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Facies- to sandbody-scale heterogeneity in a tight-gas fluvial reservoir analog: Blackhawk Formation, Wasatch Plateau, Utah, USA

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ABSTRACT

Using photomosaics and measured sections, this outcrop study characterizes facies- to sandbody-scale heterogeneity in the fluvial and coastal-plain deposits of the Blackhawk Formation of the Wasatch Plateau, Utah, USA, as an outcrop analog for the fluvial tight-gas reservoirs of the adjacent greater western Rocky Mountain basins as well as for conventional fluvial reservoirs elsewhere. Analysis on eight contiguous, vertical cliff-faces comprising both depositional-dip- and -strike-oriented segments provides field-validation and calibration of entire range of fluvial heterogeneity, where: 1) large-scale heterogeneity (10's of m vertically and 100's of m laterally) is associated with stacking of channelized fluvial sandbodies encased within coastal-plain fines, 2) intermediate-scale heterogeneity (1's of m vertically and 10's of m

laterally) is related to type and distribution of architectural elements like bar-accretion and crevasse-splay units within individual sandbodies, and 3) small-scale heterogeneity (10's of cm vertically and 1's of m laterally) is attributed to facies spatial variability within individual architectural elements.

At a reservoir-scale (~ 6 km strike-transect), impact of these heterogeneities has resulted in potential stratigraphic compartmentalization in varied patterns and scales within and among three zones, which have similar lateral extents. Distinct vertical or lateral compartmentalization, contrasting net-to-gross pattern, width-constraint by either large- or intermediate-scale heterogeneity, disparity in communication between principal reservoir compartments by intermediate-scale heterogeneity, and reservoir-quality segregation to barrier styles rendered by small-scale heterogeneity are documented in an array of trends. These intriguing trends are challenging to correlate across the reservoir-scale dataset, contributing to multiple, analogous exploration and production uncertainties. For improved tight-gas exploration and production strategy of the western Rocky Mountain basins, study results were also used in developing potential predictive tools: 1) thickness threshold of individual channelized sandbody favoring multiple well intersection, 2) aspect ratio in performing probabilistic sandbody-width estimation, and 3) prediction of sandbody amalgamation using underlying coal thickness.

1. Introduction

Tight-gas sandstone reservoirs form a key component of U.S. unconventional gas production with an enormous projected potential (e.g., Fletcher, 2005; Smith et al., 2010). Growing energy consumption and a persistent drive for secure and environmentally-clean energy have emphasized the importance of tight-gas resources, particularly in the Rocky Mountain region of U.S. (Nehring, 2008). However, many tight-gas plays and reservoirs are associated with significant appraisal and extraction challenges, including low net-to-gross ratios, anomalous petrophysical behavior, and pronounced production variability, that restrict commercial production to “sweet spot” areas (Surdam, 1997). The ‘low net-to-gross’ refers to less abundance of sandbody, with respect to gross thickness, in a succession (i.e., net-to-gross ratio is <50%; Cole and Cumella, 2005; Pranter and Sommer, 2011; Kukulski et al., 2013). Addressing the above challenges requires improved geologic understanding to calibrate, validate, and evaluate heterogeneities and uncertainties in tight-gas reservoirs (e.g., Cumella et al., 2008).

Previous works on fluvial tight-gas reservoir evaluation and performance from cores, cuttings, well logs, and seismic data (e.g., Shanley, 2004; Laubach and Gale, 2006; Higgs et al., 2007; Olson et al., 2009; Tobin et al., 2010) are insufficient for understanding of the fuller degree of reservoir heterogeneities at inter-well scale. For example, core and well-log data capture the vertical dimension of depositional elements, but do not constrain their lateral extent. Also, well-log data cannot extract bed-scale sedimentary structures (i.e., dune-stratification, ripple-lamination, parallel-lamination etc.). Likewise, lithologic contrasts between sandstones and mudstones may not generate sufficiently strong impedance contrasts at

conventional seismic resolution level, including that of 3D seismic data (e.g., Shanley, 2004; House and Shemeta, 2008). In contrast, such heterogeneities of sandbodies vs. mudstones in the context of lithologic variation, stratigraphic architecture, stacking pattern, and internal sedimentary structures can be constrained in outcrop analogs at a range of scales.

Previous outcrop analog studies on fluvial tight-gas reservoirs have focused on dimensional compilation of fluvial sandbodies (e.g., Cole and Cumella 2005; White et al., 2008; Pranter et al., 2009), and documented heterogeneity at the scale of architectural elements within such sandbodies (e.g., Pranter et al., 2007). However, heterogeneity in fluvial reservoirs is complex, and ranges in size from small-scale (10's of cm vertically and 1's of m laterally; e.g., facies transitions and cross-stratification style) to intermediate-scale (1's of m vertically and 10's of m laterally; e.g., stacking of architectural elements) to large-scale (10's of m vertically and 100's of m laterally; e.g., spatial distribution of channelized sandbodies encased within floodplain mudstones) (Miall, 1988; Jones et al., 1987; Larue and Hovadik, 2006). Heterogeneity at each of these scales can potentially give rise to stratigraphic reservoir compartmentalization that is defined by segregation of flow units with distinctly different porosity and permeability properties. Therefore, a detailed characterization of this entire range of fluvial heterogeneities (both vertically and laterally) honored on a single reservoir-scale outcrop dataset can illustrate wider range of stratigraphic compartmentalization potential than what were documented in previous outcrop studies. A study of this kind linked to tight-gas relevance is largely lacking, particularly for the producing fluvial tight-gas reservoirs of the hydrocarbon-prolific western Rocky Mountain basins, despite the fact that improved geological knowledge is required to

address their significant exploration and production challenges (Shanley, 2004; House and Shemeta 2008; Cole and Cumella, 2005).

The aims of the paper are fourfold: (1) conduct a detailed characterization of a single outcrop dataset, comprising a series of contiguous cliff faces oriented in both depositional-dip and –strike directions, that illustrate facies distributions, stratigraphic architecture, and fluvial heterogeneity across a range of scales in the lower Blackhawk Formation, Wasatch Plateau, Utah, USA, (2) assess how these heterogeneities influence potential stratigraphic compartmentalization at field-scale, (3) correlate these results to show how they, as a conditioning dataset, bear analogy to the producing fluvial tight-gas reservoirs of the adjacent western Rocky Mountain basins, and (4) explore any predictive tool development that might aid towards improved upstream practices.

2. Geologic setting

The studied outcrop section is from Cottonwood Creek in the Wasatch Plateau, central Utah (Figure 1). The Wasatch Plateau is contiguous with, and crops out approximately perpendicular to the extensively studied Book Cliffs of Utah and Colorado, which have served as the natural outcrop laboratory underpinning sequence stratigraphic concepts in shallow- and marginal-marine settings (e.g., Van Wagoner, 1995; Howell and Flint, 2003). These strata were deposited in the Cretaceous Western Interior Seaway that formed in response to higher sea-level during greenhouse late Cretaceous as a vast epicontinental sea stretching from Alaska to northern Mexico. The seaway occupied the retro-arc foreland basin formed by subduction-related kinematics of the Farallon Plate (e.g., Liu et al., 2011), and was bordered by the

tectonically active highlands of the Sevier orogenic belt in the west and by stable, cratonic lowlands in the east (Kauffman and Caldwell, 1993; DeCelles and Coogan, 2006). The coeval Columbian-Sevier orogeny uplifted areas west of the seaway, and rivers sourced from these highland fold-and-thrust zones dispersed sediments eastward to the seaway over a source-to-sink distance of over 100 km. This sediment flux resulted in the development of prograding siliciclastic wedges of coastal-plain and shallow-marine deposits that transition eastward into offshore mudstones (e.g., Young, 1955; Hampson, 2010). The combined effect of subduction tectonics, eustasy, and varying sediment supply from the Sevier fold-and-thrust zone principally controlled relative sea-level fluctuations in the Seaway, as reflected in the stratal stacking pattern of shallow-marine sandstones and their intertonguing relationships with offshore shales (Houston et al., 2000; Miall and Arush, 2001; Hampson, 2010).

In comparison to strata exposed in the Book Cliffs, the contemporaneous strata of the Wasatch Plateau are less well documented. The study provides a detailed outcrop characterization of the Cretaceous Blackhawk Formation, Mesaverde Group (Figure 2) from part of the outcrop belt exposed in cliff faces in the eastern Wasatch Plateau, which forms a continuous 100-km long escarpment oriented roughly parallel to regional depositional strike. Here, the Blackhawk Formation is mudstone- and coal-prone where the proportion of sandstone is c. 10-30% over the outcrop belt (Hampson et al., 2012). The formation consists of marginal-marine, coastal-plain deposits in its lower part that transition to continental, alluvial-plain deposits in its upper part (e.g., Flores et al., 1984; Dubiel et al., 2000; Adams and Bhattacharya, 2005; Hampson et al., 2012). The studied section belongs to the lower Blackhawk

Formation and comprises channelized sandbodies, coastal-plain mudstones, and numerous coal seams.

The Blackhawk Formation extends into the subsurface of the Uinta Basin (Figure 1) where it has attained burial maturity (Nuccio and Roberts, 2003), and its base defines the basal part of the Mesaverde Total Petroleum System in this area of the western Rocky Mountain region (Johnson and Roberts, 2003). The coal quality, sandbody thickness and distribution patterns, and depositional characteristics of the Blackhawk Formation in the study area are similar to those of producing tight-gas reservoirs in other part of the western Rocky Mountain region (e.g., Uinta and Piceance Basins; Stancel et al., 2008; Yurewicz et al., 2008). Therefore, the Blackhawk Formation in the study area provides a direct reservoir analog to tight-gas plays in the western Rocky Mountain basins.

3. Dataset and methodology

Using photomosaics and measured sections, a detailed sedimentological investigation was conducted on a single, encompassing outcrop dataset comprising eight contiguous and vertical cliff faces in Cottonwood Creek, eastern Wasatch Plateau, Utah (Figure 3). In combination, these cliff faces crop out a series of depositional-dip and -strike oriented segments with high quality and scales (Figure 3). Depositional dip vs. strike orientations were interpreted from paleocurrent analysis (Figure 3C). The investigated interval is ~100 m thick, and crops out for ~ 4 km in depositional-dip extent and ~ 6 km in depositional-strike extent.

To record the location of collected data, a global positioning system (GPS) of sub-meter accuracy has been used. Sedimentological descriptions, tape measurements, lithological logs,

and digital photographs have been used for detailed facies and architectural element analysis. All photos in each cliff face were taken serially not only at the same distance from the cliff face to ensure scale preservation, but also with $\sim 30\%$ overlap with adjacent photos to maintain the continuity of sedimentologic elements during generation of photomosaics. Photomosaics have been constructed by stitching together individual photos in commercially available software ensuring that the correct geometry of sedimentologic elements is maintained with minimal parallax error. Bedding diagrams have been generated from photomosaics, documenting the geometry of channelized sandbodies (e.g., apparent thickness and width, truncation relationships) and stratigraphic architecture (e.g., sandbody abundance, horizontal and vertical facies distributions, net-to-gross ratio). Using a high-resolution binocular in the field, all macro- to micro-scale sedimentological structures (e.g., barform, dunes, ripples, mud clasts, etc.) have been meticulously populated on their near-accurate spatial position on the bedding-diagram panels. Measured sections (i.e., lithologs) were generated to document vertical facies distributions, and to calibrate the bedding diagrams (Figure 3). As our studied succession (the lower Blackhawk unit) has been influenced, though mildly, by structural deformation, it exhibits variation in its stratigraphic thickness at the length-scale of our data. As a result, there exists some minor variation in documented thickness of lithologs. Notably, as our dataset adequately comprise a series of both depositional-dip- and -strike-oriented exposures, for more appropriate lateral dimensional estimates of channel sandbodies and other architectural elements, we have targeted only strike-oriented rather than dip-oriented segments. Hence, we have purposefully avoided lateral dimensional statistics of dip-oriented segments that could have brought spurious quantification inconsistent to paleoflow-constrained estimates.

Paleocurrent data have been synthesized in rose diagrams to analyze overall paleoflow directions. To determine the near-perfect width of individual channelized sandbodies that are partially-preserved due to cliff edge limitation and/or alignment in dip-oriented section, we have applied an aspect ratio ($W/T=35$), which has been computed from the calculation of fully-preserved sandbodies in our dataset. This value is in good agreement to the similar estimation for these sandbodies in a LiDAR-integrated study of this outcrop succession (Rittersbacher et al., 2013), and also lies within the distributary envelope calculated for coastal-plain setting (*sensu* Gibling, 2006). Furthermore, we have pursued shale bed length correction based on the procedures of Geehan and Underwood (1993) to quantify less-biased population of shale length-scales for dimensional analysis. A combination of cliff-faces having strike-oriented segments and near-rectangular exposure rendered suitable for this correction procedure that has been performed by previous studies using the same dataset advantage (e.g., Stephen and Dalrymple, 2002; Burton and Wood, 2011 & 2013).

Thickness variations of each coal seam (of Axel Anderson coal zone; Sanchez and Brown, 1986; Hampson et al., 2012) were documented at accessible outcrop locations. In addition, subsurface coal thickness data of mining areas behind studied cliff faces have been utilized for channel sandbody vs. coal thickness correlation. For net-to-gross estimation, pseudowells were positioned at ~ 100 m well spacing spanning the entire dataset. Quantified datasets of channel sandbodies and other architectural elements along with their GPS readings have been utilized in ArcGIS software to generate geo-referenced, spatial distribution maps.

4. Results

Studied coastal-plain succession comprises depositional elements that are characterized with different lithology, internal sedimentary structure, dimension, and sub-environment of deposition. Here we discretize them by six depositional facies (Table 1; Figure 4) and five architectural elements (Table 2; Figure 5).

4.1. Facies analysis

Six facies have been recognized in this study (Table 1): (1) trough cross-stratified sandstones, (2) parallel-laminated sandstones, (3) thinly interbedded mudstones, siltstones and rippled sandstones, (4) mudstones and siltstones, (5) carbonaceous mudstones, and (6) coal. These facies are characterized and differentiated mainly on the basis of grain size, lithology, and sedimentary structures. Measured sections (e.g., lithologs 1 to 11 in Figure 3) provide vertical description of these facies.

Trough cross-stratified sandstones (Facies 1) are mostly medium-grained, and contain predominantly (>90%) trough cross-beds with minor (<10%) current-ripple cross-lamination (Figure 4A, B). Mostly, ripple cross-laminations occur towards the upper part of this facies. Cross-stratification sets range from 10 to 50 cm in thickness and are commonly stacked vertically into cosets. The facies is characterized by erosional bases, which exhibit curved, concave-upward geometries at some locations, and a progressively fining-upward grain-size trend. A few sole marks have been found at the erosional bases. Rip-up mudclasts are commonly scattered throughout sandbodies, but unusually large clasts (up to ~ 10 cm in diameter) occur locally within convoluted patches. Dune and ripple data shows unimodal

paleocurrent distribution (Figure 3C). The cross-stratified sandstones are interpreted to be deposited by migration of dunes and ripple bedforms in response to unidirectional currents. The facies shows a good correspondence between grain-size and bedform types. For example, dune-scale cross-strata are present in medium-grained sandstones whereas ripple-scale cross-laminations are observed within fine-grained sandstones usually towards the top of a sandbody. Localized presence of large clasts with convolution indicates deposition due to soft-sediment deformation likely related to liquefaction process (e.g., Owen, 1986).

Parallel-laminated, fine-grained sandstones (Facies 2) are encased within mudstones (Facies 4) (Figure 4C). This facies (Facies 2) forms thin (~ 0.1 -1 m thick), but laterally persistent sheets that occur at the margins of channelized bodies of trough cross-stratified sandstone (Facies 1). Mud rip-up clasts are rarely present. Parallel-lamination within the sheet bodies is attributed to deposition under upper-plane bed conditions during high-stage flooding events in nearby channels. They form only a small proportion on outcrop panels (Figures 6, 7), but a more distinct proportion on Figure 8.

Thinly interbedded mudstones, siltstones, and rippled sandstones (Facies 3) represent a heterolithic deposition wherein bed-scale thickness variation is laterally distinct. Rippled-sandstones are sheet-type and fine-grained. Intercalated mudstones and siltstones are generally structureless to crudely planar-bedded (lower flow regime) (Figure 4D). This facies grades laterally into mudstones (Facies 4) in the floodplain area. The thinly interbedded mudstones, siltstones, and rippled sandstones record floodplain deposition in response to episodic fluctuations in flow velocity and sand supply during flooding events.

Mudstones and siltstones (Facies 4) are massive and show nodular to fissile weathering features. Rootings and pedogenesis were observed locally. This facies records suspension fall-out deposition of unconfined flows in floodplain area during waning stage of flooding events adjacent to main channels. The facies is pervasive in outcrop panels (Figures 6-8).

Carbonaceous mudstones (Facies 5) are gray to light black in color, and marked by abundant plant material and leaf impressions (Figure 4E). Localized root penetration (up to ~ 20 cm) is visible in places, indicating plant colonization. Hence, this facies was likely developed in a partly subaerial, highly vegetated floodplain environment. Carbonaceous mudstones appear adjacent to and interbedded with coal (Facies 6) that implies its deposition in swampy conditions similar to those for coals.

Coal (Facies 6) is distinct, easily recognized (Figure 4F) and appears as numerous individual seams (~ 1-2 m thick) showing considerable lateral-continuity (up to ~ 500 m) (Figures 6, 7). In places, coal beds have been moderately bioturbated (bioturbation index = ~ 2), showing *Teredolites* burrows at the base of coal seams. The accumulation of coal, notably in the lower Blackhawk Formation, has been attributed to favorable peat preservation in a swampy environment during periods of clastic sediment starvation (Flores et al., 1984). Although coal constitutes a small proportion of the outcrop data (Figure 3), its presence is significant for stratigraphic correlation and stratal subdivision of the Blackhawk Formation in the Wasatch Plateau (e.g., Flores et al., 1984; Dubiel et al., 2000; Hampson et al., 2012).

4.2. Architectural element analysis

Hierarchy of architectural units is represented by bounding-surface relationships which range in spatial scale from ripple-scale cross-stratification sets (1st order), dune-scale cross-stratification sets (2nd order), bar-accretion increment (3rd order), individual bar macroform (4th order), channel storey (5th order), channel belt (6th order), to channel-belt complex (7th order) (e.g., Miall, 1988). We illustrate this hierarchical arrangement through detailed documentation of bounding surfaces and architectural elements on cliff face photomosaics (Figures 6-8). We also evaluate external and internal geometry, dimensions, and facies composition of architectural elements. Five architectural elements have been recognized on the outcrop panels (Table 2): (A) channel, (B) bar-accretion macroform, (C) overbank fines, (D) crevasse delta, and (E) overbank and crevasse splays.

A: Channel (Figure 5A)

Channel-fill sandbodies are typically 1-17 m thick, medium-grained, and white to light-brown colored. They mostly comprise facies 1 (Table 1, Figure 5A), and are commonly found laterally adjacent to coeval bar deposits (architectural element B) and overbank fines (architectural element C). Sedimentary structures include dune-scale trough cross-stratification with set thickness ranging from 10 cm to 50 cm, and subordinate ripple cross-lamination that principally occurs towards channel-fill tops, defining a fining-upward trend. Channel bases are commonly concave-upward erosional surfaces lined by discontinuous lags of mud rip-up clasts. Mud clasts are also scattered throughout channel-fill sandbodies.

Channel elements represent the fills of formative rivers. To estimate water depths of paleorivers from dune cross-set thickness, methods of Bridge and Tye (2000), Leclair and Bridge (2001), and Bhattacharya and Tye (2004) have been followed. From the compiled dune cross-set thickness data (ranges from 10 to 50 cm), mean cross-set thickness (s_m) and standard deviation (s_{sd}) were calculated. When s_m/s_{sd} is ~ 0.88 , average dune height (h_m) was estimated using equation (Bridge and Tye 2000; Bridge 2003):

$$h_m = 5.3 \beta + 0.001\beta^2 \quad (\text{where } \beta \approx s_m/1.8)$$

As the flow-depth scales to 6-10 times of average dune height (Allen 1984; Bridge and Tye 2000; Leclair and Bridge, 2001; Li et al., 2010), the water depths of paleorivers were estimated as ~ 2 -15 m, which provides a good correspondence to measured thickness (1-17 m) of channel sandbodies in outcrop data (e.g., Figures 6-8). The overall paleoflow direction recorded by dune-scale cross-bedding, ripple-scale cross-lamination, bar-accretion bedding, and sole marks was towards northeast (Figure 3C), which broadly matches to documented regional paleoflow trend of the area (e.g., Kamola and Van Wagoner, 1995; Hampson et al., 2012).

B: Bar-accretion macroform (Figure 5B)

Bar deposits comprising accretion units are distinctly developed and abundant (e.g., Figures 6-8). Locally, they pass laterally to adjacent, coeval channel-fill sandbodies or overbank fines (architectural elements A and C, respectively). Individual bar-accretion elements range in thickness from 2 m to 15 m, but appear as laterally continuous, sheet sandbodies as a result of continuous accretion increments. These elements predominantly contain Facies 1 (i.e., trough cross-stratified sandstones; Table 1, Figure 4A-B). Their basal surfaces are erosional (Figures 6-

8), whereas their top surfaces are relatively gradational. Accretion surfaces dip gently (6-11°, calculated from outcrop data; Figures 6-8) in the directions mostly oblique or nearly perpendicular to mean paleocurrent flow.

Upward-fining, bar-accretion macroform elements are formed by deposition on the inner bend of sinuous channel reaches (Allen 1963, 1970). Dip directions of accretion beds that are nearly perpendicular to mean paleoflow indicates a greater lateral than downstream component of accretion development. Their abundance in the study area attributes to sinuous, and possibly meandering (sinuosity >1.5), nature of individual channels that developed point-bar deposits on their inner banks. To generate a first-order estimation of paleoriver sinuosity, we have used the method of Schumm (1972):

$$P = 3.5 * (W / D)^{-0.27}$$

Where P = sinuosity, W = bankfull channel width, D = bankfull channel depth

Using this relationship, moderate-to-high sinuosity values (~ 1.5-1.7) have been estimated for the paleorivers.

C: Overbank fines (Figure 5A)

Overbank fines are dominated by mudstones and siltstones (Facies 4; Table 1, Figure 4E), carbonaceous mudstones (Facies 5; Table 1, Figure 4E) and coal (Facies 6; Table 1, Figure 4F). Mudstones are pervasive, but carbonaceous mudstones and coals occur at distinct stratigraphic levels. Overbank fines were probably deposited on the floodplain during the waning stage of flooding events or during channel avulsion (e.g., Smith et al., 1989). The occurrence of laterally continuous coal seams of moderate thickness (~ 1-2 m) suggests

favorable conditions for accumulation and preservation of peat, as a result of a high water table and clastic sediment starvation (Bohacs and Suter, 1997). Overbank fines element occurred as laterally continuous thick to thin sheet-type deposits as well as patchy, discontinuous deposits as it was eroded away laterally by channel.

D: Crevasse delta (Figure 5C)

A coarsening-upward, lenticular, and heterolithic unit (c. 7 m thick, ~ 50 m wide), containing distinct clinoformal beds ($<10^\circ$ dip), shows a lateral facies change from proximal, ripple-laminated sandstones to distal, silty mudstones (Figure 9). Sandstones in the package are fine-grained, parallel-laminated, and contain abundant plant debris (Facies 2; Table 1, Figure 4C). Individual sandstone beds intertongue with siltstones, mudstones and carbonaceous mudstones (Facies 3; Table 1, Figure 4D). The package is overlain by channel-fill and bar-accretion elements (architectural elements A and B, respectively) (Figure 9).

The heterolithic, convex-upward, and coarsening-upward unit is interpreted as crevasse delta deposit that developed on the floodplain through a breached levee, where flow was poorly confined and dissipated as a jet (Allen, 1965; Kraus, 1987). The stacking of multiple clinoformal sandstone beds into a clinoform set demonstrates delta buildup via repeated, episodic flow events that are separated by waning-flow mudstones. The proximal delta, being adjacent to the source channel, shows high energy deposition and thus coarser grain size (Litholog 1 of Figure 9), whereas the distal delta is finer grained and contains more mud and plant debris, consistent with deposition further from the channel (Litholog 3 of Figure 9). The measured thickness (c. 7 m) and width (~ 50 m) of this architectural element refers only to its

minimum preserved dimensions, as the element has been eroded by an overlying channelized sandbody (Figure 9).

E: Overbank and crevasse splays (Figure 5D)

This architectural element is composed of both overbank and crevasse splay deposits. Overbank splays occur as thin (0.1-1 m), isolated sandbodies that extend laterally over tens to hundreds of meters. Overbank splay sandstone beds have ribbon and sheet geometries, and comprise parallel-laminated, nearly horizontal-bedded, fine-grained sandstones and siltstones (Facies 2; Table 1, Figure 4C) that lack basal erosional relief. They are gradational with overlying overbank fines (architectural element C).

In contrast, crevasse splay deposits, composed of both parallel-laminated sandstones (Facies 2; Table 1) and thinly interbedded mudstones, siltstones and rippled sandstones (Facies 3; Table 1), show a lenticular cross-sectional geometry, notably in strike-oriented sections (e.g., Figures 6, 8). They comprise fine-grained sandstones proximal to the source channel that gradually pass distally into siltstones and mudstones. Individual bed commonly forms a fining upward trend, but a bedset usually form coarsening-upward successions with erosional basal surfaces in proximal locations that become gradational at more distal locations. These coarsening-upward packages have thicknesses of ~ 0.7-9.5 m and lateral extents of ~ 2-131 m (Figure 11). They lack clinoforms that characterize crevasse delta (architectural element D; Figure 9).

Thin, sheet-sandstone beds interpreted as overbank splay deposits were formed when sediment-laden floodwaters from main river channel spilled into the adjoining floodplain during

high-stage flooding events, without breaching the channel levee. The ribbon to sheet geometry of these beds, with their high aspect ratios (i.e., width/thickness) is suggestive of relatively low-energy sand influx to the floodplain, consistent with the interpretation of overbank splays. In contrast, when excess discharge during flooding events breached the channel levee, crevasse splay deposits characterized by proximal scour and tapering lens geometries accumulated on the floodplain. The absence of clinoformal geometries within crevasse splay successions suggests a lack of repeated clastic influx via the same route to topographically low basins on the floodplain, which implies that crevasse splay networks were isolated and short-lived.

4.3. Lithologic heterogeneity

A significant challenge in characterization and modeling of fluvial reservoirs is presented by the various scales of heterogeneity that exist between and within fluvial depositional elements (Jackson, 1977; Miall, 1988; Willis, 1989; Sharp et al., 2003). These heterogeneities constrain the distribution of, and contrasts between lithologic and petrophysical properties in inter-well volumes, and hence, their evaluation is critical to reservoir connectivity and producibility (Richardson et al., 1978; Lasseter et al., 1986; Tyler and Finley, 1991; Hartkamp-Bakker and Donselaar, 1993; Larue and Hovadik, 2006; Pranter and Sommer, 2011). Below we assess the length scales and organization of heterogeneity in the studied outcrop analog.

Large-scale heterogeneity (10's of m vertically, 100's of m laterally)

Large-scale heterogeneity pertains to the spatial distribution of channelized fluvial sandbodies encased within fine-grained coastal-plain deposits. These sandbodies vary in their dimension

(thickness range: 1-17 m, and width range: 29-724 m; Figures 10A-B). As shown by field-validation (cliff faces 1, 2, and 6; Figures 3, 6-8), they exhibit internal organizations that define: 1) single-storey channel bodies, 2) channel-belts, and 3) channel-belt complexes. A single lateral-accretion bar macroform (architectural element B) combined with a laterally adjacent channel-fill deposit (architectural element A) constitutes a single-storey channel body (~ 1-11 m thick and ~ 50-300 m wide; Figures 6, 7) (*sensu*, Friend et al., 1979). Discrete bar-macroform deposits that are laterally stacked together at the same stratigraphic level form a channel-belt (~ 15 m thick and ~ 230 m wide; Figures 6, 7), which typically appears as a laterally-amalgamated sandstone sheet (Figures 6-8). Each channel-belt is produced by lateral swing and sweep of an individual channel (Pettijohn et al., 1972). Vertical superposition of channel-belts results in the development of channel-belt complexes (~ 25 m thick and ~ 270 m wide; Figures 6, 7). Channel-belts and channel-belt complexes are thus composite sandbodies and hence, their formation resulted in increased connectedness of sandbodies (Figures 6, 7) as well as increased net sandstone thickness (e.g., in the southeastern part of cliff faces 1 and 2, towards the left side of Figure 6 and the right side of Figure 7). Lateral trends in sandbody amalgamation in the study area can be related to changes in the thickness of underlying coal seams, as explained below.

Thickness variations in coals and overlying sandstones:

Field documentation on cliff faces 1 and 2 (Figures 6, 7) demonstrates a general positive correlation between thickness of coal and overlying amalgamated sandbodies. Compaction of coal-precursor peat can profoundly affect the local subsidence patterns and thus

accommodation available for fluvial sedimentation (e.g., Hunt et al., 1996; Hofmann et al., 2011), because peat compacts by a factor of 10 or more soon after deposition (e.g., Ryer and Langer, 1980). Along cliff face 1 (Figure 3), the coal seam at the base of the studied stratigraphic interval (Axel Anderson coal zone; Sanchez and Brown, 1986) shows lateral variation in its thickness by ~ 1 m (Figure 6). It has been found that channelized sandbodies are amalgamated more above thicker coal sections, but less in areas overlying thinner coal sections (Figures 11A, D). Thicker coal sections likely experienced greater compactional subsidence, which may have generated topographic depressions that acted as sites for channel reoccupation, resulting in thicker and more amalgamated sandbodies. This observation is consistent with the adjacent subsurface coal thickness data (unpublished reports of Energy West Mining Company), and with findings in other coal-bearing basins (Michaelsen et al., 2000; Rajchl and Uličný, 2005; Hofmann et al., 2011).

Intermediate-scale heterogeneity (1's of m vertically, 10's of m laterally)

Different types of architectural elements, each with characteristic depositional and geomorphic attributes (Table 2) condition intermediate-scale heterogeneity. For field-validation and calibration, we have used cliff faces 1 and 2 (Figures 6, 7). In cliff face 1 that is oriented along depositional-strike, the abundance of architectural elements is as follows (Figure 12): (A, B) channel and bar-accretion macroform (36%, in combination); (C) overbank fines ($\sim 54\%$); (D) crevasse delta ($\sim 0.1\%$); and (E) overbank and crevasse splays (10%). In cliff face 2 that is oriented along depositional-dip, their abundance differs (Figure 12): (A, B) channel and bar-accretion macroform (51%); (C) overbank fines (41%); (D) crevasse delta (0%); and (E) overbank

and crevasse splays (8%). Overbank fines (architectural element C) display the greatest contrast in abundance (54% vs. 41% in strike vs. dip sections, respectively). Even on the same cliff face, its proportion varies laterally; for example in cliff face 1, the proportion varies from ~ 35% at the left side to ~ 80% at the right side (pseudowells 3 and 7 in Figure 11D). Although the proportion of overbank and crevasse splay deposits (architectural element E) is similar in cliff face 1 (~ 10%; Figures 6, 12) and cliff face 2 (~ 8%; Figures 7, 12), crevasse splay deposits (n = 44) show considerable variation in their thickness and width-extent (Figures 10C, D).

Small-scale heterogeneity (10's of cm vertically, 1's of m laterally)

Small-scale heterogeneity is related to the abundance and spatial distribution of sedimentological facies (Table 1) nested within architectural elements. For its representative documentation, we have targeted cliff faces 1 and 2 (Figures 6, 7). Trough cross-stratified sandstones (Facies 1) occupy 36% of cliff face 1 and 51% of cliff face 2 (Figure 12A). This facies comprises channel and bar-accretion elements (architectural elements A and B) almost entirely. Cross-bedded, medium-grained sandstones (> 90%) passing upwards into subordinate, ripple cross-laminated, very fine- to fine-grained sandstones (< 10%) characterize its internal lithologic heterogeneity, which is further enhanced by scattered mudstone chips. Moreover, heterogeneity of Facies 1 is further manifested within lateral-accretion elements where individual accretion bed notably shows a gradual up-dip decrease in grain size from medium-grained sandstones to finer-grained sandstones and intercalated siltstones (Figure 5B). Overbank fines (architectural element C) are the most abundant architectural element (Figure 12B), and are composed of a diverse assemblage of constituent facies (Figure 12C). The

proportions of these facies in cliff face 1 are: mudstones and siltstones (Facies 4; 83%), carbonaceous mudstones (Facies 5; 6%), and coal (Facies 6; 11%). In contrast, their proportions vary in cliff face 2: mudstones and siltstones (90%), carbonaceous mudstones (5%), and coal (5%). Crevasse delta, and overbank and crevasse splays elements (architectural elements D and E) consist predominantly of parallel-laminated, fine-grained sandstones (Facies 2) and thinly interbedded mudstones, siltstones and rippled sandstones (Facies 3). The abundance of these two facies is broadly similar for cliff faces 1 and 2 (Figure 12A).

5. Potential for stratigraphic compartmentalization at field-scale

Stratigraphic architecture exerts a fundamental control on reservoir compartmentalization that can be evaluated through appropriate static connectivity analysis, encompassing net-to-gross ratio, sandbody geometry and spatial distribution (e.g., Ainsworth, 2005; Kukulski et al., 2013), as well as assessment of facies-dependent rock fabrics. These aspects are constrained below through analysis of potential impact of each scale of fluvial heterogeneity. The extent of our dataset (~ 6 km strike-transect distance; Figure 3) approximates to a field-scale dimension, wherein we have divided the transect broadly into three equal zones (zone 1 to 3; Figure 13) for improved analysis. Within each zone, assemblage of lithologs constructed from outcrop data has been populated. Two laterally extensive coal seams, Axel-Anderson coal seam (~ 2 m thick) and Bear Canyon coal zone (~ 1-2 m thick), provide stratigraphic datums such that the bottom of each zone is demarcated by the underlying Axel-Anderson coal seam whereas the Bear Canyon coal zone divides each zone near-equally into two units (lower vs. upper) (Figure 13).

5.1. Impact of large-scale heterogeneity:

Total net sand thickness of the upper unit (246 m) (i.e., overlying bear-canyon coal zone; Figure 13) is estimated to be 170% times more of that of the lower unit (146 m). This demonstrates that the upper unit is dominantly a sand-rich interval whereas the lower unit is relatively sand-poor. Manifestation of large-scale heterogeneity on the studied dataset has been analyzed through net-to-gross distribution by estimating net-to-gross ratio for channelized sandbodies in pseudowells at a uniform spacing (~ 100 m distance; Figure 14). This spacing, which corresponds to the 2.5-ac well spacing in symmetrical pattern, constitutes a very closely-spaced well layout that is denser than the latest petroleum industry practice in the tight-gas program (e.g., 8-ac spacing for the tight-gas producing Jonah field; Pasternack, 2010). We purposefully chose 100 m well spacing to illustrate potential exploration and production uncertainty at a shorter distance. Net-to-gross ratio distribution shows highest (73%), lowest (17%), mean (41%), and median (39%) values (Figure 14). Notably, there is a drastic decrease of their values at adjacent wells: 36% to 21 % (pseudowells 6-7, cliff face 1, Figure 11; Figure 14), 58% to 19%, 48% to 26% (cliff face 5; Figure 14), 46% to 25% (cliff face 7; Figure 14), 51% to 37%, and 61% to 44% (cliff face 8; Figure 14) – this emphasizes how these contrasting values can be conditioned within this shorter distance that may contribute to extraction challenges.

Laterally, there is a gradual decrease in the net-to-gross values (Figure 15A) from zone 1 (55% overall) to zone 2 (39% overall) to zone 3 (37% overall). This demonstrates 1) rapid decrease from zone 1 to 2, and 2) diminishing decrease from zone 2 to 3. Further, net-to-gross values are manifested discretely at intra-zone level that distinguishes analogous reservoir

character of each zone from the other. For zone 1, there is broadly an increasing trend from left to right for both its lower and upper units (albeit Litholog 4) (Figures 13 & 15A). However, of particular importance is the average net-to-gross value calculated for its upper unit (68%) being two times higher than the lower unit value (32%) (Figure 15A). This implies that zone 1 is distinctly compartmentalized vertically into sand-rich upper vs. sand-poor lower units. In contrast for zone 2, minimal variation among the average net-to-gross values (39%; overall), upper unit (42%), and lower unit (35%) emphasizes less vertical than lateral compartmentalization (Figure 15A). For zone 3, net-to-gross values vary laterally in a complex way, but well differentiate vertically where the upper unit has a lower value (29%) than the lower unit (46%) (Figure 15A). This demonstrates that zone 3 is also compartmentalized vertically similar to zone 1, but opposite in the context because it shows sand-poor upper vs. sand-rich lower units.

Another large-scale heterogeneity that poses production uncertainty is the width-constraint of channelized sandbodies, which affects their degree of static connectivity in regard to extraction (cf. Pranter and Sommer, 2011). Compilation of strike-oriented width values of sandbodies reveals that majority of these sandbodies (>50%; 28 out of 53; Figure 10B) have width in the range of 1-200 m. This implies that these sandbodies can be penetrated by one well, or two wells at maximum, with a 100 m well spacing. Further, for zone wise analysis, we populated near-true width of individual channelized sandbody appearing in lithologs of each zone (Figure 13) by extrapolation method described earlier. This brings varying well to sandbody interference scenarios in different zones: 1) for zone 1, 55% of the total sandbodies (total n=33) can be penetrated by one well or two wells at most, 2) well interference to

sandbody is very poor for zone 2 as majority (~ 80%) of the sandbodies (total n=24) have width below 200 m, thus can be penetrated by only one well, and 3) ~ 70 % of the sandbodies in zone 3 (total n=22) will be intersected by two wells at most.

5.2. Impact of intermediate-scale heterogeneity:

At this scale, channel and bar-accretion deposits (Table 2) most likely contribute to net pay. However, these two elements can differ in their own drainage pattern. Whereas both of them show fining-upward grain-size trends that likely result in an upward decrease in permeability, occurrence of inclined beds in bar-accretion deposits, comprising downdip coarser sandstones grading updip to finer sandstones and siltstones (Figure 5B), introduces a dipping component to permeability anisotropy within these elements. Thus, depositional-strike-oriented cliff faces (e.g., 1, 7, 8; Figure 3) that are more likely of having variable distribution of these two elements (e.g., cliff face 1; Figure 6) than depositional-dip-oriented cliff faces (e.g., cliff face 2; Figure 7) can experience greater variability in reservoir drainage.

Overbank fines (Table 2) are too fine-grained to form net pay, and are likely to act as barriers or baffles to flow between stratigraphic reservoir compartments. Lateral and vertical variation in grain size within sandstone beds of ribbon, sheet and lenticular geometry that occur within crevasse delta (Figures 5C & 9), and overbank and crevasse splays elements (Table 2) defines their internal permeability structure. Intercalated mudstones and siltstones in these elements result in much lower vertical than horizontal permeability. These elements may not contribute to net pay, but can serve as connections between principal reservoir compartments formed by channel and bar-accretion sandbodies (e.g., Shanley, 2004).

The combined proportion of channel and bar deposits replicates the decreasing trend of net-to-gross values from zone 1 to zone 3 (Figure 15A). In contrast, crevasse splay bodies show overall increasing trend of its average proportion value from zone 1 (4%) to zone 2 (5%) to zone 3 (15%) (Figure 15B). Although their proportions do not show much variation for the lower vs. upper units in zones 1 and 3, their role as connectors to major reservoir-bearing compartments can be better realized in the lower unit of zone 3. Zone 2 is characterized with the highest variance in proportion of crevasse splay bodies between its lower vs. upper units. For drainage of these crevasse splay bodies across the entire length of the studied dataset, well intersection is necessary, to which their width-constraints (Figure 10D) demonstrate an important uncertainty. Almost all crevasse splay sandbodies (~ 91%; 39 out of 43) are less than 100 m wide, implying that these sandbodies will be either penetrated by one well at most (e.g., pseudowells 2, 3, 4 and 5 penetrate crevasse splay deposits; Figure 11) or left un-intersected (e.g., crevasse delta and ~ 50% of crevasse splay deposits are not penetrated by pseudowells; Figure 11) at 100 m well spacing.

5.3. Impact of small-scale heterogeneity:

Reservoir quality can be affected fundamentally by constituent facies types because attributes of grain size, lithology, and sedimentary structure associated with individual facies exert characteristic control on reservoir flow anisotropy (e.g., Weber, 1982; Ringrose et al., 1993, Moreton et al., 2002; Shanley 2004). Thus, small-scale fluvial heterogeneity in terms of spatial facies variability can influence reservoir flow behavior. Lateral and vertical facies-diversity encountered on pseudowells and along a horizontal slice on outcrop panels (Figure 11)

demonstrates how it can potentially impose uncertainties to lateral and vertical communication of reservoir flow units. Breaks in facies continuity at a meter to sub-meter scale (Figures 11B-C) can likely exert boundary conditions to individual flow unit.

In fluvial plays, cross-stratified sandstones are known lithofacies of superior reservoir quality (e.g., Shanley, 2004), as they demonstrate higher permeability class (Moreton et al., 2002), whereas mudstones act as barriers to fluid flow (e.g., Weber, 1982). Assuming these facies are of similar petrophysical character in our dataset, their variable distribution pattern among and within zones brings potential for reservoir anisotropy development. Overall, average proportion of trough cross-stratified sandstones (Facies 1) decreases from zone 1 (55%) to zone 2 (39%) to zone 3 (37%), implying that reservoir quality is expected to decrease laterally from zone 1 to zone 3. Vertical compartmentalization is likely within individual zone – more in zones 1 and 3 than zone 2, based on the variance in vertical distribution of this facies.

Further, reservoir body is variably segregated by distribution of mudstones (Facies 4). Notably, in contrast to the lateral decreasing trend of trough cross-stratified sandstones, the average proportion of mudstones follows a variable trend laterally from zone 1 (33%) to zone 2 (46%) to zone 3 (28%) (Figure 15C). Whereas the sealing capacity of this facies is minorly affected by intercalation of Facies 2 (parallel-laminated sandstones) and Facies 3 (thinly interbedded mudstones, siltstones, and rippled sandstones) in the floodplain area of zones 1 and 2, it is distinctly punctuated in zone 3 (Figure 13). Assessment of this facies variability through distribution of shale lengths shows significant inter-zone variations (Figs. 15 D & E). From the adjusted (accounted for partial shale beds) distribution of shale length estimations (Fig. 15E), it is clear that: 1) shale lengths of smaller size (< 100 m) are predominant in zone 1

whereas of larger size (> 100 m) are more common in zones 2 and 3. This suggests that, at the 100 m well spacing, less number of shale beds will be encountered in zone 1 compared to the higher numbers for zones 2 and 3. Shale beds being encountered in fewer vs. higher well interference point to their stochastic vs. deterministic character, respectively (cf. Snedden, 2014). As such, zone 1 shows the potential of having more stochastic shale bed occurrences in contrast to zones 2 and 3. Given that stochastic vs. deterministic shale bed occurrence influences barrier styles differently (Snedden, 2014), relative distribution of shale length across three zones suggests that flow anisotropy is expected to vary across zones.

6. Comparison with subsurface tight-gas reservoirs in the western Rocky

Mountain basins

Insights from study results are applicable for improved exploration and production strategy of fluvial reservoirs in general. Specifically, their application as a tight-gas reservoir analog is relevant on two merits: 1) study area is located adjacent to the broader west Rocky Mountain basins that host numerous and significant producing fluvial tight-gas reservoirs, and 2) study results provide a range of analogies to the subsurface characteristics of these producing reservoirs, as discussed below. Notably, while there are other factors (e.g., diagenesis, fracture orientation etc.) that have compelling effect on tight-gas reservoir heterogeneities (e.g., Laubach and Gale, 2006; Tobin et al., 2010), this study demonstrates how stratigraphic variabilities alone can influence fluvial tight-gas reservoir characteristics, as also attempted in other studies (e.g., White et al., 2008; Pranter and Sommer, 2011; Kukulski et al., 2013).

Distinct segregation of sand-rich vs. sand-poor interval (i.e., upper vs. lower unit demarcated with two coal zones) shown in our study is analogous to the similar type of sand-interval characterization with respect to coal datums for the Mamm Creek field, Piceance Basin, Colorado (Cole and Cumella, 2005). Little well-to-well communication between fluvial sandbodies is encountered in interference tests in the Rulison field, Piceance Basin even at a well spacing of 280 m (Shanley, 2004), implying that sandbody width is mostly < 280 m. As shown in Figure 10B, ~ 70% of the estimated sandbody width in our study matches to this width-constraint of sandbodies for the Rulison field. For the giant Greater Natural Buttes field in the Uinta Basin of Utah, analogies include: 1) reservoir-bearing sandbodies of the field are channel and bar deposits (cf. architectural elements A and B; Table 2) (e.g., Longman and Koepsell, 2005; White et al., 2008), 2) ~ 90% of the channel sandbody thickness in our dataset (Figure 10A) fits well within the thickness range (~ 0.1-10 m) of the producing Mesaverde fluvial sandbodies therein (Stancel et al., 2008).

Our study results are particularly analogous to the Lance Formation reservoir of the Jonah field, Green River Basin, Wyoming, which is the largest fluvial tight-gas reservoir in the onshore USA (Robinson and Shanley, 2004). The Jonah field reservoir has a low to moderate net-to-gross overallly (10-35% to 40%; Cluff and Cluff, 2004; Shanley, 2004). Nearly all net-to-gross values (80% of total estimation) of our dataset demonstrate a similar range (17-46%; Figure 16A). Single-storey channel sandbody thickness of the Jonah field is ~ 3-5 m (Shanley, 2004), which matches to 3-7 m thickness range shown by two-third of single-storeyed sandbodies of our dataset (Figure 16B). A broadly positive correlation has been achieved between the width range of Jonah-Pinedale channel sandbodies having 2.5-5 m thickness

(Shanley, 2004) and channel sandbodies of our dataset (Figure 16C). Particularly, this relationship is more apparent in 30-100% range.

Regarding reservoir quality assessment analysis, net pay in the Jonah field reservoir is dominated by trough cross-stratified sandstones (cf. Facies 1; Table 1) (Shanley, 2004) that occur in sinuous-channel and point-bar sandbodies (cf. architectural elements A and B; Table 2) (Dubois et al., 2004). Crevasse splay sandbodies in this field provide reservoir connectivity, enhancing reservoir drainage (Shanley, 2004); similar splay sandbodies (architectural elements D and E; Table 2) constitute a significant component of our dataset. Based on these analogies, our outcrop data (Figures 6, 7, 11) may provide insights to inter-well architecture of the Jonah field that cannot be achieved from seismic, core, and well-log data. Inter-well connectivity of sandbodies is a major uncertainty in this field where individual sandbodies are hardly correlatable, even for a well spacing of 91 m (House and Shemeta, 2008). We illustrate this uncertainty in our outcrop panels by positioning pseudowells at 91 m spacing in Figure 11. From the total population ($n=39$; 100%) of channelized sandbodies, a few ($n=2$; 5%) remain un-intersected, and several are penetrated by one pseudowell ($n=8$; 21%) or two adjacent pseudowells ($n=6$; 15%). Similarly, other fine-grained sandbody types like crevasse deposits (one crevasse delta and 24 crevasse splays in Figure 11) show very limited well-penetration or are not intersected at all.

7. Towards development of predictivity for improved exploration and production strategy in the western Rocky Mountain basins

The western Rocky Mountain basins have significant resource potential, and are experiencing accelerated upstream activities for production growth (Fletcher, 2005; Nehring, 2008) despite major appraisal and extraction challenges. Especially, places like the western Wasatch Plateau (an immature tight-gas basin, *sensu* Meckel and Thomasson, 2008) can experience future exploration and production activity. Given these, it is important to develop predictive tools that can aid for improved risk analysis. Here, we provide some new predictivities that are drawn upon mainly from our study results and calibrated to outcrop and/or producing field data of this region. We expect refinement of these predictivities in future works.

Single-storeyed sandbodies in the Jonah field with thickness of 3-5 m are hardly correlatable at ~ 100 m well spacing (Shanley, 2004; House and Shemeta, 2008). This is broadly conformable when we apply our sandbody aspect ratio ($W/T = 35$) such that a sandbody thickness of ≤ 5 m generates < 200 m width that falls short of two well penetration at 100 m well spacing. We propose that single-storey sandbody thickness of 5 m may be a threshold value for 100 m well-intersection. Using our aspect ratio (35) or other computed from outcrop data of the Piceance Basin (45; Pranter et al., 2009), a single-storey sandbody with thickness of > 5 m can have a width of > 200 m, and thus experience two well penetration at 100 m well spacing. Additionally, this range of aspect ratio (35-45) can be a predictive tool for probabilistic estimation of sandbody width. Sandbody width evaluation is a key assessment for optimization

of well layout, for which evaluation of water content of sandbody can also be important (e.g., Hood and Yurewicz, 2008).

Another observation from our study results that might render as a predictive tool is the positive relationship between sandbody amalgamation and underlying coal thickness (section 4.3; Figure 6). Coal-bearing successions of the Blackhawk and Williams Fork Formations are major stratigraphic units in the western Rocky Mountain basins that, as part of the Mesaverde Total Petroleum System, are associated with reservoir development (Johnson and Roberts, 2003). Thus, this prediction of sandbody amalgamation using underlying coal thickness data can be useful for the region. However, this has been neither evaluated in stratigraphic studies of the Rocky Mountain basins until now nor explored in reservoir appraisal analysis of this region.

8. Fracture analysis

Natural fractures, if present, influence reservoir drainage pattern, particularly for tight-gas reservoirs (e.g., Laubach and Gale, 2006; Olson et al., 2009). Outcrop data with good quality and sufficient length can aid in fracture analysis efficiently (e.g., Bisdom et al., 2014). Our outcrop dataset has the potential for delineating fracture patterns for analogous fluvial tight-gas reservoirs. As an example, here we present a fracture system analysis performed on one cliff-face (Fig. 17A). This documentation reveals several trends of fracture attributes: 1) the cliff-face nests different sizes of fracture heights (0-50 m length-scales) and shows that the fracture network is non-uniformly distributed (i.e., left-half contains more fractures than the right-half of the cliff-face; Fig. 17B), 2) the class distribution of fractures are different in left- versus right-

halves (larger fractures are more in the left-half; Fig. 17C), and 3) statistical parameters (mean, median, stdev) obtained for the left-half fractures are twice of those of the right-half fractures. These differences are likely due to the fact that left-half has more amalgamated sandbodies than the right-half. The demonstrated variations in fracture dimension and distribution across the cliff-face can be an important factor for reservoir flow variability and depletion. However, a detailed documentation of fracture systems at the length-scale of our entire dataset, their pattern analysis with respect to distinctive environments (channelized vs. unchannelized depositional environments), and their interaction with both syndepositional and post-depositional (i.e., diagenesis) influences are beyond the focus and limit of this paper.

9. Conclusions

Field-validation and calibration of the entire range of fluvial heterogeneities have been constrained on a single outcrop dataset that are hard to capture from subsurface reservoir data (i.e., seismic, well-log, and core). These heterogeneities have been characterized at various length-scales: 1) large-scale (10's of m vertically and 100's of m laterally) is constrained by geometry and spatial distribution of channelized fluvial sandbodies encased within coastal-plain mudstones, 2) intermediate-scale (1's of m vertically and 10's of m laterally) is demonstrated by spatial distribution of five architectural elements (channel; bar-accretion macroform; overbank fines; crevasse delta; and overbank and crevasse splays), and 3) small-scale (10's of cm vertically and 1's of m laterally) is defined by diversity and organization of six facies (trough

cross-stratified sandstones; parallel-laminated sandstones; thinly interbedded mudstones, and rippled sandstones; mudstones; carbonaceous mudstones; and coal).

Sedimentologic and stratigraphic details reveal how these heterogeneities can bring reservoir anisotropy ranging from net-to-gross distribution to drainage pattern to reservoir-quality segregation. Improved analysis by dividing this reservoir-scale dataset into three zones (of ~ 2 km lateral-extent each) captures intriguing trends at both intra- and inter-zone level. This has resulted in a range of stratigraphic compartmentalization potential, like: distinct compartmentalization of net sand either vertically (zone 1 and 3) or laterally (zone 2); abundance of crevasse splay sandbodies either vertically segmenting reservoir (zone 2) or rendering communication between reservoir units (lower part of zone 3); barrier styles of mudstone facies in terms of stochastic (zone 1) vs. deterministic (zones 2 and 3) shale length distribution. In sum, these trends of stratigraphic compartmentalization potential are hard to correlate laterally or vertically across the field-scale outcrop window, thereby demonstrating a greater challenge to reservoir-scale extrapolation.

This outcrop study provides a range of analogies to the producing fluvial tight-gas reservoirs of the hydrocarbon-prolific western Rocky Mountain basins, USA. Our results calibrated with other outcrop and/or producing field data of the region were used to develop potential predictive tools: 1) individual sandbody thickness of ≤ 5 m as a threshold for intersection by only one well at 100 m well spacing, 2) a range of aspect ratio (35-45) in performing probabilistic sandbody width estimation, and 3) coal thickness as a predictor to overlying sandbody amalgamation: thicker the coal higher the sandbody amalgamation.

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Table 1. Facies scheme of the lower Blackhawk Formation in the Cottonwood Creek outcrops.

Facies	Lithofacies description	Figure	Depositional Process
Facies 1: trough cross-stratified sandstones	Medium-grained; trough cross-stratification with 10-50 cm set thickness; subordinate ripple cross-lamination towards top part when grain size grades to fine to very fine sand; erosional bases with rip-up clasts; scattered mud-clasts throughout; soft-sediment deformation (i.e., convolute bedding up to ~ 2 m) with outsized clasts (up to ~ 10 cm) at some locations.	4A & B	Migration of sandy dunes and ripples in response to unidirectional flow.
Facies 2: parallel-laminated sandstones	Parallel-laminated, fine-grained sandstones; bed thickness of 0.1-1 m; commonly intercalated within mudstones and siltstones (Facies 4).	4C	Deposition under upper flow-regime conditions during high-stage flooding events in nearby channels.
Facies 3: thinly interbedded mudstones, siltstones and rippled sandstones	Interbedded mudstones, siltstones and very fine- to fine-grained, rippled sandstones; subordinate parallel lamination in sandstones.	4D	Episodic fluctuations in flow velocity and sand supply.
Facies 4: mudstones and siltstones	Mudstones to sandy siltstones; dirty-white to light-gray color; massive to fissile.	4E	Suspension settling in floodplains during waning flooding stage.
Facies 5: carbonaceous mudstones	Organic-rich mudstones with leaf impressions and plant debris; root-penetrated (root height up to ~20 cm) at some locations; intertonguing with coal (Facies 6).	4E	Vegetated muddy environment; high organic content indicates poorly oxygenated environment; root-penetration indicates plant colonization on floodplain.
Facies 6: coal	Coal seams (~1-2 m thick, traceable for ~ 0.5 km laterally), intertonguing with carbonaceous mudstones (Facies 5); <i>Teredolites</i> burrows at some locations.	4F	Peat preservation in coastal-plain environments; episodic marine influence indicated by <i>Teredolites</i> burrows.

Table 2. Architectural elements of the lower Blackhawk Formation in the Cottonwood Creek outcrops.

Architectural elements	Description	Figure	Dominant facies assemblage
A: Channel	Lens or sheet geometry; concave-up, erosional basal surface with rip-up clasts indicating thalweg scouring and filling; fining-upward succession with gradational top; dominated by trough cross-stratification with ~ 10-50 cm set thickness with minor ripple-scale cross-lamination; localized, scattered mud-clasts throughout channel bodies.	5A	Facies 1
B: Bar-accretion macroform	Wedge or sheet geometry; distinct development of lateral accretion surfaces dipping ~ 6-11°, mostly oblique or nearly perpendicular to mean paleocurrent direction; dominated by dune-scale cross-stratification with minor ripple-scale cross-lamination; incremental and persistent bar growth on inner bank of sinuous channel produced laterally extensive sandstone sheet.	5B	Facies 1
C: Overbank fines	Thin to thick blanket geometry; fine-grained deposition on floodplain during flooding events and commonly intercalated with thin sandstone beds (architectural element E); contains carbonaceous shale and coal at specific horizons where peat was accumulated and preserved on floodplain.	5A	Facies 3-6
D: Crevasse delta	Heterolithic coarsening-upward unit (~7 m thick, ~50 m wide) developed as a delta lobe due to progradation of successive crevasse splays on to floodplain during high energy flooding events; individual beds form clinoforms (dip <10°) in which grain size decreases with increasing distance from channel.	5C	Facies 2-3
E: Overbank and Crevasse splays	Isolated, thin (0.1-1 m thick), ribbon to sheet (10s-100s m lateral extent), nearly horizontal sandstone beds or thicker (0.7-3.9 m), lenticular (2-65 m) sandstone beds deposited on floodplain during high-stage flow events; commonly interbedded with overbank fines (architectural element C).	5D	Facies 2-3

Figure 1. A) Late Cretaceous paleogeography of the study area (modified after Gani and Bhattacharya, 2007). B) Location of the study area in the Wasatch Plateau, central Utah. The Upper Cretaceous Blackhawk Formation, Mesaverde Group, crops out in the study area (modified from Johnson and Roberts, 2003; Hampson, 2010). The study area is adjacent to the greater western Rocky Mountain Basins that constitute one of the key areas of current US tight-gas production (Nehring, 2008).

Figure 2. A) Stratigraphic succession of the Cretaceous and Tertiary sedimentary rocks in the Wasatch Plateau (modified from Henry and Finn, 2003). B) Lithostratigraphic summary chart of the Blackhawk Formation and surrounding strata in the Wasatch Plateau and northwestern Book Cliffs (from Hampson et al., 2011). The study area lies in the northern Wasatch Plateau (central column). The Blackhawk Formation comprises coastal-plain to alluvial-plain deposits in the study area. The Blackhawk Formation and similar deposits are part of the Mesaverde Total Petroleum System in the Uinta-Piceance province (Figure 1).

Figure 3. A) Studied outcrop dataset comprising eight contiguous, and vertical cliff faces (1-8) (from Google earth). B) Map view of cliff faces (2316 m contour line is shown for reference). Lithologs (1-11) have been constructed for vertical description of the Blackhawk Formation. The line AB has been used as a projection plane for all lithologs for along-strike correlation used in Figure 14. C) Paleocurrent rose diagram for dune and ripple cross-strata of the studied outcrop showing an overall northeast paleoflow direction.

Figure 4. Representative photos of facies in the lower Blackhawk Formation at Cottonwood Creek (Table 1). A, B) Facies 1: trough cross-stratified sandstones (A) with subordinate current-ripple cross-lamination (B). C) Facies 2: parallel-laminated sandstone. D) Facies 3: heterolithic deposit comprising thinly interbedded mudstones, siltstones and rippled sandstones. E) Facies 4 (mudstones and siltstones) and Facies 5 (carbonaceous mudstones). F) Facies 6: Coal seam showing highly compacted and pygmatically folded burrow. Scale bar is 5 cm long. A high

compaction factor (at least 10) was calculated for coal-precursor peat by restoring the burrow to its original shape, which was assumed to be gently sinusoidal.

Figure 5. Representative photos of architectural elements in the lower Blackhawk Formation at Cottonwood Creek (Table 2). A) Channel element (architectural element A) encased within overbank fines, and overbank and crevasse splays (architectural elements C and E, respectively). B) Bar-accretion macroform (architectural element B) with distinct development of inclined lateral accretion-strata, which shows individual beds are amalgamated and coarser-grained downdip that gradually transitions updip to finer sandstones and siltstones. This is a product of helical turn of the paleochannel flow at the meander loop. C) Crevasse delta (architectural element D) developed as prograding clinoformal package (dipping to the right) underlain and overlain by overbank fines (architectural element C). D) Overbank and crevasse splays (architectural element E) developed as package of stacked, thin, parallel-laminated sandstone beds encased in overbank fines (architectural element C).

Figure 6. A) Photomosaic of cliff-face 1 (location shown in Figure 3), which is oriented along depositional-strike (i.e. perpendicular to paleoflow). B, C) Line drawings of interpreted facies distributions (B) and architectural elements (C) of this photomosaic that demonstrates decreases in net-to-gross ratio and channel-sandbody amalgamation from left (south) to right (north). Marked measured sections (Lithologs 1 and 2) provide vertical facies descriptions for the contrasting sandbody stacking patterns in two locations along the cliff face. A coal seam near the base of the panel thins from left (1.8 m) to right (1 m).

Figure 7. A) Photomosaic of cliff-face 2 (location shown in Figure 3), which is oriented along depositional-dip (i.e. parallel to paleoflow). B, C) Line drawings of interpreted facies distributions (B) and architectural elements of this photomosaic (C). Note increase in channel-sandbody amalgamation towards the right (east), at the junction with strike-oriented panel (Figure 6). For legend, see Figure 6.

Figure 8. A) Photomosaic of cliff-face 6 (Figure 3), which comprises both depositional-dip- and – strike-oriented segments. B, C) Line drawings of interpreted facies distributions (B) and architectural elements of this photomosaic (C). For legend, see Figure 6.

Figure 9. Photo of crevasse delta (architectural element D) containing distinct clinoforms, erosionally truncated by an overlying channelized sandbody. The delta is represented by a heterolithic, coarsening-upward succession in measured sections 1 and 2 that laterally transitions to overbank fines (architectural element C) in measured section 3. The photo is located in Figure 6A.

Figure 10. Frequency histograms for the dimensions of channelized fluvial sandbodies (composed of architectural elements A and B; Table 2) and crevasse splay sandbodies (architectural element E; Table 2) as measured from outcrop data (Figure 3): A) thickness and B) apparent width of preserved channelized sandbodies; C) thickness and D) apparent width of crevasse splay sandbodies. Many channelized sandbodies are truncated by erosion at their tops, resulting in a decrease in their preserved thickness (Figure 9).

Figure 11. A) Position of pseudowells (numbered 1 to 7) in both the strike-oriented (Figure 6A) and dip-oriented (Figure 7A) outcrop panels, and a hypothetical horizontal slice dissecting these two panels. Inter-well spacing was set to 91 m to match that in the tight-gas producing Jonah field, Wyoming, USA. An approximate net-to-gross ratio has been calculated for each pseudowell. B) Spatial distribution of facies (Table 1) on horizontal slice, and C) in vertical pseudowells. D) Cumulative proportion of facies in vertical pseudowells.

Figure 12. Relative proportions of A) facies (Table 1), B) architectural elements (Table 2), and C) facies proportions within overbank fines (architectural element C), in depositional-dip-oriented cliff face 2 (Figure 7) (left), and -strike-oriented cliff face 1 (Figure 6) (right).

Figure 13. Along depositional-strike correlation panel of the study area (for location, see Figure 3). Lithologs (1-11) have been correlated using two stratigraphic datums: Axel Anderson Coal zone, and Bear Canyon Coal zone. Three zones (1-3) with similar lateral extent have been defined for comparative analysis. Solid line (red color) for individual single-storey sandbody in each litholog approximates the width of respective sandbody laterally. For legend, see Figure 6.

Figure 14. A) Net-to-gross map of the study area. Black circles represent locations of pseudowells that were positioned at a ~ 100 m well spacing. B) Quantification of net-to-gross ratio of pseudowells on cliff faces (1-8) along both dip- and strike-orientation.

Figure 15. Comparative analysis of three zones of Figure 13. A) Spatial variability of net-to-gross ratio. B) Spatial variability of crevasse splay sandbody frequency. C) Spatial variability of mudstones and siltstones frequency (Facies 4; Table 1; Figure 4). D & E) Length-scale analysis of shale beds on strike-oriented sections of different zones (cliff-face 1 for zone 1, strike-segment of cliff-face 4 for zone 2, and strike-segment of cliff-face 7 for zone 3; for their locations, see Figure 3). Complete shale (i.e., both side terminations of a shale bed are observed within the outcrop limit) lengths are shown in D that does not account for partial lengths. In E, a less-biased, adjusted (for partial lengths) length distributions of shale are shown using procedures of Geehan and Underwood (1993).

Figure 16. Comparative analysis of study results with tight-gas producing Jonah field of Wyoming, USA. Data of Jonah field have been adopted from Cluff and Cluff (2004) and Shanley (2004). A) Overall net-to-gross distribution, B) single-storey channel sandbody thickness, and C) single-storey channel sandbody width. Overall, these comparisons demonstrate a good correspondence.

Figure 17. A) Fracture traces (red lines) of different heights on cliff-face 1 (for location, see Figure 3). Major bed boundaries (channel bases) are drawn as yellow lines. B) Class distribution

of fracture heights, and proportion of fractures on two halves of the cliff face. C) Comparative analysis of fracture distribution on left vs. right halves of the cliff face.

A)

Age		Picks (Ma)	Stratigraphic units
Tertiary (Part)	Eocene (Part)		Green River Formation
			Colton Formation
		55.0	Flagstaff Limestone
			North Horn Formation
Late Cretaceous	Paleocene	65.5	Price River Formation
		71.3	Castlegate Sandstone
	Campanian		Blackhawk Formation
			Star Point Sandstone
		83.5	Blue Gate Member (Upper)
			Emery Sandstone Member
	Coniacian	85.8	Blue Gate Member (Lower)
		89.0	Ferron Sandstone Member
	Turonian		Tununk Member
		93.5	Dakota Sandstone
	Cenomanian		

B)

A Sedimentological facies:

Dip-section

Strike-section

B Architectural elements:

Dip-section

Strike-section

C Facies variation within architectural element:

Overbank fines on dip-section

Overbank fines on strike-section

B	Estimated net-to-gross ratio (%) on pseudowells (and lithology)		
	Cliff faces	dip-segment	strike-segment
	Cliff face 1		57, 39, 43, 36, 21
	Cliff face 2	39, 58	
	Cliff face 3	56, 61, 71, 72, 73, 71, 63, 66, 54, 62	
	Cliff face 4	35, 33, 32, 33, 39, 24, 26, 41, 33	
	Cliff face 5	27, 22, 58, 19, 18, 48, 26	25, 17, 24, 32, 24
	Cliff face 6	40, 36, 40, 35	33, 39, 35, 31, 28, 34
	Cliff face 7	36, 37, 42, 31, 38	46, 44, 46, 43, 39, 36, 30, 46, 25
	Cliff face 8	56	51, 37, 43, 59, 49, 61, 44, 49

A**Overall net-to-gross distribution** **B****Single-storey channel sandbody thickness** **C****Single-storey channel sandbody width**

- Entire range of fluvial heterogeneities constrained on a single outcrop dataset.
- Stratigraphic compartmentalization documented in varied patterns and scales.
- Outcrop analog for conventional fluvial reservoirs in general.
- Outcrop analog for fluvial tight-gas reservoirs in specific.
- Insightful for improved upstream practices in western Rocky Mountain basins, USA.