction in the hydraulic fracture conductivity due to the additional effective net stress generated with the choke change (Figure IX).

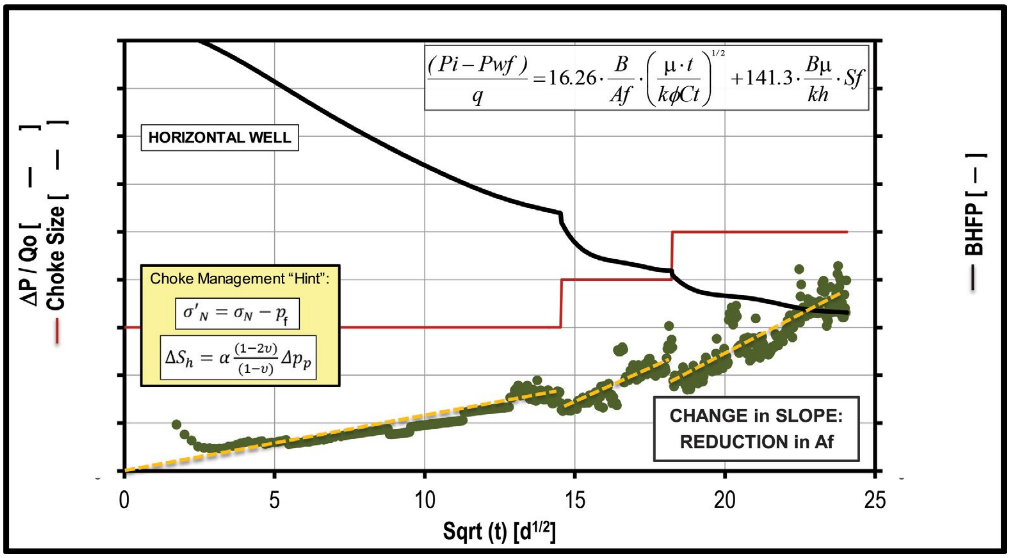

Figure IX. A reduction in the Afidentified in every Choke Change using a Linear Flow plot

Production Benchmark

Frequently, initial production (i.e.: Peak Oil) or cumulative hydrocarbon at different periods of time normalized per number of stages is frequently usedto benchmark productivity between different wells. This is not a recommended practice. These key performance indicators do not consider the pressure decline, meaning that you could potentially have a better well by simply increasing the choke size to accelerate production but seriously impacting the EUR due to the additional hydraulic fracture conductivity damage (Figure X). To avoid this issue, the Linear Flow Parameter can be extracted from the slope in the Linear Flow Plot and used as a proxy of ultimate recovery for each well (Figure XI).

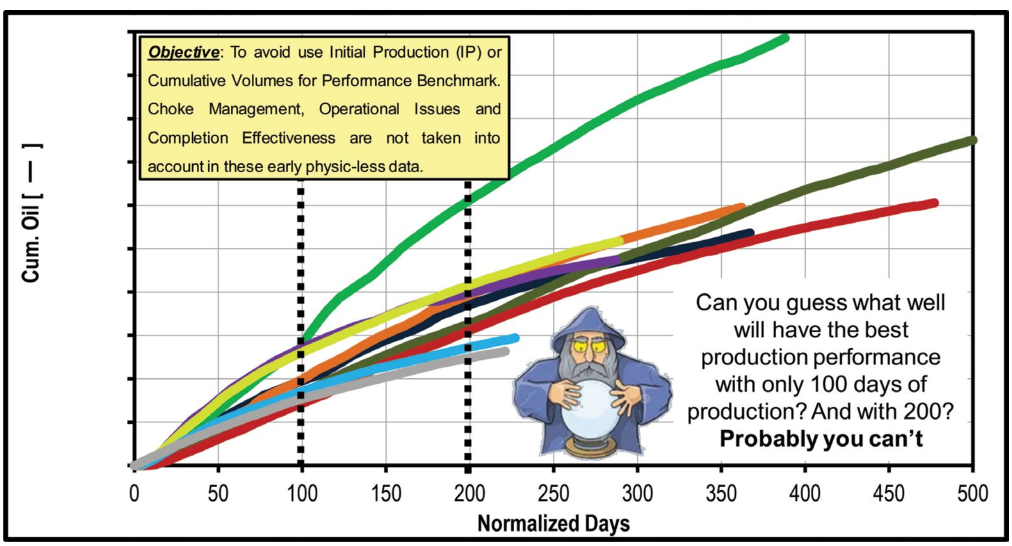

Figure X. Cumulative Oil from different horizontal wells drilled in a similar HC properties area

From a small population of horizontal wells located in the same area with similar fluid properties and a very good data quality, a good correlation($R2 > 0.85$) has been found betweenultimate recovery, obtained from DCA using the whole production history of each well, and the Linear Flow Parameter extracted using the first 3-months of production data (Figure XII). This approach it is a powerful way to early evaluate the performance of any pilot before moving into a factory mode (i.e.: Completion Designs, Landing Points, etc.).

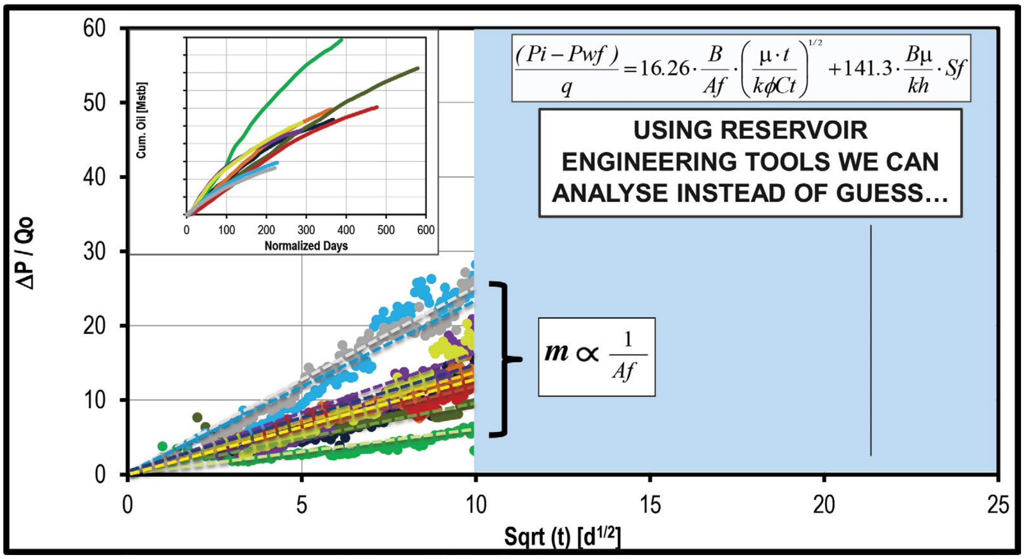

Figure XI. A Linear Flow Plot used for production performance comparison

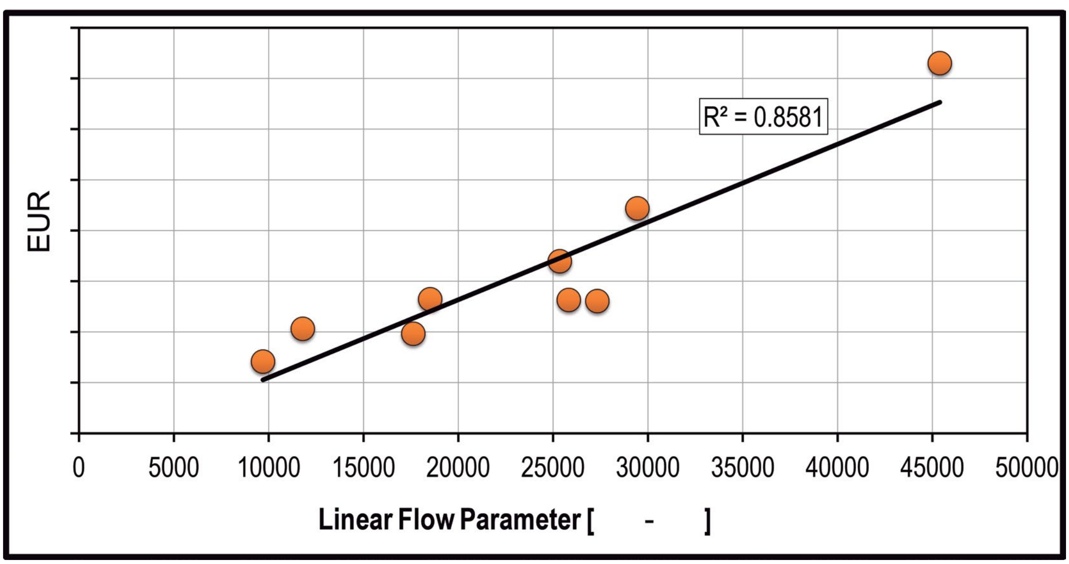

Figure XII. EURs from DCA vs. Linear Flow Parameters obtained from 3 months production history

A similar approach to benchmark production performance can be done using the Log-Log Plot and compare Productivity Index Values (Q_o / ΔP) at a certain time (i.e.: 200 material balance days). The higher the Productivity Index value, the higher should be the EUR (Figure XIII).

It is also interesting to observe that, since water and oil are immiscible phases, this plot can also be used to understand the water production flow regime (Figure XIV). In this field example, the water is being produced under the Boundary Dominated Flow regime (-1/2 Slope), meaning that most of the water is coming from the hydraulic fracture network (flowback water).

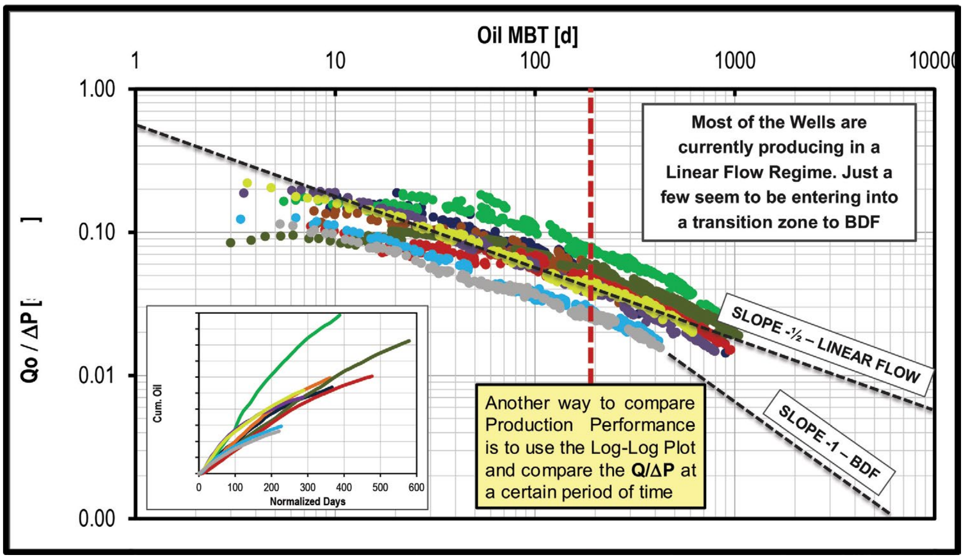

Figure XIII. A Log-Log Plot used for production performance comparison

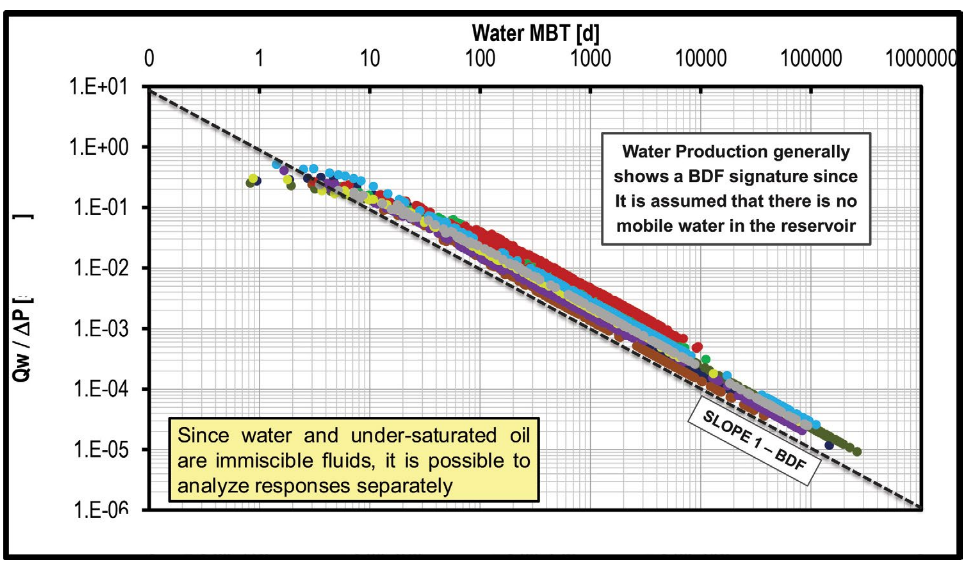

Figure XIV. A Log-Log Plot showing a clear BDF signature for the water phase

CONCLUSIONS

Best Practices

- Monitor the hydraulic fracture conductivity using diagnostic plots to make sure that the choke management is not compromising the EUR.
- Instead of usingInitial Production (IP) or Cumulative Volumes to compare production performance between wells, use the linear flow parameter or the Productivity Index at a certain period of time.
- Use Diagnostic Plots in “High Profile” wells to understand any operational issues (paraffin deposition, asphaltenes, liquid loading, etc.) and optimize production to evaluate the real potential of the reservoir.

Lessons Learned

- Non-physics basedparameters like Initial Production (IP) and Cumulative Volumesare not good indicators of future performance.
- An unexpected change observed from a Diagnostic Plot can indicate a performance problem even if no operational issues have been reported.
- A Good Choke Management, especially in over-pressured reservoirs, is critical to maximize EUR. Rock Mechanics must be considered for this optimization.

CHALLENGES

- Break the “acceptedParadigm” and do notcorrelate early production with future performance without including physics.

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NOMENCLATURE

MFHW: Multi Fractured Horizontal Well
RTA: Rate Transient Analysis
Pr: Reservoir Pressure

BHFP/Pwf: Bottomhole Flowing Pressure
Pi: Reservoir Pressure
q: rate
B: Volumetric Factor
A_f: Hydraulic Fracture Area (n_{fx} h x X_f)
n_f: Number of Hydraulic Fractures
μ: Viscosity
t: Time
C_t: Total Compressibility
ϕ: Porosity
k: Permeability
S_f: Hydraulic Fracture Skin
h: Reservoir Thickness
PDG: Permanent Downhole Gauges
HC: Hydrocarbon
BDF: Boundary Dominated Flow
α: Biot's Alpha
S_h: Minimum Stress
NPV: Net Present Value
DCA: Decline Curve Analysis

REFERENCES

P. Liang, L. Mattar, 2012, Importance of the Transition Period to Compound Linear Flow in Unconventional Reservoirs. Presented in SPE Canadian Unconventional Resources Conference held in Calgary, Alberta, Canada - SPE 162646.

Monograph 4, Estimating Ultimate Recovery of Developed Wells in Low-Permeability Reservoirs – SPEE – 2016

J.M. Thompson, P. Liang and L. Mattar, What's Positive about Negative Intercepts. Presented in SPE Canadian Unconventional Resources Conference held in Calgary, Alberta, Canada - SPE 162647.