SAND-BODY DIMENSIONS IN OUTCROP AND SUBSURFACE,
LOWER WILLIAMS FORK FORMATION,
PICEANCE BASIN, COLORADO

by

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ABSTRACT

The purpose of this study is to quantify sand-body dimension and determine net-to-gross ratio in the lower Williams Fork Formation, Piceance basin, Colorado. There are two types of data used in this research. The first data type consists of outcrop measurements and an aerial LiDAR survey. The second data type consists of subsurface information from the MWX-2 core and RWF542-20 borehole image log located in Rulison field, approximately 50 mi (80 km) east of the outcrop area. Both types of data have similar formation characteristics and depositional environments.

Observations from a well-exposed multi-story point-bar deposit in Coal Canyon outcrop show dip magnitudes of cross beds and lateral-accretion surfaces are similar (3 to 37°, average 15°), but dip directions vary by roughly 90°. Cross beds generally dip to the east (88°), which correlates to the direction to the Cretaceous seaway in the Piceance basin.

From 451 ft (137 m) of core in the MWX-2 core, there are 12 facies interpreted. These range from coals and muddy floodplain deposits to structureless and trough cross-bedded sandstones. There are 5 kinds of architectural elements: single-story channel-fill (Cf), superimposed channel-fill (SCf), crevasse-splay (CS), floodplain (Fp), and delta plain-delta front (DP/F) deposits. There are 2 Cf, 3 SCf, and 3 CS sand bodies interpreted from the core. The channel-fill (Cf and SCf) thicknesses range from 9 to 40 ft (3 to 8 m). Each type of sand body has distinctive log signatures.

The RWF542-20 image log is located 2.5 mi (4 km) to the northwest of the MWX-2 well. The lower Williams Fork gross interval is 1970 ft (600 m). Dips from shale beds with gamma ray values higher than 90 API units indicate that structural dip is less than 5°. Dominant dip direction is 31° for cross beds. There are 4 Cf, 16 SCf, and 26 CS sand bodies interpreted. The channel-fill deposit thicknesses range from 8 to 34 ft
(2.4 to 10 m). By assuming net sandstone as the combined thickness of Cf, SCf, and CS intervals, the computed net-to-gross ratio is 16.7%.

Channel width (Wc) and channel-belt width (Wm) of Cf and SCf deposits from the MWX-2 and RWF542-20 well have been estimated using published empirical equations. In the MWX-2 well, Wc ranges from 124 to 1,314 ft (38 to 400 m) and Wm ranges from 531 to 9,744 ft (162 to 2,971 m). In the RWF542-20 well, Wc ranges from 66 to 1,016 ft (20 to 310 m) and Wm ranges from 256 to 7,567 ft (78 to 2,307 m).

Exposed sand bodies (Cf, SCf and CS) in the outcrop area have been traced using aerial LiDAR. There are 633 sand bodies along a 5.7 mi (9.2 km) transect in the NE-trending and NW-trending segments of Coal Canyon. These consist of 109 (17%) Cf, 258 (41%) SCf and 266 (42%) CS sand bodies. Cf sand bodies range in thickness from 4 to 21 ft (1.2 to 6.4 m), SCf sand bodies range in thickness from 4.5 to 32.5 ft (1.3 to 10 m), and CS sand bodies range in thickness from 0.5 to 6.5 ft (0.1 to 2 m). Sand-body shapes of point bars (Cf and SCf) are assumed to be half circles, and crevasse-splay deposits are assumed to be circles. The half circle is generally oriented 75°, according to the average flow direction from published paleocurrent measurements. Sand-body widths of Cf at the 75° orientation range from 46 to 894 ft (14 to 272 m) and SCf at the 75° orientation range from 38 to 2,553 ft (12 to 778 m). The net-to-gross ratio of the Cf, SCf, and CS intervals is 15%, similar to the RWF542-20 subsurface result.

The LiDAR data set has been used to quantify the total number of sand bodies intersected by pseudo-wells at 10-acre (0.04 km$^2$) and 20-acre (0.08 km$^2$) well spacing. Of 633 total sand bodies, 10-acre (0.04 km$^2$) wells intersected 304 sand bodies (48%), and 20-acre (0.08 km$^2$) wells intersected 234 sand bodies (37%). When the data set is decimated to odd- and even-numbered wells, there are 158 sand bodies (25%) intersected by 40-acre (0.16 km$^2$) wells, and 127 sand bodies (20%) intersected by 80-acre (0.32 km$^2$) wells. This shows that more dense well spacing intersects more sand bodies. However, even 10-acre well spacing is inefficient, in that only 48% of the total number of sand bodies are intersected. Of 367 total Cf and SCf sand bodies combined, 10-acre (0.04
km$^2$) wells intersected 209 sand bodies (57%), 20-acre (0.08 km$^2$) wells intersected 180 sand bodies (49%), 40-acre (0.16 km$^2$) wells intersected 105 sand bodies (29%), and 80-acre (0.32 km$^2$) wells intersected 96 sand bodies (26%).

Channel dimensions determined from subsurface data and outcrop data differ significantly. The Cf and SCf sand-body widths from LiDAR-based outcrop measurements are considered to be the “ground truth.” Published equations for channel-belt width (Wm) in the subsurface are too optimistic by 3 to 11 times when compared to the outcrop results.
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Dan kepada Juru Selamat ku yang selalu mendengarkan dan mengabulkan doa mereka, meskipun seringkali aku tidak taat kepada Mu.

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Puji dan syukur ku nyayikan kepada Mu.
CHAPTER 1

INTRODUCTION

The Late Cretaceous Mesaverde Group (Illes and Williams Fork Formation) is a significant natural gas producer in the Piceance basin, Colorado. Johnson (1988) estimated that there are 300 Tcf (trillion cubic feet) of natural gas in place in this tight-gas sand. Because of the economic potential of the Piceance basin, studies of sand-body dimension are needed to optimize development programs.

This research compares outcrop and subsurface data for sand-body dimension interpretation. Outcrop exposures in Coal Canyon, northwest Colorado, provide an analog for reservoir assessment in the subsurface. Different types of fluvial sand bodies (e.g., point bars and crevasse splays) are observed in the outcrop and in the subsurface.

1.1. Research Objectives

This thesis is a stratigraphic study within a fluvial system in the lower Williams Fork Formation. There are two main objectives in this study:

- Quantify sand-body dimension in Coal Canyon using a digital aerial LiDAR survey. Point bars and crevasse splays have different dimensions (thickness and width). Dimensions are quantified and analyzed for each sand-body type.
- Measure net-to-gross-ratio and quantify sand-body intersected by comparing outcrop type with available subsurface data (log, core and borehole image log) from Rulison field. The purpose of this work is to better predict stratigraphic attributes in a 3D reservoir model.
1.2. Data

There are two types of data used in this research. The first data is outcrop data, located in the Wild Horse Range, Coal Canyon, Colorado (Figure 1.1). Coal Canyon preserves an excellent exposure of the Williams Fork Formation. For the purpose of this study, an aerial LiDAR survey was conducted through the entire study area by Merrick & Company in 2005. Digital data from aerial LiDAR consist of: LAS elevation data points, ASCII elevation data points, and orthophotos. Integration of three types of data is important to view the digital elevation with an accuracy less than 3 ft (1 m).

The second type of information is subsurface data from Rulison field, located 50 mi (80 km) to the northeast of Coal Canyon (Figure 1.1). The available subsurface data are conventional core from the MWX-2 well and a borehole image log from the RWF 542-20 well. The distance between the two wells is approximately 2.5 mi (4 km) (Figure 1.2). There are two MWX-2 core intervals. The first interval is in the Cameo-Wheeler zone from 7080-7388 ft, and the second interval is located above the Cameo-Wheeler zone from 6390-6568 ft. The borehole image log from well RWF-542-20 covers about 1800 ft (600 m) of gross interval. Conventional logs from both wells penetrate the entire Williams Fork interval.

1.3. Previous Work

There have been numerous publications about regional stratigraphy in the Piceance basin, such as Johnson et al. (1983, 1986, 1990, and 2003), Kirschbaum and Hettinger (1998, 2004), Patterson et al. (2003), Lorenz (1985), and others. This research draws upon work by Cole and Cumella (2003, 2005) and Ellison (2004) in the lower Williams Fork interval in Coal Canyon.
Figure 1.1. Location of Coal Canyon area and Rulison field. Modified from (http://oil-gas.state.co.us).
Figure 1.2. Location map of wells MWX-2 and RWF 542-20 in Rulison field. Modified after Davis (2004). These wells occur in T6S-R94W. Abbreviations: DOE= Department of Energy; RCP= Reservoir Characterization Project.
Ellison (2004) studied the effect of heterogeneity within a point bar deposit on fluid flow. Her study is based on a single point-bar outcrop in Coal Canyon and involved measured sections and a ground-based LiDAR survey. Her flow simulation showed that heterogeneity caused various fluid-flow anomalies. The cross-bed measurements in this research were conducted in the same point bar (see Chapter 3).

Cole and Cumella (2003, 2005) studied stratigraphy within the fluvial system of the lower Williams Fork Formation. They measured 15 sections and recorded GPS (Global Positioning System) way-points for 136 sand bodies. The total stratigraphic interval is approximately the lower two-thirds of the sand-poor Williams Fork Formation. The upper one third was not investigated because of steep slopes and precipitous cliffs.

This study expands the work of Cole and Cumella (2003, 2005) to cover the entire sand-poor interval. Previous measured sections and way-points are used to guide sand-body identification and measurement. An advantage of using aerial LiDAR is to be able to cover sand bodies in the entire cliffs, even in steep cliffs that were inaccessible to previous researchers.

Lorenz (1985) studied the MWX core site to estimate the channel width and channel-belt dimensions using the Leeder (1974) method. In Lorenz (1985), most figures focused on the Upper Williams Fork in the MWX-1. Although it was already described, there have been no publications that provide detailed descriptions and interpretations in the MWX-2 core interval.

1.4. Methodology

This research examines small-scale and large-scale heterogeneities (Figure 1.3). Small-scale studies include measured cross beds in the outcrop and descriptions of the MWX-2 core and RWF 542-20 borehole image log. Cross-bed orientation from outcrop data and borehole image log are used to determine apparent paleocurrent orientation.
Figure 1.3. Research framework flow chart
Core and borehole image log analysis contribute sedimentologic and stratigraphic information. Properties from identified point bars (thickness and cross-bed set thickness) from subsurface data are used to estimate channel width and channel-belt width, which represents a 2-D assessment of sand-body dimensions.

The large-scale framework consists of sand-body dimension measured in Coal Canyon using aerial LiDAR data. This measurement includes thickness and width of each sand-body within the fluvial system (crevasse-splay and point-bar deposits). The stratigraphic succession within the fluvial system is developed by tracing sand bodies on the cliff faces. Previous measured sections and way-points determined by Cole and Cumella (2003) in Coal Canyon are used to identify and trace each sand body.

Sand-body dimensions from multiple scales provide an input to determine net-to-gross ration in the lower Williams Fork Formation. Facies proportions provide input in terms of thickness and width of individual sand bodies in a manner suitable for 3-D geologic modeling. This can be used to determine optimal well spacing in reservoirs that produce from similar fluvial sandstones.

1.5. Research Contributions

- Measurements of cross beds and lateral-accretion surfaces in a well-exposed point bar in Coal Canyon show that dip magnitudes are similar, but dip directions vary by roughly 90° for the 2 types of surfaces. Cross beds generally dip to the east (88°).
- I described 451 ft (137 m) of core from well MWX-2 in Rulison field, which is in a coeval interval 50 mi (80 km) east of the Coal Canyon outcrop. The MWX-2 core description shows 12 facies, and 5 architectural elements (single-story channel-fill (Cf), superimposed channel-fill (SCf), crevasse-splay (CS), floodplain (Fp), and delta plain-delta front (DP/F) deposits). Identification of channel depth from Cf and SCf deposits provides input data to estimate the channel width (Wc) and channel-belt
width (Wm) using published equations.

- Interpreted 1,970 ft (600 m) of electrical borehole images from well RWF542-20 in Rulison field. The structural dip is less than 5° and cross-bed dip direction (31°) is different from cross-bed orientation noted in Coal Canyon. The sand-body architectural elements (Cf, SCf, and CS) in the lower Williams Fork Formation help to determine the net-to-gross ratio (16.7%) in the RWF542-20 well. Identification of channel-fill deposits provides channel-dimension assessment (Wc and Wm).

- The differentiation of 3 types of sand bodies (Cf, SCf, and CS) in the subsurface applied in Coal Canyon using airborne LiDAR.

- Interpreted and traced 633 sand bodies using an airborne LiDAR survey over Coal Canyon. The sand-body shapes of point bars (Cf and SCf) are approximated as half circles, and crevasse-splay deposits are approximated as circles. This assumption helps to measure the Cf, SCf, CS sand-body widths. The net-to-gross ratio of the Cf, SCf, and CS intervals in the lower Williams Fork Formation is 15%, which is similar to the net-to-gross ratio observed in the RWF542-20 well. This result suggests that the outcrop exposures at Coal Canyon provide an excellent approximation of the subsurface facies proportion.

- Intersected 633 traced sand bodies in the LiDAR data set with the pseudo-wells at 10-acre (0.04 km²), 20-acre (0.08 km²), 40-acre (0.16 km²), and 80-acre (0.32 km²) wells. More dense well spacing intersects more sand bodies. However, even in a 10-acre (0.04 km²) well spacing is inefficient, because less than half total sand bodies are intersected. Very few individual sand bodies are intersected by more than 1 well. This suggests that pressure-depleted sand bodies will not occur very often, even with 10-acre (0.04 km²) well spacing.

- Assuming that LiDAR-based outcrop measurements of channel width are the “ground truth,” the published equations for channel width and channel-belt width are too optimistic by 3 to 11 times.
CHAPTER 2

GEOLOGIC SETTING

2.1. Regional Stratigraphy

During the Sevier orogeny, the late Cretaceous Rocky Mountain foreland basin was flooded by marine waters to form the Western Interior Seaway. Sediments from the Sevier highlands were deposited on alluvial fans, and graded progressively into braided-plain, coastal-plain, deltaic, shoreline, and offshore environments within the Mesaverde Group (Johnson, 1989; Yurewicz et al., 2003).

The lower members of the Mesaverde Group are the Castlegate, Sego and Iles Formations. In the southern Piceance basin, the Iles Formation shows a complex intertonguing with the marine Mancos Shale (Hettinger and Kirschbaum, 2002). The Iles Formation is subdivided into the Corcoran, Cozzette, and Rollins Sandstone members (Figure 2.1), which were deposited in inner-shelf, deltaic, shoreface and lower coastal-plain settings (Cole and Cumella, 2005). Above the Rollins Sandstone, there is a thick coal-bearing interval known as the Cameo-Wheeler interval. This is the lower part of the Williams Fork Formation.

The lower Williams Fork Formation was deposited in a coastal-plain setting by meandering streams in a fluvial environment (Johnson, 1983). The thickness of the Williams Fork Formation ranges from approximately 5,000 ft (1,524 m) in the eastern part of the Piceance basin to 1,200 ft (365.7 m) at the Colorado-Utah border (Hettinger and Kirschbaum, 2002). The variation is due to regional Laramide erosion at the top of the Williams Fork and variation in subsidence during deposition (Johnson and Flores, 2003).
Figure 2.1. Upper Cretaceous to Tertiary stratigraphic column of the Piceance basin. Study interval is located in the lower Williams Fork Formation. Modified from Cole and Cumella (2003).
In the southwestern part of the Piceance basin, including the Coal Canyon area, the Williams Fork is subdivided into informal members based on lithology differences. The lower one third of the Williams Fork consists mainly of mudrock (40–70%), with subordinate sandstone and coal, and is known as the sand-poor interval. The upper two-thirds is mostly sandstone (50-80%), with subordinate mudrock and no coal, and is known as the sand-rich interval (Cole and Cumella, 2005).

Laramide tectonics caused a regional unconformity, which separates the Cretaceous and Tertiary deposits. The Wasatch, Green River and Uinta formations are exposed in different portions of the basin due to erosion over the past 30 million years. The Wasatch Formation, which immediately overlies the Mesaverde Group, was deposited in a fluvial environment.

2.2. Regional Structure

During the Late Cretaceous (Late Campanian to Maastrichtian), the Western Interior Seaway covered the central part of North America from northern Canada to Mexico. The Sevier Orogenic Belt, located to the west of the seaway, was a thrust belt complex that was the primary source of sediment for the basin (Figure 2.2). The thrust belt activity increased during the late Campanian and caused progressive movement of the shoreline to the east (Johnson, 1989). This is known as the Sevier orogeny.

The Laramide orogeny divided the foreland basin into intermontane basins, such as the Piceance basin in Colorado and the Uinta basin in Utah. Today, the Piceance basin covers over 6,000 mi² (15,540 km²) and is separated from the Uinta basin to the west by the Douglas Creek arch (Figure 2.3). The Piceance basin is an asymmetric synclinal basin with a northwest-southeast trend that dips gently on the west flank and is steeply overturned along the eastern part of the basin in a structure known as the Grand Hogback (Johnson, 1989).
Figure 2.2. Western Interior Seaway during early Maastrichtian (Late Cretaceous). Present-day North America outline is shown (black line). Modified from Gill and Cobban (1973).
Figure 2.3. Structural elements in the Piceance basin. Modified from Cole and Cumella (2003).
The Laramide orogeny had a strong influence on the NW-SE oriented structural features in the Piceance basin. Geologic structures such as monoclines, synclines and anticlines generally have the same NW-SE trend in the Piceance basin (Figure 2.3).

2.3. Local structure and stratigraphy

2.3.1. Coal Canyon

Coal Canyon is located in the southwestern part of the Piceance basin. The Rollins Sandstone and Williams Fork Formation are well exposed and have minimal structural complication, with structural dip generally <7° NE (Cole and Cumella, 2005).

In Coal Canyon, the Williams Fork Formation conformably overlies the Rollins Sandstone member of the Iles Formation. The Rollins Sandstone is characterized as sandstone and mudrock from shoreface environments (Figure 2.4). On top of the Rollins Sandstone, or at the base of the Williams Fork Formation, there is a coal interval known as the Cameo-Wheeler interval. The thickness is about 240 ft (80 m) and consists of interstratified coal, carbonaceous mudrock, sandstone, and conglomerate (Cole and Cumella, 2005). Four mappable coal seams occur in the Cameo-Wheeler interval: Cameo, Highwall, Ash and Upper (Figure 2.4).

The lower Williams Fork Formation, including the Cameo-Wheeler interval, was deposited in a coastal-plain setting with the influence of sinuous (meandering) to anastomosing streams. Cole and Cumella (2003, 2005) described 5 types of fluvial sand bodies in this interval (Figure 2.5). These are (A) narrow, (B) simple sinuous, (C) compound sinuous, (D) poorly channelized, and (E) broadly lenticular. Types A, B and C are gas reservoirs in the subsurface.
Figure 2.4. Composite stratigraphic column from 4 measured sections (left) shown in photomosaic (courtesy of Rex Cole) in Coal Canyon (right). Modified from Cole and Cumella (2005).
Figure 2.5. Classification of fluvial sand bodies in the lower Williams Fork Formation (sand-poor) in the Coal Canyon area. Potential reservoirs are sand-body types A, B and C. From Cole and Cumella (2003).
2.3.2. Rulison Field

The general geometry of Rulison field is a subtle anticline (Kuuskraa et al., 1999) with a general NW-SE trend, the same as the regional trend. Within that anticline, there is inferred strike-slip faulting with the same structural orientation (Jansen, 2005).

A similar stratigraphic succession to that exposed in Coal Canyon is found in Rulison field. In this study, the stratigraphic subdivision in Rulison field is visualized based on the MWX-2 core and the RWF 542-20 borehole image log. Both wells penetrated the entire Williams Fork Formation and into the Illes Formation, approximately 8,000 ft (1,600 m) of measured depth (Figure 2.6). The Cameo coal interval thickness is approximately 950 ft (310 m), which is thicker than exposures in Coal Canyon.

2.4. Petroleum System

In a basin-centered gas play, such as that in the Piceance basin, mature gas-prone source rock is important for hydrocarbon occurrence. Yurewicz et al. (2003) studied the source rock and hydrocarbon generation in the northern Piceance basin using outcrop and core data. Their results indicate that there are three main source facies: 1) marine shales within the Mancos Shale and Mesaverde Group, 2) coal seams within the Iles and Williams Fork Formations, and 3) non-marine shales within the Iles and Williams Fork Formations. The largest volume of gas was generated from the Cameo coal interval within the Mesaverde Group. Generation of gas began at approximately 55 Ma, and peak generation occurred between 50 and 20 Ma in the eastern half of the basin (Yurewicz et al., 2003).
Figure 2.6. Marker beds in the study wells in Rulison field. Datum is the Rollins Sandstone. Marker (green text) and perforation depths are courtesy of Williams Corp. RC2, 3, 4 and 7 are coal beds. Depth is in feet. Abbreviations: GR=gamma ray; ILD=deep induction log.
The mature gas-prone source rocks were connected to the reservoir mainly through faults and their associated natural fractures. This structure occurred due to reactivation of older structures and Laramide compression. The major natural gas production comes from the Williams Fork Formation in the southern portion of the Piceance basin (Rulison, Grand Valley, Parachute and Mamm Creek fields). Natural gas is also produced from the Iles Formation (Corcoran-Cozzette) in the southern part and from the Wasatch Formation in the northern part of the Piceance basin (Figure 2.7).

Average reservoir permeability is 5 to 80 microdarcies. Therefore, this is considered a tight-gas reservoir. Geometric characteristics of the reservoir include lenticular fluvial sandstones with low productivity and high-cost resources (Kuuskraa et al, 1999). Therefore, secondary permeability from natural fractures is very important as a gas-producing mechanism.
Figure 2.7. Structure map on top of the Rollins Sandstone, Mesaverde Group. Map shows Mesaverde outcrops and location of major gas fields in the Piceance basin. After Yurewicz et al. (2003).
CHAPTER 3

OUTCROP DESCRIPTION

Outcrop description is focused on a point-bar sand body in Coal Canyon, which is located in the Wild Horse Range near the town of Palisade (Figure 3.1). Stratigraphically, the sand body is located in the Cameo-Wheeler interval in the lower Williams Fork Formation. Observations include internal sedimentary structures, cross-bed orientations, and architectural analysis of the sand body.

The point bar was previously studied by Ellison (2004) by making 12 measured sections. The purpose of observing the sand body in this study is to understand the sedimentary structures to improve later core and borehole image interpretations.

3.1. Sedimentary Structures and Architecture Interpretation

The point-bar sand body that was observed in this study is a multi-story channel-fill deposit herein as a superimposed point bar. The sand body is well exposed and accessible near Coal Canyon road. It is capped at the top by a mud plug and crevasse-splay sand body (Figure 3.2). The mud plug is a floodplain deposit.

From the photomosaic, it is clear that the point-bar deposit has several lateral accretion surfaces. A lateral accretion surface is part of a meandering stream in a sinuous river. The lateral accretion surface set in the point-bar is eroded by a scour surface, which defines this sand as a stack of two point-bar deposits.
Figure 3.1. Location of outcrop observations in Wild Horse Range. Modified from BLM map, Grand Junction.
Figure 3.2. Photomosaic of superimposed point bar overlain by floodplain and crevasse-splay deposits. The point bar is composed of 2 channel-fill deposits separated by a scour surface. Modified after Ellison (2004); Cole and Cumella (2003).
Primary sedimentary structures in the channel-fill deposit differ from those in the crevasse-splay deposit. The main sedimentary structure in the channel-fill deposit is cross bedding (Figure 3.3). In the crevasse-splay, the primary sediment structure is ripple lamination (Figure 3.4). This sedimentary structure difference will help determine the type of sand body. Cross bedding in the channel-fill deposit was measured to determine the apparent paleocurrent direction.

Other sedimentary structures observed in the channel-fill deposit are mud chips and ripple laminations (Ellison, 2004). Mud chips (Figure 3.5) are concentrated near the base of channel fills and lateral accretion surfaces. Mud chips are associated with cross bedding, which in turn grades up to ripple lamination only at the lateral accretion package. Changes in sedimentary structures from near the base to the top of the channel-fill sandstone are related to decreased sediment energy. Mud chips and cross beds were deposited by high-energy traction currents. Within the channel, they grade up the accretion set to lower-energy ripple lamination.

Based on Ellison (2004) and Cole and Cumella (2003), the thickness of this channel-fill deposit 25 ft (7.6 m). The channel-fill maximum thickness is considered to be equivalent to the maximum bankfull depth. Sand-body dimensions will be discussed further in Chapter 5.

### 3.2. Paleocurrent Analysis

Paleocurrent orientation in a fluvial system can be estimated from the orientation of trough axes in channel-fill deposits. Measurements were conducted in the area that could be reached safely. Access near the top of the channel-fill sand is difficult due to steep outcrop exposures.
Figure 3.3. Photo showing cross beds near the base of channel-fill sand. Scale bar is in cm.
Figure 3.4. Photo showing cross-section view of ripple to climbing ripple laminations in a crevasse-splay deposit. Scale bar is in cm.
Figure 3.5. Photo showing mud chips (circled) in channel-fill deposit.
There were 128 cross-bed orientations (Appendix A) measured from the channel-fill sandstones. A lower hemisphere stereonet plot of 128 cross-bed poles shows a mean lineation vector of 268° and a plunge of 84° (Figure 3.6). The cross-bed mean dip azimuth is 88° and the dip is 6° (Figure 3.7). The cross-bed dip ranges from 3° to 37°, with an arithmetic mean value of 15°. Ellison (2004) measured cross beds and determined a 94° dip-azimuth orientation. Although these were trough cross beds, I purposely measured individual cross beds rather than the axes of the troughs. This is because individual cross beds more closely resemble the measurements obtained from borehole image logs. As such, these outcrop measurements provide a rough estimate of paleocurrent orientation. Outcrop-based stereonets should be similar to those obtained from borehole images.

Lateral accretion surfaces were measured to see the mean direction of sedimentation. When doing the measurements, I stood some distance from the outcrop (10’s of ft, m). I tried to stand perpendicular to the outcrop face. Therefore, these are apparent dips. The rose diagram (Figure 3.8) shows that the mean dip azimuth of accretion surfaces is 203°. The dip magnitude ranges from 5° to 21°, with an arithmetic mean value of 11°. This indicates that point-bar accretion on this one was relatively toward the S-SW. It also indicates that the accretion surface in a point-bar deposit is close to perpendicular to the dip azimuth of cross bedding.

3.3. Discussion

Characteristics observed in the outcrop give important insights to help describe the core and interpret borehole images. This outcrop is close to an ideal cross section in a point-bar deposit.
Figure 3.6. Lower hemisphere equal area (Schmidt) stereonet plot of 128 cross beds with Mean Lineation Vector (MLV) pole of $268^\circ/84^\circ$, which makes the dip direction/dip vector $88^\circ/6^\circ$. 
Figure 3.7. Dip-azimuth rose diagram displaying 128 cross-bed orientations collected from channel-fill deposits with mean dip azimuth of 88° (above), and cross-bed dip-frequency plot with arithmetic mean dip of 15° (below).
Figure 3.8. Dip-azimuth rose diagram displaying 20 lateral accretion surfaces collected from channel-fill deposits with mean dip direction of 203° (above) and lateral accretion dip-frequency histogram with arithmetic mean dip value of 11° (below).
The channel-fill deposit in Coal Canyon has medium to fine-grained sand, cross beds, lateral-accretion surfaces, mud chips, and ripple laminations in the upper part. The crevasse-splay deposit has fine-grained sand and ripple lamination with cross bedding.

The apparent paleocurrent orientation indicates that the flowed to SE, which is consistent with the shore of the Cretaceous seaway being towards the east in this part of the Piceance basin. The apparent paleocurrent direction will later be compared with the cross-bed orientation in the RWF542-20 borehole image log. The range in dip magnitude of cross beds and lateral-accretion surfaces is similar. This close range makes it difficult to differentiate between cross beds and lateral-accretion surfaces in borehole images. However, the dip direction varies, so this can be used to determine the origin of bedding features noted in logs. Also, scour surfaces may be apparent at lateral-accretion surfaces in borehole images.
CHAPTER 4

CORE DESCRIPTION

The purpose of describing the core is to obtain lithologic data to help interpret the EMI (Electrical Micro Imager) log in Rulison field. Two core interval in the MWX-2 were chosen in this study is from the lower Williams Fork Formation. The first interval is located in the Cameo-Wheeler zone, and the second interval is located above the Cameo-Wheeler zone (Figure 4.1). In the core description (Appendix B), the core depth is corrected to match the well-log curves (GR, CAL, ILD, RHOB, and NPHI). The depth corrections from both intervals have different values. In the first cored interval (7080 to 7351 ft, core depth), the depth correction is adjusted 12 ft (3.5 m) up from the drilling depth. The second cored interval (6390 to 6570 ft, core depth) has two different depth corrections: 5 ft (1.5 m) up and 3 ft (1 m) up from the drilling depth (Appendix B). All further discussions of core refer to log depth.

The core description focuses on facies descriptions, associations, and architectural elements. Coal, mudstone, siltstone, and sandstone are the lithologies observed in the core. Because the core is stratigraphically coeval to the Coal Canyon outcrop, the core interpretation directly relates to the outcrop analog. This interval is interpreted to be an alluvial deposit (Cole and Cumella, 2003). Sand-body type (e.g., channel fill, crevasse splay) is the main focus of the description. Channel-fill sand-body analysis is expanded further for channel-dimension estimation using the Leeder (1974) and Bridge and Tye (1993) methods.
Figure 4.1. Core depth in MWX-2 well after depth correction. The first core is located in the Cameo-Wheeler interval and the second core is located above the Cameo-Wheeler interval. Abbreviations: CALI=caliper; GR=gamma ray; ILD=deep induction resistivity; NPHI=neutron porosity; RHOB=bulk density (g/cc).
4.1. Facies and Facies Association

Lithologic descriptions of the core include rock type, grain size, and sedimentary and biogenic structures. A body of rock is characterized by a particular combination of lithology. Physical and biogenic structures can be differentiated from intervals above and below, and intervals are called a specific facies. Facies that are genetically related to one another and which have a similar depositional environment are grouped into facies associations (Walker, 1992).

There are 12 facies described from the core. The subdivision of facies is based on the lithology description and there is no paleontologic analysis, other than trace-fossil description, in this study. Facies are interpreted based on rock type, sedimentary structures, and the occurrence of bioturbation. The summary of the facies description is shown in Table 4.1.

4.1.1 Coal (C)

Coal is black, and is loose, rubbly, and translucent. The bottom contact of a given coal seam is gradational and is associated with underlying carbonaceous mudstone (Md2). The upper contact is commonly sharp, as it underlies and is scoured by sandstone (Figure 4.2). The thickness of a coal seam can be 3 ft to > 9 ft (0.9 to >2.7 m), but it could be thicker due to missing core interval. Because coal layers have a distinctive wireline-log response (low GR, high CAL, high ILD, very low RHOB, and very high NPHI), the thickness can be estimated by using the log character.

A coal seam is formed largely from the settling of rafted vegetation, or collapse and decay of plant cover (Galloway, 1996). The plant material must remain protected from detrital influx and be maintained in a low pH condition to be transformed into coal. Coal resources are commonly associated with alluvial fan, fluvial, deltaic and lacustrine
Table 4.1. Summary of facies, facies associations and architectural elements in the Lower Williams Fork Formation based on core description in MWX-2. Ichnofossils are *Skolithos* (Sk), *Paleophycus* (Pa), *Planolites* (P), *Teichichnus* (Te), and *Diplocraterion* (Dp).

<table>
<thead>
<tr>
<th>Facies Name</th>
<th>Facies Code</th>
<th>Grain Size Range</th>
<th>Sorting</th>
<th>Set/ Bed Thickness Range (cm)</th>
<th>Ichnofossils</th>
<th>Facies Association; Facies Code; Inferred Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>C</td>
<td>m, s, v, f, m, c</td>
<td>Poor</td>
<td>50, 100, &gt;200</td>
<td>Barren</td>
<td>Md2; swamp (Delta Plain)</td>
</tr>
<tr>
<td>Bioturbated Mudstone</td>
<td>Ms1</td>
<td></td>
<td></td>
<td>Common-abund; Sk, Pa, P, Te</td>
<td>ConMdS1; lower delta front (?)</td>
<td></td>
</tr>
<tr>
<td>Unbioturbated Mudstone</td>
<td>Ms2</td>
<td></td>
<td></td>
<td>Barren</td>
<td>RoS1, ConMdS1; floodplain</td>
<td></td>
</tr>
<tr>
<td>Rooted Siltstone</td>
<td>RoS1</td>
<td></td>
<td></td>
<td>Rare</td>
<td>ConMdS1; floodplain</td>
<td></td>
</tr>
<tr>
<td>Contorted Mud-Silt</td>
<td>ConMdS1</td>
<td></td>
<td></td>
<td>Common-abund; Pa, Sk, Te</td>
<td>Ms2, RoS1; floodplain</td>
<td></td>
</tr>
<tr>
<td>Interbedded Mudstone and Sandstone</td>
<td>IntMdSs</td>
<td></td>
<td></td>
<td>Common-abund; Sk, Pa, P, Dp, Dp</td>
<td>Ms1, RpMdSs; delta front (lower shoreface ?)</td>
<td></td>
</tr>
<tr>
<td>Parallel- wavy Laminated Sandstone</td>
<td>PrWyLm</td>
<td></td>
<td></td>
<td>Barren</td>
<td>RpSs, RuCls; upper channel-fill (point bar)</td>
<td></td>
</tr>
<tr>
<td>Ripple with Mud-drape Sandstone</td>
<td>RpMdSs</td>
<td></td>
<td>Barren-rare</td>
<td>IntMdSs, Ms1; Upper shoreface</td>
<td>RpCls, CvSs, StGs, PrWyLm; channel fill, crevasse splay</td>
<td></td>
</tr>
<tr>
<td>Ripple-Dominated Sandstone</td>
<td>RpSs</td>
<td></td>
<td>Barren</td>
<td>CrSs, StSs, PrWyLm; channel fill, crevasse splay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rip-up Clasts Sandstone</td>
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<td></td>
<td>Barren</td>
<td>CrSs, StSs, PrWyLm; channel fill, crevasse splay</td>
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<td></td>
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<tr>
<td>Structureless Sandstone</td>
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<td>Barren</td>
<td>RpMdSs, IntMdSs; upper shoreface</td>
<td>RpSs, RpMdSs; channel fill, crevasse splay</td>
<td></td>
</tr>
<tr>
<td>Convolute Sandstone</td>
<td>CvSs</td>
<td></td>
<td>Barren</td>
<td>RpSs, RpMdSs; channel fill, crevasse splay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross-beded Sandstone</td>
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<td></td>
<td>Barren</td>
<td>RuCls, RpSs, RpMdSs; channel fill, crevasse splay</td>
<td></td>
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</tr>
</tbody>
</table>
Figure 4.2. Core photo of coal layer (Facies C) at 7274.5 ft log depth (7286 ft core depth) characterized with black color and below a scour surface at the base of a clast-rich sandstone.
systems (Galloway, 1996). Association of coal layers with other facies will give a hint about the environmental setting.

Facies C is also observed in Coal Canyon. The exposed coal seams are mappable and can be used as correlation markers (Cole and Cumella, 2005). In the subsurface, the coal seams are good markers for correlation between wells in the Rulison field (Figure 2.6).

**4.1.2 Mudstone (Ms)**

The mudstone facies is subdivided into two subfacies: 1) bioturbated mudstone (Ms1); and unbioturbated mudstone (Ms2). The mudstone color is dark brown, and the main difference between the two subfacies is the occurrence of bioturbation (Figure 4.3).

The bioturbation or ichnofossil density in the Ms1 facies ranges from sparse to abundant. Ichnofossils are typically from the *Skolithos* ichnofacies: *Skolithos* and *Paleophycus*. *Teichicnus* and *Planolites* from the *Cruziana* ichnofacies are also associated with this facies (Pemberton, 1992). The occurrences of both ichnofacies give a possible interpretation that this zone was deposited in a nearshore-foreshore or bay environment.

Abundant bioturbation in Ms1 commonly comes with soft-sediment deformation. Thin, parallel, wavy lamination commonly occurs in a sparsely to moderately bioturbated mudstone. The thickness of this subfacies commonly ranges from 1 to > 5 ft (0.9 to >1.5 m), and it only occurs in the lower Cameo-Wheeler interval. It is associated with other bioturbated facies such as interbedded mudstone and sandstone facies (IntMdSs), and ripples with mud-drape sandstone (RpMdSs).

Compared to the Ms1 facies, there are no ichnofossils in Ms2. The shale is commonly structureless, with thin planar lamination, and is carbonaceous with occasional siderite, plant debris, and plant roots. Siderite can occur as nodules (1-3 cm) or as thin
Figure 4.3. Core photo of bioturbated sandy mudstone (left) from facies Ms1 at 7,081 ft log depth (7,093 ft core depth), and unbioturbated carbonaceous-rich mudstone from facies Ms2 at 6,405 ft log depth (6,393 ft core depth).
layers (5 cm). Facies Ms2 is very rubbly in the core and is commonly associated with rooted siltstone (facies RoSl) and contorted siltstone facies (ConMdSl). Thickness ranges from 0.2 ft to >5 ft (6 cm to >1.5 m).

The core description shows that the Ms2 facies usually occurs above the Cameo-Wheeler interval. Characteristics of the Ms2 facies are similar to the mudrock description by Cole and Cumella (2003) in Coal Canyon. This is interpreted as a floodplain deposit, formed in a marshy and swampy environment.

4.1.3. Rooted Siltstone (RoSl)

Rooted siltstone is gray with plant roots and mud, and is commonly structureless with rare thin mud laminae, plant debris, siderite and barren to very rare bioturbation (Figure 4.4). The siltstone can be muddy or sandy in different intervals. Roots and plant debris are not always present in this facies. Facies thickness ranges from 1 ft to > 3 ft (0.3 to >0.9 m).

Preserved roots in the siltstone suggest that there was less detrital influx. It is associated and commonly grades up to contorted siltstone (ConMdSl). This facies only occurs above the Cameo-Wheeler interval. The RoSl facies compares to the gray siltstone and fissile silt claystone described by Cole and Cumella (2005) in Coal Canyon. It is common above the Cameo interval and is interpreted as an alluvial floodplain deposit.
Figure 4.4. Core photo of rooted siltstone from facies RoSl at depth 6,563 ft log depth (6,568 ft core depth) (left) and at depth 6,409 ft log depth (6,411 ft core depth) (right).
4.1.4. Contorted Mud-Silt (ConMdSl)

The contorted mud-silt facies is dark gray, contorted, with small plant debris, and is bioturbated. The composition is muddy to sandy siltstone. Occasionally, there is mud lamination with minor faulting (Figure 4.5). Thickness ranges from 0.5 to >3 ft (15 to 91 cm). The density of bioturbation ranges from common to abundant. The ichnofossil types are *Paleophycus* and *Teichincus* from the *Skolithos* ichnofacies, and *Planolites* from the *Cruziana* ichnofacies (Pemberton, 1992). The ichnofossil diversity in the ConMdSl facies is similar with ichnofossils in the Ms1 and IntMsSs facies.

Commonly, Ms2 facies and RoSl facies grade up to ConMdSl facies. This association only occurs above the Cameo-Wheeler interval. This facies has not been reported in Coal Canyon, but it could be a floodplain deposit, similar to the RoSl facies. RoSl, ConMdSl, and Ms2 facies are commonly deposited on top of sand bodies.

4.1.5. Interbedded Mudstone and Sandstone (IntMdSs)

The interbedded mudstone and sandstone is gray to dark gray, with mud and sand beds that commonly form wavy or lenticular bedding. Ripple lamination occurs only in thin sandstone beds (Figure 4.6). The sandstone bed is muddy with an upper very fine grain size. The average sand-bed thickness ranges from 0.5 to 2 cm. The IntMsSs facies thickness ranges from 0.5 to 2 ft (15 to 61 cm).

Bioturbation in this facies is common. Types of ichnofossils are *Skolithos*, *Paleophycus*, and *Diplocraterion* from the *Skolithos* ichnofacies. *Teichincus* and *Planolites* from the *Cruziana* ichnofacies are also observed in this facies (Pemberton, 1992). Generally, the ichnofossil type in this facies is similar to the Ms1 facies. Therefore, the IntMsSs and Ms1 association could be related to nearshore to foreshore settings. Like the Ms1 facies, the IntMsSs facies is not reported in Coal Canyon.
Figure 4.5. Core photo of highly contorted mudstone at depth 7,299 ft log depth (7,311 ft core depth) (left) and contorted mud-silt due to minor fault at depth 6,476.5 ft log depth (6,481.5 ft core depth) from facies ConMdSl. Ichnofossils are *Planolites* (P) and *Paleophycus* (Pa).
Figure 4.6. Core photo of facies IntMsSs at 7,335.5 ft log depth (7,347.5 ft core depth). Ichnofossils are *Skolithos* (Sk), *Planolites* (P), *Paleophycus* (Pa) and *Terebelina* (Te).
4.1.6. Parallel-wavy Laminated Siltstone-Sandstone (PrWyLm)

This facies can occur in sandy siltstone or sandstone. It is gray to dark gray. Parallel-wavy lamination commonly forms low-angle laminations, which are occasionally deformed (Figure 4.7). Facies thickness ranges from 0.5 to >1 ft (15 to >30 cm), and commonly the composition becomes muddy or silty upward.

In sandy siltstone, the PrWyLm facies commonly grades up to Ms2 facies. Bioturbation is commonly found in this zone. This association is related to a floodplain or lake deposit.

The PrWyLm facies in upper very fine sandstone occurs near the top of the sand body of a channel fill or near the base of a crevasse-splay deposit. It is associated at the top with ripple-laminated sandstone (RpSs) and rip-up clasts (RuClS). There is rare bioturbation observed in this facies.

A subclassification can be made for the PrWyLm lamination based on the depositional origin. The first subfacies relates to less detrital influx in a floodplain deposit. It is comparable to floodplain deposits described in Coal Canyon. The second subfacies relates to more detrital influx in channel-fill and crevasse-splay deposits.

4.1.7. Ripple with Mud-draped Sandstone (RpMdSs)

This facies is gray, and is composed of lower to upper very fine sand with small carbonaceous debris, and thin ripple laminations mixed with mud drapes (Figure 4.8). The RpMdSs facies is associated with several facies, which yield different environmental interpretations. Association of RpMdSs with IntMsSS and Ms1 facies relate to the bay or tidal environment, which only occurs in the Cameo-Wheeler interval. Diversity of ichnofossils is similar with IntMdSs and Ms1 facies. Facies thickness ranges from 0.5 to 2 ft (15 to 60 cm). The contact between facies is commonly sharp and recognizable.
Figure 4.7. Core photo of low-angle parallel-wavy lamination from facies PrWyLm at depth 7,253 ft log depth (7,265 ft core depth).
Figure 4.8. Core photo of ripples with thin mud drape from RpMdSs facies at depth 7,338 ft log depth (7,350 ft core depth).
Association of RpMdSs with rip-up clast (RuCls) facies, convolute sand (CvSs), structureless sand (StSs) and parallel-wavy lamination (PrWyLm) occurs in the upper part of point-bar or crevasse-splay deposits. The thickness ranges from 10-17 cm, and the facies contacts are commonly gradational. If the thickness is 5 cm and RpMdSs is associated with RoSI and ConMdSl, it is interpreted as a floodplain deposit. Characteristics of this facies have not been reported in Coal Canyon.

**4.1.8. Ripple-Dominated Sandstone (RpSs)**

The ripple-dominated sandstone is gray, upper very fine sandstone with ripple structures, siderite minerals, and small carbonaceous plant debris at the top contact (Figure 4.9). Ripple laminations can be convolute in the upper part. Siderite minerals can occur as nodules or as thin (5 cm) layers in crevasse-splay deposits (at 7,128 ft log depth). The facies thickness ranges from 1 to 6 ft (0.3 to 1.8 m).

This facies is commonly associated with and occurs above cross-bed facies (CrSs) or small rip-up clast facies (RuCls). It is also associated with structureless sandstone facies (StSs) and convolute sand facies (CvSs). It can occur as the upper portion of a channel-fill sand or as the main sedimentary structure in a crevasse-splay deposit.

Ripple-dominated structure in a sand body is also observed in Coal Canyon outcrops (see Chapter 3). Sand bodies form sheet dimension and are interpreted as crevasse-splay deposits (Ellison, 2004).
Figure 4.9. Core photo of ripple-dominated to slightly climbing ripple (left) with fluid escape shown with arrows at depth 7,108 ft log depth (7,120 ft core depth) and ripple lamination set with drapes at depth 6,537 ft log depth (6,542 ft core depth) from facies RpSs.
4.1.9. Rip-Up Clast Sandstone (RuCls)

The rip-up clast sandstone facies is composed of conglomerate clasts, subangular-subrounded clasts, mud and siderite clasts with an upper very fine to lower fine sandstone matrix (Figure 4.10). The size of rip-up clasts ranges from coarse to granule size. Thickness ranges from 0.1 to >5ft (3 cm to >1.5 m). The abundant mud clasts in a sand body are thick enough to make the GR log reading higher, although the matrix lithology is sandstone (low radioactive, low GR).

The top of the RuCls facies is commonly associated with cross-bed facies (CrSs), structureless sandstone (StSs), ripple-dominated (RpSs), and parallel-wavy lamination sandstone (PrWyLm). It can be associated with scour surfaces into the underlying siltstone, mudstone or coal beds. Scour surfaces that have rip-up clasts in channel-fill deposits can indicate amalgamation. This facies is similar to the conglomerate mud-chip facies described by Ellison (2004).

4.1.10. Structureless Sandstone (StSs)

The structureless sandstone is gray, upper very fine to lower fine grained sandstone with small carbonaceous plant debris and no bioturbation. This zone looks massive with no sedimentary structures (Figure 4.11). It could be caused by dewatering, which totally reworked the original sedimentary structure. The thickness of this facies ranges from 0.5 to >2 ft (15 to >61 cm).

Structureless sandstone facies (StSs) are associated with many other sandstone facies (RpMdSs, RpSs, CrSs, CvSs, and RuCls). This facies commonly occurs between associated facies, and it could disrupt the original facies succession.
Figure 4.10. Core photo of abundant mud rip-up clasts associated with scour surface (left) at depth 7,266 ft log depth (7,278 ft core depth) and mixed mud clasts with siderite clasts (brown) at depth 6,529 ft log depth (6,534 ft core depth) from facies RuCls.
Figure 4.11. Core photo of structureless or massive sandstone at depth 7,263.5 ft log depth (7,275.5 ft core depth) (left) and carbonaceous plant debris and siderite nodule in massive sandstone at depth 7,121.5 ft log depth (7,133.5 core depth) (right) from facies StSs.
Massive sandstone also occurs in some channel-sand bodies in Coal Canyon (Cole and Cumella, 2005).

### 4.1.11. Convolute Sandstone (CvSs)

The convolute sandstone is gray, upper very fine to lower fine grain sandstone with small carbonaceous plant debris. Convolute structure can be caused by soft-sediment deformation, outlined with small amounts of carbonaceous debris concentration or muddy layers (Figure 4.12). Facies thickness ranges from 0.25 to 1 ft (7.6 to 30 cm).

The CvSs facies is associated with the structureless sandstone facies (StSs), ripple with mud drapes sandstone (RpMdSs), and ripple-dominated sandstone (RpSs). This facies commonly occurs in the upper part of channel-fill deposits. Convolute structure in this facies could be related to soft-sediment deformation in the upper part of channel sand bodies described by Cole and Cumella (2005).

### 4.1.12. Cross-bedded Sandstone (CrSs)

The cross-bedded sandstone is gray and is composed of upper very fine – lower fine grained sandstone, with low to high angle tabular and trough cross bedding, siderite nodules, and carbonaceous plant debris. Facies thickness ranges from 1 to >14 ft (0.3 to >4.2 m). The cross-bed structures can form as trough cross beds or as tabular cross beds. Preserved cross-bed structure in a sand body can form into cross-bed sets with thicknesses that range from 2 to >15 cm (Figure 4.13).
Figure 4.12. Core photo of convolute muddy layer at depth 7,254.5 ft log depth (7,266.5 ft core depth) (left) and convolute sandstone outlined by carbonaceous debris at 6,525.5 ft log depth (6,530.5 ft core depth) (right) from facies CvSs.
Figure 4.13. Core photo of trough cross bedding at depth 6540 ft log depth (6545 ft core depth (left) and high-angle cross bedding at depth 6544.5 ft log depth (6549 ft core depth) (right) from facies CrSs.
This facies always occurs near the base of a channel-fill deposit. The CrSs facies is commonly associated with structureless sand (StSs), because of this, it is difficult to make cross-bed set-thickness measurement. Missing core interval also makes the cross-bed set-thickness difficult to measure.

The CrSs facies is also associated with RpSs and RpMdSs facies. Commonly, RuClst facies occurs below the CrSs facies. Cross bedding indicates high detrital influx, and is commonly preserved at the base of channel-fill deposits. Similar facies is also found in the point-bar sand body in Coal Canyon (see Chapter 3). It is also observed at the base of channel sand bodies in Cole and Cumella (2003 and 2005).

4.2. Architectural Elements

Each depositional system is constructed from associated facies. In a larger scale, facies associations can be grouped into architectural elements (Allen, 1993). This term emphasizes the three-dimensional (3D) geometry of facies associations. Facies associations also provide evidence for environmental interpretations (Reading, 1978).

The MWX-2 core represents 1D data. Detailed core descriptions appear in Appendix B. Because architectural elements emphasize 3D geometry, assumptions are needed to convert 1D data into architectural elements. Interpretations of architectural elements are based upon modern examples in alluvial systems and the outcrop analog of the Williams Fork Formation in Coal Canyon. Architectural elements from core descriptions are shown in five figures, displayed in order from the deepest to the shallowest (Figure 4.15 through 4.20). There are four elements related to alluvial architecture (channel-fill, crevasse-splay, floodplain and abandonment channel plug) and there is one architectural element related to deltaic deposits (delta plain-delta front).
Figure 4.14. Sedimentary symbols, lithology colors, lithology symbols and facies colors used for the core descriptions.
Figure 4.15. Core description and facies interpretation of a delta plain-delta front architecture in the Cameo-Wheeler interval. For facies names and colors see Figure 4.14. Detailed core description is in Appendix B. Abbreviations: CALI=caliper; GR=gamma ray; ILD=deep induction resistivity; NPHI=neutron porosity; RHOB=bulk density (g/cc).
Figure 4.16. Core description and facies interpretation of a superimposed channel-fill (SCf1) deposit in the Cameo-Wheeler interval. For facies names and colors see Figure 4.14. Detailed core description is in Appendix B. Abbreviations: CALI=caliper; GR=gamma ray; ILD=deep induction resistivity; NPHI=neutron porosity; RHOB=bulk density (g/cc).
Figure 4.17. Core description and facies interpretation of crevasse-splay (CS1) deposit from Cameo-Wheeler interval. For facies names and colors see Figure 4.14. Detailed core description is in Appendix B. Abbreviations: CALI=caliper; GR=gamma ray; ILD=deep induction resistivity; NPHI= neutron porosity; RHOB=bulk density (g/cc).
Figure 4.18. Core description and facies interpretation of a single-story channel fill (Cf1), crevasse splay (CS2), and super-imposed channel fill (SCf2) from above the Cameo-Wheeler interval. For facies names and colors see Figure 4.14. Detailed core description is in Appendix B. Abbreviations: CALI= caliper; GR=gamma ray; ILD=deep induction resistivity; NPHI= neutron porosity; RHOB=bulk density (g/cc).
Figure 4.19. Core description and facies interpretation of single-story channel fill (Cf2) and crevasse-splay (CS2) deposits from above the Cameo-Wheeler interval. For facies names and colors see Figure 4.14. Detailed core description is in Appendix B. Abbreviations: CALI=caliper; GR=gamma ray; ILD=deep induction resistivity; NPHI= neutron porosity; RHOB=bulk density (g/cc).
Figure 4.20. Core description and facies interpretation of a superimposed channel fill (SCf3) from above the Cameo-Wheeler interval. For facies names and colors see Figure 4.14. Detailed core description is in Appendix B. Abbreviations: CALI=caliper; GR=gamma ray; ILD=deep induction resistivity; NPHI=neutron porosity; RHOB=bulk density (g/cc).
4.2.1. Channel-Fill (Cf)

Channel fills are the building blocks of fluvial systems. Each channel fill is composed of a variety of lithofacies bounded by bedding and erosional surfaces (Allen, 1983; Miall, 1985).

High-sinuosity channel deposits are characterized by lateral-accretion surfaces in point-bar deposits. This is clearly shown in the lower Williams Fork Formation in Coal Canyon (see Chapter 3). Low-sinuosity channels are usually related to braided deposits in upstream rivers. Sand bodies can be deposited as single-story or superimposed channels.

An ideal succession of a point-bar shows a vertical decrease of grain size because sediment transport moved up and out of the channel onto the bar (Galloway, 1996). The channel floor is composed of the coarsest material transported in the river. The basal contact is a scour surface that resulted from an erosional process, and it is shown as a sharp contact with the underlying facies. Rip-up clasts and plant debris are commonly concentrated near the scour surface. Mud clasts are scoured or eroded from adjacent facies, such as floodplain or lake deposits. This process relates to lateral migration and aggradation of the next channel fill. Subrounded to rounded siderite clasts near the base of the scour may be transported from further upstream or from digenesis process.

Simple sinuous channel-fill deposits can be recognized by their internal structure. However, channel-fill sequences may vary in composition, vertical sequence, and internal structure. The base of each point bar is commonly dominated by trough cross stratification (CrSs). Ripple to slightly climbing ripple (RpSs), ripple with mud drapes (RpMdSs), convolute sandstone (CvSs), parallel-wavy lamination (PrWyLm), structureless sandstone (StSs) and soft-sediment deformation occur in the upper channel fill where water depth became shallower and flow velocities decreased. Repetition of a single channel succession generated amalgamation or superimposed channel fills.

The top of each channel fill is commonly capped with mudstone (Md2) facies or rooted siltstone (RoSl) facies from floodplain deposits. Channel-fill deposits are bounded
by basal scour surfaces and capped by floodplain deposits. This boundary is important to measure the maximum bankfull depth of a channel, which can be used to estimate channel dimension. However, the maximum bankfull depth for superimposed channel fills is based on the individual channels. Therefore, the amalgamated channels need to be broken down into individual channels. The thickest channels will be the maximum bankfull depth. In this study, the thickness of each superimposed channel fill is used to estimate the channel-belt dimensions, which will be compared to the outcrop data and further discussed in Chapter 7.

Based on those characteristics, there are 2 single point bars (Cf1 and Cf2), and 3 superimposed point bars (SCf1, SCf2 and SCf3) interpreted from the cored interval. Internal structure of each channel varies, but generally they have similar sedimentary structures.

Cf1 (Figure 4.18) is difficult to interpret because of the intensity of dewatering structures. The basal contact with mudstone is sharp with carbonaceous plant debris, but no mud or siderite clasts occur. Cross stratification (CrSs) near the base grades up into massive sandstone (StSs), then rippled sandstone with mud-drape structure (RpMdSs). The presence of ripple lamination above cross lamination is characteristic of a high-sinuosity channel deposit. This zone is capped at the top by floodplain mudstone (Ms1), which gives 9 ft (2.7 m) of maximum bankfull depth.

The internal structure of Cf2 (Figure 4.19) is similar to Cf1, but Cf2 is mainly composed of massive sandstone. Cross stratification (CrSs) appears at the base to the middle portion of the unit. In the middle part, the sandstone is dominantly massive (StSs) with few drapes and carbonaceous debris. Ripple lamination (RpSs) with convolute structure (CvSs) appears near the top. This Cf2 sand interval is capped by muddy siltstone, and grades up to mudstone from floodplain deposits. The maximum bankfull depth is equal to 17 ft (5.1 m). The sharp contact at the top of Cf2 makes it different from other channel-fill deposits, which commonly have gradational contacts with the overlying facies.
SCf1 (Figure 4.16) is deposited on top of coal layers. Conglomerate mud-clast (RuClst) facies is approximately 35-40% of the sand body. SCf1 can be subdivided into 4 amalgamated channel fills. The repetitive cycle of fining-upward, mud clasts, and scour surfaces within the sand body suggest amalgamation of point bars. Internal structures in the lower portion are mud clasts (RuClst), massive sand (StSs) and cross bedding (CrSs). The upper part is dominated by parallel-wavy lamination (PrWyLm) that is only found in this SCf1 zone. The SCf1 deposit is capped by muddy siltstone from floodplain deposits, which makes the gross thickness equal to 40 ft (12 m). However the maximum bankfull depth from individual channels is 11 ft (3.3 m).

Unlike SCf1 in the Cameo-Wheeler interval, SCf2 and SCf3 have less domination of mud clasts. Mud clasts near the basal surface are mixed with siderite clasts. SCf2 is deposited on top of 1.5 ft (45 cm) of ripple-dominated sandstone from a crevasse-splay deposit (Figure 4.18). The base of SCf2 is filled with high-angle oriented mud and siderite clasts. The internal characteristic is different with downstream channel-fill (SCf 1). The original internal structure of this sand body is difficult to determine because 20-30% of the section is structureless (massive) sandstone and 30% is missing core interval. Primary structures that can be observed are high-angle cross beds (CrSs). Ripple structures occur near the top, but are only a minor component. Due to lack of information about internal structure, it is difficult to determine the number of repetitive bars in this zone. Judging from the fining-upward sequence of grain size, it is possible that this zone consists of at least 2 amalgamations. SCf2 is capped by mudstone from floodplain deposits. From the SCf2 basal boundary to the floodplain deposits, the gross thickness is 38 ft (11.5 m). The maximum bankfull depth from individual channels is 26 ft (7.9 m).

SCf3 is a good example of a superimposed channel fill (Figure 4.20). It is composed of 3 amalgamated channel fills. Repetitive sedimentary structures occur in this zone. The basal interval is filled with mud and siderite rip-up clasts from the RuCls facies. Cross stratification (CrSs) grades up to rippled to slightly climbing-rippled (RpSs)
sandstones, which suggests an upward decrease of velocity. Cross stratification in the upper part is disrupted by soft-sediment deformation. This channel-fill sandstone is capped by rooted siltstone with mud drapes from floodplain deposits. The gross thickness of SCf3 equals 37 ft (11.2 m). However, the maximum bankfull depth from individual channels equals 20 ft (6.1 m).

Channel fills can be deposited on top of any architectural element in an alluvial system. This is due to high-energy sedimentation that could erode the underlying lithology. The basal contact is sharp with the underlying lithology and each unit is capped at the top with gradational or sharp floodplain deposit. The internal facies succession in channel fills can be diverse.

### 4.2.2. Crevasse Splay (CS)

Crevasse-splay deposits develop when flood water pours through localized breaches in channel levees (Galloway and Hobday, 1996). Flow becomes unconfined as velocity decreases rapidly away from the channel. Channeling of flow through the levee may cause scouring and deepening of the crevasse channel. The crevasse splay is developed adjacent to channel deposits and above floodbasin deposits. Systematically, the grain size decreases and the proportion of ripple increases from the crevasse axis, which leads to proximal and distal splay deposits (Galloway and Hobday, 1996; Shanley, 2004).

There are three crevasse-splay deposits interpreted from the core. Splay successions show an upward-coarsening pattern, capped with fining-upward sediment. Internal structure commonly consists of rippled to slightly climbing-rippled lamination (RpSs), ripple with mud drapes (RpMsSs), low angle parallel-wavy lamination (PrWyLm), and scour surfaces with small mud clasts (RuClst).

The first crevasse-splay deposit (CS1) overlies a coal bed. It is composed of
stacked splay successions with heterogeneous internal structures, reflecting multiple flood events (Figure 4.17). It is indicated by multiple scour surfaces that formed channel-splay events. Grain size in this channel splay is upper very fine sand. There is also low-angle and contorted wavy lamination, which could relate to slump events near the high topography of the levee. Therefore, this crevasse splay could be deposited near the adjacent channel fill or near the axis of the channel splay. Near the upper part, 20% of the core is missing. Several fluid-escape structures are outlined by abundant carbonaceous plant debris near the top. The fluid-escape structures occur in the upper portion of splays where they stand above the local water table (Galloway, 1996).

The second crevasse-splay deposit (CS2) overlies mudstone from a floodplain deposit (Figure 4.18). The occurrence of thin (3 cm) low-angle cross beds at the base indicates that this splay was deposited near the splay channel, adjacent to the main channel fill. It is eroded by a channel-fill deposit (Scf2) bounded with high-angle mud and siderite clasts. Due to erosion, this splay zone is only 1.5 ft (40 cm) thick.

The third crevasse-splay deposit (CS3) has a sharp basal contact on top of floodplain deposits (Figure 4.19). The base of CS3 is composed of sandy siltstone, coarsening up into upper very fine grained sandstone that then fines upward to the top. Thin laminations of mud near the base of this splay are disrupted with a minor fault. Internal structure in this zone is composed of ripples with mud drapes (RpMdSS), grading up into rippled to climbing-rippled lamination (RpSs), and massive structureless sand (StSs). CS3 is capped at the top by rooted siltstone (RoSl), which makes CS3 thickness equal to 8 ft (2.4 m).

4.2.3. Floodplain (Fp)

Floodplain deposits occur when sediment-laden flood waters overflow the river banks and spill across interchannel areas (Galloway and Hobday, 1996). Sediment is
deposited in suspended load with low rates, which makes it possible for plant growth and reworking by burrowing.

Floodplain (Fp) deposits are composed of structureless siltstone (StSs) or mudstone (Md2), with plant roots, siderite nodules, carbonaceous plant debris, and mud drapes. Thin layers of sandstone (<1 ft, 30 cm) are also found in a floodplain deposit. Commonly, this facies caps channel-fill and crevasse-splay deposits. The top of maximum bankfull depth measurements of channel-fill deposits are marked by the occurrence of floodplain deposits.

Interchannel lake deposits are characterized by thin horizontal laminations and parallel-wavy laminations. Generally, interchannel lake lithology is similar to floodplain deposits, which makes them difficult to differentiate. An example of a thin (10 cm) lake deposit grades upward into floodplain facies on top of Cf2 (Figure 4.18).

4.2.4. Delta Plain-Delta Front (DP-F)

This architecture only occurs in the lower part (7329 to 7298 ft, log depth) of the first cored interval, which is the lower portion of the Cameo-Wheeler interval. Successions are composed of interbedded delta-front sand and IntMdSs facies. This zone is characterized by the occurrence of *Skolithos* and *Cruziana* ichnofacies. The stratigraphic succession indicates that this core interval (Figure 4.15) is part of progradation from delta front to delta plain.

The IntMdSs unit is part of the lower delta front, with a thickness that ranges from 0.5 to 2 ft (15 to 60 cm). Sand bodies within this interval are commonly structureless or massive (StSs) and have rippled mud-drape structure (RpMdSs), with a thickness that ranges from 0.5 to 2.5 ft (15 to 76 cm). This sandstone unit may have been deposited in the upper delta front. The contact between both interbedded units is sharp. Diversity of ichnofossils shows similar types in both units. In the upper portion, the sand body
changes into low-angle cross-bedded sandstone with *Skolithos* ichnofossils, which is part of a distributary channel in the delta plain. Coal seams (facies C) are commonly associated with delta-plain deposits in swampy areas.

Association between the two units indicates repetitive sequences of delta plain and delta front. This zone was deposited in a shallow-marine environment, which indicates seawater influence during deposition.

### 4.3. Well-Log Curve Shape

Facies successions represent distinctive log curve patterns. The shape of well-log curves can be related to certain facies successions, which resemble their grain-size successions (Selley, 1978). Description of well-log curves is important to interpret intervals that do not have core data. However, interpretation based only on well-log curve shape is imprecise.

This study uses a classification of log curve shape names from Cant (1992), based on his study of core examples (Figure 4.21). The most common well-log curve is GR, because it represents sand and shale proportion in the vertical succession. However, other logs such as caliper (CAL), resistivity (ILD), neutron (NPHI), and density (RHOB) are sometimes useful. There are five architectural elements interpreted in the Lower Williams Fork Formation interval. Each architectural element has a distinctive well-log curve shape. Galloway and Hobday (1996) give an example of GR log curve characteristics for different elements in a fluvial system (Figure 4.22). This distinctive GR log curve also gives insight for architectural elements interpreted from well logs.

Generally, single point-bar deposits show a smooth bell-shaped GR curve with an abrupt basal contact (Cf1 and Cf2). Well-log curve shape for superimposed channel fills may have a bell shape or cylindrical (blocky) shape, related to the origin of deposition. Downstream channel deposits have serrated bell-shaped GR log curves due to the
Figure 4.21. GR log curve shape and interpreted depositional environments. Modified from Cant (1992).
Figure 4.22. Lateral and vertical relationship in a fluvial system represented in gamma ray logs. Fluvial building blocks are natural levee sandy mud and silts (A), crevasse delta (B), channel-fill point-bar sand (C), crevasse splay (D), floodbasin (E), and abandoned channel plugs (F). From Galloway and Hobday (1996).
abundance of mud clasts. This could be misinterpreted as shale layers (SCf1). However, log-curve deflection may also relate to siltstone or mudstone layers (e.g., depth 6536 ft in Figure 4.15). This is an example of how it is important to integrate core description to well log curves. Cylindrical shapes are related to upstream channel-fill deposits, where they are more sand rich.

Well-log curve shapes for crevasse-splay deposits commonly show funnel shapes with gradational changes at the base and abrupt changes at the top (CS3). However, gradational curve change could also occur at the top, as it relates to channel-splay deposits (CS1). Funnel shapes and gradational change at the base are the main characteristics that can differentiate splay deposits from channel-fill deposits. Well-log curves for floodplain deposits have high GR values. The well-log curve commonly forms an irregular shape or a relatively flat curve.

Delta plain-delta front deposits have serrated funnel shapes. Serrated shape relates to IntMdSs facies within the progradation succession. Funnel shape is similar to a crevasse-splay deposit, but the GR and NPHI log curve is more serrated in delta plain-delta front deposits. Swamp deposits in the delta plain have distinctive characteristics as they represent coal seams. The easiest way to identify a coal seam is from the NPHI and RHOB log curves, which commonly overlie each other and go off scale to high porosity values, caliper (CAL) log deflections indicate washouts, and the value of deep-resistivity is high (Figure 4.16 and Figure 4.17).

4.4. Depositional Environment

Cole and Cumella (2003 and 2005) stated that the lower Williams Fork Formation was deposited in a lower coastal-plain setting where fluvial systems were sinuous to anastomosing, floodplains were poorly drained, and peat-forming mires, marshes, swamps and lakes were common. Coastal plains are constructed of fluvial, deltaic, and
shore-zone systems (Galloway and Hobday, 1996). In this system, groundwater flows towards the strandline and turns into mixed-meteoric groundwater with seawater.

Based on the MWX-2 strata succession from the core description, the basal core interval shows a mix of marine and fluvial influences. Marine influence is indicated by the presence of *Skolithos* and *Cruziana* ichnofacies in nearshore-foreshore or delta plain-delta front deposits. Coal seams in the Cameo-Wheeler interval were deposited in swamps or marshes in a delta-plain setting. Repetitive cycles of coal seams in a delta plain with delta front/lower shoreface facies indicate a progradational sequence. The occurrence of coal seams can be used as an indication of progradational cycles. Coal layers can develop in the backswamp in a fluvial system (Galloway and Hobday, 1996). Because the coal layers are associated with delta-front settings, it is most likely that the coal seams relate to delta-plain deposits.

This interval was interrupted with the presence of downstream alluvial deposits by unit SCf1. The occurrence of SCf1 indicates a downstream fluvial system or upper delta plain. Transition from a delta front, delta plain and fluvial setting in a coastal-plain environment indicates regression events or a progradational succession in the lower portion of the Cameo-Wheeler interval.

Missing core between the first core interval and second core interval (Figure 4.1) makes it difficult to interpret the environment. Judging from the log curve and the repetitive occurrence of coal seams, it represents a sequence of downstream fluvial or delta-plain deposits. Fluvial systems become prominent with the occurrence of channel-fill SCf1 above the Cameo-Wheeler interval.

### 4.5. Channel-Dimension Estimation

Empirical equations for sand-body dimensions in alluvial systems apply to channel-fill deposits. Channel depth in a channel-fill deposit is measured from the
maximum bankfull depth in each single story, including those of superimposed channel deposits. The maximum bankfull depth of an active alluvial deposit is the main input to estimate the channel width and channel-belt width dimension. Maximum bankfull depth, channel width and channel-belt width is illustrated by Bridge and Mackey (1993) and shown in Figure 4.23.

The paleo-channel depth measurement must be corrected for the effect of post-depositional compaction. Ethridge and Schumm (1978) suggested that a 10% compaction factor is reasonable and applicable to channel-fill deposits. The bankfull depth should be divided by 0.9 in order to approximate the original paleo-channel depth or bankfull depth.

Core examination from well MWX-2 suggests that single-story channel fills (Cf1 and Cf2) range in thickness from 9 to 18 ft (2.7 to 5.5 m). Individual channels from superimposed channel fills (SCf1, SCf2 and SCf3) have thicknesses that range from 11 to 26 ft (3.4 to 7.9 m). Therefore, the maximum bankfull depth for all channel-fill deposits ranges from 9 to 26 ft (2.7 to 7.9 m). After decompaction, the original bankfull depth ranges from 10 to 29 ft (3 to 8.8 m).

There are two methods used in this study for channel-dimension assessment. Both methods use the metric scale for the channel-width and channel-belt width calculations. The calculation summaries are shown in Table 4.2. After channel dimensions are calculated in metric units, the numbers are converted into feet.

The first method is by Leeder (1973). He was able to relate bankfull depth with channel width in high-sinuosity or meandering rivers. His method uses the single-story channel as a maximum depth (h) that can estimate the channel width (Wc) using the following equation:

\[ Wc = 6.8h^{1.54} \]

Lorenz et al. (1985) used the Leeder (1973) channel-width equation and combined it with Leopold and Wolman (1960) and Carlston (1965) to derive an empirical relationship
Figure 4.23. Definition of alluvial stratigraphy model (a); definition of bankfull depth at cross over (b). Note that $h=$ maximum bankfull depth and $d_m=$ mean bankfull depth. Modified after Bridge and Mackey (1993).
Table 4.2. Summary of channel width and channel-belt width calculations based on interpreted channel-fill deposits in the MWX-2 core. The channel fills are sorted based on the maximum bankfull depth from individual channels. Blue texts are individual channel-fill and pink texts are gross-thickness from superimposed channel-fill deposits. Table format is modified after Shanley (2004).

<table>
<thead>
<tr>
<th>Channel Fill</th>
<th>Channel Depth Analysis</th>
<th>Channel Width Analysis</th>
<th>Channel Belt Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum bankfull depth (h)</td>
<td>10% Decompaction of Maximum Bankfull Depth (h)</td>
<td>Mean bankfull depth $dm=0.57h$</td>
</tr>
<tr>
<td>C2f</td>
<td>9</td>
<td>2.7</td>
<td>10.0</td>
</tr>
<tr>
<td>C2</td>
<td>18</td>
<td>5.5</td>
<td>20.0</td>
</tr>
<tr>
<td>Scf1</td>
<td>11</td>
<td>3.4</td>
<td>12.2</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>12.2</td>
<td>44.4</td>
</tr>
<tr>
<td>Scf3</td>
<td>20</td>
<td>6.1</td>
<td>22.2</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>11.3</td>
<td>41.1</td>
</tr>
<tr>
<td>Scf2</td>
<td>26</td>
<td>7.9</td>
<td>28.9</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>11.6</td>
<td>42.2</td>
</tr>
</tbody>
</table>
between channel width and channel-belt width ($W_m$). In Table 4.2, the channel-belt width column is written as in Lorenz et al. (1985). The $W_m$ equation is:

$$W_m = 7.44W_c^{1.01}$$

The second method was proposed by Bridge and Mackey (1993). This method is also applied for individual channel deposits the same way as the Leeder (1973) method. They developed an algorithm by using mean cross-bed set thickness ($S_m$) in channel-fill deposits to estimate the mean bankfull depth ($d_m$). Unfortunately, the cross-bed sets are not well preserved due to dewatering processes and missing core in the MWX-2 core. However, the mean bankfull depth ($d_m$) can be estimated from the maximum bankfull depth ($h$). The mean bankfull depth equation is:

$$d_m = 0.57h$$

The $d_m$ value is an input for channel width ($W_c$) with meander sinuosity or the ratio of channel length with channel straight line ($S_n$) > 0.1. The $W_c$ equation is:

$$W_c = 15.85d_m^{1.58}$$

Bridge and Mackey (1993) and Bridge and Tye (2000) also developed algorithms to estimate channel-belt width ($W_m$) by using $d_m$ as an input data. The $W_m$ equation is:

$$W_m = 192d_m^{1.37}$$

Bridge and Mackey (1993) explained that an active channel-belt ($W_m$) within a modern alluvial deposit represents a single-story channel-fill ($C_f$) deposit. Therefore, channel belt is applied to both meandering and braided-stream rivers. The superimposed channel-fill ($SC_f$) deposits correlate with multi-story channel belts in the modern environment. Therefore, the $SC_f$ deposit needs to be broken down into individual channel fills to estimate the channel-belt width. In Table 4.2, the maximum bankfull depth from individual channel stories is shown in blue text. The gross thickness for each $SC_f$ deposit is shown in pink text. Although it is not the maximum bankfull depth, the gross thickness of superimposed channels is used to estimate the channel-belt width. For example, the $SC_f1$ (Figure 4.16) maximum observed bankfull depth from individual thickness is 11 ft (3.3 m), but the gross thickness is 40 ft (12 m) (Table 4.2). In single channel-fill deposits
like Cf1 (Figure 4.18), the maximum bankfull depth is equal to the gross thickness, which is 18 ft (5.4 m). The channel dimensions for SCf deposits later will be used to compare with the SCf sand-body dimensions measured in the outcrop.

### 4.6. Discussion

Channel-fill and crevasse-splay sand bodies are the main building blocks in alluvial deposits. Both sand-body types occur within the Williams Fork Formation in Coal Canyon and well MWX-2. They are coeval and separated by approximately 50 mi (80.5 km). Five sand-body types (Type A, B, C, D and E) described in Coal Canyon by Cole and Cumella (2003) equivalent with sand-body types in Rulison field. Coal Canyon sand-body subdivisions are based on internal structures and geometry or lateral extent in the outcrop, but the MWX-2 subdivision is based only on internal structures.

Channel-fill deposits in Coal Canyon have coarse to medium grain size, but in well MWX-2, sand size ranges from fine to very fine grained. Internal structures were mainly constructed by cross bedding (CrSs). Single-story channel deposits are equivalent to Type B (simple sinuous) sand bodies, and superimposed channel fills are equivalent to Type C (compound sinuous) sand bodies. Type A (narrow) sand bodies are difficult to relate with MWX core because it depends on the narrow lateral extent or geometry.

Crevasse-splay deposits are generally constructed from rippled to slightly climbing-ripple structure (RpSs). Crevasse splay is equivalent to Type C and D deposits in Coal Canyon. Grain size ranges from very fine to fine grained in Coal Canyon, but in well MWX-2, the sandstone is commonly very fine grained.

Other than the internal structures, the significant difference is the occurrence of delta plain-delta front deposits in the MWX-2 core in the lower portion of the Lower Williams Fork Formation. This facies has not been reported in the Coal Canyon area. It could be related to the basin setting during the late Cretaceous. The regional seaway was
towards the east (Figure 2.2). Coal Canyon is relatively landward and Rulison field is relatively seaward. Therefore, it is possible that the fluvial system is more dominant in Coal Canyon and there is a gradation downstream into a deltaic environment (marine influence) near Rulison field. It could be related to the regional setting that sediment was sourced relatively from the west to east. This explains why coarser grain size in Coal Canyon becomes finer towards Rulison field. The paleo-current direction from cross bedding structures in channel-sand bodies in Coal Canyon also indicates eastward flow.

The channel sand bodies in Coal Canyon are coeval to the channel sand bodies described in the MWX-2 core. The channel dimension assessment results in the MWX-2 core (Table 4.2) from both methods shows different numbers. However, the channel-width numbers are close in cases of thin maximum bankfull depth. Results become skewed towards deeper maximum bankfull depth. This is because the channel-width calculations use exponential equations. The channel-width input for Leeder (1973) is the maximum bankfull depth (h) and for Bridge and Mackey (1993) is the mean bankfull depth (dm). The maximum bankfull depth values are about twice the dm values. The channel-width equation from Leeder (1973) is about half of the Bridge and Mackey (1993) equation. Therefore, they overlap each other. However, because it is an exponential equation, the result from both methods makes large differences if the input number becomes bigger. This is also reflected in the channel-belt width result.

The input number for channel-belt width (Wm) estimation is the channel width (Wc). Because the input number (Wc) is already high, the difference in both methods becomes large. Channel-belt width estimation using Lorenz et al. (1985) shows higher number than Bridge and Mackey (1993) method (Table 4.2). The channel-belt numbers provide an important input for the sand-body width in the outcrop and are discussed further in Chapter 7.
CHAPTER 5

BOREHOLE IMAGE INTERPRETATION

The RWF542-20 borehole image log in the Rulison field is analyzed for sedimentary and structural features. Sedimentary analysis includes paleocurrent, facies, facies association, architectural elements, and channel-dimension estimation. Other conventional openhole logs such as the gamma ray, caliper, resistivity, neutron and density are also used to assist sedimentary analysis.

The gamma ray log is used to define shale beds, which are used for structural dip analysis. There is no fracture analysis in this study. Distinctive log curve shape (‘electrofacies’) distinguished from the well MWX-2 core analysis will give insights for architectural interpretation in the image log.

5.1. EMI Borehole Image Log

Borehole image log analysis in the RWF542-20 well is only focused on the Williams Fork Formation. The gross interval of the Williams Fork is 1,970 ft (600 m), which ranges from 5,955 to 7,925 ft log depth.

5.1.1. Introduction to EMI

Borehole image logs display electronic pictures of rocks and fluids encountered by a wellbore (Hurley, 2004). The images provide information about bedding dip,
fractures, faults, paleocurrent directions, vugs, and other geologic features. The electric image is produced from microresistivity electrodes arranged around the wellbore on pads pressed against the borehole wall.

Microresistivity images differ depending on the producer of the borehole image log (Figure 5.1). The RWF542-20 is an EMI (Electrical Micro Imaging) tool developed by Halliburton. The EMI has 6 pads with 25 electrodes on each pad for a total of 150 electrodes. The high-resolution electrodes detect resistivity differences in the formation and create high-resolution images. The EMI image acquires electrical image data around the borehole, which is then unwrapped (Figure 5.2) and viewed in 2 dimensions using interpretation software.

The EMI images can be displayed in static and dynamic modes. Static images are created from one resistivity contrast setting applied to the entire borehole length. The dynamic image is created to enhance small resistivity contrasts over short intervals. Geologic features such as fractures, vugs, and bed boundaries are better viewed in dynamic images that have variable contrast applied in a moving window (Rider, 1996). Static and dynamic images are displayed in hue to each resistivity values. Dark colors represent conductive rock, and bright colors indicate non-conductive rock.

5.1.2. Image Processing

EMI image processing using Recall/Review software was conducted by Janine Carlson in 2005. The image quality is good, although there are intervals that have streaked images. Streaked images (Figure 5.3) happen when the tool travels too fast to properly record the image, or when mud or debris builds up on the pads (Minton, 2002). Rapid speed of the tool in response to increased tension on the wireline could cause out-of-phase pads. It will give poor-quality images which are not good for interpretation. There are 5 intervals in the RWF542-20 that show out-of-phase images (Table 5.1)
DIPMETER

4 Pads

SHDT (1982)
2 buttons / pad
10 mm diameter
8 buttons total

ELECTRICAL BOREHOLE IMAGERS

4 Pads

FMS (1988)
16 buttons / pad
6.7 mm diameter
64 buttons total

4 Flaps

FMI (1991)
24 buttons / pad
5 mm diameter
192 buttons total

4 Pads

EMI (1994)
25 buttons / pad
5 mm diameter
150 buttons total

6 Pads

STAR (1996)
24 buttons / pad
4 mm diameter
144 buttons total

Figure 5.1. Schematic illustration of pad and electrode configuration for one dipmeter and all of the common electrical borehole image logs. After Hurley (2004).
Figure 5.2. Borehole-image displays. The images from borehole (A) are presented on a flat surface (screen or hard copy plot) by “unwrapping” onto a vertical depth grid and horizontal grid of compass bearing. (B) The horizontal and vertical surfaces are unchanged but dipping surfaces become represented by a sinusoid or sine wave. (C) Dip and azimuth from sine wave is represented on a dipmeter tadpole plot. Modified from Rider (1996).
Figure 5.3. EMI image from RWF 542-20 showing out-of-phase pads which make bed boundaries difficult to interpret. Depth scale is in feet.
Table 5.1. Table showing intervals in the EMI log that have out-of-phase pads.

<table>
<thead>
<tr>
<th>Bottom depth of interval</th>
<th>Top depth of interval</th>
<th>Number of feet missing</th>
</tr>
</thead>
<tbody>
<tr>
<td>6,070</td>
<td>6,071</td>
<td>1</td>
</tr>
<tr>
<td>6,442</td>
<td>6,454</td>
<td>12</td>
</tr>
<tr>
<td>6,580</td>
<td>6,590</td>
<td>10</td>
</tr>
<tr>
<td>7,326</td>
<td>7,327</td>
<td>1</td>
</tr>
<tr>
<td>7,358</td>
<td>7,387</td>
<td>29</td>
</tr>
</tbody>
</table>
5.1.3. Sedimentary Features

Sedimentary features such as bed boundaries, cross bedding, and scour surfaces were picked manually and are represented as sine waves. Each picked sine wave is oriented in a certain direction that is represented as a tadpole (Figure 5.2). All identified sedimentary features from the RWF542-20 borehole image are comparable to the MWX-2 core, although the wells are 2 mi (4 km) apart. Appendix C shows the interpreted EMI log.

**Bed boundary** is the main sedimentary feature, because it differentiates resistive beds (bright color) and non-resistive beds (dark color). It is also used in conjunction with the gamma ray log, which differentiates high and low radioactive zones (Figure 5.4). Identification of shale beds can be made by using more than 90 API gamma ray units. Other than sand and shale beds, coal layers are also recorded in the borehole image. Coal seams have the brightest color and appear grainy in the image log (Figure 5.5). Caliper, resistivity, NPHI and RHOB log curves can be used to confirm the occurrence of coal seams.

**Cross bedding** can only be found in sandstone intervals. It can be picked from static and dynamic images. Sine waves with tadpole dips greater than 5° are cross beds or lateral-accretion surfaces. Oriented tadpoles from cross beds may have distinctive dip azimuths (Figure 5.6). Steeply dipping boundaries between cross stratification may be scour surfaces. Cross bedding is not always preserved well enough to be recorded in the image log, especially in the Cameo-Wheeler interval.

**Scour surfaces** are defined as truncation of underlying laminations (Figure 5.6). It could also relate to the base of channel-fill sand bodies. In the MWX-2 core, each of the channel-fill deposits can erode the adjacent deposit like the shale from the floodplain deposit (Figure 5.7). The basal channel scouring surfaces may also occur within sandstone intervals, and they are commonly associated with rip-up clasts and carbonaceous plant debris. Mud clasts appear as dark color with an irregular shape. Clasts
Figure 5.4. Shale beds on EMI image. Shale beds are low-conductivity beds which are dark in color. Each sine wave represents a shale-bed orientation and is shown as an oriented tadpole. Depth scale is in feet.
Figure 5.5. Coal layer in EMI image log. Caliper logs Dmax (purple), Dmin (red) show washouts in the coal bed. Resistivity is high. Depth scale is in feet.
Figure 5.6. Cross beds in EMI image. Scour surface at 6,859.6 ft separates cross beds of different orientation. Depth scale is in feet.
Figure 5.7. Basal channel surface which relates to channel scouring of the underlying shale floodplain in EMI image. The basal scour is associated with mud rip-up clasts within the sand body. Scour surface separates resistive layer (sand) and conductive layer (shale). Depth scale is in feet.
Figure 5.8. Rip-up clasts in EMI image. Rip-up clasts occur in resistive (sand) interval. The clasts appear in dark colors (mud clasts) and bright colors (siderite clasts?, as described in the MWX-2 core). Depth scale is in feet.
also appear in bright colors which could be siderite clasts, as described in the MWX-2 core.

**Soft-sediment deformation** in a sand body appears as irregular shapes that cannot be picked as sine waves. Soft-sediment deformation commonly disrupts cross beds. Deformed sandstones may be associated with dark clasts, which could relate to small carbonaceous plant debris as described in the MWX-2 core. The plant debris appears as dark color (conductive) within the deformed sandstone (Figure 5.9).

The image logs cannot see images less than 0.5 cm. This also applies for grain size, individual cross-bed and individual ripple lamination structure. However, thick sets of ripple laminations in sand bodies can be seen in the image log (Figure 5.10). Although ripples or climbing ripples could be recognized in the image log, it is difficult to interpret the bedding plane or to pick sine waves.

**5.1.4. Structural Analysis**

Structural analysis is made for structural dip determination. Determination of structural dip is based on the analysis of shale bed boundaries represented by high gamma ray values. Shale beds were assumed to be originally deposited as horizontal beds. Certain structural events could change the shale-bed orientations. This step is trying to reconstruct the shale beds into the original setting and identify structural changes.

Structural dip analysis is done by making a cumulative dip plot. In this method, shale beds were chosen by using a GR >90 API cut-off. The high gamma ray reading is chosen to exclude sandstone and siltstone beds that occur throughout the entire interval. Shale bed boundaries influenced by slump, draping and loading were eliminated from the data set. After filtering all bed boundaries, there are 1,889 shale beds interpreted throughout the borehole image interval.
Figure 5.9. Soft-sediment deformation in EMI image. Small rounded dark features (conductive) within the sand (resistive) could be carbonaceous plant debris. Depth scale is in feet.
Figure 5.10. Ripple lamination sets in EMI image. Ripple structures with thickness <0.5 cm are not recorded very well in electrical images. Depth scale is in feet.
The cumulative dip plot curve is made from plotting cumulative dip magnitude versus sample number. The sample number is chosen rather than depth because the vertical interval between EMI bedding planes is normally irregular (Hurley, 1994). The cumulative dip plot highlights domain changes in dip magnitude. Dip domains are straight-line segments that occur between inflection points.

The result from plotting 1,889 shale beds in a cumulative dip plot indicates 4 domains of dip magnitude (Figure 5.11). The inflection points are located at depth 4,911, 5,848 and 7,447 ft. All of the inflection points are located in the Williams Fork Formation.

After making the cumulative dip plot, the next step is to make the azimuth plot using a stereonet. The pole from each shale bed is plotted in the lower-hemisphere equal-area Schmidt net. In the Schmidt net, all poles are represented as one mean lineation vector. This step is important to see whether the dip value is steep enough to require structural-dip correction. Commonly, dip >5° will need structural-dip correction.

The result from plotting 1,889 shale beds in the Schmidt plot shows that the mean lineation vector is N201.5°E/85°NE (Figure 5.11). Therefore, the shale beds azimuth is generally dipping to N21.5°E with a dip of 4.7°. Because the dip is <5°, there is no need to do dip correction. This result is an important insight for the paleocurrent or cross-bedding orientation analysis.

5.1.3. Paleocurrent

Paleocurrent analysis is based on cross-bed orientation in sand bodies picked as bed boundaries in the EMI image. There are two steps to analyze the orientation. The first step is to choose bed boundaries only picked in the sandstone intervals by making cut-offs on the gamma ray log. The gamma ray cut-off is <60 API. The purpose of making a gamma ray cut-off is to avoid shale and sandy shale layers that do not relate to
Figure 5.11. Comparison between lower hemisphere equal area (Schimdt) plot (above) and cumulative dip plot (below).
paleocurrent. The second step is to sort all bed boundaries by their dip angle and type. Bed boundaries with dip angle <5° are eliminated. The reason to eliminate bed boundaries <5° is to avoid flat planes that are not related to cross beds. This also includes elimination of soft-sediment deformation. All sorted bed boundaries are plotted in a rose diagram to see the mean orientation.

After the two steps, there are 2,197 bed boundaries that represent cross beds and lateral-accretion surfaces. The results show that apparent paleocurrent or cross-bedding orientation in the Williams Fork Formation is N31°E (Figure 5.12) with a mean dip magnitude of 16°.

5.2. Architectural Elements

Architecture interpretation using the borehole image data is based on the MWX-2 core description. There are 4 architectures interpreted based on the well-log curve shape and the internal sedimentary structures in this well.

5.2.1. Channel-fill Deposits

Channel-fill deposits are characterized by a bell-shaped to blocky well-log curve signature and dominant cross-bed structures. The well-log curve shapes could be serrated, which relates to the occurrence of rip-up clasts as described in the MWX-2 core. Based on the MWX2- core description, channel-fill deposits are differentiated into single story (Figure 5.13) and multi-story or superimposed (Figure 5.14) deposits. In the lower Williams Fork interval, there are 20 channel-fill deposits composed of 4 single channel-fill (Cf) deposits and 16 superimposed channel-fill (Scf) deposits. Each of the channel-fill zones are named in order from the deepest to the shallowest (Appendix D). The
Figure 5.12. Rose diagram of cross-bed orientations with vector mean of $31^\circ$ (above) and dip frequency histogram with mean arithmetic value of $16^\circ$ (below).
Figure 5.13. Single channel-fill (Cf2) deposited above coal seam in EMI image log. Abbreviation: GR=gamma ray; Dmin=minimum diameter; Dmax=maximum diameter; NPHI=neutron porosity; DPHI=density porosity; EMI_STA=static EMI image; EMI_DYN=dynamic EMI image.
Figure 5.14. Superimposed channel-fill (SCf8) in EMI image log. Abbreviation: GR=gamma ray; Dmin=minimum diameter; Dmax=maximum diameter; NPHI=neutron porosity; DPHI=density porosity; EMI_STA=static EMI image; EMI_DYN=dynamic EMI image.
thickness summary of all channel fills is shown in Table 5.2.

The SCf could be recognized from opposed tadpoles or bed forms (Koepsell et al., 2003), which relates to channel scour. An example of opposed bed forms is shown in Figure 5.14. The opposed bed forms are not always ideally opposed to each other, which makes it difficult to determine. In SCf8, opposed bed forms only occur at the base of individual channels. However, scour surfaces and rip-up clasts also occur in individual channels, which makes the SCf composed of 3 individual stacked channels. The repetitive occurrence of rip-up clasts in a superimposed channel could indicate repetitive cycles of channel amalgamation.

SCf deposits and Cf deposits generally can be differentiated from the gamma ray log. SCf commonly has serrated gamma ray log, but Cf deposits are smoother and bell shaped. Both types could also be differentiated from the bed boundaries orientation. In (Cf2) the bed boundaries orientation commonly shows unidirection (Figure 5.13). Superimposed channel fills show more diverse multidirections and indicate multiple channel stories (Figure 5.14).

5.2.2. Crevasse-Splay Deposits

Crevasse-splay deposits are characterized by a funnel-shaped curve. In the image log, few bed boundaries could be picked because it is composed of ripple lamination. The tadpole orientation in a crevasse-splay deposit is commonly scattered (Figure 5.15). There are 26 crevasse-splay deposits interpreted in the lower Williams Fork Formation. The summary table of all 26 crevasse-splay deposits is shown in Table 5.3.
Table 5.2. Summary table of 5 single channel-fill (Cf) and 16 superimposed channel-fill (SCf) deposits in the lower Williams Fork Formation from the deepest to the shallowest depth, EMI log, well RWF542-20.

<table>
<thead>
<tr>
<th>Channel-fill</th>
<th>Top Sand (ft)</th>
<th>Base sand (ft)</th>
<th>Gross Thickness (ft)</th>
<th>Max observed single channel (ft)</th>
<th>GR profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCf16</td>
<td>6,053</td>
<td>6,066</td>
<td>13</td>
<td>7</td>
<td>Blocky</td>
</tr>
<tr>
<td>SCf15</td>
<td>6,185</td>
<td>6,212</td>
<td>27</td>
<td>13</td>
<td>Blocky</td>
</tr>
<tr>
<td>SCf14</td>
<td>6,292</td>
<td>6,311</td>
<td>19</td>
<td>8</td>
<td>Blocky - Bell shaped</td>
</tr>
<tr>
<td>Cf4</td>
<td>6,318</td>
<td>6,329</td>
<td>11</td>
<td>11</td>
<td>Bell shaped</td>
</tr>
<tr>
<td>SCf13</td>
<td>6,348</td>
<td>6,362</td>
<td>14</td>
<td>9</td>
<td>Blocky (serrated)-Bell shaped</td>
</tr>
<tr>
<td>SCf12</td>
<td>6,398</td>
<td>6,409</td>
<td>11.5</td>
<td>8</td>
<td>Blocky - Bell shaped</td>
</tr>
<tr>
<td>SCf11</td>
<td>6,501</td>
<td>6,523</td>
<td>22</td>
<td>12</td>
<td>Blocky - Bell shaped</td>
</tr>
<tr>
<td>Cf3</td>
<td>6,525</td>
<td>6,533</td>
<td>8</td>
<td>8</td>
<td>Blocky</td>
</tr>
<tr>
<td>SCf10</td>
<td>6,701</td>
<td>6,732</td>
<td>31</td>
<td>10</td>
<td>Blocky (serrated)</td>
</tr>
<tr>
<td>SCf9</td>
<td>6,750</td>
<td>6,776</td>
<td>26</td>
<td>13</td>
<td>Blocky - Bell shaped</td>
</tr>
<tr>
<td>SCf8</td>
<td>6,839</td>
<td>6,862</td>
<td>23</td>
<td>11</td>
<td>Blocky (serrated)-Bell shaped</td>
</tr>
<tr>
<td>SCf7</td>
<td>6,931</td>
<td>6,950</td>
<td>18.5</td>
<td>10.5</td>
<td>Bell shaped</td>
</tr>
<tr>
<td>SCf6</td>
<td>7,018</td>
<td>7,029</td>
<td>11</td>
<td>6</td>
<td>Blocky - Bell shaped</td>
</tr>
<tr>
<td>Cf2</td>
<td>7,036</td>
<td>7,044</td>
<td>8</td>
<td>8</td>
<td>Bell shaped</td>
</tr>
<tr>
<td>SCf5</td>
<td>7,149</td>
<td>7,164</td>
<td>15</td>
<td>8.5</td>
<td>Blocky</td>
</tr>
<tr>
<td>Cf1</td>
<td>7,180</td>
<td>7,191</td>
<td>11</td>
<td>11</td>
<td>Blocky</td>
</tr>
<tr>
<td>SCf4</td>
<td>7,507</td>
<td>7,524</td>
<td>16.5</td>
<td>8.5</td>
<td>Bell shaped</td>
</tr>
<tr>
<td>SCf3</td>
<td>7,540</td>
<td>7,566</td>
<td>26</td>
<td>10</td>
<td>Bell shaped (serrated)</td>
</tr>
<tr>
<td>SCf2</td>
<td>7,608</td>
<td>7,634</td>
<td>26</td>
<td>12</td>
<td>Blocky (serrated)-Bell shaped</td>
</tr>
<tr>
<td>SCf1</td>
<td>7,666</td>
<td>7,690</td>
<td>34</td>
<td>19</td>
<td>Blocky (serrated)-Bell shaped</td>
</tr>
</tbody>
</table>

**TOTAL** 203.5
Figure 5.15. Inferred crevasse-splay deposit in EMI image log.
Table 5.3. Summary table of 26 crevasse-splay deposits from EMI image log, well RWF542-20.

<table>
<thead>
<tr>
<th>Splay Name</th>
<th>Top (ft)</th>
<th>Bottom (ft)</th>
<th>Thickness (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS26</td>
<td>6,092</td>
<td>6,096</td>
<td>4</td>
</tr>
<tr>
<td>CS25</td>
<td>6,103</td>
<td>6,107</td>
<td>4</td>
</tr>
<tr>
<td>CS24</td>
<td>6,113</td>
<td>6,116</td>
<td>3</td>
</tr>
<tr>
<td>CS23</td>
<td>6,125</td>
<td>6,130</td>
<td>5</td>
</tr>
<tr>
<td>CS22</td>
<td>6,178</td>
<td>6,183</td>
<td>5</td>
</tr>
<tr>
<td>CS21</td>
<td>6,270</td>
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<tr>
<td>CS20</td>
<td>6,456</td>
<td>6,461</td>
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<td>CS19</td>
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<td>6,546</td>
<td>7</td>
</tr>
<tr>
<td>CS18</td>
<td>6,541</td>
<td>6,546</td>
<td>5</td>
</tr>
<tr>
<td>CS17</td>
<td>6,572</td>
<td>6,576</td>
<td>4</td>
</tr>
<tr>
<td>CS16</td>
<td>6,656</td>
<td>6,660</td>
<td>4</td>
</tr>
<tr>
<td>CS15</td>
<td>6,669</td>
<td>6,674</td>
<td>5</td>
</tr>
<tr>
<td>CS14</td>
<td>6,812</td>
<td>6,818</td>
<td>6</td>
</tr>
<tr>
<td>CS13</td>
<td>6,892</td>
<td>6,896</td>
<td>4</td>
</tr>
<tr>
<td>CS12</td>
<td>6,914</td>
<td>6,921</td>
<td>7</td>
</tr>
<tr>
<td>CS11</td>
<td>6,970</td>
<td>6,974</td>
<td>4</td>
</tr>
<tr>
<td>CS10</td>
<td>6,978</td>
<td>6,982</td>
<td>4</td>
</tr>
<tr>
<td>CS9</td>
<td>7,054</td>
<td>7,059</td>
<td>5</td>
</tr>
<tr>
<td>CS8</td>
<td>7,066</td>
<td>7,070</td>
<td>4</td>
</tr>
<tr>
<td>CS7</td>
<td>7,197</td>
<td>7,201</td>
<td>4</td>
</tr>
<tr>
<td>CS6</td>
<td>7,206</td>
<td>7,209</td>
<td>3</td>
</tr>
<tr>
<td>CS5</td>
<td>7,248</td>
<td>7,253</td>
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</tr>
<tr>
<td>CS4</td>
<td>7,264</td>
<td>7,270</td>
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</tr>
<tr>
<td>CS3</td>
<td>7,282</td>
<td>7,287</td>
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</tr>
<tr>
<td>CS2</td>
<td>7,480</td>
<td>7,488</td>
<td>8</td>
</tr>
<tr>
<td>CS1</td>
<td>7,753</td>
<td>7,758</td>
<td>5</td>
</tr>
</tbody>
</table>

TOTAL 125
5.2.3. Floodplain

Floodplain deposits are composed of shale and/or sandy shale. They are easily recognized from high gamma-ray log values and also dark color in the image log. Most of the bed boundaries in floodplain deposits are used in structural analysis because they represent the shale beds (Figure 5.16). The floodplain is deposited adjacent to channel-fill and/or crevasse-splay deposits. Commonly, it caps the channel-fill and/or crevasse-splay deposits. In Figure 5.16, the floodplain occurred on top of the SCf8 deposit, which also marks the top of the channel-fill deposit as described in the MWX-2 core.

5.2.4. Delta Plain – Delta Front

As described in the MWX-2 core, the delta plain-delta front deposits are composed of interbedded sandstone and mudstone with serrated gamma-ray log-curve shape. The interbeds are clearly recognized in the image log. In the image log, the sandstone appears as resistive conductive layers (bright color) and the mudstone appears as conductive layers (dark color) in the image. Bed boundaries can be picked to differentiate sandstone and mudstone in this zone. All of the bed boundaries in this zone are commonly oriented in a consistent direction (Figure 5.17).

5.3. Net-To-Gross Ratio

The term net-to-gross ratio in this chapter is defined as the net thickness of interpreted sand bodies versus the gross thickness of the lower Williams Fork Formation. Sand bodies include the channel-fill deposits (Cf and SCf) and crevasse-splay deposits (CS). Other than Cf, SCf and CS sand bodies are considered as shale layers.
Figure 5.16. Floodplain deposit above the channel-fill (Scf8) deposit in EMI image log.
Figure 5.17. Inferred delta plain-delta front (?) deposit.
The gross thickness of the Williams Fork Formation in well RWF542-20 is 1,970 ft (600 m). There are 4 Cf deposits, 16 SCf deposits, and 26 CS deposits. The total net thickness is 328.5 ft (100 m). Therefore, the net-to-gross thickness is 16.7%. This number will be compared with the outcrop data in Chapter 7.

5.4. Channel-Dimension Estimation

Channel-dimension estimation using a borehole image log is similar to the MWX-2 core evaluation. The estimation, based on the Bridge and Mackey method (1993) and Leeder (1975) method, is already explained in Chapter 4. Both methods use maximum bankfull depth of individual channels as an important input for channel-dimension estimation. All calculations are conducted in metric units.

Bridge and Mackey (1993) used the range of cross-bed set thickness (Sm) to predict the mean bankfull depth (dm) as an input for channel dimension. The equation for mean bankfull depth is dm=16Sm. By using the same method, the mean bankfull depth can be calculated from the maximum bankfull depth (h) with the equation dm=0.57h. The maximum bankfull depth for single-story channels is similar with the gross thickness, but for superimposed channels, the result is based on the individual channels (Table 5.2).

By using the cross-bed set thickness method to determine the bankfull depth, the results are not consistent with the bankfull depth determined in Table 5.2. For example, the cross-bed set Cf2 unit ranges from 0.4 to 0.7 ft (0.12 to 0.21 m). Thus, the maximum bankfull depth ranges from 11.7 to 18.8 ft (3.4 to 5.7 m). However, the measured Cf2 maximum bankfull depth in Table 5.2 is only 8 ft (2.4 m), which becomes 8.9 ft (2.7m) after 10% decompaction, which is less than the range from cross-bed set calculations.

Another example from SCf8 also has the same result. The SCf8 cross-bed set thickness ranges from 0.7 to 1.0 ft (0.2 to 0.3 m). The maximum bankfull depth result ranges from 18.8 – 27.6 ft (5.7 to 8.4 m). However, SCf8 maximum bankfull depth from
individual channels in Table 5.2 is only 11 ft (3.4 m) and then becomes 12.2 ft (3.7 m), which is less than the range from cross-bed set calculations. The comparison summary table for this result is shown in Table 5.4.

Because the input cross-bed set thickness is a range, the bankfull depth result is also a range. In this study, the maximum bankfull depth numbers from well RWF542-20 will use the numbers from individual channel measurements from Table 5.4, similar to the MWX-2 core evaluation. This way, the result will be consistent.

Channel-width and channel-belt width calculations are summarized in Table 5.5. In Table 5.5, the maximum bankfull depth from individual channel stories is shown in blue text. The gross thickness for each superimposed channel-fill deposit is shown in pink text. The table format and explanation is similar to Table 4.2 in the MWX-2 core interpretations.

By using the Bridge and Mackey (1993) and Bridge and Tye (2000) method, the channel-belt width (Wm) for individual channels (the blue text in Table 5.5) ranges from 770.2 to 3,736 ft (235 to 1,139 m). By using the gross thickness from the superimposed channels (the purple text in Table 5.5), the channel-belt width ranges from 1,767 to 8,292 ft (539 to 2,528 m).

Based on the Leeder (1973) method, the channel-belt width for individual channels (the blue text in Table 5.5) ranges from 510 to 3,061 ft (155 to 933 m). By using the same equations for the gross thickness of superimposed channels (the blue text in Table 5.5), the channel-belt width (Wm) ranges from 1,402 to 7,568 ft (427 to 2,307 m).
Table 5.4. Comparison of mean and maximum bankfull depth using cross-bed set range thickness with direct measurement from the borehole image log.

<table>
<thead>
<tr>
<th>Channel Fill Name</th>
<th>Using Cross-bed Set</th>
<th>Measurement from Image log</th>
<th>Max. observed single channel (h) from Table 5.2 after 10% decompaction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cross-bed set range thickness (Sm)</td>
<td>Mean bankfull depth (dm) ( dm = 16 \text{Sm} )</td>
<td>Maximum bankfull depth (h) ( h = 0.57 \text{dm} )</td>
</tr>
<tr>
<td>SCf16</td>
<td>0.4 - 0.7 0.1 - 0.2</td>
<td>6.4 - 11.2 2.0 - 3.4</td>
<td>3.6 - 6.4 1.1 - 1.9</td>
</tr>
<tr>
<td>SCf15</td>
<td>0.7 - 1.2 0.2 - 0.4</td>
<td>11.2 - 19.2 3.4 - 5.9</td>
<td>6.4 - 13.7 1.9 - 3.3</td>
</tr>
<tr>
<td>SCf14</td>
<td>0.7 - 0.9 0.2 - 0.3</td>
<td>11.2 - 14.4 3.4 - 4.4</td>
<td>6.4 - 8.2 1.9 - 2.5</td>
</tr>
<tr>
<td>Cf4</td>
<td>0.5 - 0.8 0.15 - 0.2</td>
<td>8.0 - 12.8 2.4 - 3.9</td>
<td>4.6 - 7.3 1.4 - 2.2</td>
</tr>
<tr>
<td>SCf13</td>
<td>0.6 - 0.9 0.2 - 0.3</td>
<td>9.6 - 14.4 2.9 - 4.4</td>
<td>5.5 - 8.2 1.7 - 2.5</td>
</tr>
<tr>
<td>SCf12</td>
<td>0.5 - 0.7 0.15 - 0.2</td>
<td>8.0 - 11.2 2.4 - 3.4</td>
<td>4.6 - 6.4 1.4 - 1.9</td>
</tr>
<tr>
<td>SCf11</td>
<td>0.6 - 1.2 0.2 - 0.4</td>
<td>9.6 - 19.2 2.9 - 19.2</td>
<td>5.5 - 10.9 1.7 - 3.3</td>
</tr>
<tr>
<td>Cf3</td>
<td>0.5 - 0.7 0.15 - 0.2</td>
<td>8.0 - 11.2 2.4 - 3.4</td>
<td>4.6 - 6.4 1.4 - 1.9</td>
</tr>
<tr>
<td>SCf10</td>
<td>1.0 - 1.5 0.3 - 0.5</td>
<td>16 - 24 4.9 - 7.3</td>
<td>9.1 - 13.7 2.8 - 4.2</td>
</tr>
<tr>
<td>SCf9</td>
<td>0.8 - 1.7 0.2 - 0.5</td>
<td>12.8 - 27.2 3.9 - 8.3</td>
<td>7.3 - 15.5 2.2 - 4.7</td>
</tr>
<tr>
<td>SCf8</td>
<td>0.7 - 1.0 0.2 - 0.3</td>
<td>11.2 - 16 3.4 - 4.9</td>
<td>6.4 - 9.1 1.9 - 2.8</td>
</tr>
<tr>
<td>SCf7</td>
<td>0.5 - 1.3 0.15 - 0.4</td>
<td>8.0 - 20.8 2.4 - 6.3</td>
<td>4.6 - 11.9 1.4 - 2.5</td>
</tr>
<tr>
<td>SCf6</td>
<td>0.5 - 0.9 0.15 - 0.3</td>
<td>8.0 - 14.4 2.4 - 4.4</td>
<td>4.6 - 8.2 1.4 - 2.5</td>
</tr>
<tr>
<td>Cf2</td>
<td>0.4 - 0.7 0.1 - 0.2</td>
<td>0.7 - 1.0 0.21 - 0.3</td>
<td>11.7 - 18.8 3.42 - 5.7</td>
</tr>
<tr>
<td>SCf5</td>
<td>0.7 - 1.2 0.2 - 0.4</td>
<td>11.2 - 19.2 3.4 - 5.9</td>
<td>6.4 - 10.9 1.9 - 3.3</td>
</tr>
<tr>
<td>Cf1</td>
<td>0.4 - 0.5 0.1 - 0.15</td>
<td>6.4 - 8.0 2.0 - 2.4</td>
<td>3.6 - 4.6 1.1 - 1.4</td>
</tr>
<tr>
<td>SCf4</td>
<td>0.5 - 1.0 0.15 - 0.3</td>
<td>8.0 - 16.0 2.4 - 4.9</td>
<td>4.6 - 9.1 1.4 - 2.8</td>
</tr>
<tr>
<td>SCf3</td>
<td>0.6 - 1.6 0.2 - 0.5</td>
<td>9.6 - 25.6 2.9 - 7.8</td>
<td>5.5 - 14.6 1.7 - 4.4</td>
</tr>
<tr>
<td>SCf2</td>
<td>0.6 - 1.3 0.2 - 0.4</td>
<td>9.6 - 20.8 2.9 - 6.3</td>
<td>5.5 - 11.9 1.7 - 3.6</td>
</tr>
<tr>
<td>SCf1</td>
<td>0.7 - 2.2 0.2 - 0.7</td>
<td>11.2 - 35.2 3.4 - 10.7</td>
<td>6.38 - 20.1 1.9 - 6.1</td>
</tr>
</tbody>
</table>
Table 5.5. Summary of channel width and channel-belt width calculations based on interpreted channel-fill deposits in the RWF542-20 image log. Blue texts are individual channel-fill and pink texts are gross-thickness from superimposed channel-fill deposits. Table format is modified after Shanley (2004).

<table>
<thead>
<tr>
<th>Channel Depth Analysis</th>
<th>Channel Width Analysis</th>
<th>Channel Belt Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum bankfull depth (h)</strong></td>
<td><strong>10% Decompaction of Maximum Bankfull depth (h)</strong></td>
<td><strong>Mean bankfull depth dm=0.57h</strong></td>
</tr>
<tr>
<td><strong>(0.57h)</strong></td>
<td><strong>(1.57h)</strong></td>
<td><strong>(dm)</strong></td>
</tr>
<tr>
<td><strong>Wc=6.8h^{1.54}</strong></td>
<td><strong>Wc=15.85dm^{1.58}</strong></td>
<td><strong>Wm=7.44Wc^{1.01}</strong></td>
</tr>
<tr>
<td><strong>SCf1</strong></td>
<td><strong>SCf2</strong></td>
<td><strong>SCf3</strong></td>
</tr>
<tr>
<td>11</td>
<td>3.4</td>
<td>12.2</td>
</tr>
<tr>
<td>3.7</td>
<td>7.0</td>
<td>2.1</td>
</tr>
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<td>51.5</td>
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</tr>
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<td>52.1</td>
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<td>398.8</td>
</tr>
<tr>
<td>762.0</td>
<td>232.3</td>
<td>546.2</td>
</tr>
<tr>
<td>166.5</td>
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<td></td>
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<td><strong>SCf5</strong></td>
<td><strong>SCf6</strong></td>
<td><strong>SCf7</strong></td>
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<td>147.0</td>
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<td>343.9</td>
</tr>
<tr>
<td>641.9</td>
<td>195.7</td>
<td>486.0</td>
</tr>
<tr>
<td>148.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SCf11</strong></td>
<td><strong>SCf12</strong></td>
<td><strong>SCf13</strong></td>
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</tr>
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<td>517.2</td>
</tr>
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<td>687.0</td>
</tr>
<tr>
<td>203.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SCf17</strong></td>
<td><strong>SCf18</strong></td>
<td><strong>SCf19</strong></td>
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<tr>
<td>148.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SCf23</strong></td>
<td><strong>SCf24</strong></td>
<td><strong>SCf25</strong></td>
</tr>
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<td>687.0</td>
</tr>
<tr>
<td>203.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ \Delta Wm = \text{(Lorenz et al. (1985) method) - (Bridge and Mackey (1993) method)}} \]
Figure 5.18. Frequency histograms of channel depth after 10% decompaction (in feet) and channel-belt width (in feet). The Cf deposits data is derived from all individual channel (blue text) and SCf deposits data is derived from the gross thickness (purple text) in Table 5.5.
5.5. Discussion

The internal structure and architecture in well MWX-2 have similar characteristics with the RWF 542-20 borehole image log. However, there are several difficulties to identify internal structures such as scour surfaces, parallel-wavy lamination and ripple lamination. Therefore, it is important to have core data as an analog. The MWX-2 core contributes important insight for the borehole image interpretation.

The cross beds in channel-fill deposits are important for the apparent paleocurrent orientation. The apparent paleocurrent orientation result in well RWF542-20 (N31°E) is different from the general trend in the Coal Canyon outcrop, which is N88°E. This difference could be related to the sinuosity of meandering channels or different rivers. It could also indicate that the rivers are different.

The cross-bed structure is also used as the parameter for bankfull estimation in the Bridge and Mackey (1993) method. However, the result shows inconsistency with the bankfull depth measurements from individual channel stories. It is also important to notice that the range of input numbers yields a range of bankfull depth. This is different than the evaluation in the MWX-2 core. Some of the individual bankfull depth numbers are in the range of estimation of bankfull depth using the cross-bed method, but most of it is out of the range.

Results show that it is difficult to estimate channel dimensions from borehole data. Cross-bed set thickness is difficult to measure in the image log and on outcrop. The cross beds do not always occur through the entire channel-fill sand. Cross beds in the channel-fill sands could be obscured by dewatering in the sand unit. Dewatering is observed intensively in Scf2 unit in the MWX-2 core description (see Chapter 4). Therefore, dewatering could affect the channel bankfull depth estimation using the cross-bed set range thickness in the Bridge and Mackey (1993) method.

It could also indicate that this method is not always correct. Bridge and Mackey (1993) explained that the channel-dimension estimation is more likely to fit modern
environments than ancient deposits. Therefore, is not likely that the channel-estimation numbers are always correct. In Chapter 7, both the channel dimensions from the MWX-2 core and RWF542-20 interpretations will be compared with the sand-body widths observed in Coal Canyon.
CHAPTER 6

LIDAR INTERPRETATION

6.1. Introduction to LiDAR

LiDAR stands for (Light Detection And Ranging), a technique which uses a low-energy laser pulse and sensitive receiver to acquire detailed digital elevation models. LiDAR was first developed in the 1960’s for use in atmospheric studies (Bellian et al., 2002). Since then, LiDAR technology has made its way to geology research in outcrop data collection.

LiDAR technology rapidly transmits pulses of light that reflect from terrain. The return pulses are converted from photons to electrical impulses and collected by a high-speed data recorder (http://ww.merrick.com). Collected data transmission includes the positional (x,y) and elevation (z) values at pre-defined intervals. The 3D data points are then converted to a 3D virtual surface in a visualization program.

Coal Canyon LiDAR data acquisition and processing was conducted by Merrick & Corporation. The LiDAR data were collected using an aerial survey that was shot from an airplane and covered Coal Canyon, Main Canyon and Plateau Creek in northwest Colorado (Figure 6.1). The flight acquires vertical (mapping), airborne GPS, and landscape (oblique) photography using black and white, color, and/or color infrared film. Merrick & Corporation used Airborne GPS (ABGPS) to control photogrammetric mapping with a highly precise and cost-effective results (http://ww.merrick.com). In Coal Canyon, the LiDAR is divided into 65 tiles. Each tile covers a square box of 2500 ft (762 m) in each side. Each tile has LAS data points, ASCII data points, and orthophotos.
The advantage of using these data for sand-body dimension is the high-resolution digital-elevation model, with 0.5 m horizontal and 0.076 m vertical resolution. Aerial LiDAR covers the entire Coal Canyon cliff, even in steep areas that previous researchers could not access. In an outcrop study, LiDAR technology can help to reduce difficulty in collecting oucrop data in a traditional way.

6.2. Methodology

Two software applications are used for sand-body measurement: (1) MARS, and (2) Petrel version 2004. MARS software, available from Merrick & Company, is the primary software used to display LAS data points and orthophotos. Petrel software is used to display ASCII data draped with the orthophoto data, and is able to create 3D displays. The advantage of using Petrel is to be able to trace a sand body as a polygon while showing it in a 3D view.

Cole and Cumella (2003) measured 136 sand bodies using GPS (Global Positioning System), but only 128 of their sand bodies are covered in the LiDAR orthophotos (Figure 6.2). Cole and Cumella’s (2003) sand-body waypoints cover 7 LiDAR tile areas. The uncovered sand bodies are located in the eastern part of tile numbers 37 and 58. The 128 sand bodies are mostly located in a gently sloping area that does not cover the entire lower Williams Fork Formation.

The outcrop study in this research is focused on the entire lower Williams Fork interval (Figure 6.3). The study boundary covers 21 tiles from the LiDAR survey with 5.7 mi (9.2 km) transect the NE trending and NW trending segments of Coal Canyon. The 128 sand bodies documented by Cole and Cumella (2003) were traced on the LiDAR data and are included in this research.
Figure 6.1. Orthophotos of aerial LiDAR survey in Coal Canyon, Main Canyon, and Plateau Creek. In Coal Canyon, orthophotos are overlaid by digital elevation LAS data viewed in MARS software, subdivided into 65 tile files survey (2,500 ft$^2$ each), and numbered.
Figure 6.2. Location of 136 sand bodies, 15 measured section (MS), and paleocurrent summary conducted by Cole and Cumella (2003). Tile boundaries from LiDAR data are also shown. Modified after Cole and Cumella (2003).
Figure 6.3. LiDAR and photomosaic taken from the NW Coal Canyon leg showing the study interval.
Sand-body measurement using LiDAR in Petrel is presented in thickness and width. The top and bottom of each sand body is used to measure the thickness. However, the aerial LiDAR itself does not accurately record the sand-body thickness, especially for vertical cliffs. In a vertical or steep morphology, the orthophotos smear. Commonly in the high-slope area, shale is exposed beneath the sand. This could lead into misinterpreting the entire slope as the sand-body thickness. Therefore, photomosaics of the cliff outcrop are needed to overcome that problem. The photomosaics are also used to guide the continuity of sand-body measurement using the LiDAR data.

Figures 6.4 and 6.5 show examples of a vertical cliff that is smeared on the orthophotos. The top of the sand body commonly lies on the top of the vertical cliff, but the bottom is not well imaged. The photomosaic that was taken in the same area helps to identify the bottom of the sand body. It could also help to identify other sand bodies that stack in the vertical cliff. In some areas, the entire cliff could also represent the thickness of the sand. This occurs in the Upper Williams Fork Formation which has a high net-to-gross ratio. An example of a vertical cliff that represents the sand-body thickness in the Upper Williams Fork Formation is shown in Figure 6.5. Because of smearing, there is a limitation to the thickness-measurement accuracy from LiDAR.

The limitation from the aerial LiDAR also causes this study to simplify the sand bodies into 3 types, which are superimposed channel-fill, single channel-fill and crevasse splay deposits. The 3 types of sand bodies are similar to those described in the MWX-2 core.

Identification of single channel-fill (Cf), superimposed channel-fill (SCf) and crevasse splay (CS) deposits is only based on the photomosaic taken along the cliffs. The SCf is characterized by compound sand-body layers which have channel scouring (Figure 6.5). A good example of a superimposed channel-fill in Coal Canyon is described in Chapter 3. Previous measured sections from Cole and Cumella (2003) showed that crevasse splays have thicknesses that range from 0.5 to 6.5 ft (0.15 to 1.9 m).
Figure 6.4. An example of smeared LiDAR orthophoto (left) and photomosaic taken from the same area (right) to control sand-body thickness. Abbreviations: SCf=superimposed channel-fill deposit; Cf=single channel-fill deposit; CS=crevasse-splay deposit.
Figure 6.5. An example of smeared LiDAR data (left) and photomosaic taken from the same area (right) to control sand-body thickness. Abbreviations: SCf=superimposed channel-fill deposit; Cf=single channel-fill deposit; CS=crevasse-splay deposit.
The type of sand body will influence the width measurement method. In simple terms, a channel-fill shape in a modern environment is close to a half-circle in shape. Therefore, all channel-fill deposits are modeled as a half-circle shape. The radius of the half circle (r) is the width of the channel. The diameter of the half circle is one half of the wavelength of a meander bend. Unlike the thickness issue, the width measurement is more accurate.

The half circle is oriented according to the paleocurrent. Cole and Cumella (2003) showed that the mean paleocurrent orientation is 75° from measuring trough cross beds. Since each of the channel-fill sand bodies has a different orientation, the half circle will be oriented in the paleocurrent range from 25° to 115°. The long axis of the half circle is oriented 25° to 115° with 10° increment. This covers the entire range of possible channel orientations based upon the paleocurrent data. Each half-circle area is counted to determine the range of drainage areas.

The orientation of the channel-fill sand body in the outcrop affects the sand-body width, especially in a channel-fill deposit. There are two major orientations of channel-fill (Cf and SCf) deposits, which are NE-SW and NW-SE. The width of the sand body (r) will be higher if the half circle is oriented parallel to the sand-body orientation. The sand-body width becomes less if radius (r) of the half circle is perpendicular to the sand-body orientation. A cross-plot between orientation of the half circle versus width for a NE-SW sand body shows a positive trend (Figure 6.6). The NW-SE sand body cross plot shows a negative trend (Figure 6.7). The NE-SW sand body commonly occurs in the NE cliff and NW-SE sand body commonly occurs in the NW cliff of Coal Canyon. However, both sand-body orientations could occur in either of the Coal Canyon legs.

Sand-body width measurement for a channel fill is different from a crevasse-splay deposit. The crevasse-splay deposits are assumed to be a full-circle shape in the modern environment. Therefore, the sand-body trace in Petrel will be to position a full circle and the diameter (d) will be the width of the crevasse splay sand body (Figure 6.8). Because
Figure 6.6. An example of sand-body width measurement technique from an SCf sand-body with a NE-SW orientation and a cross plot between the half-circle orientation. Each half circle is constrained by the orientation and the two end points of the traced sand body. The cross plot shows the radius variation of the half circles as a function of variable orientation.
Figure 6.7. An example of sand-body width measurement technique from SCF sand-body with a NW-SE orientation. Each half circle is constrained by the orientation and the two end points of the traced sand body. The cross plot shows the radius variation of the half circles as a function of variable orientation.
Figure 6.8. An example of sand-body width measurement technique from crevasse-splay deposit from the NE leg of Coal Canyon by measuring the diameter of the full circle. The size of the full circle is constrained only by the end points of the traced sand body.
crevasse-splay deposits use the full circle, the orientation of the sand body does not affect the width. Therefore, the crevasse-splay sand body has only one number, but each channel-fill deposit (Cf and SCf) has 10 numbers. Beside the radius (r) of the channel fill, the area is determined in every variable orientation. The half-circle area reflects the possible area of each channel-fill sand body.

The half circle (Cf and SCf) shapes and circle (CS) shapes are constrained by the end points of the traced sand bodies. The two end points in each sand-body are not represents sand-body pinch out.

### 6.3. Result: Sand-Body Quantification

After interpretations in Petrel, there are 633 sand bodies traced in the study area (Figure 6.9). The sand bodies have variable lateral and vertical dimension. There are 363 sand bodies exposed in the NE leg and 383 sand bodies in the NW leg of the study area. The 633 sand bodies are composed of 109 (17%) Cf deposits, 258 (41%) SCf deposits, and 266 (42%) crevasse-splay deposits. Differentiation between Cf and SCf is subjective. Therefore, statistical analysis for both types of channel-fill deposits are combined. It is easier to distinguish channel-fill deposits from crevasse-splay deposits. Each sand body is named based on the location of the tile name (Appendix E).

All sand bodies have thickness, width and variable drainage area. The measurements from each sand body are summarized in Table 6.1 and Appendix E. The frequency histogram is shown in Figure 6.10 and Appendix F. The width and area for channel-fill deposits in Table 6.1 is the radius (r) and the area of a half-circle oriented at 75°, based on the average paleocurrent orientation. The width and area for crevasse-splay deposits in Table 6.1 is the diameter (d) and area of the full circle. Cumulative frequency of all sand bodies is shown in Figure 6.11. Cross plots of the thickness versus width, and thickness versus area of Cf, SCf, and CS deposits are shown in Figure 6.12 and 6.13.
Figure 6.9. Map showing 633 sand bodies in the study area.
Table 6.1. Statistical summary of 633 sand bodies in Coal Canyon. The width and area in channel-fill deposits are equal to the radius and area of the half-circle at the 75° orientation. The width and area in crevasse-splay deposits are the diameter and area of the full circle.

<table>
<thead>
<tr>
<th>Sand-Body</th>
<th>N</th>
<th>Min</th>
<th>Mean</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Channel-Fill (Cf)</td>
<td>109</td>
<td>3.9</td>
<td>9.7</td>
<td>21.1</td>
</tr>
<tr>
<td>Thickness (ft)</td>
<td>45.7</td>
<td>261</td>
<td>893.6</td>
<td></td>
</tr>
<tr>
<td>Width at 75° (ft)</td>
<td>0.08</td>
<td>3.6</td>
<td>28.78</td>
<td></td>
</tr>
<tr>
<td>Area at 75° (acre)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superimposed Channel-Fill SCf</td>
<td>258</td>
<td>4.5</td>
<td>13.9</td>
<td>32.5</td>
</tr>
<tr>
<td>Thickness (ft)</td>
<td>38.2</td>
<td>400</td>
<td>2553.4</td>
<td></td>
</tr>
<tr>
<td>Width at 75° (ft)</td>
<td>0.05</td>
<td>9.9</td>
<td>235.00</td>
<td></td>
</tr>
<tr>
<td>Area at 75° (acre)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cf + SCf</td>
<td>367</td>
<td>3.9</td>
<td>12.7</td>
<td>32.5</td>
</tr>
<tr>
<td>Thickness (ft)</td>
<td>45.7</td>
<td>359</td>
<td>2553.4</td>
<td></td>
</tr>
<tr>
<td>Width at 75° (ft)</td>
<td>0.05</td>
<td>8.1</td>
<td>235.00</td>
<td></td>
</tr>
<tr>
<td>Area at 75° (acre)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crevasse Splay</td>
<td>266</td>
<td>0.5</td>
<td>2.7</td>
<td>6.5</td>
</tr>
<tr>
<td>Thickness (ft)</td>
<td>45.9</td>
<td>245</td>
<td>1661.2</td>
<td></td>
</tr>
<tr>
<td>Width (ft)</td>
<td>0.15</td>
<td>6.1</td>
<td>198.9</td>
<td></td>
</tr>
</tbody>
</table>
Figure 6.10. Frequency histogram of thickness, width, and area of channel-fill deposits (Cf+SCf) and crevasse-splay deposits (CS). The width and area numbers for channel-fill deposits are taken from the 75° orientation.
Figure 6.11. Cumulative frequency distribution of sand-body thicknesses (above) and sand-body widths (below). Sand-body widths for Cf and SCf sand bodies are based on the half circle radius at 75° orientation. Sand-body widths for CS sand bodies are based on the circle diameter.
Figure 6.12. Cross plot of sand-body thickness versus width. The widths of channel-fill deposits (Cf and SCf) are the radius of the half circle at the 75° orientation. The widths of crevasse-splay (CS) deposits are the diameter of the full circle.
Figure 6.13. Cross plot of sand-body thickness versus area. The areas of channel-fill deposits (Cf and SCf) are the areas of the half circle at the 75° orientation. The areas of crevasse-splay deposits (CS) are the area of the full circle.
The channel-fill (Cf+SCf) thickness ranges from 4 to 32.5 ft (1.2 to 10 m). The channel-fill sand-body width and area uses the 75° orientation, which is close to the mean paleocurrent orientation presented by Cole and Cumella (2003). The channel-fill (Cf+SCf) sand-body width ranges from 45.6 to 2,553 ft (14 to 778 m) and the drainage area ranges from 0.05 to 235 ac (202 to 951,004 m²). The crevasse-splay (CS) thickness ranges from 0.5 to 6.5 ft (0.15 to 2 m), the width ranges from 46 to 1,661 ft (14 to 506 m), and the area ranges from 0.15 to 199 ac (607 to 804,913 m²).

Cole and Cumella (2005) differentiated all sand body populations in the NE leg and NW leg of Coal Canyon to see any differences of the sand-body dimension. In this study, the sand-body population is greater than what they measured. The sand-body populations in the NW leg and NE leg are differentiated and summarized in Table 6.2. From all 633 sand bodies in the study area, 250 sand bodies are located in the NE leg and 383 sand bodies are located in the NW leg. The channel-fill sand-body width and area in Table 6.2 represent the radius and area of the half-circle at 75° orientation. The crevasse-splay deposit in Table 6.2 represents the diameter (d) of a full circle.

6.4. Pseudo Well Spacing

Pseudo wells represent pseudo measured sections along Coal Canyon, which are used to calculate net-to-gross ratio and the number of sand body intersected by each well. The pseudo well spacing is built using 20-acre and 10-acre spacing. Each pseudo well is traced and draped manually onto the digital elevation model of Coal Canyon.

The well spacing position and number starts from the NE leg to the NW leg of Coal Canyon. The pseudo wells are oriented roughly perpendicular to the cliff and/or sand-body orientation. For the 20-acre spacing, the distance between each well is 933 ft (284 m) and for the 10-acre spacing, the distance is 660 ft (201 m). The draping process of each line (pseudo wells) is conducted manually by making a polygon in Petrel. The
Table 6.2. Comparison between the sand-body populations in the NE leg and NW leg of Coal Canyon. The width and area in channel-fill deposits are the radius and area of the half circle at the $75^\circ$ orientation. The width and area in crevasse-splay deposits are the diameter and area of the full circle.

<table>
<thead>
<tr>
<th>Outcrop</th>
<th>Sand-body</th>
<th>N</th>
<th>Min</th>
<th>Mean</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE</td>
<td>Cf + SCf</td>
<td>134</td>
<td>4.2</td>
<td>13.6</td>
<td>32.5</td>
</tr>
<tr>
<td></td>
<td>Thickness (ft)</td>
<td></td>
<td>68</td>
<td>386</td>
<td>2294.8</td>
</tr>
<tr>
<td></td>
<td>Width at $75^\circ$ (ft)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Area at $75^\circ$ (acre)</td>
<td></td>
<td>0.17</td>
<td>9.40</td>
<td>189.79</td>
</tr>
<tr>
<td></td>
<td>Crevasse Splay</td>
<td>116</td>
<td>0.5</td>
<td>2.82</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>Thickness (ft)</td>
<td></td>
<td>60</td>
<td>286</td>
<td>1661.2</td>
</tr>
<tr>
<td></td>
<td>Width (ft)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Area (acre)</td>
<td></td>
<td>0.26</td>
<td>8.70</td>
<td>198.93</td>
</tr>
<tr>
<td>NW</td>
<td>Cf + Scf</td>
<td>233</td>
<td>3.9</td>
<td>12.16</td>
<td>29.2</td>
</tr>
<tr>
<td></td>
<td>Thickness (ft)</td>
<td></td>
<td>38.22</td>
<td>343</td>
<td>2553.4</td>
</tr>
<tr>
<td></td>
<td>Width at $75^\circ$ (ft)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Area at $75^\circ$ (acre)</td>
<td></td>
<td>0.05</td>
<td>7.30</td>
<td>235.00</td>
</tr>
<tr>
<td></td>
<td>Crevasse Splay</td>
<td>150</td>
<td>0.8</td>
<td>2.55</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>Thickness (ft)</td>
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<td>45.9</td>
<td>213.7</td>
<td>733.6</td>
</tr>
<tr>
<td></td>
<td>Width (ft)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Area (acre)</td>
<td></td>
<td>0.15</td>
<td>4.16</td>
<td>38.79</td>
</tr>
</tbody>
</table>
The process of tracing a polygon is similar to the process of making a polygon for a sand-body trace in Petrel.

Each pseudo well is not like an actual vertical well, but rather a directional well as it is draped to the outcrop surface. The pseudo wells are used to calculate the net-to-gross ratio and the number of sand bodies intersected by each pseudo wells in Coal Canyon. There are 35 pseudo wells in a 20-acre spacing named 20-1 to 20-35 (Figure 6.14) and 49 pseudo wells in a 10-acre spacing named 10-1 to 10-49 (Figure 6.15).

The orientation of each well is generally perpendicular to the sand bodies and the cliff face. Due to the variety of sand-body orientations, there are 3 pseudo-well orientations. The first is oriented relatively perpendicular to the NE leg outcrop, the second is orientated perpendicular to the NW outcrop, and the last is oriented bearing NS near the intersection of the NW leg and NE leg.

The pseudo wells in the NW leg cover the bottom and the top boundaries of the lower Williams Fork interval. There are 51 pseudo wells (21 wells from 20-acre spacing and 30 wells from 10-acre spacing) that cover the entire lower Williams Fork Formation. The average gross thickness of the lower Williams Fork Formation from 51 pseudo wells is 446 ft (136 m).

Each of the pseudo wells intersects a certain number of sand bodies and type of sand body. The surface morphology in Coal Canyon influences the plan view of all sand bodies traced in Figure 6.14 and 6.15. The lower portion of the lower Williams Fork has gentle morphology and gradually becomes steeper into the upper Williams Fork Formation. Sand bodies located in the gentle morphology are clear in map view. However, sand bodies that occur in the steeper morphology overlap and are difficult to count from the plan view map. This could lead to errors in counting the sand bodies that intersect each pseudo well. The counting process for the number of sand bodies intersected by pseudo wells is conducted in 3D view using Petrel.
Figure 6.14. Sand-body traces in Coal Canyon with 20-acre spacing pseudo wells.
Figure 6.15. Sand-body traces in Coal Canyon with 10-acre spacing pseudo wells.
The number of sand bodies that intersect each well is viewed in a cross plot of well number versus the number of intersected sand bodies (Figure 6.16). The single channel-fill and superimposed channel-fill deposits are grouped into channel-fill deposits to generally differentiate them from crevasse splays.

The type and thickness from 51 wells that cover the Williams Fork Formation is used to determine the net-to-gross ratio. The thickness and type of sand bodies intersected in each well is shown in Appendix G. Intervals other than channel-fill and crevasse-splay deposits are considered to be covered intervals or shale. Results show that the net-to-gross ratio of sandstone is 15%. This number will be compared with the RWF542-20 well and further discussed in Chapter 7.

In this study, all pseudo wells were analyzed to see the effects of well spacing variations. The number of intersected sand bodies in 20-acre and 10-acre spacing is not randomly distributed. The number of sand bodies intersected by each pseudo well depends on the location of the well. This means that in a well with 10-acre spacing, there is no guarantee that it will hit a sand body any more than the 20-acre spacing, and vice versa. For example, wells 10-8, 10-9 and 10-10 do not intersect any sand bodies, but well 20-7, located between the 3 wells, intersects 5 sand bodies. Therefore, the dimension and the location of the wells influences the number of sand bodies intersected by one well. However, the higher density of well spacing increases the total number of sand-bodies intersected by all pseudo wells.

The total number of sand bodies intersected by wells at 20-acre spacing is 238 out of 633 (36%). The total number of sand bodies intersected by wells at 10-acre spacing is 304 out of 633 (48%). The total number of sand bodies in 10-acre spacing is 28% more sand bodies than the 20-acre spacing (Figure 6.17). The well spacing difference also contributes to the number of sand bodies not intersected by 1 well. From the total of 633 sand bodies, there are 331 sand bodies in a 10-acre spacing and 394 sand-bodies in a 20-acre spacing that are not intersected by any well (Figure 6.18).
Figure 6.16. Frequency histogram of sand bodies intersected by pseudo wells in 20-acre spacing (above) and 10-acre spacing (below).
Figure 6.17. Comparison of total sand bodies intersected by 1 pseudo well in 20-acre and 10-acre spacing.

Figure 6.18. Comparison of total sand bodies not intersected by 1 pseudo well in 20-acre and 10-acre spacing.
The result of the well-spacing variation is viewed in Figure 6.19. We can decimate the data set to determine sand-body intersection as 40-acre spacing and 80-acre spacing. To do this, we can consider the odd and even numbered wells. After decimate the odd and even number for 10-acre spacing, the distance between well becomes 1320 ft (402 m) for 40-acre spacing. After decimate the odd and even number for 20-acre spacing, the distance between well becomes 1866 ft (569 m) for 80-acre spacing. The 10-acre spacing has the highest number of sand bodies and the 80-acre spacing has the lowest number of sand bodies intersected by 1 well.

Sand-body width also influences the chance to be intersected. Figure 6.19 shows that the channel-fill (Cf and SCf) sand bodies have more probability of being intersected by 1 well compared to the crevasse-splay (CS) deposits. Of 367 total Cf and SCf sand bodies combined, 10-acre wells intersected 209 sand bodies (57%), 20-acre wells intersected 180 sand bodies (49%), 40-acre wells intersected 105 sand bodies (29%), and 80-acre wells intersected 96 sand bodies (26%). This indicates that the channel-fill deposits most likely have broader widths as shown in Table 6.1.

A sand body can be intersected by more than 1 well if it is very wide. Figure 6.20 shows the number of sand bodies intersected by more than 1 well in different well spacings. Using the 10-acre spacing, there are 24 sand bodies (23 channel-fill and 1 crevasse splay) intersected by more than 1 well. Using the 20-acre spacing, there are 14 channel-fill sand bodies that are intersected by more than 1 well. Only 5 SCf deposits are intersected by more than 1 well in 40-acre spacing and 3 SCf deposits are intersected more than 1 well in 80-acre spacing.

From 4 well-spacing variations, only 1 crevasse-splay deposit was intersected by more than 1 well, which is in the 10-acre spacing. This indicates that the channel-fill deposits will more likely be intersected by more than 1 well in different well spacings. The mean drainage area of each channel-fill deposit is 8.1 acre (Table 6.1). The value at 8.1 acre spacing in Figure 6.20 indicates that there will be roughly 24 sand bodies intersected by more than 1 well.
Figure 6.19. Cross plots of total sand bodies intersected by 1 well versus well spacing in Cartesian plot (above) and semilog plot (below).
Figure 6.20. Cross plot of total sand bodies that are intersected by more than 1 well versus well spacing. The value of 8.1 acre is the arithmetic mean area of channel-fill deposits (Table 6.1).
6.5. Discussion

Aerial LiDAR technology had some pitfalls, such as smearing the data in steep topography and reducing detail in the outcrop surface. Ground LiDAR surveys can overcome this. An example is the Ellison (2004) study in Coal Canyon. However, the high cost of using ground LiDAR with broader area coverage gives a disadvantage to this approach.

Broader area coverage provides more sand-body measurement. However, the thickness measurement is a major concern due to the smeared data. Photomosaics help overcome the thickness accuracy problem. Despite the inaccuracy in thickness measurements, the sand-body width measurement is reliable. The accuracy of sand-body tracing in Petrel also contributes to the accuracy of the sand-body measurement technique.

The width-measurement technique used in this study gave different numbers than the Cole and Cumella (2005) research. Their technique in measuring the sand-body apparent width values used the linear distance from the GPS locations of the end points. More sand-body measurements in this study also contributed to the differences. According to their results, the width of 37 sand bodies in the NE leg range from 69 to 2,791 ft (21 to 851 m) with an average of 881 ft (268 m). The width of 99 sand bodies in the NW leg ranges from 40 to 2,034 ft (12 to 620 m), with an average of 396 ft (121 m). In this study the widths (radius/ r) of 367 sand bodies in the NE leg range from 60 to 2,295 ft (18 to 700 m), with an average of 340 ft (104 m). The widths of 383 sand bodies in the NW leg range from 38 to 2,553 ft (12 to 778 m), with an average of 293 ft (Table 6.2).

Average widths from this study and Cole and Cumella (2005) show that sand bodies in the NE leg are wider than those in the NW leg, although this study shows that the values are close. This difference may be related to the quality of outcrop exposure. It is important to note that the sand bodies are not 100% exposed in the outcrop. Exposure
quality is influenced by recent erosion. Cole and Cumella (2005) defined this as the outcrop slice direction.

Cole and Cumella (2005) mentioned that the outcrop slice direction relates to the 75° paleocurrent data. The fluvial system generally flows to the east, which is towards the shore of the Cretaceous seaway. According to Cole and Cumella (2005), the sand-body populations in the NE leg are more or less perpendicular and the sand-body populations in the NW leg are more or less parallel to the dominant paleocurrent direction. Thus, the average sand-body populations in the NE have a greater dimension than the NW leg population. This study suggests that the differences are minor.

The thickness versus width (Figure 6.12) and thickness versus area cross plots (Figure 6.13) show that there are no significant relationships that can be drawn. The channel-fill (Cf and SCf) sand-body dimensions are not always wider than those of crevasse-splay deposits. The width (r) of channel-fill deposits is a function of drainage area and the diameter (d) of crevasse-splay deposits is a function of drainage area. Therefore, the drainage area depends on the radius and/or the diameter. Despite the width and drainage area, the thickness shows that commonly crevasse-splay deposits are thinner than channel-fill deposits and the SCf sand bodies have the thickest sand bodies.

The implication of sand-body exposure variety shows in the number of sand bodies intersected as a function of well spacing. The dimension and the location of pseudo wells influence the number of sand bodies that will be intersected by the pseudo wells. Since the SCf sand bodies have the broadest width, it is more likely the SCf will be intersected than the others. A single SCf deposit even can be intersected by more than 1 well, as shown in Figure 6.20.
CHAPTER 7

COMPARISON OF DATA SETS

This chapter deals with comparing sand-body dimensions and net-to-gross ratio results from the subsurface and outcrop data. The results of this interpretation can aid field-scale modeling in the subsurface. Comparison

7.1. Net-To-Gross Ratio

The comparison of net-to-gross ratio is between the RWF542-20 borehole image log and the Coal Canyon well spacing results. The MWX-2 core well is not used because the core data is not continuous through the lower Williams Fork Formation. The borehole image log covers the entire study interval.

The gross thickness of the lower Williams Fork Formation in well RWF542-20 is 1970 ft (600 m). The average gross thickness of the lower Williams Fork Formation from outcrop data is 269 ft (82 m), which is 7 times less than the RWF542-20. The large difference in the gross thickness may be caused by differences in the accommodation space during the Cretaceous in the Piceance basin. Erosion may have removed some of the formation to the west of Rulison field.

Despite the large gross thickness difference, the net-to-gross ratio from both data sets is similar. The net-to-gross ratio from the RWF542-20 well is 16.7% and the net-to-gross ratio from the outcrop is 15%. This result indicates that the outcrop pseudo wells may be a good example for the subsurface analog. However, this is only a comparison to 1 subsurface well. It is important to note that the pseudo wells in the outcrop do not
represent vertical wells, but rather deviated wells. Future studies comparing the outcrop result with more subsurface well data will be valuable.

7.2. Sand-Body Dimensions

Comparison of sand-body dimensions from the outcrop to the subsurface in this study only applies to channel-fill deposits. Only channel-fill sands in fluvial systems have empirical equations to estimate the channel width and the channel-belt width. Similar characteristics of channel-fill sandstones and coeval stratigraphy in the lower Williams Fork Formation to that observed in the MWX-2 core make it possible to do this comparison.

There are several relevant studies about the channel-dimension estimation. Lorenz (1985) studied the channel dimensions by using the MWX core from the Rulison field and compared it with the outcrop exposure in Rifle Gap. Shanley (2004) studied available core data from the Jonah field and tried to estimate the channel dimension using the channel-estimation equations. Both of them explicitly related or defined the channel-belt width (Wm) estimation as the sand-body width in their papers. This means that the sand-body width (the radius of the half circle in this study) measured in the outcrop correlates to the Wm width estimation from the subsurface. In alluvial model drawn by Bridge and Mackey (1993) in Figure 4.23, the Wm also represents the sand-body width. However, a single channel belt represents a single-story channel-fill deposit, which is defined as a Cf deposit in this study. This means that the Cf sand-body width from the outcrop (r) correlates to the Cf channel-belt width (Wm) estimation from the subsurface. Because of this definition, the Wm equation becomes unreliable for the superimposed channel-fill deposits (SCf). The SCf deposits are multi-story, amalgamated deposits. To estimate the channel-belt width, the SCf deposits need to be broken down into individual channel stories.
The depth of individual channels or the maximum bankfull depth measured in the subsurface is the main input for channel-dimension estimation. This means that to compare the Wm width from the subsurface with the outcrop sand body width (r), the thickness of each Cf sand body in outcrop is considered to be the bankfull depth.

In the subsurface data (MWX-2 and RWF542-20), the SCf deposits are already broken down into individual channel stories. In the LiDAR outcrop study, it is difficult to recognize the individual channel stories due to the quality of the LiDAR data. Therefore, the Wm width estimation in the subsurface using the gross thickness is not related to the radius (r) of the SCf sand-body width measured from Coal Canyon outcrop. Although in theory it is not the same, the Wm width using the gross thickness of SCf in the subsurface will be compared to the SCf sand-body width in the outcrop to see if there is any correlation.

The sand-body dimension comparison between the subsurface data (MWX-2 and RWF542-20 well) with Coal Canyon outcrop is summarized in Table 7.1, and Figure 7.1, and 7.2. The input data for the MWX-2 core is driven from Table 4.2 and the input data from the RWF542-20 image log well is driven from Table 5.4. The channel-belt width (Wm) differed by individual channel story (blue text) and superimposed channel-fill deposits (purple text). The sand-body width from the outcrop is driven from Table 6.1 using the width of the half-circle (r) at 75° orientation.

Most of Cf and SCf data points from outcrop measurement are lower than the subsurface (MWX-2 and RWF542-20 wells) data points. There are several subsurface data that are closer to the outcrop data. The Cf sand-body thickness versus the Cf sand-body width cross plot (Figure 7.1) shows that there are few data points from the subsurface that are close to the outcrop data points. Data points based on the Bridge and Mackey (1993) equation are a better fit to the outcrop data than data points from the Lorenz (1985) approach. However, this does not mean that the Bridge and Mackey (1993) method is better. The same result is also observed in SCf sand-body width cross plot in Figure 7.2.
Table 7.1. Comparison of channel dimension between the subsurface data and the outcrop LiDAR measurements. In the MWX-2 and RWF542-20 column, the Cf thickness is driven from all individual channels and the SCf thickness and width is driven from the gross thickness of SCf deposits. In the aerial LiDAR column, the width is driven from the radius (r) of the half circle at 75° orientation.

<table>
<thead>
<tr>
<th>Sand-body Type</th>
<th>MWX-2 and RWF542-20</th>
<th>Aerial LiDAR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Channel depth after 10% compaction</td>
<td>Channel-belt width (Wm)</td>
</tr>
<tr>
<td></td>
<td>min - max (ft)</td>
<td>min - max (ft)</td>
</tr>
<tr>
<td>Cf</td>
<td>6.7 - 28.9</td>
<td>509.6 - 4985.8</td>
</tr>
<tr>
<td>SCf</td>
<td>12.2 - 44.4</td>
<td>1380.2 - 9743.9</td>
</tr>
</tbody>
</table>
Figure 7.1. Cross plot of single story channel-fill (Cf) thickness versus width in meter. The Cf sand-body width from the outcrop is the width (radius) of the half circle at 75° orientation. The Cf thickness and channel-belt widths from the Bridge and Mackey (1993) and Lorenz (1985) approaches values are derived from all single-story channels interpreted in the MWX-2 core (Table 4.2) and RWF542-20 well (Table 5.5).
Figure 7.2. Cross plot of superimposed channel-fill (SCf) thickness versus width in meter. The SCf sand-body width from the outcrop is the width (radius) of the half circle at 75° orientation. The SCf thickness and channel-belt widths from the Bridge and Mackey (1993) and Lorenz (1985) approaches values are driven from all superimposed channel-fill gross-thicknesses interpreted in the MWX-2 core (Table 4.2) and RWF542-20 well (Table 5.5).
The sand-body widths from outcrop are probably the best data and are used as the “ground truth” in this study. Most of subsurface data points do not match the outcrop data. The published equations used for the subsurface data seem to overestimate the channel-belt width. In the published equations, the channel-belt width increases with the thickness. This is not true with the outcrop data, which show channel-belt widths or sand-body widths may vary in the same sand-body thicknesses. The sand-body widths using published equations are too optimistic. Based on outcrop data of sand-body width versus thickness cross plots (Figures 7.1 and 7.2) the equation for sand-body width \((y)\) are

\[ y = 30.2x^{0.72} \]  

for Cf deposits and \(y = 38.9x^{0.63}\) for SCf deposits. Both equations based on the thickness \((x)\) of channel-fill deposit. The results indicate that the sand-body widths are 5 to 11 times more for the Lorenz et al. (1985) approach and 3 to 8 times more for the Bridge and Mackey (1993) approach than the outcrop results.

There are several explanations for this difference. Paleogeographic location of both data sets may cause the sand-body dimension differences. The MWX-2 and RWF542-20 are located nearer the shoreline to the Cretaceous seaway in the Piceance basin. Commonly, an alluvial river becomes broader towards downstream. As discussed previously, the outcrop data is not 100% exposed, which causes variation in sand-body dimension. Other plausibility is that equations from previous researchers are not always correct or can not be applied in this study area.

### 7.3. Well Spacing and Sand-Body Dimension

As discussed earlier in Chapter 6, the number of sand bodies intersected by 1 well depends on the dimension and the position of pseudo wells in the outcrop. The summary table of the half-circle area for subsurface data is shown in Table 7.2 and for outcrop data is shown in Table 7.3. In the subsurface data, the Cf areas range from 2.4 to 896 ac (0.0008 to 3.6 km\(^2\)) and the SCf areas range from 68.7 to 3,422 ac (69 to 14 km\(^2\)). In
Table 7.2. Channel-belt width and drainage area of channel-fill deposits from the MWX-2 and RWF542-20 wells. The channel-belt width is used as the radius (r) for calculating the half-circle area.

<table>
<thead>
<tr>
<th>Sand-body Type</th>
<th>MWX-2 and RWF542-20</th>
<th>Lorenz et al. (1985) approach</th>
<th>Bridge and Mackey (1993) approach</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Channel depth after 10% compaction</td>
<td>area (acre)</td>
<td>area (acre)</td>
</tr>
<tr>
<td></td>
<td>min - max (ft)</td>
<td>min-max</td>
<td>mean</td>
</tr>
<tr>
<td>Cf</td>
<td>6.7 - 28.9</td>
<td>9.4 - 895.9</td>
<td>80.2</td>
</tr>
<tr>
<td>SCf</td>
<td>12.2 - 44.4</td>
<td>68.7 - 3,422</td>
<td>748.6</td>
</tr>
</tbody>
</table>

Table 7.3. Channel-fill sand-body width and drainage area from outcrop data. The sand-body width is used as the radius (r) to calculate the half-circle drainage area.

<table>
<thead>
<tr>
<th>Sand-body Type</th>
<th>Aerial LiDAR</th>
<th>Sand-body dimension at 75° orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thickness/Channel-depth</td>
<td>Sand-body width (ft)</td>
</tr>
<tr>
<td></td>
<td>min - max (ft)</td>
<td>min-max</td>
</tr>
<tr>
<td>Cf</td>
<td>3.9 - 21.1</td>
<td>45.7 - 893.6</td>
</tr>
<tr>
<td>SCf</td>
<td>4.5 - 32.5</td>
<td>38.2 - 2553.4</td>
</tr>
</tbody>
</table>
Figure 7.3. Half-circle illustration of mean channel-belt width (Wm) from the subsurface data and mean sand-body width (r) from outcrop data. The drainage area is the half-circle area.
outcrop data, the Cf areas range from 0.08 to 894 ac (0.003 to 3.6 km²) and the SCf areas range from 0.05 to 2553 ac (0.002 to 10.3 km²). The differences between the subsurface data and outcrop data are illustrated in Figure 7.3. The illustration uses the arithmetic mean area from both data sets. The area arithmetic mean differences between subsurface data and outcrop data is large. However, it is important to note that the minimum to maximum range of areas overlap.

The size of half circle will influence the number of wells that will cover the half-circle. An example of drainage area is shown in Table 7.4 by assuming the channel depth of Cf deposit is 10 ft (3m) and SCf deposit is 20 ft (6.1 m) after 10% decompaction.

Effects of different well spacing on the drainage areas are illustrated in Figures 7.4 and 7.5. There are 3 different half circles for each Cf and SCf deposit. The first half-circle represents the Lorenz et al. (1985) approach and the second half-circle represents the Bridge and Mackey (1993) approach. The size of half circles for both of their approaches is based on Figure 7.4. The size of the third half circle is based on the values of arithmetic mean sand-body width of Cf and SCf deposits in outcrop data from Table 7.3.

Each half circle is overlain with a 20-acre and 10-acre spacing grid. The center of each block is assumed to be the well location. The result indicates that in 10 ft (3 m) of Cf thickness, the drainage area ranges from 0.6 to 10.5 ac (0.002 to 0.04 km²). If the half circle is overlain by 10-acre well spacing, the sand body may be hit by 1 to 6 wells (Figure 7.4). If the half-circle is overlain by 20-acre well spacing, the sand body may be hit by 1 to 4 wells (Figure 7.5).

In 20 ft (6.1 m) of SCf thickness, the drainage area ranges from 1.9 to 90.9 ac (0.007 to 0.37 km²). If the half circle is overlain by 10-acre well spacing, the sand body may be hit by 1 to 35 wells. If the half-circle is overlain by 20-acre well spacing, the sand body may be hit by 1 to 17 wells. Roughly, the number of wells in 10-acre spacing may be hit 1.5 times or even 2 times more than in 20-acre spacing. However, there is no definitive trend for this result.
Table 7.4. Example of drainage area comparison based on different equations by assuming the channel depth or sand-body thickness of Cf deposit is 10 ft and SCf deposit is 20 ft. The Wm and y is the radius of half circle and the drainage area is the half-circle area.

<table>
<thead>
<tr>
<th>Sand-body Type</th>
<th>Channel-depth (h) after 10% decompaction</th>
<th>Channel-belt width equations from previous Researchers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Lorenz et al.(1985) approach</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bridge and Mackey (1993) approach</td>
</tr>
<tr>
<td></td>
<td>ft</td>
<td>m</td>
</tr>
<tr>
<td>Cf</td>
<td>10</td>
<td>3.0</td>
</tr>
<tr>
<td>SCf</td>
<td>20</td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td>ft</td>
<td>m</td>
</tr>
</tbody>
</table>


Figure 7.4. Illustration of mean channel-belt width (Wm) from the subsurface data and mean sand-body width (r) from outcrop data overlain with 10-acre spacing block.
Figure 7.5. Illustration of mean channel-belt width (Wm) from the subsurface data and mean sand-body width (r) from outcrop data overlay with 20-acre spacing block.
This example is an illustration of the relationship of well spacing to drainage area. It is important to notice that the thickness or channel-depth is the basic input in all approaches. The results of sand-body dimension and area from Table 7.2 can be used as parameters in field-scale modeling. However, there is no guarantee that the result will be correct, which also applies to all equations from previous researchers. Further study in the subsurface by using seismic data might help to achieve better dimension comparison between the subsurface and outcrop data.
8.1 Conclusions

The purpose of this study is to quantify and compare sand-body dimensions and net-to-gross ratio in the lower Williams Fork Formation, Piceance basin, northwestern Colorado, by integrating the MWX-2 core data and the RWF 542-20 borehole image data from Rulison field, and aerial LiDAR data from outcrops in Coal Canyon. Both subsurface and outcrop locations have similar depositional environments. Major conclusions are:

1. Measurements of cross beds and lateral-accretion surfaces in a well-exposed point bar in Coal Canyon found that dip magnitudes (3 to 37°, average 15°) are similar, but dip directions vary by roughly 90° for the 2 types of surfaces. Cross beds generally dip to the east (88°).

2. Described 451 ft (137 m) of core from well MWX-2 in Rulison field, which is in a coeval interval 50 mi (80 km) east of the Coal Canyon outcrop. Identified 12 facies, ranging from coals and muddy floodplain deposits to structureless and trough cross-bedded sandstones. There are 5 kinds of architectural elements: single-story channel-fill (Cf), superimposed channel-fill (SCf), crevasse-splay (CS), floodplain (Fp), and delta plain-delta front (DP/F) deposits. Log signatures are distinctive for each type of facies assemblage. Two single-story and three amalgamated, multi-story sand bodies occur in the cored interval. Individual channel thicknesses range from 9 to 26 ft (3 to 8 m). The gross thickness of multi-story sand bodies ranges from 37 to 40 ft (11 to 12 m). Thicknesses of Cf sandstones and individual
amalgamated sandstones in SCf intervals were used to compute channel width and channel-belt width using published equations. Channel widths range from 124 to 1,314 ft (38 to 400 m) and channel-belt widths range from 531 to 9,744 ft (162 to 2,971 m).

3. Interpreted 1,970 ft (600 m) of electrical borehole images from well RWF542-20 in Rulison field. This well is 2.5 mi (4 km) from the MWX-2 well. Determined from dips of shale beds, with gamma ray values higher than 90 API units, that the structural dip is less than 5°. The dominant dip direction is 31° for cross beds, using gamma ray values less than 60 API units. This differs from the more easterly cross-bed orientation noted at Coal Canyon. There are 4 single-story channel (Cf), 16 superimposed channel-fill (SCf), and 26 crevasse-splay (CS) deposits in the lower Williams Fork Formation. The net sandstone is the sum of the thicknesses of Cf, SCf, and CS intervals. The net-to-gross ratio is 16.7%. The thickness of Cf sandstones ranges from 8 to 11 ft (2.4 to 3.4 m), and averages 9.5 ft (3 m). The thickness of SCf sandstones ranges from 11 to 34 ft (3.4 to 10.4 m), and averages 21 ft (6 m). The thicknesses of Cf sandstones and individual amalgamated sandstones in SCf intervals have been used to compute channel width and channel-belt width using published equations. Channel widths range from 66 to 1,016 ft (20 to 310 m) and channel-belt widths range from 256 to 7,567 ft (78 to 2,307 m).

4. Sand-body types in the lower Williams Fork Formation are grouped into 3 major types: single channel-fill (Cf), superimposed channel-fill (SCf) and crevasse-splay (CS) deposits. In the subsurface, 3 type sand bodies are differentiated from their internal structure. SCf deposit is differentiated from repetitive cycle or amalgamation of Cf deposit internal structures such as cross-bed and rip-up clasts. CS deposit is differentiated by the dominant occurrence of ripple laminations. In the outcrop observation, the 3 types of sand bodies are differentiated from photomosaics and thickness.
5. Interpreted sand-body geometries from an airborne LiDAR survey over the Coal Canyon outcrops. I traced 633 sand bodies along a 5.7 mi (9.2 km) transect in the NE-trending and NW-trending segments of Coal Canyon. Traced 109 (17%) single-story channel-fill (Cf), 258 (41%) superimposed channel-fill (SCf), and 266 (42%) crevasse-splay (CS) sand bodies. Determined thicknesses from photomosaics superimposed on the LiDAR digital-elevation model. Thicknesses of Cf sand bodies range from 4 to 21 ft (1.2 to 6.4 m), SCf sand bodies range from 4.5 to 32.5 ft (1.3 to 10 m), and CS sand bodies range from 0.5 to 6.5 ft (0.1 to 2 m). The sand-body shapes of point bars are approximated as half circles, and crevasse-splay deposits are approximated as circles. Constrained the dimension of the half circles using the end points of traced sand bodies, and a range of flow directions, in 10° increments, from 25° to 115°. These flow directions were determined from published outcrop measurements. The average flow direction is 75°. Computed the channel widths and surface areas of Cf, SCf, and CS sand bodies. Widths of Cf sand bodies at the 75° orientation range from 46 to 894 ft (14 to 273 m). Widths of SCf sand bodies at the 75° orientation range from 38 to 2,553 ft (12 to 778 m). Widths of CS sand bodies range from 46 to 1,161 ft (14 to 354 m). The net-to-gross ratio of the Cf, SCf, and CS intervals in outcrop is 15%. The remarkable similarity to the net-to-gross ratio in the RWF542-20 well suggests that the outcrop exposures at Coal Canyon provide an excellent approximation of the subsurface facies proportion.

6. Intersected the LiDAR data set with pseudo-wells at a 10-acre (0.04 km²) and 20-acre (0.08 km²) well spacing. Of 633 total sand bodies, 10-acre (0.04 km²) wells intersected 304 sand bodies (48%). 20-acre (0.08 km²) wells intersected 234 sand bodies (37%). When the data set is decimated to odd- and even-numbered wells, 158 sand bodies (25%) are intersected by 40-acre (0.16 km²) wells, and 127 sand bodies (20%) are intersected by 80-acre (0.32 km²) wells. This shows that more dense well spacing intersects more sand bodies. However, even 10-acre (0.04 km²) well spacing is inefficient, in that only 48% of the total number of sand bodies are
intersected. Very few individual sand bodies are intersected by more than 1 well. There are 24 sand bodies in 10-acre (0.04 km²) wells, 14 sand bodies in 20-acre (0.08 km²) wells, 5 sand bodies in 40-acre (0.16 km²) wells, and 4 sand bodies in 80-acre (0.32 km²) wells that are intersected by more than 1 well. This suggests that pressure-depleted sand bodies will not occur very often, even with 10-acre (0.04 km²) well spacing.

7. Assuming that LiDAR-based outcrop measurements of channel width are the “ground truth,” the published equations for channel width and channel-belt width are too optimistic by 3 to 11 times.

**8.2. Recommendations**

- Advance data processing needs to be done for the aerial LiDAR data to overcome the smearing of data in steep terrain. Ground-based Lidar can be acquired in key areas to better constrain bed thicknesses.
- Future work need to be done to apply the results of this study to a field-scale 3D model.
REFERENCES


