Sandstone-body dimensions in a lower coastal-plain depositional setting: Lower Williams Fork Formation, Coal Canyon, Piceance Basin, Colorado

Matthew J. Pranter, Rex D. Cole, Henrikus Panjaitan, and Nicholas K. Sommer

ABSTRACT

This study addresses the field-scale architecture and dimensions of fluvial deposits of the lower Williams Fork Formation through analysis of outcrops in Coal Canyon, Piceance Basin, Colorado. The lower Williams Fork Formation primarily consists of mud rock with numerous isolated, lenticular to channel-form sandstone bodies that were deposited by meandering river systems within a coastal-plain setting. Field descriptions, global positioning system traverses, and a combination of high-resolution aerial light detection and ranging data, digital orthophotography, and ground-based photomosaics were used to map and document the abundance, stratigraphic position, and dimensions of single-story and multistory channel bodies and crevasse splays.

The mean thickness and apparent width of the 688 measured sandstone bodies are 12.1 ft (3.7 m) and 364.9 ft (111.2 m), respectively. Single-story sandstone bodies (N = 116) range in thickness from 3.9 to 29.9 ft (1.2 to 9.1 m) and from 44.1 to 1699.8 ft (13.4 to 518.1 m) in apparent width. Multistory sandstone bodies (N = 273) range in thickness from 5.0 to 47.1 ft (1.5 to 14.4 m) and from 53.2 to 2791.1 ft (16.2 to 850.7 m) in apparent width. Crevasse splays (N = 279) range in thickness from 0.5 to 15.0 ft (0.2 to 4.6 m) and from 40.1 to 843.3 ft (12.2 to 257.0 m) in apparent width.

These data show that most sandstone bodies are smaller than the distance between wells at 10-ac spacing (660 ft [201 m]). Analyses of interwell sandstone-body connectivity...
suggest that even at 10-ac spacing, only half of the sandstone bodies are intersected and few are intersected by more than one well.

INTRODUCTION

Significant quantities of natural gas are produced from fluvial and marine deposits of gross thickness exceeding 1000 ft (305 m) in Upper Cretaceous strata within the Piceance Basin of western Colorado and surrounding basins (e.g., Uinta and Green River basins). Of these, the Williams Fork Formation (Mesaverde Group) is a major producer of natural gas in the Piceance Basin. Within the Williams Fork Formation, discontinuous fluvial deposits form the main reservoirs, and their stratigraphic distribution and low continuity make them difficult to correlate and map (Knutson et al., 1971; Kuuskraa et al., 1997; Cole and Cumella, 2005; Pranter et al., 2008). Also, well spacing has decreased from 20 to 10 ac (1320 to 660 ft [402 to 201 m]) to increase natural gas reserves by intersecting additional reservoir sandstones (isolated compartments), and in some cases, wells are spaced 330 ft (100 m) apart to account for stratigraphic variability and the orientation of fractures that enhance permeability following hydraulic fracturing of the formation. As an analog, the sedimentological and depositional characteristics of the Williams Fork Formation are similar in many ways to other fluvial deposits. Some of the formations that are analogous include the Lance and Almond formations (Green River Basin), Farrer and Neslen formations (Uinta Basin), Meeteetse Formation (Wind River Basin), Eagle Sandstone (Crazy Mountain Basin), Hell Creek Formation (Williston Basin), Menefee Formation (San Juan Basin), and formations in the Bohai Basin of China, offshore Thailand, and the Texas Gulf Coast.

This study addresses the field-scale architecture and dimensions of channel-form fluvial sandstone deposits of the lower Williams Fork Formation through analysis of outcrops in Coal Canyon near Palisade, Colorado. The study area is located approximately 30 mi (48 km) southwest of significant natural-gas fields in the southern Piceance Basin that produce from the same stratigraphic interval; for example, Mamm Creek, Rulison, Parachute, and Grand Valley (Figures 1, 2). Within Coal Canyon, the study area extends for approximately 5.7 mi (9.2 km), and the lower Williams Fork Formation ranges in thickness from about 500 to 700 ft (152 to 213 m). The Coal Canyon outcrops are useful for evaluating sandstone-body dimensions and architecture because vegetation is sparse, the rocks are well exposed, structural complexities are minimal, and access is good.
Observations and measurements can be made from these outcrop analogs, which are not possible with subsurface data. Various types of fluvial deposits (e.g., point bars or crevasse splays) have been interpreted from the outcrops. Information on the stratigraphic architecture and dimensions of the fluvial sandstone bodies from outcrop is useful as a guide to correlate and map sandstone bodies within the subsurface. The dimensional data by sandstone-body type are also essential inputs for constructing

Figure 1. Map of the Piceance Basin. Outcrops of the Mesaverde Group are exposed along the basin margin. Modified from Johnson (1989), Tyler and McMurry (1995), and Hoak and Klawitter (1997).
Figure 2. (A) Aerial LIDAR-orthophoto composite for the Coal Canyon, Main Canyon, and Plateau Creek Canyon area. (B) Topographic map of the Coal Canyon area (modified from the U.S. Geological Survey cameo, Colorado 7.5 minute Quadrangle, 1955). The location of outcrops of the lower part of the Williams Fork Formation is highlighted in yellow. The approximate locations of the outcrops in Figures 4 and 6 (F4 and F6, respectively) are shown in panel B. The box outlined in gray in panel A is the approximate area of panel B.
three-dimensional (3-D) reservoir models of fluvial architectural elements (e.g., dimensional data for object-based modeling).

**METHODS**

Mapping of 668 fluvial sandstone bodies of the lower Williams Fork Formation within Coal Canyon was conducted to document their abundance, stratigraphic position, apparent width, and thickness. The term “sandstone body” as used herein is defined as a volume of sandstone and interbedded mud rock that forms a 3-D outcrop with discrete thickness and lateral extent. The linear distance between sandstone-body terminations is defined hereinafter as the “apparent width.” The apparent width of the sandstone body that is observed in outcrop is related to (1) the preserved size of the sandstone body at the time of deposition, (2) the orientation of the sandstone body with respect to the canyon wall, and (3) the degree of present-day erosion. Therefore, the apparent width does not necessarily correspond to the actual width or length of the sandstone body. To address this uncertainty, for each sandstone body, a range of possible width values was estimated by assuming a model shape for a body and a range of possible orientations.

Two methods were used to map and measure the dimensions of single-story and multistory channel bodies and crevasse-splay deposits in 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. The GPS receivers have a positional accuracy of ±20 ft (±6 m) and a vertical accuracy of ±50 ft (±15 m). The GPS measurements were used to obtain apparent-width values, whereas thickness measurements were obtained for each sandstone body using a tape measure and/or Jacob staff.

LIDAR is a form of remote sensing in which laser systems gather positional \((x, y)\) and elevation \((z)\) points at predefined intervals, resulting in a very dense network of elevation postings. The aerial LIDAR and orthophotography survey was conducted using an airborne laser scanner (58 kHz pulse rate) in situ with digital airborne camera systems. The survey covers approximately a 65-mi² (168-km²) area that includes Coal Canyon and the surrounding area. 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). These data were used to create high-resolution 3-D digital elevation models (herein referred to as LIDAR-orthophoto composite) upon which orthophotos were draped.

Geospatial and 3-D reservoir analysis and modeling software was used to visualize data, map the distribution of sandstone bodies, and measure their dimensions. Merged LIDAR scans (tiles) and georeferenced orthophotographs were used in conjunction with ground-based digital photomosaics to measure sandstone-body dimensions. The sandstone-body dimensions were measured by tracing (digitizing) ground-based photomosaic interpretations upon LIDAR scans textured with orthophotos and then measuring the sandstone-body dimensions (apparent width and thickness) within the 3-D modeling package. During mapping, the top and base of each sandstone body were traced (digitized) on the LIDAR and orthophotographs between its apparent terminations (sandstone-body pinch-out or covered).

**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 from the Late Cretaceous through the Eocene (~75–40 Ma) (Tweto, 1975; Johnson and Flores, 2003; DeCelles, 2004). The Piceance Basin is bounded by the Axial arch on the north, White River uplift on the east, Sawatch uplift on the southeast, Gunnison uplift and Elk Mountains on the south, Uncompahgre uplift on the southwest, Douglas Creek arch to the west, and Uinta Mountain uplift on the northwest (Figure 1). Prior to the Laramide orogeny, the Piceance Basin area was part of a much larger Rocky Mountain foreland basin system that...
was created by the Sevier orogeny (∼140–50 Ma). Tectonic uplift of the Sevier orogenic belt (now central Utah and southwestern Wyoming) produced sediment that was transported eastward and deposited in alluvial plain, coastal plain, and marine environments to form the Mesaverde Group. In this article, we follow the stratigraphic terminology of Hettinger and Kirschbaum (2002, 2003) for the Mesaverde Group in the southwestern Piceance Basin (Figure 3). The Mesaverde Group includes the Iles and Williams Fork formations, which overlie the Mancos Shale. The Iles Formation (also named the Mount Garfield Formation in the Book Cliffs area of the western Piceance Basin; Gill and Hail, 1975) consists of regressive marine sandstones (in ascending order: Corcoran, Cozzette, and Rollins sandstone members) separated by intervals of marine Mancos Shale (Young, 1955; Johnson, 1989; Hettinger and Kirschbaum, 2002). Several transgressions and regressions of the Western Interior seaway during the late Campanian occurred during deposition of the Corcoran and Cozzette.

**Figure 3.** Stratigraphic nomenclature of the Upper Cretaceous and Tertiary strata of the southern Piceance Basin. The undifferentiated Williams Fork Formation is divided into a lower (sand poor) interval and an upper (sand rich) interval. Modified from Young (1955, 1966), Fisher et al. (1960), Donnell (1961), Collins (1976), Johnson and May (1980), Tyler et al. (1996), Hettinger and Kirschbaum (2002, 2003), Cole and Cumella (2003, 2005), Johnson and Roberts (2003), Patterson et al. (2003), German (2006), and Burger (2007).
sandstone members, whereas deposition of the Rollins Sandstone Member is more progradational and aggradational.

In the study area, the Williams Fork Formation conformably overlies the Rollins Sandstone Member and is overlain disconformably by the Wasatch Formation (Paleocene–Eocene). However, Patterson et al. (2003) interpreted a regional unconformity at the top of the Rollins Sandstone Member based on observed truncation of the Rollins Sandstone Member in outcrop exposures in Hunter Canyon (western Piceance Basin). Facies-equivalent strata of the Williams Fork Formation are named the Hunter Canyon Formation in the western Piceance Basin (Erdmann, 1934). The Williams Fork Formation is approximately 5000 ft (1524 m) thick on the eastern margin of the Piceance Basin and thins to approximately 1200 ft (365 m) thick at the Colorado-Utah state line (Hettinger and Kirschbaum, 2002, 2003). The westward stratigraphic thinning is thought to be related to regional truncation at the top of the Williams Fork Formation and variations in subsidence during deposition (Hettinger and Kirschbaum, 2002; Johnson and Roberts, 2003). Along the Grand Hogback on the eastern margin of the Piceance Basin, strata are very steeply dipping to overturned, unlike in the study area where strata dip gently eastward into the basin at about 4–7°.

In the southwestern Piceance Basin, the Williams Fork Formation is not divided into formal members; however, two gross intervals are defined based on lithology. The lower Williams Fork Formation or approximately the lower third of the formation ranges in thickness from 500 to 700 ft (152-213 m) in Coal Canyon and primarily consists of mud rock with numerous, isolated, channel-form sandstone; the net-to-gross ratio of the interval is approximately 15% (Figure 4). The lower Williams Fork Formation was deposited by 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). The Cameo-Wheeler coal zone occurs at the base of the Williams Fork Formation and is approximately 240 ft (73 m) thick within Coal Canyon (Figure 4). The numerous coal seams of the Cameo-Wheeler coal zone were deposited in peat bogs and mires (muddy marshes). Within the study area, mud-rock lithofacies are mostly abundant and account for approximately 60 to 80% of the lower Williams Fork Formation within Coal Canyon (Cole and Cumella, 2005). 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).

The middle to upper Williams Fork Formation has net-to-gross ratios between 50 and 80% (Cole and Cumella, 2003; German, 2006) and is interpreted to have been deposited by a low-sinuosity braided river system in an alluvial-plain setting (Patterson et al., 2003; Cole and Cumella, 2005; German, 2006). Sandstone bodies of the upper Williams Fork Formation lack observable lateral-accretion surfaces, and paleocurrent data indicate unimodal flow with low variance (German, 2006). Upper Williams Fork Formation sandstones are described as highly amalgamated and sheetlike. Channel-form sandstone bodies that make up the amalgamated complexes have high width-to-thickness (W:T) ratios (8:1 to 100:1, average = 34:1) (German, 2006).

SANDSTONE-BODY TYPES, UNCERTAINTIES, AND STATISTICS

Fluvial sandstone bodies that are observed and interpreted in the Williams Fork Formation include (1) crevasse splays, (2) single-story channel bodies, (3) multistory (sensu Gibling, 2006) channel bodies, and (4) much larger amalgamated channel complexes (Cole and Cumella, 2005) (Figure 5). Single-story and multistory channel bodies form the dominant gas reservoirs in the subsurface; the larger amalgamated channel complexes are associated with the middle to upper Williams Fork Formation and also form significant reservoirs.

Crevasse splay deposits (Figure 5A) have a broadly lenticular form and are very fine to fine grained, ripple laminated to cross-stratified, and commonly bioturbated (Cole and Cumella, 2005). Narrow (single-story), possibly anastomosing, channel bodies...
with thin levees are also present but are rare and are included herein with single-story channels. The narrow channel sandstone bodies are fine to medium grained, cross-stratified to ripple laminated, and have poorly defined lateral-accretion beds but well-developed levees (or splays). Single-story

Figure 4. Comparison of (A) outcrop photomosaic and (B) outcrop LIDAR-orthophoto composite for a similar field of view within Coal Canyon.
Figure 5. Classification of sandstone-body types of the Williams Fork Formation. Sandstone-body types of panels A, B, and C are associated with the lower Williams Fork Formation and are the focus of this study. (A) Crevasse-splay body, (B) single-story channel body, (C) multistory or multilateral channel body, and (D) amalgamated channel complex examples are shown with a schematic map view of the depositional setting, cross-sectional view of the body, and a representative outcrop photo. Amalgamated channel complexes are associated with the middle to upper Williams Fork Formation and are presented here for completeness. The classification is modified from Cole and Cumella (2005).
Figure 6. (A) Example LiDAR-orthophoto composite image showing the outlines of single-story (blue), multistory (magenta), and crevasse splay (yellow) sandstone bodies. (B) Corresponding outcrop photomosaic. The field of view of the photomosaic is within the dashed black box on the LiDAR-orthophoto composite image. The letters A, B, C, and D mark the locations of common points on the LiDAR-orthophoto composite image and the outcrop photomosaic. The white lines on the LiDAR-orthophoto composite image correspond to the locations of measured sections.
sandstone bodies are fine to medium grained, cross-stratified to ripple laminated, and commonly have mud-chip lags at their bases and lateral-accretion bedding (Figure 5B). Single-story channel bodies represent isolated point bars that were deposited within sinuous-channel systems. Multistory-channel bodies (Figure 5C) consist of stacked channel-form bodies that display multiple scour surfaces and commonly have mud-chip lags (indicating bank failure). Amalgamated channel complexes (Figure 5D) are associated with the middle to upper Williams Fork Formation and are characterized by sheetlike
Figure 8. Method used to estimate the range of possible width values for a sandstone body. (A) The sandstone-body trace in the LIDAR-orthophoto composite image data. The arrows point to the sandstone-body termination in outcrop. (B) Hypothetical fluvial channels and point bars for 25°, 75°, and 115° orientations. (C) Using a half circle for the plan-view shape of a point bar and paleocurrent data for the lower Williams Fork Formation in Coal Canyon, 10 equally likely width values were obtained. The half circles were fitted to the center of the outcrop trace, rotated to an inferred paleocurrent orientation, and adjusted in size. Widths were determined for paleocurrent values for every 10° from 25° to 115°. (D) Graph of the 10 equally likely width values for the sandstone body of panel A.
sandstone bodies and associated mud rocks. Single-story and multistory sandstone bodies that comprise the amalgamated channel complexes have dimensions that range from 1.0 to 54 ft (0.30 to 16.5 m) in thickness and 204 to 2565 ft (62 to 782 m) in apparent width (German, 2006). This study focuses on the characteristics and dimensions of single-story and multistory channel bodies and crevasse-splay deposits of the lower Williams Fork Formation.

Within Coal Canyon, 668 sandstone bodies in the lower Williams Fork Formation have been mapped and measured (Figures 6, 7). In this population, 116 (17%) are single-story channel bodies, 273 (41%) are multistory channel bodies, and 279 (42%) are crevasse splays. One hundred sixty-two of the sandstone bodies in the total population (47 single-story channel bodies, 60 multistory channel bodies, and 55 crevasse splays) were field mapped (GPS and tape) to determine their apparent width and thickness. In addition to the field measurements, apparent width and thickness values were measured for 627 sandstone bodies using a combination of high-resolution aerial LIDAR, digital orthophotography, and ground-based outcrop photomosaics (Figure 6). Of the 627 sandstone bodies, 121 are the same as those measured by field mapping, and 506 are additional sandstone bodies. A comparison of apparent-width values from these...
different mapping methods for the 121 common sandstone bodies shows that they are very similar ($R^2 = 0.93$). The differences in apparent-width values between the methods are associated with two main factors: (1) the lower positional accuracy of the GPS receiver as compared to the high-resolution LIDAR and orthophoto data, and (2) the error associated with interpreting (picking) the exact sandstone-body terminations on the LIDAR and orthophoto data with ground-based photomosaics. None of the sandstone bodies that were measured had apparent-width values that were less than the positional accuracy of the GPS receiver or resolution of the LIDAR data. A comparison of sandstone-body maximum thickness values for the common sandstone bodies shows that the values are also similar ($R^2 = 0.85$) (Sommer, 2007). The difference in the thickness measurements between the methods is primarily because of the distortion of the aerial orthophotos in some areas where vertical cliffs are poorly imaged.

Ideally, the sandstone-body width corresponds to the dimension that is measured perpendicular to the dominant paleoflow direction, whereas the sandstone-body length corresponds to the dimension that is measured parallel to the dominant paleoflow direction. Given the moderate to high sinuosity of the individual channels in the lower Williams Fork Formation, determining if the apparent-width measurements for a certain outcrop-slice orientation represent sandstone-body width or length is difficult. In addition, uncertainty regarding what

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<th>Table 1. Statistical Summary of Sandstone-Body Dimensional Data</th>
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<td>Crevasse splay</td>
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<td>Single-story channel body</td>
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<td>Multistory channel body</td>
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*Apparent width values at 75° and area values are reported for LIDAR-based measurements ($N = 627$). Area values for single-story and multistory sandstone bodies are reported for the average paleocurrent orientation of 75° for sandstone bodies in Coal Canyon.
part of the sandstone body is actually exposed is observed (i.e., is the sandstone body exposed near the middle of the body or only exposed near the edge). Gibling (2006) discussed the difficulties associated with measuring the dimensions of fluvial deposits and provides a comprehensive summary of a previous work on the dimensions of channel bodies in the modern and ancient record. Given this uncertainty in the measurements, for each channel sandstone body, a range of width values was estimated assuming a range of paleocurrent orientations from outcrop-based measurements. This was done by modeling a channel sandstone body as a half circle (e.g., an idealized point-bar shape) and fitting the half circle to the endpoints of the sandstone-body trace in plan view using the LIDAR data set (Panjaitan, 2006) (Figure 8). This process was repeated at 10 orientations to span the range of paleocurrent data for the lower Williams Fork Formation in Coal Canyon (Cole and Cumella, 2005, determined a paleocurrent vector mean of 74.8° based on 1646 measurements). A half circle was fitted to the sandstone-body trace every 10° from 25° to 115° centered at 75° (Panjaitan, 2006) (Figure 8). This method addresses 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 channel sandstone body, the minimum, mean, and maximum width values were determined (Sommer, 2007) (Figure 9). These dimensional data were used to construct 3-D architectural-element models for the lower Williams Fork Formation to assess the impact of sandstone-body width on static reservoir connectivity (to be discussed).

For each orientation, in addition to the apparent sandstone-body width (radius of the half circle), the area (drainable area) of a channel sandstone body (area of the half circle) was also determined. For crevasse splays, the apparent width was assumed to be the actual width, and the trace of the sandstone body in outcrop was simply fitted with a circle to estimate a single drainable-area value for that body (Panjaitan, 2006). The drainable area is an estimated maximum area that could be drained by a well and assumes that the entire sandstone body could be drained (i.e., a homogeneous body).

A statistical summary of sandstone-body dimensions by type is presented in Table 1. The apparent-width values reported in Table 1 also include the sandstone-body width values at the 75° paleocurrent orientation for comparison. Thickness values

![Figure 10](image-url)
for the 668 sandstone bodies (total population) range from 0.5 to 47.1 ft (0.2 to 14.4 m) with a mean value of 12.1 ft (3.7 m) (Figures 10, 11). The apparent-width values for the total population (Figures 10, 11) range from 40.1 to 2791.1 ft (12.2 to 850.7 m) with a mean value of 364.9 ft (111.2 m). Single-story sandstone bodies ($N = 116$) range in thickness from 3.9 to 29.9 ft (1.2 to 9.1 m) and apparent width from 44.1 to 1699.8 ft (13.4 to 518.1 m). The mean $W:T$ ratio for single-story sandstone bodies is 44.7. Multistory sandstone bodies ($N = 273$) range in thickness from 5.0 to 47.1 ft (1.5 to 14.4 m) and apparent width from 53.2 to 2791.1 ft (16.2 to 850.7 m). The mean $W:T$ ratio for multistory sandstone bodies is 45.8. Crevasse-splay sandstone bodies ($N = 279$) have a mean $W:T$ ratio of 94.6. Crevasse splays range in thickness from 0.5 to 15.0 ft (0.2 to 4.6 m) and apparent width from 40.1 to 843.3 ft (12.2 to 257.0 m). The estimated drainable area for the 668 sandstone bodies ranges from 0.05 to 235 ac (0.0002 to 0.95 km²) with a mean of 7.0 ac (0.03 km²) (Table 1). Single-story sandstone bodies (primarily isolated point-bar deposits) have the smallest mean drainable area (3.3 ac [0.013 km²]) and a value range of 0.08 to 17.4 ac (0.0003 to 0.07 km²).

**SANDSTONE-BODY DISTRIBUTION AND CONNECTIVITY TO WELLS**

A visual inspection of how the sandstone bodies are distributed within the lower Williams Fork Formation (Figure 6) suggests that, in two dimensions, most of the sandstone bodies are not connected or that connectivity is very low. To illustrate, in
approximately two dimensions, how lower Williams Fork Formation sandstone bodies are intersected by wells for different well spacings, traverses that represent pseudowells (well paths) were positioned along the outcrop face using the LIDAR and orthophoto data. These wells were used to calculate the net-to-gross ratio and the number and type of sandstone bodies intersected (Figure 12).

Figure 12. Maps of Coal Canyon that show the locations of sandstone bodies within the lower Williams Fork Formation and pseudowells with (A) 20- and (B) 10-ac spacings. Each pseudowell is similar to a directional well that is positioned along the outcrop surface. Thirty-five pseudowells for the 20-ac spacing (labeled 20-1 to 20-35) and 49 pseudowells for the 10-ac spacing (labeled 10-1 to 10-49) are observed (modified from Panjaitan, 2006).
Pseudowells are positioned with 20-ac (distance between wells is 933 ft [284 m]) and 10-ac (distance between wells is 660 ft [201 m]) spacings. Each pseudowell is similar to a directional well that is positioned along the outcrop surface. Thirty-five pseudowells for the 20-ac spacing (labeled 20-1 to 20-35, Figure 12A) and 49 pseudowells for the 10-ac spacing (labeled 10-1 to 10-49, Figure 12B) are present. The pseudowells in the northwest leg of Coal Canyon (wells 10-20 through 10-49 and 20-15 through 20-35, Figure 12) cover the entire stratigraphic interval of the lower Williams Fork Formation. Based on the 51 pseudowells (21 wells for the 20-acre spacing and 30 wells for the 10-acre...
spacing), the average thickness of the lower part of the Williams Fork Formation is 446 ft (136 m), and the overall net-to-gross ratio is 15%.

To differentiate channel deposits from crevasse splays, single-story and multistory sandstone bodies are grouped for this analysis. The number and types of sandstone bodies intersected by the pseudowells varies across the outcrop, as shown in Figure 13. Although a higher well density increases the total number of sandstone bodies intersected by all wells, individual wells for a given well spacing intersect a range of sandstone bodies. For example, wells 10-8, 10-9, and 10-10 do not intersect any sandstone bodies, but well 20-7, located between the three wells, intersects five sandstone bodies (Figures 12, 13). The total number of sandstone bodies intersected by wells at 20- and 10-ac spacings is 238 out of 627 (38%) and 304 out of 627 (49%), respectively; 28% more sandstone bodies for the 10- versus 20-ac spacing (Figure 14). For the 627 sandstone bodies, 394 and 331 sandstone bodies for the 20- and 10-acre spacings, respectively, are not intersected by a well.

The number of wells was decimated to evaluate 80-ac (1866-ft [569-m] well spacing) and 40-ac (1320-ft [402-m] well spacing) scenarios (Figure 14). Channel sandstone bodies (single-story and multistory) have a higher probability of being intersected compared to the crevasse-splay bodies (Figure 14). Of the 627 sandstone bodies in the evaluation area, 10-ac wells intersected 209 (33%) channel sandstone bodies and 95 (15%) crevasse splays, whereas only 96 (15%) channel sandstone bodies and 31 (5%) crevasse splays were intersected based on the 80-ac (1866-ft [569-m] well spacing) scenario.

In considering incremental reserves versus accelerated production, also consider the number of sandstone bodies intersected by more than one well for different well spacings. For the 80-, 40-, 20-, and 10-ac spacings, 3, 5, 14, and 23 channel sandstone bodies are intersected by more than one well, respectively. Therefore, a very small percentage of sandstone bodies is intersected by more than one well. For these four well spacings, only one crevasse splay was intersected by more than one well (for the 10-ac spacing case).

As previously described, from the 10 possible sandstone-body width values for each single-story and multistory sandstone body (half-circle method), histograms of the minimum, mean, and maximum width values were produced (Sommer, 2007) (Figure 9). To expand the analysis of sandstone-body connectivity to three dimensions, the dimensional data and other outcrop data (e.g., sandstone-body types, stratigraphic position) were used to

Figure 14. Crossplot showing the number of sandstone bodies intersected by pseudowells for 10-, 20-, 40-, and 80-ac well spacings. Trendlines correspond to data for all sandstone bodies, single- and multistory bodies, and crevasse-splay bodies (modified from Panjaitan, 2006).
construct 3-D reservoir models (fluvial architectural-element models) that represent three different sandstone-body width scenarios (minimum, mean, and maximum sandstone-body width) for the lower Williams Fork Formation (Figure 15A, B). The models were used to assess the impact of sandstone-body width on static reservoir connectivity. Given the lower net-to-gross ratio for the lower Williams Fork Formation (commonly <30%), static sandstone-body connectivity is sensitive to sandstone-body width (Sommer, 2007). Higher W:T ratios correlate to greater static sandstone-body connectivity for a given net-to-gross ratio (Sommer, 2007). The increase in connectivity between the minimum- and maximum-width scenarios is more significant at lower net-to-gross ratios: for a 10-ac well 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 15C); for a 20-ac well spacing, the difference in connectivity between minimum and maximum widths is 26% at 10% net-to-gross and 14% at 20% net-to-gross (Figure 15D). 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

Figure 15. (A, B) Examples of the connected sandstone bodies for the 3-D architectural-element model of the minimum-width scenario (10% net-to-gross ratio and 10-ac well spacing). The model domain is 500 ft (152 m) thick and one quarter of a square mile (160 ac; 2650 × 2650 ft [808 × 808 m]) in area. This model thickness approximates the thickness of the lower Williams Fork Formation as exposed in Coal Canyon and also approximates one to two typical hydraulic-fracture stimulation stages in Williams Fork Formation wells in the Piceance Basin. The model domain aerial size was specified to be large enough to contain the widest multistory channel sandstone body in Coal Canyon and, hence, closely simulates channel-belt width. (C, D) Graphs of net-to-gross ratio versus sandstone-body connectivity for the width scenarios at (C) 10- and (D) 20-ac spacings. Thirty realizations were run for each scenario and, of these, P10, P50, and P90 values are plotted. Connectivity as used for the 3-D analysis is the proportion (percentage) of sandstone connected to wells directly or indirectly (i.e., through amalgamation) divided by the total sandstone volume. The maximum-width scenario produces the highest sandstone-body connectivity, especially at lower net-to-gross ratios. Modified from Sommer (2007).
spacing. Also, because fluvial sandstone bodies are internally heterogeneous and fluid flow is affected by the lithologic and petrophysical heterogeneity (e.g., Tyler and Finley, 1991; Hartkamp-Bakker and Donselaar, 1993; Willis and White, 2000; Pranter et al., 2007), production from the fluvial sandstones will likely be inhibited to compartmentalized.

Sandstone-body apparent-width data collected from outcrop exposures in Coal Canyon indicate that a significant part of the channel sandstones is smaller than the distance between wells even at 20- and 10-ac spacings (1320 and 660 ft [402 and 201 m]). This suggests that reserves will still be added with infill drilling.

CONCLUSIONS

The lower Williams Fork Formation as exposed within Coal Canyon consists mostly of mud rock with numerous, isolated, lenticular to channel-form fluvial sandstone bodies that were deposited within a coastal-plain setting. Field description, GPS traverses, aerial LIDAR data, digital orthophotography, and ground-based outcrop photomosaics were used in combination to evaluate the characteristics and dimensions of single-story and multistory channel sandstone bodies and crevasse splay deposits.

Thickness values for the 668 sandstone bodies range from 0.5 to 47.1 ft (0.2 to 14.4 m) with a mean value of 12.1 ft (3.7 m). The apparent-width values for the total population range from 40.1 to 2791.1 ft (12.2 to 850.7 m) with a mean value of 364.9 ft (111.2 m). Single-story sandstone bodies \((N = 116)\) range in thickness from 3.9 to 29.9 ft (1.2 to 9.1 m), have a range of apparent-width values from 44.1 to 1699.8 ft (13.4 to 518.1 m), and a mean \(W:T\) ratio of 44.7. Multistory sandstone bodies \((N = 273)\) range in thickness from 5.0 to 47.1 ft (1.5 to 14.4 m), have a range of apparent-width values from 53.2 to 2791.1 ft (16.2 to 850.7 m), and a mean \(W:T\) ratio of 45.8. Crevasse-splay sandstone bodies \((N = 279)\) have a mean \(W:T\) ratio of 94.6, range in thickness from 0.5 to 15.0 ft (0.2 to 4.6 m), and have a range of apparent-width values from 40.1 to 843.3 ft (12.2 to 257.0 m). The estimated drainable area for the 668 sandstone bodies ranges from 0.05 to 235 ac (0.0002 to 0.95 km²) with a mean of 7.0 ac (0.03 km²).

The sandstone-body width data indicate that a significant part of the channel sandstones is smaller than the distance between wells at 20- and 10-ac spacings (1320 and 660 ft [402 and 201 m]). For different well spacings along the outcrop face, the percentage of sandstone bodies intersected at 20- and 10-ac spacings is 38% and 49%. Therefore, even with a 10-ac spacing, only half of the sandstone bodies are intersected and few are intersected by more than one well. Three-dimensional architectural-element (reservoir) models that are constrained to outcrop data from Coal Canyon show that static sandstone-body connectivity is sensitive to sandstone-body width and that the increase in sandstone-body connectivity between the minimum- and maximum-width scenarios is more significant at lower net-to-gross ratios. Therefore, for lower net-to-gross–ratio Williams Fork reservoirs and similar deposits, it is important to have representative sandstone-body width statistics for reservoir characterization and modeling.

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