Fluvial Architecture and Connectivity of the Williams Fork Formation, Piceance Basin, Colorado: Combining Outcrop Analogs and Reservoir Modeling for Stratigraphic Reservoir Characterization*

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Abstract

This study addresses the field-scale architecture and static connectivity of fluvial sandstones of the lower Williams Fork Formation through analysis and reservoir modeling of analogous outcrop data from Coal Canyon, Piceance Basin, Colorado. The Upper Cretaceous lower Williams Fork Formation is a relatively low net-to-gross ratio (commonly <30%) succession of fluvial channel sandstones, crevasse splays, flood-plain mudstones, and coals that were deposited by meandering river systems within a coastal-plain setting. The lower Williams Fork outcrops serve as proximal reservoir analogs because the strata dip gently eastward into the Piceance Basin where they form natural gas reservoirs.

Three-dimensional architectural-element models (3-D reservoir models) of the lower Williams Fork Formation that are constrained to outcrop-derived data (e.g., sandstone body types, dimensions, stratigraphic position) from Coal Canyon show how static sandstone body connectivity is sensitive to sandstone body width and varies with net-to-gross ratio and well spacing. With a low well density (e.g., 160-acre well spacing), connectivity is low for net-to-gross ratios less than 20%; connectivity increases between net-to-gross ratios of 20 to 30%, and levels off above a net-to-gross ratio of 30%. As well density increases, static connectivity increases more linearly with an increasing net-to-gross ratio. For a 20-acre well spacing, static connectivity can range from approximately 35 to 75% and 45 to 80% for net-to-gross ratios of 10 and 15%, respectively, depending on sandstone body width. Given the lower net-to-gross ratio and continuity of lower Williams Fork deposits, this underscores the importance of representative sandstone body statistics (e.g., sandstone body type, dimensions) to aid in subsurface correlation and mapping and to constrain reservoir models.

Selected References


Fluvial architecture and connectivity of the Williams Fork Formation, Piceance Basin Colorado: combining outcrop analogs and reservoir modeling for stratigraphic reservoir characterization

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OCGS Luncheon
Outline

- Research objectives
- Study area, setting, stratigraphy
- Fluvial sandstone-body types
- Outcrop-based dimensional data
- Controls on fluvial reservoir connectivity
- Final thoughts…
Research Objectives

For the Cretaceous Williams Fork Formation and equivalent strata:

• Evaluate the stratigraphic variability and reservoir-scale architecture of fluvial sandstone bodies

• Establish a database of fluvial sandstone-body dimensions for reservoir modeling (mapping)

• Evaluate relationships among sandstone-body parameters and reservoir connectivity

• Apply outcrop-based concepts and statistics for integrated reservoir characterization
Study Area

Pranter et al. (2009)
Study Area

- Lower Williams Fork Formation
- Cameo Zone
- Rollins Sandstone
- Iles Formation
- Coal Canyon
Late Cretaceous (~75 ma)
Regional Stratigraphy

~350 Miles

West

Maestrichtian

Price River Fm.
Castlegate Ss.

Campanian

Neslen Fm.

Santonian

Emery Ss. Mbr.

Con. Tur.

Ferron Ss. Mbr.

Tur.

Tuscher & Ferrer Fms.

Buck Tng.

Lance Fm.

Lewis Sh.

Lamprop Fm.

Fox Hills Ss.

Iles Fm.

Pierre Sh.

SW Piceance Basin

Mancos Sh.

Non-Marine (Alluvial Plain & Coastal Plain)

Marginal Marine (Strandline & Deltaic)

Marine (Shelf/Ramp)

Modified from Molenaar and Rice (1988)
Depositional Setting

Sevier Mountains

Piedmont

Alluvial Plain

Coastal Plain

Mancos Sea

Strandline / Deltaic

Rollins (Illes)

Paludal

Cameo Coal

Modified from Ryer and McPhillips (1983); Provided by Rex Cole
Stratigraphy and Fluvial Styles

- Braided
- Meandering
- Anastomosed
The Teredolites Ichnofacies is identified by the presence of borings in wood (e.g., Teredolites), especially those produced by marine bivalves such as the modern shipworm, Teredo.
Skolithos Ichnofacies – indicating marine influence

After Benton & Harper (1997)
Stratigraphy and Type Well

**Sommerville No. 1**
(26, 97W, 11S)

- **Atwell Gulch Member**
  - (Wasatch Formation)
- **Sandstone-Rich**
- **Sandstone-Poor**
- **Rollins Sandstone Member**
  - (Iles Formation)

**Ohio Creek**

**Total Thickness ~ 1,660 ft**

**Cameo Interval**
- (Coal Bearing)

**GR**

**RES**
Sandstone-Poor
lower Williams Fork Formation

Sommerville No. 1
(26, 97W, 11S)

Atwell Gulch Member (Wasatch Formation)

Sandstone-Rich

Sandstone-Poor

Rollins Sandstone Member (Iles Formation)

Williams Fork Formation

Coal Canyon

Cameo-Wheeler Zone

Photo by Steve Cumella

Compound, Sinuous Fluvial Systems

Simple, Sinuous Fluvial Systems

Crevasse Splays & Crevasse Channels

RCML
Compound, Sinuous Architectural Element

*Multistory / Multilateral Channel Body*

Modified from Cole and Cumella (2005) & Pranter et al. (2009)
Sandstone-Rich lower to middle Williams Fork Formation

Sommerville No. 1
(26, 97W, 11S)

Atwell Gulch Member
(Wasatch Formation)

Sandstone-Rich

Williams Fork Formation

Sandstone-Poor

Rollins Sandstone Member
(Iles Formation)

Main Canyon

Low-Sinuosity to Braided Fluvial Systems

Compound, Sinuous Fluvial Systems
Low-Sinuosity to Braided Fluvial Systems

Animas River, Colorado

Main Canyon

Sandstone-Rich lower to middle Williams Fork Formation

Compound, Sinuous Fluvial Systems

Low-Sinuosity to Braided Fluvial Systems
Sandstone-Rich middle and upper Williams Fork Formation

Sommerville No. 1
(26, 97W, 11S)

Atwell Gulch Member
(Wasatch Formation)

Williams Fork Formation

Sandstone-Rich

Sandstone-Poor

Rollins Sandstone Member
(Iles Formation)

~1,200 ft

~200 ft

Plateau Creek Canyon

Amalgamated Low-Sinuosity to Braided Fluvial Systems

Apparent width of 100s to 10,000s of feet
Sandstone-Rich middle and upper Williams Fork Formation

Sommerville No. 1
(26, 97W, 11S)

Atwell Gulch Member
(Wasatch Formation)

Sandstone-Rich
Williams Fork Formation

Sandstone-Poor

Rollins Sandstone Member
(Iles Formation)

Apparent width of 100s to 10,000s of feet

Amalgamated Low-Sinuosity to Braided Fluvial Systems

Sharma (2013)
Summary of Fluvial Architectural Elements

A Crevasse-splay body

B Single-Story channel body

C Multistory / Multilateral channel body

D Amalgamated channel complex (middle and upper Williams Fork Formation)

Apparent width of hundreds to thousands of feet

Pranter et al. (2009); Pranter and Sommer (2011)
Methodology: *Outcrop Measurements*

**Fluvial Sandstone-Body Dimensions were Measured 3 Ways**

1. Field Mapping (GPS & Measured Sections); *Ground Pounding*
2. Aerial LiDAR coupled with Aerial Orthophotographs (Petrel)
3. Calibrated Photo Panoramas of Cliff Faces

- **65 mi²**
- **39 Flight Lines**
- **1.5-ft Resolution**
Sandstone-Body Distribution

Study Area Boundary
/Area ~ 800 Acres/

N = 136

Sand Body Mapped by GPS
MS = Measured Section

2001 & 2002

Cole and Cumella (2005)
Ground-Based LiDAR – “pilot” study

May 2003

Horses for scale
Architectural-Element Heterogeneity

Modified from Ellison (2004) and Pranter et al. (2007)
Architectural-Element Heterogeneity

Hanging out on the Rocks!

Graduate student for scale
Architectural-Element Heterogeneity

Modified from Ellison (2004) and Pranter et al. (2007)
2-D and 3-D Point-Bar Reservoir Models

Modified from Ellison (2004) and Pranter et al. (2007)
**Lithology Model 1:**
Homogeneous point bar deposit

**Lithology Model 2:**
Fluid baffles along lateral accretion surfaces

**Lithology Model 3:**
Fluid baffles associated with shale breaks on lateral accretion surfaces

**Grain-Size Model:**
Based on measured section data from outcrop

Modified from Ellison (2004) and Pranter et al. (2007)
Significance of Architectural-Element Heterogeneity

Lithology Model 1

Lithology Model 2

Lithology Model 3

Modified from Ellison (2004) and Pranter et al. (2007)
Significance of Architectural-Element Heterogeneity

South porosity & perm modeled using same method

Lithology Model 1
BTT = 29 days; SE = 85.7%

Lithology Model 2
BTT = 52 days; SE = 83.2%

Lithology Model 3
BTT = 22 days; SE = 59.7%

Modified from Ellison (2004) and Pranter et al. (2007)
Aerial LiDAR - Light Detection And Ranging

April - June, 2005

Pranter, Cole, Panjaitan, Sommer (2009)
Pranter et al. (2009)

LiDAR - Coal Canyon

2006 & 2007

Sandstone-Body Dimensions:
Thickness and Apparent Width

Panjaitan (2006)
“Slice” Geometries in Modern Point Bar Complex

Apparent Width

Brazos River, Texas

Sand Body
Mud Plug
Data from Cole and Cumella (2005), Panjaitan (2006), and Pranter et al. (2009)
Mapped Fluvial Deposits - LiDAR

Data from Cole and Cumella (2005), Panjaitan (2006), and Pranter et al. (2009)
Fluvial Sandstone-Body Dimensions by Type: Coal, Main, and Plateau Creek Canyons

Data from Cole and Cumella (2005), Panjaitan (2006), and Pranter et al. (2009)
Geologically Constrained Architectural-Element Estimation

Manual Interpretation

Channel Bar/Point Bar Criteria
- $\leq 96$ API GR_NRM cut-off
- fining upward GR_NRM log signature
- $0.05 - 0.25$ DPHI_NRM log signature
- sharp base
- thickness: 2’ – 30’

Crevasse Splay Criteria
- $\leq 96$ API GR_NRM cut-off
- coarsening upward GR_NRM log signature
- $<0.05$ DPHI_NRM log signature
- thickness: $\sim1’ - 15’$

Floodplain Criteria
- $> 96$ API GR_NRM cut-off

Coal Criteria
- $\leq 96$ API GR_NRM cut-off
- $> 0.25$ DPHI_NRM log signature

Constrained Quantitative Interpretation

Overall Accuracy $= 84\%$

2010 - 2013

Allen (2013)
Reservoir Connectivity

Fluvial 3-D models to assess connectivity of reservoir sandstone bodies

Various modeling methods are used:
SIS, Object-Based, MPS, merged

Sommer (2007); Hewlett (2010);
Pranter and Sommer (2011);
Sloan (2012); Pranter et al. (2013)
Connectivity Results / Significance

Model dimensions:
0.25 mi² (160 acres), 500-ft thick
106 x 106 x 250 cells (I,J,K)
cell dimensions 25 ft x 25 ft x 2 ft

Pranter and Sommer (2011)
Impact of Crevasse Splays

Static Sandstone-Body Connectivity

Connectivity based solely on Point Bars

Connectivity of Point Bars and Crevasse Splays

“Connected Volumes” using Petrel

Static Connectivity

Net-to-Gross Ratio
What are the *preserved* shapes and distributions of the fluvial deposits that form the reservoirs?

Two Scenarios (out of many)
Impact of Mudstone Plugs (abandonment channel fill) on Well Performance

Cumulative gas recovery after 30 years comparing the string-of-beads MPS model with the mudstone-plug MPS model for 64 wells at 10-ac (4-hectare, 330-ft) spacing. Shows the variation in recovery. The string-of-beads MPS model shows the highest recovery over 30 years.

**Dynamic Connectivity**

Cumulative production probability comparing the string-of-beads MPS model to the mudstone-plug MPS models at 10-ac (4-hectare, 330-ft) spacing. A difference of 18% production between the two models occurs at 0.50 probability. The 18% difference in production is related to the presence of mudstone plugs.
Deep, deep thoughts…
well, perhaps just common sense…

• Evaluation of reservoir heterogeneity, connectivity, and performance relies on sound geological characterization at different scales…

• Reservoir connectivity is directly related to the stratigraphy, sedimentology, and other geological characteristics…it is a 3-D issue and is actually a dynamic issue…

• Static connectivity analysis based on 3-D reservoir models provides, at best, a qualitative assessment of reservoir connectivity…highly constrained 3-D static reservoir models and dynamic simulation are essential…

• There are many questions regarding the characteristics of fluvial deposits and reservoirs, and importantly, how to properly address the various scales of heterogeneity that exist…
Thank you!