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Research paper

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

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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 the 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

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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 a wider range of stratigraphic compartmentalization potential than that 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 illustrates 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 the Cottonwood Creek in the Wasatch Plateau, central Utah (Fig. 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 (Fig. 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 (Fig. 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 the Cottonwood Creek, eastern Wasatch Plateau, Utah (Fig. 3). In combination, these cliff faces crop out a series of depositional-dip and -strike oriented segments with high quality and scales (Fig. 3). Depositional dip vs. strike orientations were interpreted from paleocurrent analysis (Fig. 3C). The investigated interval is ~100 m thick, and crops out for ~4 km in depositional-dip