Static connectivity of fluvial sandstones in a lower coastalplain setting: An example from the Upper Cretaceous lower Williams Fork Formation, Piceance Basin, Colorado

Matthew J. Pranter and Nicholas K. Sommer

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-ac 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

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increases, static connectivity increases more linearly with an increasing net-to-gross ratio. For a 20-ac 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.

INTRODUCTION

The Upper Cretaceous lower Williams Fork Formation in the Piceance Basin produces natural gas from numerous isolated lenticular to channel-form sandstone bodies that were deposited by meandering river systems within a coastal-plain setting. Much research, at the reservoir or field scale, has been conducted on the Williams Fork Formation because the reservoirs are discontinuous and difficult to correlate and map, even with dense (e.g., 10-ac, 660-ft [201-m] well spacing) well control (Johnson, 1989; Hemborg, 2000; Cumella and Ostby, 2003; Ellison, 2004; Cole and Cumella, 2005; Pranter et al., 2007, 2009). In addition, porosity and permeability values are low (6–12%, 0.1–2 microdarcys, respectively) and sandstone reservoirs are internally heterogeneous. As a result, well spacing has been reduced from 20 to 10 ac (933 to 660 ft [284 to 201 m], respectively), and wells are preferentially aligned to maximize natural-gas recovery by intersecting additional reservoir sandstones (compartments) and to minimize the interference between wells associated with hydraulic-fracture stimulation of the fluvial sandstones.

This study focuses on the static connectivity of fluvial sandstones of the lower Williams Fork Formation through analysis and modeling of analogous outcrop data. Static connectivity as used herein is a percentage that is calculated as the volume of sandstone bodies connected to a particular pattern of wells (directly or indirectly; i.e., through amalgamation) divided by the total sandstone volume. This measure of connectivity does not account for the dynamic flow of fluids through the reservoir. The fluvial sandstone body data for the analyses and modeling are derived from the lower Williams Fork Formation outcrops within Coal Canyon on the western margin of the Piceance Basin (Figure 1), just north of Palisade, Colorado. Exposures of the lower Williams Fork Formation within Coal Canyon extend for approximately 5.7 mi (9.2 km) and serve as outcrop-reservoir analogs. Producing fields from the same stratigraphic
interval of the Williams Fork Formation are located as close as 25 mi (40 km) to the east into the Piceance Basin (Figure 1).

The connectivity of fluvial sandstones whose dimensions are below the resolution of conventional three-dimensional (3-D) seismic data is difficult to assess from one-dimensional (1-D) well data. Two-dimensional (2-D) connectivity is generally lower than 3-D connectivity based on outcrop (Pringle et al., 2004) and theoretical models (King, 1990; Hovadik and Larue, 2007). Therefore, it is appropriate to model fluvial sandstones in 3-D to

Figure 1. Map of the Piceance Basin. Outcrops of the Mesaverde Group are exposed along the basin margin. Reprinted from Pranter et al. (2009); used with permission from AAPG. Modified from Johnson (1989), Tyler and McMurray (1995), and Hoak and Klawitter (1997).
investigate static connectivity. Allen (1978) studied connectivity of channel belts in 2-D models and described how regularly packed uniform sandstone bodies are virtually unconnected in alluvial suites containing 50% or more overbank mudstone. Once the proportion of sandstone bodies increases more than 50%, the degree of connectivity rises steeply (Allen, 1978). King (1990) and Allard and HERESIM Group (1993) studied connectivity based on the principles of percolation theory, which involves connectivity in random systems. As the model sandstone fraction rises, the connectivity of sand cells remains low until a certain sand percentage (net-to-gross ratio) is reached, called the percolation threshold. Connectivity rises sharply, and many smaller isolated sand bodies become connected into one large sand body with only a small increase in net-to-gross ratio (Hovadik and Larue, 2007). King (1990) showed that the percolation threshold in 2-D occurred at about a 60% net-to-gross ratio, but that in 3-D models, it occurred at about a 25% net-to-gross ratio. Larue and Hovadik (2006) referred to the range of net-to-gross ratio in which connectivity increases steeply as the “cascade zone” and described the relationship between net-to-gross ratio and connectivity as an S-curve because of the trend observed when the two are depicted graphically. Donselaar and Overeem (2008) suggest that if channel-floor sandstone ribbons connect point-bar deposits (forming a string-of-beads sandstone body, specifically in low-gradient, mixed-load fluvial systems), this could shift the S-curve such that static sandstone body connectivity increases more steeply at lower net-to-gross ratios.

Measures of static connectivity have been defined differently by different workers. Larue and Hovadik (2006) describe sandstone body and geobody connectivities as measures of connectivity of reservoir architectural elements to each other. These measures of connectivity are reported as a percentage, defined by the volume of the largest reservoir rock divided by the total reservoir rock volume (termed “connectivity [%]” by Larue and Hovadik, 2006). A geobody is one or more connected reservoir rock bodies. Sandstone body and geobody connectivities are measures of the “depositional connectivity” as described by Ainsworth (2005). Depositional connectivity does not consider structural deformation (faulting/fracturing and/or folding) or fluid flow. Reservoir connectivity has been described as the part of a reservoir that is connected to wells and is also measured as a percentage (the volume of reservoir rock that is connected to wells divided by the total volume of reservoir rock (Larue and Hovadik, 2006). Other definitions of connectivity involve characterization of permeability heterogeneity and evaluation of subsurface fluid flow.

Through this study, 3-D reservoir models based on the detailed statistics of fluvial sandstone body dimensions, orientations, shape, and stratigraphic distribution are used to quantitatively evaluate static connectivity and the sensitivity of fluvial sandstone body connectivity to these parameters. In this study, reservoir rock includes fluvial channel sandstones and crevasse splays; flood-plain mudstones are considered as nonreservoir strata. The 3-D static-connectivity results provide insight concerning expected connected reservoir volumes for various model input parameters at different net-to-gross ratios and well spacings. Understanding the static connectivity of the fluvial sandstones is important for the lower Williams Fork gas reservoirs because gas can only be produced from reservoir rock that is connected to a wellbore. In addition, representative models of static connectivity and reservoir geometries are useful for reserve estimation, infill-drilling program design, and the selection of intervals for completion.

TECTONIC AND STRATIGRAPHIC SETTING

The Piceance Basin is an asymmetrical northwest-southeast–elongated basin that is surrounded by uplifts that developed during the Laramide orogeny (~75–40 Ma): the White River uplift to the east, Axial arch and Uinta Mountains to the north, Douglas Creek arch to the west, Uncompahgre uplift to the southwest, Gunnison uplift and Elk Mountains to the south, and Sawatch uplift to the southeast (Figure 1). Before the Laramide orogeny began in the Late Cretaceous, the area now occupied by the Piceance Basin was part of a much
larger Rocky Mountain foreland basin system that was created by the Sevier orogeny (∼140–50 Ma). Laramide uplifts partitioned the Colorado Plateau region into the mosaic of basins and uplifts present today (Johnson and Flores, 2003; DeCelles, 2004). The White River uplift created the Grand Hogback along the eastern margin of the Piceance Basin. Here, the strata are very steeply dipping to overturned, unlike the study area on the western margin of the basin, where the strata dip gently eastward into the basin at about 4 to 7°.

In this article, we follow the stratigraphic terminology of Hettinger and Kirschbaum (2002) and Hettinger et al. (2003) for the Mesaverde Group in the southwestern Piceance Basin (Figure 2). The Mesaverde Group includes the Iles and Williams Fork formations and overlies a thick interval of marine Mancos Shale (Figure 2). The Iles Formation consists of regressive marine shoreface sandstones (in ascending order, the Corcoran, Cozzette, and Rollins sandstone members) separated by transgressive intervals (tongues) of the Shale (Young,
The Williams Fork Formation, as exposed within Coal Canyon, conformably overlies the Rollins Sandstone Member and consists dominantly of strata deposited by fluvial systems with minor marine influences. The Williams Fork Formation is approximately 5000 ft (1524 m) thick near the Grand Hogback on the eastern margin of the basin and thins to approximately 1200 ft (365 m) thick at the Colorado-Utah state line (Hettinger and Kirschbaum, 2002; Hettinger et al., 2003). Within Coal Canyon, the lower Williams Fork Formation ranges in thickness from approximately 500 to 700 ft (152–213 m). The westward stratigraphic thinning is thought to be related to regional truncation at the top of the Williams Fork Formation and variations in subsidence across the Piceance Basin (Hettinger and Kirschbaum, 2002; Johnson et al., 2003). The coarser grained uppermost part of the Williams Fork Formation is called the Ohio Creek Member (or the Ohio Creek conglomerate) and is interpreted as lowstand deposits formed by braided-fluvial streams active in the Paleocene (Patterson et al., 2003; Burger, 2007). The base of the Ohio Creek conglomerate is a regionally extensive unconformity that is attributed to the onset of the Laramide orogeny (Patterson et al., 2003). The Wasatch Formation unconformably overlies the Ohio Creek conglomerate and is a generally low net-to-gross ratio fluvial unit that contains some sandstone-rich intervals (for instance, the Molina Member) (Johnson, 1989; Johnson and Flores, 2003).

The Williams Fork Formation is subdivided into lower (sandstone-poor) and middle to upper (sandstone-rich) intervals based on outcrops in the southwestern part of the Piceance Basin (Cole and Cumella, 2005). The lower Williams Fork Formation as exposed in Coal Canyon has an average net-to-gross ratio of approximately 15%; however, the net-to-gross ratio varies stratigraphically. The lower Williams Fork Formation was deposited within anastomosing to meandering river systems within a coastal-plain setting (Lorenz, 1987; Johnson, 1989; Hemborg, 2000; Cole and Cumella, 2003, 2005; Patterson et al., 2003; Pranter et al., 2007, 2009).

The Cameo-Wheeler coal zone comprises the lowermost 240 ft (73 m) of the Williams Fork Formation in Coal Canyon and consists of interstratified coal, carbonaceous mudstone, and sandstone. The four mappable coal seams of the Cameo-Wheeler coal zone were deposited in peat bogs and marshes (mires). Within the study area, mudstone lithofacies are mostly abundant and account for approximately 60 to 80% of the lower Williams Fork Formation within Coal Canyon (Cole and Cumella, 2005; Pranter et al., 2009). Other common lithofacies include trough cross-bedded sandstone, massive sandstone, conglomeratic mud-chip sandstone, current-rippled sandstone, bioturbated silty sandstone, and coal and bentonite beds (Ellison, 2004; Cole and Cumella, 2005; Pranter et al., 2007, 2009).

The middle-to-upper Williams Fork Formation is interpreted to have been deposited by a low-to-moderate sinuosity braided river system in an alluvial-plain setting (Patterson et al., 2003; Cole and Cumella, 2005; German, 2006) and has a net-to-gross ratio between 50 and 80% (Cole and Cumella, 2005; German, 2006). This interpretation has primarily been based on limited information such as the low-to-moderate range of paleocurrent values, the paucity of sandstones with distinct lateral accretion surfaces, and to a lesser extent, the relatively higher net-to-gross ratio for the middle to upper Williams Fork Formation. However, additional data are needed to convincingly document the braided fluvial interpretation for the middle to upper Williams Fork Formation and to address how the fluvial system stratigraphically changes throughout the Williams Fork Formation. Middle to upper Williams Fork Formation sandstone bodies, as exposed in Plateau Creek and Main canyons (Figure 3), are highly amalgamated and sheetlike. These composite sandstone bodies have high width-to-thickness (W:T) ratios (8:1–100:1; average, 34:1) (German, 2006). The static connectivity of the middle-to-upper Williams Fork Formation sandstones is thought to be higher than that of the lower Williams Fork Formation because of the high net-to-gross ratio (50–80%) and high W:T ratios of the sandstone bodies (German, 2006).
Figure 3. (A) Aerial LIDAR-orthophoto composite for the Coal Canyon, Main Canyon, and Plateau Creek Canyon areas. (B) Topographic map of the Coal Canyon area (modified from the U.S. Geological Survey Cameo, Colorado 7.5 minute Quadrangle, 1955). The locations of mapped sandstone bodies (by type) of the lower part of the Williams Fork Formation are shown. The approximate locations of the outcrops of Figures 4 and 9 are shown in (B). The approximate locations of the outcrop areas in Coal Canyon that were analyzed and used to create the vertical proportion curves (vertical proportion curve [VPC]; used as a modeling constraint) of Figure 11 are shown as bold black lines. The gray outlined box in (A) is the approximate area of (B). Modified from Pranter et al. (2009).
METHODS

The outcrops of fluvial sandstones of the Williams Fork Formation have been analyzed for abundance, type, apparent width, thickness, and orientation (Ellison, 2004; Cole and Cumella, 2005; Panjaitan, 2006; German, 2006; Pranter et al., 2007, 2009; Sommer, 2007). The term “sandstone body” or “channel body” as used herein is defined as a volume of sandstone and interbedded mudstone that has a discrete thickness and lateral extent.

For the lower Williams Fork Formation, two methods were used to map and measure the dimensions of single-story and multistory channel bodies and crevasse-splay deposits in the outcrop: (1) global positioning system (GPS) traverses combined with field descriptions and tape measurements, and (2) high-resolution aerial light detection and ranging (LIDAR) data and digital orthophotography combined with ground-based photomosaics (Figures 3, 4) (Cole and Cumella, 2005; Panjaitan, 2006; Sommer, 2007; Pranter et al.,

**Figure 4.** Comparison of (A) outcrop photomosaic and (B) outcrop LIDAR-orthophoto composite for a similar field of view within Coal Canyon. The approximate location of the outcrop within Coal Canyon is shown in Figure 3. Modified from Pranter et al. (2009).
The GPS receivers have a positional accuracy of ±20 ft (±6 m) and a vertical accuracy of ±50 ft (±15 m). The LIDAR data have a horizontal resolution of 1.5 ft (0.5 m) and a vertical resolution of 0.25 ft (0.076 m). The corresponding georeferenced digital orthophotographs have a pixel resolution of 1.5 ft (0.5 m). Outcrop data are used to create and constrain 3-D architectural-element models (reservoir models) of the lower Williams Fork Formation that are representative of subsurface reservoirs. The goal of the modeling was to approximate the 3-D sedimentary architecture of the lower Williams Fork Formation while accounting for uncertainties associated with using outcrop-analog data (from 2-D outcrops). The dimensions, orientation, net-to-gross ratio, and stacking patterns of the fluvial sandstones determine their static connectivity. Based on the output models, the static connectivity of the fluvial sandstone bodies was analyzed.

Various methods could be used to model the fluvial deposits of this study; however, stochastic object-based modeling was used for the following reasons: (1) the fluvial sandstones form “bodies” or “objects” with distinct geometries and boundaries (vs. deposits with gradational contacts), and object-based modeling simulates the reservoir/nonreservoir (fluvial sandstone body/flood-plain mudstone) juxtaposition; (2) to directly take advantage of the extensive dimensional data from outcrop that were used to model the sizes of objects that represent the fluvial sandstone bodies; and (3) given the uncertainty of the input data, stochastic (object-based) modeling is useful to generate different model scenarios with multiple realizations to evaluate the sensitivity of the fluvial sandstone body static connectivity to various parameters.

Uncertainties associated with the lateral dimensions and orientations of reservoir sandstones as well as the objects chosen to represent the channel sandstones were addressed in this study through multiple model scenarios. Seven different scenarios were modeled using four different volume-based net-to-gross ratios (10, 20, 30, and 40%), each consisting of 30 realizations for a given set of input data, resulting in a total of 840 models. One variable at a time was changed within a scenario grouping; single-story and multistory channel body width distributions, orientation distributions, and object types were varied.

MEANDERING RIVER SANDSTONE BODY TYPES AND STATISTICS

Cole and Cumella (2005), Panjaitan (2006), Sommer (2007), and Pranter et al. (2009) present outcrop and subsurface data for lower Williams Fork Formation sandstone bodies, including their types, dimensions, stratigraphic architecture, and inferred connectivity. Within Coal Canyon, sandstone bodies of the lower Williams Fork Formation were mapped and measured based on field descriptions, GPS traverses, aerial LIDAR data, digital orthophotography, and ground-based outcrop photomosaics (Figure 3). Details regarding the mapping methods and sandstone body statistics are presented in Pranter et al. (2009). Fluvial sandstone bodies that are observed and interpreted in the Williams Fork Formation include (1) crevasse splays, (2) single-story channel bodies, (3) multistory channel bodies (sensu Gibling, 2006; used to describe bodies with several stories however disposed), and (4) much larger amalgamated channel complexes (Cole and Cumella, 2005; Pranter et al., 2009) (Figure 5). The relatively thin single-story channel sandstone bodies are commonly composed of a single sharp-based fining-upward sandstone body (“story or storey” of Friend et al., 1979). In contrast, the relatively thicker channel sandstone bodies comprise two or more vertically stacked to laterally coalesced stories that are commonly separated by scour surfaces and lag deposits and are referred to herein as “multistory channel bodies.” Data exist for more than 668 sandstone bodies of the lower Williams Fork Formation from Coal Canyon (Pranter et al., 2009); however, at the time of this study, available data for 636 sandstone bodies were used. Of this population, 265 (42%) are crevasse splays, 116 (18%) are single-story (and narrow) channel bodies, and 255 (40%) are multistory channel bodies. A statistical summary of lower Williams Fork Formation sandstone body dimensions used in this study is presented in Table 1.
Figure 5. Classification of sandstone body types of the Williams Fork Formation. Sandstone body types of (A), (B), and (C) are associated with the lower Williams Fork Formation and are the focus of this study. (A) Crevasse splay, (B) single-story channel body, (C) multistory channel body, and (D) amalgamated channel complex examples are shown with a schematic map view of the depositional setting and cross-sectional view of the body. Amalgamated channel complexes are associated with the middle to upper Williams Fork Formation and are presented here for completeness. The map view images represent the plan view geometry and distribution of fluvial deposits at a snapshot in time. Classification is modified from Cole and Cumella (2005). Schematic classification images were provided by Rex Cole. Figure is modified from Pranter et al. (2009).
Crevasse-splay deposits (Figure 5A) are broadly lenticular in cross sectional view, very fine to fine grained, ripple laminated to cross stratified, and commonly bioturbated (Cole and Cumella, 2005). Single-story channel bodies (Figure 5B), commonly isolated point-bar deposits (Ellison, 2004; Cole and Cumella, 2005; Pranter et al., 2007, 2009), are fine to medium grained, cross stratified to ripple laminated, and commonly have mud-chip lags at their bases and lateral accretion bedding. Narrow (possibly anastomosing) channel bodies are rare (1.4% of population), commonly fine to medium grained, and cross stratified to ripple laminated. These deposits are distinguished from the other sandstone body types in that they exhibit well-developed wings (levees and splays) and are more narrow (Cole and Cumella, 2005). Multistory channel bodies (Figure 5C) consist of vertically and laterally stacked channel form bodies that exhibit multiple scour surfaces (Cole and Cumella, 2005; German, 2006). Single-story and multistory channel bodies and crevasse splays are common in the lower Williams Fork Formation as exposed within Coal Canyon. Within the Plateau Creek and Main canyons (Figure 3A), the middle to upper Williams Fork Formation is dominated by high net-to-gross ratio (commonly 50–80%) amalgamated channel complexes (Figure 5D) that are characterized by sheet-like sandstone bodies and associated mudstones (German, 2006). German (2006) presents outcrop and subsurface data for middle to upper Williams Fork Formation sandstone bodies (N = 113) in Plateau Creek Canyon. The map view image of Figure 5B represents the plan view geometry of the channel and distribution of point bars at a snapshot in time. At this time, the pattern of point bars could form semi-isolated deposits or, in some cases, channel floor sandstone ribbons might exist that connect point bars to form a string-of-beads pattern (Donselaar and Overeem, 2008; an example of deposits preserved in a low-gradient mixed-load fluvial system). However, because meandering fluvial systems are dynamic, and channel-bend migration, changes in channel sinuosity, scouring, amalgamation, abandonment, and other processes occur through time, the ultimate preserved shape and

<table>
<thead>
<tr>
<th>Sandstone-Body Type</th>
<th>n</th>
<th>Minimum</th>
<th>Mean</th>
<th>Median</th>
<th>Maximum</th>
<th>Standard Deviation</th>
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<td>Crevasse Splay</td>
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<td>9.3</td>
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<td>398.2</td>
<td>1717.0</td>
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*Data modified from Cole and Cumella (2005), Panjaitan (2006), and Pranter et al. (2009).
distribution of the deposits will commonly be highly variable (e.g., from more elongate to more circular in plan view shape); that is, the preserved rock record is commonly a relatively complex mosaic of fluvial deposits, built from partially eroded remnants of the genetic elements of the active river (North and Davidson, 2010). Meander loop migration, cutoff, and avulsion within a meander belt will ultimately create a complex pattern of isolated to interconnected fluvial deposits. In the case of the lower Williams Fork Formation, in lower net-to-gross ratio intervals and in plan view, the preserved fluvial deposits are interpreted to form somewhat isolated equidimensional to elongate sandstone bodies and only in rare cases might form sinuous channels or ribbons of sandstone. In higher net-to-gross ratio intervals, the sandstone bodies become amalgamated and form multistory sandstone bodies and larger amalgamated channel complexes.

For a fluvial sandstone body, the width corresponds to the dimension that is measured perpendicular to the dominant paleoflow direction; length corresponds to the dimension that is measured parallel to the dominant paleoflow direction. The linear distance between sandstone body terminations in the outcrop is defined herein as the “apparent width.” The apparent width of the sandstone body that is observed in the outcrop is related to the preserved size of the sandstone body, the orientation of the sandstone body with respect to the canyon wall, and the degree of present-day erosion (or the amount of the sandstone body that is exposed). Based on empirical relationships and measurements of a well-exposed point-bar deposit in the outcrop, estimates of the paleochannel size (bank-full channel depth and width) and channel sinuosity were computed (Ellison, 2004). These estimates suggest that the individual channels (within meander belts) of the lower Williams Fork Formation are moderately to highly sinuous (sinuosity, 1.7–1.9; Ellison, 2004; Pranter et al., 2007). Given the sinuosity of the channels, the actual sandstone body width (dimension perpendicular to paleoflow) can only be approximated from outcrop measurements (thus, the term “apparent width” is used). Because of the uncertainty in the width measurements, for each channel sandstone body, a range of possible width values was estimated by assuming a range of paleocurrent orientations from outcrop-based measurements (Panjaitan, 2006; Pranter et al., 2009). This was done by modeling a channel sandstone body as a half ellipse and fitting the half ellipse to the end points of the sandstone body trace in plan view using the LIDAR data set. This process was repeated at 10 orientations to span the range of paleocurrent data for the lower Williams Fork Formation in Coal Canyon (see Panjaitan, 2006, and Pranter et al., 2009, regarding the details of this method). A crescent, whole ellipse, or other shape with a constant aspect ratio (W:L = 1:2) could also be used and would provide similar results. This method was used to address the uncertainty in sandstone body width by producing a range of width values for each of the channel sandstone bodies based on the most likely orientations of the preserved sandstones. From the 10 possible width values for each sandstone body, minimum, mean, and maximum width values were determined (Figure 6). Given the non-Gaussian character of the minimum, mean, and maximum width histograms (Figure 6), triangular distributions that represent the width data were used in the modeling process (Table 2). These data were used to model three different width scenarios for the lower Williams Fork Formation to approximate the range of uncertainty in sandstone body width and to assess the impact of sandstone body width on static sandstone body connectivity.

**MODELING FLUVIAL DEPOSITS**

Three-dimensional models were created based on the outcrop statistics collected in Coal Canyon to represent hypothetical subsurface reservoirs of the lower Williams Fork Formation in the Piceance Basin and to evaluate their static sandstone body connectivity to wells. The 3-D models cover 0.25 mi² (160 ac; 2650 × 2650 ft [808 × 808 m]) in area and are 500 ft (152 m) thick. This thickness approximates the thickness of the lower Williams Fork Formation as exposed in Coal Canyon and also approximates a vertical interval of 1 to 2 typical hydraulic-fracture stimulation stages in Williams...
Figure 6. Frequency histograms for (A) minimum, (B) mean, and (C) maximum width values for single-story (left column) and multistory (right column) channel sandstone bodies of the lower Williams Fork Formation. Values are calculated from sandstone body dimensional data for the lower Williams Fork Formation in Coal Canyon from Cole and Cumella (2005), Panjaitan (2006), and Pranter et al. (2009).
Fork Formation wells in the Piceance Basin. The model extent was specified to be large enough to contain the widest multistory channel sandstone body as observed in Coal Canyon. All models have a regular orthogonal 3-D grid with individual cells measuring 25 × 25 × 2 ft (7.6 × 7.6 × 0.61 m) in the x, y, and z dimensions, respectively. The cell size provides adequate resolution, so the smallest sandstone bodies are simulated and results in model grids that consist of 2,809,000 cells. Several model scenarios were produced that represent the possible spatial distributions of the fluvial deposits, and 30 realizations were generated for each model scenario. As an example, one model scenario (with 30 realizations) was based on minimum sandstone body width statistics as compared with a second model scenario (with 30 realizations) based on maximum width values. Several model scenarios were produced that represent the possible spatial distributions of the fluvial deposits, and 30 realizations were generated for each model scenario. As an example, one model scenario (with 30 realizations) was based on minimum sandstone body width statistics as compared with a second model scenario (with 30 realizations) based on maximum width values. Models presented herein represent fluvial reservoir heterogeneity between intermediate and large scales (i.e., architectural elements within a channel belt similar to heterogeneity levels 2 and 3 of Jordan and Pryor, 1992), in contrast to intermediate-scale heterogeneity (lithologic and petrophysical) within an isolated point bar (Pranter et al., 2007) or large-scale heterogeneity associated with large channel belts (Mackey and Bridge, 1995).

The following modeling constraints are specified: (1) volumetric net-to-gross ratio, (2) architectural element percentages, (3) object types used to represent sandstone bodies, (4) sandstone body width distributions, (5) sandstone body width-to-length ratio distributions, (6) sandstone body thickness distributions, (7) sandstone body orientation distributions, (8) sandstone body vertical proportion curves (VPCs), (9) amplitude and wavelength

of narrow sinuous channel sandstones, (10) erosion rules, and (11) the model seed number.

Four net-to-gross ratios (10, 20, 30, and 40%) were specified for each model scenario to construct models with different sandstone percentages for a variety of meandering fluvial systems. The percentages of each type of sandstone body were determined from outcrop analog data presented by Cole and Cumella (2005) and Panjaitan (2006). Volumetric percentages of each architectural element were calculated based on average area and thickness and the total number of observations.

Table 2. Sandstone Body Width Triangular Distribution Values Used in Object-Based Modeling*

<table>
<thead>
<tr>
<th>Architectural Element</th>
<th>Minimum</th>
<th>Mean</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crevasse splay</td>
<td>Same as mean</td>
<td>46, 212, 869</td>
<td>Same as mean</td>
</tr>
<tr>
<td>Single-story channel body</td>
<td>38, 157, 547</td>
<td>49, 202, 731</td>
<td>66, 247, 940</td>
</tr>
<tr>
<td>Narrow channel body</td>
<td>32, 225, 924</td>
<td>46, 297, 1374</td>
<td>58, 364, 7717</td>
</tr>
<tr>
<td>Multistory channel body</td>
<td>Same as mean</td>
<td>46, 297, 1374</td>
<td>Same as mean</td>
</tr>
</tbody>
</table>

*From Sommer (2007).
Table 3. Sandstone Body Orientation Values*

<table>
<thead>
<tr>
<th>Architectural Element</th>
<th>Orientation Ranges (mean direction, circular standard deviation)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Narrow</td>
</tr>
<tr>
<td>Crevasse splay</td>
<td>45°, 59°</td>
</tr>
<tr>
<td>Single-story channel body</td>
<td>91°, 35°</td>
</tr>
<tr>
<td>Narrow channel body</td>
<td>45°, 50°</td>
</tr>
<tr>
<td>Multistory channel body</td>
<td>72°, 44°</td>
</tr>
</tbody>
</table>

*The total percentage of each type of architectural element (except narrow channel bodies) that was modeled was divided into two groups with orientations of 180° out of phase with each other to represent deposits on both sides of a channel. From Sommer (2007). Data are modified from Cole and Cumella (2005).

Given the varied range of point-bar sizes, channel body width and length were modeled to cover a range of W:L ratios. The W:L ratio for channel sandstone bodies was defined with a triangular distribution with minimum, median, and maximum values of 0.8, 1.1, and 1.4, respectively. Therefore, the resulting sandstone bodies that are modeled will have minor width values that directly honor the outcrop statistics and have length values that are determined based on the triangular distribution for W:L ratio as previously noted. Width-to-length ratios for crevasse splays were arbitrarily constrained to a triangular distribution, with minimum, median, and maximum values of 0.8, 1.0, and 1.2, respectively. Thickness values for all sandstone body types were constrained to outcrop thickness data (Table 1). Thickness data were represented by triangular distributions and were held constant for all model scenarios. The two main uncertainties concerning sandstone body orientation are related to the mean paleoflow direction and the degree of variation (Martinius and Naess, 2005). In this study, sandstone body orientations were constrained to paleocurrent data (Cole and Cumella, 2005) for each architectural element modeled; each type observed in the outcrop has unique mean paleocurrent directions and circular standard deviations. Three model scenarios constrained to a range of paleocurrent values (narrow, intermediate, and wide orientations) were generated (Table 3). Channel sandstone and crevasse-splay body orientations were constrained to a normal distribution centered about the mean paleocurrent direction of Cole and Cumella (2005). Circular standard deviation was arbitrarily multiplied by 0.75 to create the narrow orientation scenario and by 1.25 to create the wide orientation scenario; the intermediate orientation scenario honors the circular standard deviation value of Cole and Cumella (2005) for the given sandstone body type. The different orientation scenarios were chosen to produce a range of values to assess the sensitivity of sandstone body orientation on static connectivity. The total percentage of each type of architectural element (except the sinuous narrow channel bodies) that was modeled was divided into two groups, with orientations 180° out of phase with each other to represent deposits on both sides of a channel. For reference, the scenario based on the mean width, intermediate orientation, and fan-shaped object consists of 120 models (30 realizations for each of the 4 net-to-gross ratio scenarios) and is considered the base case scenario; this scenario is compared with other scenarios, with only one variable differing between the two.

The proportion of different architectural elements (sandstone bodies) that exist in a given stratigraphic interval (layer) in the 3-D model is, in part, controlled by a VPC. A VPC is a vertical 1-D trend (values between 0 and 1.0) that represents the variability in the proportion of sandstone body types within each layer (i.e., stratigraphically). In this study, the VPC is constrained to outcrop data, and thus represents the vertical distribution of sandstone bodies, as observed in Coal Canyon outcrops. The VPCs were created from outcrop observations for multistory channel bodies and crevasse splays (Figure 7). Qualitative observations in the field and with the LIDAR data set show a uniform distribution of narrow and single-story channel bodies, therefore, they were not specifically constrained to VPCs. Two sections near the bend of the canyon were chosen for VPC data collection (Figure 3B); this area contains exposures in both legs of the canyon, has minimal talus cover, and contains fairly continuous sandstone body exposures for most of the vertical section exposed. A point count process was used to acquire the data for the multistory channel body and crevasse-splay
VPCs. A grid was superimposed over the LIDAR data for two sections (one in the north-south leg and one in the east-west leg) 500 ft (152 m) high and 2650 ft (808 m) wide. Grid cells were 5 ft (1.52 m) high × 530 ft (162 m) wide. Vertically, the variability in the percentage of flood-plain mudstone, multistory channel bodies, and crevasse splays was estimated for each cell (Figure 7).

Narrow channel sandstones are rare (1.4% of population) but were modeled as sinuous-meandering fluvial channel objects. The channel amplitude and wavelength were constrained to triangular distributions based on observed sandstone body apparent widths. The orientation was constrained to a normal distribution using paleo-current data from Cole and Cumella (2005). The sinuosity of the lower Williams Fork Formation has been estimated to be between 1.7 and 1.9 (Ellison, 2004). The maximum single-story sandstone body width is controlled by the meander belt width (Collinson, 1978), which is related to channel amplitude. Therefore, channel amplitude and wavelength values were constrained to apparent width data for channel sandstones observed in the outcrop. The channel amplitude and wavelength were constrained to triangular distributions with minimum, median, and maximum values of 250, 500, 2800 ft (76, 152, 853 m) and 500, 1000, 5600 ft (152, 305, 1707 m), respectively. Narrow channel body apparent width and thickness values were also constrained to data of Cole and Cumella (2005) (Table 1). Figure 8 shows an example of a resulting 3-D architectural-element model that is based on the mean sandstone body width statistics and 20% net-to-gross scenario. Figure 9 shows a visual comparison of a cross sectional view of an architectural element model with an outcrop of the lower Williams Fork Formation in Coal Canyon.

Figure 7. Vertical proportion curve (VPC) for multistory channel bodies and crevasse splays. The VPC shows the percentages of multistory sandstone bodies and crevasse splays as a function of layer (stratigraphic position) within the model. The approximate locations of the outcrop areas in Coal Canyon that were analyzed and used to create the VPCs are shown in Figure 3.

STATIC CONNECTIVITY OF FLUVIAL DEPOSITS

A software program developed at the University of Colorado (Z. A. Reza, 2005, personal communication) that computes well-pattern–based static connectivity, WCONN, was used to quantitatively investigate static sandstone body connectivity for the different user-defined well patterns. In this study, WCONN was used to (1) calculate static sandstone body connectivity (volume-based percentages of sandstone bodies connected to wells) and (2) generate the corresponding 3-D models of connected sandstone bodies for visualization. Input data for WCONN includes a 3-D architectural element model containing a facies association; code (representing different architectural elements in this study) and a unique object; identifier (a unique number for each object in the model). The facies association code could represent different facies associations, architectural elements, or lithologies, depending on what properties are modeled. Other inputs include information on the model size, cell size, facies of interest for the connectivity analysis, and connectivity adjacency geometry (face, edge,
corner; Figure 10A). The face connectivity adjacency geometry was used for all connectivity analyses. The face connectivity calculates lower connected volumes relative to edge connectivity, and corner connectivity gives the largest connected volumes. For the connectivity analysis, the model cells intersected by well paths for a given well pattern are also defined. All wells used herein are vertical, but deviated and horizontal wells can be used.

Five well-pattern–based static connectivity analyses were conducted for each of the 840 models created: 160-, 40-, 20-, 10-, and 2.5-ac (2640, 1320, 1320 or 660, 660, and 330 ft [805, 402, 402 or 201, 201, and 101 m] respectively) well spacings were used (Figure 10B), resulting in 4200 scenarios analyzed. All well patterns, except the 20-ac spacing, contain symmetrical grids of wells; the 20-ac spacing was created with a lay-down pattern (Figure 10B), with wells aligned in an east-west direction.

RESULTS

Results of static connectivity analyses show how variations in fluvial sandstone body shape, size,
and orientation affect static connectivity. Figure 11 shows 3-D models of connected sandstone bodies for 160-, 40-, and 10-ac spacings for the mean width scenario (intermediate orientation and fan-shaped object scenario) and shows how static connectivity increases with the net-to-gross ratio and well density. The increase in static connectivity with the net-to-gross ratio is not always linear (Figure 12) as the S-curve trend is observed for the 160-ac well-spacing analyses. As well density increases, the relationship between static connectivity and the net-to-gross ratio becomes more linear. Figure 12 shows the net-to-gross versus connectivity for the five well spacings and the mean-width scenario. Static connectivity for the 160-ac case increases most steeply between the 20 and 30% net-to-gross ratio. This is also true for the 40- and 20-ac cases; however, static connectivity does not increase as
steeply as it does for 160-ac spacing. The 10- and 2.5-ac cases show essentially linear relationships between connectivity and the net-to-gross ratio.

Panels A to C of Figure 13 show plots comparing model net-to-gross ratio versus connectivity at 40-, 20-, and 10-ac spacing for the minimum, mean, and maximum width scenarios. These plots reveal that the maximum width models produce the highest connectivity and, thus, wider sandstone bodies enhance connectivity at a given net-to-gross ratio.

Figure 13D is a plot of net-to-gross ratio versus connectivity at 10-ac spacing for the narrow, intermediate, and wide orientation scenarios. Connectivity is essentially insensitive to changes in sandstone body orientation. This is because the channel sandstones of the lower Williams Fork Formation, as modeled herein, are relatively equidimensional (W:L constrained to a triangular distribution with minimum, median, and maximum values of 0.8, 1.1, and 1.4, respectively). Therefore, varying the sandstone body orientation did not significantly

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The text continues with a discussion of the models and their results, showing the relationship between connectivity and net-to-gross ratio for different spacings and orientations. The diagrams illustrate the effects of varying well patterns and spacings on connectivity and net-to-gross ratio, with a focus on the impact of sandstone body width.

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**Figure 10.** (A) Adjacency geometry for connectivity analyses (face, edge, corner). (B) Well patterns and spacings analyzed for each model realization. The number of wells (n) and distances between wells are shown.
impact connectivity. If sandstone bodies are more elongated, it is likely that greater variability in sandstone body orientation would cause connectivity to be diminished, as was shown by Martinius and Naess (2005) for ribbon sandstones modeled with low W:T and low W:L. Determining W:L (and channel sinuosity) of meandering fluvial sandstones in the outcrop is extremely difficult. More work concerning modern point-bar W:L ratios is necessary to constrain these parameters in subsurface reservoir models and reduce uncertainties concerning meandering fluvial sandstone W:L.

Figure 13E is a plot of net-to-gross ratio versus connectivity at 10-ac spacing for the half ellipse, fan-shaped, and whole ellipse object scenarios. The lack of separation between the curves, which are
based on hundreds of realizations, shows that connectivity is insensitive to changes in the object used to model channel sandstones. Note that this is true only for the accompanying suite of input data used to construct these models.

**DISCUSSION**

The increase in connectivity between the minimum and maximum width scenarios is significant, especially at low net-to-gross ratios: at 20-ac spacing, the difference in connectivity (P50 values) between minimum and maximum widths is 26% at 10% net-to-gross and 14% at 20% net-to-gross (Figure 13A); at 10-ac spacing, the difference in connectivity between minimum and maximum widths is 22% at 10% net-to-gross and 11% at 20% net-to-gross (Figure 13B). This underscores the importance of having representative sandstone body width statistics for reservoir modeling applications. Wells in the Piceance Basin targeting the Williams Fork Formation are typically drilled between 20- and 10-ac spacing.

Based on these results, relatively large and average width channel deposits are intersected at 20-ac well spacing. At increasingly dense well spacings, connectivity increases more gradually as additional relatively smaller sandstone bodies are intersected. In some cases, drilling on 10-ac spacing is likely to accelerate production to some degree because larger sandstones will be intersected by more than one well. However, fluvial sandstone bodies are internally heterogeneous, and fluid flow is affected by internal lithologic changes (Weber, 1982; Pranter et al., 2007); accelerated production because of multiple wells intersecting fluvial sandstone bodies will likely be inhibited by internal heterogeneities, especially in low-permeability tight-gas sandstones. Given this, the static connectivity results presented herein most likely provide an upper boundary on reservoir connectivity because internal heterogeneities and dynamic effects will lower ultimate connectivity. Alternatively, if the fluvial deposits exist more like a string of beads (Donselaar and Overeem, 2008), which assumes connectivity between individual point-bar elements through sandy channel floor ribbons, then static connectivity would be much greater compared with these results for a given net-to-gross ratio.

Compared with single-story and multistory sandstone bodies, crevasse-splay sandstone bodies are relatively small, with thickness values less than 7 ft (<2.1 m) and apparent width values less than 870 ft (<265 m). However, larger crevasse-splay deposits exist (Anderson, 2005), and crevasse splays can have favorable porosity and permeability (Shanley, 2004). Crevasse splays commonly have large ratios of area to thickness, thus increasing the likelihood of being intersected if the well density is adequate. Crevasse splays can increase overall connectivity, especially in gas reservoirs, if they are connected to the channel sandstones (and the channels) from which they originate. One would expect that dense infill drilling would intersect a greater volume of single-story channel bodies and crevasse splays that could lead to increased recovery from added reserves and enhanced production because of increased connectivity. This increased

![Figure 12. Graph of net-to-gross ratio versus connectivity for the mean width, intermediate orientation, fan-shaped object scenario for all well spacings analyzed. The P10, P50, and P90 connectivity values (based on 30 realizations) are plotted. At a low well density, the connectivity is low at a low net-to-gross ratio, increases between a 20 and 30% net-to-gross ratio, and levels off at a net-to-gross ratio more than 30%. These results represent an S-curve relationship (gray shading) between net-to-gross ratio and connectivity at a low well density (e.g., 160-ac well spacing). As the well density increases, the connectivity increases more linearly with increasing net-to-gross ratio. At a 10% net-to-gross ratio, for a 10-ac well spacing, the connectivity is typically more than 60% and can be as high as 85%, depending on the widths of the sandstone bodies.](image-url)
connectivity could be significant in certain plays, including the lower Williams Fork Formation, especially considering the large number of crevasse-splay sandstones observed in the outcrop (42% of sandstone bodies).

Sandstone body apparent width data collected from outcrop exposures in Coal Canyon indicate that a significant part of channel sandstones are smaller than the distance between wells at 20- and 10-ac spacings (1320 and 660 ft [402 and 201 m]). This suggests that reserves will be added with infill drilling or by the use of horizontal drilling in preferred orientations. Williams Production RMT Company (2006) stated that results from Williams Fork Formation 10-ac well spacing pilot programs in the Piceance Basin indicate that expected recovery factors nearly doubled, from approximately 32 to 36% to approximately 72 to 76%, between 20- and 10-ac (660 ft [201 m]) spacings, respectively.

CONCLUSIONS

Well-pattern–based static connectivity analyses of fluvial architectural element models of the lower Williams Fork Formation show how static connectivity is sensitive to sandstone body width and varies with the net-to-gross ratio and well spacing. The 3-D models and associated connectivity analyses are based on outcrop-derived sandstone body statistics (e.g., sandstone body types, dimensions, stratigraphic position). Uncertainties associated with
sandstone body width, orientation, and the objects chosen to represent channel sandstones were addressed through seven different model scenarios using four different net-to-gross ratios.

Static connectivity analyses reveal that the architectural element models of the lower Williams Fork Formation based on the maximum width sandstone body statistics produce the highest connectivity, and thus wider sandstone bodies enhance connectivity at a given net-to-gross ratio. The results show that the increase in sandstone body connectivity between the minimum and maximum width scenarios is more significant at lower net-to-gross ratios. Static connectivity also increases with net-to-gross ratio and well density. Connectivity analyses presented herein reveal that the S-curve relationship between net-to-gross ratio and connectivity described by previous workers is most evident at 160-ac well spacing; as the net-to-gross ratio rises, connectivity rises relatively steeply. With a low well density (e.g., 160-ac 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 at a net-to-gross ratio of more than 30%. As well density increases, static connectivity increases linearly with an increasing net-to-gross ratio, particularly at 10- and 2.5-ac well spacings. For a 20-ac 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. Even at a 10% net-to-gross ratio, connectivity for the 10-ac spacing is typically more than 60% and can be as high as approximately 85% (for the maximum width scenario). Although static connectivity was shown to be essentially insensitive to sandstone body orientation and object type, this is primarily because the fluvial deposits of the lower Williams Fork Formation, as modeled herein, are relatively equidimensional. Sandstone bodies with greater aspect ratios would most likely produce varied values of static connectivity and exhibit greater sensitivities to sandstone body orientation. The sandstone body width data show that most sandstone bodies are smaller than the distance between wells at 20- and 10-ac spacings (1320 and 660 ft [402 and 201 m]). Given the lower net-to-gross ratio (commonly <30%) and lower 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.

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