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FLUVIAL ARCHITECTURE OF THE BURRO CANYON FORMATION USING  
UAV-BASED PHOTOGRAMMETRY AND OUTCROP-BASED MODELING:  
IMPLICATIONS FOR RESERVOIR PERFORMANCE, RATTLESNAKE CANYON,  
SOUTHWESTERN PICEANCE BASIN, COLORADO

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A THESIS APPROVED FOR THE  
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BY

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This thesis is dedicated to the friends and family who encouraged me throughout the last two years. Especially to my parents for their love, support and guidance, to Justin for his friendship and help with the field work, and Ryan for his love and ability to always brighten my day.

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## **Abstract**

The stratigraphic variability of fluvial architectural elements and their internal lithological and petrophysical heterogeneity influence static connectivity and fluid flow. To explore the impact of fluvial architecture and facies heterogeneity on reservoir performance, well-exposed outcrops of the Cretaceous Burro Canyon Formation in Rattlesnake Canyon, Colorado, are evaluated. Analysis of the sedimentology and channel architecture of the Burro Canyon Formation provides insights into the low net-to-gross ratio, sandy, braided-fluvial style. The Burro Canyon Formation represents a South Saskatchewan type, perennial, braided fluvial system. A single depositional sequence is present in Rattlesnake Canyon containing a series of stacked amalgamated and semi-amalgamated channel complexes, composed of four architectural elements: amalgamated channel complexes, amalgamated fluvial-bar deposits, isolated fluvial-bar deposits, and floodplain fines.

Stratigraphic measured sections, outcrop gamma-ray measurements, and UAV-based (Unmanned Aerial Vehicle-based) photogrammetry are used to constrain two-dimensional (2-D) and three-dimensional (3-D) static reservoir models of the fluvial deposits. Resulting breakthrough times (BTT) and sweep efficiency suggest subsurface performance is most effective perpendicular to paleoflow direction in amalgamated channel sequences. Perpendicular to paleoflow, BTT occurs 9% faster than parallel to the paleoflow and sweep efficiency is, on average, 16% greater. Sweep efficiency and BTT are greater perpendicular to paleoflow due to greater sandstone connectivity in this orientation. Variability of preserved channels and lateral pitchouts results in lower recovery efficiency. Reservoir heterogeneity can account for 50% variation in BTT and

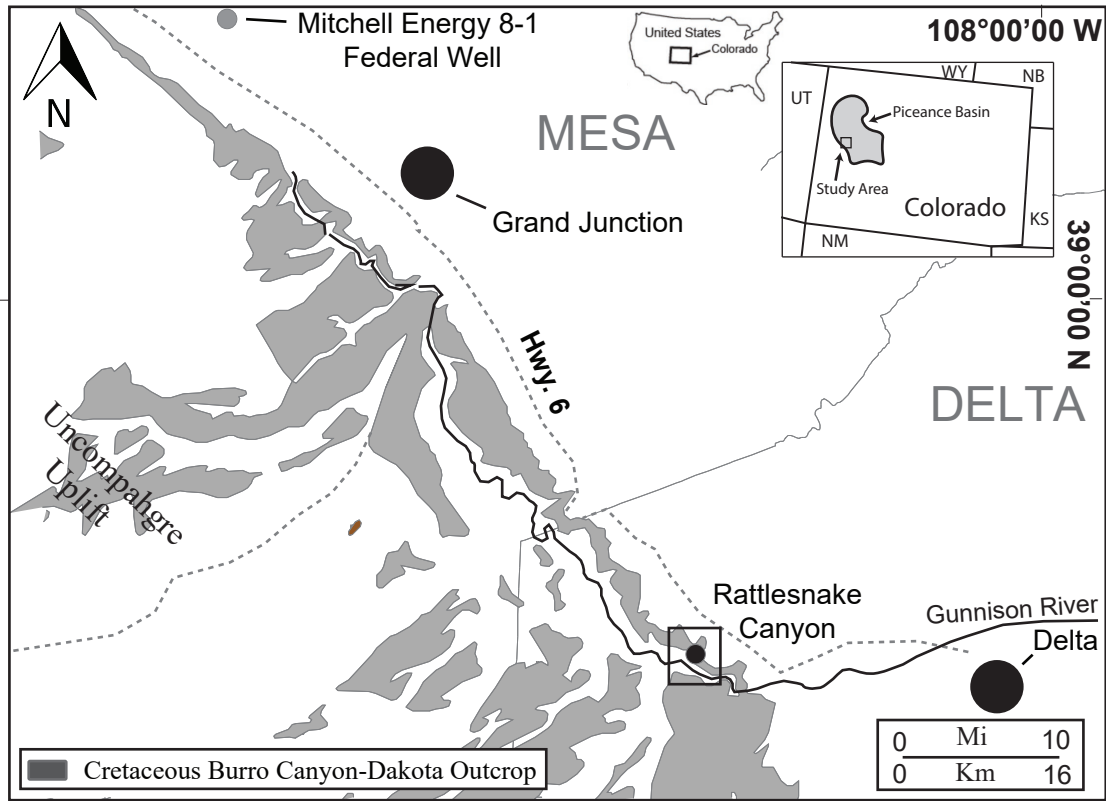
lower recovery efficiency by 5% through low petrophysical zones that trap fluids.

Cemented conglomeratic facies decrease recovery efficiency by 15%, but increase sweep efficiency and BTT by 28% and 32%, respectively, creating fluid-flow barriers as conglomeratic facies fill basal scours in the Burro Canyon Formation.

## **Introduction**

The stratigraphic variability of fluvial deposits and their internal lithofacies and petrophysical heterogeneity influence petroleum reservoir connectivity and fluid flow. At the reservoir scale, architectural elements and their stacking patterns create large-scale heterogeneity that influences reservoir productivity (Pranter et al., 2007, 2009; Villamizar et al., 2015). Smaller scale features such as lithofacies associations and their associated reservoir properties create internal heterogeneity within fluvial architectural elements that can also impact fluid-flow and reservoir performance (Pranter et al., 2007; Patterson et al., 2012; Massart et al., 2016). Understanding the impact of the different scales of sedimentological heterogeneity on fluvial reservoir performance (e.g., sweep efficiency, recovery efficiency, breakthrough time of injected fluids at producing wells) is useful when characterizing and developing numerical models for these types of subsurface reservoirs. To further explore how these types of larger and smaller scale sedimentological heterogeneities impact fluvial reservoir performance, well-exposed fluvial outcrop analogs of the Lower Cretaceous Burro Canyon Formation in Colorado are used as an example.

The Lower Cretaceous Burro Canyon Formation is exposed in numerous canyons along the Gunnison River in the southwestern Piceance Basin, northwestern Colorado (Figure 1), and forms sandstone petroleum reservoirs within the basin (Young, 1975). The Burro Canyon Formation represents braided to meandering river deposits that formed in a coastal-plain setting (Kirkland et al., 1999; Kirkland and Madsen, 2007; Currie et al., 2008; McPherson et al., 2008; Ludvigson et al., 2010; Cole,

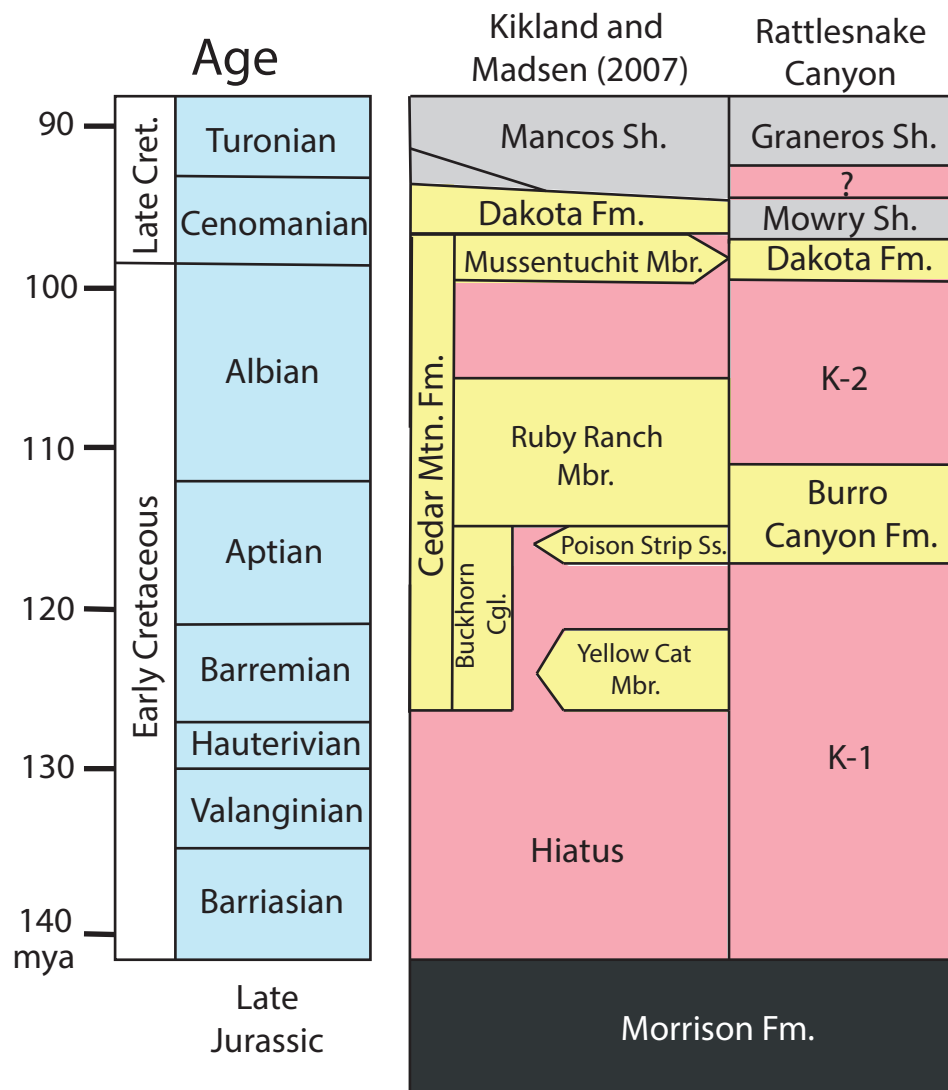


**Figure 1.** The Rattlesnake Canyon study area is located in the Cretaceous Burro Canyon - Dakota outcrops in the southwest portion of the Piceance Basin, between Grand Junction and Delta, Colorado. Proximal location of the Mitchell Energy Federal 8-1 well to Rattlesnake Canyon can be observed to the northwest of the canyon. Porosity and permeability data have been derived from cored intervals of the Burro Canyon Formation in this well.

2017). Outcrop-based studies, including Stokes (1952), Kirkland et al. (1999), Kirkland and Madsen (2007), Currie et al. (2008), and Cole (2017) document various aspects of the sedimentology, channel-complex architecture, and environment of deposition of the Burro Canyon Formation and its lateral equivalent in eastern Utah, the Cedar Mountain Formation, throughout the southwestern Piceance and eastern Uinta basins.

Using non-marine microfossils, plants and mollusks, Stokes (1952) described the stratigraphy and constrained the age of the Burro Canyon Formation at its type locality in San Miguel County, Colorado, and classified the environment of deposition through multiple outcrops in western Colorado and southeastern Utah. The Burro Canyon Formation unconformably overlies the Upper Jurassic Morrison Formation and is unconformably overlain by the Cretaceous Dakota Formation (Young, 1975) (Figure 2). The base of the Burro Canyon Formation contains freshwater gastroliths including ganoid fish scales, fresh-water ostracods, and plant fragments, indicating freshwater fluvial deposits. The calcareous mudstones of the Burro Canyon Formation are lacustrine or paludal in origin as demonstrated by the presence of *Metacypris angularis*, *Cypridea* cf. *C. brevicornis*, and *Clavator harissa* (Stokes, 1952).

Using regional stratigraphic well-log cross sections, McPherson (2008) subdivided the laterally equivalent Cedar Mountain Formation in the Uinta Basin into two submembers; the Buckhorn Conglomerate Member and the Upper Shale Member. The Buckhorn Conglomerate Member is a clast supported pebble to cobble conglomerate with medium- to very-coarse grained sandstone matrix and exhibits an overall upward-fining trend in grain size. The Upper Shale Member includes discontinuous fluvial sandstones, calcareous floodplain mudstones, and characteristic



**Figure 2.** Early Cretaceous stratigraphy in the Piceance and Uinta Basins, showing comparison with Cedar Mountain Formation nomenclature. Within the study area, the Burro Canyon Formation is bounded by the K-1 and K-2 regional unconformities. Late Cretaceous Dakota Formation unconformably overlies the Burro Canyon Formation and Late Jurassic Morrison Formation unconformably underlies it. Modified from Cole, 2017.

thin micritic limestones. Kirkland and Madsen (2007) noted distinguishing features of the Cedar Mountain Formation include abundant carbonate nodules commonly with a basal thick black paleosol, polished chert pebbles identified as gastroliths, and the absence of dinosaur bones. McPherson et al. (2008) classified the Cedar Mountain Formation as gravelly, sandy braided and low-sinuosity fluvial deposits.

Cole (2017) evaluated the lithofacies of the Burro Canyon Formation from numerous outcrops including those in Whitewater, Escalante, and Old Canyon Trail canyons in the southwestern Piceance Basin. Cole (2017) noted that the formation primarily consists of three lithofacies: 1) fine- to coarse-grained sandstone and conglomerate, 2) sandy granule-pebble conglomerate, and 3) green calcareous mudrock. The sandstone and conglomeratic lithofacies are concentrated in the lower sandstone-rich half of the Burro Canyon Formation, and the upper half of the formation has a higher percentage of mudrock with isolated to amalgamated sandstones.

This study further establishes the depositional environment and stratigraphic architecture of the Burro Canyon Formation. The significance of the stratigraphic architecture and the different scales of fluvial sedimentological heterogeneity on reservoir performance are explored using the well-exposed outcrop analogs of the Burro Canyon Formation in Rattlesnake Canyon, Colorado. Related to the Burro Canyon Formation, this study addresses the following questions: (1) What is the sedimentology and stratigraphic hierarchy and how does this relate to the environment of deposition? (2) What are the types, geometries, and percentages of architectural elements and how do they vary stratigraphically? and (3) What is the impact of the different scales of fluvial sedimentological heterogeneity on reservoir performance in terms of sweep

efficiency (SE), recovery efficiency (RE), and breakthrough time (BTT) of injected fluids at producing wells?

Stratigraphic measured sections, core data, and unmanned-aerial-vehicle (UAV) photogrammetry are used to characterize and map the stratigraphy and sedimentology of the Burro Canyon Formation for selected outcrop windows. The outcrop imagery and measurements are used to create digital-outcrop models and high-resolution two-dimensional (2-D) and three-dimensional (3-D) outcrop reservoir models that represent the Burro Canyon stratigraphy, lithofacies architecture, and petrophysical properties. Results of dynamic fluid-flow simulations (black oil and water) for multiple scenarios illustrate the impact of the different scales of fluvial heterogeneity on reservoir performance.

### **Tectonic and Stratigraphic Setting**

The Piceance Basin is in northwestern Colorado (Figure 1). It is a northwest-southeast-trending basin that is bounded by the Douglas Creek arch to the west, Axial arch and Uinta Mountains to the north, the White River uplift and Grand Hogback to the east and Elk Mountains and Sawatch, Gunnison, and Uncompahgre uplifts to the south (Collins, 1970; Johnson, 1989). The Piceance Basin is asymmetrical with gently dipping western and southwestern flanks and a steepened eastern ( $>60^\circ$ ) flank.

The Piceance Basin resides in an area once occupied by a much larger Rocky Mountain Foreland Basin formed by the Sevier Orogeny (c. 140-50 Ma) (Johnson and Flores, 2003). Early Cretaceous clastic sediments deposited in the Rocky Mountain Foreland Basin were transported from the Sevier fold-thrust belt to the east and northeast and deposited in the distal portion of the basin (Johnson, 1989; Van Wagoner



et al., 1990; DeCelles, 2004). Deposition of the clastic sediments took place in a series of pulses due to orogenic movements from Aptian to Albian times. During the Aptian, braided to meandering rivers formed, transporting sediment to the southwestern portion of the basin. Fluvial deposition was followed by an erosional period due to lack of orogenic pulses. Entering the Albian, renewed orogenic activity and down-warping of the basin created an influx of clastic sediments into the basin. Simultaneously a shallow sea began to form, growing from the southwest to the northeast, changing the depositional style from fluvial to shallow marine (Young, 1975). In the Maastrichtian, the Laramide Orogeny caused structural deformation and formation of the modern day Piceance Basin (DeCelles, 2004).

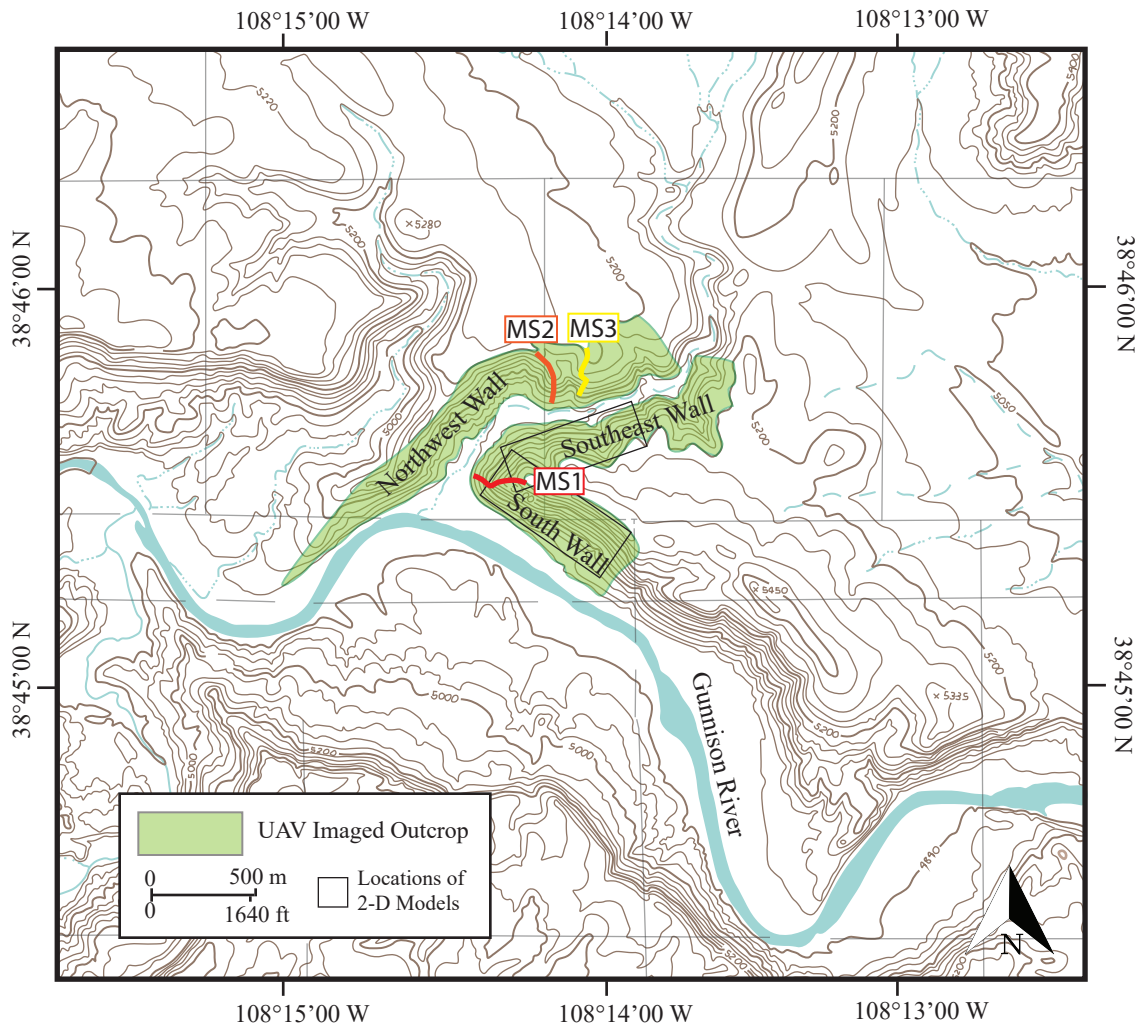
The Lower Cretaceous (Aptian-Albian) Burro Canyon Formation ranges from 0–130 ft (0–40 m) thick along the Utah-Colorado border west of Grand Junction, Colorado (Cole, 2017). The Burro Canyon Formation unconformably overlies the Jurassic Morrison Formation and is unconformably overlain by the Dakota Formation (Figure 2) (Young, 1970). Interbedded within the Burro Canyon Formation are conglomerates, sandstones, and mudstones with occasional limestones and cherts (Stokes, 1948).

Within Rattlesnake Canyon, the Burro Canyon Formation contains four lithofacies: (1) a fine- to medium-grained pebble conglomerate, (2) medium- to fine-grained trough cross-bedded sandstone, (2) fine-grained planar laminated sandstone, and (4) green calcareous mudrock. The sandstones and conglomerates of the Burro Canyon Formation have been interpreted as low-sinuosity braided-river deposits within incised valleys, and the mudstones are interpreted as alluvial floodplain deposits (Young, 1975; Cole, 2017).

## **Methodology**

### **Conventional Field and Lab Methods**

Well-exposed outcrops of the Burro Canyon Formation were analyzed for lithology, grain-size distributions, sedimentary structures, bounding surfaces, and deposit width, thickness, and orientation. Two methods were used to measure, describe, and map the characteristics and dimensions of the fluvial deposits: 1) measured section traverses with field descriptions and channel-body measurements; and 2) Unmanned Aerial Vehicle (UAV)-based photogrammetry data combined with ground-based photomosaics (Figure 3). The Burro Canyon Formation is exposed on three sides of Rattlesnake Canyon. The formation on the northwest, southeast, and southwest canyon walls is approximately 5430 ft (1655 m), 3090 ft (942 m), and 3850 ft (1174 m) long, respectively and 127 ft (39 m) thick. The outcrop orientations provide perspectives of the deposits that are both perpendicular and parallel to the paleoflow direction. Outcrop dip varies from 0 to 1° across the exposed windows. To the east in the Piceance Basin, the structural dip increases where sandstones become natural gas reservoirs ~30 mi (~48 km) to the northwest (e.g., Roberts Canyon Field; Figure 1) (Young, 1975). Three stratigraphic measured sections (MS-1 to MS-3; total length ~360 ft, ~110 m) were acquired within Rattlesnake Canyon to describe the Burro Canyon Formation. MS-1 (230 ft; 70 m) was acquired on the southeastern exposure and includes the upper Morrison Formation and the entire Burro Canyon Formation. MS-2 (92 ft; 28 m) and MS-3 (67 ft; 20 m) were acquired on the northwestern exposure of the canyon and includes the Burro Canyon Formation and the lowermost Dakota Formation sandstones. Measured sections descriptions include lithology, grain size, bedding structures, and



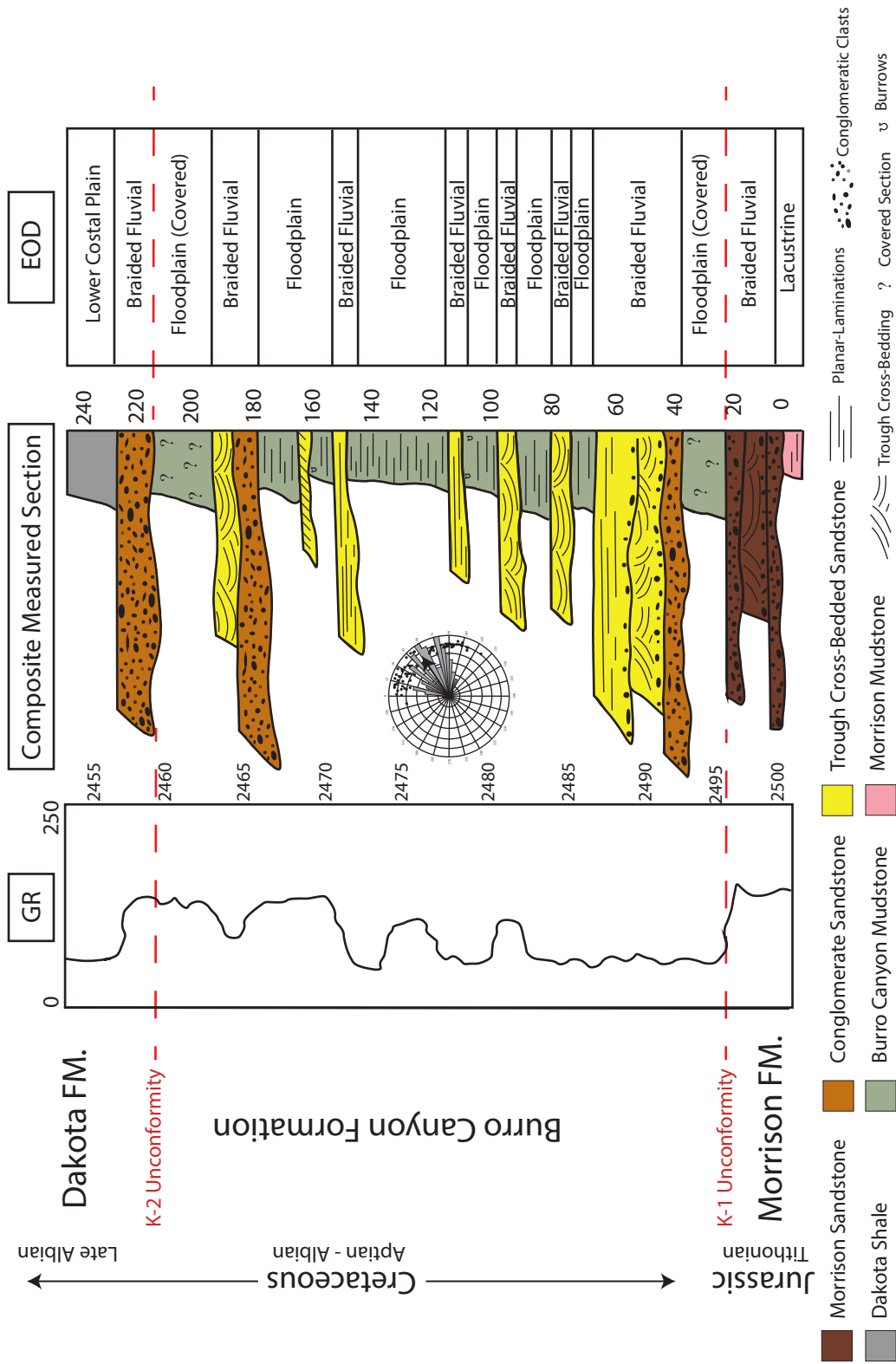
**Figure 3.** Rattlesnake Canyon study area contains three walls with exposed Burro Canyon Formation outcrop, which can be seen shaded in green. The locations of three measured section traverses are shaded in red, orange and yellow. Green highlights also indicate extent of outcrop mapped through use of UAV-(Unmanned Aerial Vehicle-) photogrammetry. Three exposed sides of Rattlesnake Canyon can be identified with Burro Canyon Formation exposures, the Northwest wall, Southeast wall, and South wall. Black boxes indicate locations of photomosaics for Figures 10 and 11.

bounding surfaces (Figure 4). For each measured section, outcrop total-count gamma-ray measurements were acquired with a 1-ft (0.33-m) sampling interval using a Super-Spec RS-125 scintillometer (Radiation Solutions, Inc.). Additionally, outcrop samples were obtained at significant lithological changes along the outcrop for petrographic analysis of thin sections. Nine unpolished thin sections were acquired from the hand samples. Blue epoxy was injected to highlight porosity, and the thin sections were stained with alizarin red S to identify calcite. A Zeiss Axio Imager.Z1m microscope was used to observe the sections in normal transmitted, plane polarized, and cross polarized light. Observations of mineralogic and diagenetic properties were used to reinforce provenance interpretations. A Suunto compass was used to acquire paleocurrent measurements (N=124) through measurement of dip and azimuth of cross stratification for multiple stratigraphic levels of the Burro Canyon Formation.

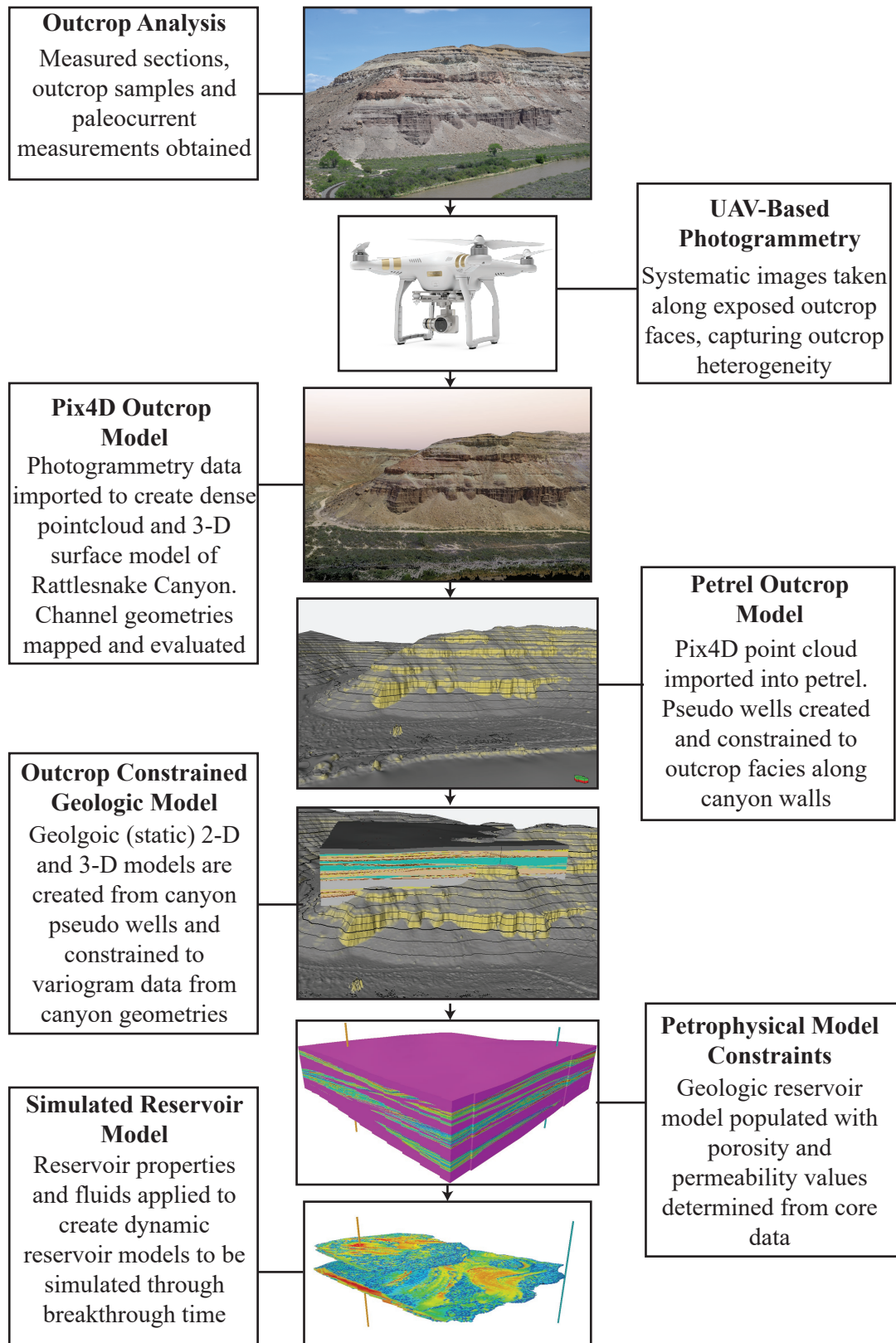
### **Unmanned Aerial Vehicle- (UAV-) Based Photogrammetry**

Rattlesnake Canyon contains 2,370 ft (3,770 m) of exposed Burro Canyon Formation along three walls of the canyon, with use of a DJI Phantom 3 drone, high-resolution images were systematically taken to image the canyon (Figure 5). The outcrop windows were completely imaged at three different distances from the outcrop ranging from 10-100 ft (3-30 m) to capture large-scale features such as channel geometries and architectural elements and small-scale features such as sedimentary structures. Images were acquired along a systematic grid with photos overlapping to ensure full 3-D coverage of Rattlesnake Canyon.

The georeferenced images were used to create a digital 3-D point-cloud model of Rattlesnake Canyon using Pix4DMapper pro software. Width and thickness values of



**Figure 4.** Composite measured section of the Burro Canyon Formation as present in Rattlesnake Canyon. Gamma Ray log taken from Mitchell Energy well (API:05-077-08026) shown. Paleocurrent measurements (N=124, M=58) were taken throughout Rattlesnake Canyon.



**Figure 5.** Seven step workflow to create reservoir model simulations of outcrop data.

67 sandstone bodies were measured using the 3-D digital outcrop model. By combining the channel geometries and dimensions measured from the 3-D digital outcrop model and lithofacies observed from outcrop measured sections, 127 vertical lithofacies logs (pseudo wells) were created along the exposed outcrops using a 30 ft (10 m) lateral spacing and 0.33 ft (0.1 m) vertical sample increment. The pseudo wells capture the bounding surfaces and lithofacies as exposed in Rattlesnake Canyon. Pseudo wells were imported into Petrel with their corresponding lithofacies logs and the scour surfaces observed in the pseudo wells were digitized as surfaces to create individual zones for geologic (static) models.

### **Outcrop Reservoir Modeling**

#### *Model Grids (Sandstone-Body and Channel-Fill Models)*

Outcrop analog data were used in conjunction with core data from the Mitchell Energy Federal 8-1 well, to constrain 2-D and 3-D outcrop reservoir models (static reservoir models) of the Burro Canyon Formation. Two 2-D outcrop model grids with associated model zones are oriented parallel to paleoflow, and two 2-D model grids with associated model zones are oriented perpendicular to paleoflow. In addition, one 3-D model grid with model zones was created. The 2-D model grids have three dimensions; however, the third dimension is minor; thus, they are referred to as 2-D outcrop models. Dimensions of the 2-D reservoir model grids are 1200 ft x 72 ft x 300 ft (366 m x 22 m x 90 m) and contain 3,000,000 cells. The 3-D reservoir model grid is 1315 ft x 1315 ft x 300 ft (400 m x 400 m x 90 m) and contain 853,000,000 cells. Both 2-D and 3-D grids have cell dimensions that are 3 ft x 3 ft x 0.3ft (1 m x 1 m x 0.1 m). The 2-D and 3-D models include the stratigraphic interval from the base of the

uppermost channel in the Morrison Formation to the base of the Dakota Formation; thus, incorporating the entire Burro Canyon interval present in Rattlesnake Canyon.

For each paleoflow orientation, the stratigraphic zones associated with the two 2-D grids reflect different levels of stratigraphic detail. The first grid has zones defined for each isolated-sandstone body (e.g., fluvial channel fill; Patterson et al., 2012) and amalgamated-sandstone body (herein referred to as the sandstone-body model [SB1 and SB2 models for parallel and perpendicular orientations, respectively]); note that smaller scale zones are not defined within the amalgamated-sandstone bodies. The second grid includes more stratigraphic detail and zones are defined for each channel fill (herein referred to as the channel-fill model [CF1 and CF2 models for parallel and perpendicular orientations, respectively]); note that smaller scale zones are defined for each channel fill that are amalgamated to form larger sandstone bodies. Therefore, in the CF models, the channel fills that form each zone exist as isolated sandstone bodies and more complex amalgamated sandstone bodies composed of stacked channel fills. For the SB models, twelve stratigraphic surfaces are used to define 11 sandstone bodies (model zones). For the CF models, twenty stratigraphic surfaces define 19 channel fills (model zones). Layering within each of the zones was set at 0.3 ft (0.1 m) to preserve small-scale lithofacies variations within the channel fills.

The 3-D model grid includes the same stratigraphic details and zones as defined for the 2-D CF model (3DCF model). For the 3DCF model, zones (channel fills) of the 2-D CF model were mapped in three dimensions by using projected stratigraphic surfaces defined from the 3-D digital outcrop model and 151 pseudo wells. Of the total 151 pseudo wells used to constrain the 3-D model, 127 are directly tied to outcrop and



constrained at a horizontal spacing along exposed outcrop of 30 ft (10 m) and a vertical increment of 3.28 ft (0.1 m). The remaining 24 pseudo wells are used to constrain the model domain between the walls of the canyon. Interpolating channel boundaries from their locations on either side of the canyon. Instances in which channels did not appear to cross the canyon, surfaces were truncated at angles consistent with the angles of pinch outs observed in outcrop. Pseudo wells not constrained to outcrop were populated with lithofacies following the patterns of those observed along the walls of Rattlesnake Canyon to create a realistic representation of the deposit. As with the 2-D CF model, for the 3-D CF model, the channel fills that form each zone exist as both isolated sandstone bodies and more complex amalgamated sandstone bodies composed of stacked channel fills.

### *2-D Lithofacies Modeling*

For each paleoflow orientation, lithofacies were modeled within channel fills of the CF models; however, lithofacies were not modeled within the sandstone bodies of the SB models. The SB models remained unchanged to only depict the spatial distribution of sandstones and mudstones within the Burro Canyon Formation. Using the CF models, high-resolution lithofacies models were created using sequential-indicator simulation with the following data and constraints: (1) CF models (lithofacies were modeled within each channel fill); (2) lithofacies logs for pseudo wells (N=38); and (3) variogram parameters. Variogram inputs were estimated from outcrop measurements of lateral and vertical lithofacies continuity derived from measured sections, pseudo well lithofacies logs, and the 3-D digital outcrop models (Table 1). Three different lithofacies model scenarios were produced by using different horizontal

## Lithofacies Models Variograms

### CF1-L1 / CF2-L1 / 3DCF-L1

| Zones            | Facies    | Layering:    | #:  | Method: | Sill | Nugget | Type             | Major dir | Minor dir | Vertical | Azimuth | Dip |
|------------------|-----------|--------------|-----|---------|------|--------|------------------|-----------|-----------|----------|---------|-----|
| Dakota           | Mudstone  | Proportional | 21  | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS8 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 690       | 660       | 2        | 58      | 0   |
| Burro Canyon Ms  | Mudstone  | Proportional | 12  | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS7 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 690       | 660       | 2        | 58      | 0   |
| Burro Canyon SS6 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 690       | 660       | 2        | 58      | 0   |
| Burro Canyon Ms  | Mudstone  | Proportional | 42  | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS5 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 450       | 130       | 1        | 58      | 0   |
| Burro Canyon Ms  | Mudstone  | Proportional | 14  | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS4 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 2200      | 2000      | 2        | 58      | 0   |
| Burro Canyon Ms  | Mudstone  | Proportional | 30  | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS3 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 2200      | 2000      | 2        | 58      | 0   |
| Burro Canyon Ms  | Mudstone  | Proportional | 3   | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS2 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 2200      | 2000      | 2        | 58      | 0   |
| Burro Canyon Ms  | Mudstone  | Proportional | 3   | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS1 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 160       | 150       | 1        | 58      | 0   |
| Morrison Ms      | Mudstone  | Proportional | 42  | AV      |      |        |                  |           |           |          |         |     |
| Morrison SS      | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 500       | 430       | 1        | 58      | 0   |
| Morrison SS      | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 500       | 430       | 1        | 58      | 0   |
| Morrison Ms      | Mudstone  | Proportional | 20  | AV      |      |        |                  |           |           |          |         |     |

### CF1-L2 / CF2-L2

| Zones            | Facies    | Layering:    | #:  | Method: | Sill | Nugget | Type             | Major dir | Minor dir | Vertical | Azimuth | Dip |
|------------------|-----------|--------------|-----|---------|------|--------|------------------|-----------|-----------|----------|---------|-----|
| Dakota           | Mudstone  | Proportional | 21  | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS8 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 345       | 330       | 1        | 58      | 0   |
| Burro Canyon Ms  | Mudstone  | Proportional | 12  | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS7 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 345       | 330       | 1        | 58      | 0   |
| Burro Canyon SS6 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 345       | 330       | 1        | 58      | 0   |
| Burro Canyon Ms  | Mudstone  | Proportional | 42  | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS5 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 225       | 65        | 0.5      | 58      | 0   |
| Burro Canyon Ms  | Mudstone  | Proportional | 14  | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS4 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 1100      | 1000      | 1        | 58      | 0   |
| Burro Canyon Ms  | Mudstone  | Proportional | 30  | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS3 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 1100      | 1000      | 1        | 58      | 0   |
| Burro Canyon Ms  | Mudstone  | Proportional | 3   | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS2 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 1100      | 1000      | 1        | 58      | 0   |
| Burro Canyon Ms  | Mudstone  | Proportional | 3   | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS1 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 80        | 75        | 0.5      | 58      | 0   |
| Morrison Ms      | Mudstone  | Proportional | 42  | AV      |      |        |                  |           |           |          |         |     |
| Morrison SS      | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 250       | 215       | 0.5      | 58      | 0   |
| Morrison SS      | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 250       | 215       | 0.5      | 58      | 0   |
| Morrison Ms      | Mudstone  | Proportional | 20  | AV      |      |        |                  |           |           |          |         |     |

### CF1-L3 / CF2-L3

| Zones            | Facies    | Layering:    | #:  | Method: | Sill | Nugget | Type             | Major dir | Minor dir | Vertical | Azimuth | Dip |
|------------------|-----------|--------------|-----|---------|------|--------|------------------|-----------|-----------|----------|---------|-----|
| Dakota           | Mudstone  | Proportional | 21  | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS8 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 1380      | 1320      | 4        | 51      | 0   |
| Burro Canyon Ms  | Mudstone  | Proportional | 12  | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS7 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 1380      | 1320      | 4        | 51      | 0   |
| Burro Canyon SS6 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 1380      | 1320      | 4        | 51      | 0   |
| Burro Canyon Ms  | Mudstone  | Proportional | 42  | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS5 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 900       | 260       | 2        | 51      | 0   |
| Burro Canyon Ms  | Mudstone  | Proportional | 14  | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS4 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 4400      | 4000      | 4        | 51      | 0   |
| Burro Canyon Ms  | Mudstone  | Proportional | 30  | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS3 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 4400      | 4000      | 4        | 51      | 0   |
| Burro Canyon Ms  | Mudstone  | Proportional | 3   | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS2 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 4400      | 4000      | 4        | 51      | 0   |
| Burro Canyon Ms  | Mudstone  | Proportional | 3   | AV      |      |        |                  |           |           |          |         |     |
| Burro Canyon SS1 | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 320       | 300       | 2        | 51      | 0   |
| Morrison Ms      | Mudstone  | Proportional | 42  | AV      |      |        |                  |           |           |          |         |     |
| Morrison SS      | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 1000      | 860       | 2        | 51      | 0   |
| Morrison SS      | Sandstone | Follow Base  | 0.1 | SIS     |      | 1      | 0.0001 Spherical | 1000      | 860       | 2        | 51      | 0   |
| Morrison Ms      | Mudstone  | Proportional | 20  | AV      |      |        |                  |           |           |          |         |     |

**Table 1.** Lithofacies model variograms for the Channel-Fill (CF) models. Individual sandstone bodies have been defined by spatial location along outcrop and applied variogram ranges that reflect the average distribution of the lithofacies within that location.

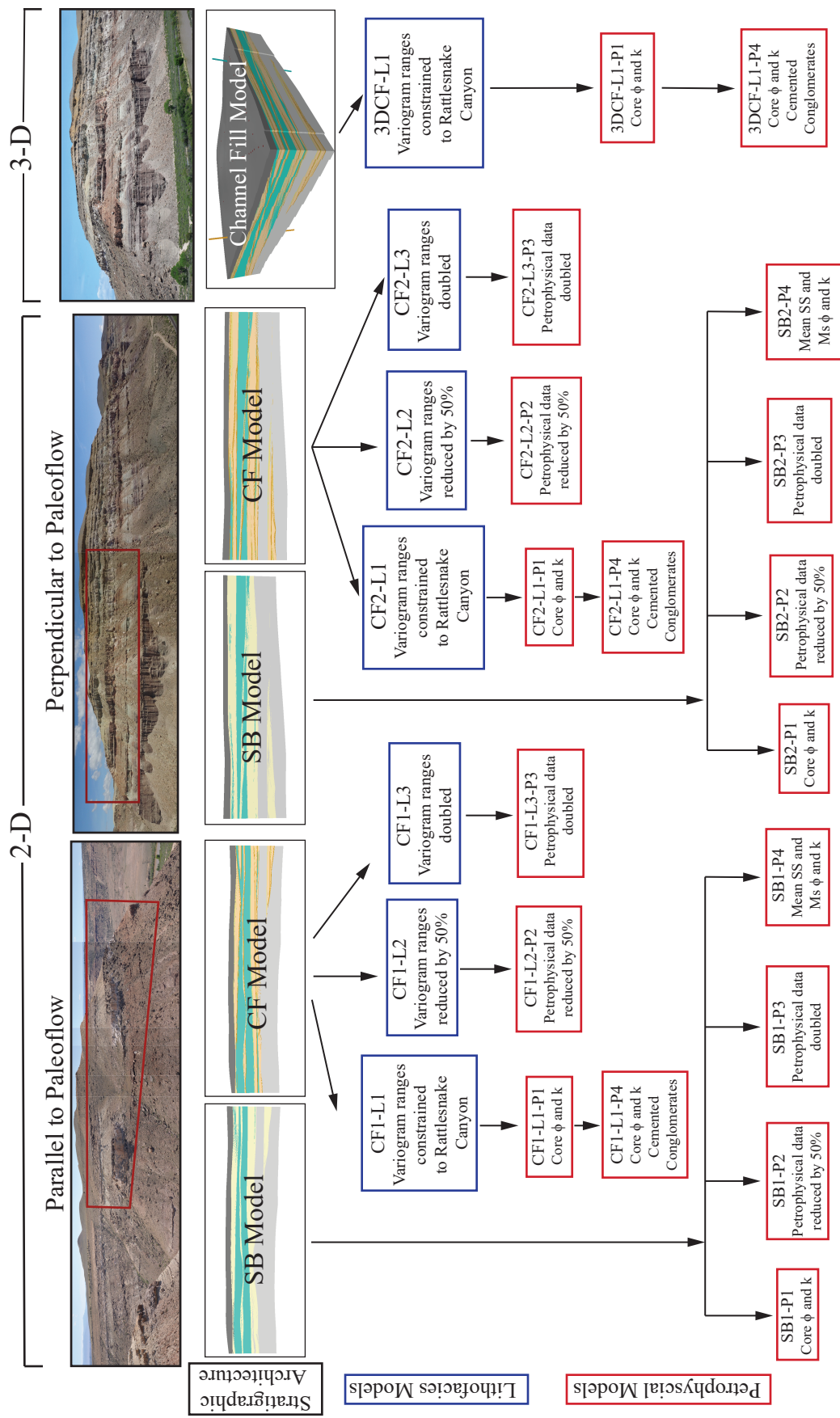
variogram ranges to explore the impact of lateral lithofacies continuity on various reservoir performance metrics (Table 1). This resulted in 6 lithofacies models (3 parallel to paleoflow and 3 perpendicular to paleoflow that are constrained to the CF models). The vertical variogram ranges are consistent for each scenario and both vertical and horizontal variogram ranges vary by facies and by zone (Table 1). The first lithofacies models (CF1-L1, CF2-L1) are based on horizontal variogram ranges that reflect values that are most representative of the lateral lithofacies continuity as observed in outcrop. For the second lithofacies models (CF1-L2, CF2-L2), horizontal variogram ranges are arbitrarily set at half the length of the first lithofacies models. The third lithofacies models (CF1-L3, CF2-L3) have horizontal variogram ranges set at twice the length of the CF-L1 model (Table 1).

### *3-D Lithofacies Modeling*

A high-resolution 3-D lithofacies model (3DCF-L1) was also constructed using sequential-indicator simulation with the following data and constraints: (1) 3DCF model (lithofacies were conditioned to the 3-D channel-fill model); (2) lithofacies logs for pseudo wells (N=127); (3) lithofacies distributions as observed in the two modeled outcrop windows and (4) variogram parameters as used in the 2-D CF-L1 model (Figure 6).

### *2-D Petrophysical Modeling*

For both paleoflow orientations, porosity and permeability models were generated using the SB models and CF lithofacies models as constraints. Permeability models were constrained through the use of collocated co-kriging to porosity models using a constant coefficient of 0.8. High-resolution porosity and permeability models



**Figure 6.** Diagram depicting model scenarios created using Burro Canyon Formation data from Rattlesnake Canyon. Two-dimensional and three-dimensional models contain both lithofacies model and petrophysical models.

were created by either assigning average values or mapped using sequential-Gaussian simulation (SGS) with the following data and constraints: (1) SB models or CF lithofacies models; (2) triangular porosity and permeability distributions for sandstone and mudstone, or average values of porosity and permeability, or triangular porosity and permeability distributions for each lithofacies (core data from the Mitchell Energy Federal 8-1 well), and (3) variogram parameters.

For both paleoflow orientations and for each of the SB models, four porosity and permeability model scenarios were generated. For the first model scenarios (SB1-P1, SB2-P1; P1=porosity and permeability models), triangular porosity and permeability distributions (defined by minimum, mean, and maximum values) for sandstone and mudstone were used with SGS to map these properties within sandstone and mudstone model lithologies. For the second and third model scenarios (SB1-P2, SB2-P2, SB1-P3, SB2-P3), the porosity and permeability values were reduced by 50% and doubled, respectively. Table 2 summarizes the variogram parameters. For the fourth model scenarios (SB1-P4, SB2-P4), more simplistic models were produced as average sandstone and mudstone porosity and permeability values were assigned to the corresponding model lithologies.

For each of the six CF lithofacies models (includes both paleoflow orientations), a corresponding porosity and permeability model was generated (Figure 6). For the first porosity and permeability models (CF1-L1-P1 and CF2-L1-P1; constrained to lithofacies models CF1-L1 and CF2-L1), triangular porosity and permeability distributions for each lithofacies were used with SGS to map the properties. For comparison, for the second and third model scenarios (CF1-L2-P2, CF1-L3-P3, CF2-

## SB Petrophysical Variograms

### SB1-P1 / SB2-P1

| Zones           | Method       | Global Seed | VA | Sill | Nugget | Type      | Major dir | Minor dir | Vertical | Azimuth | Dip | Porosity |      |      |      | Permeability |     |      |        |
|-----------------|--------------|-------------|----|------|--------|-----------|-----------|-----------|----------|---------|-----|----------|------|------|------|--------------|-----|------|--------|
| Dakota          | Assign Value | 17000       | 0  |      |        |           |           |           |          |         |     | Min      | Max  | Mean | Std  | Min          | Max | Mean | Std    |
| Burro Canyon 4  | Gaussian     | 17000       | 0  | 1    | 0.0001 | Spherical | 550       | 500       | 2        | 58      | 0   | 0.9      | 14.6 | 8.3  | 3.67 | 0.1          | 48  | 4.4  | 10.606 |
| Burro Canyon Ms | Assign Value | 17000       | 0  |      |        |           |           |           |          |         |     |          |      |      |      |              |     |      |        |
| Burro Canyon 3  | Gaussian     | 17000       | 0  | 1    | 0.0001 | Spherical | 400       | 100       | 1        | 58      | 0   | 0.9      | 14.6 | 8.3  | 3.67 | 0.1          | 48  | 4.4  | 10.606 |
| Burro Canyon Ms | Assign Value | 17000       | 0  |      |        |           |           |           |          |         |     |          |      |      |      |              |     |      |        |
| Burro Canyon 2  | Gaussian     | 17000       | 0  | 1    | 0.0001 | Spherical | 1800      | 1500      | 2        | 58      | 0   | 0.9      | 14.6 | 8.3  | 3.67 | 0.1          | 48  | 4.4  | 10.606 |
| Burro Canyon Ms | Assign Value | 17000       | 0  |      |        |           |           |           |          |         |     |          |      |      |      |              |     |      |        |
| Burro Canyon 1  | Gaussian     | 17000       | 0  | 1    | 0.0001 | Spherical | 130       | 110       | 1        | 58      | 0   | 0.9      | 14.6 | 8.3  | 3.67 | 0.1          | 48  | 4.4  | 10.606 |
| Morrison Ms     | Assign Value | 17000       | 0  |      |        |           |           |           |          |         |     |          |      |      |      |              |     |      |        |
| Morrison SS     | Gaussian     | 17000       | 0  | 1    | 0.0001 | Spherical | 480       | 410       | 1        | 58      | 0   | 0.9      | 14.6 | 8.3  | 3.67 | 0.1          | 48  | 4.4  | 10.606 |
| Morrison Ms     | Assign Value | 17000       | 0  |      |        |           |           |           |          |         |     |          |      |      |      |              |     |      |        |

### SB1-P2 / SB2-P2

| Zones           | Method       | Global Seed | VA | Sill | Nugget | Type      | Major dir | Minor dir | Vertical | Azimuth | Dip | Porosity |     |      |       | Permeability |     |      |       |
|-----------------|--------------|-------------|----|------|--------|-----------|-----------|-----------|----------|---------|-----|----------|-----|------|-------|--------------|-----|------|-------|
| Dakota          | Assign Value | 17000       | 0  |      |        |           |           |           |          |         |     | Min      | Max | Mean | Std   | Min          | Max | Mean | Std   |
| Burro Canyon 4  | Gaussian     | 17000       | 0  | 1    | 0.0001 | Spherical | 275       | 250       | 1        | 58      | 0   | 0.45     | 7.3 | 4.15 | 1.835 | 0.05         | 24  | 2.2  | 5.303 |
| Burro Canyon Ms | Assign Value | 17000       | 0  |      |        |           |           |           |          |         |     |          |     |      |       |              |     |      |       |
| Burro Canyon 3  | Gaussian     | 17000       | 0  | 1    | 0.0001 | Spherical | 200       | 50        | 0.5      | 58      | 0   | 0.45     | 7.3 | 4.15 | 1.835 | 0.05         | 24  | 2.2  | 5.303 |
| Burro Canyon Ms | Assign Value | 17000       | 0  |      |        |           |           |           |          |         |     |          |     |      |       |              |     |      |       |
| Burro Canyon 2  | Gaussian     | 17000       | 0  | 1    | 0.0001 | Spherical | 900       | 750       | 1        | 58      | 0   | 0.45     | 7.3 | 4.15 | 1.835 | 0.05         | 24  | 2.2  | 5.303 |
| Burro Canyon Ms | Assign Value | 17000       | 0  |      |        |           |           |           |          |         |     |          |     |      |       |              |     |      |       |
| Burro Canyon 1  | Gaussian     | 17000       | 0  | 1    | 0.0001 | Spherical | 65        | 55        | 0.5      | 58      | 0   | 0.45     | 7.3 | 4.15 | 1.835 | 0.05         | 24  | 2.2  | 5.303 |
| Morrison Ms     | Assign Value | 17000       | 0  |      |        |           |           |           |          |         |     |          |     |      |       |              |     |      |       |
| Morrison SS     | Gaussian     | 17000       | 0  | 1    | 0.0001 | Spherical | 240       | 205       | 0.5      | 58      | 0   | 0.45     | 7.3 | 4.15 | 1.835 | 0.05         | 24  | 2.2  | 5.303 |
| Morrison Ms     | Assign Value | 17000       | 0  |      |        |           |           |           |          |         |     |          |     |      |       |              |     |      |       |

### SB1-P3 / SB2-P3

| Zones           | Method       | Global Seed | VA | Sill | Nugget | Type      | Major dir | Minor dir | Vertical | Major dir | Dip | Porosity |      |      |      | Permeability |     |      |        |
|-----------------|--------------|-------------|----|------|--------|-----------|-----------|-----------|----------|-----------|-----|----------|------|------|------|--------------|-----|------|--------|
| Dakota          | Assign Value | 17000       | 0  |      |        |           |           |           |          |           |     | Min      | Max  | Mean | Std  | Min          | Max | Mean | Std    |
| Burro Canyon 4  | Gaussian     | 17000       | 0  | 1    | 0.0001 | Spherical | 1100      | 1000      | 4        | 58        | 0   | 1.8      | 29.2 | 16.6 | 7.34 | 0.2          | 96  | 8.8  | 21.212 |
| Burro Canyon Ms | Assign Value | 17000       | 0  |      |        |           |           |           |          |           |     |          |      |      |      |              |     |      |        |
| Burro Canyon 3  | Gaussian     | 17000       | 0  | 1    | 0.0001 | Spherical | 800       | 200       | 2        | 58        | 0   | 1.8      | 29.2 | 16.6 | 7.34 | 0.2          | 96  | 8.8  | 21.212 |
| Burro Canyon Ms | Assign Value | 17000       | 0  |      |        |           |           |           |          |           |     |          |      |      |      |              |     |      |        |
| Burro Canyon 2  | Gaussian     | 17000       | 0  | 1    | 0.0001 | Spherical | 3600      | 3000      | 4        | 58        | 0   | 1.8      | 29.2 | 16.6 | 7.34 | 0.2          | 96  | 8.8  | 21.212 |
| Burro Canyon Ms | Assign Value | 17000       | 0  |      |        |           |           |           |          |           |     |          |      |      |      |              |     |      |        |
| Burro Canyon 1  | Gaussian     | 17000       | 0  | 1    | 0.0001 | Spherical | 260       | 220       | 2        | 58        | 0   | 1.8      | 29.2 | 16.6 | 7.34 | 0.2          | 96  | 8.8  | 21.212 |
| Morrison Ms     | Assign Value | 17000       | 0  |      |        |           |           |           |          |           |     |          |      |      |      |              |     |      |        |
| Morrison SS     | Gaussian     | 17000       | 0  | 1    | 0.0001 | Spherical | 960       | 820       | 2        | 58        | 0   | 1.8      | 29.2 | 16.6 | 7.34 | 0.2          | 96  | 8.8  | 21.212 |
| Morrison Ms     | Assign Value | 17000       | 0  |      |        |           |           |           |          |           |     |          |      |      |      |              |     |      |        |

### SB1-P4 / SB2-P4

| Zones           |           | Method       | Global Seed | VA Porosity | VA Permeability |
|-----------------|-----------|--------------|-------------|-------------|-----------------|
| Dakota          | Mudstone  | Assign Value | 17000       | 0           | 0               |
| Burro Canyon 4  | Sandstone | Assign Value | 17000       | 8.1         | 4.2             |
| Burro Canyon Ms | Mudstone  | Assign Value | 17000       | 0           | 0               |
| Burro Canyon 3  | Sandstone | Assign Value | 17000       | 8.1         | 4.2             |
| Burro Canyon Ms | Mudstone  | Assign Value | 17000       | 0           | 0               |
| Burro Canyon 2  | Sandstone | Assign Value | 17000       | 8.1         | 4.2             |
| Burro Canyon Ms | Mudstone  | Assign Value | 17000       | 0           | 0               |
| Burro Canyon 1  | Sandstone | Assign Value | 17000       | 8.1         | 4.2             |
| Morrison Ms     | Mudstone  | Assign Value | 17000       | 0           | 0               |
| Morrison SS     | Sandstone | Assign Value | 17000       | 8.1         | 4.2             |
| Morrison Ms     | Mudstone  | Assign Value | 17000       | 0           | 0               |

**Table 2.** Petrophysical variogram distributions for the Sandstone-Body (SB) models. P1, P2 and P3 models use petrophysical variogram ranges from core, with P2 and P3 having ranges reduced by 50% and doubled respectively. P4 utilizes an average value for porosity and permeability to create a "tank" distribution.

L2-P2, CF2-L3-P3), porosity and permeability values were reduced by 50% and doubled, respectively. Tables 3 and 4 summarize the variogram parameters.

Two additional porosity and permeability models were generated (1 for each orientation; CF1-L1-P4, CF2-L1-P4) that were conditioned to the CF1-L1 and CF2-L1 lithofacies models. These models assume that the conglomerates are significantly cemented; therefore, the corresponding porosity and permeability values were reduced to a range of 0–8% (mean = 4%) and 0.001–0.5 mD (mean = 0.02), respectively, similar to previously documented cemented braided-fluvial deposits (Clarke, 1979; Cant and Eth, 1984).

### *3-D Petrophysical Modeling*

Two 3-D porosity and permeability model scenarios were generated with sequential-Gaussian simulation using the 3DCF-L1 lithofacies model as a constraint. The first models (3DCF-L1-P1 - porosity and permeability) use the same porosity and permeability histogram and variograms as with the 2-D CF1-L1-P1 and CF2-L1-P1 porosity and permeability models. Like the 2-D cemented conglomerate scenario, a second set of porosity and permeability models were generated (3DCF-L1-P4 - porosity and permeability) that assume the conglomerates are significantly cemented; therefore, the corresponding porosity and permeability values were reduced to a range of 0–8% (mean = 4%) and 0.001–0.5 mD (mean = 0.02), respectively, similar to the 2-D CF1-L1-P4 and CF2-L1-P4 scenarios (Table 4).

### *Fluid-Flow Simulation*

Two-phase oil-water fluid-flow simulations are performed using single injector and production wells with ECLIPSE (Schlumberger) reservoir simulation software. In

## CF Petrophysical Variograms

### CF1-L1-P1 / CF2-L1-P1/ 3DCF-L1-P1

| Zones            | Facies   | Method | Global Seed | VA    | Sill | Nugget | Type      | Major dir | Minor dir | Vertical | Azimuth | Dip | Porosity |     |      |      | Permeability |     |      |       |
|------------------|----------|--------|-------------|-------|------|--------|-----------|-----------|-----------|----------|---------|-----|----------|-----|------|------|--------------|-----|------|-------|
|                  |          |        |             |       |      |        |           |           |           |          |         |     | Min      | Max | Mean | Std. | Min          | Max | Mean | Std   |
| Dakota           | Mudstone | AV     |             | 0     |      |        |           |           |           |          |         |     |          |     |      |      |              |     |      |       |
| Burro Canyon S58 | Planar   | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 550       | 500       | 1.5      | 58      | 0   | 0.9      | 5.7 | 2.67 | 2.64 | 0.1          | 0.2 | 0.1  | 0.1   |
|                  | Trough   | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 550       | 500       | 2        | 58      | 0   | 4        | 13  | 8.9  | 3.2  | 0.1          | 48  | 8.25 | 15.76 |
|                  | Conglom  | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 550       | 500       | 0.33     | 58      | 0   | 5        | 11  | 8.27 | 2.64 | 0.3          | 34  | 4.76 | 9.42  |
| Burro Canyon Ms  | Mudstone | AV     |             | 17000 | 0    |        |           |           |           |          |         |     |          |     |      |      |              |     |      |       |
| Burro Canyon S57 | Planar   | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 550       | 500       | 1        | 58      | 0   | 0.9      | 5.7 | 2.67 | 2.64 | 0.1          | 0.2 | 0.1  | 0.1   |
|                  | Trough   | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 550       | 500       | 2        | 58      | 0   | 4        | 13  | 8.9  | 3.2  | 0.1          | 48  | 8.25 | 15.76 |
|                  | Conglom  | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 550       | 500       | 0.33     | 58      | 0   | 5        | 11  | 8.27 | 2.64 | 0.3          | 34  | 4.76 | 9.42  |
| Burro Canyon S56 | Planar   | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 550       | 500       | 1        | 58      | 0   | 0.9      | 5.7 | 2.67 | 2.64 | 0.1          | 0.2 | 0.1  | 0.1   |
|                  | Trough   | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 550       | 500       | 2        | 58      | 0   | 4        | 13  | 8.9  | 3.2  | 0.1          | 48  | 8.25 | 15.76 |
|                  | Conglom  | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 550       | 500       | 0.33     | 58      | 0   | 5        | 11  | 8.27 | 2.64 | 0.3          | 34  | 4.76 | 9.42  |
| Burro Canyon Ms  | Mudstone | AV     |             | 17000 | 0    |        |           |           |           |          |         |     |          |     |      |      |              |     |      |       |
| Burro Canyon S55 | Planar   | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 400       | 100       | 0.5      | 58      | 0   | 0.9      | 5.7 | 2.67 | 2.64 | 0.1          | 0.2 | 0.1  | 0.1   |
|                  | Trough   | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 400       | 100       | 2        | 58      | 0   | 4        | 13  | 8.9  | 3.2  | 0.1          | 48  | 8.25 | 15.76 |
|                  | Conglom  | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 400       | 100       | 0.33     | 58      | 0   | 5        | 11  | 8.27 | 2.64 | 0.3          | 34  | 4.76 | 9.42  |
| Burro Canyon Ms  | Mudstone | AV     |             | 17000 | 0    |        |           |           |           |          |         |     |          |     |      |      |              |     |      |       |
| Burro Canyon S54 | Planar   | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 1800      | 1500      | 0.5      | 58      | 0   | 0.9      | 5.7 | 2.67 | 2.64 | 0.1          | 0.2 | 0.1  | 0.1   |
|                  | Trough   | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 1800      | 1500      | 2        | 58      | 0   | 4        | 13  | 8.9  | 3.2  | 0.1          | 48  | 8.25 | 15.76 |
|                  | Conglom  | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 1800      | 1500      | 0.33     | 58      | 0   | 5        | 11  | 8.27 | 2.64 | 0.3          | 34  | 4.76 | 9.42  |
| Burro Canyon Ms  | Mudstone | AV     |             | 17000 | 0    |        |           |           |           |          |         |     |          |     |      |      |              |     |      |       |
| Burro Canyon S53 | Planar   | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 1800      | 1500      | 0.5      | 58      | 0   | 0.9      | 5.7 | 2.67 | 2.64 | 0.1          | 0.2 | 0.1  | 0.1   |
|                  | Trough   | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 1800      | 1500      | 2        | 58      | 0   | 4        | 13  | 8.9  | 3.2  | 0.1          | 48  | 8.25 | 15.76 |
|                  | Conglom  | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 1800      | 1500      | 0.33     | 58      | 0   | 5        | 11  | 8.27 | 2.64 | 0.3          | 34  | 4.76 | 9.42  |
| Burro Canyon Ms  | Mudstone | AV     |             | 17000 | 0    |        |           |           |           |          |         |     |          |     |      |      |              |     |      |       |
| Burro Canyon S52 | Planar   | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 1800      | 1500      | 0.5      | 58      | 0   | 0.9      | 5.7 | 2.67 | 2.64 | 0.1          | 0.2 | 0.1  | 0.1   |
|                  | Trough   | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 1800      | 1500      | 2        | 58      | 0   | 4        | 13  | 8.9  | 3.2  | 0.1          | 48  | 8.25 | 15.76 |
|                  | Conglom  | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 1800      | 1500      | 0.33     | 58      | 0   | 5        | 11  | 8.27 | 2.64 | 0.3          | 34  | 4.76 | 9.42  |
| Burro Canyon Ms  | Mudstone | AV     |             | 17000 | 0    |        |           |           |           |          |         |     |          |     |      |      |              |     |      |       |
| Burro Canyon S51 | Planar   | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 130       | 110       | 0.33     | 58      | 0   | 0.9      | 5.7 | 2.67 | 2.64 | 0.1          | 0.2 | 0.1  | 0.1   |
|                  | Trough   | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 130       | 110       | 2        | 58      | 0   | 4        | 13  | 8.9  | 3.2  | 0.1          | 48  | 8.25 | 15.76 |
|                  | Conglom  | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 130       | 110       | 0.33     | 58      | 0   | 5        | 11  | 8.27 | 2.64 | 0.3          | 34  | 4.76 | 9.42  |
| Burro Canyon Ms  | Mudstone | AV     |             | 17000 | 0    |        |           |           |           |          |         |     |          |     |      |      |              |     |      |       |
| Morrison S52     | Planar   | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 480       | 410       | 0.33     | 58      | 0   | 0.9      | 5.7 | 2.67 | 2.64 | 0.1          | 0.2 | 0.1  | 0.1   |
|                  | Trough   | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 480       | 410       | 2        | 58      | 0   | 4        | 13  | 8.9  | 3.2  | 0.1          | 48  | 8.25 | 15.76 |
|                  | Conglom  | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 480       | 410       | 0.33     | 58      | 0   | 5        | 11  | 8.27 | 2.64 | 0.3          | 34  | 4.76 | 9.42  |
| Morrison S51     | Planar   | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 480       | 410       | 0.33     | 58      | 0   | 0.9      | 5.7 | 2.67 | 2.64 | 0.1          | 0.2 | 0.1  | 0.1   |
|                  | Trough   | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 480       | 410       | 2        | 58      | 0   | 4        | 13  | 8.9  | 3.2  | 0.1          | 48  | 8.25 | 15.76 |
|                  | Conglom  | SGS    |             | 17000 | 1    | 0.0001 | Spherical | 480       | 410       | 0.33     | 58      | 0   | 5        | 11  | 8.27 | 2.64 | 0.3          | 34  | 4.76 | 9.42  |
| Burro Canyon Ms  | Mudstone | AV     |             | 17000 | 0    |        |           |           |           |          |         |     |          |     |      |      |              |     |      |       |

### CF1-L2-P2 / CF2-L2-P2

| Zones            | Facies   | Method | Global Seed | VA | Sill | Nugget | Type      | Major dir | Minor dir | Vertical | Azimuth | Dip | Porosity |      |       |      | Permeability |     |       |      |
|------------------|----------|--------|-------------|----|------|--------|-----------|-----------|-----------|----------|---------|-----|----------|------|-------|------|--------------|-----|-------|------|
|                  |          |        |             |    |      |        |           |           |           |          |         |     | Min      | Max  | Mean  | Std. | Min          | Max | Mean  | Std  |
| Dakota           | Mudstone | AV     |             | 0  |      |        |           |           |           |          |         |     |          |      |       |      |              |     |       |      |
| Burro Canyon S58 | Planar   | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 275       | 250       | 0.75     | 58      | 0   | 0.45     | 2.85 | 1.335 | 1.32 | 0.05         | 0.1 | 0.05  | 0.05 |
|                  | Trough   | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 275       | 250       | 1        | 58      | 0   | 2        | 6.5  | 4.45  | 1.6  | 0.05         | 24  | 4.125 | 7.88 |
|                  | Conglom  | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 275       | 250       | 0.165    | 58      | 0   | 2.5      | 5.5  | 4.135 | 1.32 | 0.15         | 17  | 2.38  | 4.71 |
| Burro Canyon Ms  | Mudstone | AV     | 17000       | 0  |      |        |           |           |           |          |         |     |          |      |       |      |              |     |       |      |
| Burro Canyon S57 | Planar   | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 275       | 250       | 0.5      | 58      | 0   | 0.45     | 2.85 | 1.335 | 1.32 | 0.05         | 0.1 | 0.05  | 0.05 |
|                  | Trough   | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 275       | 250       | 1        | 58      | 0   | 2        | 6.5  | 4.45  | 1.6  | 0.05         | 24  | 4.125 | 7.88 |
|                  | Conglom  | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 275       | 250       | 0.165    | 58      | 0   | 2.5      | 5.5  | 4.135 | 1.32 | 0.15         | 17  | 2.38  | 4.71 |
| Burro Canyon S56 | Planar   | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 275       | 250       | 0.5      | 58      | 0   | 0.45     | 2.85 | 1.335 | 1.32 | 0.05         | 0.1 | 0.05  | 0.05 |
|                  | Trough   | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 275       | 250       | 1        | 58      | 0   | 2        | 6.5  | 4.45  | 1.6  | 0.05         | 24  | 4.125 | 7.88 |
|                  | Conglom  | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 275       | 250       | 0.165    | 58      | 0   | 2.5      | 5.5  | 4.135 | 1.32 | 0.15         | 17  | 2.38  | 4.71 |
| Burro Canyon Ms  | Mudstone | AV     | 17000       | 0  |      |        |           |           |           |          |         |     |          |      |       |      |              |     |       |      |
| Burro Canyon S55 | Planar   | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 200       | 50        | 0.25     | 58      | 0   | 0.45     | 2.85 | 1.335 | 1.32 | 0.05         | 0.1 | 0.05  | 0.05 |
|                  | Trough   | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 200       | 50        | 1        | 58      | 0   | 2        | 6.5  | 4.45  | 1.6  | 0.05         | 24  | 4.125 | 7.88 |
|                  | Conglom  | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 200       | 50        | 0.165    | 58      | 0   | 2.5      | 5.5  | 4.135 | 1.32 | 0.15         | 17  | 2.38  | 4.71 |
| Burro Canyon Ms  | Mudstone | AV     | 17000       | 0  |      |        |           |           |           |          |         |     |          |      |       |      |              |     |       |      |
| Burro Canyon S54 | Planar   | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 900       | 750       | 0.25     | 58      | 0   | 0.45     | 2.85 | 1.335 | 1.32 | 0.05         | 0.1 | 0.05  | 0.05 |
|                  | Trough   | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 900       | 750       | 1        | 58      | 0   | 2        | 6.5  | 4.45  | 1.6  | 0.05         | 24  | 4.125 | 7.88 |
|                  | Conglom  | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 900       | 750       | 0.165    | 58      | 0   | 2.5      | 5.5  | 4.135 | 1.32 | 0.15         | 17  | 2.38  | 4.71 |
| Burro Canyon Ms  | Mudstone | AV     | 17000       | 0  |      |        |           |           |           |          |         |     |          |      |       |      |              |     |       |      |
| Burro Canyon S53 | Planar   | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 900       | 750       | 0.25     | 58      | 0   | 0.45     | 2.85 | 1.335 | 1.32 | 0.05         | 0.1 | 0.05  | 0.05 |
|                  | Trough   | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 900       | 750       | 1        | 58      | 0   | 2        | 6.5  | 4.45  | 1.6  | 0.05         | 24  | 4.125 | 7.88 |
|                  | Conglom  | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 900       | 750       | 0.165    | 58      | 0   | 2.5      | 5.5  | 4.135 | 1.32 | 0.15         | 17  | 2.38  | 4.71 |
| Burro Canyon Ms  | Mudstone | AV     | 17000       | 0  |      |        |           |           |           |          |         |     |          |      |       |      |              |     |       |      |
| Burro Canyon S52 | Planar   | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 900       | 750       | 0.25     | 58      | 0   | 0.45     | 2.85 | 1.335 | 1.32 | 0.05         | 0.1 | 0.05  | 0.05 |
|                  | Trough   | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 900       | 750       | 1        | 58      | 0   | 2        | 6.5  | 4.45  | 1.6  | 0.05         | 24  | 4.125 | 7.88 |
|                  | Conglom  | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 900       | 750       | 0.165    | 58      | 0   | 2.5      | 5.5  | 4.135 | 1.32 | 0.15         | 17  | 2.38  | 4.71 |
| Burro Canyon Ms  | Mudstone | AV     | 17000       | 0  |      |        |           |           |           |          |         |     |          |      |       |      |              |     |       |      |
| Burro Canyon S51 | Planar   | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 65        | 55        | 0.165    | 58      | 0   | 0.45     | 2.85 | 1.335 | 1.32 | 0.05         | 0.1 | 0.05  | 0.05 |
|                  | Trough   | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 65        | 55        | 1        | 58      | 0   | 2        | 6.5  | 4.45  | 1.6  | 0.05         | 24  | 4.125 | 7.88 |
|                  | Conglom  | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 65        | 55        | 0.165    | 58      | 0   | 2.5      | 5.5  | 4.135 | 1.32 | 0.15         | 17  | 2.38  | 4.71 |
| Burro Canyon Ms  | Mudstone | AV     | 17000       | 0  |      |        |           |           |           |          |         |     |          |      |       |      |              |     |       |      |
| Morrison Ms      | Mudstone | AV     | 17000       | 0  |      |        |           |           |           |          |         |     |          |      |       |      |              |     |       |      |
| Morrison S52     | Planar   | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 240       | 205       | 0.165    | 58      | 0   | 0.45     | 2.85 | 1.335 | 1.32 | 0.05         | 0.1 | 0.05  | 0.05 |
|                  | Trough   | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 240       | 205       | 1        | 58      | 0   | 2        | 6.5  | 4.45  | 1.6  | 0.05         | 24  | 4.125 | 7.88 |
|                  | Conglom  | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 240       | 205       | 0.165    | 58      | 0   | 2.5      | 5.5  | 4.135 | 1.32 | 0.15         | 17  | 2.38  | 4.71 |
| Morrison S51     | Planar   | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 240       | 205       | 0.165    | 58      | 0   | 0.45     | 2.85 | 1.335 | 1.32 | 0.05         | 0.1 | 0.05  | 0.05 |
|                  | Trough   | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 240       | 205       | 1        | 58      | 0   | 2        | 6.5  | 4.45  | 1.6  | 0.05         | 24  | 4.125 | 7.88 |
|                  | Conglom  | SGS    | 17000       |    | 1    | 0.0001 | Spherical | 240       | 205       | 0.165    | 58      | 0   | 2.5      | 5.5  | 4.135 | 1.32 | 0.15         | 17  | 2.38  | 4.71 |
| Morrison Ms      | Mudstone | AV     | 17000       | 0  |      |        |           |           |           |          |         |     |          |      |       |      |              |     |       |      |



## CF Petrophysical Variograms

### CF1-L3-P3 / CF2-L3-P3

| Zones            | Facies   | Method | Global Seed VA | Sill | Nugget | Type      | Major dir | Minor dir | Vertical | Azimuth | Dip | Porosity |      |       |      | Permeability |     |      |       |
|------------------|----------|--------|----------------|------|--------|-----------|-----------|-----------|----------|---------|-----|----------|------|-------|------|--------------|-----|------|-------|
|                  |          |        |                |      |        |           |           |           |          |         |     | Min      | Max  | Mean  | Std. | Min          | Max | Mean | Std   |
| Dakota           | Mudstone | AV     |                | 0    |        |           |           |           |          |         |     |          |      |       |      |              |     |      |       |
| Burro Canyon S58 | Planar   | SGS    | 17000          | 1    | 0.0001 | Spherical | 1100      | 1000      | 3        | 58      | 0   | 1.8      | 11.4 | 5.34  | 5.28 | 0.2          | 0.4 | 0.2  | 0.2   |
|                  | Trough   | SGS    | 17000          | 1    | 0.0001 | Spherical | 1100      | 1000      | 4        | 58      | 0   | 8        | 26   | 17.8  | 6.4  | 0.2          | 96  | 16.5 | 31.52 |
|                  | Conglom  | SGS    | 17000          | 1    | 0.0001 | Spherical | 1100      | 1000      | 0.66     | 58      | 0   | 10       | 22   | 16.54 | 5.28 | 0.6          | 68  | 9.52 | 18.84 |
| Burro Canyon Ms  | Mudstone | AV     | 17000          | 0    |        |           |           |           |          |         |     |          |      |       |      |              |     |      |       |
| Burro Canyon S57 | Planar   | SGS    | 17000          | 1    | 0.0001 | Spherical | 1100      | 1000      | 2        | 58      | 0   | 1.8      | 11.4 | 5.34  | 5.28 | 0.2          | 0.4 | 0.2  | 0.2   |
|                  | Trough   | SGS    | 17000          | 1    | 0.0001 | Spherical | 1100      | 1000      | 4        | 58      | 0   | 8        | 26   | 17.8  | 6.4  | 0.2          | 96  | 16.5 | 31.52 |
|                  | Conglom  | SGS    | 17000          | 1    | 0.0001 | Spherical | 1100      | 1000      | 0.66     | 58      | 0   | 10       | 22   | 16.54 | 5.28 | 0.6          | 68  | 9.52 | 18.84 |
| Burro Canyon S56 | Planar   | SGS    | 17000          | 1    | 0.0001 | Spherical | 1100      | 1000      | 2        | 58      | 0   | 1.8      | 11.4 | 5.34  | 5.28 | 0.2          | 0.4 | 0.2  | 0.2   |
|                  | Trough   | SGS    | 17000          | 1    | 0.0001 | Spherical | 1100      | 1000      | 4        | 58      | 0   | 8        | 26   | 17.8  | 6.4  | 0.2          | 96  | 16.5 | 31.52 |
|                  | Conglom  | SGS    | 17000          | 1    | 0.0001 | Spherical | 1100      | 1000      | 0.66     | 58      | 0   | 10       | 22   | 16.54 | 5.28 | 0.6          | 68  | 9.52 | 18.84 |
| Burro Canyon Ms  | Mudstone | AV     | 17000          | 0    |        |           |           |           |          |         |     |          |      |       |      |              |     |      |       |
| Burro Canyon S55 | Planar   | SGS    | 17000          | 1    | 0.0001 | Spherical | 800       | 200       | 1        | 58      | 0   | 1.8      | 11.4 | 5.34  | 5.28 | 0.2          | 0.4 | 0.2  | 0.2   |
|                  | Trough   | SGS    | 17000          | 1    | 0.0001 | Spherical | 800       | 200       | 4        | 58      | 0   | 8        | 26   | 17.8  | 6.4  | 0.2          | 96  | 16.5 | 31.52 |
|                  | Conglom  | SGS    | 17000          | 1    | 0.0001 | Spherical | 800       | 200       | 0.66     | 58      | 0   | 10       | 22   | 16.54 | 5.28 | 0.6          | 68  | 9.52 | 18.84 |
| Burro Canyon Ms  | Mudstone | AV     | 17000          | 0    |        |           |           |           |          |         |     |          |      |       |      |              |     |      |       |
| Burro Canyon S54 | Planar   | SGS    | 17000          | 1    | 0.0001 | Spherical | 3600      | 3000      | 1        | 58      | 0   | 1.8      | 11.4 | 5.34  | 5.28 | 0.2          | 0.4 | 0.2  | 0.2   |
|                  | Trough   | SGS    | 17000          | 1    | 0.0001 | Spherical | 3600      | 3000      | 4        | 58      | 0   | 8        | 26   | 17.8  | 6.4  | 0.2          | 96  | 16.5 | 31.52 |
|                  | Conglom  | SGS    | 17000          | 1    | 0.0001 | Spherical | 3600      | 3000      | 0.66     | 58      | 0   | 10       | 22   | 16.54 | 5.28 | 0.6          | 68  | 9.52 | 18.84 |
| Burro Canyon Ms  | Mudstone | AV     | 17000          | 0    |        |           |           |           |          |         |     |          |      |       |      |              |     |      |       |
| Burro Canyon S53 | Planar   | SGS    | 17000          | 1    | 0.0001 | Spherical | 3600      | 3000      | 1        | 58      | 0   | 1.8      | 11.4 | 5.34  | 5.28 | 0.2          | 0.4 | 0.2  | 0.2   |
|                  | Trough   | SGS    | 17000          | 1    | 0.0001 | Spherical | 3600      | 3000      | 4        | 58      | 0   | 8        | 26   | 17.8  | 6.4  | 0.2          | 96  | 16.5 | 31.52 |
|                  | Conglom  | SGS    | 17000          | 1    | 0.0001 | Spherical | 3600      | 3000      | 0.66     | 58      | 0   | 10       | 22   | 16.54 | 5.28 | 0.6          | 68  | 9.52 | 18.84 |
| Burro Canyon Ms  | Mudstone | AV     | 17000          | 0    |        |           |           |           |          |         |     |          |      |       |      |              |     |      |       |
| Burro Canyon S52 | Planar   | SGS    | 17000          | 1    | 0.0001 | Spherical | 3600      | 3000      | 1        | 58      | 0   | 1.8      | 11.4 | 5.34  | 5.28 | 0.2          | 0.4 | 0.2  | 0.2   |
|                  | Trough   | SGS    | 17000          | 1    | 0.0001 | Spherical | 3600      | 3000      | 4        | 58      | 0   | 8        | 26   | 17.8  | 6.4  | 0.2          | 96  | 16.5 | 31.52 |
|                  | Conglom  | SGS    | 17000          | 1    | 0.0001 | Spherical | 3600      | 3000      | 0.66     | 58      | 0   | 10       | 22   | 16.54 | 5.28 | 0.6          | 68  | 9.52 | 18.84 |
| Burro Canyon Ms  | Mudstone | AV     | 17000          | 0    |        |           |           |           |          |         |     |          |      |       |      |              |     |      |       |
| Burro Canyon S51 | Planar   | SGS    | 17000          | 1    | 0.0001 | Spherical | 260       | 220       | 0.66     | 58      | 0   | 1.8      | 11.4 | 5.34  | 5.28 | 0.2          | 0.4 | 0.2  | 0.2   |
|                  | Trough   | SGS    | 17000          | 1    | 0.0001 | Spherical | 260       | 220       | 4        | 58      | 0   | 8        | 26   | 17.8  | 6.4  | 0.2          | 96  | 16.5 | 31.52 |
|                  | Mudstone | AV     | 17000          | 0    |        |           |           |           |          |         |     |          |      |       |      |              |     |      |       |
| Morrison Ms      | Mudstone | AV     | 17000          | 0    |        |           |           |           |          |         |     |          |      |       |      |              |     |      |       |
| Morrison S52     | Planar   | SGS    | 17000          | 1    | 0.0001 | Spherical | 960       | 820       | 0.66     | 58      | 0   | 1.8      | 11.4 | 5.34  | 5.28 | 0.2          | 0.4 | 0.2  | 0.2   |
|                  | Trough   | SGS    | 17000          | 1    | 0.0001 | Spherical | 960       | 820       | 4        | 58      | 0   | 8        | 26   | 17.8  | 6.4  | 0.2          | 96  | 16.5 | 31.52 |
|                  | Conglom  | SGS    | 17000          | 1    | 0.0001 | Spherical | 960       | 820       | 0.66     | 58      | 0   | 10       | 22   | 16.54 | 5.28 | 0.6          | 68  | 9.52 | 18.84 |
| Morrison S51     | Planar   | SGS    | 17000          | 1    | 0.0001 | Spherical | 960       | 820       | 0.66     | 58      | 0   | 1.8      | 11.4 | 5.34  | 5.28 | 0.2          | 0.4 | 0.2  | 0.2   |
|                  | Trough   | SGS    | 17000          | 1    | 0.0001 | Spherical | 960       | 820       | 4        | 58      | 0   | 8        | 26   | 17.8  | 6.4  | 0.2          | 96  | 16.5 | 31.52 |
|                  | Conglom  | SGS    | 17000          | 1    | 0.0001 | Spherical | 960       | 820       | 0.66     | 58      | 0   | 10       | 22   | 16.54 | 5.28 | 0.6          | 68  | 9.52 | 18.84 |
| Morrison Ms      | Mudstone | AV     | 17000          | 0    |        |           |           |           |          |         |     |          |      |       |      |              |     |      |       |

### CF1-L1-P4 / CF2-L1-P4 / 3DCF-L1-P4

| Zones            | Facies   | Method       | Global Seed | VA | Sill   | Nugget    | Type | Major dir | Minor dir | Vertical | Azimuth | Dip | Porosity |      |      |       | Permeability |      |       |     |
|------------------|----------|--------------|-------------|----|--------|-----------|------|-----------|-----------|----------|---------|-----|----------|------|------|-------|--------------|------|-------|-----|
|                  |          |              |             |    |        |           |      |           |           |          |         |     | Min      | Max  | Mean | Std.  | Min          | Max  | Mean  | Std |
| Dakota           | Mudstone | Assign Value |             |    | 0      |           |      |           |           |          |         |     |          |      |      |       |              |      |       |     |
| Burro Canyon S58 | Planar   | SGS          | 17000       | 1  | 0.0001 | Spherical | 550  | 500       | 1.5       | 58       | 0       | 0.9 | 5.7      | 2.67 | 2.64 | 0.1   | 0.2          | 0.1  | 0.1   |     |
|                  | Trough   | SGS          | 17000       | 1  | 0.0001 | Spherical | 550  | 500       | 2         | 58       | 0       | 4   | 13       | 8.9  | 3.2  | 0.1   | 48           | 8.25 | 15.76 |     |
|                  | Conglom  | SGS          | 17000       | 1  | 0.0001 | Spherical | 550  | 500       | 0.33      | 58       | 0       | 0   | 8        | 4    | 2    | 0.001 | 0.5          | 0.02 | 0.01  |     |
| Burro Canyon Ms  | Mudstone | Assign Value | 17000       | 0  |        |           |      |           |           |          |         |     |          |      |      |       |              |      |       |     |
| Burro Canyon S57 | Planar   | SGS          | 17000       | 1  | 0.0001 | Spherical | 550  | 500       | 1         | 58       | 0       | 0.9 | 5.7      | 2.67 | 2.64 | 0.1   | 0.2          | 0.1  | 0.1   |     |
|                  | Trough   | SGS          | 17000       | 1  | 0.0001 | Spherical | 550  | 500       | 2         | 58       | 0       | 4   | 13       | 8.9  | 3.2  | 0.1   | 48           | 8.25 | 15.76 |     |
|                  | Conglom  | SGS          | 17000       | 1  | 0.0001 | Spherical | 550  | 500       | 0.33      | 58       | 0       | 0   | 8        | 4    | 2    | 0.001 | 0.5          | 0.02 | 0.01  |     |
| Burro Canyon S56 | Planar   | SGS          | 17000       | 1  | 0.0001 | Spherical | 550  | 500       | 1         | 58       | 0       | 0.9 | 5.7      | 2.67 | 2.64 | 0.1   | 0.2          | 0.1  | 0.1   |     |
|                  | Trough   | SGS          | 17000       | 1  | 0.0001 | Spherical | 550  | 500       | 2         | 58       | 0       | 4   | 13       | 8.9  | 3.2  | 0.1   | 48           | 8.25 | 15.76 |     |
|                  | Conglom  | SGS          | 17000       | 1  | 0.0001 | Spherical | 550  | 500       | 0.33      | 58       | 0       | 0   | 8        | 4    | 2    | 0.001 | 0.5          | 0.02 | 0.01  |     |
| Burro Canyon Ms  | Mudstone | Assign Value | 17000       | 0  |        |           |      |           |           |          |         |     |          |      |      |       |              |      |       |     |
| Burro Canyon S55 | Planar   | SGS          | 17000       | 1  | 0.0001 | Spherical | 400  | 100       | 0.5       | 58       | 0       | 0.9 | 5.7      | 2.67 | 2.64 | 0.1   | 0.2          | 0.1  | 0.1   |     |
|                  | Trough   | SGS          | 17000       | 1  | 0.0001 | Spherical | 400  | 100       | 2         | 58       | 0       | 4   | 13       | 8.9  | 3.2  | 0.1   | 48           | 8.25 | 15.76 |     |
|                  | Conglom  | SGS          | 17000       | 1  | 0.0001 | Spherical | 400  | 100       | 0.33      | 58       | 0       | 0   | 8        | 4    | 2    | 0.001 | 0.5          | 0.02 | 0.01  |     |
| Burro Canyon Ms  | Mudstone | Assign Value | 17000       | 0  |        |           |      |           |           |          |         |     |          |      |      |       |              |      |       |     |
| Burro Canyon S54 | Planar   | SGS          | 17000       | 1  | 0.0001 | Spherical | 1800 | 1500      | 0.5       | 58       | 0       | 0.9 | 5.7      | 2.67 | 2.64 | 0.1   | 0.2          | 0.1  | 0.1   |     |
|                  | Trough   | SGS          | 17000       | 1  | 0.0001 | Spherical | 1800 | 1500      | 2         | 58       | 0       | 4   | 13       | 8.9  | 3.2  | 0.1   | 48           | 8.25 | 15.76 |     |
|                  | Conglom  | SGS          | 17000       | 1  | 0.0001 | Spherical | 1800 | 1500      | 0.33      | 58       | 0       | 0   | 8        | 4    | 2    | 0.001 | 0.5          | 0.02 | 0.01  |     |
| Burro Canyon Ms  | Mudstone | Assign Value | 17000       | 0  |        |           |      |           |           |          |         |     |          |      |      |       |              |      |       |     |
| Burro Canyon S53 | Planar   | SGS          | 17000       | 1  | 0.0001 | Spherical | 1800 | 1500      | 0.5       | 58       | 0       | 0.9 | 5.7      | 2.67 | 2.64 | 0.1   | 0.2          | 0.1  | 0.1   |     |
|                  | Trough   | SGS          | 17000       | 1  | 0.0001 | Spherical | 1800 | 1500      | 2         | 58       | 0       | 4   | 13       | 8.9  | 3.2  | 0.1   | 48           | 8.25 | 15.76 |     |
|                  | Conglom  | SGS          | 17000       | 1  | 0.0001 | Spherical | 1800 | 1500      | 0.33      | 58       | 0       | 0   | 8        | 4    | 2    | 0.001 | 0.5          | 0.02 | 0.01  |     |
| Burro Canyon Ms  | Mudstone | Assign Value | 17000       | 0  |        |           |      |           |           |          |         |     |          |      |      |       |              |      |       |     |
| Burro Canyon S52 | Planar   | SGS          | 17000       | 1  | 0.0001 | Spherical | 1800 | 1500      | 0.5       | 58       | 0       | 0.9 | 5.7      | 2.67 | 2.64 | 0.1   | 0.2          | 0.1  | 0.1   |     |
|                  | Trough   | SGS          | 17000       | 1  | 0.0001 | Spherical | 1800 | 1500      | 2         | 58       | 0       | 4   | 13       | 8.9  | 3.2  | 0.1   | 48           | 8.25 | 15.76 |     |
|                  | Conglom  | SGS          | 17000       | 1  | 0.0001 | Spherical | 1800 | 1500      | 0.33      | 58       | 0       | 0   | 8        | 4    | 2    | 0.001 | 0.5          | 0.02 | 0.01  |     |
| Burro Canyon Ms  | Mudstone | Assign Value | 17000       | 0  |        |           |      |           |           |          |         |     |          |      |      |       |              |      |       |     |
| Burro Canyon S51 | Planar   | SGS          | 17000       | 1  | 0.0001 | Spherical | 130  | 110       | 0.33      | 58       | 0       | 0.9 | 5.7      | 2.67 | 2.64 | 0.1   | 0.2          | 0.1  | 0.1   |     |
|                  | Trough   | SGS          | 17000       | 1  | 0.0001 | Spherical | 130  | 110       | 2         | 58       | 0       | 0   | 8        | 4    | 2    | 0.1   | 48           | 8.25 | 15.76 |     |
|                  | Mudstone | Assign Value | 17000       | 0  |        |           |      |           |           |          |         |     |          |      |      |       |              |      |       |     |
| Morrison Ms      | Mudstone | Assign Value | 17000       | 0  |        |           |      |           |           |          |         |     |          |      |      |       |              |      |       |     |
| Morrison S52     | Planar   | SGS          | 17000       | 1  | 0.0001 | Spherical | 480  | 410       | 0.33      | 58       | 0       | 0.9 | 5.7      | 2.67 | 2.64 | 0.1   | 0.2          | 0.1  | 0.1   |     |
|                  | Trough   | SGS          | 17000       | 1  | 0.0001 | Spherical | 480  | 410       | 2         | 58       | 0       | 4   | 13       | 8.9  | 3.2  | 0.1   | 48           | 8.25 | 15.76 |     |
|                  | Conglom  | SGS          | 17000       | 1  | 0.0001 | Spherical | 480  | 410       | 0.33      | 58       | 0       | 0   | 8        | 4    | 2    | 0.001 | 0.5          | 0.02 | 0.01  |     |
| Morrison S51     | Planar   | SGS          | 17000       | 1  | 0.0001 | Spherical | 480  | 410       | 0.33      | 58       | 0       | 0.9 | 5.7      | 2.67 | 2.64 | 0.1   | 0.2          | 0.1  | 0.1   |     |
|                  | Trough   | SGS          | 17000       | 1  | 0.0001 | Spherical | 480  | 410       | 2         | 58       | 0       | 4   | 13       | 8.9  | 3.2  | 0.1   | 48           | 8.25 | 15.76 |     |
|                  | Conglom  | SGS          | 17000       | 1  | 0.0001 | Spherical | 480  | 410       | 0.33      | 58       | 0       | 0   | 8        | 4    | 2    | 0.001 | 0.5          | 0.02 | 0.01  |     |
| Morrison Ms      | Mudstone | Assign Value | 17000       | 0  |        |           |      |           |           |          |         |     |          |      |      |       |              |      |       |     |

the 2-D models, injector and producer wells are located on either end of the model spaced 866 ft (264 m) apart. In the 3-D models, injector and producer wells are in diagonal corners 1220 ft (372 m) apart. Models were constructed at reservoir depth utilizing the Burro Canyon Formation depths from the Mitchell Energy 8-1 Federal well to accurately represent the temperature and pressure environment during the fluid-flow simulation process.

Isotropic horizontal permeability (i- and j-orientation) is used and vertical permeability (k-orientation) was scaled to 10% of the horizontal permeability. Gas-oil and oil-water contacts are set above and below the model interval to prevent flow interference. Reservoir conditions use a reference pressure of 215 bar (3120 psi), oil gravity of 45 dAPI, and water salinity of 3000 ppm, to mimic subsurface conditions. Flow from the producer well was controlled by a maximum flow rate of 300 sm<sup>3</sup>/d and upon pressure decline, producer well flow was controlled by a bottom hole pressure of 25 bar (363psi). Flow through the injector well is controlled by a maximum injection flow rate of 334 sm<sup>3</sup>/d or maximum bottom hole pressure of 425 bar (6164 psi).

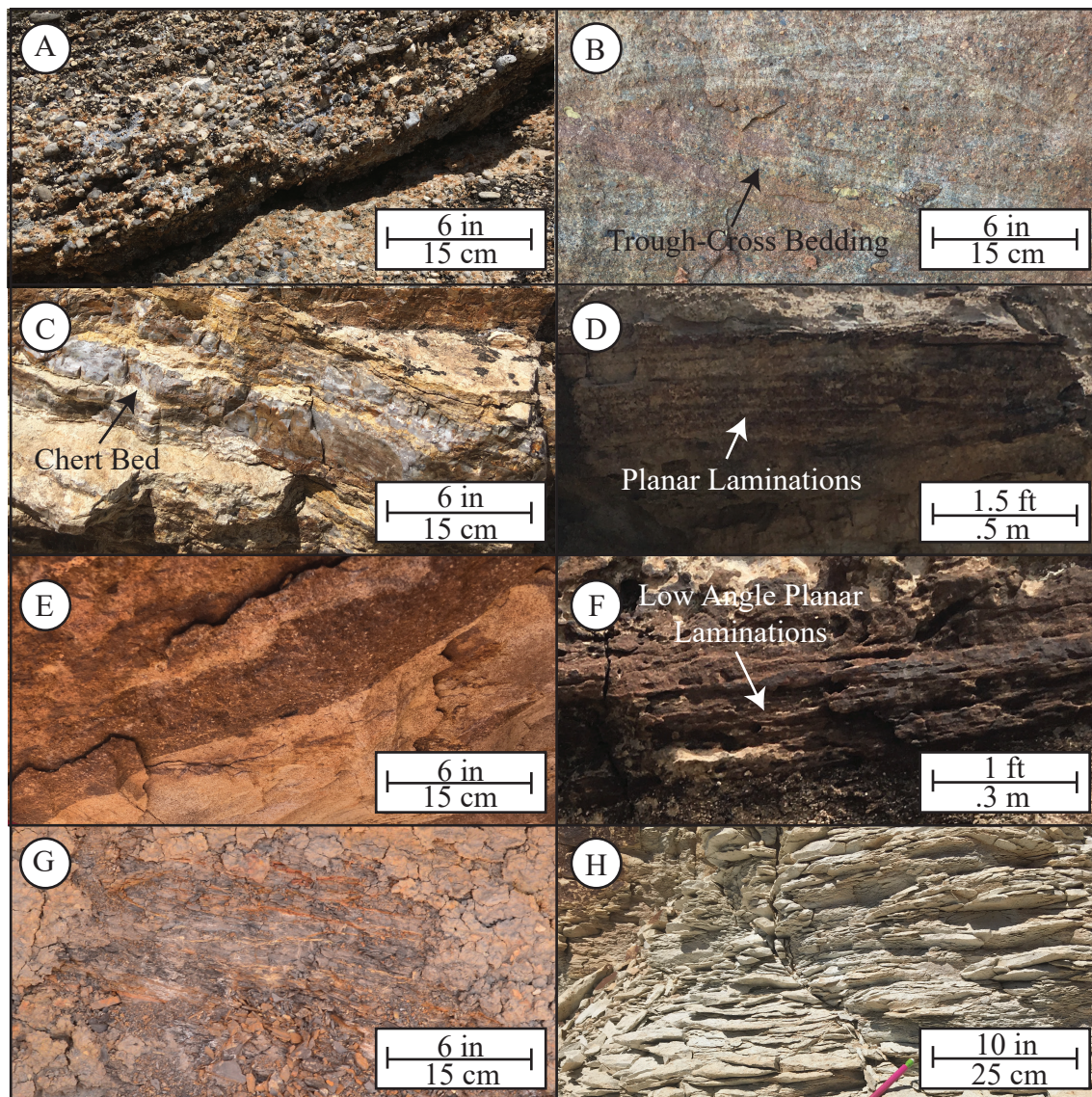
Simulations for 2-D models are each run for 100 years to ensure water breakthrough at the production well in each model. Three-dimensional models are run for 120 years to ensure water breakthrough at the production well. Simulations are evaluated in terms of 1) breakthrough time (BTT), 2) volumetric sweep efficiency at BTT, 3) recovery efficiency at BTT and at 100 years, and 4) cumulative production of oil, gas, and water at 100 years.

## **Results**

## **Lithofacies and Stratigraphic Architecture**

The Burro Canyon Formation consists of alternating lenticular beds of fine- to medium-grained sandstones and conglomerates interbedded with gray-green mudstones. In Rattlesnake Canyon, the Burro Canyon Formation is approximately 126 ft (38.5 m) thick and consists of eight lithofacies: (1) granule-pebble conglomerate; (2) trough cross-bedded sandstone; (3) chert-rich sandstone; (4) planar-laminated sandstone; (5) structureless sandstone; (6) low-angle planar-laminated sandstone; (7) fissile gray-black mudstone; and (8) gray-green mudstone (Figure 7 and Table 5). Framework grains of the Burro Canyon Formation include quartz and occasional chert grains, iron oxides, lithics, and intraclasts of carbonate mud. Calcite cement is most common with variable and less common silica cement observed in channel sandstones. Grains are well rounded and well sorted with occasional quartz overgrowths (Figure 8). Evidence of suture contacts can be observed in certain samples indicating high compaction during lithification (Figure 8).

The Burro Canyon Formation contains isolated to amalgamated sandstone bodies that range from 3.7–33.8 ft (1.1–10.3 m) in thickness and often exhibit an upward-fining grain-size profile. The sandstones are generally conglomeratic at the base and beds thin upward into a fine- to medium-grained sandstone. Basal conglomeratic beds contain granule- to pebble-size clasts supported in a medium- to coarse-grained sandstone matrix. Fine- to medium-grained sandstones commonly exhibit trough cross-bedding, planar laminations, and occasionally low-angle planar laminations near the top of sandstone beds. Sandstone bodies are bounded at the base by sharp scour surfaces



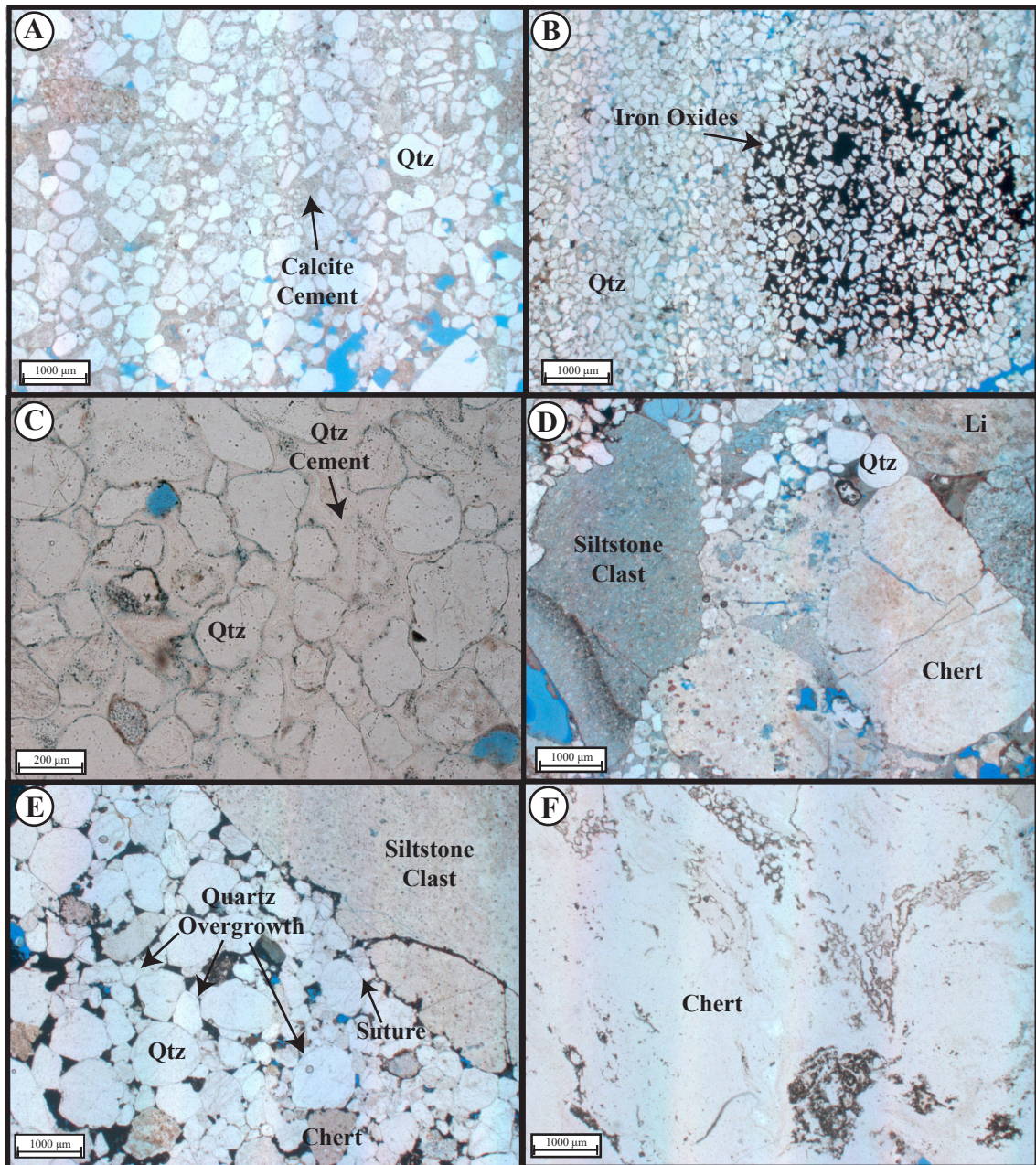
**Figure 7.** Photos of outcrop lithofacies derived from the burro canyon formation. Facies A, granule-pebble conglomerate; Facies B, trough cross-bedded sandstone; Facies C, chert-rich sandstone; Facies D, planar laminated sandstone; Facies E, structureless sandstone; Facies F, low angle planar laminated sandstone; Facies G, black, fissile, carbonaceous mudstone; Facies H, gray-green mudstone. Structureless sandstone is likely trough cross-bedded sandstone that has been highly weathered and appears structureless in outcrop.

## Outcrop Lithofacies

| Facies Code | Facies Name                            | Grain Size                 | Sorting         | Stratification              | Color           | Cement Type      | Clast Type                | Thickness | Depositional Environments            |
|-------------|----------------------------------------|----------------------------|-----------------|-----------------------------|-----------------|------------------|---------------------------|-----------|--------------------------------------|
| A           | Conglomeratic Granule-Pebble Sandstone | Granule-Pebble             | Poor-Moderate   | —                           | Dark Brown/Tan  | Calcite          | Quartzite, Chert, Lithics | 1-3 ft    | Channel Floor Lag                    |
| B           | Trough Cross-Bedded Sandstone          | Fine- to Medium-Grained    | Moderate - High | Trough-Cross Stratification | Light Brown/Tan | Calcite / Silica | Quartz, Chert             | 1-15 ft   | Cross Channel Bars and Compound Bars |
| C           | Chert-Rich Sandstone                   | —                          | High            | 2-6 in laminations          | Light Gray      | —                | Chert                     | 2 ft      | Diagenetic                           |
| D           | Planar Laminated Sandstone             | Very Fine- to Fine-Grained | Moderate - High | Planar Laminated            | Light Brown/Tan | Calcite          | Quartz, Calcite           | 1-5 ft    | Compound Bars                        |
| E           | Structureless Sandstone                | Fine- to Medium-Grained    | Moderate - High | —                           | Light Brown/Tan | Calcite / Silica | Quartz, Chert             | 1-15 ft   | Cross Channel Bars and Compound Bars |
| F           | Low-Angle Planar Laminated Sandstone   | Very Fine- to Fine-Grained | Moderate - High | Low-Angle Laminated         | Rust Brown      | Calcite          | Quartz, Calcite           | 1-5 ft    | Compound Bars                        |
| G           | Fissile Mudstone                       | Clay-Sized                 | High            | Thinly Laminated            | Gray-Black      | Calcite          | Mudstone                  | 5-30 ft   | Floodplain                           |
| H           | Gray-Green Mudstone                    | Clay-Sized                 | High            | Thinly Laminated            | Gray-Green      | Calcite          | Mudstone                  | 5-30 ft   | Floodplain/ Lacustrine               |

**Table 5.** Outcrop lithofacies descriptions from three measured sections in Rattlesnake Canyon.





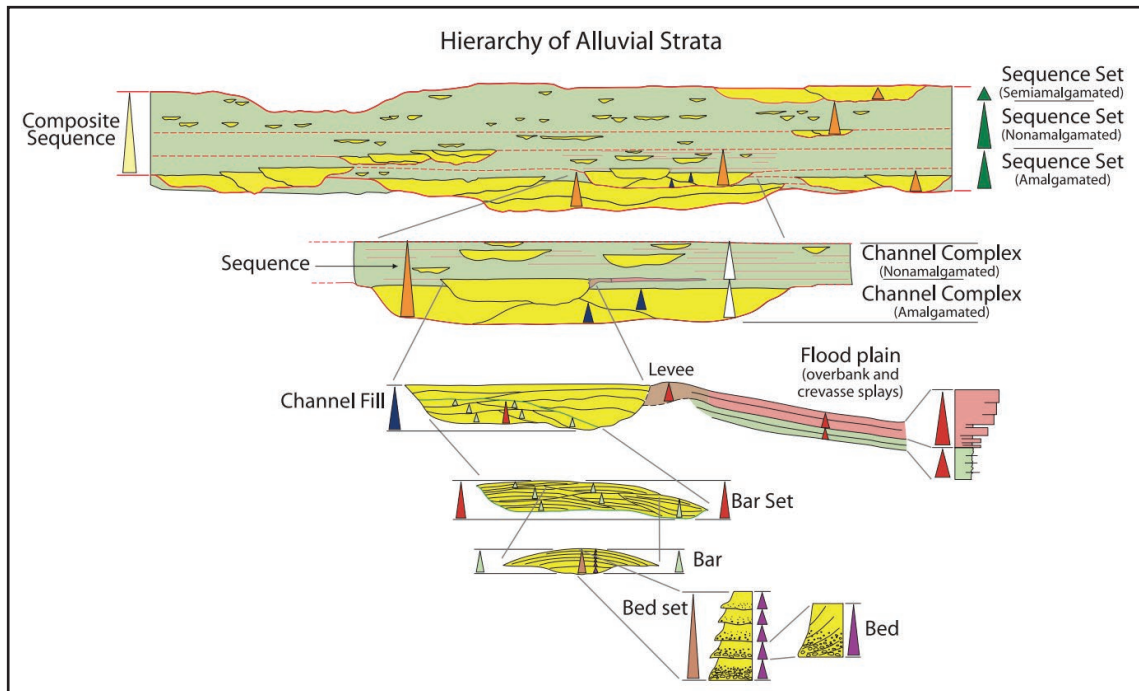
**Figure 8.** Thin section photos showing major depositional differences occurring throughout the Burro Canyon Formation. A) Quartz and minor chert grains cemented with calcite. B) Iron oxide encompassing quartz and minor chert grains, cement composed of calcite. C) Quartz grains in a silica cement. D) Sample of conglomeratic beds, showing quartzite, lithics (Li) and siltstone clasts surrounded by a quartz sandstone matrix with calcite cement. E) Siltstone clast in quartz and chert sandstone matrix with calcite cement. F) Chert from upper chert bed in the Burro Canyon Formation.

and are commonly amalgamated. Lenticular sandstones of the Burro Canyon Formation are overlain by a green-gray mudstone.

This study follows the hierarchy of alluvial strata established by Patterson et al. (1995; 2002; 2010) and Sprague et al. (2002) which utilizes physical characteristics and bounding surfaces of fluvial sandstone bodies (Patterson et al., 2012) (Figure 9). The Burro Canyon Formation represents a single depositional sequence that is composed of a lower amalgamated channel complex and overlying semi-amalgamated channel complex. In addition, the upper Morrison Formation forms a semi-amalgamated channel complex. Channel complexes are comprised of distinct channel-fill elements. Patterson et al., (2010) defined the channel-fill element as a relatively conformable succession of genetically related bar or bar-set deposits within a channel defined by bankful discharge. Small-scale elements such as bed sets and bar sets are observed in measured section descriptions.

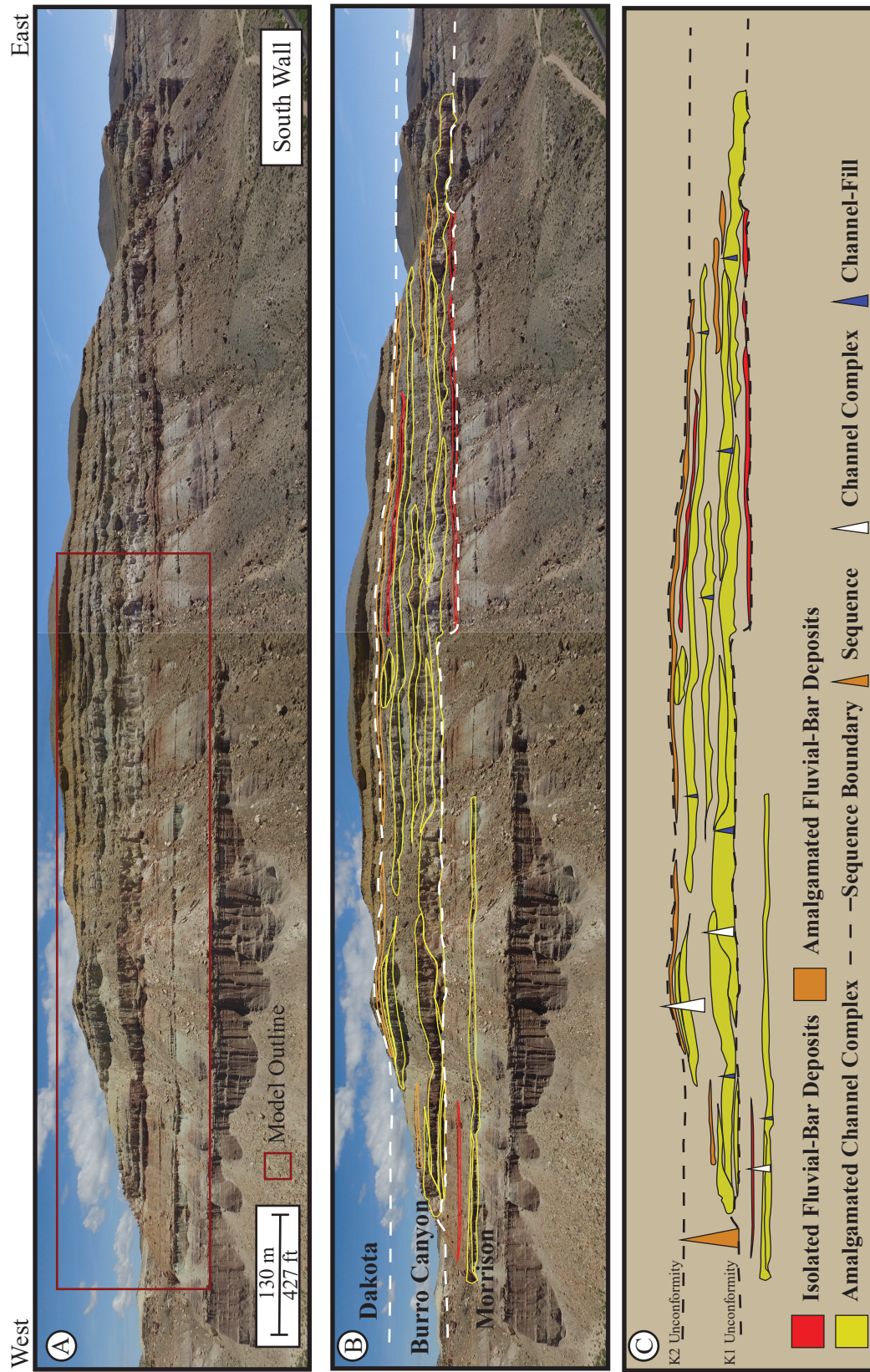
Using the hierarchy of alluvial strata as defined by Patterson et al. (2010), alluvial strata of the Burro Canyon Formation consist of four key architectural elements (facies associations) that can stack to form a depositional sequence: (1) channel complex (amalgamated, semi-amalgamated), (2) amalgamated fluvial-bar deposits, (3) isolated fluvial-bar deposits (sand flats), and (4) floodplain fines (Figures 10 and 11).

The largest architectural element in the Burro Canyon Formation, amalgamated channel complexes, consist of channel-fill elements that are vertically stacked and overlain by a mudstone-dominated interval of semi-amalgamated channel complex elements. The amalgamated channel complex is sandstone-prone and possesses an erosional base interpreted as a sequence boundary (Patterson et al., 2012). Above the



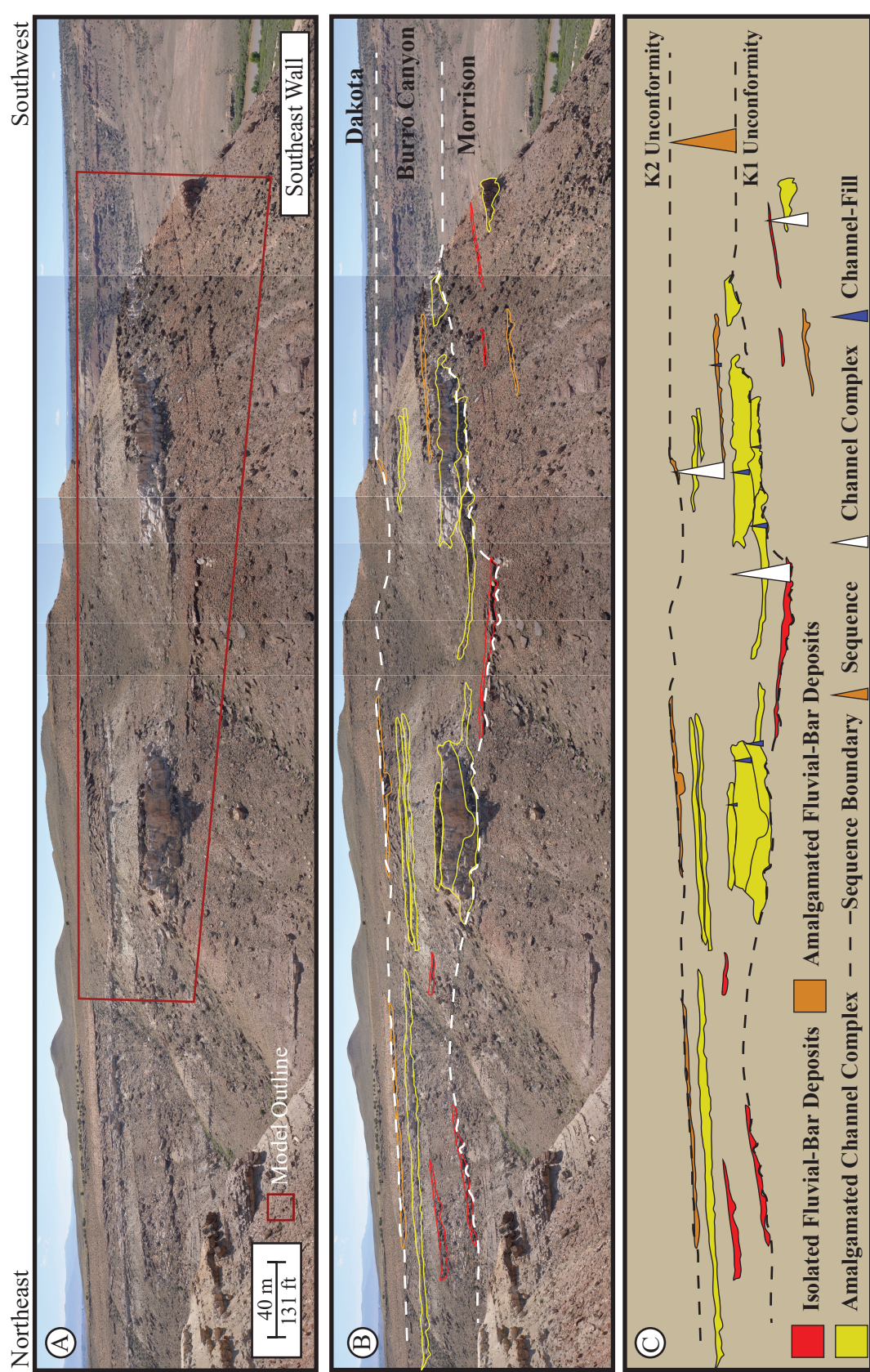
**Figure 9.** Schematic diagram of alluvial hierarchical elements from Patterson et al., 2012 and Sprague et al., 2002. Fluvial sandstones are shown in yellow with floodplain mudstones in green, levee sandstones in brown and crevasse splays in pink. Colored triangles represent hierarchical elements associated with alluvial strata.





**Figure 10.** Photomosaic of architectural elements and hierarchical elements along the South wall of Rattlesnake Canyon associated with those defined by Patterson et al., 2012 and Sprague et al., 2002.





**Figure 11.** Photomosaic of architectural elements and hierarchical elements along the Southeast wall of Rattlesnake Canyon associated with those defined by Patterson et al., 2012 and Sprague et al., 2002.

basal scour surface, conglomeratic lag (limited sandstone matrix) deposits are common and are overlain by conglomeratic sandstones. This conglomeratic sequence is topped by a fining-upward sequence of fine-to-medium-grained bar sets that are commonly trough cross-stratified to horizontally planar laminated. Bar sets are topped with low angle planar laminations that grade into mudstone facies. Commonly, the top of bar sets is not preserved as the channels have scoured into the bed sets below. The amalgamated channel complex ranges from 7 to 45 ft (2 to 14 m) thick and extends laterally from 197 to 1805 ft (60 to 550 m) throughout the observed portion of Rattlesnake Canyon.

Amalgamated fluvial-bar deposits are sandstone beds with an upward-fining nature and are horizontal-planar laminated to low-angle planar-laminated lithofacies. Individual beds stack vertically to create bar sets that comprise amalgamated fluvial-bar deposits. Amalgamated fluvial-bar deposits are encased in floodplain mudstones and are less extensive than amalgamated channel complexes in Rattlesnake Canyon. Individual amalgamated fluvial-bars range from 4 ft to 35 ft (1.2 m to 10.5 m) in thickness with width-to-thickness ratios ranging from 5:1 – 155:1.

Isolated fluvial-bar deposits (or sand flats) are fining-upward sandstone successions encased in floodplain mudstones that together form a semi-amalgamated channel complex. Low-angle planar laminations and minor horizontal-planar laminations are common in these architectural elements and mudstone rip-up clasts occur irregularly throughout the deposits. This architectural element is composed of sandstone channels that are approximately 7 ft (~2 m) wide and less than 1.5 ft (0.5 m) thick that conjoin to create laterally continuous sand flats (Lorenz and Nadon, 2002).

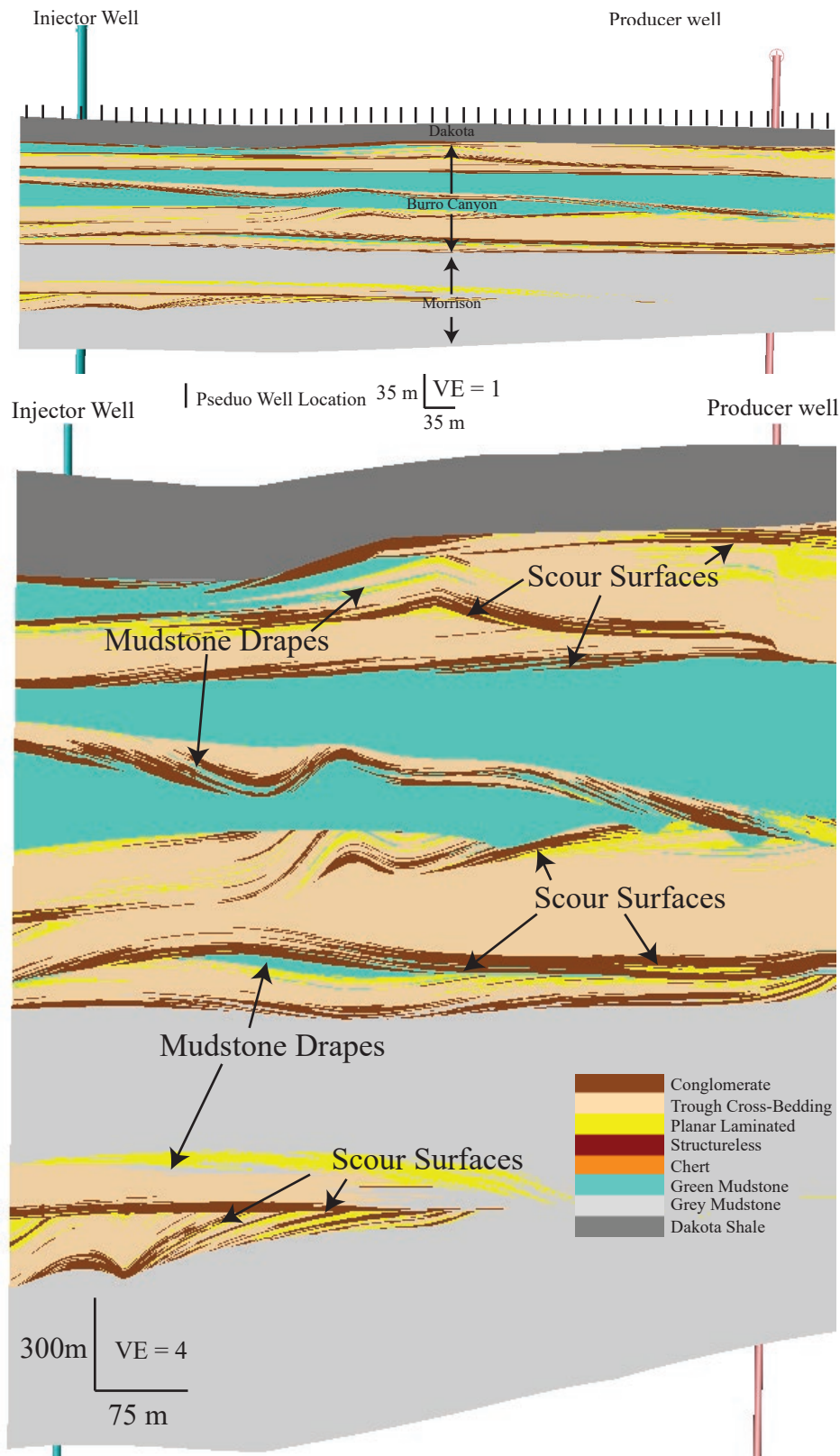
Within Rattlesnake Canyon, isolated fluvial-bar deposits are relatively thin and laterally continuous, averaging 2 ft (0.6 m) in thickness and can be traced along the outcrop for approximately 656 ft (~200 m) in the perpendicular-to-paleoflow orientation and for 557 ft (~170 m) parallel to paleoflow.

The gray-green mudstones are interpreted as alluvial floodplain (floodplain fines) and are indicative of the Burro Canyon Formation throughout the Piceance Basin (Currie et al., 2008; McPherson et al., 2008). Floodplain deposits encase channel deposits and have no discrete boundaries. Floodplain deposits are considered as non-reservoir rocks in this study.

## **Outcrop Reservoir Models**

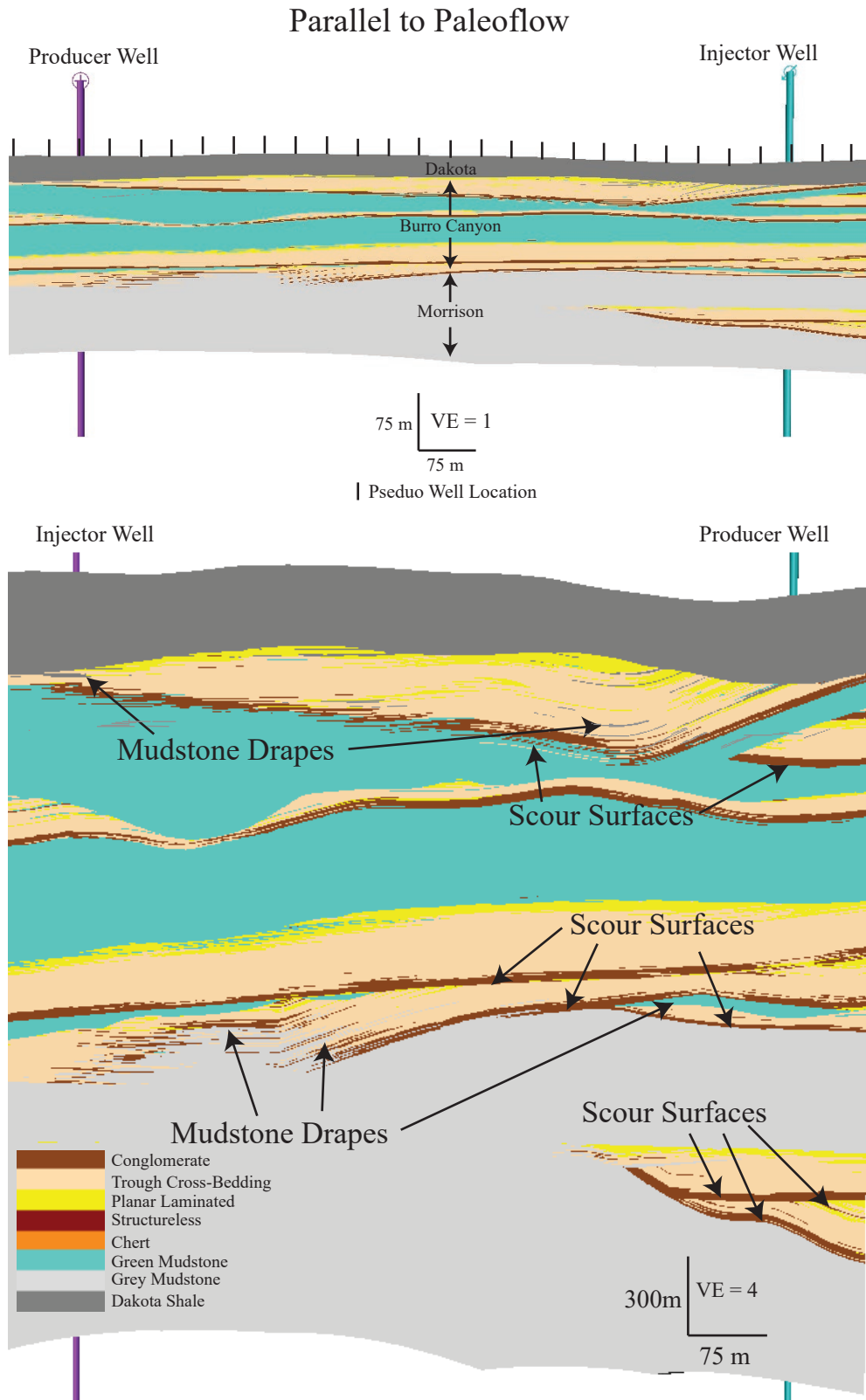
### *Lithofacies Models*

The most representative 2-D models of the stratigraphic architecture and lithofacies for the Burro Canyon Formation as exposed in Rattlesnake Canyon are models CF1-L1 and CF2-L1 (Figures 12 and 13). The channel-fill architectures include channel-scour surfaces and geometries within which the lithofacies are populated. A fining-upward nature of the lithofacies can be observed within the channel-fill deposits. Similarly, lithofacies models CF1-L2, CF2-L2, CF1-L3, and CF2-L3 include the channel geometries that are representative of those in outcrop, incorporate all lithofacies associations, and preserve the internal heterogeneity associated with the deposits. Lithofacies of models CF1-L2 and CF2-L2 are relatively less laterally continuous and basal conglomerates form thin lenses as compared to the thick conglomeratic deposits of lithofacies models CF1-L1 and CF2-L1. Mudstones appear as thin lenses throughout the reservoir bodies and are not laterally extensive. Lithofacies of models CF1-L3 and



**Figure 12.** Top: Two-dimensional static geologic model of Rattlesnake Canyon showing orientation parallel to paleoflow (VE=1). Black lines indicate position of 38 pseudo wells created to constrain model. Bottom: Vertically exaggerated (VE=4) model revealing internal heterogeneity present.





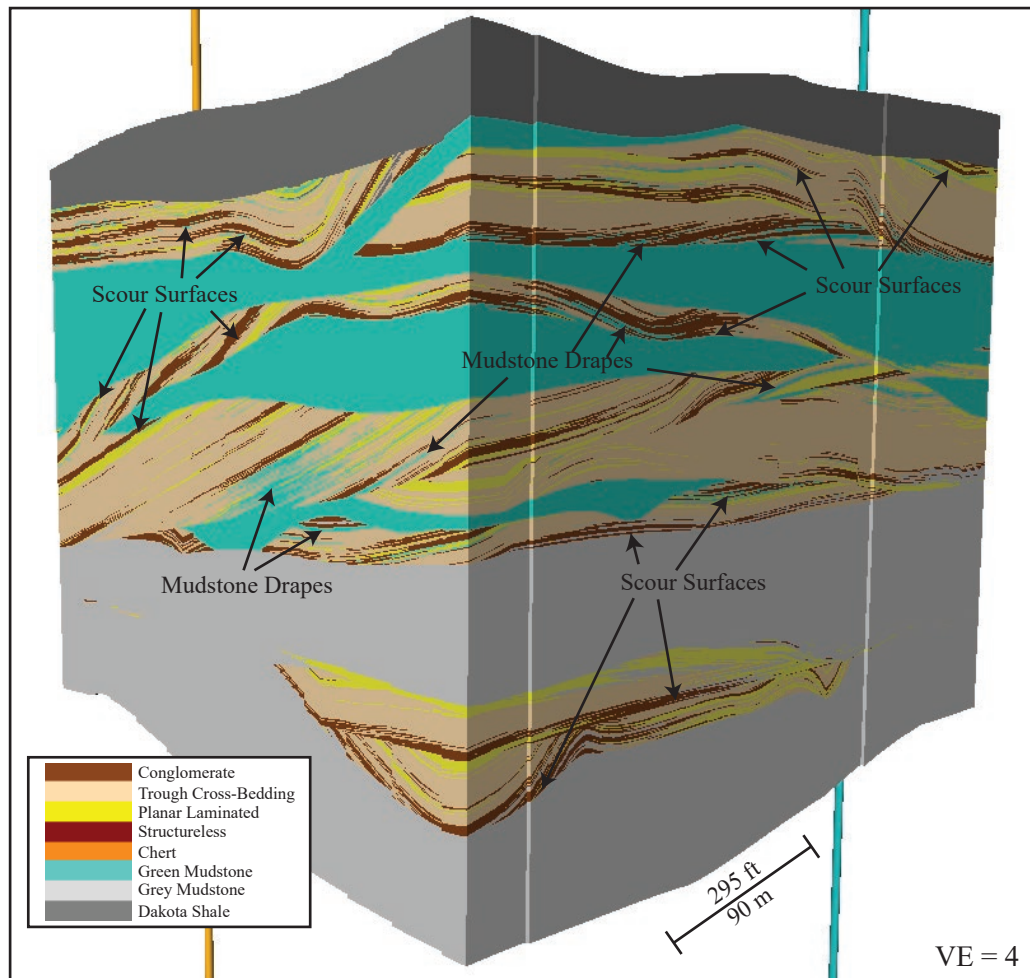
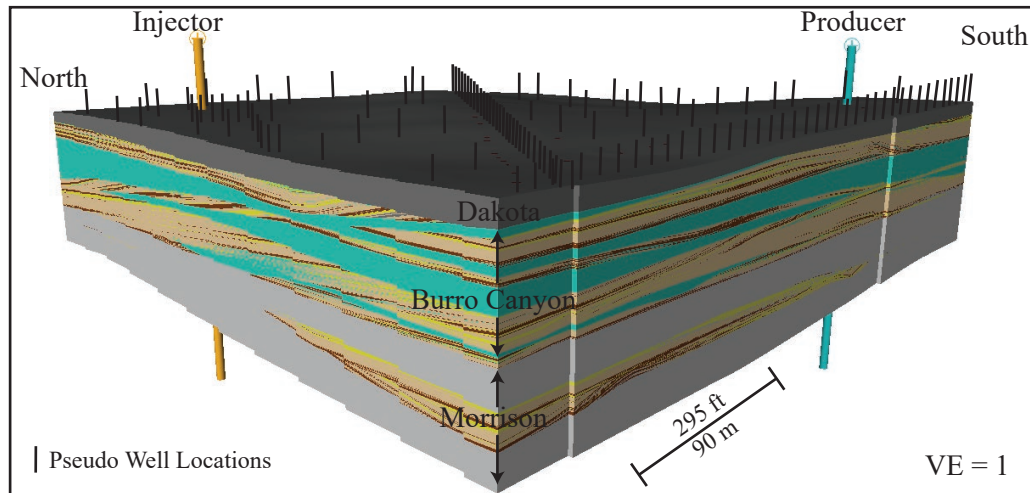
**Figure 13.** Top: Two-dimensional static geologic model of Rattlesnake Canyon showing orientation parallel to paleoflow (VE=1). Black lines indicate position of 38 pseudo wells created to constrain model. Bottom: Vertically exaggerated (VE=4) model revealing internal heterogeneity present.

CF2-L3 exhibit greater facies continuity laterally and vertically. Mudstones are thicker relative to the other cases and can create fluid-flow barriers within the sandstones.

The 3DCF-L1 lithofacies model includes the amalgamated and semi-amalgamated channel complexes and internal channel geometries and channel scour surfaces represented in 3-D. Lithofacies included are planar laminated sandstone, trough cross-bedded sandstone and conglomeratic sandstone similar to 2-D cases. Lithofacies distributions throughout models display scour surfaces within individual channels and a fining-upwards succession within channel-fill deposits. 3DCF-L1 displays channel geometries representative of those observed in outcrop and incorporate all lithofacies associations identified with the Burro Canyon Formation in Rattlesnake Canyon (Figure 14).

#### *Petrophysical Models*

Porosity and permeability models SB1-P1 and SB2-P1 illustrate spatial distributions that are only constrained by lithology and associated petrophysical variograms and not to channel geometry, channel bounding surfaces, or lithofacies. For the SB models, the P2 (porosity range of 0.5–7% [mean = 4%]; permeability range of 0.05-24 mD [mean = 2.2 mD]) and P3 (range of 2–30% [mean = 16%]; permeability range of 0.2-96 mD [mean = 8.8 mD]) models display the similar porosity and permeability distributions as SB1-P1 and SB2-P1 models but with reduced or enhanced spatial continuity, respectively. SB1-4 and SB2-4 (mean porosity = 8.1%; mean permeability = 4.2 mD) illustrate only the mean value for porosity and permeability to create uniform properties in sandstones and mudstones. The SB models have higher mean porosity and permeability values than corresponding CF models. This is because



**Figure 14.** Top: Three-dimensional static geologic model of Rattlesnake Canyon (VE=1). The model consists of 19 zones, static model is 1315 ft x 1315 ft x 300 ft (400 m x 400 m x 90 m) and contains 853,000,000 grid cells. Black lines indicate position of 151 pseudo wells used to constrain model. Bottom: Vertically exaggerated (VE=4) geologic model of Rattlesnake Canyon, showing internal heterogeneity in sandstone bodies present.,



the trough cross-bedding that is prevalent in the CF models has lower mean values of porosity and permeability; therefore the CF models are skewed to those lower mean values.

For the CF models, four sets of porosity and permeability models were generated for each paleoflow orientation. CF1-L1-P1 and CF2-L1-P1 (Table 3) incorporate channel-bounding surfaces that control the lithofacies and porosity and permeability trends to more accurately represent the Burro Canyon Formation in Rattlesnake Canyon. Petrophysical values for these models also exhibit upward-fining trends within the channel-fills. For the CF1-L2-P2 and CF2-L2-P2 models, the magnitude of the porosity and permeability values and associated variogram ranges are reduced by 50% relative to the CF-L1-P1 and CF2-L1-P1 models. This, in turn, decreases the storage and flow capacity of the reservoir intervals. Conglomerates exhibit limited porosity and permeability and create fluid-flow barriers within the Burro Canyon Formation. Trough cross-bedding exists as thin layers of relatively higher petrophysical values. CF1-L3-P3 and CF2-L3-P3 exhibits significantly higher values of porosity and permeability than the previous cases, while still following trends of the facies associations. CF1-L1-P4 and CF2-L1-P4 (Table 4) show significant variation in petrophysical properties owing to the cemented conglomerates. Basal scours of channel-fills exhibit low porosity and permeability; thus, confining reservoir storage and flow potential to trough cross-bedded and planar-laminated sandstones. Channel-bounding surfaces, in this case, control the lateral extent of the high petrophysical property regions.

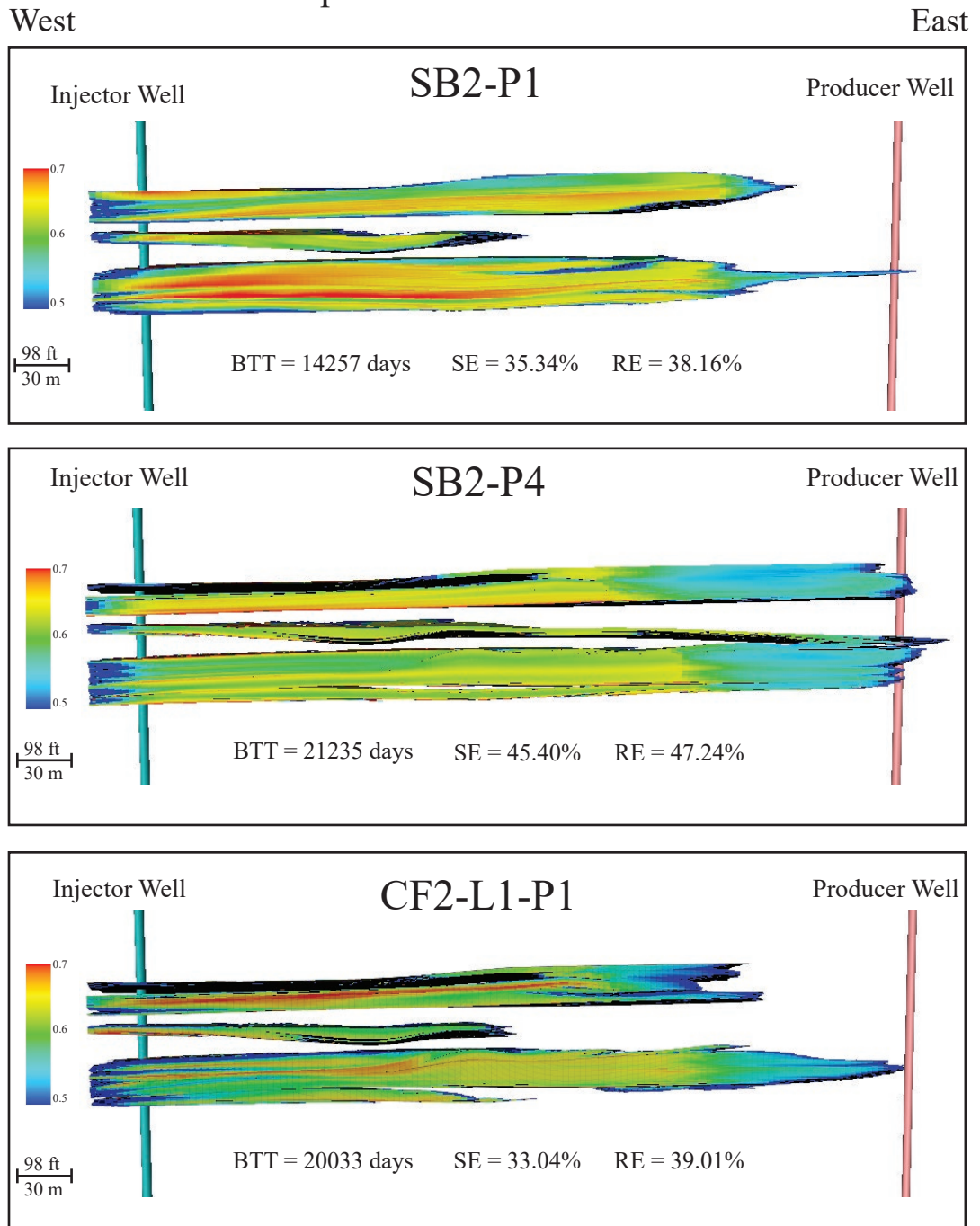
For the 3-D models, two sets of porosity and permeability models were generated. 3DCF-L1-P1 (Table 3) incorporates channel-bounding surfaces that control the lithofacies and porosity and permeability trends to more accurately represent the Burro Canyon Formation in Rattlesnake Canyon. Bounding surfaces are preserved and upward-fining petrophysical trends within channel-fills are observed. Model 3DCF-L1-P4 (Table 4) also shows significant variation in petrophysical properties owing to the cemented conglomerates. Similar to the 2-D case, basal scours of channel-fills exhibit low porosity and permeability; thus, confining reservoir storage and flow potential to trough cross-bedded and planar-laminated sandstones.

#### *Impact of Heterogeneity on Flow – Model Orientation*

Average BTT for 2-D models is approximately 50 years as compared to 112 years for the 3-D models. On average, models oriented perpendicular to paleoflow experience a 9% shorter BTT than models oriented parallel to paleoflow (Figures 15 and 16) due to greater sandstone connectivity for the orientation perpendicular to paleoflow. For both orientations, the SB1-P4 and SB2-P4 model produced the longest BTT. For the SB and CF models, model orientation produces opposite results for BTT. Model CF1-L1-P1 produces 67% shorter BTT than the SB1-P1 model. However, CF2-L1-P1 model produces 28% longer BTT than the SB2-P1 model.

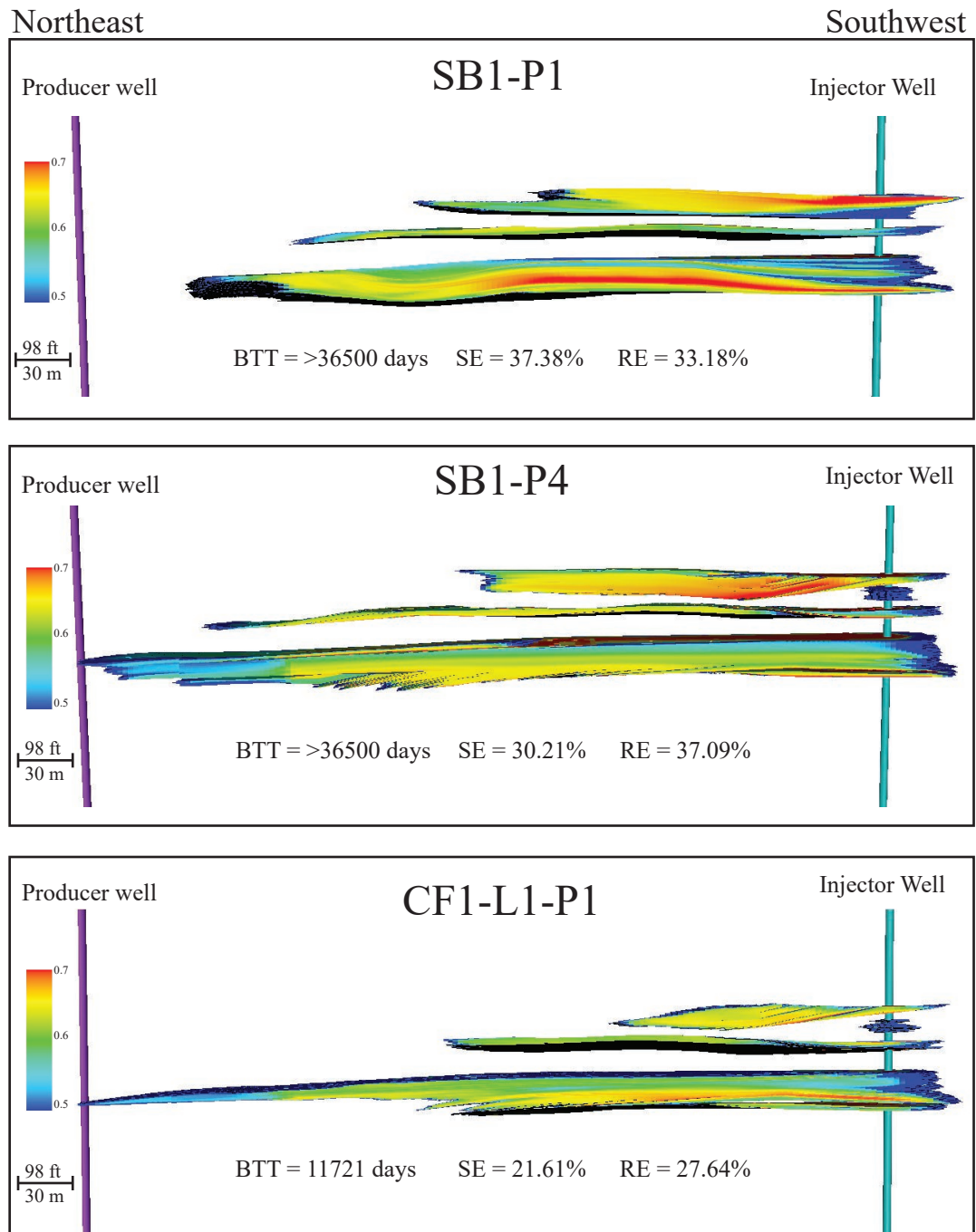
BTT was less sensitive to changes in variogram range. Data suggest that longer variogram ranges (double base case) from models CF1-L3-P3 and CF2-L3-P3 show only 1.1% faster BTT than the models with shorter variogram ranges (50% base case; CF1-L3-P2 and CF2-L3-P2). Incorporating cemented conglomerates has a more significant impact on BTT (models CF1-L1-P4 and CF2-L1-P4) causing, on average,

## Water Saturation Perpendicular to Paleoflow



**Figure 15.** Two-dimensional dynamic reservoir models for the SB2-P1, SB2,P4 and CF2-L1-P1 models oriented perpendicular to paleoflow. Breakthrough time (BTT), sweep efficiency (SE) and recovery efficiency (RE) are shown for each model.

## Water Saturation Paleoflow Direction



**Figure 16.** Two-dimensional dynamic reservoir models for the SB2-P1, SB2,P4 and CF2-L1-P1 models oriented parallel to paleoflow. Breakthrough time (BTT), sweep efficiency (SE) and recovery efficiency (RE) are shown for each model.

9% shorter BTT for 2-D models (both orientations). For 3-D models, similar results are observed; BTT decreases by 32% for model 3DCF-L1-P4 (Table 6).

For the swept volume calculation, we detected the cells with water injection greater than connate water saturation (21%). The sum of the volume of these detected cells divided by the total cell volume of the cells in the model determines the sweep efficiency (SE). Two-dimensional models orientated perpendicular to paleoflow had 16% higher sweep efficiency than those oriented parallel to paleoflow. Sweep efficiency was 26% lower perpendicular to paleoflow and 23% lower parallel to paleoflow for 2-D models with cemented conglomerates as compared to models without cemented conglomerates. 3DCF-L1-P1 exhibited an average sweep efficiency of 32% (Figure 17). Model 3DCF-L1-P4 produced 28% higher sweep efficiency than in the base-case 3-D model (3DCF-L1-P1) (Table 6).

Recovery efficiency (RE) for oil is the ratio of the cumulative amount of oil produced for a specified period of time divided by the amount of oil initially in place and is calculated at BTT and also at the end of the 100-year simulation period (Figure 18). Recovery efficiency is sensitive to similar parameters as sweep efficiency. Perpendicular to paleoflow, 2-D models, on average, result in a 14% higher recovery efficiency than 2-D models parallel to paleoflow. Recovery efficiency for model CF1-L1-P4 is 15% lower and CF2-L1-P4 13% lower when compared to models CF1-L1-P1 and CF2-L1-P1, respectively. Recovery efficiency is less sensitive to changes in variogram range (Table 6 [CF1-L1-P1, CF2-L2-P2, CF3-L3-P3, CF2-L1-P1, CF2-L2-P2 and CF2-L3-P3]). For 3D models, recovery efficiency is 22% lower with the cemented conglomerates as compared to model 3DCF-L1-P1. On average, models

## Model Simulation Results

### SB Models

|        | <b>BTT Days</b> | <b>RE @ BTT</b> | <b>SE @ BTT</b> | <b>RE @ 100 days</b> | <b>SE @ 100 days</b> |
|--------|-----------------|-----------------|-----------------|----------------------|----------------------|
| SB2-P1 | 14257           | 38%             | 35%             | 47%                  | 71%                  |
| SB1-P1 | +36500          | 37%             | 47%             | 37%                  | 47%                  |
| SB2-P2 | 8786            | 33%             | 33%             | 47%                  | 71%                  |
| SB1-P2 | 16119           | 33%             | 33%             | 40%                  | 68%                  |
| SB2-P3 | 15848           | 34%             | 32%             | 44%                  | 64%                  |
| SB1-P3 | 14319           | 29%             | 22%             | 38%                  | 50%                  |
| SB2-P4 | 21235           | 47%             | 45%             | 49%                  | 75%                  |
| SB1-P4 | +36500          | 37%             | 55%             | 37%                  | 55%                  |

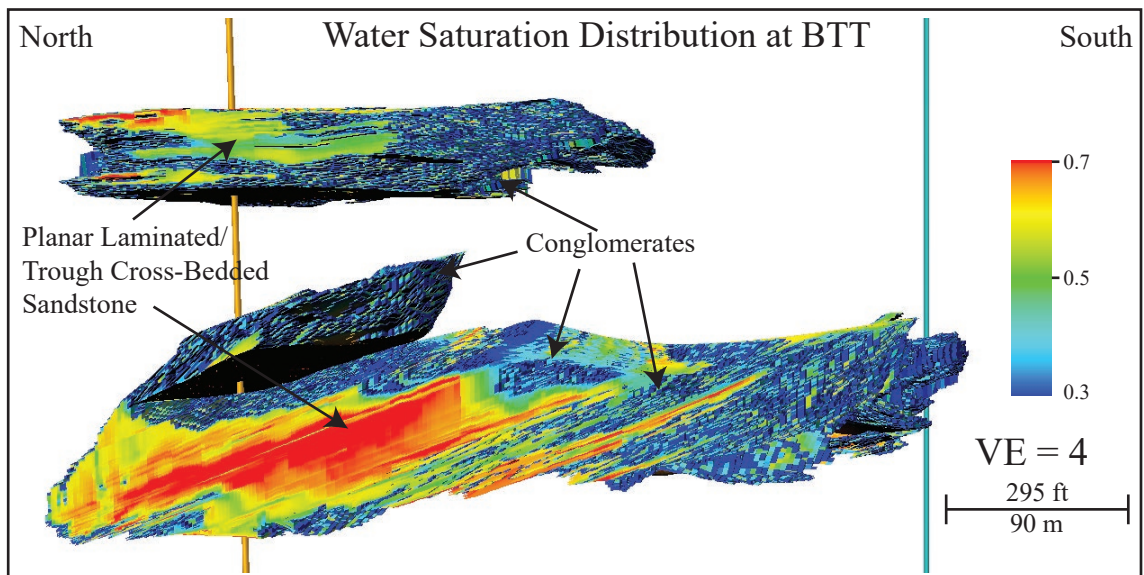
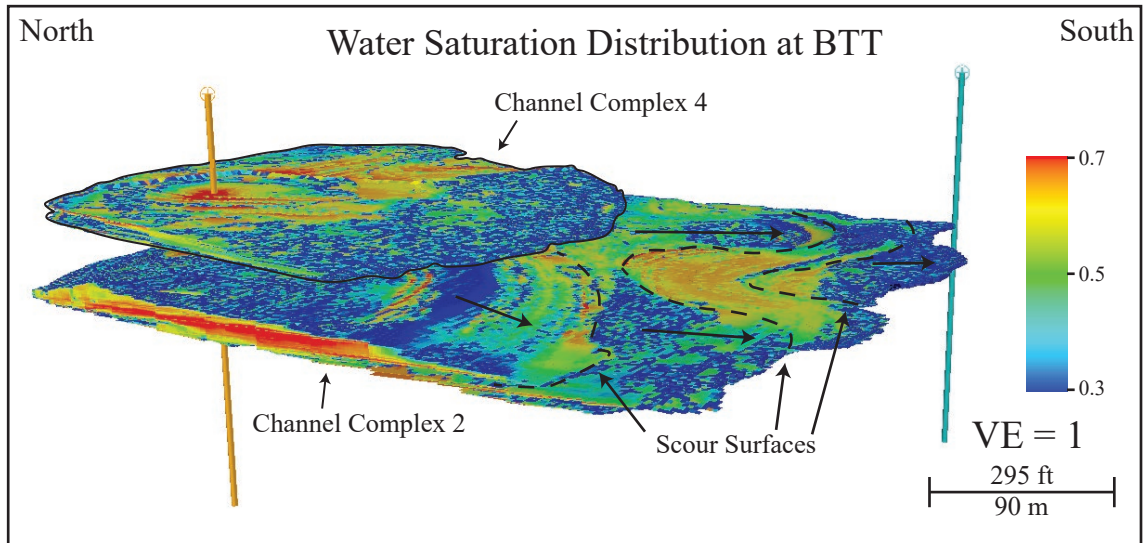
### CF Models

|           | <b>BTT Days</b> | <b>RE @ BTT</b> | <b>SE @ BTT</b> | <b>RE @ 100 days</b> | <b>SE @ 100 days</b> |
|-----------|-----------------|-----------------|-----------------|----------------------|----------------------|
| CF2-L1-P1 | 20033           | 39%             | 33%             | 46%                  | 69%                  |
| CF1-L1-P1 | 11721           | 28%             | 22%             | 41%                  | 63%                  |
| CF2-L2-P2 | 9784            | 32%             | 26%             | 47%                  | 70%                  |
| CF1-L2-P2 | 12441           | 32%             | 24%             | 44%                  | 70%                  |
| CF2-L3-P3 | 12879           | 35%             | 25%             | 43%                  | 61%                  |
| CF1-L3-P3 | 10595           | 30%             | 21%             | 39%                  | 61%                  |
| CF2-L1-P4 | 17283           | 33%             | 24%             | 41%                  | 56%                  |
| CF1-L1-P4 | 12271           | 25%             | 16%             | 33%                  | 46%                  |

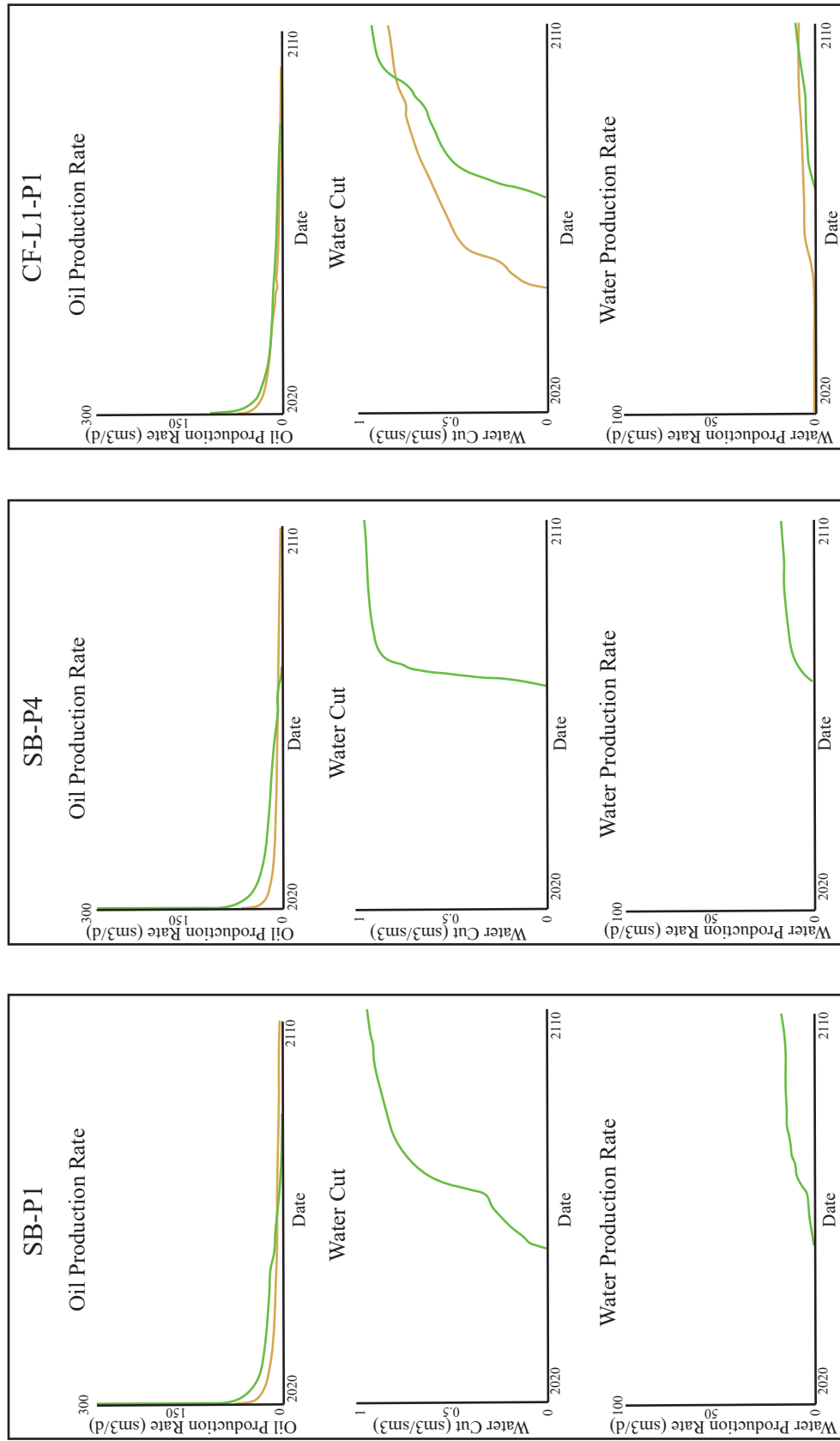
### 3-D Models

|            | <b>BTT Days</b> | <b>RE @ BTT</b> | <b>SE @ BTT</b> | <b>RE @ 100 days</b> | <b>SE @ 120 days</b> |
|------------|-----------------|-----------------|-----------------|----------------------|----------------------|
| 3DCF-L1-P1 | 47515           | 24%             | 24%             | 25%                  | 40%                  |
| 3DCF-L1-P4 | 32141           | 19%             | 28%             | 19%                  | 28%                  |

**Table 6.** Simulation results including breakthrough time (BTT), sweep efficiency (SE) at BTT, sweep efficiency at end of simulation (100 years in 2-D models; 120 years in 3-D models), recovery efficiency (RE) at BTT, and recovery efficiency at end of simulation for each Burro Canyon Formation model.



**Figure 17.** Three-dimensional dynamic reservoir model from 3DCF-L1-P1 model. This 3-D model is shown simulated through breakthrough time (BTT). Top: Channel complex 2 shows the most efficient fluid flow pathways for production. Individual scours and flow pathways can be observed. Bottom: When the water saturation distribution is magnified (VE=4), fluid-flow pathways can be observed. Water saturation is largely confined to the main channels of the reservoir in trough cross-bedded and planar laminated sandstones.



**Figure 18.** Charts depicting oil production rate, water cut and water production rate in both orientations for models representing Rattlesnake Canyon. Orange represents parallel to paleoflow and green perpendicular. In SB-P1 and SB-P4 models, the waterflood does not break through.



situated perpendicular to paleoflow produced 23% more oil than those parallel to paleoflow. Change in variogram range produced limited change in the cumulative oil produced at 100 years. In the CF1-L2-P2 and CF2-L2-P2 models, a 4% increase in the amount of oil produced is observed as compared to the CF1-L1-P1 and CF2-L1-P1 models. When variogram ranges are doubled, as in the CF1-L3-P3 and CF2-L3-P3 models, a 6% decrease in cumulative oil produced is observed as compared to the CF1-L1-P1 and CF2-L1-P1 models. Shorter variogram ranges might have a limited increase in percentage of oil produced; however additional simulations would be needed to confirm.

#### *Impact of Heterogeneity on Flow – Petrophysical Properties*

Comparison of breakthrough time (BTT), sweep efficiency (SE) at BTT and 100 years, recovery efficiency (RE), and cumulative production of oil and water illustrate the effects of reservoir heterogeneity on fluid flow. Reservoir heterogeneity has a significant impact upon BTT. SB1-P4 and SB2-P4 have the longest BTT. SB1-P1 and SB2-P1 produce 43% shorter BTT as compared to the homogenous petrophysical property distribution of models SB1-P4 and SB2-P4. Similarly, CF1-L1-P1 and CF2-L1-P1 experience 46% shorter BTT than models SB1-P4 and SB2-P4. On average, BTT occurs within the most heterogeneous reservoirs in CF1-L1-P1 and CF2-L1-P1 models 5% faster than SB1-P1 and SB2-P1.

Models SB1-P4 and SB2-P4 showed the largest sweep and recovery efficiencies of the SB and CF models. Assuming homogenous petrophysical distributions in sandstones, SB1-P4 and SB2-P4's sweep efficiency at BTT is 37% and the recovery efficiency at BTT is 27% higher than CF1-L1-P1 and CF2-L1-P1 models. Confining

petrophysical data to single facies rather than having a wide distribution across reservoir intervals decreases both sweep and recovery efficiency. The effect is greater with sweep efficiency, where CF1-L1-P1 and CF2-L1-P1 average 21% lower sweep efficiency at BTT through the waterflood than SB1-P1 and SB2-P1. Recovery efficiency at BTT is 5% greater with the SB1-P1 and SB2-P1 as compared to the CF1-L1-P1 and CF2-L1-P1 models. Variogram range between models CF1-L1-P1 and CF2-L1-P1, CF1-L2-P2 and CF2-L2-P2, and CF1-L3-P3 and CF2-L3-P3 had little to no effect on sweep efficiency (1%) and recovery efficiency (1% [Table 6]). Incorporating cemented conglomerates (CF1-L1-P4 and CF2-L1-P4) reduced cumulative oil production by 49% as compared to models CF1-L1-P1 and CF2-L1-P1 models. Cement creates fluid-flow barriers that create tortuous fluid-flow pathways in the reservoir.

## **Discussion**

### **Environment of Deposition**

The Burro Canyon fluvial system is classified as bed-load dominated (>11% total load) with a high discharge variability and high width to depth ratio (average 43:1) (Schumm, 1963; Miall, 1996). Paleocurrent measurements indicate deposition of the Burro Canyon Formation to the Northwest with a vector mean of 58° (N=124). Paleocurrent data varies not only between exposed walls of the canyon but also in between individual channel sandstones. Fine- to medium-grained sandstones that consist of low-angle laminations and trough cross-bedding form fining-upwards bedsets and are interpreted as lateral bars (Patterson et al., 2006). Due to the high degree of scouring within Rattlesnake Canyon, bank-attached braid-bar deposits are not observed,

because low angle inclined laminations are rarely present. Finer grained planar laminations, with minor amounts of small crossbeds and ripple-laminations are linked to sand flats deposited in plane-bed or critical flow (Cant, 1977; Miall, 1996).

The Burro Canyon Formation deposits align with the South Saskatchewan type of perennial, cyclic, sand-bed braided rivers (Miall, 1996). South Saskatchewan type deposits are characterized by macroforms of compound bars, sand flats or sand shoals bounded by fourth-order sequences which may or may not be preserved. In sand-dominated braided rivers, cycles develop through a combination of channel and bar evolution. The grain size fluctuations seen in the sequences are caused by rapidly branching arms of the rivers across the alluvial system. The grain sizes present within a deposit may change rapidly due to the migration of the river across that location (Cant, 1973).

South Saskatchewan type vertical profiles consist of fining upward successions of sand dominated, cyclic deposits, and dominant trough-cross bedding (Miall, 1977). Trough cross-bedding is formed through the scouring of moderate sized dunes that migrate downstream (Harms and Fahnestock, 1965; Cant, 1973). Dominant facies comprise up to 80% of the sequence in sandy braided river sedimentation. Channels are commonly floored by lag gravels above which sand is transported as coarse bedload and the presence of large sand flats within the channels are common (Miall, 1985). Facies models for sandy, cyclic, braided rivers are dominated by trough and planar crossbeds in fine- to coarse-grained sandstone. Minor amounts of low angle horizontally laminated sandstone and ripple-laminated sandstone are also present, representing beach or wind deposits on bars within the channel sequence (Cant, 1973, 1977)

## **Comparison of Channel Complex Stacking**

Preserved braided fluvial systems are highly variable in the rock record, due to avulsion and lateral channel migration (Patterson et al. 2012). In cyclic braided rivers such as the Burro Canyon Formation, lateral extent of sandstone channels preserved can be highly variable. Rattlesnake Canyon provides perpendicular to paleoflow and paleoflow direction exposures allowing for a 3-D view of the braided fluvial system. The canyon exhibits larger number of individual channel fills oriented perpendicular to paleoflow, within amalgamated and semi-amalgamated channel complexes (Figures 10 and 11). In this orientation, there are areas with high lateral connectivity of fluvial beds and areas with little to no connectivity as the channels amalgamate and scour across the outcrop. Cross sections parallel to paleoflow vary from those perpendicular to paleoflow, due to lateral extent of the individual channels. Majority of channels are laterally continuous (when not eroded) but exhibit low width to thickness ratios. Sandstone bodies perpendicular to paleoflow exhibit 13% more sand than those oriented parallel to paleoflow.

Facies present in each outcrop orientation give insight into deposition of the rocks. Perpendicular to paleoflow, facies rapidly change vertically and laterally indicating high degree of channel migration and amalgamation (Figure 10). Facies show multiple fining upwards sequences within individual sandstone bodies. Parallel to paleoflow orientations show elongated sandstone bodies with facies that are generally laterally continuous (Figure 11). In this direction, a clear fining-upwards sequence is present throughout the sandstone bodies. In general, 26% more sandstone channel fill

bodies are observed oriented perpendicular to paleoflow than either of the exposed orientations in the paleoflow direction.

## **2-D Fluid-Flow Comparison**

Due to the nature of depositional processes of a braided fluvial system, simulation results in 2-D models show higher average BTTs, sweep efficiencies and recovery efficiencies perpendicular to paleoflow than in the parallel to paleoflow orientation (Figure 18). As the Rattlesnake Canyon outcrops exhibit, sandstone connectivity is higher perpendicular to paleoflow where the presence of multiple channels allows for high probable amalgamation of channels. The large number of channels exhibited in this direction provides a higher density of fluid-flow pathways through reservoir sandstones that are not present in the parallel to paleoflow orientation. The presence of numerous fluid-flow pathways allows for additional reservoir space to be impacted by the waterflood. Since the sandstone connectivity is higher oriented perpendicular to paleoflow, fluids will occupy more space before reaching the production well, resulting in longer BTTs.

The nature of the amalgamated sandstone bodies in both orientations can be seen through comparison of the BTTs. Channel bodies oriented perpendicular to paleoflow often contain conglomerates at multiple intervals and different stratigraphic heights throughout the exposure. As fluid travels, laterally along these channel bodies, it encounters a variety of lithofacies and differing petrophysical data. Parallel to paleoflow, lithofacies and petrophysical data have a larger lateral extent due to the nature of the channel systems in the paleoflow direction. Fluids flowing laterally in this direction encounter less of a change in lithofacies and petrophysical data. This accounts

for the differing BTTs in either direction for petrophysical models. Using CF1-L1-P1 and CF2-L1-P1 BTT's, models oriented perpendicular to paleoflow have a longer duration than SB1-P1 and SB2-P1 allowing for a higher percentage of reservoir oil to be produced. This is opposite parallel to paleoflow, CF1-L1-P1 and CF2-L1-P1 models have faster BTTs than SB1-P1 and SB2-P1 due to the lateral continuity of the facies.

### **Impact of Cement**

Imposition of cementation in conglomeratic facies demonstrates subsurface conditions of many braided fluvial deposits (Clarke, 1979; Cant and Eth, 1984). Cementation has a substantial impact on reservoir performance, sweep and recovery efficiency decrease while BTT decreases. Sweep efficiency decreases in the 2-D Burro Canyon Formation models due to high amounts of conglomeratic beds in channel sequences. Cementation causes a fluid flow baffle, forcing subsurface liquids to find different flow paths. This is significant perpendicular to paleoflow when facies distributions are not as laterally continuous since the channels are scouring each other and not as continuous perpendicular to paleoflow. Parallel to paleoflow, channel bodies and facies are laterally continuous, with conglomeratic facies at the base and a lower percentage of scouring up to the sandbody surface fluid pathways are more continuous.

Three-dimensional reservoir simulation shows an opposite effect in sweep efficiency from that found in two-dimensions. Sweep efficiency increased in the cemented 3-D model, indicating that constraining flow in a single direction (2-D models) will decrease the amount of produced reservoir. This is due to the fact that cemented conglomerates are causing fluid flow barriers in 2-D between the injector and producer wells. In 3-D the conglomerates cause less of a fluid flow barrier since the

channels are scouring each other. This allows for pinch out of conglomerates in the reservoir and pathways for fluid flow. Cementation has a larger effect on sweep efficiency than recovery efficiency due to the tight nature of the conglomerates. Lack of fluid pathways through this facies leaves a percent of the reservoir untouched by waterflood methods in both two- and three-dimensions.

### **Fluid Flow through Braided River Heterogeneity**

Channel architecture in a braided fluvial system consists of series of amalgamated and semi-amalgamated channel complexes bounded in floodplain mudstone with little to no permeability. Connectivity of sandstone channel bodies in the subsurface is difficult to distinguish, the use of outcrop models can predict the nature of a braided fluvial system. Potential fluid flow inhibitors in braided environments include alluvial mudstones, rapid facies changes and unknown sandstone connectivity.

Fluid flow barriers such as laminated mudstone between individual bedsets create connectivity issues and may inhibit fluid flow. These floodplain mudstones in amalgamated channel complexes appear to be laterally extensive in the direction of paleoflow, but oftentimes eroded by channels perpendicular to flow. Reservoir simulation shows in the channel scour case that increased mudstone facies within channel complexes present, causes a decrease in reservoir fluids produced and reservoir depletion. Oriented perpendicular to paleoflow, sweep efficiency increases by 24% than that oriented parallel. This indicates production and injection wells should be oriented perpendicular to paleoflow to maximize connectivity of individual bedsets.

Facies distributions in braided fluvial settings have a fining upwards sequence. Within the Burro Canyon formation, larger percentages of the entire sequence remained present in the direction of paleoflow. Laterally continuous beds in this direction showed lower potential for scouring, allowing for facies distributions to display lateral continuity. Perpendicular to paleoflow, a higher rate of scouring is visible within the channel complexes observed. This created a rapid change in facies distributions both vertically and laterally that create potential flow barriers. Comparison between SB and CF models shows the change in facies to have a significant impact on BTT of the reservoir (Figure 17).

Stratigraphic architecture is difficult to quantify in braided fluvial systems. Understanding distributions of channelized sandstone-bodies within the reservoir, width to thickness ratios of channels and paleoflow orientation may help predict sandstone connectivity. The Burro Canyon Formation in Rattlesnake Canyon contains two continuous channel complexes, each exhibiting unique connectivity and facies. Simulation shows that the most conductive channel complex in this system is the basal channel complex of the Burro Canyon Formation. The high proportions of sandstone body connectivity between the amalgamated channels allows this sequence allows for the best subsurface fluid pathways, both perpendicular and parallel to paleoflow direction.

Resulting sweep efficiencies and recovery efficiencies within simulated reservoir models, depicting petrophysical data consistent with that of the Burro Canyon Formation, suggest subsurface performance is most effective perpendicular to paleoflow direction in an amalgamated channel sequences. The increased heterogeneity of the



reservoir in this direction decreases BTT due to added fluid flow pathways but increases amount of reservoir depleted.

## **Conclusions**

The Burro Canyon Formation represents a South Saskatchewan type, sandy, braided-fluvial deposit (Miall, 1977). This sinuous fluvial deposit provides insight into subsurface reservoirs of the Piceance Basin, containing two channel complexes of amalgamated and semi-amalgamated nature, which create connectivity between architectural elements present. Amalgamated channel complexes have proven to be the most prolific reservoir architectural element, given the connectivity between individual channel-fills and lateral continuity of the element. Amalgamated fluvial-bar deposits and isolated fluvial bar deposits show low vertical and lateral continuity, reducing the connectivity of the reservoir as they are encompassed in floodplain fines.

Two- and three-dimensional static and dynamic modeling of the deposits of the Burro Canyon Formation display the impact of heterogeneity on reservoir performance. Amalgamated channel complexes situated perpendicular to paleoflow orientation exhibit a higher degree of scouring than along paleoflow direction, increasing fluid-flow pathways within the reservoir.

A high degree of amalgamation lead to BTT increasing by 9% and sweep efficiency increasing by 16% when compared to models oriented parallel to paleoflow. Understanding the relationships of the internal lithofacies within the reservoir, impacts fluid flow. Models with a single value for porosity and permeability applied across the entire reservoir interval saw 43% longer BTT's when compared to models that were given an average range of porosity and permeability and 46% longer BTT's when

compared to models with petrophysical data confined to individual facies. Through constraining internal heterogeneity of the reservoir, fluid flow pathways are generated to transmit fluids across the reservoir interval.

Understanding reservoir heterogeneity has a significant influence on sweep efficiency of the reservoir and recovery efficiency. Through confining petrophysical data to single facies, sweep efficiency and recovery efficiency decrease by 21% and 5% respectively, due to extensive zones of lower petrophysical data and basal conglomerates scouring into prime reservoir facies.

Cementation of conglomerates increases BTT in both 2-D reservoir models but decreases oil production of the reservoir through decreased recovery efficiency (22%) as well as decreased sweep efficiency (25%), as conglomerates cause fluid flow barriers between injector and producer wells. In 2-D sweep efficiency decreases with cementation of the conglomerates, constraining fluid flow pathways by through channel scouring. In 3-D sweep efficiency increases by 28% provided that fluid flow pathways aren't wholly scoured.

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## Appendix A: Field Data

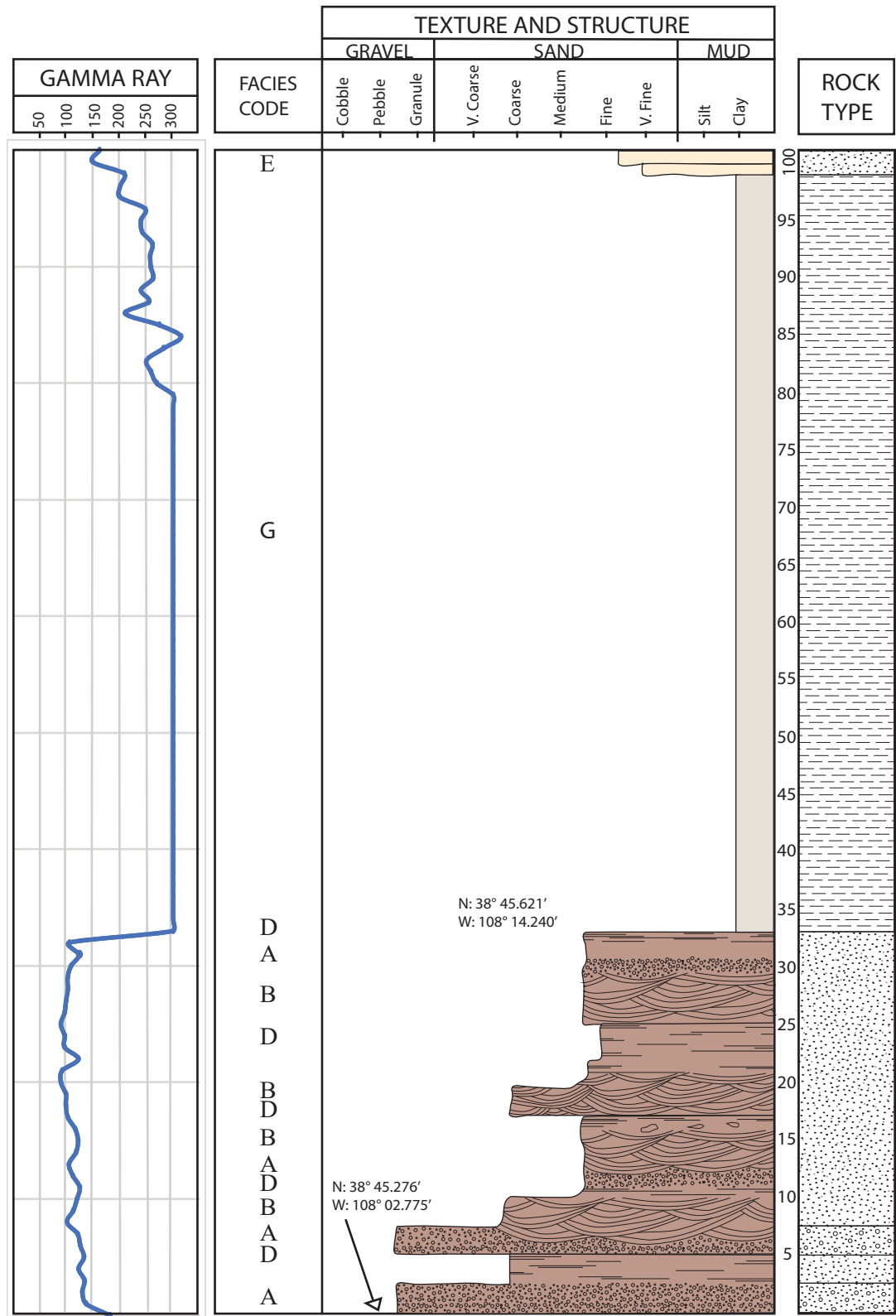
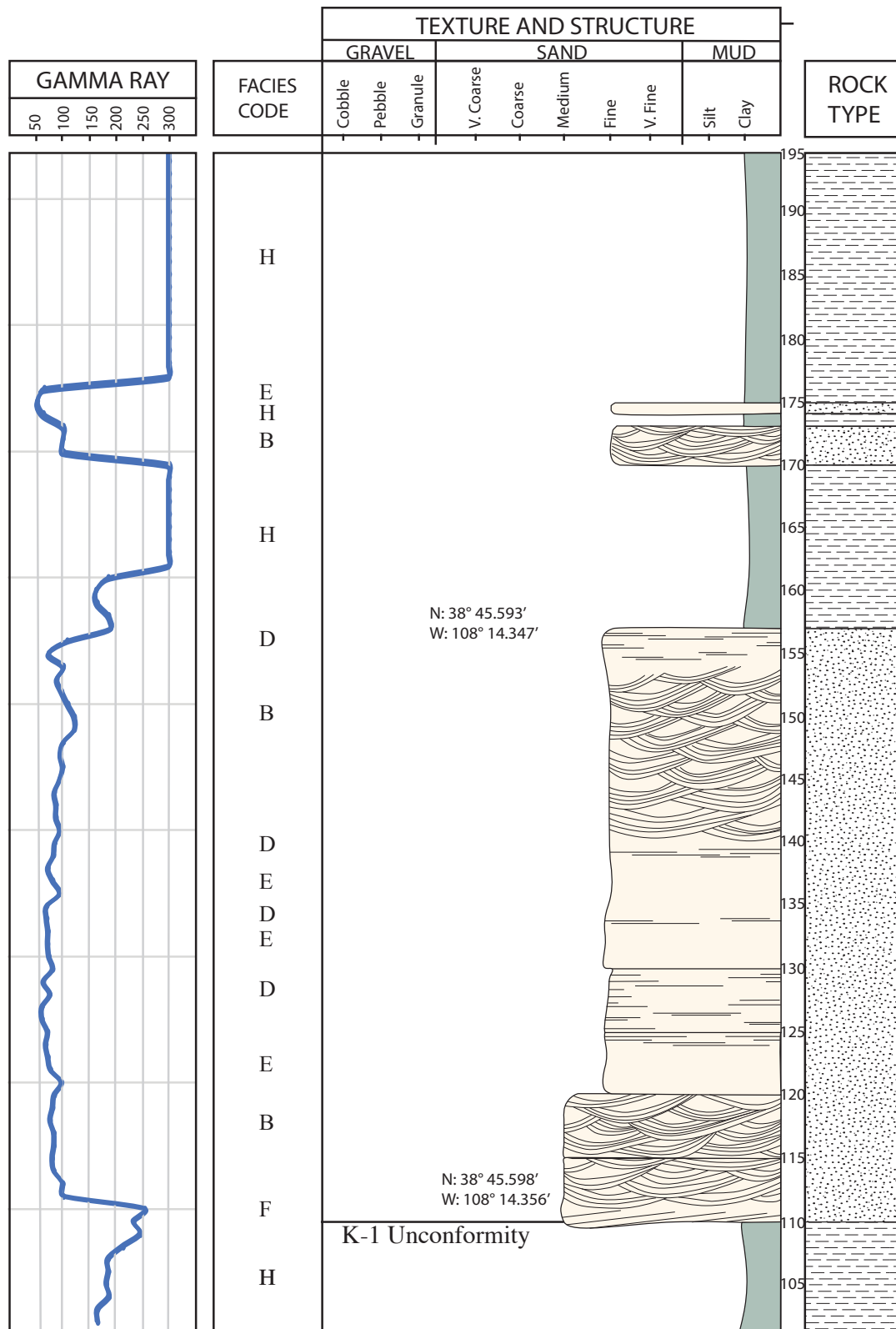
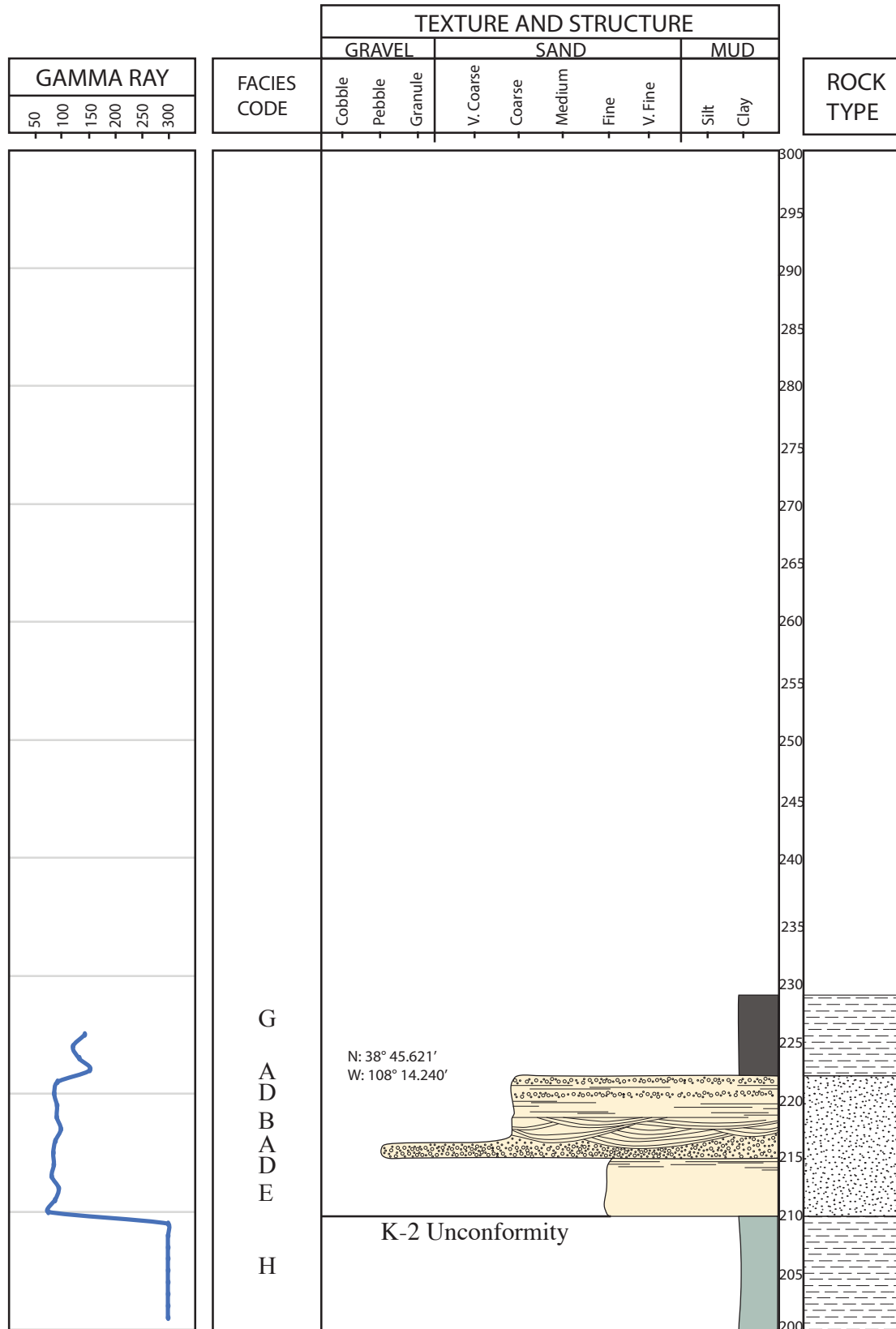


Figure A-3: First section of measured section one with gamma ray values.

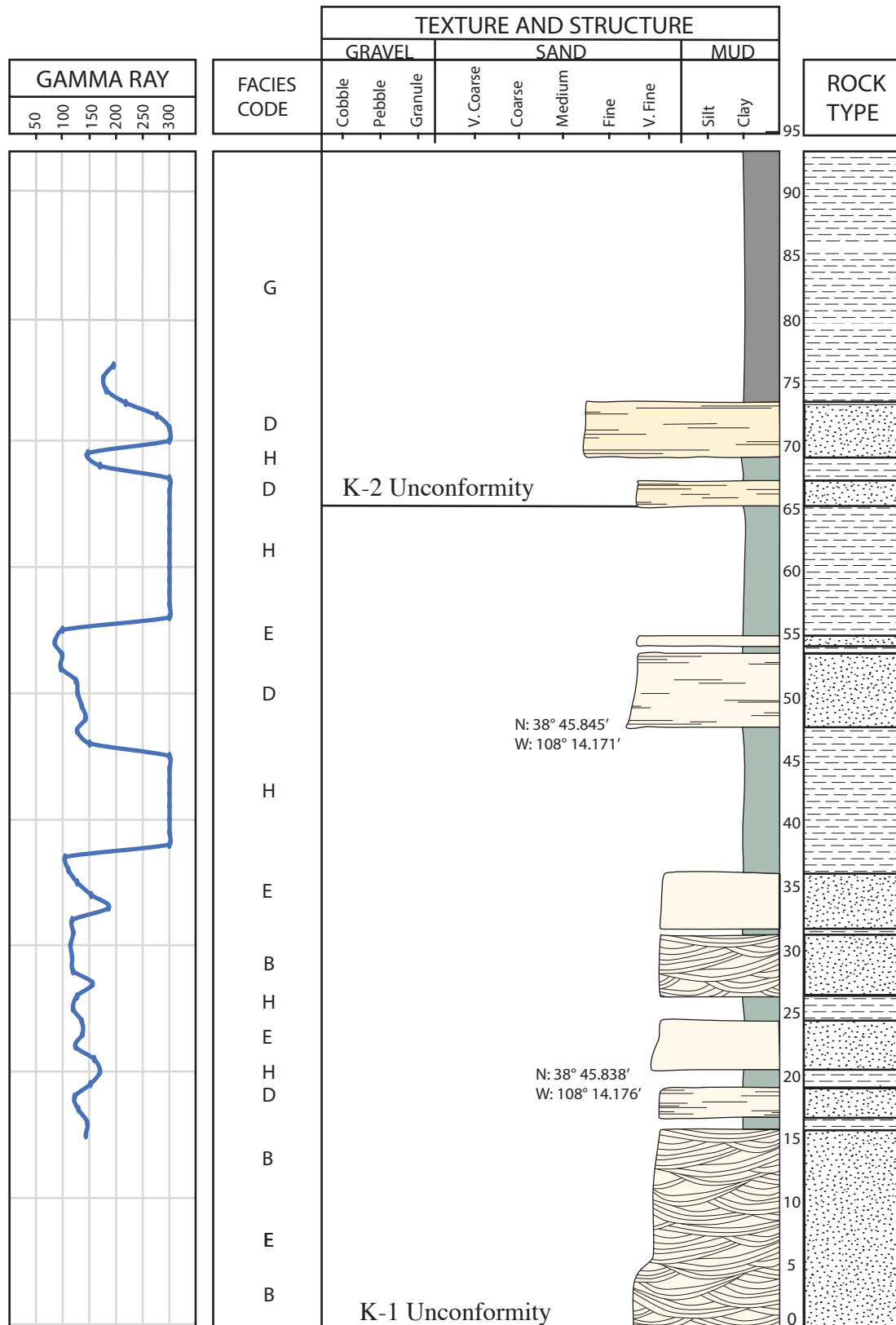


**Figure A-4:** Second section of measured section one with gamma ray values.



**Figure A-5:** Third section of measured section one with gamma ray values.





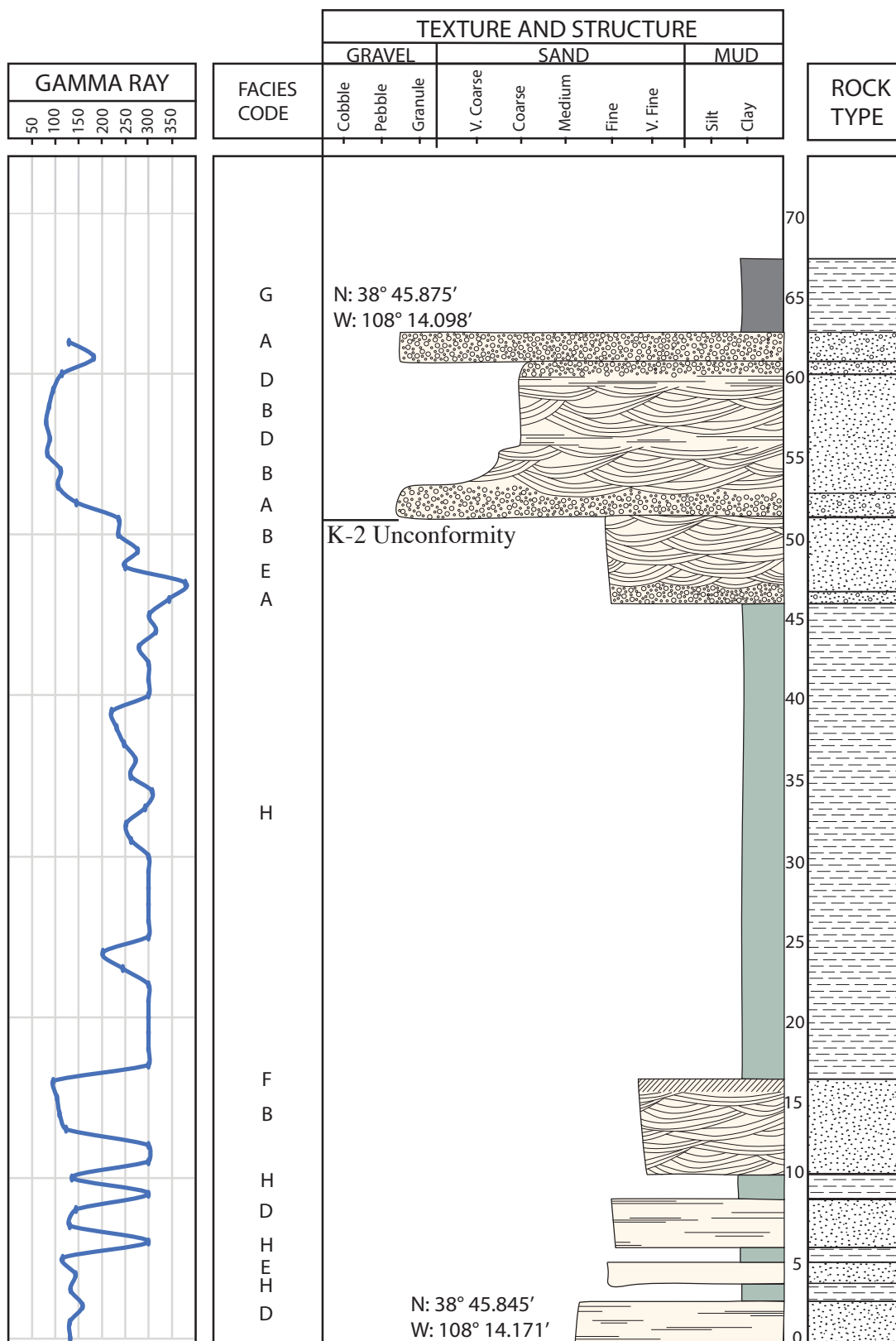
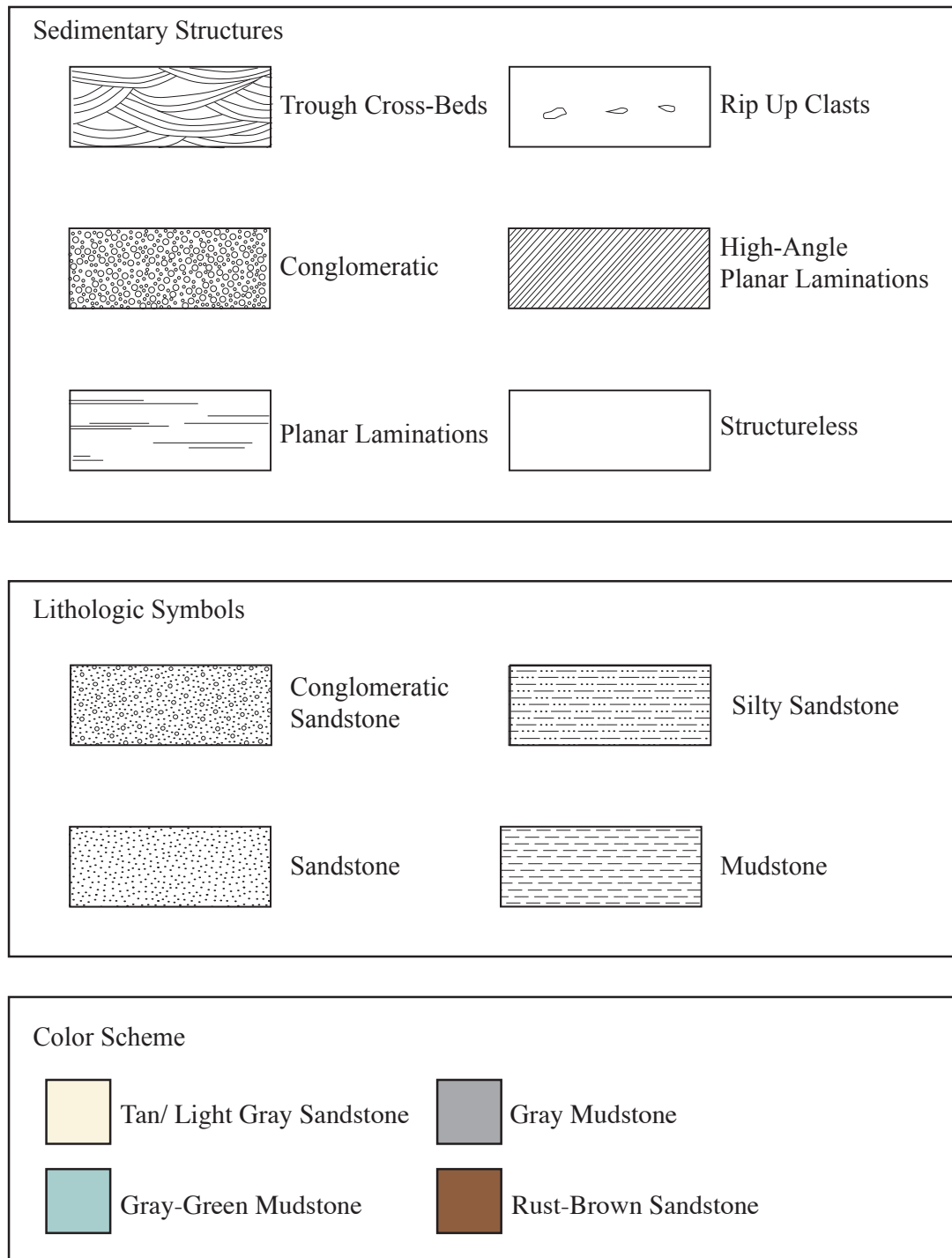
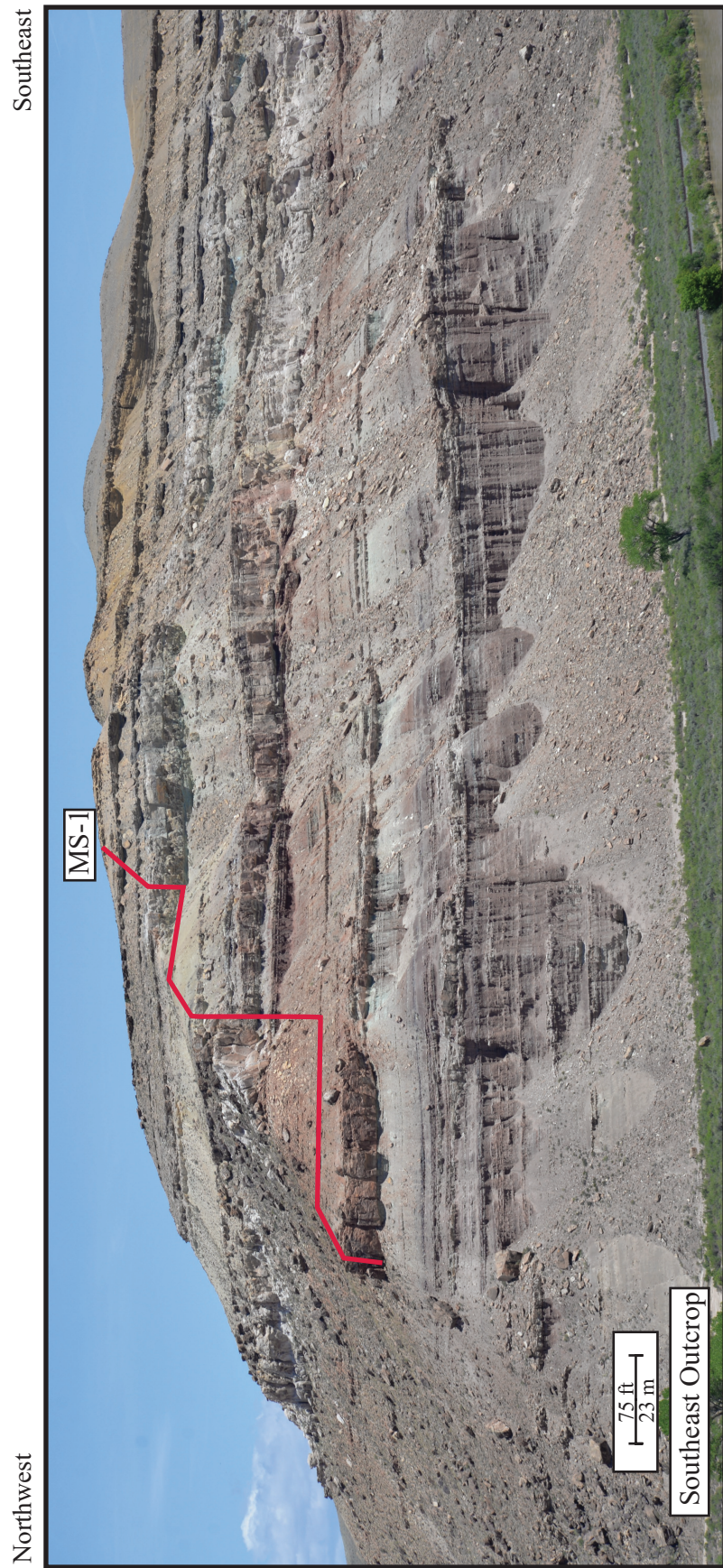


Figure A-7: Measured section 3, with gamma ray values.



**Figure A-8:** Measured section key showing sedimentary structures, lithologic symbols and color scheme used in measured section description. Covered sections on measured sections are represented by the exposed sections that are lateral to them. Northwest wall sections contained the most covered section.

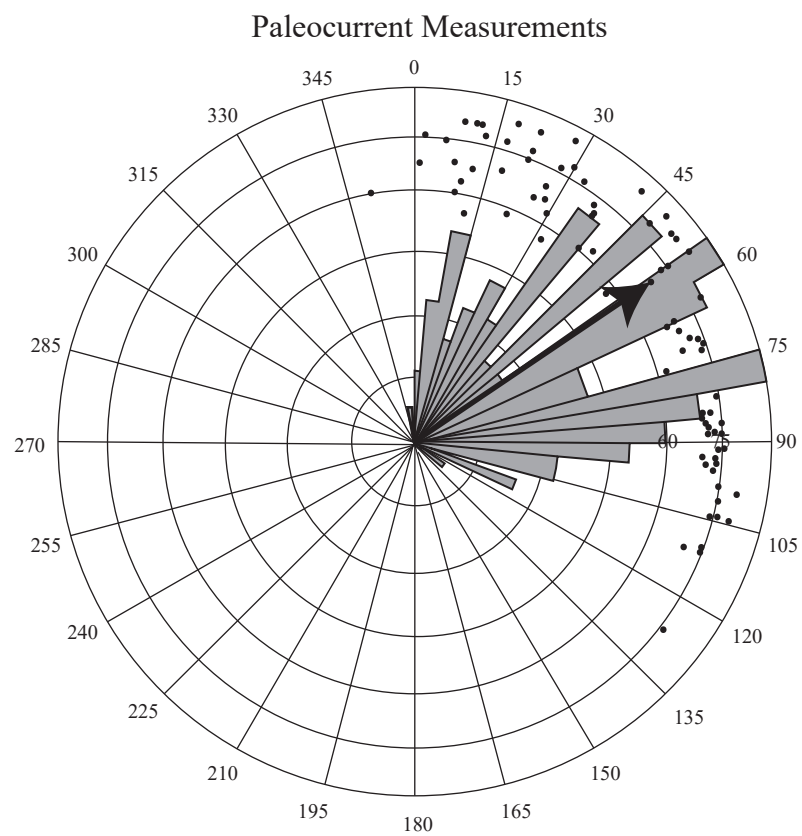


**Figure A-1:** Location of measured section 1 transverse along the corner of the south wall and southeast wall.





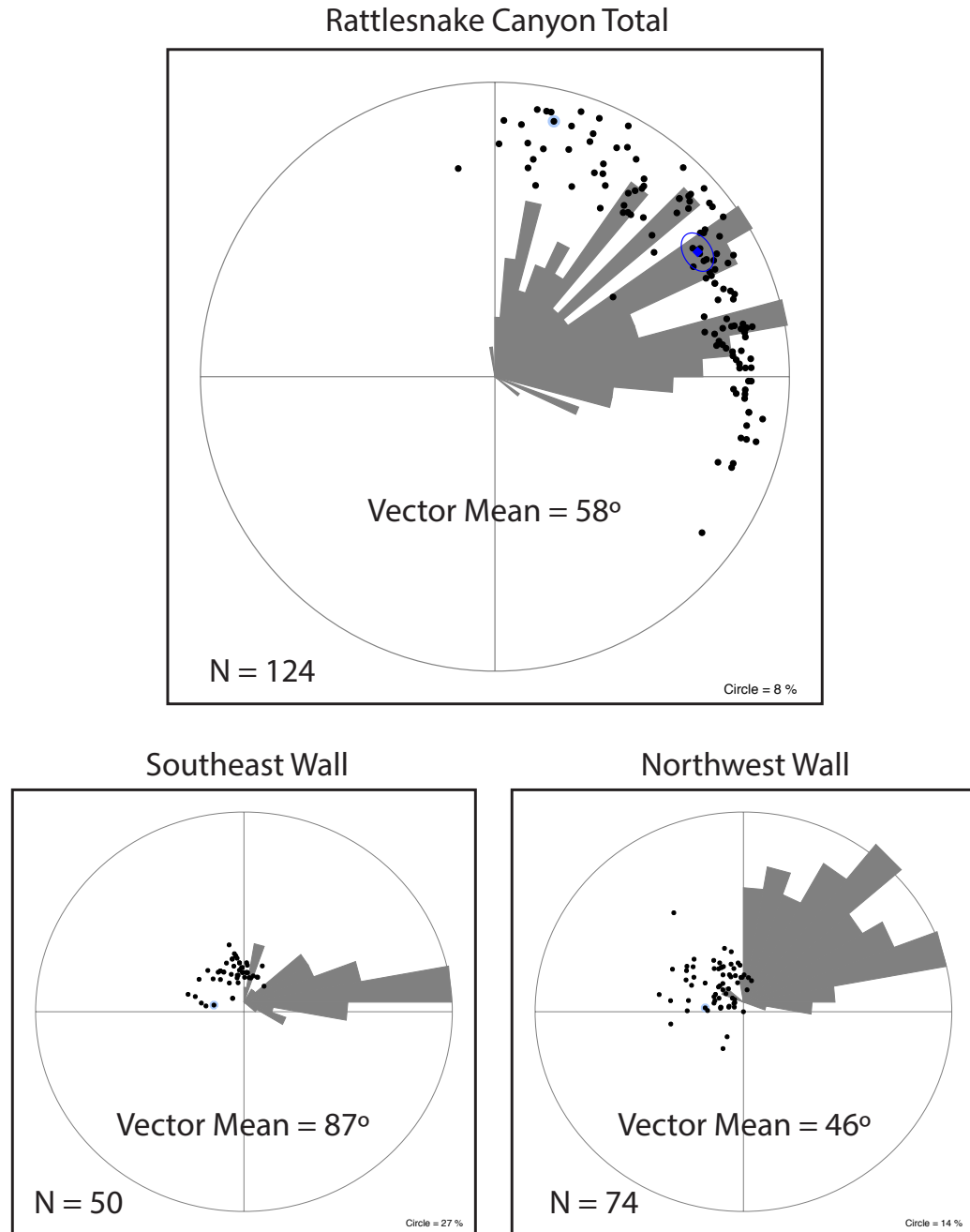
**Figure A-2:** Location of measured sections 2 and 3 transverse along the northeast wall of the outcrop.



**Figure A-9:** Paleocurrent rose diagram from measurements taken in Rattlesnake Canyon. N=124, M=58.

| No. | Dip | Direction | Latitude    | Longitude    | Wall      | No. | Dip | Direction | Latitude    | Longitude    | Wall      |
|-----|-----|-----------|-------------|--------------|-----------|-----|-----|-----------|-------------|--------------|-----------|
| 1   | 13  | 12        | 38.76459913 | -108.2350898 | Southeast | 63  | 48  | 29        | 38.76457126 | -108.2351744 | Northwest |
| 2   | 91  | 14        | 38.76456883 | -108.2351707 | Southeast | 64  | 28  | 13        | 38.76457126 | -108.2351744 | Northwest |
| 3   | 18  | 20        | 38.7645633  | -108.2351766 | Southeast | 65  | 12  | 9         | 38.76461531 | -108.2351346 | Northwest |
| 4   | 78  | 19        | 38.76459183 | -108.23494   | Southeast | 66  | 46  | 14        | 38.76461531 | -108.2351346 | Northwest |
| 5   | 82  | 23        | 38.76458537 | -108.2349316 | Southeast | 67  | 52  | 7         | 38.76462407 | -108.235097  | Northwest |
| 6   | 81  | 15        | 38.76457403 | -108.2349327 | Southeast | 68  | 48  | 12        | 38.76461238 | -108.2351052 | Northwest |
| 7   | 85  | 20        | 38.76454381 | -108.2349904 | Southeast | 69  | 30  | 11        | 38.76463484 | -108.2351224 | Northwest |
| 8   | 78  | 22        | 38.76461069 | -108.2351588 | Southeast | 70  | 22  | 12        | 38.76450199 | -108.2347273 | Northwest |
| 9   | 61  | 15        | 38.76461934 | -108.2351465 | Southeast | 71  | 28  | 4         | 38.76452743 | -108.2347673 | Northwest |
| 10  | 37  | 22        | 38.76461005 | -108.2351341 | Southeast | 72  | 88  | 14        | 38.76453002 | -108.2347707 | Northwest |
| 11  | 71  | 21        | 38.76460367 | -108.2351428 | Southeast | 73  | 64  | 20        | 38.76453153 | -108.2347856 | Northwest |
| 12  | 61  | 19        | 38.76462888 | -108.2351436 | Southeast | 74  | 55  | 14        | 38.76453153 | -108.2347856 | Northwest |
| 13  | 87  | 18        | 38.76467576 | -108.235135  | Southeast | 75  | 65  | 20        | 38.76456242 | -108.234822  | Northwest |
| 14  | 94  | 19        | 38.76466832 | -108.2351406 | Southeast | 76  | 40  | 29        | 38.76443342 | -108.2346263 | Northwest |
| 15  | 48  | 18        | 38.76454819 | -108.2348262 | Southeast | 77  | 32  | 33        | 38.76444499 | -108.2346241 | Northwest |
| 16  | 88  | 18        | 38.76452224 | -108.2347656 | Southeast | 78  | 70  | 16        | 38.76444495 | -108.2346113 | Northwest |
| 17  | 51  | 7         | 38.76447943 | -108.2346519 | Southeast | 79  | 74  | 27        | 38.76444495 | -108.2346113 | Northwest |
| 18  | 64  | 18        | 38.76454626 | -108.2348278 | Southeast | 80  | 57  | 21        | 38.76440006 | -108.2346061 | Northwest |
| 19  | 88  | 16        | 38.76454861 | -108.2347533 | Southeast | 81  | 58  | 11        | 38.76440006 | -108.2346061 | Northwest |
| 20  | 127 | 13        | 38.76454957 | -108.2347493 | Southeast | 82  | 98  | 14        | 38.76442005 | -108.2346023 | Northwest |
| 21  | 111 | 20        | 38.76452133 | -108.234769  | Southeast | 83  | 48  | 5         | 38.76442877 | -108.2346025 | Northwest |
| 22  | 95  | 16        | 38.76472645 | -108.2347035 | Southeast | 84  | 36  | 24        | 38.76442877 | -108.2346025 | Northwest |
| 23  | 93  | 16        | 38.76461649 | -108.2346926 | Southeast | 85  | 61  | 24        | 38.76442877 | -108.2346025 | Northwest |
| 24  | 79  | 14        | 38.76460798 | -108.2347759 | Southeast | 86  | 79  | 12        | 38.76443761 | -108.2345619 | Northwest |
| 25  | 80  | 15        | 38.76456753 | -108.2347962 | Southeast | 87  | 28  | 23        | 38.76444926 | -108.2345563 | Northwest |
| 26  | 64  | 13        | 38.76454797 | -108.2347825 | Southeast | 88  | 37  | 28        | 38.76445652 | -108.2345516 | Northwest |
| 27  | 55  | 16        | 38.76455913 | -108.234728  | Southeast | 89  | 350 | 29        | 38.76445622 | -108.2345592 | Northwest |
| 28  | 84  | 17        | 38.76450746 | -108.2347184 | Southeast | 90  | 9   | 29        | 38.764461   | -108.2345573 | Northwest |
| 29  | 93  | 20        | 38.76450455 | -108.234674  | Southeast | 91  | 86  | 14        | 38.764461   | -108.2345573 | Northwest |
| 30  | 104 | 15        | 38.76450312 | -108.2346802 | Southeast | 92  | 91  | 15        | 38.76446427 | -108.2345724 | Northwest |
| 31  | 83  | 22        | 38.76445275 | -108.2346214 | Southeast | 93  | 78  | 15        | 38.76445492 | -108.234571  | Northwest |
| 32  | 81  | 24        | 38.76444552 | -108.2345722 | Southeast | 94  | 47  | 10        | 38.76443154 | -108.2345863 | Northwest |
| 33  | 58  | 19        | 38.76444678 | -108.2345872 | Southeast | 95  | 82  | 25        | 38.76442789 | -108.2345932 | Northwest |
| 34  | 78  | 28        | 38.76448599 | -108.2345079 | Southeast | 96  | 47  | 11        | 38.76443485 | -108.2346402 | Northwest |
| 35  | 72  | 16        | 38.76447364 | -108.2344855 | Southeast | 97  | 43  | 27        | 38.76443485 | -108.2346402 | Northwest |
| 36  | 98  | 14        | 38.76448164 | -108.2345292 | Southeast | 98  | 12  | 34        | 38.76444403 | -108.2346434 | Northwest |
| 37  | 94  | 16        | 38.7644637  | -108.2345339 | Southeast | 99  | 78  | 18        | 38.76447638 | -108.2345863 | Northwest |
| 38  | 18  | 23        | 38.76447655 | -108.2344483 | Southeast | 100 | 62  | 17        | 38.76446423 | -108.2345963 | Northwest |
| 39  | 9   | 15        | 38.76447941 | -108.2344435 | Southeast | 101 | 67  | 20        | 38.76446058 | -108.2346253 | Northwest |
| 40  | 22  | 50        | 38.76442367 | -108.2344189 | Southeast | 102 | 52  | 32        | 38.76445731 | -108.2344461 | Northwest |
| 41  | 12  | 17        | 38.76440959 | -108.2344633 | Southeast | 103 | 67  | 20        | 38.76446766 | -108.2344516 | Northwest |
| 42  | 12  | 79        | 38.76440281 | -108.2344511 | Southeast | 104 | 84  | 20        | 38.76445773 | -108.2344557 | Northwest |
| 43  | 111 | 15        | 38.76438179 | -108.2344319 | Southeast | 105 | 65  | 22        | 38.76439537 | -108.234304  | Northwest |
| 44  | 101 | 14        | 38.76439925 | -108.2343753 | Southeast | 106 | 79  | 25        | 38.76439667 | -108.2343228 | Northwest |
| 45  | 110 | 15        | 38.76437059 | -108.2343683 | Southeast | 107 | 56  | 50        | 38.76440953 | -108.2343282 | Northwest |
| 46  | 6   | 15        | 38.76436334 | -108.2343876 | Southeast | 108 | 104 | 13        | 38.76441377 | -108.234319  | Northwest |
| 47  | 86  | 19        | 38.76435148 | -108.2342629 | Southeast | 109 | 99  | 8.8       | 38.76438736 | -108.2342881 | Northwest |
| 48  | 2   | 14        | 38.76421473 | -108.2340951 | Southeast | 110 | 76  | 20        | 38.76437559 | -108.234268  | Northwest |
| 49  | 18  | 6         | 38.76428713 | -108.2340731 | Southeast | 111 | 71  | 15        | 38.76437555 | -108.2342803 | Northwest |
| 50  | 42  | 5         | 38.76431264 | -108.2341075 | Southeast | 112 | 17  | 298       | 38.76437387 | -108.2342925 | Northwest |
| 51  | 30  | 26        | 38.76428734 | -108.2341119 | Northwest | 113 | 12  | 302       | 38.76439671 | -108.2342536 | Northwest |
| 52  | 1   | 22        | 38.76430539 | -108.2341185 | Northwest | 114 | 6   | 270       | 38.76449457 | -108.2340336 | Northwest |
| 53  | 12  | 22        | 38.76435315 | -108.2341133 | Northwest | 115 | 13  | 275       | 38.76442089 | -108.2340957 | Northwest |
| 54  | 38  | 19        | 38.76435407 | -108.2340316 | Northwest | 116 | 17  | 332       | 38.76436884 | -108.234157  | Northwest |
| 55  | 22  | 6         | 38.76435425 | -108.234031  | Northwest | 117 | 10  | 275       | 38.76436884 | -108.234157  | Northwest |
| 56  | 49  | 14        | 38.76434346 | -108.2339598 | Northwest | 118 | 9   | 296       | 38.76428456 | -108.2341349 | Northwest |
| 57  | 9   | 9         | 38.76432959 | -108.2339521 | Northwest | 119 | 14  | 283       | 38.76427832 | -108.2341373 | Northwest |
| 58  | 11  | 9         | 38.7643376  | -108.2339569 | Northwest | 120 | 7   | 260       | 38.76425145 | -108.2341054 | Northwest |
| 59  | 61  | 20        | 38.76439723 | -108.2340143 | Northwest | 121 | 12  | 255       | 38.76425145 | -108.2341054 | Northwest |
| 60  | 17  | 12        | 38.76438398 | -108.2339648 | Northwest | 122 | 11  | 240       | 38.76425145 | -108.2341054 | Northwest |
| 61  | 55  | 6         | 38.7644198  | -108.2339168 | Northwest | 123 | 12  | 351       | 38.76435874 | -108.2339894 | Northwest |
| 62  | 33  | 13        | 38.7645633  | -108.2351766 | Northwest | 124 | 0   | 70        | 38.76437525 | -108.2339962 | Northwest |

**Figure A-10:** Paleocurrent measurements and latitude and longitude of measurements taken in channel sandstones of the Burro Canyon formation in Rattlesnake Canyon.



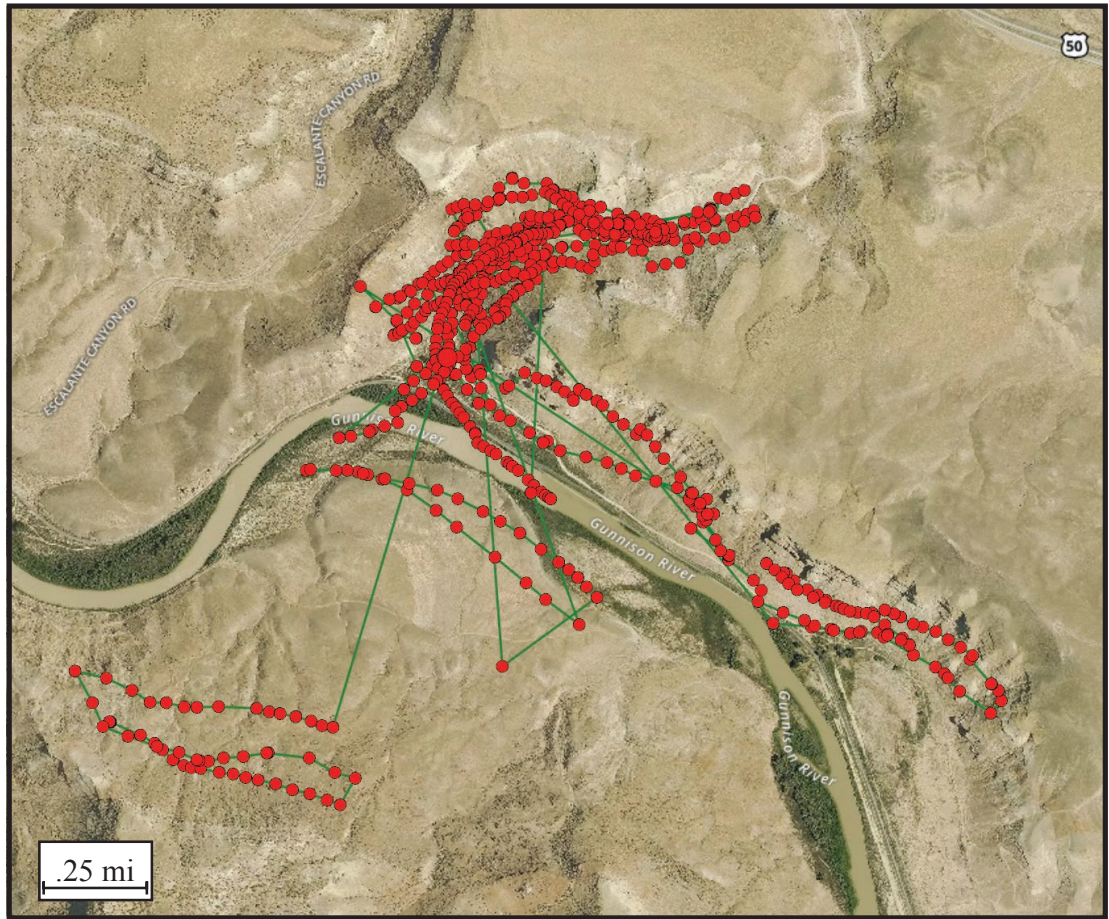
**Figure A-11:** Paleocurrent data showing multiple rose diagrams for Rattlesnake Canyon. Rattlesnake Canyon Total shows the 124 measurements and their distributions with a vector mean of  $58^{\circ}$ . Southeast wall shows measurements taken in the southeast wall measured section (MS1). Southeast wall shows a total of 50 measurements with a vector mean of  $87^{\circ}$ . Northwest wall shows measurements taken along the northwest wall measured sections (MS2 and MS3). Northwest wall shows a total of 74 measurements with a vector mean of  $46^{\circ}$ .



## **Appendix A-12. Paleocurrent Measurements**

Paleocurrent measurements were taken at 124 different locations throughout Rattlesnake Canyon, with a vector mean of  $58^{\circ}$ . Along the southeast wall (MS1), paleocurrent measurements indicate deposition to the west, with a vector mean of  $87^{\circ}$ . This differs from measurements taken along the northwest wall (MS2 and MS3), which give a paleocurrent vector mean of  $46^{\circ}$ . The difference in paleocurrent vector means across the two sides of the canyon may be due to individual channels in which measurements were obtained. The southeast wall of the canyon contained highly weathered sandstones creating issues with obtaining paleocurrent data. Majority of data taken along this wall was in the bottom most channels, including the upper Morrison channel present (~5 measurements from this channel). Paleocurrents along the northwestern wall were more evenly distributed through Burro Canyon Formation channels, and no measurements were taken in the Morrison Formation.

## Drone Photogrammetry Locations



**Figure A-13:** Locations of drone photogrammetry throughout Rattlesnake Canyon. Red dots indicate locations with panoramic images of the canyon taken. Green line indicates flight path of DJI-Phantom drone.

## **Appendix B: Sedimentology and Stratigraphy**

### **Appendix B-1. Channel Bodies**

The Burro Canyon Formation represents a low net-to-gross ratio of approximately 1:2, within which 67 individual sandstone channel fill bodies have been identified, half of which have been associated with amalgamated channel complexes and the other half semi-amalgamated channel complexes. These 67 individual sandstone channel fill bodies are divided into three different channel complexes, each of which are laterally and depositionally equivalent. Outcrop exposure depicting the three channel complexes oriented perpendicular to paleoflow contain significantly more channel fill deposits than the channel complexes present in exposures oriented parallel to paleoflow. Due to the sinuous nature of braided depositional profiles likelihood of observing channel fill bodies along exposures oriented perpendicular to paleoflow has an increased potential.

## **Appendix B-2. Lithofacies Descriptions**

Amalgamated channel complexes of Rattlesnake Canyon are characterized by a high degree of internal complexity, due to the constant reworking of sediment in a braided fluvial system. Repeated scouring and filling of the channels has resulted in trough cross-bedding across half (~51%) of the observed channel bodies. Trough cross-bedding occurs 2-20 feet (0.61 to 6.10 m) thick in sandstone bodies and is laterally extensive throughout the span of the deposits. Trough cross-bedding tends to occur throughout the main body of channels, ranging from fine- to medium-grained. Grains appear to be moderately sorted and composed of quartz and chert with occasional iron oxides and quartz overgrowths present. While trough cross-bedding appears in the majority of sandstone bodies, it is commonly difficult to identify due to high amounts of weathering observed in the outcrop.

Granule-pebble conglomerates make up ~12% of the observed sandstone bodies, and is located in the basal scours of the individual beds. These conglomeratic beds are largely composed of granule sized clasts, light brown to gray in color, supported in a medium grained sandstone matrix. Clasts are cemented in calcite and composed of chert, quartzite and quartz with minor lithics. Conglomeratic beds are commonly one to three feet (0.3 to .91m) deep and laterally extensive across Rattlesnake Canyon outcrops.

Sandstone with interbedded chert was found on the northwestern wall of Rattlesnake Canyon, this chert bed has been identified as the marker bed for the top of the Burro Canyon Formation interval (Simmons; 1957). The chert-rich sandstone occurs in laminated beds in a fine- to medium-grained matrix and has been interpreted as

remnant lacustrine deposit (Cole, 2017). Individual laminated beds are 2 to 6 inches (0.05 to 0.15 m) deep across a two-foot (0.6 m) interval. This chert-rich bed appears highly eroded and only in situ in one location in the canyon. Due to the location of the bed and the locations of the best exposures for modeling purposes, the chert-rich sandstone does not appear in the static geologic lithofacies models produced.

Planar laminations are found interbedded with trough cross-bedded sandstone. Laminations occur in very fine- to fine- grained sandstone over intervals from 0.5 to 6 ft (0.15 to 1.8 m). In Rattlesnake Canyon, planar laminations occur in the upper portion of beds indicating a slower flow regime and less scouring of the individual beds. Associated with planar laminations in the uppermost portions of beds are low angle planar laminations. These occur in very fine- to fine-grained rock and are present in few places throughout the canyon. Laminations have a faint appearance and typically occur in the upper foot (.31 m) of the beds, when this upper portion has not been eroded away.

Fine- to medium-grained structureless sandstone has been identified in measured section traverses throughout Rattlesnake Canyon. Structureless sandstone is composed of quartz grains in siliceous or calcite cement, and commonly contains iron oxides. Structureless sandstone is found interbedded with trough cross-bedding and planar laminated-bedding. The presence of this structureless sandstone is likely the product of intense outcrop weathering. It is probable that the sandbodies exhibiting a structureless stratigraphic pattern are actually trough cross-bedded or planar laminated sandstones, given the depositional environment.

Two types of mudstones occur in Rattlesnake Canyon, light gray to green mudstone and a gray-black carbonaceous mudstone. Gray to green mudstone is

indicative of the Burro Canyon Formation in Western Colorado (Currie et al., 2008).

This mudstone contains bentonitic traces in the lower section of the Burro Canyon Formation and yields a gamma ray response greater than 300 API units in Rattlesnake Canyon (McPherson et al., 2008). The upper portion of the gray-green mudstone in the Burro Canyon is thinly laminated, brittle and silicified. Gray-black fissile carbonaceous mudstone occurs in thin laminations and identifies the base of the Dakota Formation (McPherson et al., 2008).

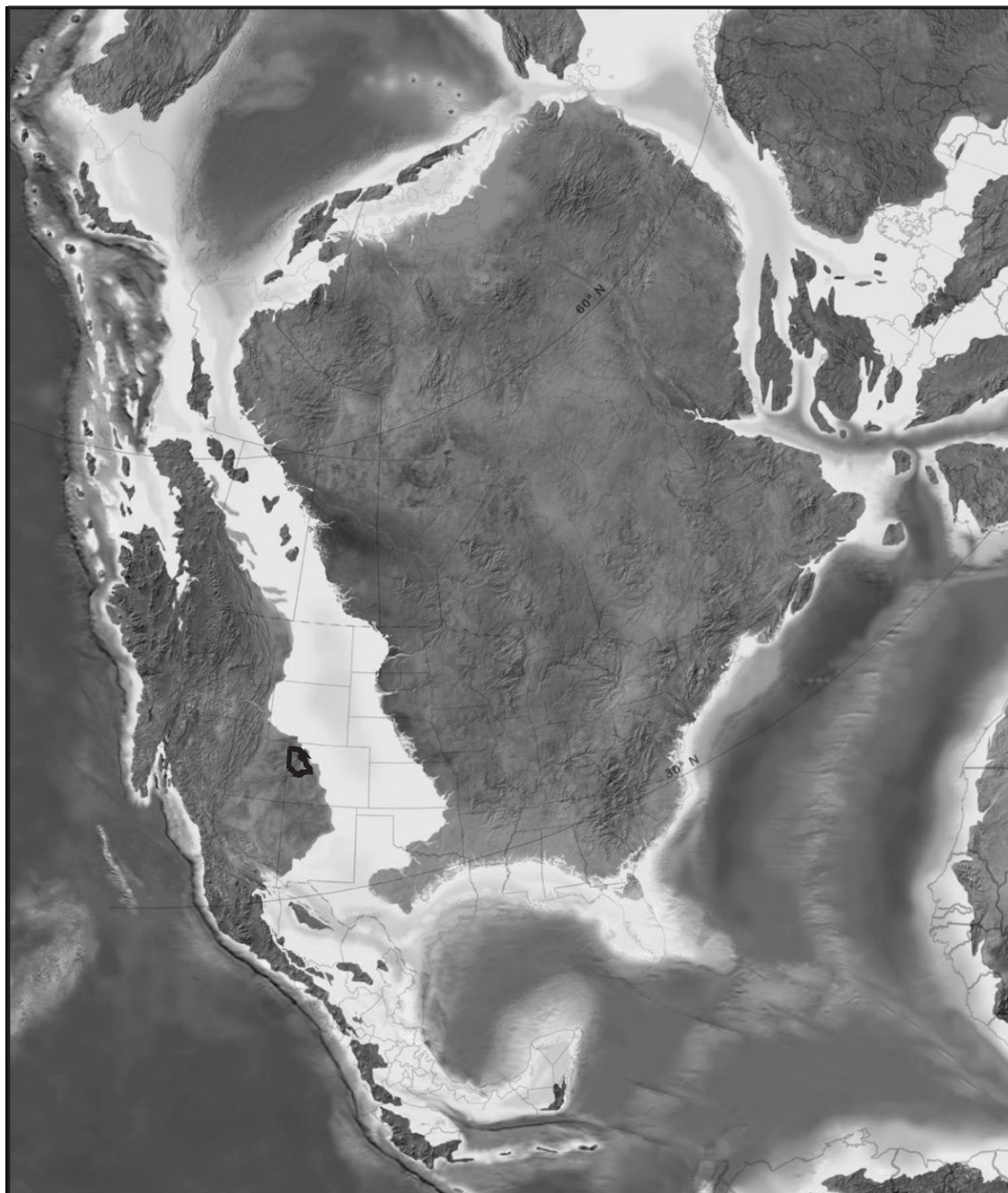
### **Appendix B-3. Isolated Fluvial-Bar Channel-Fill Deposits**

Isolated fluvial-bar channel-fill deposits are not to be confused with crevasse splay deposits. While both exhibit a relatively thin and laterally extensive geometry, the two deposit types represent different depositional styles. While isolated fluvial-bar channel-fill exhibits a fining upwards nature dominated by sandstone with low-angle planar or planar laminated lithofacies, crevasse splay's display a coarsening upwards nature with structureless lithofacies and high mudstone influence. Within Rattlesnake Canyon, there does not appear to be the presence of any crevasse splay deposits within the measured sections taken.

## **Appendix B-4 Petrophysical Data**

Porosity and permeability data of the Burro Canyon Formation are directly associated with lithofacies and rock quality present throughout the canyon. The mean porosity and permeability in the Mitchell Energy Federal 8-1 core are 8.3% and 4.4 mD respectively. These values are used in Model 1, or the base case. Throughout the Burro Canyon cored interval, porosity values ranged from 0.9% to 14.6% with a standard deviation of 3.67%, and permeability values ranged from 0.1 mD to 48 mD with a standard deviation of 10.6 mD. The range in porosity and permeability values has a direct correlation to the upwards fining lithofacies present in the cored interval. Three lithofacies have been derived from the core and correlated to the lithofacies present in outcrop along the south and southeastern exposures of Rattlesnake Canyon. These lithofacies are: (1) conglomeratic bedding; (2) Trough cross-laminations; and (3) planar laminations. In the cored interval, conglomeratic facies contained porosity ranges from 5% to 11% with a mean of 8.27% and standard deviation of 2.64% and permeability ranges from 0.3 mD to 34 mD with a mean of 4.76 mD and standard deviation of 9.42 mD. Trough cross-laminations show porosity ranging from 4% to 13% with a mean of 8.9% and standard deviation of 3.2% as well as permeability ranging from 0.1 mD to 48 mD with a mean of 8.25 mD and standard deviation of 15.76 mD. The final lithofacies, planar laminations show porosity values ranging from 0.9% to 5.7% with a mean of 2.67% and standard deviation of 2.64%, along with permeability values ranging from 0.1 mD to 0.2 mD with a mean of 0.1 mD and standard deviation of 0.1 mD.

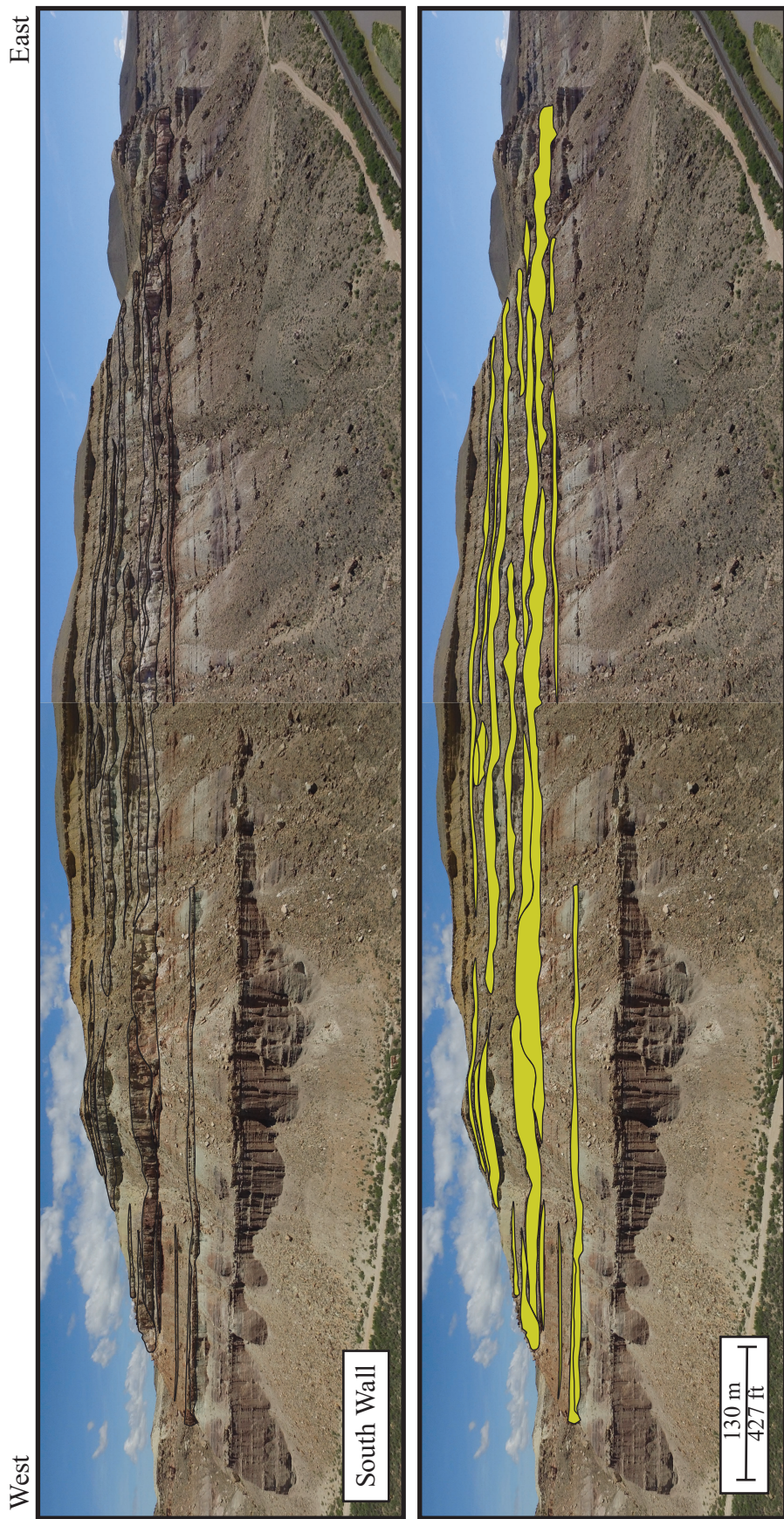




 Piceance Basin Outline

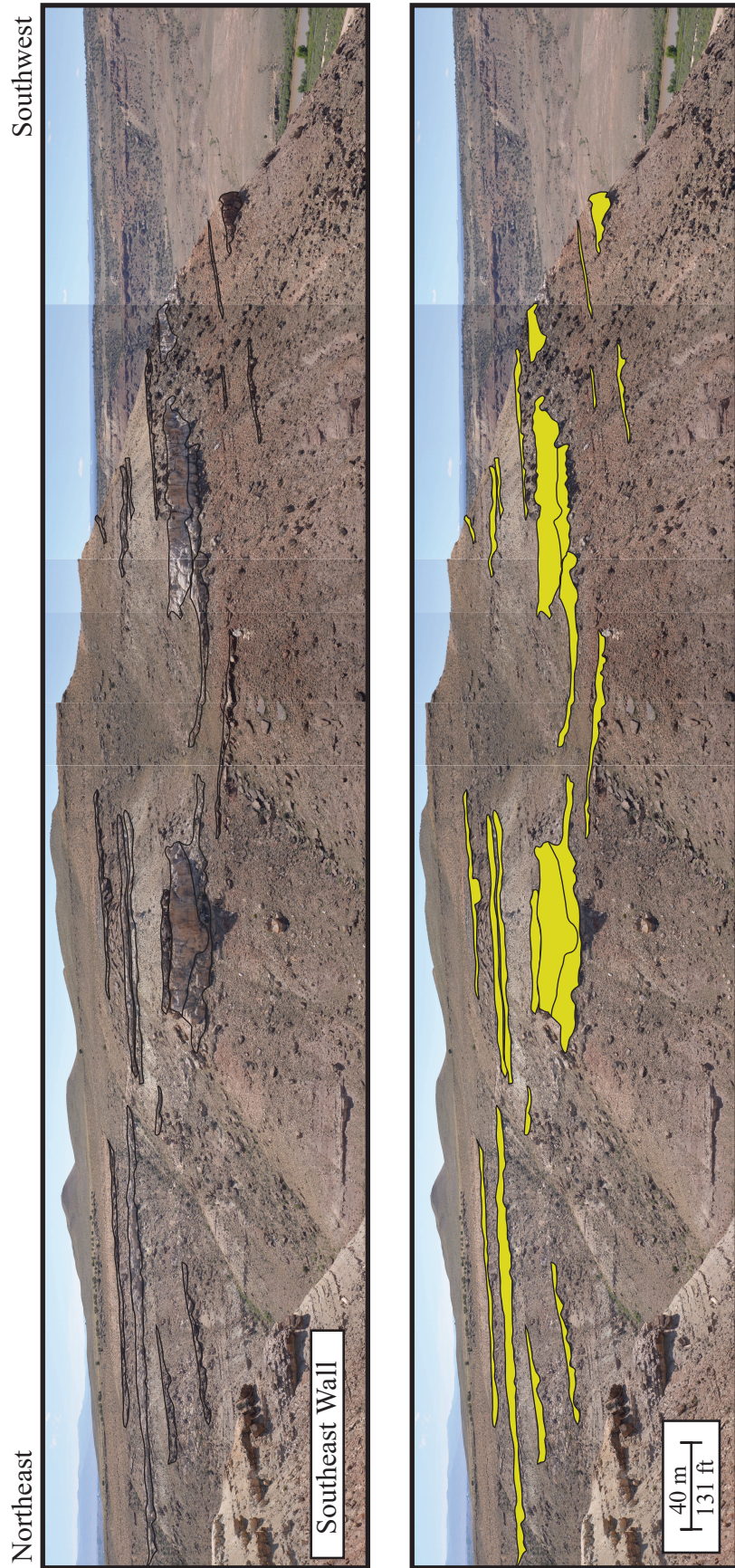
0 600 Mi  
0 1000 Km

**Figure B-4:** Paleogeographic map of North America showing the Western Interior Seaway covering a large portion of Colorado and the present day Piceance Basin on the edge of the seaway, likely indicating fluvial deposition occurring. Modified from Blakey (2006).



**Figure B-5:** Exposed outcrop Burro Canyon Formation along the south canyon wall. Sandstone bodies make up four channel complex systems in the Burro Canyon Formation. Yellow shading indicates sandstone bodies exposed.





**Figure B-6:** Exposed outcrop Burro Canyon Formation along the southeast canyon wall. Sandstone bodies make up four channel complex systems in the Burro Canyon Formation. Yellow shading indicates sandstone bodies exposed.



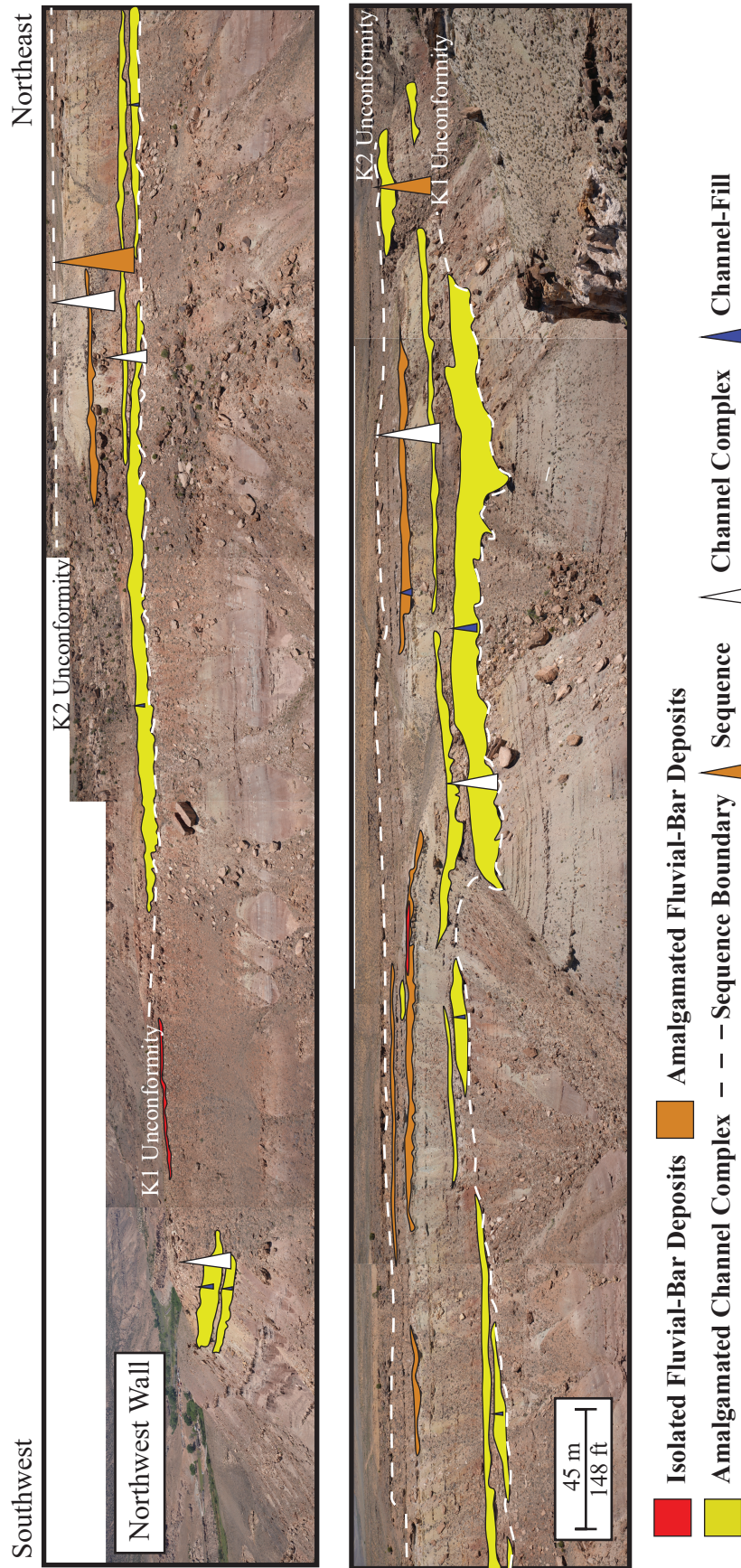
**Figure B-7:** Northwest wall view of Rattlesnake Canyon with outlined sandstone bodies.





**Figure B-8:** Exposed outcrop Burro Canyon Formation along the northwest canyon wall. Sandstone bodies make up four channel complex systems in the Burro Canyon Formation.

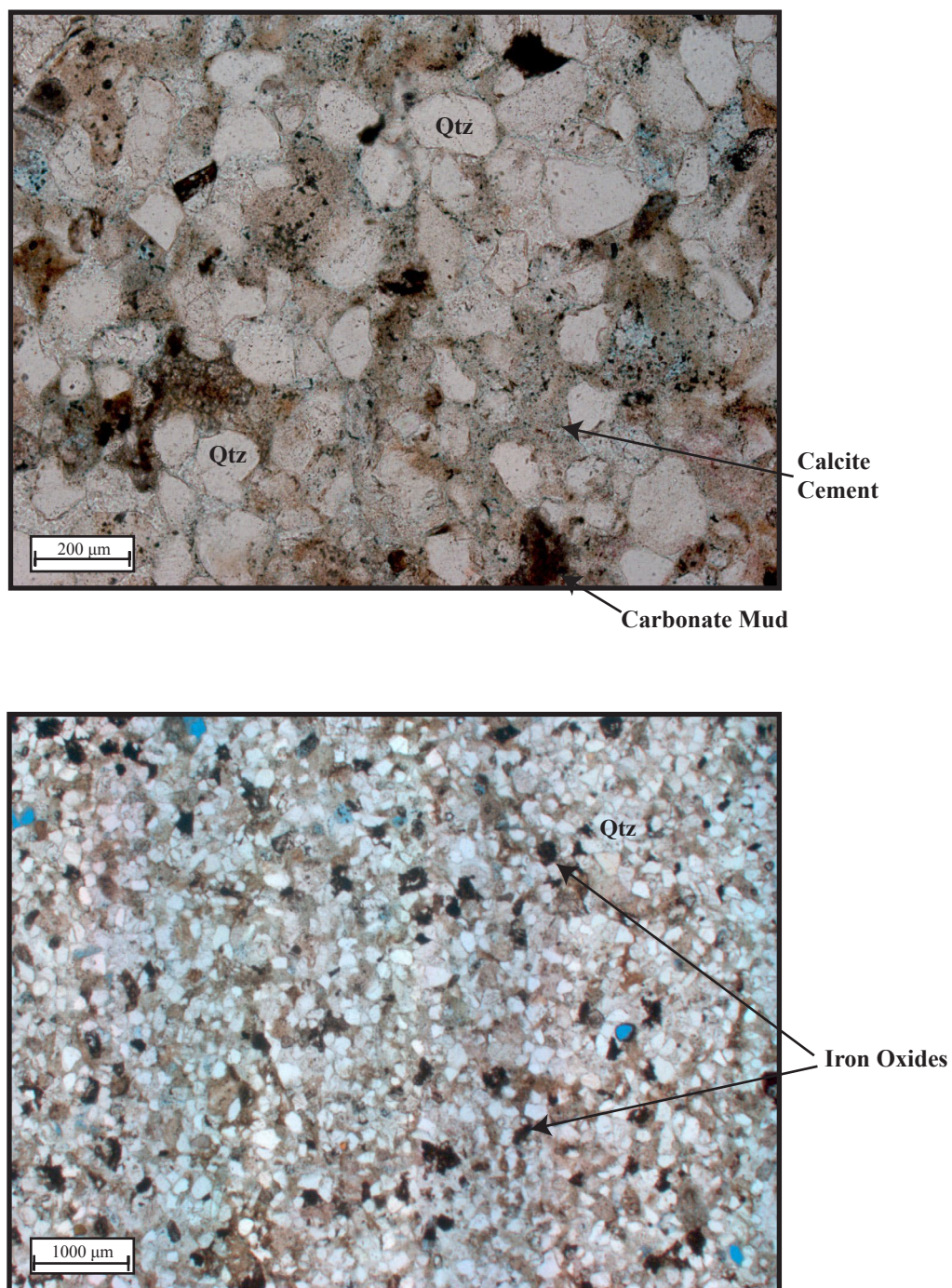




**Figure B-6:** Architectural elements associated with the Northwest Wall of Rattlesnake Canyon. A single sequence is observed between the K-1 and K-2 Unconformities in the Burro Canyon Formation. Majority of the architectural elements present are amalgamated channel complexes with minor amalgamated fluvial-bar and isolated fluvial-bar deposits. Beneath the sequence present are amalgamated channel complexes of the upper Morrison Formation.

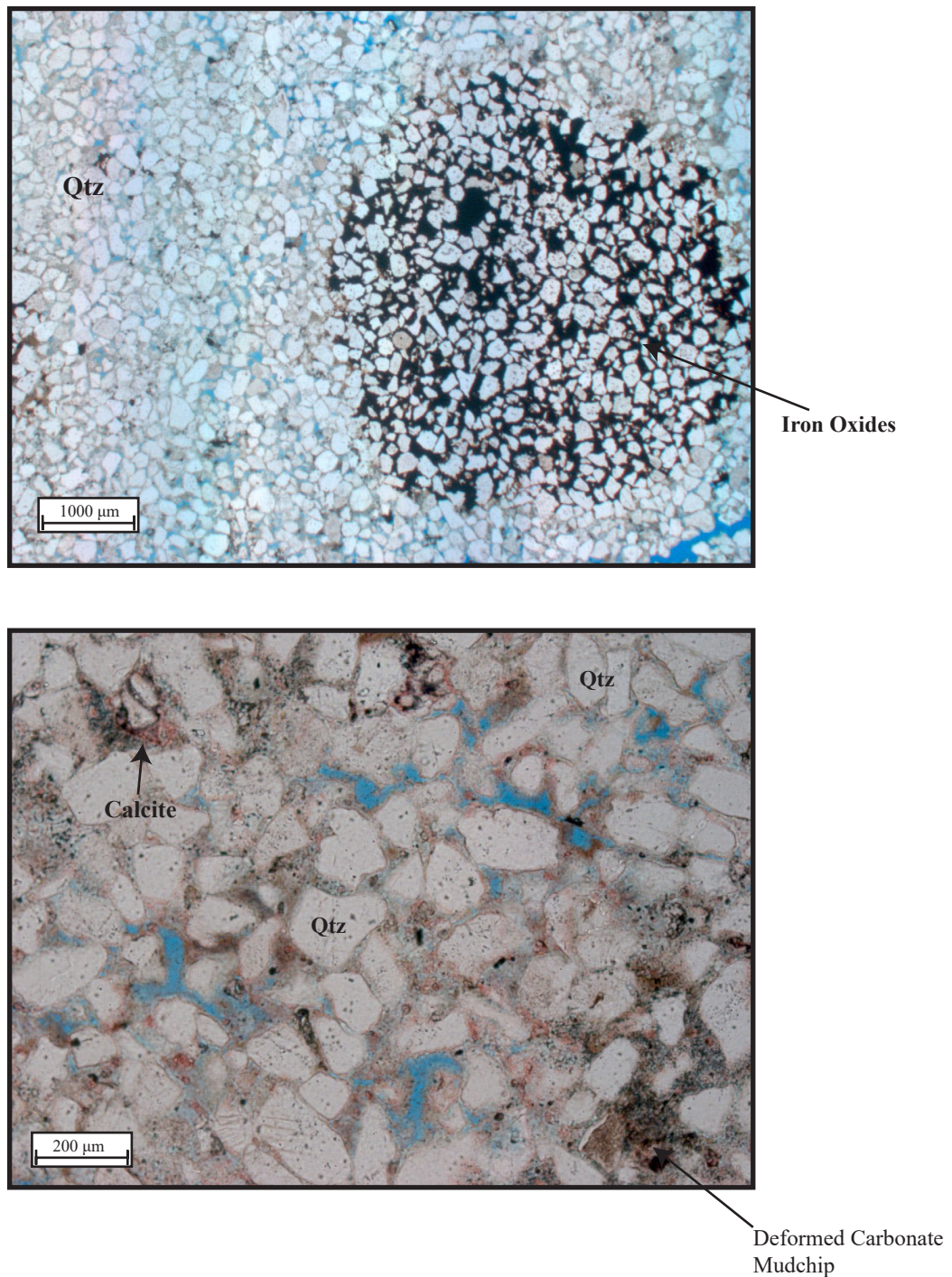


Burro Canyon  
Channel Complex 1  
Sample MS1-1



**Figure B7:** Thin section sample taken from channel complex 1 on measured section 1. This sample is predominately composed of quartz grains iron oxides and carbonate mud. Calcite cementation can be observed between grains.

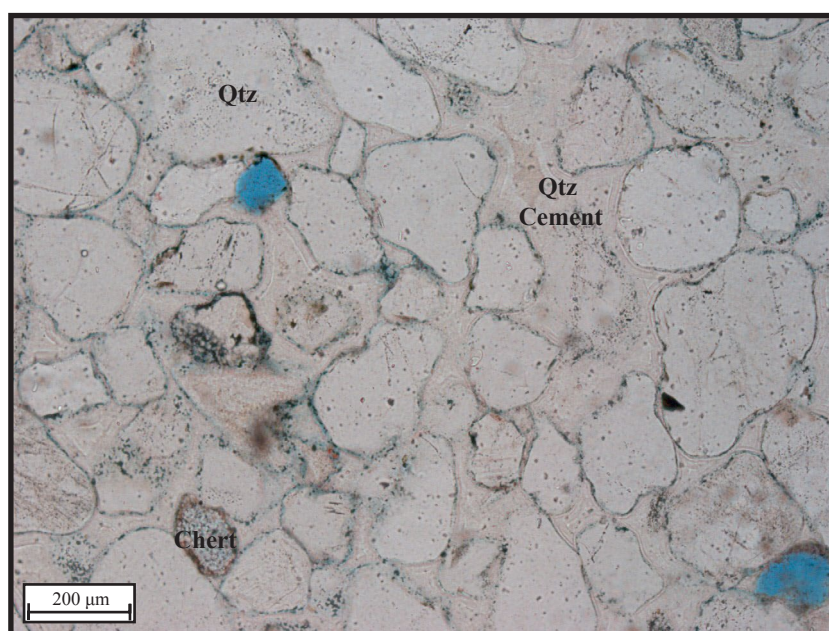
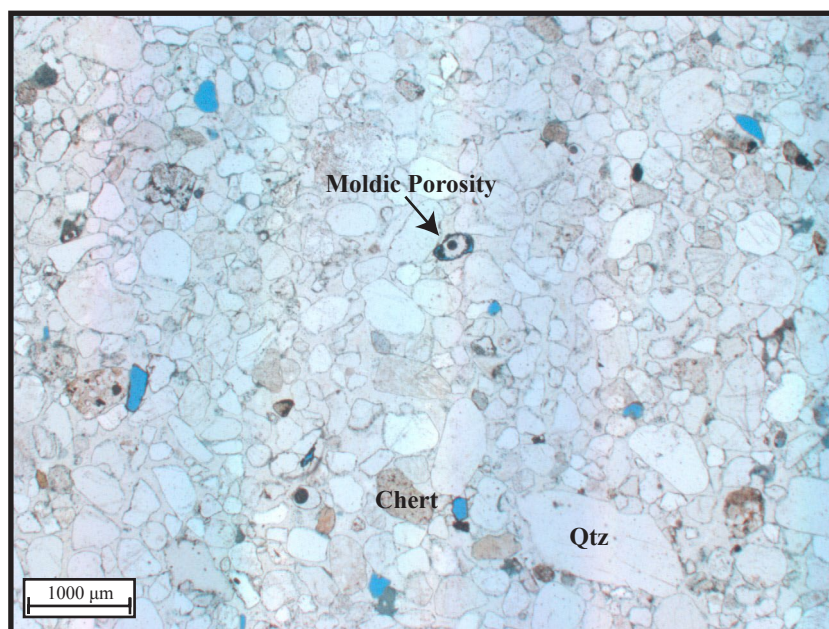
Burro Canyon  
Channel Complex 2  
Sample: MS2-1



**Figure B-8:** Thin section sample taken from channel complex 2 on measured section 2. Predominately composed of quartz grains with minor mudchips and calcite grains, cemented with calcite. Large amounts of iron oxides are present throughout this interval and can be seen in the sample.

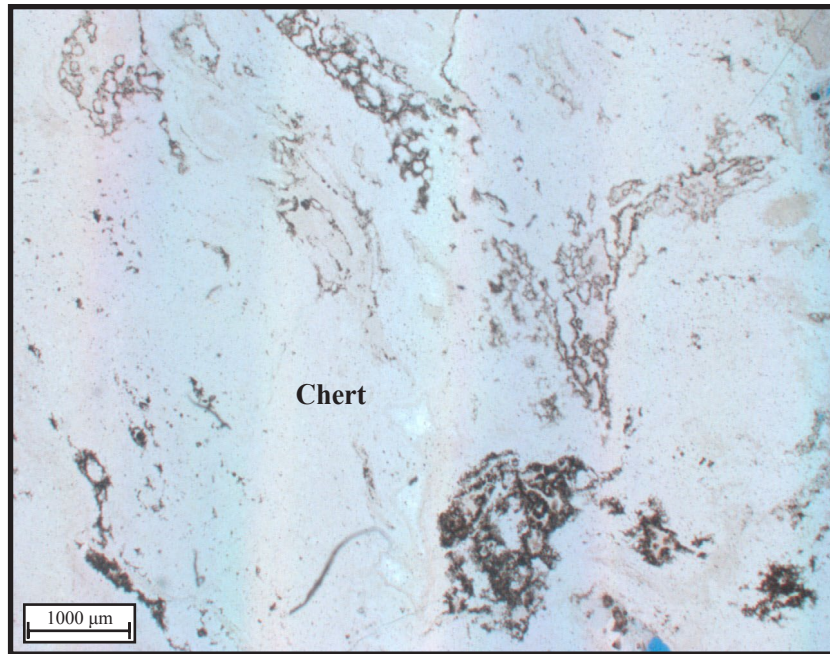


Burro Canyon  
Channel Complex 2  
Sample: MS2-2



**Figure B9:** This thin section sample was taken from channel complex 2 on measured section 2. Predominately composed of quartz grains with minor chert and silica cement. This sample shows the variability between beds of the same channel complex. Possible moldic porosity from dissolution can be observed in the upper section.

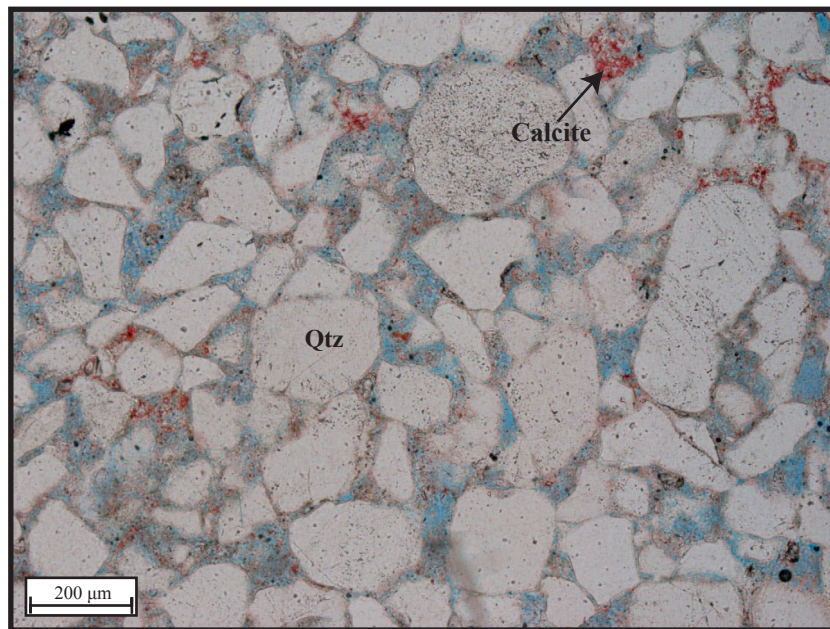
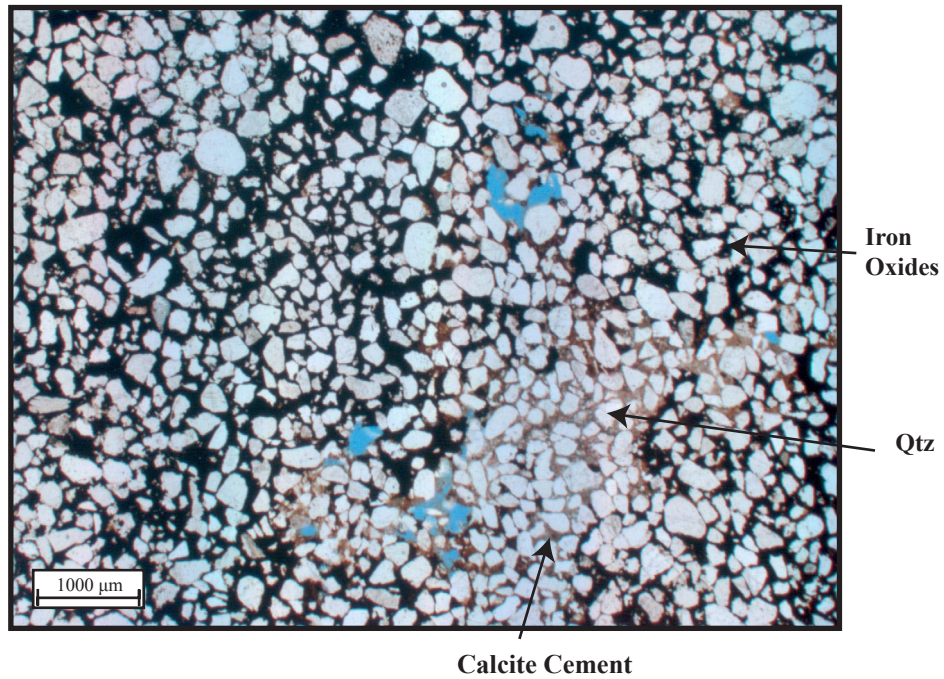
Burro Canyon  
Channel Complex 4  
Sample: MS2-3



**Figure B10:** Thin section sample taken from channel complex 4 on measured section 2. This thin section is entirely composed of chert and is representative of upper chert bed in Burro Canyon Formation. Dark areas could possibly represent presence of organics during chert formation.



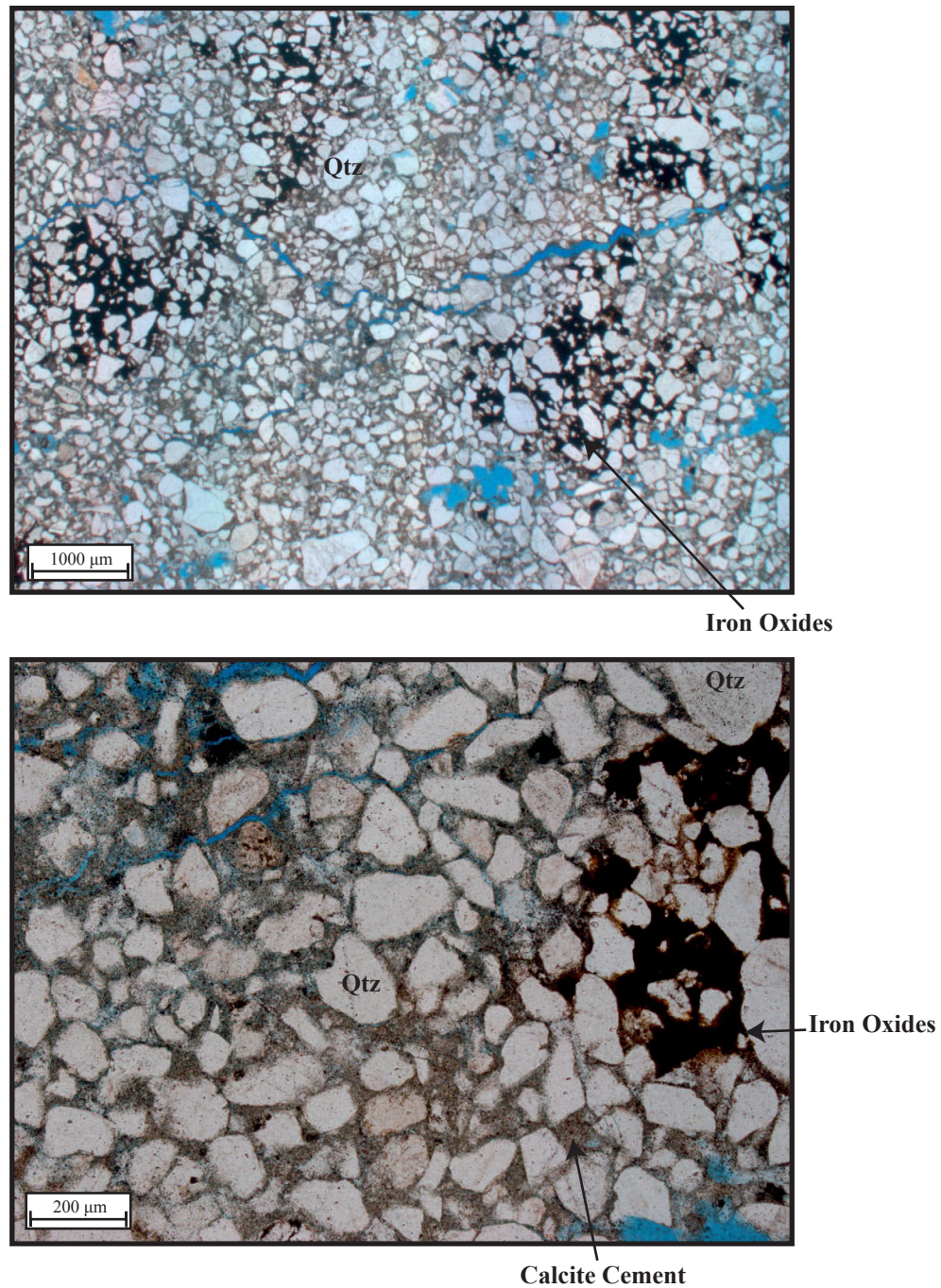
Burro Canyon  
Channel Complex 3  
Sample: MS3-1



**Figure B11:** Thin section sample taken from channel complex 3 on measured section 3. Grains are largely composed of quartz and iron oxides with minor calcite and contain calcite cement. High percentages of iron oxides can be seen in this channel complex.

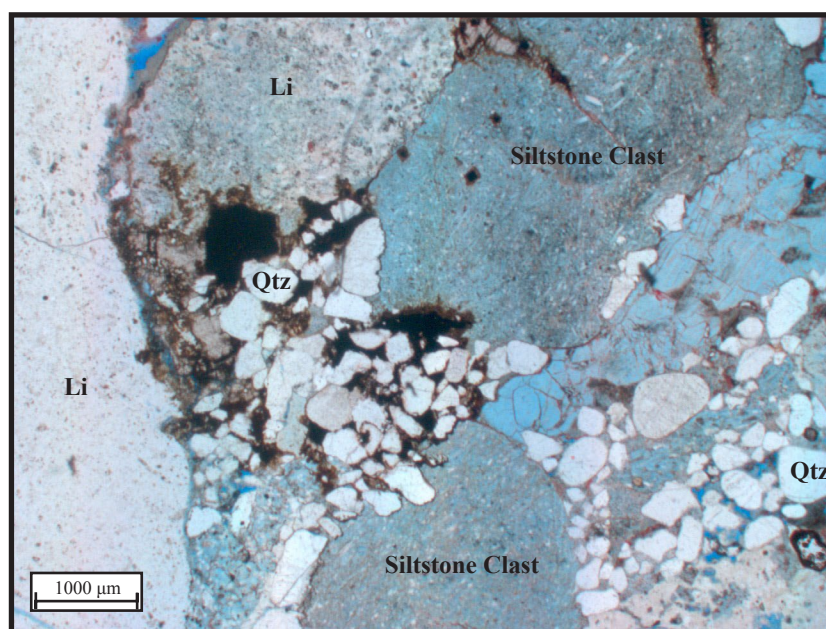
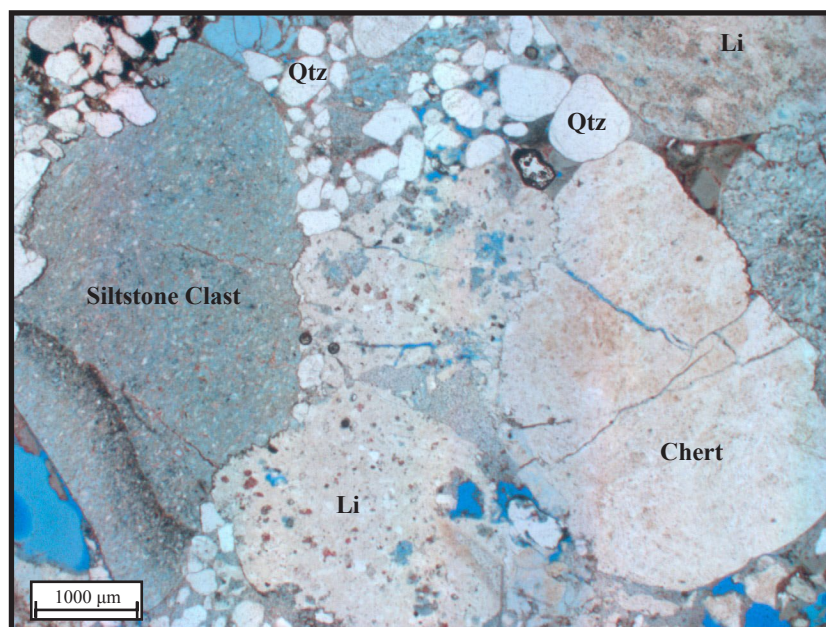


Burro Canyon  
Channel Complex 3  
Sample: MS3-2



**Figure B12:** Thin section sample taken from channel complex 3 on measured section 3. Grains are largely composed of quartz with high amounts of iron oxides present. Grains can be seen cemented in calcite.

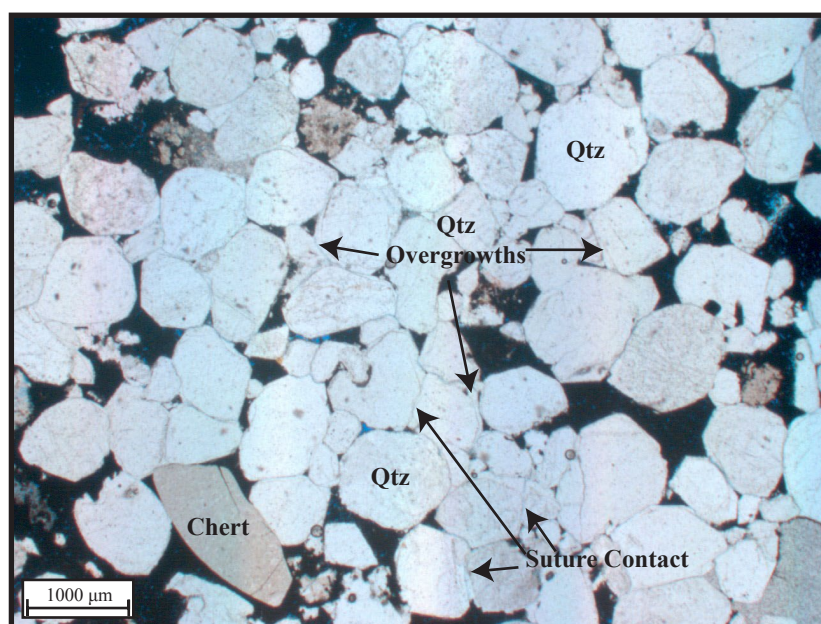
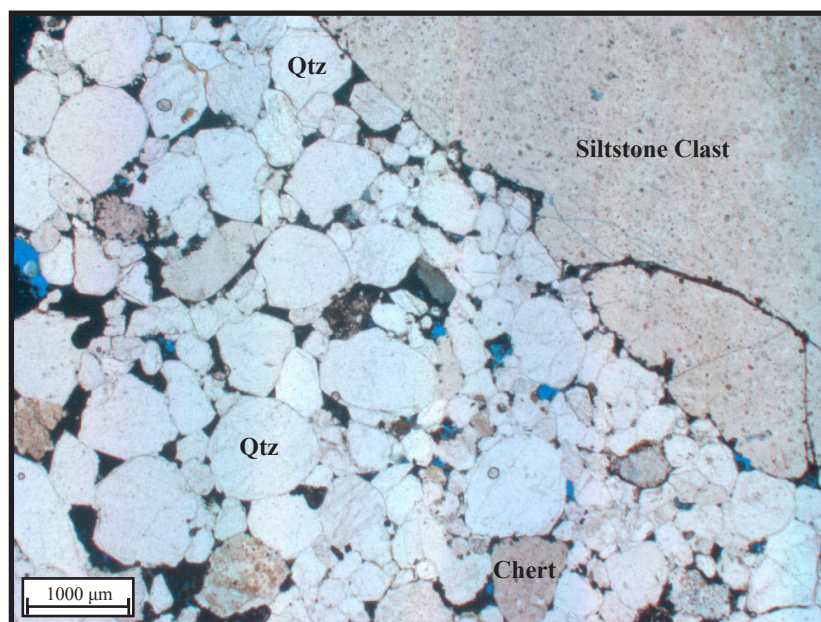
Burro Canyon  
Channel Complex 4  
Sample: MS3-4



**Figure B13:** Thin section sample taken from channel complex 4 on measured section 3. The conglomeratic interval shows clasts of siltstone, chert and lithics in a quartz grained matrix.



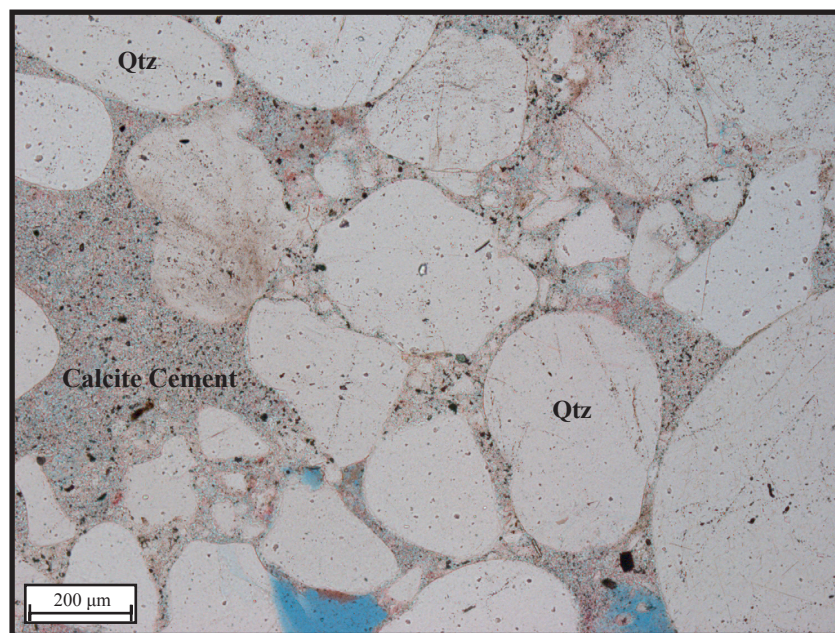
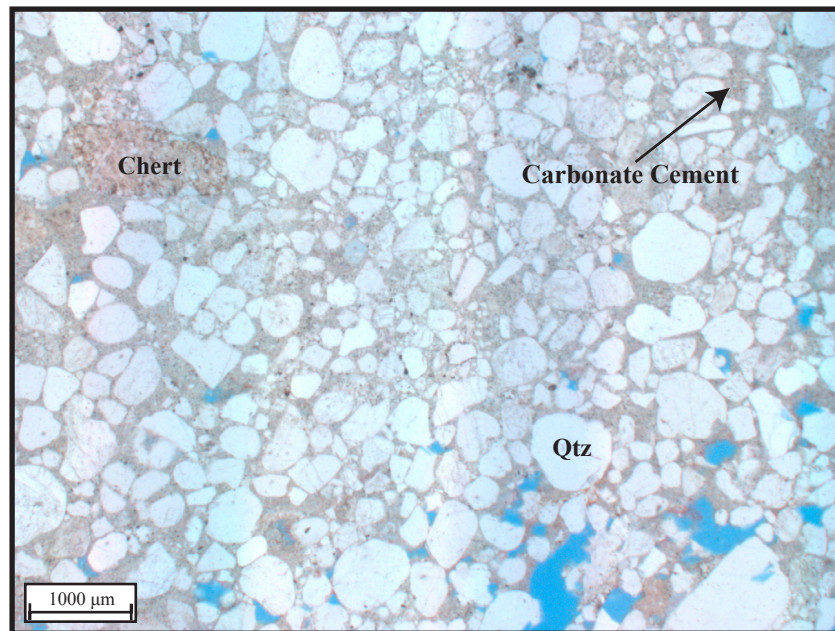
Burro Canyon  
Channel Complex 4  
Sample: MS3-5



**Figure B14:** Thin section sample taken from channel complex 4 on measured section 3. Represents transition zone from conglomerate beds into trough cross-bedded sandstone. Large quartz and chert grains are present with a siltstone clast. Quartz overgrowths common throughout the sample, along with the presence of suture contacts indicating a high degree of compaction.



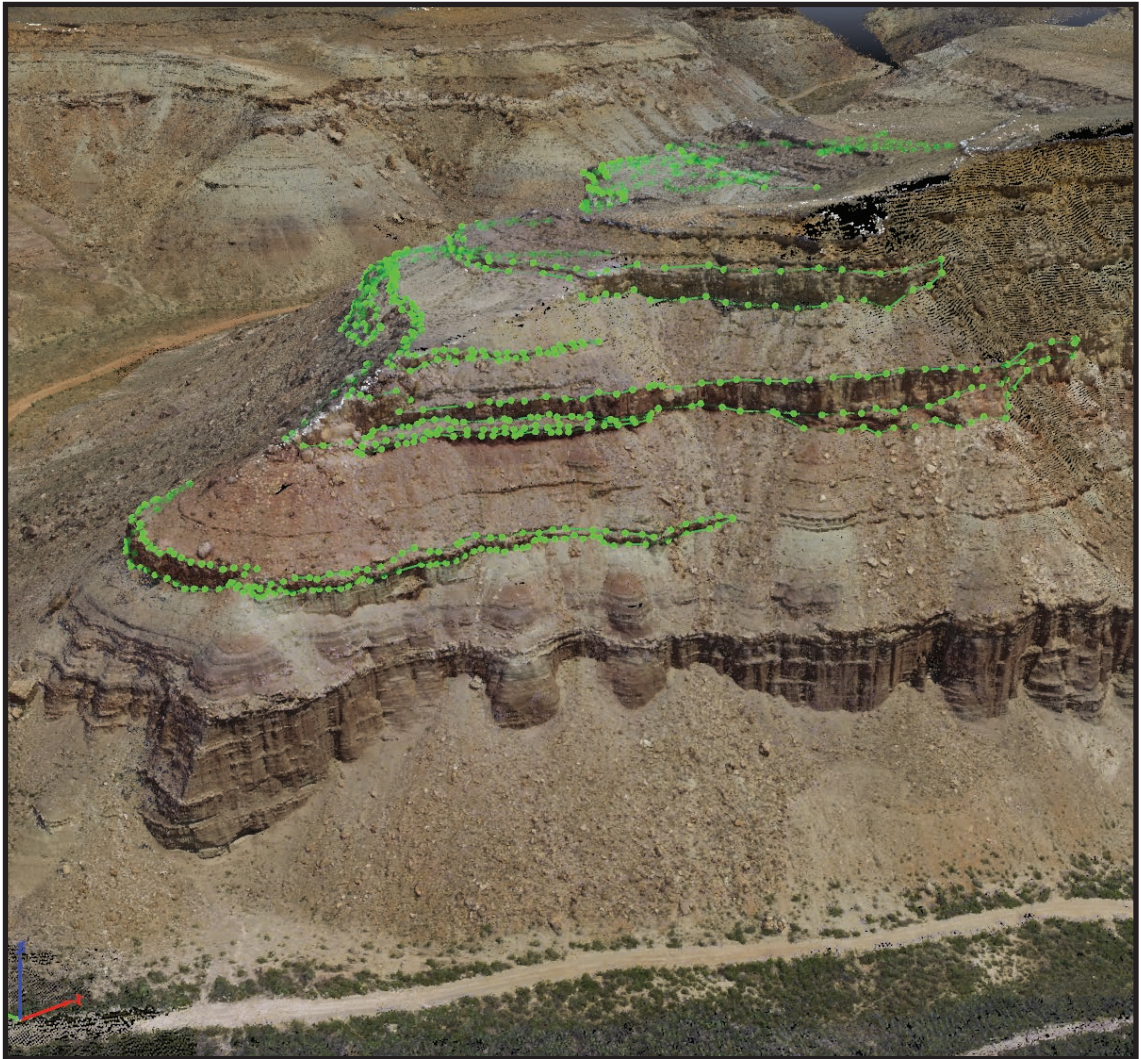
Burro Canyon  
Channel Complex 4  
Sample: MS3-6



**Figure B15:** Thin section sample taken from channel complex 4 on measured section 3. Composed of predominately quartz grains with minor chert and encompassed in calcite cement.



### Point Cloud Sandstone Body Interpretation

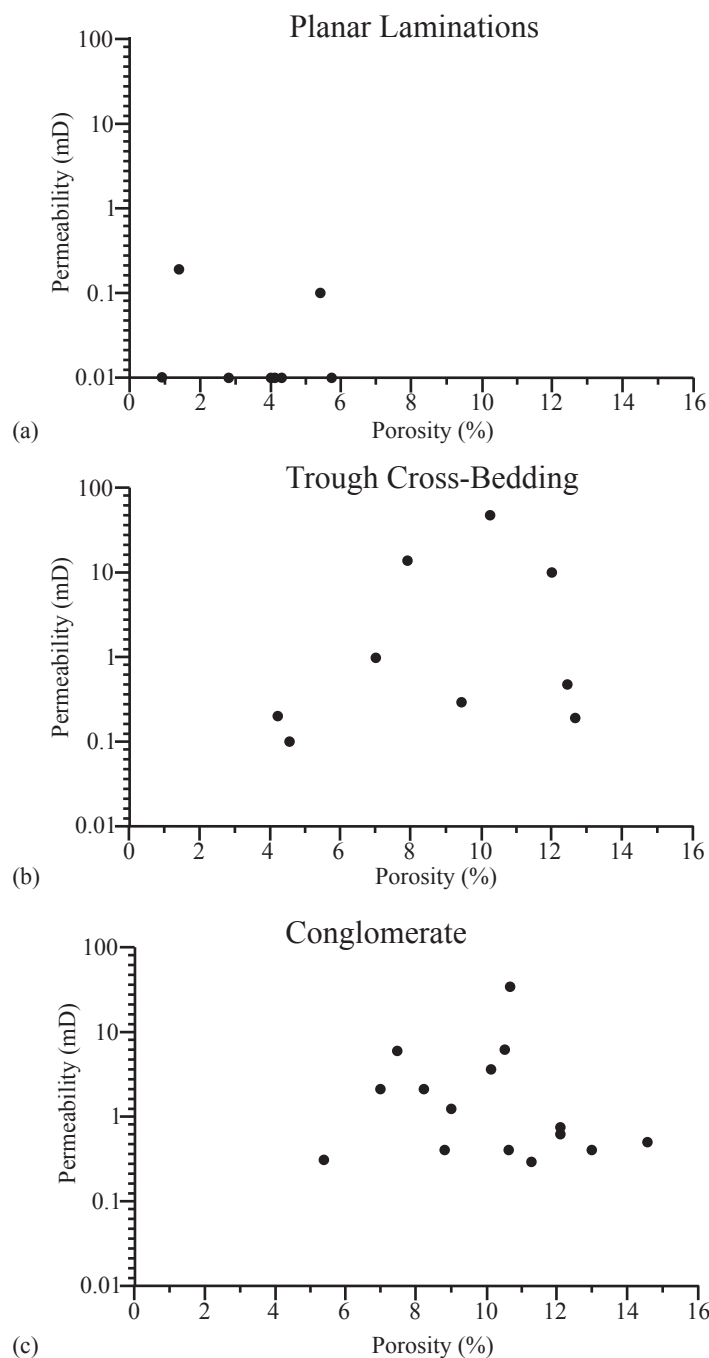


**Figure B-16:** Channel body interpretations in Pix4D software, showing dimensions of individual channel bodies along the south wall in the generated point cloud from the DJI Phantom drone.

### Sandstone Body Dimensions

| Channel # | Location       | Channel Complex # | Width (m) | Length (m) |
|-----------|----------------|-------------------|-----------|------------|
| 1         | South Wall     | 1                 | 180       | 8.57       |
| 2         | Southeast Wall | 1                 | 200       | 9.23       |
| 3         | South Wall     | 1                 | 213       | 7.75       |
| 4         | South Wall     | Sand Flat         | 208       | 1.37       |
| 5         | Southeast Wall | Sand Flat         | 216       | 1.56       |
| 6         | South Wall     | 2                 | 98.12     | 2.52       |
| 7         | Southeast Wall | 2                 | 122.54    | 5.16       |
| 8         | South Wall     | 2                 | 272.92    | 9.95       |
| 9         | South Wall     | 2                 | 243.26    | 8.71       |
| 10        | South Wall     | 2                 | 79.43     | 4.09       |
| 11        | South Wall     | 3                 | 59.62     | 4.43       |
| 12        | South Wall     | 4                 | 119.27    | 3.77       |
| 13        | South Wall     | 4                 | 545.36    | 5.12       |
| 14        | South Wall     | 4                 | 117.1     | 2.8        |
| 15        | Southeast Wall | 2                 | 33.9      | 7.61       |
| 16        | Southeast Wall | 2                 | 111.48    | 10.29      |
| 17        | Southeast Wall | 3                 | 125.58    | 4.45       |
| 18        | Southeast Wall | 3                 | 65        | 9.82       |
| 19        | Southeast Wall | 4                 | 93.6      | 3.36       |
| 20        | Southeast Wall | 4                 | 62.29     | 1.75       |
| 21        | Southeast Wall | 4                 | 67.94     | 1.13       |
| 22        | Southeast Wall | 4                 | 179.13    | 6.52       |
| 23        | Southeast Wall | 4                 | 567.06    | 7.34       |
| 24        | Southeast Wall | 4                 | 96.95     | 4.41       |
| 25        | Northwest Wall | 1                 | 423.9     | 7.35       |
| 26        | Northwest Wall | 1                 | 229.69    | 4.28       |
| 27        | Northwest Wall | 2                 | 80.5      | 8.3        |
| 28        | Northwest Wall | 2                 | 315.74    | 17.6       |
| 29        | Northwest Wall | 3                 | 361.79    | 2.51       |
| 30        | Northwest Wall | 4                 | 158.95    | 5.26       |
| 31        | Northwest Wall | 4                 | 77.16     | 3.18       |
| 32        | Northwest Wall | 4                 | 60.61     | 2.26       |
| 33        | Northwest Wall | 2                 | 229.81    | 4.3        |
| 34        | Northwest Wall | 3                 | 58.92     | 1.91       |
| 35        | Northwest Wall | 2                 | 73.6      | 7          |
| 36        | Northwest Wall | 3                 | 81.16     | 5.22       |
| 37        | Northwest Wall | 3                 | 81.91     | 4.8        |
| 38        | Northwest Wall | 3                 | 95.69     | 5.92       |
| 39        | Northwest Wall | 2                 | 107.03    | 2.79       |
| 40        | Northwest Wall | 3                 | 12.2      | 2.68       |
| 41        | Northwest Wall | 4                 | 58.23     | 4.22       |
| 42        | Northwest Wall | 3                 | 67.54     | 1.46       |
| 43        | Northwest Wall | 2                 | 267.1     | 8.9        |
| 44        | Northwest Wall | 2                 | 150.54    | 4.88       |
| 45        | Southeast Wall | 4                 | 91.74     | 2.86       |
| 46        | Southeast Wall | 3                 | 122.19    | 2.1        |
| 47        | Southeast Wall | 2                 | 112.82    | 6.8        |
| 48        | Southeast Wall | Sand Flat         | 69.07     | 5.93       |
| 49        | Southeast Wall | Sand Flat         | 80.93     | 4.42       |
| 50        | Southeast Wall | 3                 | 60.43     | 8.13       |
| 51        | Southeast Wall | 4                 | 117.74    | 10.61      |
| 52        | Southeast Wall | 2                 | 328.23    | 3.75       |
| 53        | South Wall     | 3                 | 70.05     | 3.22       |
| 54        | South Wall     | 4                 | 105.06    | 7.22       |
| 55        | South Wall     | 4                 | 51.71     | 2.72       |
| 56        | South Wall     | 3                 | 117.85    | 5.23       |
| 57        | South Wall     | 4                 | 466.07    | 7.56       |
| 58        | South Wall     | 2                 | 136.49    | 13.78      |
| 59        | South Wall     | 3                 | 82.86     | 5.65       |
| 60        | South Wall     | 4                 | 134.28    | 4.29       |
| 61        | South Wall     | 4                 | 142.32    | 3.1        |
| 62        | South Wall     | 2                 | 178.87    | 10.49      |
| 63        | South Wall     | 2                 | 168.18    | 8.45       |
| 64        | South Wall     | 3                 | 115.21    | 6.49       |
| 65        | South Wall     | 4                 | 68.45     | 8.74       |
| 66        | South Wall     | 3                 | 66.29     | 4.37       |
| 67        | South Wall     | 4                 | 45.82     | 6.79       |

**Figure B-17:** Sandstone body dimensions were measured for 67 sandstone bodies throughout rattlesnake canyon. Each body was classified by wall and channel complex location. Each sandstone body was measured for average length and width.



**Figure B18:** Porosity and permeability distributions for the three main lithofacies found in the cored interval of the Burro Canyon Formation within the Mitchell Energy Federal 8-1 well. A) Planar laminated porosity and permeability shows minimum porosity of 0.9% and maximum porosity of 5.7%. Permeability data shows a minimum of 0.1 mD and maximum of 0.2 mD. B) Trough Cross-Bedded porosity and permeability shows a minimum porosity of 4% and maximum porosity of 13%. Permeability data shows a minimum of 0.1 mD and maximum of 48 mD. C) Conglomeratic porosity and permeability shows a minimum porosity of 5% and maximum porosity of 11%. Permeability data shows a minimum of 0.3 mD and maximum of 34 mD.

## Appendix C: Variogram Distributions

### Lithofacies Distributions: Sandstone Body Models

| Perpendicular to Paleoflow Lithofacies |                      |        |        |    |        |    |    |        |        |
|----------------------------------------|----------------------|--------|--------|----|--------|----|----|--------|--------|
| Zone                                   |                      | A      | B      | C  | D      | E  | F  | G      | H      |
|                                        | DakotaB - CC4        | 0%     | 0.23%  | 0% | 0.34%  | 0% | 0% | 99.42% | 0%     |
|                                        | CC4-CC4B             | 19.03% | 62.14% | 0% | 10.17% | 1% | 0% | 0.42%  | 8.24%  |
|                                        | CC4B - CC3           | 0.70%  | 0%     | 0% | 1.06%  | 0% | 0% | 0%     | 98.24% |
|                                        | CC3 - CC3B           | 19.76% | 51.93% | 0% | 16.95% | 0% | 0% | 0%     | 11.35% |
|                                        | CC3B - CC2           | 0.89%  | 0.31%  | 0% | 0.64%  | 0% | 0% | 0%     | 98.15% |
|                                        | CC2 - CC2B           | 12.42% | 72.40% | 0% | 9.77%  | 0% | 0% | 0%     | 4.17%  |
|                                        | CC2B - Sand          | 0.16%  | 0%     | 0% | 0.22%  | 0% | 0% | 0%     | 0%     |
|                                        | Sand - SandB         | 0%     | 3.28%  | 0% | 43.25% | 0% | 0% | 0%     | 0%     |
|                                        | SandB - CC1          | 0%     | 13.21% | 0% | 21.02% | 0% | 0% | 0%     | 0%     |
|                                        | CC1 - Morrison       | 20.01% | 65.94% | 0% | 6.18%  | 0% | 0% | 0%     | 0%     |
|                                        | Morrison - MorrisonB | 0%     | 0%     | 0% | 0%     | 0% | 0% | 100%   | 0%     |

| Parallel to Paleoflow Lithofacies |                      |        |        |    |        |    |    |        |        |
|-----------------------------------|----------------------|--------|--------|----|--------|----|----|--------|--------|
| Zone                              |                      | A      | B      | C  | D      | E  | F  | G      | H      |
|                                   | DakotaB - CC4        | 0%     | 13.00% | 0% | 48.00% | 0% | 0% | 39.00% | 0%     |
|                                   | CC4-CC4B             | 15.47% | 61.54% | 0% | 13.71% | 0% | 0% | 0.70%  | 8.58%  |
|                                   | CC4B - CC3           | 0.82%  | 13.00% | 0% | 56.00% | 0% | 0% | 0%     | 30.18% |
|                                   | CC3 - CC3B           | 23.46% | 60.71% | 0% | 11.31% | 0% | 0% | 0.01%  | 4.51%  |
|                                   | CC3B - CC2           | 0%     | 0%     | 0% | 0%     | 0% | 0% | 0%     | 100%   |
|                                   | CC2 - CC2B           | 14.61% | 69.49% | 0% | 12.01% | 0% | 0% | 3.38%  | 0.51%  |
|                                   | CC2B - Sand          | 53.00% | 0%     | 0% | 35.00% | 0% | 0% | 12.00% | 0%     |
|                                   | Sand - SandB         | 71.00% | 4.29%  | 0% | 8.66%  | 0% | 0% | 16.05% | 0%     |
|                                   | SandB - CC1          | 0%     | 100%   | 0% | 0%     | 0% | 0% | 0%     | 0%     |
|                                   | CC1 - Morrison       | 23.80% | 70.73% | 0% | 4.52%  | 0% | 0% | 0.95%  | 0%     |
|                                   | Morrison - MorrisonB | 0%     | 0%     | 0% | 0%     | 0% | 0% | 100%   | 0%     |

**Figure C-1:** Percentage of lithofacies distributions in each channel zone for models parallel and perpendicular to paleoflow within the Sandstone Body models.

## Lithofacies Distributions: Channel Fill Models

| Perpendicular to Paleoflow Lithofacies |                      |        |        |    |        |    |    |        |        |
|----------------------------------------|----------------------|--------|--------|----|--------|----|----|--------|--------|
| Zone                                   |                      | A      | B      | C  | D      | E  | F  | G      | H      |
|                                        | DakotaB - CC4        | 0%     | 0.23%  | 0% | 0.34%  | 0% | 0% | 99.42% | 0%     |
|                                        | CC4 - CC4-3B         | 34.00% | 46.45% | 0% | 17.24% | 0% | 0% | 1.66%  | 0.64%  |
|                                        | CC4-3B - CC4-2       | 4.77%  | 1.05%  | 0% | 2.55%  | 0% | 0% | 0%     | 91.64% |
|                                        | CC4-2 - CC4-1        | 9.10%  | 83.68% | 0% | 6.75%  | 0% | 0% | 0%     | 0.47%  |
|                                        | CC4-1 - CC4B         | 23.04% | 63.83% | 0% | 10.59% | 0% | 0% | 0%     | 2.54%  |
|                                        | CC4B - CC3           | 0.70%  | 0%     | 0% | 1.06%  | 0% | 0% | 0%     | 98.24% |
|                                        | CC3 - CC3B           | 19.76% | 51.93% | 0% | 16.95% | 0% | 0% | 0%     | 11.35% |
|                                        | CC3B - CC2           | 1.52%  | 0.28%  | 0% | 0.85%  | 0% | 0% | 0%     | 97.34% |
|                                        | CC2 - CC2-3B         | 14.69% | 67.33% | 0% | 16.86% | 0% | 0% | 0%     | 1.12%  |
|                                        | CC2-3B - CC2-2       | 2.71%  | 0%     | 0% | 8.81%  | 0% | 0% | 0%     | 88.49% |
|                                        | CC2-2 - CC2-2B       | 10.70% | 80.09% | 0% | 4.43%  | 0% | 0% | 3.17%  | 1.47%  |
|                                        | CC2-2B - CC2-1       | 8.69%  | 5.92%  | 0% | 26.55% | 0% | 0% | 0%     | 58.84% |
|                                        | CC2-1 - CC2B         | 16.78% | 62.40% | 0% | 17.27% | 0% | 0% | 2.72%  | 0.84%  |
|                                        | CC2B - Sand          | 0%     | 0%     | 0% | 0%     | 0% | 0% | 100%   | 0%     |
|                                        | Sand - SandB         | 0%     | 3.28%  | 0% | 43.25% | 0% | 0% | 53.46% | 0%     |
|                                        | SandB - CC1          | 0%     | 13.21% | 0% | 21.02% | 0% | 0% | 65.77% | 0%     |
|                                        | CC1 - CC1-1          | 19.32% | 69.98% | 0% | 1.22%  | 0% | 0% | 11.48% | 0%     |
|                                        | CC1-1 - Morrison     | 20.49% | 63.51% | 0% | 12.62% | 0% | 0% | 3.38%  | 0%     |
|                                        | Morrison - MorrisonB | 0%     | 0%     | 0% | 0%     | 0% | 0% | 100%   | 0%     |

**Figure C-2:** Percentage of lithofacies distributions in each channel fill zone in the perpendicular to paleoflow orientation of the channel fill model.

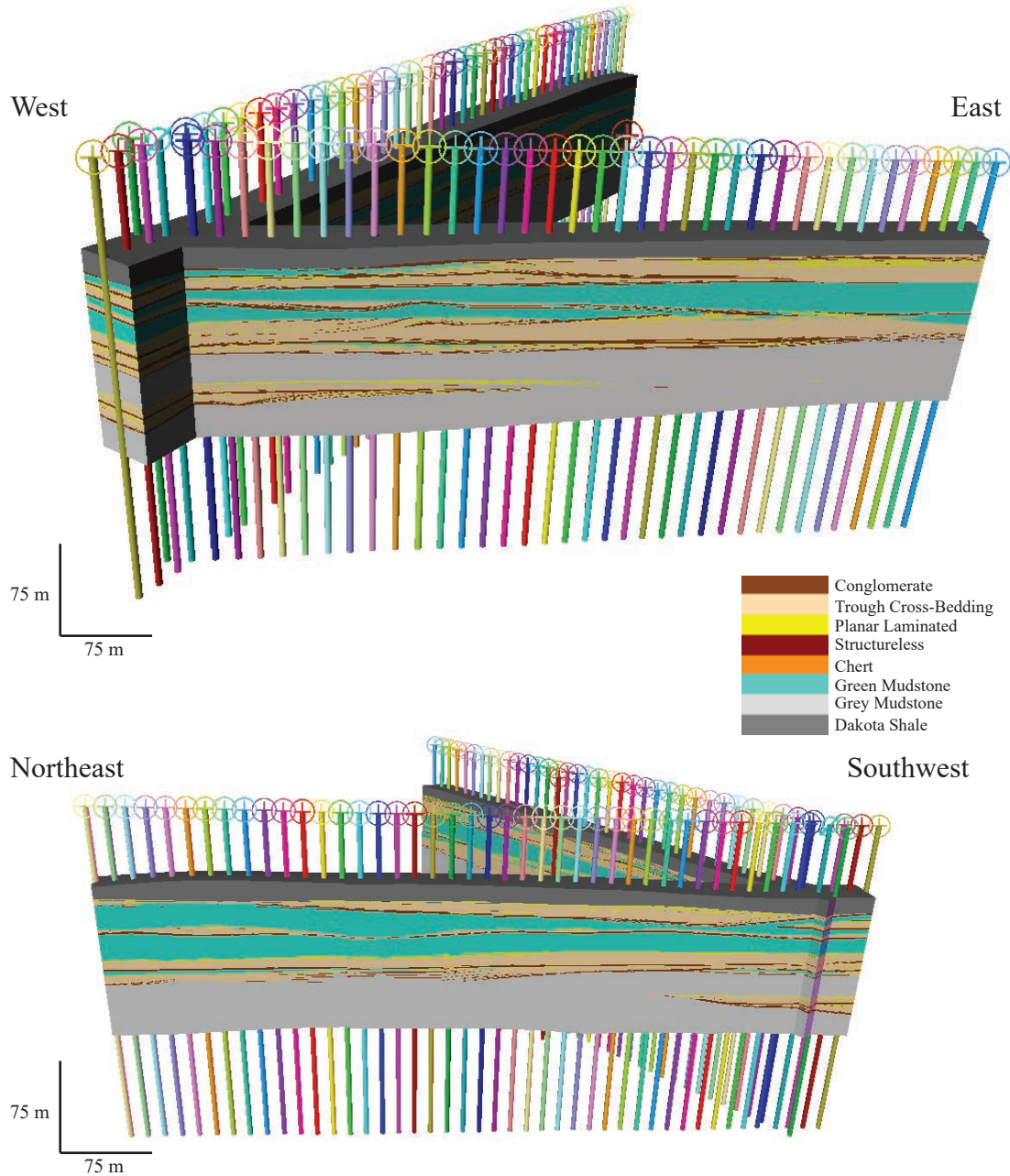


## Lithofacies Distributions: Channel Fill Models

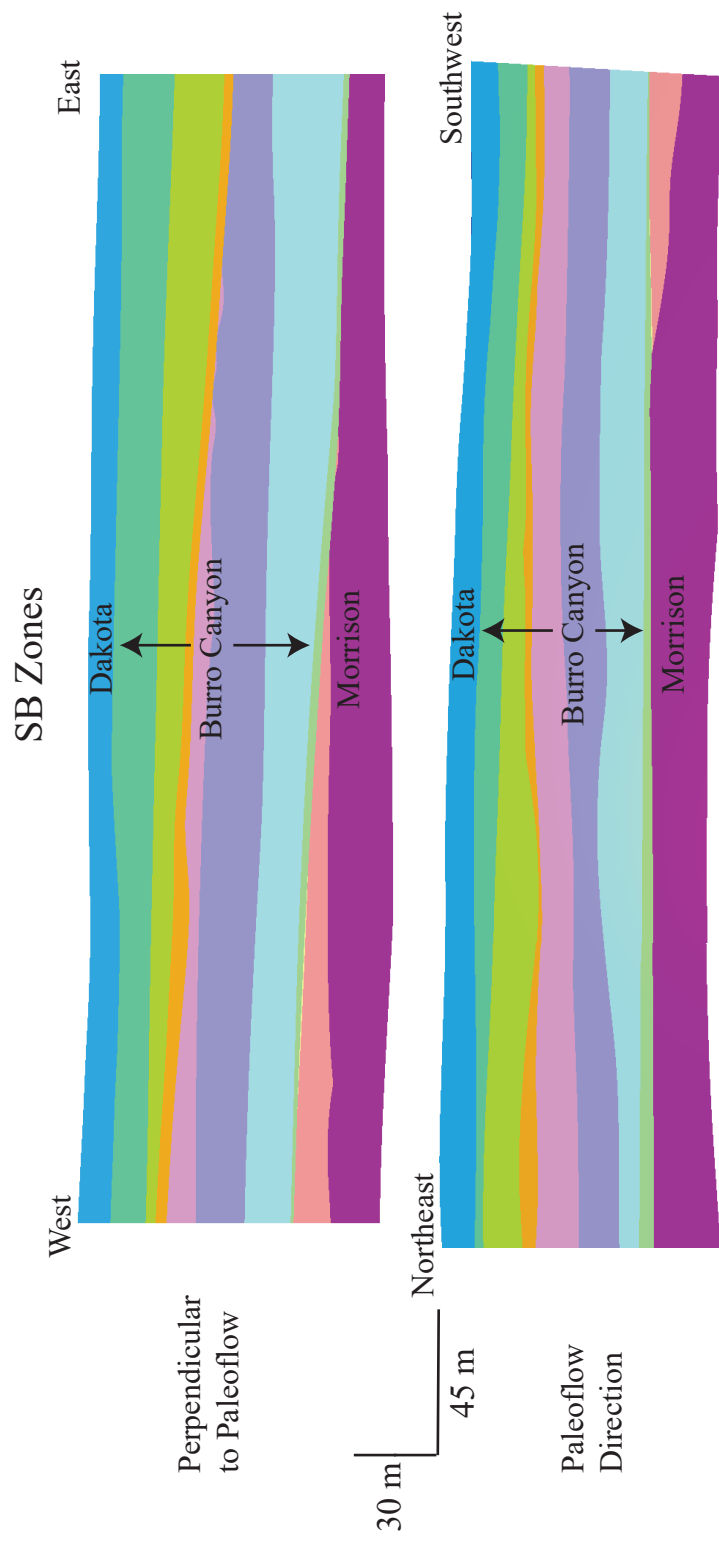
| Paralell to Paleoflow Lithofacies |                      |        |        |    |        |    |    |        |        |
|-----------------------------------|----------------------|--------|--------|----|--------|----|----|--------|--------|
| Zone                              |                      | A      | B      | C  | D      | E  | F  | G      | H      |
|                                   | DakotaB - CC4        | 0%     | 0.13%  | 0% | 0.48%  | 0% | 0% | 99.39% | 0%     |
|                                   | CC4 - CC4-3B         | 9.66%  | 41.09% | 0% | 9.45%  | 0% | 0% | 0.58%  | 39.22% |
|                                   | CC4-3B - CC4-2       | 2.04%  | 4.40%  | 0% | 0.72%  | 0% | 0% | 0%     | 92.84% |
|                                   | CC4-2 - CC4-1        | 54.27% | 36.51% | 0% | 7.08%  | 0% | 0% | 0%     | 2.14%  |
|                                   | CC4-1 - CC4B         | 21.93% | 63.28% | 0% | 12.26% | 0% | 0% | 0%     | 2.53%  |
|                                   | CC4B - CC3           | 0.36%  | 0.58%  | 0% | 0.95%  | 0% | 0% | 0%     | 98.11% |
|                                   | CC3 - CC3B           | 23.46% | 60.71% | 0% | 11.31% | 0% | 0% | 0%     | 4.51%  |
|                                   | CC3B - CC2           | 0.11%  | 0%     | 0% | 0%     | 0% | 0% | 0%     | 99.89% |
|                                   | CC2 - CC2-3B         | 11.24% | 74.32% | 0% | 13.67% | 0% | 0% | 0.17%  | 0.60%  |
|                                   | CC2-3B - CC2-2       | 15.5%  | 0%     | 0% | 10.39% | 0% | 0% | 74.11% | 0%     |
|                                   | CC2-2 - CC2-2B       | 13.41% | 57.34% | 0% | 8.15%  | 0% | 0% | 21.10% | 0%     |
|                                   | CC2-2B - CC2-1       | 39.91% | 21.82% | 0% | 28.97% | 0% | 0% | 0%     | 9.29%  |
|                                   | CC2-1 - CC2B         | 30.61% | 62.82% | 0% | 1.81%  | 0% | 0% | 4.44%  | 0.32%  |
|                                   | CC2B - Sand          | 0%     | 0%     | 0% | 0%     | 0% | 0% | 100%   | 0%     |
|                                   | Sand - SandB         | 0.71%  | 4.29%  | 0% | 8.66%  | 0% | 0% | 86.34% | 0%     |
|                                   | SandB - CC1          | 0%     | 100%   | 0% | 0%     | 0% | 0% | 0%     | 0%     |
|                                   | CC1 - CC1-1          | 22.34% | 74.78% | 0% | 2.53%  | 0% | 0% | 0.35%  | 0%     |
|                                   | CC1-1 - Morrison     | 24.92% | 66.57% | 0% | 7.38%  | 0% | 0% | 1.13%  | 0%     |
|                                   | Morrison - MorrisonB | 0%     | 0%     | 0% | 0%     | 0% | 0% | 100%   | 0%     |

**Figure C-3:** Percentage of lithofacies distributions in each channel fill zone for the parallel to paleoflow orientations of the channel fill models.

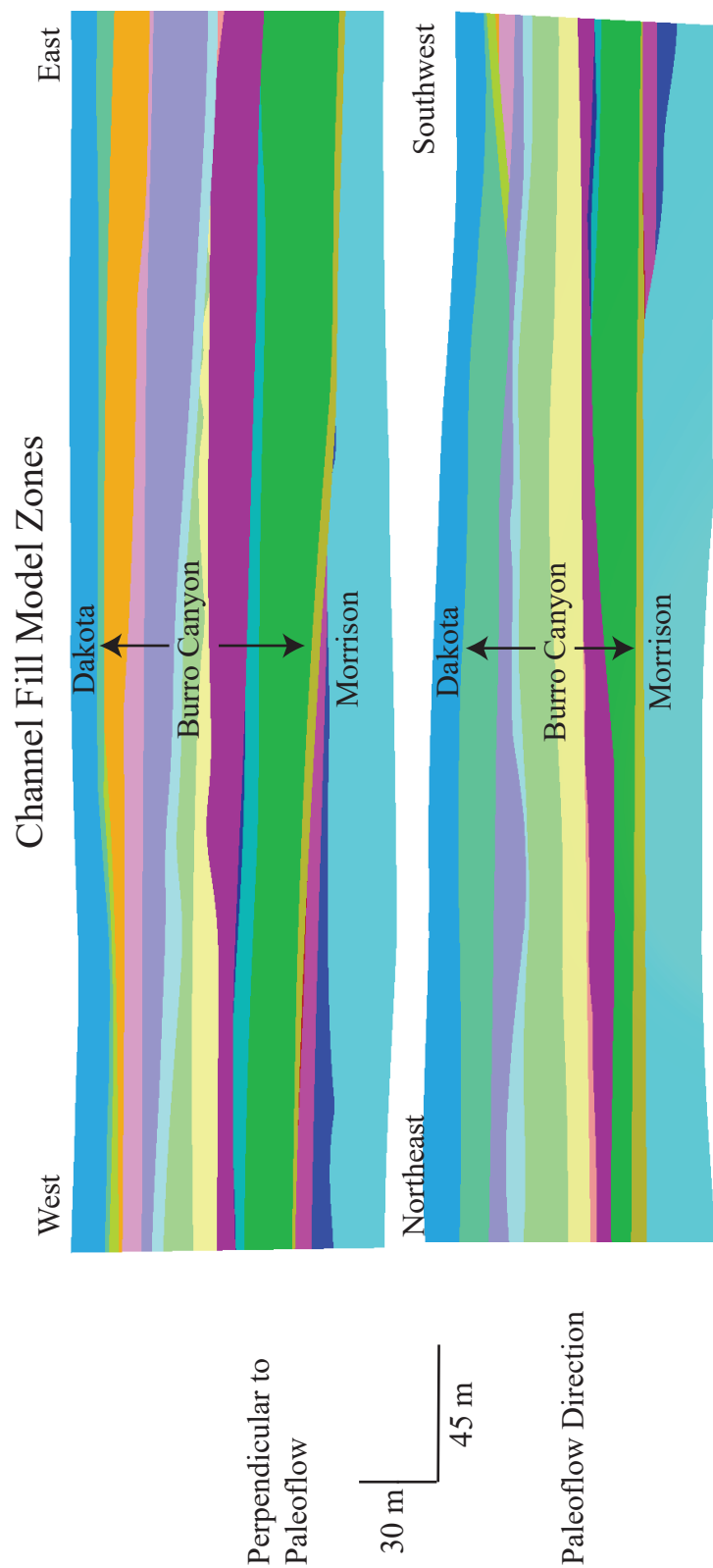
## Appendix D: Lithology Models and Waterflood Analysis



**Figure D-1:** 2-D geologic models are constrained by 80 wells. These wells have been strategically placed in order to correctly represent the geometries observed in outcrop. Wells have had individual facies and channel outlines picked in order to mimic the geometries and facies associations seen in outcrop.

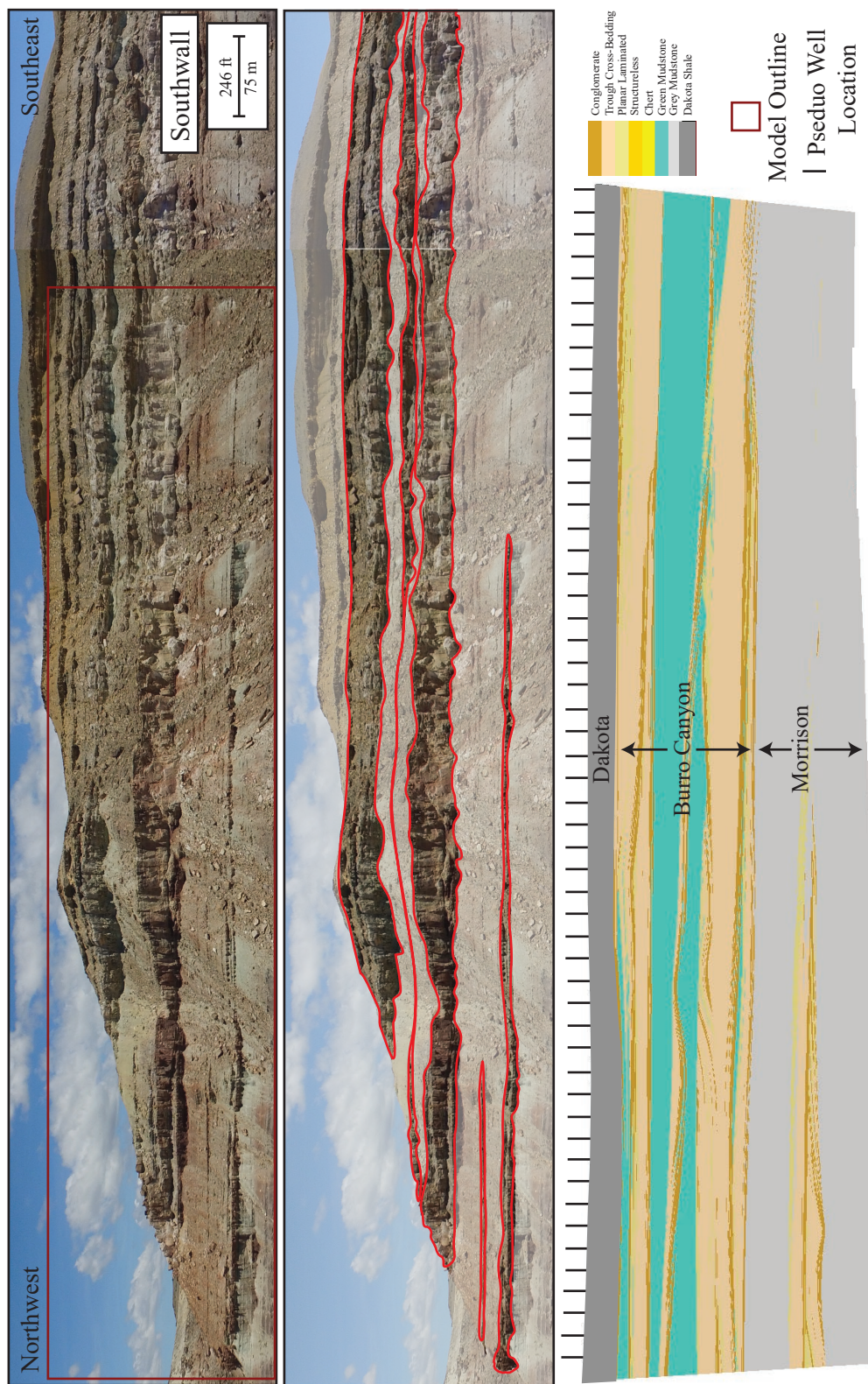


**Figure D-2:** Sandstone Body (SB) zones split out individual channel complexes present in the Rattlesnake Canyon outcrop. Zones are created from outcrop based pseudo wells.



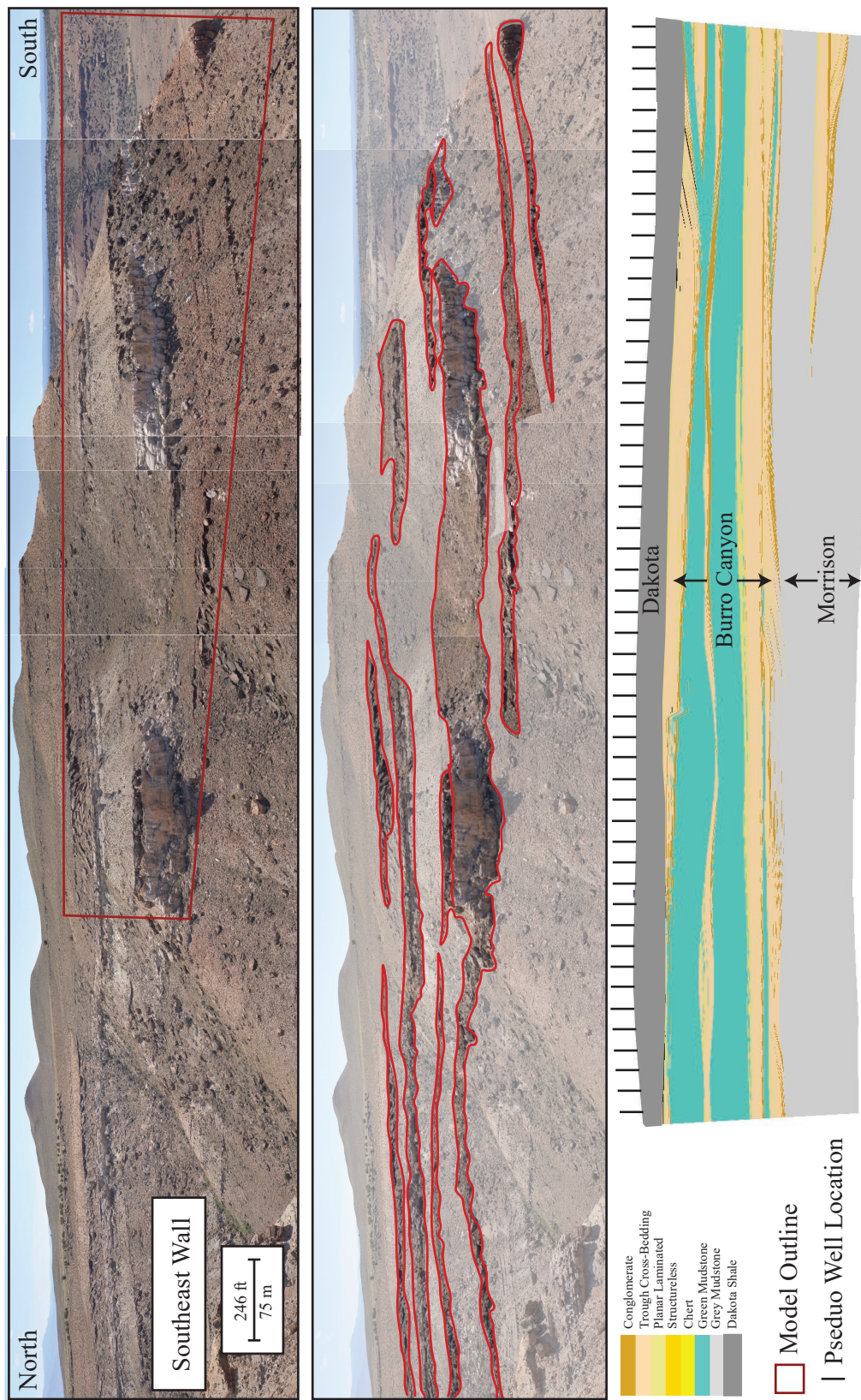
**Figure D-3:** Channel Fill (CF) model Zones in both parallel and perpendicular to paleoflow orientations representing individual scoured channels. Zones were created from outcrop based pseudowells to show geometries present on outcrop exposures in Rattlesnake Canyon.





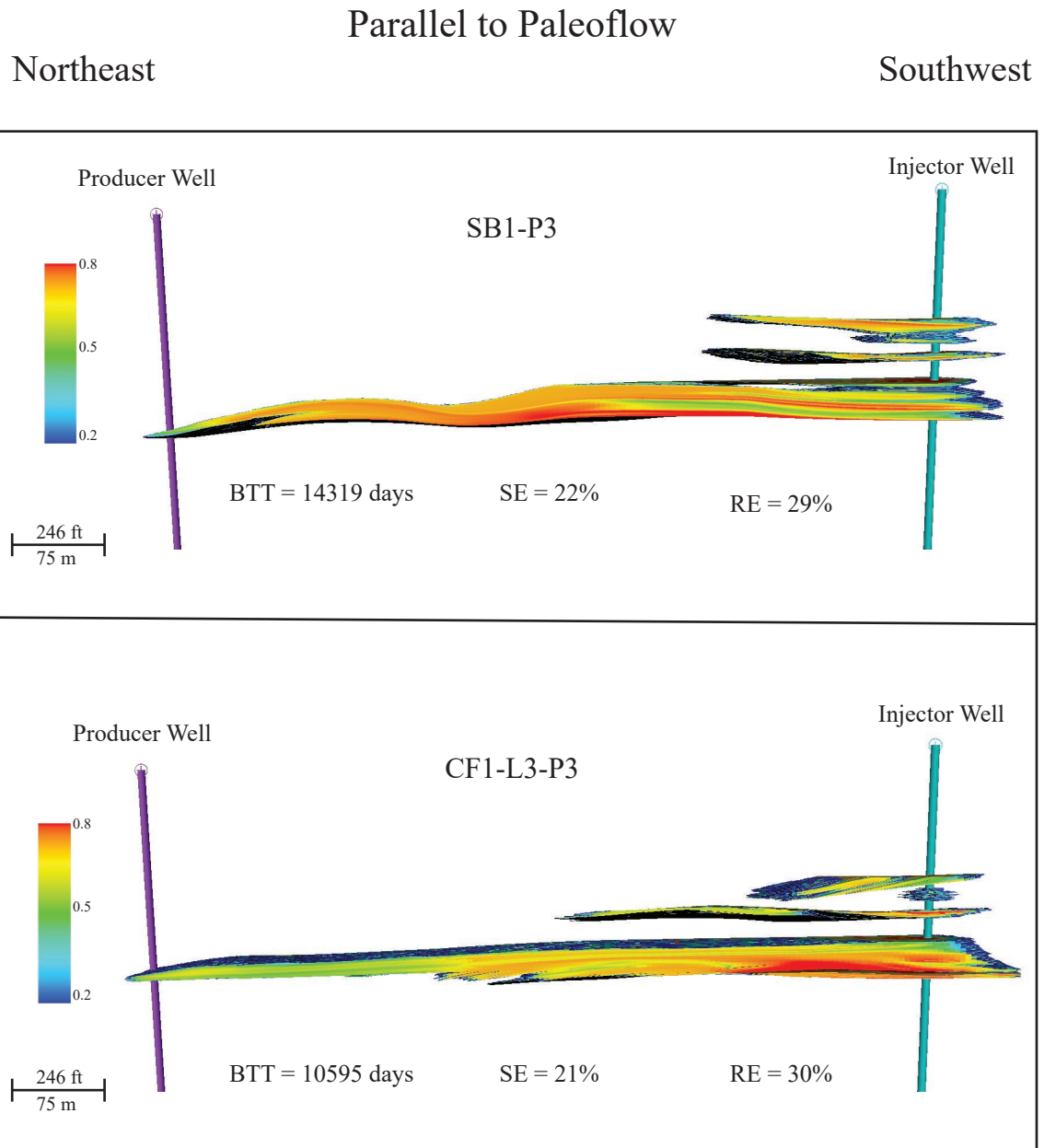
**Figure D-4:** South Wall of Rattlesnake Canyon showing model location outlined in maroon. Red highlighted zones indicate locations of model zones on outcrop exposures. Pseudo wells are systematically created along Rattlesnake Canyon in order to create accurate portrayal of canyon in 2-D model.



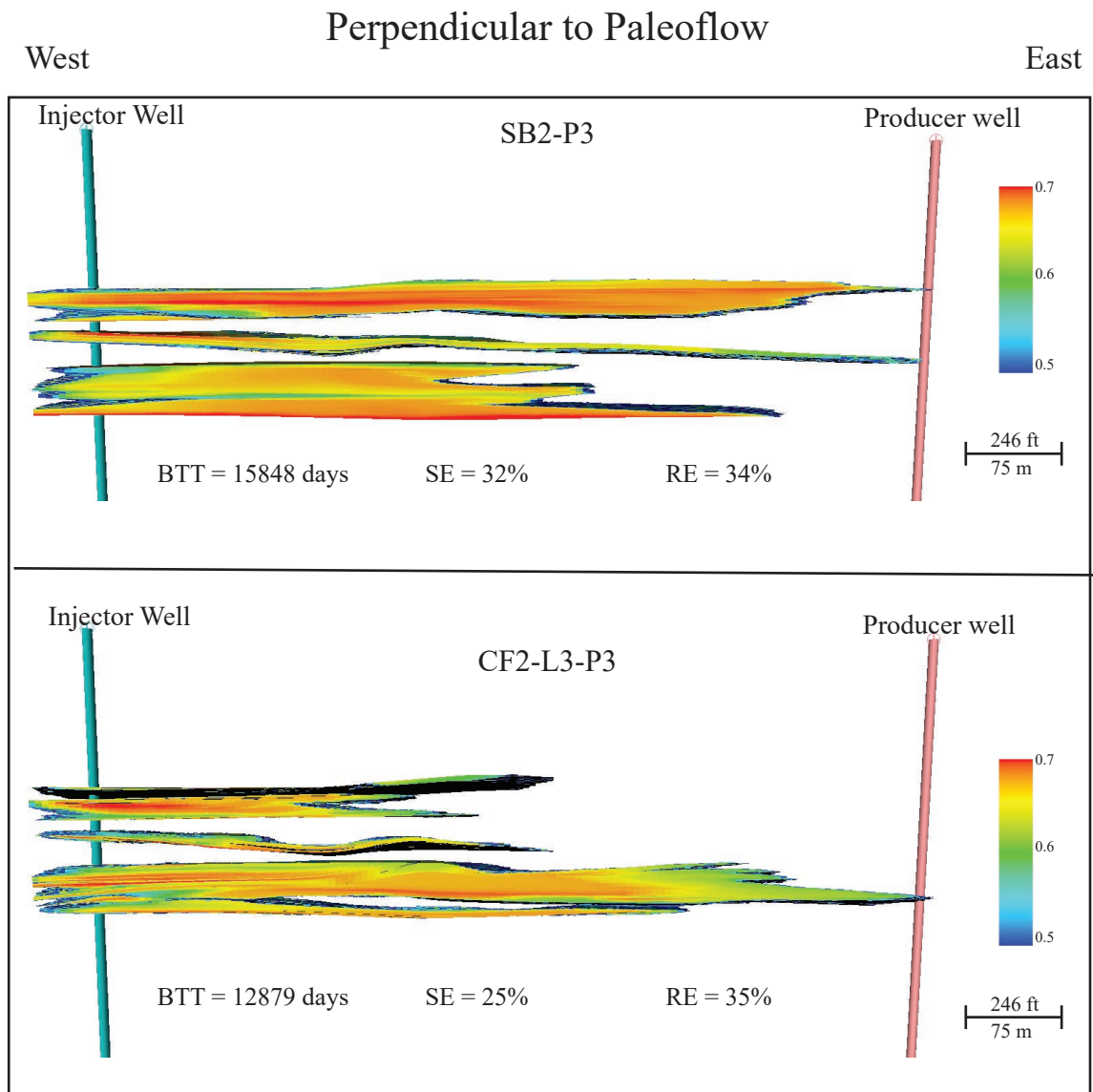


**Figure D-5:** Southeast Wall of Rattlesnake Canyon showing model location outlined in maroon. Red highlighted zones indicate locations of model zones on outcrop exposures. Pseudo wells are systematically created along Rattlesnake Canyon in order to create accurate portrayal of canyon in 2-D model.

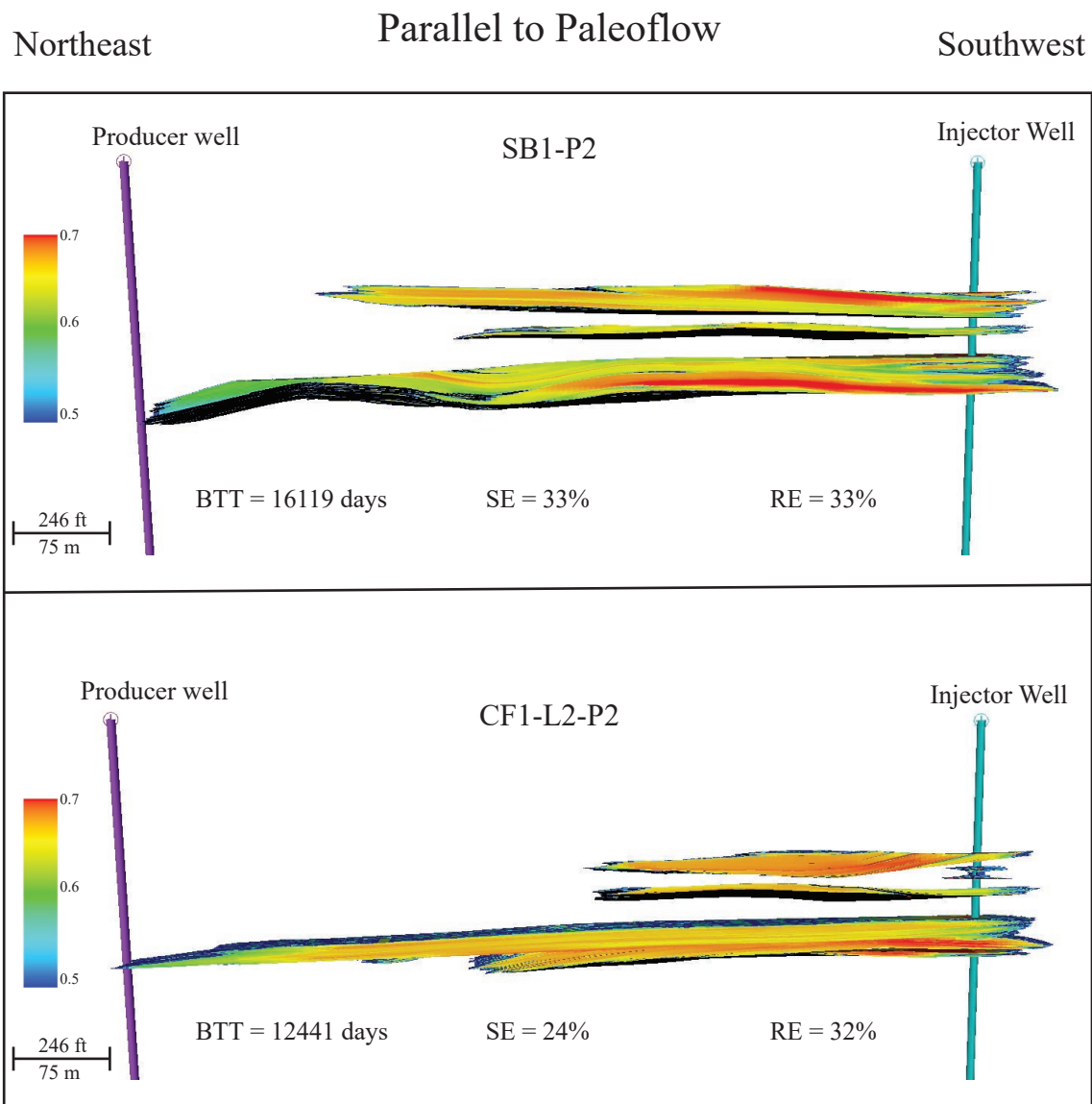




**Figure D-6:** Two-dimensional reservoir models for cases observed parallel to paleo-flow. Shows water saturation in the reservoir at BTT (breakthrough time) for SB1-P3 and CF1-L3-P3.

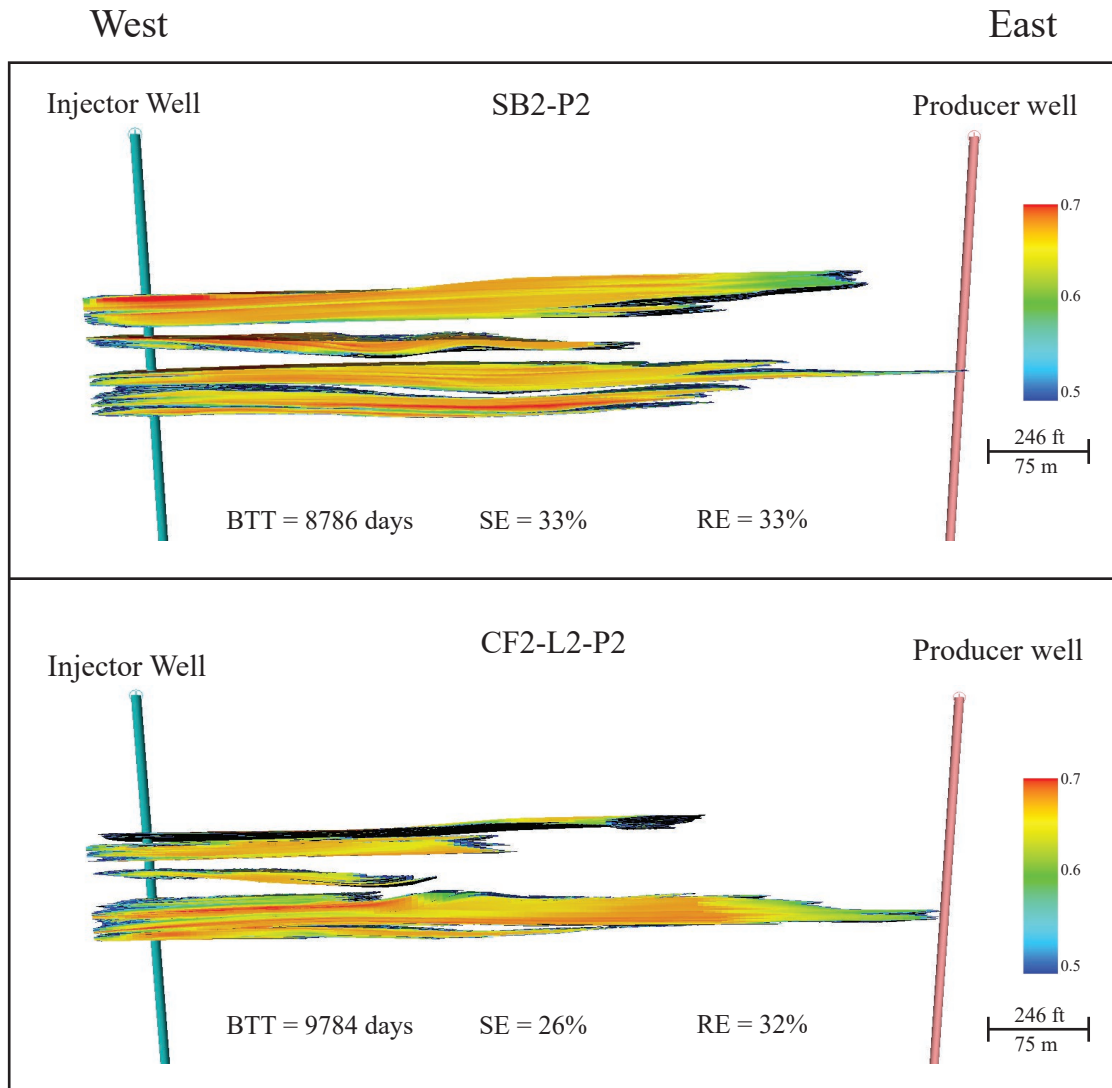


**Figure D-7:** Two-dimensional reservoir models for cases observed perpendicular to paleoflow. Shows water saturation in the reservoir at BTT (breakthrough time) for SB2-P3 and CF2-L3-P3.

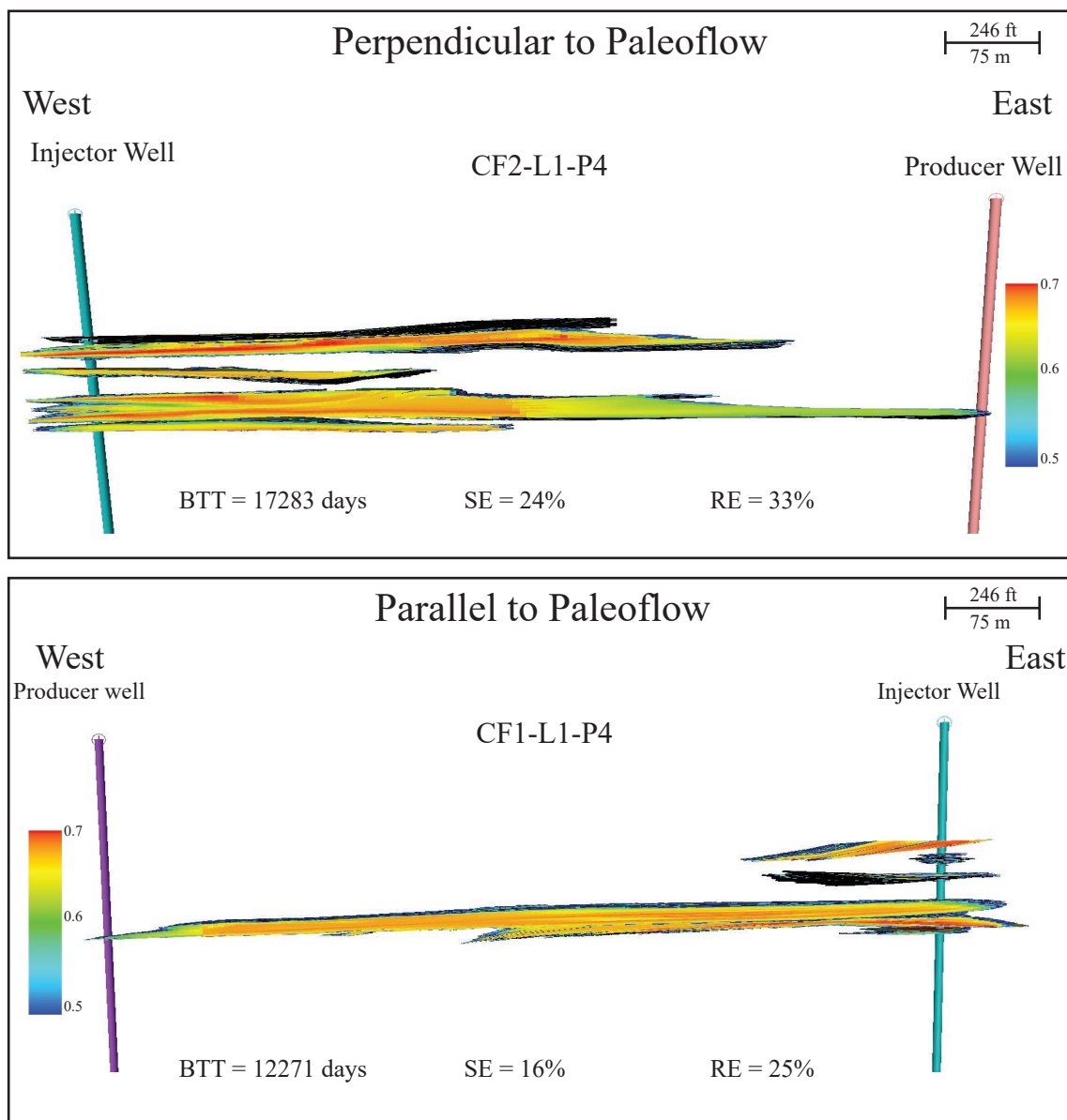


**Figure D-8:** Two-dimensional reservoir models for cases observed parallel to paleo-flow. Shows water saturation in the reservoir at BTT (breakthrough time) for SB1-P2 and CF1-L2-P2.

## Perpendicular to Paleoflow

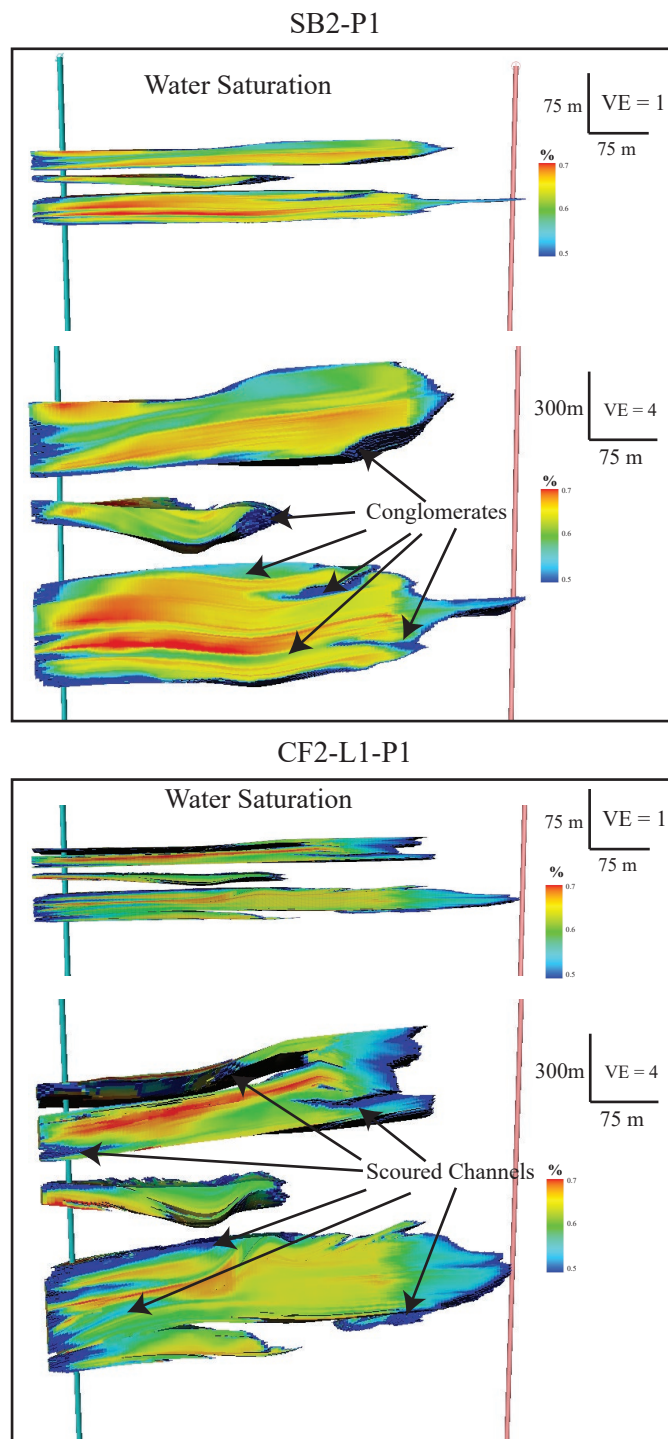


**Figure D-9:** Two-dimensional reservoir models for cases observed parallel to paleo-flow. Shows water saturation in the reservoir at BTT (breakthrough time) for SB2-P2 and CF2-L2-P2

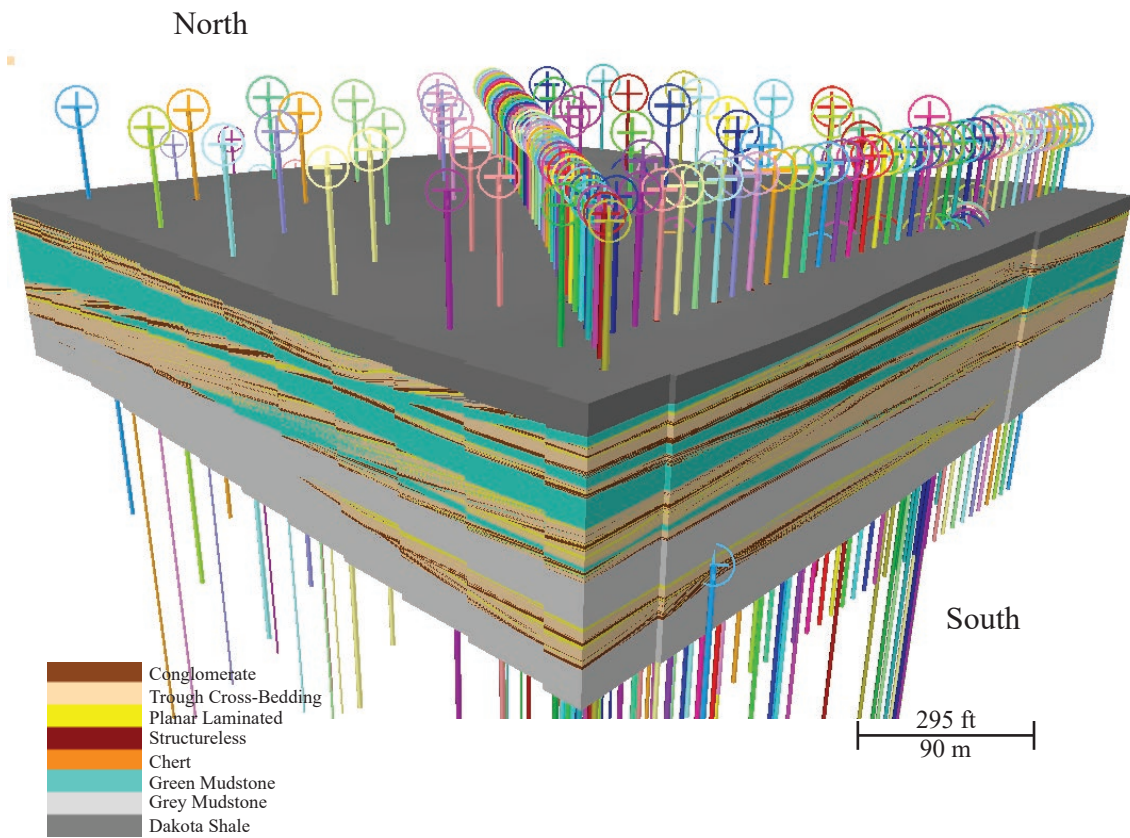


**Figure D-10:** Two-dimensional reservoir models for cases observed parallel and perpendicular to paleoflow. Shows water saturation in the reservoir at BTT (break-through time) for CF1-L1-P4 and CF2-L1-P4.



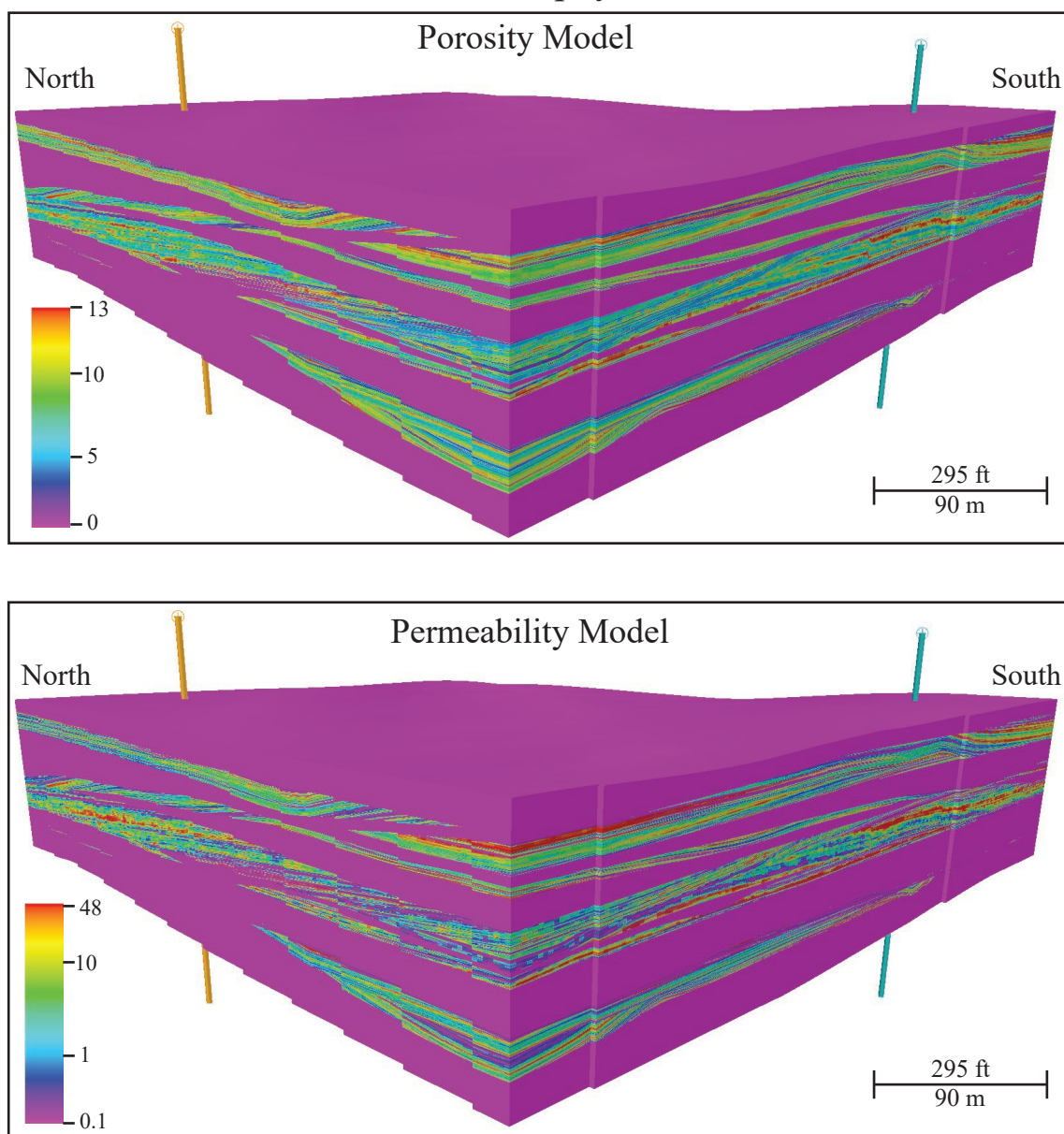


**Figure D-11:** Vertical exaggeration of the water saturation models for the Sandstone Body (SB) and Channel-Fill (CF) models show effects of breaking out individual channels in reservoirs. Sandstone Body models show higher water saturation percentages in areas with conglomeratic facies since they are given an average petrophysical distribution. Breaking out individual facies and applying porosity and permeability data to these facies shows complexities within the reservoir and provides a more accurate water saturation distribution.

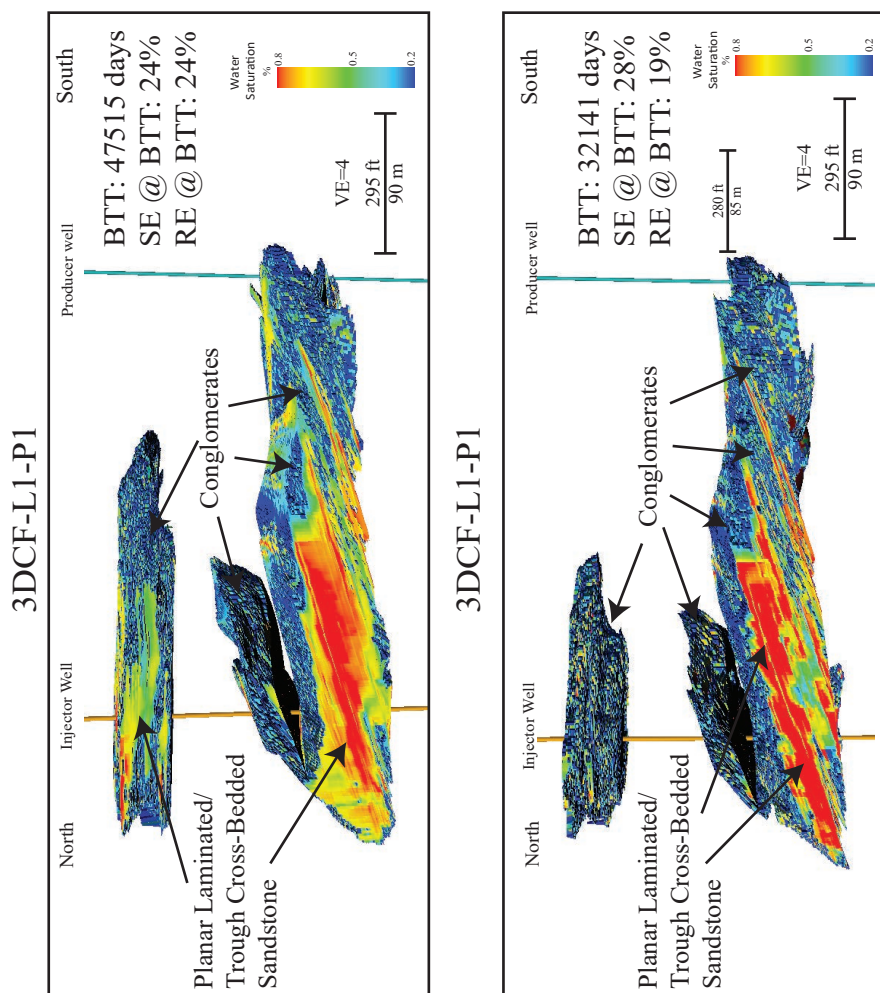


**Figure D-12:** 3-D geologic models are constrained by 118 wells. These wells include those used in the 2-D geologic models as well as additional wells that have been stratigraphically placed in order to correctly represent the geometries observed in outcrop. Wells have had individual facies and channel outlines picked in order to mimic the geometries and facies associations seen in outcrop.

### 3DCF-L1-P1 Petrophysical Models

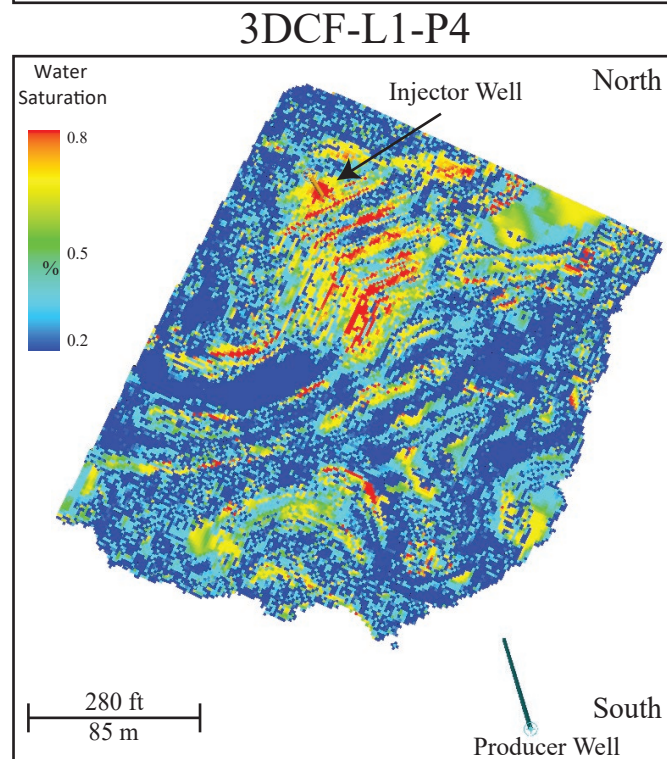
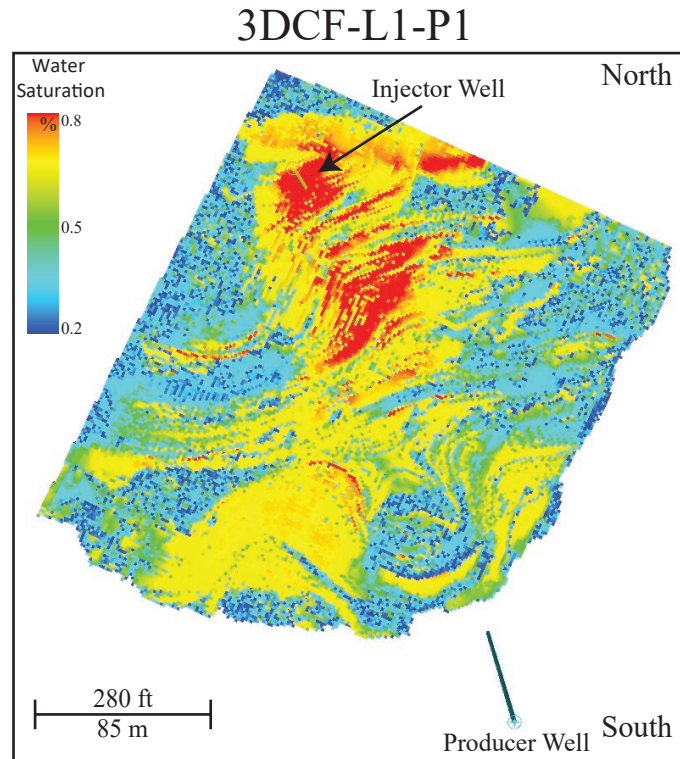


**Figure D-13:** Three-dimensional petrophysical models for the 3DCF-L1-P1 case. Top: Shows porosity distributions across the three-dimensional model, warmer colors indicate higher porosity distributions. Bottom: Shows permeability distributions across the three-dimensional model, warmer colors indicate higher permeability distributions.



**Figure D-14:** Comparison of three-dimensional water saturation volumes at breakthrough time (BTT) for the 3DCF-L1-P1 and 3DCF-L1-P4 cases. Left: Cross sectional view shows channel complex two to be the most efficient reservoir being reached then for both the 3DCF-L1-P1 and 3DCF-L1-P4. 3DCF-L1-P4 shows a larger volume of reservoir being reached then 3DCF-L1-P1. Cemented conglomeratic facies show is channelized in through cross-bedded and planar laminated sandstone

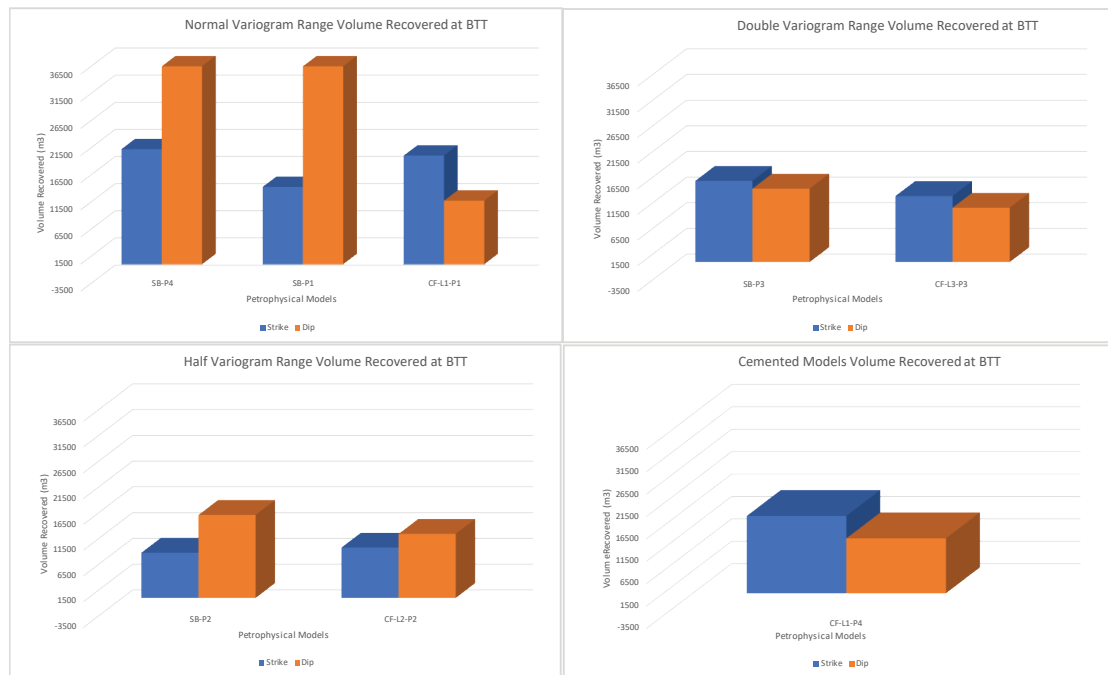




**Figure D-15:** Map view of channel 2-3 shows that the 3DCF-L1-P1 has higher water saturations across the channel indicating a higher percentage of the reservoir fluids being produced by BTT. Through cementation of the basal conglomerates, fluids are streamlined through planar laminated and trough cross-bedded sandstone to the production well.



## Appendix E: Simulation Data Results



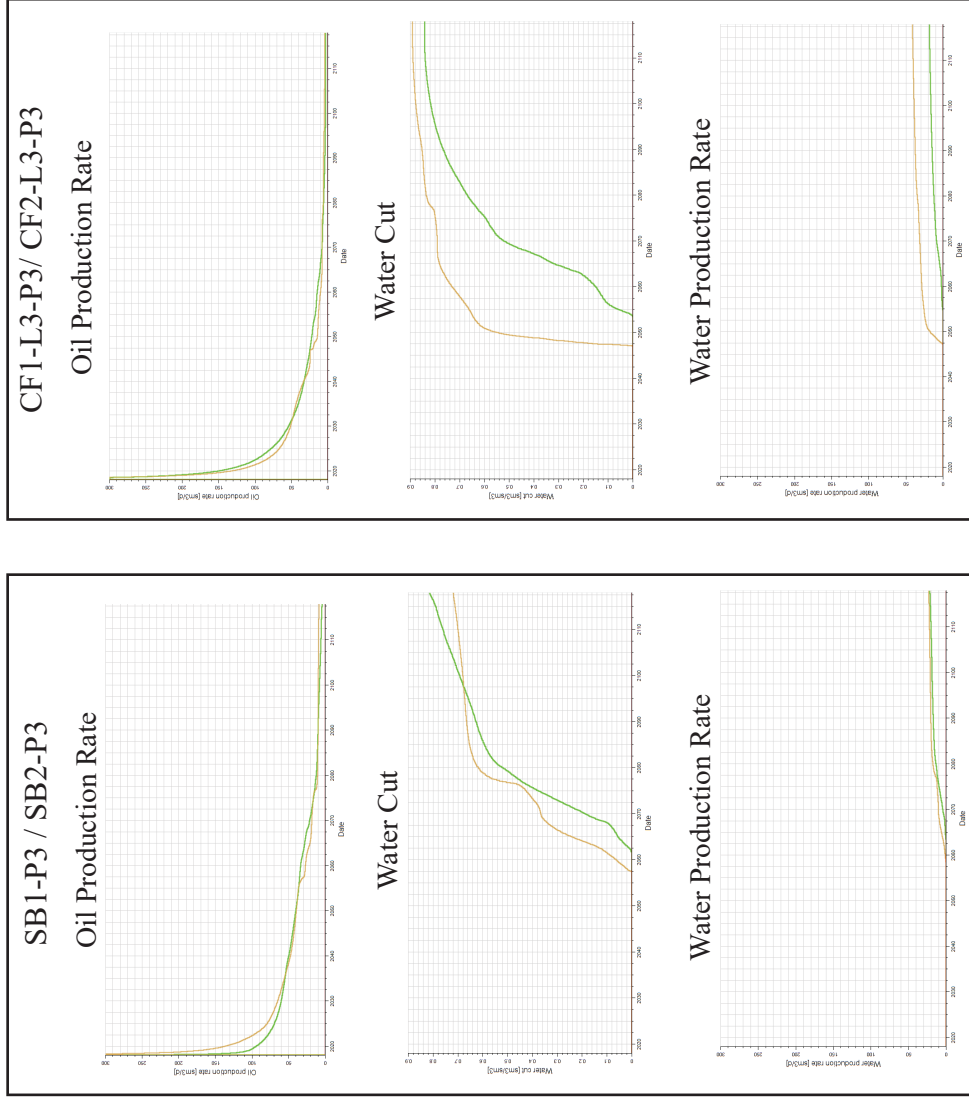
**Figure E-1:** Charts display comparison of breakthrough times through changing variogram scenarios. Outcrop based and variograms with half the range of values show higher breakthrough times in the dip direction than the strike direction while doubled variograms and cementation show higher breakthrough times in the strike direction. Tank cases yielded the greatest amount of time for fluid break through.



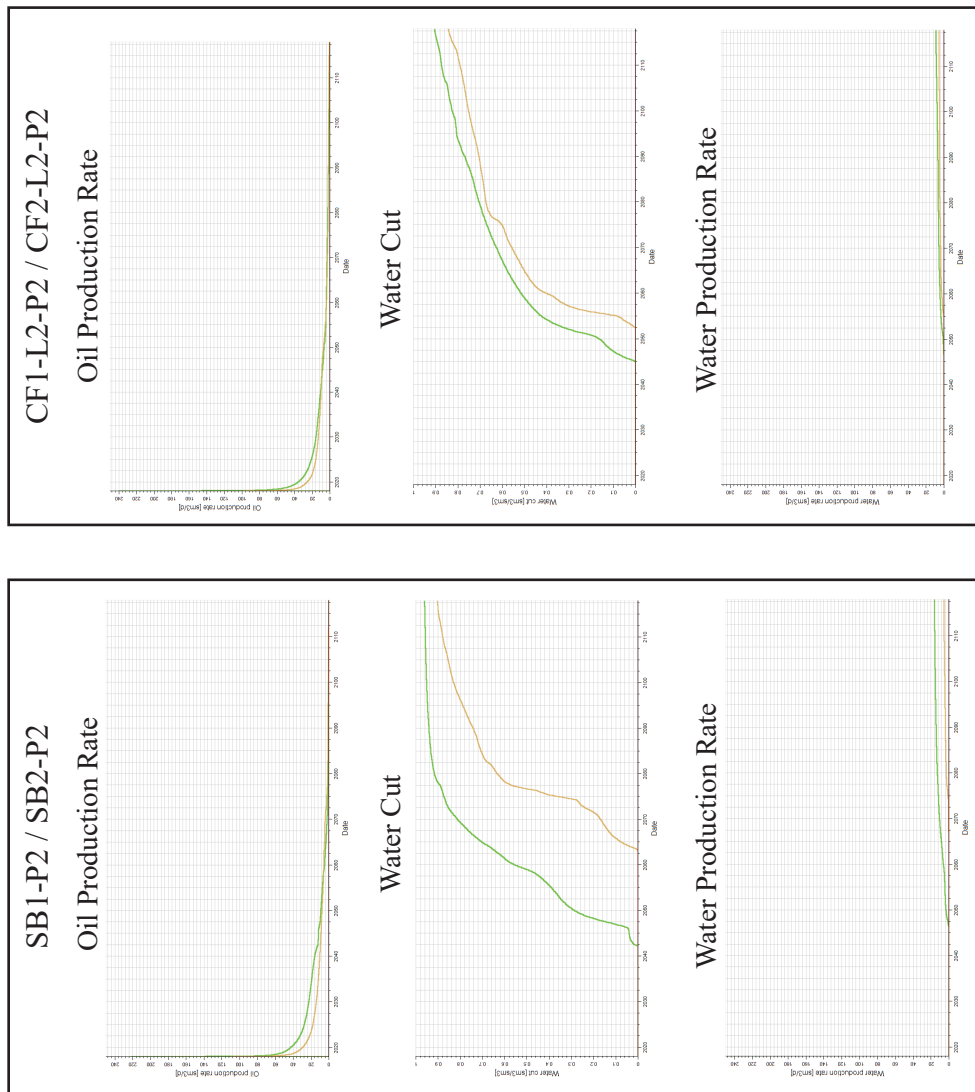
**Figure E-2:** Charts display comparison of sweep efficiency in each model scenario. Strike direction consistently display higher sweep efficiencies in each scenario at breakthrough time.



**Figure E-3:** Charts display comparison of recovery efficiency in each model scenario. Strike direction consistently display higher recovery efficiencies in each scenario at breakthrough time.

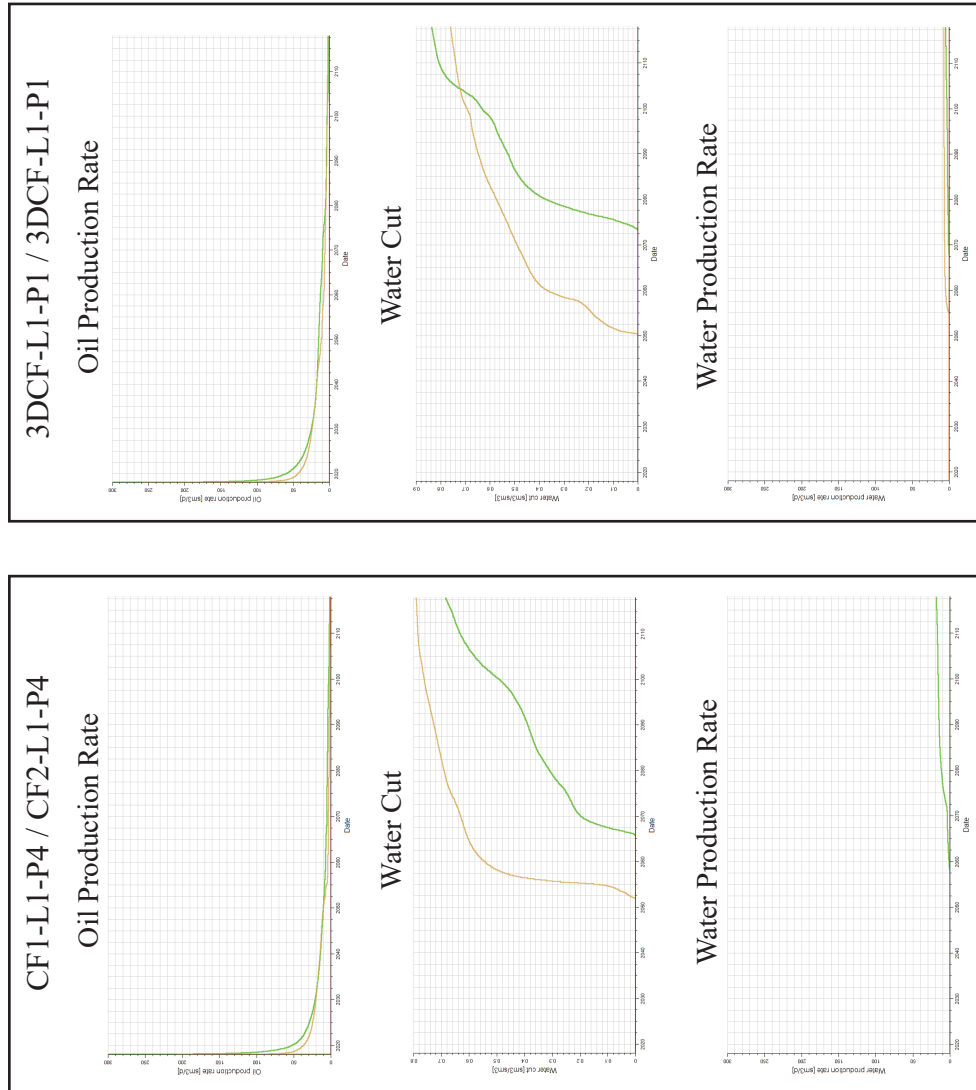


**Figure E-4:** Oil production, water cut and water production rates throughout 100 year simulation time period for doubled variograms simulations (SB-P3 and CF-L3-P3). Green line indicates strike model and orange line indicates dip model.



**Figure E-5:** Oil production, water cut and water production rates throughout 100 year simulation time period for halved variograms simulations (SB-P2 and CF-L2-P2). Green line indicates strike model and orange line indicates dip model..





**Figure E-6:** Oil production, water cut and water production rates throughout 100 year simulation time period for doubled variograms simulations (CF-L1-P4, 3DCF-L1-P1 and 3DCF-L1-P4). Green line indicates strike model and orange line indicates dip model for CF-L1-P4 charts. Green line indicates 3DCF-L1-P1 and orange line indicates 3DCF-L1-P4 in 3-D charts.