Characterization of Multi-Porosity Unconventional Reservoirs and their Relationship to Oil and Gas Productivity

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Tight Oil and Unconventional Gas
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OBJECTIVES

- Discuss multi-porosity unconventional reservoirs.
- Show that there is a continuum that goes from conventional to tight gas to shale gas to tight oil to shale oil reservoirs.
- Relate pore throat apertures to oil and gas rates in vertical and horizontal wells.
- Make the work tractable by using actual published data.
A multidisciplinary integration of:

- Geoscience (G)
- Formation evaluation (F)
- Reservoir drilling, completion and stimulation (R)
- Reservoir engineering (RE)
- Economics and externalities (EE)

Focus is on increasing production rates and ultimate recoveries economically and responsibly from tight oil and unconventional gas reservoirs.
OUTLINE

- Dual-porosity
- Triple-porosity
- Multi-porosity in shales
- Effect on water saturation
- Flow units: from conventional, to tight gas, to shale gas, to tight oil, to shale oil, to condensate reservoirs
- Link of petrophysics with decline analysis
- Conclusions
(A) Frontier Formation, (B) William Fork, (C) Travis peak, (D) Travis Peak: Shanley et al., 2004
Cadomin Fm. - Elmworth Deep Basin (7-23-69-13W6)

2660 m
$\phi = 5.0\%$, $K_{\text{max}} = 24 \text{mD}$

Flourescence

(Moslow, 2005)
Porosity in Organic Matter (Barnett Shale) (Ruppel and Loucks, 2008)
COLORADO SHALE (CANADA)

Porosity in Organic Matter

SEM Imaging, thin section Colorado Shale (courtesy D. Rokosh, ERCB, SPE 137795)
DUAL POROSITY
Matrix and Fractures
(or Matrix and Slot Porosity)
BORAI’S DATA (SPE FE, 1987)
Area= 10,000 Km², 5 Formations in 14 Abu Dhabi Fields
$m$ (Aguilera) vs. $m$ (Borai)

Abu Dhabi Carbonates, Khuff, Araej, Arab, Thamama and Mishrif Formations, $mb = 2.2, v = 0.058$
Porosity Exponent m, Mesa Verde Formation, USA
(Data Source: Byrnes et al., Kansas Geological Survey, 2006)
Fit Using Dual Porosity Model (Matrix and Slots)
POSTDAM (CAMBRIAN), QUEBEC, $m_b=1.77$, $m_f = 1.2$, $\phi_2 = 0.65\%$
Dual Porosity Model (Matrix and Fractures), \( m_f = 1.0 \) or >1.0
Source: Aguilera, SPE 114174, 2008

\[ m = \text{porosity exponent of composite system of matrix and fractures} \]
\[ m_b = \text{porosity exponent of the matrix} \]
\[ \varnothing = \text{total porosity, fraction} \]
\[ \varnothing_b = \text{matrix porosity of unfractured plug, fraction} \]
\[ \varnothing_2 = \text{fracture porosity} = v \varnothing, \text{fraction} \]
\[ v = \text{partitioning coefficient} \]

\[
m = \frac{\log\left(\frac{1}{\{(v\phi)^{m_f} + [1 - (v\phi)^{m_f}] / \phi'_{b}^{-m_b}\}}\right)}{- \log \phi}
\]

\[
\phi'_{b} = \frac{\phi - \phi_2^f}{1 - \phi_2^f}
\]

\[
f = m_f - (m_f - 1) \frac{\ln \phi}{\ln \phi_2}
\]

Last equation valid for \( \phi_2 \) greater than zero
CHART FOR EVALUATING NATURALLY FRACTURED RESERVOIRS (mb=2.2)

TOTAL POROSITY, $\phi$

DUAL POROSITY EXPONENT, $m$

MATRIX POROSITY, $\phi_b$

(Aguilera, 2003)
TRIPLE POROSITY
Matrix, Fractures and
Non-Effective Porosity
Schematic of Triple Porosity Model
(Source: Al Ghamdi et al., SPE 132879, 2010)

Non touching vugs
(or non-effective porosity)

Fractures

Matrix


Triple Porosity Model
(nomenclature as in previous equations)

Al Ghamdi et al, SPE 132879

\[ m = \log \left( \phi_{nc} + \frac{(1 - \phi_{nc})^2}{\phi_2 + \frac{(1 - v\phi)}{\phi_b^{-m_b}}} \right) \]

- \( m \) = porosity exponent of triple porosity system
- \( m_b \) = porosity exponent of the matrix
- \( \phi \) = total porosity, fraction
- \( \phi_{nc} \) = non-connected (or isolated) porosity = \( v_{nc} \) \( \phi \), fraction
- \( v_{nc} \) = vug porosity ratio
TRIPLE POROSITY MODEL, $mb = 2.0$
Shales: Multiple Porosity Rocks

• (1) adsorbed gas into the kerogen material
• (2) free gas trapped in nonorganic inter-particle (matrix) porosity
• (3) free gas trapped in microfracture porosity
• (4) free gas stored in fractures created during stimulation of the shale reservoir
• (5) free gas trapped in a pore network developed within the organic matter or kerogen
m = porosity exponent (multiple porosities)

\(m_b\) = porosity exponent of the matrix

\(\varnothing\) = total porosity, fraction

\(\varnothing_b\) = matrix porosity scaled to bulk volume of the matrix, fraction

\(V_{tker}\) = total volume of kerogen = \(\varnothing_{org} + \varnothing_{ads} + V_{diff}\), fraction

\[m = \frac{-\log\left[ V_{tker} + \frac{(1-V_{tker})^2}{\phi_2 + (1-\phi_2-V_{tker})/\phi_b^{-m_b}} \right]}{\log\phi}\]
Modified Pickett crossplot including variable values of $m$ calculated with multiple porosity model (SPE 171638)

Zone 1: $\phi = 5\%$, $\phi_m = 3.9\%$, $\phi_2 = 0.63\%$, $\phi_{org} = 0.9\%$, $\phi_{ads} = 0.2\%$
MATERIAL BALANCE APPLICATION (Lopez and Aguilera, SPE 165681, 2013)

Contribution of free gas, adsorbed gas and diffusion gas from kerogen to total cumulative gas production in Devonian shale gas reservoirs (Appalachian Basin)
FLOW UNITS: FROM CONVENTIONAL TO TIGHT GAS TO SHALE GAS TO TIGHT OIL TO SHALE OIL RESERVOIR (THERE IS A CONTINUUM)
FLOW UNIT

A flow unit is defined as a stratigraphically continuous reservoir subdivision characterized by a similar pore type (Hartmann and Beaumont, 1999), for example by a similar $r_{p35}$ (Aguilera, 2002):

$$r_{p35} = 2.665 \ (k/100\phi)^{0.45}$$
Conventional vs. Continuous Type Accumulations
(Used mostly to Explain Tight Gas)
(Pollastro and Schenk; 2002, Moslow, 2008)
Real Data
Conventional and Low Permeability Rocks
Elk City Oil Field (Sneider et al., 1983)

[Diagram showing the relationship between porosity and gas permeability with different symbols for different types of reservoirs.]
Unconventional Reservoirs, Elk City Oil Field (SPE 165350, 2013)  
Data from Sneider et al., 1983
Unconventional Reservoirs (Elk City Oil Field)

Sneider et al, 1983

Multi-Porosity
Unconventional Reservoirs, Cardium SS, Pembina Oil Field  
(Source of Data: MacKenzie, 1975)
Real Data
Shale Gas
Flow Units

Proof of Concept

![Graph showing relationship between Permeability (MD) and Porosity with data points for different formations: Fayetteville, Horn River, Barnett, and Soft Shales.](image)
Unconventional Reservoirs: Shale Gas (SPE 132845)

The graph illustrates the relationship between permeability (MD) and porosity for different shale formations. The data points and curves indicate the permeability distribution for the Fayetteville, Horn River, Barnett, and Soft Shales regions, showing the variability in reservoir properties across these unconventional reservoirs.
Real Data
Shale Gas and Tight Gas
Flow Units
Real Data
Tight Oil
Unconventional Reservoirs: Bakken Tight Oil

![Graph showing permeability vs. porosity for different formations like SASK, BRUTUS, FOOGHORN, JACKSON, F, HR_B. The x-axis represents porosity ranging from 0 to 30, and the y-axis represents permeability in MD (meg达西). The graph includes various data points and lines for different formations, illustrating the relationship between permeability and porosity.](image-url)
Unconventional Reservoirs, Cardium SS, Pembina Oil Field
(Source of Data: MacKenzie, 1975; Hamm and Struyk, 2011)
Unconventional Reservoirs: Tight and Shale
Flow Units
Theoretical Data

Pore Scale Modeling
Flow Units (Pore Scale Modeling)

Rahmanian et al., SPE 133611
Microsimulation at the pore throat level:
• Pore throat radii
• Permeability
• Porosity
• Relative perms
• Cap pressures
• Electrical properties
• Rock Mechanics
• Stimulation
• Prod allocation in commingled completions
Unconventional Reservoirs and Potential Oil and Gas Rates

Microsimulation at the pore throat level will supplement results of $r_p$, $k$, phi, rel perms, cap pressures, electrical properties, rock mechanics

Brittle? Ductile? Type of Stimulation? Effect of $S_w$, mud filtrate, leak-off on embedment?

Source: GFREE Research Team, U of Calgary, 2013
Microsimulation at the pore throat level will supplement results of $r_p$, $k$, phi, rel perms, cap pressures, electrical properties, rock mechanics, Brittle, Ductile, Type of Stimulation, Effect of Sw, mud Filtrate, leak-off on embedment

Unconventional Reservoirs and Potential Oil and Gas Rates

Source: GFREE Research Team, U of Calgary, 2013
OIL RATE VS. $r_{P35}$
(Source of rate data: Martin, Solomon and Hartmann, 1997)
(Source of $r_{p35}$ data: Aguilera, 2002-2003)

$$q = 295.87(r_{p35})^{1.4703}$$

$R^2 = 0.9992$

Gaspe HTD potential / well $\sim 120$ BOPD
(or gas equivalent)

Vertical Well

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OIL RATE VS. $r_{p35}$
(Source of rate data: Martin, Solomon and Hartmann, 1997)
(Source of $r_{p35}$ data: Aguilera, 2002-2003)

$$q = 295.87(r_{p35})^{1.4703}$$
$$R^2 = 0.9992$$

Published sources
Best fit

Gaspe HTD potential / well ~ 120 BOPD
(or gas equivalent)

HTD $r_{p35}$ ~ 0.3 to 1.5 μm

© Servipetrol, Dr. Roberto Aguilera, 2004

JUNEX PRESS RELEASE, Feb 23, 2015: 316 BOPD
Non-stimulated horizontal well, Forillon Formation
PETROPHYSICAL DUAL, TRIPLE AND MULTIPLE POROSITY MODELS DISCUSSED PREVIOUSLY CAN BE LINKED TO OIL AND GAS PRODUCTIVITY
Linear Flow in a Dual-Porosity Reservoir towards a Hydraulic Fracture of Infinite Conductivity
(Adapted from Aguilera, SPE 16442, 1987)
DECLINE ANALYSIS IN INFINITE-ACTING TRIPLE POROSITY RESERVOIR WITH RESTRICTED INTERPOROSITY FLOW DOMINATED BY LINEAR/BILINEAR FLOW (Leguizamon and Aguilera, SPE 142727, 2011)

$q_D = \text{dimensionless rate}, \ t_D = \text{dimensionless time}, \ w = \text{storativity ratio}, \ f = \text{function}, \ cc = \text{commingled completion exponent}, \ d = \text{dual}, \ t = \text{triple}$

\[
\frac{1}{q_D} = \frac{\pi}{2} \sqrt{\frac{\pi t_D}{[\omega_d + (1 - \omega_d) \cdot f(t_D, \tau_{D_d})] \cdot [\omega_t + (1 - \omega_t) \cdot f(t_D, \tau_{D_t})]}}
\]

\[
f(t_D, \tau_{D_d}) = [1 - \exp \left( - \frac{t_D}{\tau_{D_d}} \right) ]^{cc_d}
\]

\[
f(t_D, \tau_{D_t}) = [1 - \exp \left( - \frac{t_D}{\tau_{D_t}} \right) ]^{cc_t}
\]
Infinite-Acting Linear Reservoir with Restricted Interporosity Flow
Infinite-Acting Reservoir with Unrestricted Interporosity Flow

Decline Rate
Dual Porosity Model Dominated by Linear Flow

\[ D_t \]

\[ tD \]
Tight Gas Field (WCSB)
Tight Gas Field, Well i1

Well #

- Measured Rate

\( q, \text{m}^3/\text{d} \)

\( 1.0 \times 10^6 \quad 1.0 \times 10^5 \quad 1.0 \times 10^4 \quad 1.0 \times 10^3 \)

\( 1.0 \times 10^1 \quad 1.0 \times 10^2 \quad 1.0 \times 10^3 \quad 1.0 \times 10^4 \quad 1.0 \times 10^5 \)

Time, hours

Leguizamon& Aguilera, SPE 142727, 2011
Triple Porosity q Decline

Commingled Completion Production Matching

History Matching Well 2
- Measured Rate
- Calculated rate
Tight Gas Field, Well i1

Well #

- Measured Rate
- Calculated rate

Commingledd Completion

$q, m^3/d$

Time, hours

Leguizamón & Aguilera, SPE 142727, 2011
Tight Gas Field, Well i3
Tight Gas Field, Well i3
Inter-linear Flow Period
Decline Rate with Unrestricted Inter-Linear Transition Flow
Triple Porosity Model Dominated by Linear Flow

- Linear Flow (slope = -0.5)
- Unrestricted Transition (slope ~ -0.75)
- Linear Transition

Multi-Porosity • Unconventional Reservoirs
Production from the Cardium Tight Oil Reservoir

- East Pembina 2009
- East Pembina 2010
- East Pembina 2011
- West Pembina 2009
- West Pembina 2010
- West Pembina 2011
- Type Well

Hamm and Struik (2011)
Slope – 0.75

Production from the Cardium Tight Oil Reservoir and Unrestricted Transition between Linear Flow Periods (this study)

- East Pembina 2009
- East Pembina 2010
- East Pembina 2011
- West Pembina 2009
- West Pembina 2010
- West Pembina 2011
- Type Well
- Transition slope -0.75

Multi-Porosity • Unconventional Reservoirs
Slope – 0.75

Production from the Cardium Tight Oil Reservoir and Unrestricted Transition between Linear Flow Periods (this study)

Decline Rate with Unrestricted Inter-Linear Transition Flow
Triple Porosity Model Dominated by Linear Flow

Unrestricted Transition (slope ~ 0.75)
Conclusions

• Multi-porosity models allow integration of petrophysical and production decline analysis and provide input data for material balance (and simulation) studies.

• There is a continuum between conventional gas, tight gas and shale gas reservoirs (same for oil reservoirs).
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