Outcrop to Subsurface Reservoir Characterization of the Lower Mesaverde Group, Red Wash Field, Uinta Basin and Douglas Creek Arch, Utah and Colorado*

Chelsea Fenn\(^1\) and Matthew Pranter\(^2\)

Search and Discovery Article #50995 (2014)**
Posted August 11, 2014

\*Adapted from oral presentation at AAPG Annual Convention and Exhibition, Houston, Texas, April 6-9, 2014
**AAPG©2014 Serial rights given by author. For all other rights contact author directly.

\(^1\)Geological Sciences, University of Colorado, Boulder, Colorado (chelsea.fenn@colorado.edu)
\(^2\)ConocoPhillips School of Geology and Geophysics, University of Oklahoma, Norman, Oklahoma, US

Abstract

The Mesaverde Group within the Uinta Basin produces oil and natural gas from unconventional fluvial sandstone reservoirs. This study addresses the stratigraphic architecture and connectivity of fluvial reservoirs through a combination of outcrop analysis and static and dynamic modeling of equivalent reservoirs. The Cretaceous Mesaverde Group in outcrop and at Red Wash field, Uinta Basin, Utah, serves as an excellent outcrop analog and consists of a succession of fluvial channel sandstones, crevasse splays, floodplain mudstones, and paludal coals that were deposited by meandering- and braided-river systems within coastal- and alluvial-plain settings. Fluvial reservoir bodies are inherently heterogeneous at a range of scales. To analyze the range of spatial variability and to aid in constraining subsurface reservoir models, field descriptions including hand-held spectral-gamma-ray measurements were acquired for four stratigraphic sections (total footage= 650 ft; 198 m) from lower Mesaverde outcrops (near Dinosaur, Colorado). Detailed core descriptions yield facies, facies associations, and architectural elements present within the subsurface at Red Wash Field for comparison to outcrop. The outcrop/core observations and statistics, combined with fluvial sandstone-body statistics from three additional localities (Douglas Creek Arch), and subsurface well data are used to reconstruct local depositional styles, to aid in subsurface correlation, and to condition multiple-point geostatistical models (i.e., multipoint statistics – MPS) of fluvial reservoirs at Red Wash Field. Geologically constrained, well-log-based electrofacies are estimated in non-cored wells using a k-nearest neighbor approach combined with outcrop-based thickness criteria. Three-dimensional models of architectural elements, porosity, and permeability show the spatial variability of reservoir properties and are used to evaluate static and dynamic connectivity across the field and stratigraphically. Static modeling and dynamic-simulation results explore the significance of crevasse splays and channel-sandstone bodies (fluvial bars) on reservoir connectivity and effective well spacing.
Selected References


Outcrop-to-Subsurface Reservoir Characterization of the Lower Mesaverde Group, Red Wash Field, Uinta Basin and Douglas Creek Arch, Utah and Colorado

Chelsea A. Fenn\textsuperscript{1} and Matthew J. Pranter\textsuperscript{2}

\textsuperscript{1} Department of Geological Sciences
University of Colorado

\textsuperscript{2} ConocoPhillips School of Geology and Geophysics
University of Oklahoma

AAPG ACE 2014 – Houston, Texas, April 8\textsuperscript{th}, 2014

Reservoir Characterization and Modeling Laboratory
Acknowledgements

Mark Longman
Russ Griffin
John Still
Greg Gromadzki

Rex Cole
Chris Beliveau
Dan King
Kevin Toeneboehn

AAPG
Williams Fork Consortium Sponsors
Outline

• Introduction
  • Research focus, study area, geologic history

• Outcrop Analysis
  • Facies associations and paleocurrent data

• 3-D Reservoir Modeling
  • Modeling techniques and workflow

• Fluvial Reservoir Connectivity
  • Analysis and results – well-based connectivity
Research Focus

For the lower Mesaverde Group:

• What is the stratigraphic variability of sedimentary and reservoir properties (lithology, architectural elements, porosity, permeability)?

• How does static reservoir connectivity vary with well spacing, net-to-gross ratio, and sandstone-body type?
Study Area

Modified from Johnson and Roberts (2003)

Outcrop location

Red Wash Field – subsurface study area

Modified from Johnson and Roberts (2003)
Geologic History

Modified From Ron Blakey (2004)
Depositional Setting

Modified from Ryer and McPhillips (1983); Provided by Rex Cole
Mesaverde Group: Stratigraphy

**TERTIARY STRATA**

- Sand-Rich
  - Williams Fork Fm.
- Sand-Poor
  - Williams Fork Fm.
- Iles Fm.
- Cozzette Mbr.
- Rollins Mbr.
- Corcoran Mbr.
- Upper Sego
- Lower Sego
- Anchor Mine Tng. (Mancos)
- Buck Tng. (Mancos)
- Neslen Fm.
- Bluecastle Tng.
- Farrer Fm.
- Price River Fm.
- Price River Fm.

**MESAVERDE GROUP**

- Desert Mbr.
- Grassy Mbr.
- Sunnyside Mbr.
- Kenilworth Mbr.
- Aberdeen Mbr.
- Spring Canyon Mbr.
- Storrs Tng.
- Panther Tng.
- Castlegate Ss.
- Sego Ss.
- "Traditional" Castlegate Ss.

**E. UINTA BASIN**
- Dark Canyon Interval

**DCA**
- Unconformity
- Kmvu
- Kmvc
- Study interval

**W. PICEANCE BASIN**
- Ohio Creek Interval
- Rollins Mbr.
- Cozzette Mbr.
- Corcoran Mbr.
- Nescen Fm.
- Bluecastle Tng.
- Farrer Fm.
- Price River Fm.

**Mancos Shale**

- Modified from Hettinger and Kirschbaum (2003); Figure from Cole (2010)

- Kmvu = Upper Mesaverde (rare coal)
- Kmvc = Main Coal-Bearing Mesaverde Interval
- Kmvl = Lower Coal-Bearing Mesaverde Interval

**E. UINTA BASIN**
- Dark Canyon Interval

**DCA**
- Unconformity
- Kmvu
- Kmvc
- Study interval

**W. PICEANCE BASIN**
- Ohio Creek Interval
- Rollins Mbr.
- Cozzette Mbr.
- Corcoran Mbr.
- Nescen Fm.
- Bluecastle Tng.
- Farrer Fm.
- Price River Fm.

**Mancos Shale**

- Modified from Hettinger and Kirschbaum (2003); Figure from Cole (2010)

- Kmvu = Upper Mesaverde (rare coal)
- Kmvc = Main Coal-Bearing Mesaverde Interval
- Kmvl = Lower Coal-Bearing Mesaverde Interval
Field Area

Mesaverde outcrops
roadcut
6S 25E
7S 25E
Dinosaur, CO

Castlegate
UTAH
COLORADO
Outcrop Analysis

- 4 measured sections
  - Total: ~650 ft
- Paleocurrent indicators

- Facies descriptions
  - Lithology
  - Physical structures
  - Ichnology
Facies Associations

Unit 2, MS-03

Level of marine influence low

- Ripple cross-laminated sandstone
- Coal w/ abundant plant fragments
- Fissile, organic-rich mudstone
Outcrop Analysis

Sand-body thickness, facies associations, and paleocurrent data → 3D fluvial reservoir modeling
Subsurface Data

Red Wash Field

3D reservoir model area
Mesaverde Group

Neslen

Sego sandstone

Architectural-Element Logs

Channel/Fluvial bar criteria
- < 96 API GRN cut-off
- < 0.25 DPHI signature
- Fining-upward log signature
- Sharp base

Crevasse Splay criteria
- < 96 API GRN cut-off
- Coarsening-upward log signature

Floodplain criteria
- > 96 API GRN cut-off

Coal criteria
- < 96 API GRN cut-off
- > 0.25 DPHI signature
Stratigraphic Framework

Zone 1

Zone 2

Zone 3

Zone 4

Zone 5

Zone 6

Cell size: 50 x 50 ft X 1.5 ft
Model area: 6260 x 4210 ft
Model thickness: ~500-600 ft

V.E. = 4x
Modeling Techniques

- **Sequential Indicator Simulation (SIS)**
  - Assign geologic/petrophysical properties cell-by-cell
  - Variogram based - geologic shapes are difficult to model

- **Object-based (Boolean)**
  - Defined facies objects to populate the model
  - Size, geometry, and orientation of distinct geologic bodies (i.e., from outcrop)

- **Multi-point Statistics (image-based)**
  - Training image → replaces the variogram
  - Model spatial geologic relationships and concepts
What are the preserved geometries of the deposits?

Crescent-shaped fluvial bars?

Sinuous channel sandstones / fluvial bars?

Probably none of the above…
Integrated Modeling Approach

Multiple-point geostatistics (MPS)

Training images →

- object-based modeling of two scenarios

- Generated for each zone

- Constrained to outcrop-based statistics

- Training image size: 7810 x 8820 x 30 ft
- Cell size: 50 x 50 x 1 ft
MPS-Based Fluvial Reservoir Models

**Sinuous channels / fluvial bars**

- Floodplain
- Fluvial channel/bar
- Crevasse splay
- Coal

V.E. = 4x

Top Neslen

**Crescent-shaped fluvial bars**

V.E. = 4x

Top Sego
Static Connectivity

Static connectivity =

Connected Sandstone Volume

---

Total Sandstone Volume

Example: 40-ac spacing

58.4%

4.9%/well
Static Connectivity

10 wells (approx. 40-ac)
3 wells (2640 ft apart)
12 wells (1320 ft apart)
54 wells (660 ft apart)
228 wells (330 ft apart)

Sandstone connectivity & “Reservoir-quality” sandstone connectivity (6%-15% porosity)
Static Connectivity

- Sinuous Channels
- Crescent Fluvial Bars
- All Sandstone
- “Reservoir” Sandstone

Well-based Static Connectivity

- Total Connectivity
- Connectivity per well

Connectivity (%)

Well Spacing

- 3 wells
- 12 wells
- 54 wells
- 228 wells

Total connectivity

Connectivity per well
Impact of Crevasse Splays

Static reservoir sandstone connectivity impacted by the presence of crevasse splay.
Static Connectivity by Zone

Stratigraphic variation in connectivity and N:G ratio

Net:Gross Ratio

<table>
<thead>
<tr>
<th>Zone</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>35.3</td>
</tr>
<tr>
<td>Zone 2</td>
<td>39.5</td>
</tr>
<tr>
<td>Zone 3</td>
<td>48.1</td>
</tr>
<tr>
<td>Zone 4</td>
<td>55.3</td>
</tr>
<tr>
<td>Zone 5</td>
<td>54.2</td>
</tr>
<tr>
<td>Zone 6</td>
<td>27.6</td>
</tr>
</tbody>
</table>

V.E. = 4x
Static Connectivity by Zone

2.5-ac Spacing (highest well density)

High well density → little variation in connectivity

160-ac Spacing (lowest well density)

Low well density → variable connectivity based on N:G ratio
Conclusions

For the lower Mesaverde Group:

- Consists of continental fluvial deposits, where the occurrence of fluvial bars and N:G increases up section

- No significant difference in static connectivity between the two MPS modeling scenarios (average 6% difference)

- Static connectivity varies stratigraphically with well density and N:G ratio, which also varies as a function of stratigraphy

- Crevasse splays enhance static connectivity at all well spacings; therefore, understanding their reservoir quality and spatial distribution is important

Presenter’s notes: Outcrop dimensions are consistent with other studies conducted along the DCA. Uncertainty regarding the preserved geometry of fluvial deposits was addressed using two MPS modeling scenarios: sinuous channel fill/bars & crescent-shaped channel bars. Static connectivity of fluvial sandstones increases with higher well density, but decreases on a per-well basis. High well density (2.5-ac) produces little variation in static connectivity regardless of N:G ratio. Low well density (160-ac) produces variable static connectivity as N:G ratio varies stratigraphically.


BACKUP SLIDES
Previous Work: Static Connectivity

- Static connectivity: the percentage value that is calculated by the volume of sandstone connected to a particular pattern of wells divided by the total sandstone volume

Pranter and Sommer (2011)
- Synthetic outcrop-based model with various net-to-gross and well-spacing scenarios
Previous Work: Static Connectivity

Relationship between net-to-gross ratio and connectivity for multiple well-spacing scenarios

From Pranter and Sommer (2011)
Background: Architectural Elements

- Architectural elements
  - distinct geometry
  - spatial distribution
  - facies/facies associations

- Analog: Williams Fork Formation, Piceance Basin
  - (Anderson, 2005; Cole and Cumella, 2005; Pranter et al., 2009; Harper, 2011; Hlava, 2011; Pranter and Sommer, 2011)

From Pranter et al. (2009)
Training Image Testing

Sinuous channel fill/fluvial bars

Fluvial crescent-shaped bars

MPS Model Result for Zone 6

Training Images for Zone 6
### Connectivity per Well

<table>
<thead>
<tr>
<th></th>
<th>160-ac spacing</th>
<th>40-ac spacing</th>
<th>10-ac spacing</th>
<th>2.5-ac spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Connected</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Channel</td>
<td>56.1%</td>
<td>61.6%</td>
<td>68.1%</td>
<td>68.8%</td>
</tr>
<tr>
<td></td>
<td>18.7%/well</td>
<td>5.1%/well</td>
<td>1.3%/well</td>
<td>0.3%/well</td>
</tr>
<tr>
<td><strong>Isolated</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Point Bars</td>
<td>53.6%</td>
<td>58.4%</td>
<td>65.7%</td>
<td>66.4%</td>
</tr>
<tr>
<td></td>
<td>17.9%/well</td>
<td>4.9%/well</td>
<td>1.2%/well</td>
<td>0.3%/well</td>
</tr>
</tbody>
</table>
Porosity Model

“Reservoir-quality” sandstone connectivity (6%-15% porosity)

Sequential Gaussian Simulation
Connectivity by Zone

Stratigraphic variation in connectivity and N:G ratio

<table>
<thead>
<tr>
<th>Zone</th>
<th>Reservoir Connectivity</th>
<th>Net:Gross</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>64.6</td>
<td>35.3</td>
</tr>
<tr>
<td>2</td>
<td>84.2</td>
<td>39.5</td>
</tr>
<tr>
<td>3</td>
<td>92.0</td>
<td>48.1</td>
</tr>
<tr>
<td>4</td>
<td>86.8</td>
<td>55.3</td>
</tr>
<tr>
<td>5</td>
<td>87.5</td>
<td>54.2</td>
</tr>
<tr>
<td>6</td>
<td>45.5</td>
<td>27.6</td>
</tr>
</tbody>
</table>
Connectivity by Zone & N:G Ratio
Well-based Connectivity

**Connectivity - Connected Channels**

<table>
<thead>
<tr>
<th>Well Spacing</th>
<th>Reservoir</th>
<th>Bulk</th>
</tr>
</thead>
<tbody>
<tr>
<td>current</td>
<td>60.5</td>
<td>86.4</td>
</tr>
<tr>
<td>160-ac</td>
<td>56.1</td>
<td>82.7</td>
</tr>
<tr>
<td>40-ac</td>
<td>61.6</td>
<td>89.4</td>
</tr>
<tr>
<td>10-ac</td>
<td>68.1</td>
<td>95.3</td>
</tr>
<tr>
<td>2.5-ac</td>
<td>68.8</td>
<td>96.1</td>
</tr>
</tbody>
</table>

**Connectivity - Isolated Point Bars**

<table>
<thead>
<tr>
<th>Well Spacing</th>
<th>Reservoir</th>
<th>Bulk</th>
</tr>
</thead>
<tbody>
<tr>
<td>current</td>
<td>56.8</td>
<td>80.4</td>
</tr>
<tr>
<td>160-ac</td>
<td>53.6</td>
<td>77.1</td>
</tr>
<tr>
<td>40-ac</td>
<td>58.4</td>
<td>85.4</td>
</tr>
<tr>
<td>10-ac</td>
<td>65.7</td>
<td>92.6</td>
</tr>
<tr>
<td>2.5-ac</td>
<td>66.4</td>
<td>93.4</td>
</tr>
</tbody>
</table>
Sequential Indicator Simulation

- **Sequential Indicator Simulation (SIS - cell-based)**
  - Assign geologic/petrophysical properties cell-by-cell
  - Most common industry standard; highly tested
  - Can honor large amounts of data
  - Geologic shapes are difficult to model
Object-Based Modeling

- Object-based (Boolean)
  - Defined facies objects to populate the model
  - Rock properties modeled within objects
  - Honor geologic rules
  - More difficult to honor large amounts of data
  - Size, geometry, and orientation of distinct geologic bodies (i.e., from outcrop)
Multi-Point Statistics (MPS)

- Multi-Point Statistics (MPS)
  - Training image → replaces the variogram
  - SNESIM algorithm
  - Model spatial geologic relationships and concepts
Paleocurrent Data

MS-01 Unit 5

MS-01 Unit 4

MS-01 Unit 3

MS-02 Unit 5

MS-02 Unit 4

n=34

n=24

n=4

n=24

n=16
Paleocurrent Data

MS-04 Unit 5
n=7

MS-04 Unit 4
n=16

MS-03 Base Sand
n=26
Methods: Fieldwork

- Field observations
  - Lateral and vertical changes in lithology
  - Grain size and sorting
  - Bioturbation
  - Sedimentary structures
  - Paleocurrent indicators
  - Significant surfaces

- Sandstone body measurements
  - Dimensions
  - Abundance
  - Stacking patterns

- Measured sections
Locations of Measured Section

- MS-01
- MS-02
- MS-03
- MS-04

Utah
Colorado
Common Facies Present

**Ripple cross-laminated sandstone**
- White to beige fine- to medium-grained sandstone
- Climbing asymmetrical ripples

**Fissile mudstone**
- Dark grey to black, organic-rich, fissile mudstone
- Abundant plant debris
- Associated with thin (<1 ft) coal beds
Common Facies Present

**Convolute sandstone**
- Beige fine- to medium-grained sandstone
- Soft sediment deformation

**Sandstone with wood fragments**
- White fine- to medium-grained sandstone
- Poorly indurated
- Wood fragments and plant debris

**Cross-bedded sandstone**
- Low- to high-angle cross-bedded sandstone
Geologic History

Modified from Blakey (2004) and White et al. (2008)
Depositional Setting

Modified from Ryer and McPhillips (1983); Provided by Rex Cole
Methods: Subsurface Data Set

- Well logs for ~70 wells in Red Wash Field
- Manual interpretation of architectural elements

Normalized gamma ray curves in PowerLog

Multi-well histograms for grouped gamma ray log normalization using PowerLog