Impact of Geological Variation and Completion Type in the U.S. Bakken Oil Shale Play Using Decline Curve Analysis and Transient Flow Character*

Elliott V. Hough and Thomas McClurg

Search and Discovery Article #40857 (2011)  
Posted December 19, 2011

*Adapted from oral presentation at AAPG International Conference and Exhibition, Milan, Italy, October 23-26, 2011

1ConocoPhillips, Houston, TX (evhough@conocophillips.com)

Abstract

A performance analysis study of production data from over 2,300 Bakken oil shale wells in North Dakota, U.S.A., was conducted and the results are correlated with significant geologic and completion type variations across the play. Historical rate-time data were analyzed to identify the transient flow character (wellbore storage, 1/2 slope, ¼ slope or pseudo radial flow) and matched using the Arps equation to estimate ultimate recoveries. Numerical modeling studies were also performed on individual and time-normalized average historical well production to validate reservoir model(s) that best fit the observed well transient production declines.

Differences in transient flow character were defined and mapped using Arps hyperbolic “b” values. Wells completed in areas with a high permeability non-shale Middle Bakken carrier bed, with vertical pressure support from the overlying Upper Bakken and the underlying Lower Bakken Shales, are readily identified and have a characteristic transient decline distinguished by a certain range of “b” values. In other areas, where the Middle Bakken is either much lower perm or not present, producing wells will exhibit a much different transient, shale-dominated, decline and are characterized by an entirely different “b” value.

Integrated analysis that ties well performance to the reservoir geology and completion type lead to much improved reservoir models that can be leveraged to focus development in play sweet spots and optimize completion and well spacing strategies.
References


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E.V. Hough, T.A. McClurg ConocoPhillips, Houston Texas

AAPG ICE
Milan, Italy
23-26 October 2011
Key Points

- Tied well performance for 3200 Bakken wells back to geology using Arps b-values
  - $b < 0.5$: Single layer in depletion (conventional reservoir)
  - $b > 0.5$ and $< 1.0$: Multiple layers in depletion (conventional)
  - $b > 1$: Transient formation linear flow into fractures (unconventional)
- Shales exhibit long duration linear flow (1/2 slope)
- Explained by ultra low nanodarcy perm matrix in contact with long planar fractures
- $\frac{1}{2}$ slope can be matched empirically using Arps $b=2$
- Dual Perm system present when Arps $b > 0.5$
- $b$-values $> 1.0$ when production from nanodarcy perm rock
- Increasing completion size $\rightarrow$ increases EUR
Shales Exhibit Long Duration Linear Flow

- Linear flow = Transient flow
- Long duration linear flow observed in + 90% of all L48 Shales
- Long duration Linear Flow means
  - Very low perm (nano darcy)
  - Long Induced fracture lengths

**Effective Productive Interval (EPI)**
- **Anadarko:** 1/2 Slope, 20 years linear flow
- **Arkoma:** 1/2 Slope, 4 yrs linear flow
- **Bakken:** 1/2 Slope, 18 years linear flow
- **Barnett:** 1/2 Slope, 16 yrs linear flow
- **Eagle Ford/AC:** 1/3 Slope, 28 yrs linear flow
- **Fayetteville:** 1/2 Slope, 5.5 yrs linear flow
- **Haynesville:** 1/2 Slope, Avg 91 hz wells
- **Marcellus:** 1/2 Slope, 2 yrs linear flow
- **Arkoma:** 1/2 Slope, 20 years linear flow
- **Bakken:** 1/2 Slope, 18 years linear flow
Linear Flow Types

½ Slope
Formation Linear Flow

\[ F_{CD} = \frac{k_f \times w}{K \times X_f} \]

\( F_{CD} > 30 \)

1/4 Slope
Bi-Linear Fracture Flow

\( F_{CD} < 30 \)

5.5 years

6 years
Bakken Example of Long Duration Linear Flow
17 Years on ½ Slope

½ Slope can be matched empirically with Arps $b=2$
Performance of very low perm fractured wells

\[ k = 0.0015 \text{ md} \]
\[ X_f = 200' \]
\[ \text{Area} = 160 \text{ acres} \]

½ slope Linear flow into fractures
Transition to Pseudo Radial flow
Pseudo Radial flow
Start of Depletion
Boundary Dominated Flow
Fetkovich Type Curve (SPE 4629)

\[ \frac{1}{2} \text{ Slope } b = 2 \]

\[ \text{re/rw} = 10 \ (X_e/X_f = 5) \]

Unconventional

Conventional
Fig. 1—Schematic of finite-conductivity fracture.

Entire productive life of a well can be in linear flow with nanodarcy perm

Hence, valid to estimate EURs from performance using b-values >1

\[
\frac{Dx_f}{t} = \frac{0.00633 k_r \Phi * \mu_g * Ct * X_f^2}{F}
\]
Reservoir Model b values

1. Conventional single layer depletion
   \[ b = 0 \text{ to } 0.5 \]

2. Conventional multi layered depletion
   \[ b = 0.5 \text{ to } 1.0 \]

3. Carrier bed or fracture volume depletion and linear flow
   Moderate matrix perm (1-5 nD)
   \[ b = 1.0 \text{ to } 2 \]
   then late time linear flow \[ b = 2 \text{ to } 4 \]

4. Fracture volume depletion and linear flow
   Sub nano darcy matrix perm
   \[ b = 0.5 \text{ to } 1 \]
   then later time linear flow \[ b = 2 \text{ to } 4 \]

5. Formation linear flow with minor fracture volume depletion
   Good matrix perm > 5 nD
   linear flow \[ b = 2 \]

\[ k_m = 6 \text{ md} \]
\[ b = 0.5 \]
\[ k = 0.1 \text{ mD} \]
\[ k = 1.0 \text{ mD} \]
\[ k_R = 10 \]
\[ V_R = 1 \]

\[ k_m = 5 \text{ nD} \]
\[ b = 1.4 \]
\[ k_m = 0.1 \text{ nD} \]

\[ b = 0.5 \]
\[ b = 2 \]

\[ k_m = 15 \text{ nD} \]
\[ b = 2 \]
Modeling Long Term Linear Flow

$\frac{1}{2}$ Slope
Nesson Anticline Study Area

589 Bakken Oil wells
- 510 wells in linear flow (85%)

164 Wells > 30 months prod since 2005
- 140 wells long term linear flow (85%)
- 130 wells ½ slope b=2 (79%)
Time Normalized Average Well History – 130 wells

- **Bison Point #14-34H**
  - ½ slope
  - 35 Year EUR = 334 mbo
  - \( b = 2 \)
  - 9003’ Lateral
  - 1,052 Mlbs Proppant in 1 stage

Avg Oil Rate (1/2 Slope)

Bison Point #14-34H
History Match of Bison Point #14-34H

Log-log oil rate vs time

Best match with nanodarcy perm!

Lateral = 9,000’
30 Natural Fractures

Microdarcy
k = 2000 nD, Xf= 50’
h = 43’
383 mbo

Nanodarcy
k = 8.2 nD, Xf = 700’
h = 120’
333 mbo
EUR & Rate Increase with Completion Size

Log-log oil rate vs time

Time Normalized Average Well History – 130 wells

$k = 8 \text{ nD}, X_f = 700'$

20 stg 80 frac, 5,000’ Lat
751 mbo (829 mboe)

15 stg 60 frac, 5,000’ Lat
605 mbo (667 mboe)

7 stg 30 frac, 5,000’ Lat
314 mbo (345 mboe)
Dual Perm system

$\mathbf{b} - \text{values between 1 and 2}$

High perm depletion volume (fractures) connected to nanoperm matrix volume in long term linear flow
b = 1.3

Anvik #4-18H

Oil Rate [stb/day], GOR [scf/bbl]

Days

Oil Rate

Gas Rate

GOR

BHP

Xf = 1,200 ft
Nf = 35
F_pV = 251.3 mb
V_/A_r = 0.14 ft^2/ft
km = 10 nD
kf = 56.4 mD
P_i = 4,500 psi
P_wf = 900 psi

½ slope

b = 1.3
When fracture depletion dominates...
Early $b$-values less than 1.0

Nanoperm and sub nanoperm matrix connected to high perm high pore volume natural fractures
Late Time Linear

Bakken - FTB-Fed Com #2H

- $X_f = 1,200'$
- $N_f = 60$
- $F_{pv} = 492$ mb
- $V_r/A_r = 0.16 \text{ ft}^3/\text{ft}^2$
- $k_m = 0.825$ nD
- $k_f = 49.5$ md
- $P_i = 6,081$ psi
- $P_{wf} = 500$ psi
Log-log oil rate vs time

Niobrara (Avg Silo Well)

$\frac{1}{2}$ slope

Oil Rate vs GOR

- $b = 0.5$

- **4,000’ Lateral, 120 Natural fracs,\n  $k = 5$ nD, $X_f = 600’$\n  EUR = 454 MBO, 524 MBOe**

- **2,000’ Lateral, 60 Natural fracs,\n  $k = 5$ nD, $X_f = 600’$\n  EUR = 227 MBO, 262 MBOe**

- Hz open hole laterals w/ no stimulation

  Productivity dominated by natural fractures

  EUR and rate driven by lateral length
Matching Dual Perm b-values

$b = 0.5$

$b = 1.2$

$b = 1.3$

$b = 1.4$

$b = 1.6$

**Late Time Linear**
99.4% of 3200 wells have $b > 1.0$.
Bakken Well Performance Characteristics

Elm Coulee Area
- 761 Wells
- 464 wells b=2
- 15 wells b=3
- 5 wells b=4
- 260 wells b>1 &<2
- 5 wells b<1

Depletion
- b = 0.9
- 30 wells

Sanish Area
- 829 wells
- 691 wells b=2
- 17 wells b=3
- 1 wells b=4
- 120 wells b>1 &<2
- 7 wells b<1

Depletion and Linear
- b>1 &<2
- b = 1.4
- 502 wells

Bakken Well Performance Characteristics

Billings Nose Area
- 311 wells
- 138 wells b=2
- 117 wells LTL
- 13 wells b=3
- 4 wells b=4
- 27 wells b>1 &<2

Late Time Linear
- b = 2
- 117 wells

Sanish Area
- 829 wells
- 691 wells b=2
- 17 wells b=3
- 1 wells b=4
- 120 wells b>1 &<2
- 7 wells b<1

Late Time Linear
- b = 2
- 795 wells b=2
- 31 wells b=3
- 6 wells b=4
- 84 wells b>1 &<2
- 6 wells b<1

Bakken Well Performance Characteristics

Sanish Area
- 829 wells
- 691 wells b=2
- 17 wells b=3
- 1 wells b=4
- 120 wells b>1 &<2
- 7 wells b<1

Long Term Linear
- b = 2
- 2,424 wells
- 80%

Bakken Well Performance Characteristics

Nesson Anticline
- 916 wells
- 795 wells b=2
- 31 wells b=3
- 6 wells b=4
- 84 wells b>1 &<2
- 6 wells b<1

Storage then Linear
- b = 2
- 829 wells

Bakken Well Performance Characteristics

Nesson Anticline
- 916 wells
- 795 wells b=2
- 31 wells b=3
- 6 wells b=4
- 84 wells b>1 &<2
- 6 wells b<1

Storage then Linear
- b = 2
- 829 wells

Bakken Well Performance Characteristics

Nesson Anticline
- 916 wells
- 795 wells b=2
- 31 wells b=3
- 6 wells b=4
- 84 wells b>1 &<2
- 6 wells b<1

Storage then Linear
- b = 2
- 829 wells
Bakken EUR Distributions (mboe)

Bakken Horizontal Well EUR's Determined from Decline Curve Analysis

1. Elm Coulee
   - Data_Mean=410.1
   - Data_Median=353.1
   - Data_P90/P10=127.9/800.2

2. Billings Nose
   - Data_Mean=199.3
   - Data_Median=175.7
   - Data_P90/P10=12.8/426.1

3. Nessan Anticline
   - Data_Mean=450.9
   - Data_Median=390.6
   - Data_P90/P10=111.5/805.7

4. Sanish Area
   - Data_Mean=664.7
   - Data_Median=537.7
   - Data_P90/P10=180.8/1264.8

5. Rough Rider Area
   - Data_Mean=440.6
   - Data_Median=449.6
   - Data_P90/P10=72.5/770.1

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Bakken Stratigraphic Cross Section

Well EUR mboe

Producing Zone

B Value

Structure Contours on top Upper Bakken Shale

CI=250 ft

Carrington
Scallion
Upper Bakken Shale
Middle Bakken
Lower Bakken Shale
Upper Three Forks

Cross section datum = Top of Upper Bakken Shale

Total Productive Interval

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Bakken wells exhibit long duration linear flow

Best explained with ultra low nano darcy matrix in contact with long planar fracs

Fractures provide enough high perm PV to give dual perm rate decline behavior

When b-values ~ 2.0

- Better or more surface area contact with nano darcy matrix perm

When b-values in 0.5 to 1.5 range,

- more influence from fracture pore volume, less influx from matrix
- less surface area contact with matrix relative to total fracture pore volume

In late time, ultra low perm matrix will dominate and decline will flatten to a b = 2

- 1/2 slope on a log log plot

Increasing completion size, pumping more water and sand in more stages to create more planar fractures:

- Increases surface area contact with nano darcy perm matrix
- Creates more high perm pore volume associated with both propped and natural fractures improving early time well performance
- Combining to achieve higher well rates and higher EUR’s