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Basinward Trends in Fluvial Architecture, Connectivity, and Reservoir Characterization of the Trail Member, Ericson Sandstone, Mesaverde Group in Wyoming, Utah, and Colorado, USA

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A thesis submitted to the faculty of
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Master of Science

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ABSTRACT

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The Late Cretaceous Trail Member of the Ericson Sandstone represents a regionally extensive fluvial system that transported sediments from the Sevier fold and thrust belt and Uinta Mountain uplift to the Western Interior Seaway. The Trail Member is a petroleum reservoir target that has unpredictable production rates due to the unknown behavior and connectivity of channel sandstones. The abundant outcrop, wellbore, and core data available allows for a comprehensive analysis of how the fluvial architecture, connectivity, and reservoir quality change along 65 km of depositional dip.

Observations made at Flaming Gorge and Clay Basin (most landward field locations) suggest a highly mobile fluvial system that was influenced by both autogenic channel clustering and allogenic forcing. Evidence is seen for movement along the Sevier fold and thrust belt and early Laramide uplift of the Uinta Mountains. Specifically, three zones identify temporal tectonic changes throughout deposition of the Trail Member. The Upper and Lower Trail zones represent times of low accommodation as the fluvial system must avulse and move laterally to find available space. The Middle Trail zone represents a higher accommodation setting with internal autogenic channel clustering. This shows that on a finer timescale, autogenic processes control sediment distribution, while on a longer timescale, external drivers, specifically tectonics, control the distribution of sediment in the Trail fluvial system.

Significant changes were observed within the Trail Member towards the basin. At Northern Colorado, lenticular, fluvial-dominated sands are still common, preserved organic and woody material, mud cracks, and increased bioturbation are observed that are not present elsewhere. The sandstone channels are slightly wider, have more common occurrences of low flow-regime sedimentary structures such as ripples and mud cracks, and appear to be more individually isolated with thin fine-grained material surrounding the channels. On a larger scale, photogrammetric analysis shows a rapid lateral change (0.3 km) from a sand-rich, channel-dominated expression to a mud-rich, channel-poor character. These observations suggest a lower energy fluvial system focused within a possible incised valley showing that the fluvial system is being influenced primarily by eustatic forces, rather than tectonics. Subsurface data from twelve wells located north of the Northern Colorado locality show a rapid (15 km) increase in thickness (97 m to 182 m) and decrease in net-to-gross (89.3% to 65.3%). Early subsidence of the Washakie sub-basin just east of the wells could account for the rapid increase in accommodation. Another possible explanation for the rapid thickness increase to the northeast could be the presence of an incised valley. These possibilities show the complexity of the environment within which the Trail Member fluvial system deposited sediments.

Keywords: Trail Member, porosity, permeability, net-to-gross, fluvial architecture, Sevier fold and thrust belt, Uinta Mountain uplift, reservoir, photogrammetry, facies

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Introduction

The Late Cretaceous Ericson Sandstone, located in Wyoming, Utah, and Colorado, contains three members deposited by fluvial and estuarine processes transporting sediments to the Western Interior Seaway (WIS) from the Sevier fold and thrust belt and the Uinta Mountain uplift (Figure 1). Specifically, this study focuses on the lowermost member of the Ericson Sandstone: the fluvial-dominated Trail Member. The Trail Member, which is exposed along hundreds of kilometers due to post-depositional Laramide uplift and has regionally available well and core data, is commonly a hydrocarbon exploration target. Previous production from the Trail Member, however, exhibits unpredictable recovery rates due to complexity at multiple scales that affects connectivity of the channel sandstones. The abundant outcrop and subsurface data utilized in the study allow for a comprehensive analysis of how the fluvial architecture, connectivity, and reservoir quality change temporally and spatially along 65 km of depositional dip from Utah to Colorado.

Previous fluvial architecture research focused on the Rusty and Canyon Creek Members of the Ericson Sandstone suggest that vertical and lateral stacking patterns of fluvial sand bodies are primarily controlled by the relationship between sediment supply and accommodation (Martinsen et al., 1999). Martinsen et al. (1999) suggest that the resulting autogenic channel clustering is influenced by allogenic processes (i.e. tectonics, climate, or eustacy). For example, when the basin experienced higher accommodation such as during deposition of the Rusty Member, the fluvial system built upon itself vertically due to the available space and therefore does not avulse as frequently. The resulting architecture is defined by multi-story channel complexes, more frequently preserved intervals of marginal and overbank mud deposits, and an overall lower net-to-gross ratio (NTG; Figure 2). On the other hand, when the basin experienced relative low accommodation, such as during deposition of the Canyon Creek Member, the fluvial system fills limited accommodation more rapidly and avulses frequently to find available space. Therefore, the resulting fluvial architecture is comprised of more laterally continuous amalgamated sand bodies, less preserved marginal and overbank deposits, and an overall higher NTG (Figure 2). This study aims to investigate if accommodation is a primary driver in the stacking pattern of Trail Member channel complexes, as is suggested for the younger Rusty and Canyon Creek Members, and how the fluvial architecture varies along depositional dip based on this or other controls on fluvial architecture.

Figure 1. Regional location map showing major Sevier- and Laramide-age structural features within the Greater Green River basin. The Trail Member fluvial system transported sediments from west to east towards the Western Interior Seaway. Field and subsurface localities are outlined in the colored boxes. Modified from DeCelles and Mitra (1995) and Roehler (1987).

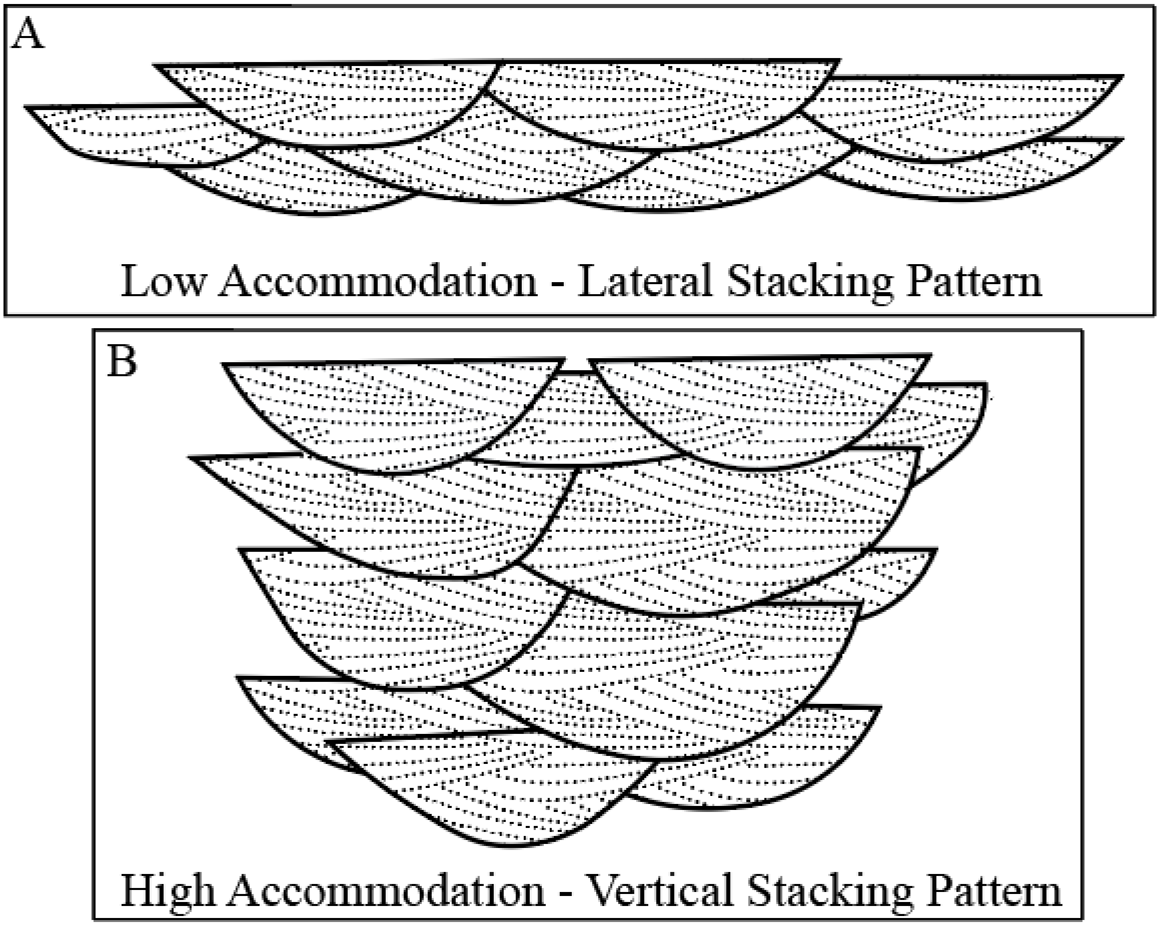


Figure 2. Diagram showing the fluvial architecture resulting from low and high accommodation settings as described by Martinsen et al. (1999). A. Low accommodation settings result in a lateral stacking pattern. B. High accommodation settings result in multi-story channel complexes.

Connectivity of reservoir-quality sandstones is perceived to be a major issue in natural gas production from the Trail Member. Sandstone connectivity controls the fluid movement within a reservoir and the potential reservoir volume that can be produced (Pranter, 2008). Despite high NTG, the Trail Members exhibits heterogeneity as reservoir-quality channel complexes are potentially compartmentalized by mud-rich intervals separating the major sandstone bodies. The Trail Member is also compartmentalized (or at least complicated) by mud drapes within individual and amalgamated channels and channel complexes. Pranter (2008) showed that within channel point-bar sandstones of the fluvial Williams Fork Formation, mud drapes along lateral accretion surfaces can act as a barrier to fluid flow and cause more complex migration pathways as hydrocarbons flow downward along the mud drapes. Understanding the scale of heterogeneity within the Trail Member and how it changes along depositional dip adds further detail on how the reservoir sandstones are connected and how fluid flow is affected.

The reservoir quality of sandstones within the Trail Member depends significantly on the porosity and permeability, which is controlled by the composition, texture, and diagenetic history of the resulting sandstone (Taylor et al., 2010). Understanding the influence on the proximity to sediment sources, facies associations and distribution, and burial history are crucial in understanding how the reservoir quality may change along depositional dip and where future production wells are placed within the Trail Member.

This history of the Trail Member as a hydrocarbon producing reservoir began in 1958 (Greenhalgh, 2019). Early efforts to produce out of the Trail Member, however, were mainly unsuccessful due to formation damage from drilling fluids. The Mountain Fuel Supply Co. was able to successfully complete and produce out of the Trail Member when they changed the drilling fluid to natural gas and early production consisted mainly of gas, water, and some oil. The high water cut caused early production to slow and development of the Trail Member ceased until 2010 when geologists began to understand the high level of compartmentalization. The compartmentalization of the reservoir is thought to cause complex migration paths that result in incomplete sourcing of the sandstone reservoir. Therefore, the Trail Member sandstones are a heterogeneous mixture of well-charged gas and oil sands with partially-charged gas and oil sands and water-bearing sands (Greenhalgh, 2019). Currently, approximately 200 wells target, perforate, and hydraulically fracture vertical sections of the Trail Member within the Canyon Creek and Trail fields. The Trail and Canyon Creek field produce from a total of 243 wells that target the Trail and Canyon Creek Members and the Almond Formation (Wyoming Oil and Gas, 2019).

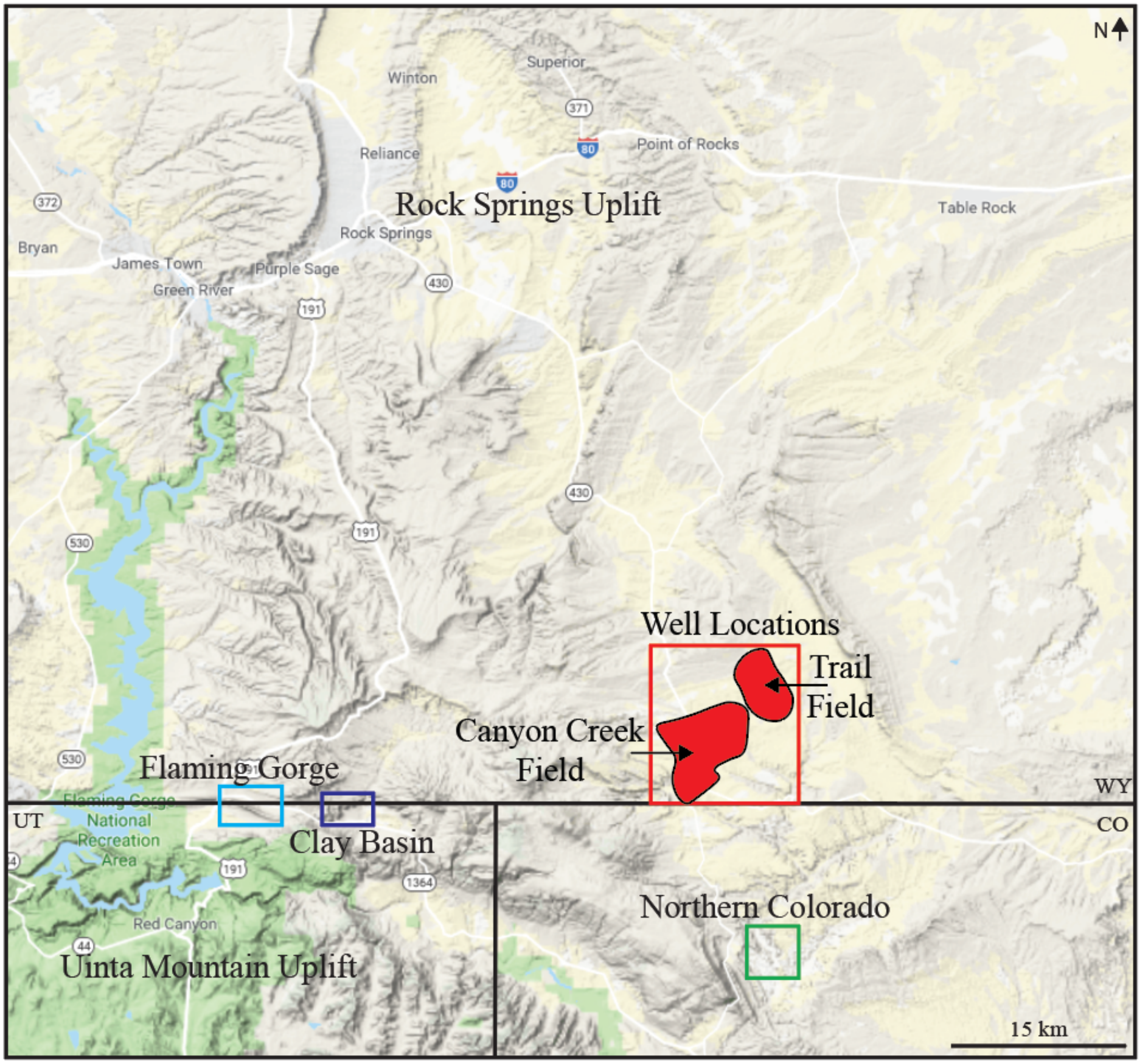


Figure 3. Map showing the four field areas (Flaming Gorge, Clay Basin, Northern Colorado, and well locations) and the Canyon Creek and Trail gas fields. Modified from Wyoming Oil and Gas (2019).

The study area is 65 kilometer transect using both outcrop and well data that was reconstructed to accurately represent how the fluvial system changes from a more proximal location near the Sevier fold and thrust belt and Uinta Mountain uplift sediment sources to a more distal location towards the Western Interior Seaway (Figures 1 and 3). Three main outcrop locations were identified along this transect. The furthest west, or most proximal location, the Flaming Gorge (FG) field area, is located near the Utah/Wyoming border along the east side of Flaming Gorge Reservoir just north of the Uinta Mountains (Figure 3). The middle field area is located approximately 15 km east of Flaming Gorge with Clay Basin (CB; Figure 3). Clay Basin is also located just north of the Uinta Mountain uplift. The third and most distal outcrop location is found approximately 50 km southeast of Clay Basin in the Sandwash sub-basin (Figure 3; Dickinson et al., 1988; Pranter, 2008; Gomez-Veroiza and Steel, 2010). The Trail Member in the Northern Colorado locality is tilted nearly vertical owing to its proximity to the Sparks Ranch thrust fault, which was active during the Laramide orogeny (Roehler, 1987; Figure 1).

In addition to the outcrop localities, twelve wells were utilized to study the Trail Member within the subsurface. These twelve wells are located within the Canyon Creek and Trail fields approximately 20 km north of the Northern Colorado locality on the margins of the Washakie sub-basin (Figures 1 and 4). Core was also taken and analyzed from one of these twelve wells (Canyon Creek Unit 64 well; Figure 4). The well logs and core data were provided by Dominion Energy, but are publicly available and allow for the analysis and comparison of the subsurface and outcrop Trail Member.

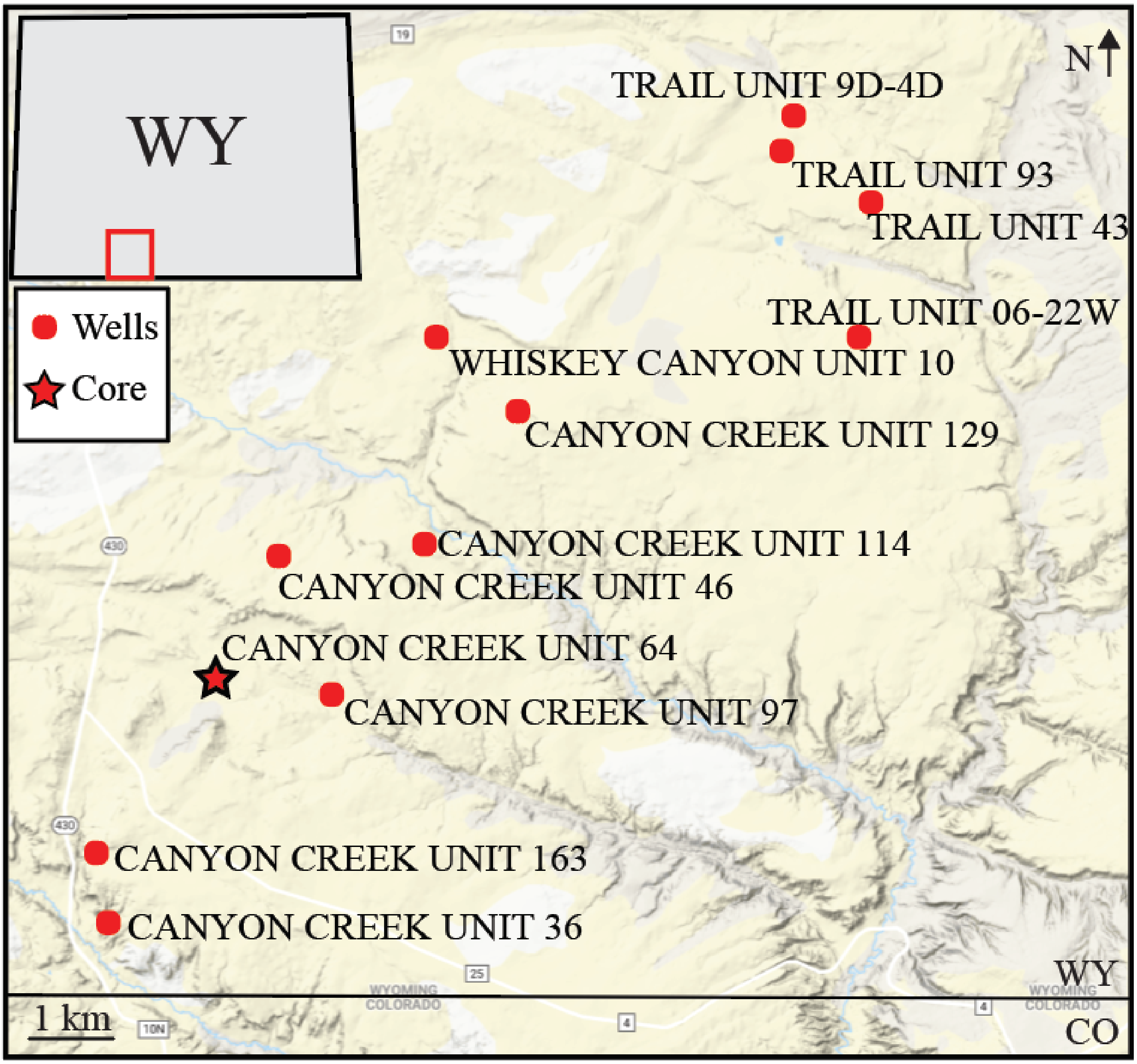


Figure 4. Subsurface well location map within the Canyon Creek and Trail natural gas fields (see Figure 3). Well data included gamma ray, porosity, and resistivity logs. Red star with black outline indicates the location of both well log and core data.

Background

Geologic History

The late Campanian Trail Member of the Ericson Sandstone is located within the greater Green River basin, covering parts of Wyoming, Utah, and Colorado (Figure 1). The greater

Green River basin is a sedimentary basin that is bounded by the Sevier fold and thrust belt to the west, the Uinta Mountain uplift to the south, and the Wind River Range to the north (Figure 1; Roehler, 1990). The greater Green River basin formed during an active tectonic period that began in the Early Cretaceous as the Farallon and Kula oceanic plates subducted underneath the western edge of the North American continent initiating compressional forces on the continental plate (Figure 5; Kauffman and Caldwell, 1993; Leva-Lopez and Steel, 2015). This initiated the Sevier Orogeny, which is characterized by thin-skinned thrust faulting and formed the north-south trending Sevier fold and thrust belt that extended from western Canada to southeastern California (DeCelles, 2004; Liu et al., 2005; Leary et al., 2015). The Sevier fold and thrust belt caused an increase in crustal loading that initiated flexural subsidence east of the mountain belt and formed the north-south trending, asymmetrical foreland basin that extended from central Canada into New Mexico (Figure 5; Cross, 1986; Leary et al., 2015; Leva-Lopez and Steel, 2015). During the Cretaceous, global climate reflected greenhouse conditions that were characterized by higher temperatures, elevated CO2 concentrations, a reduced temperature gradient from the equator to the poles, and loss of ice in the Polar regions (Hay, 2008; Dennis et al., 2013). These global climate conditions caused eustatic sea level to rise drastically, filling the foreland basin and creating the epicontinental Western Interior Seaway (WIS) that periodically connected the Gulf of Mexico to the south and the Arctic Ocean to the north (Figure 5; Cross and Pilger, 1978; Pranter, 2008; Leva-Lopez and Steel, 2015).

Near the end of the late Cretaceous (approximately 80 Ma), the western edge of North America experienced another change in orogenic style due to the flat-slab subduction of the Farallon plate causing compressional stresses to be transferred further into the continent (English and Johnston, 2004). This initiated a change from primarily flexural subsidence to dynamic

(2018).

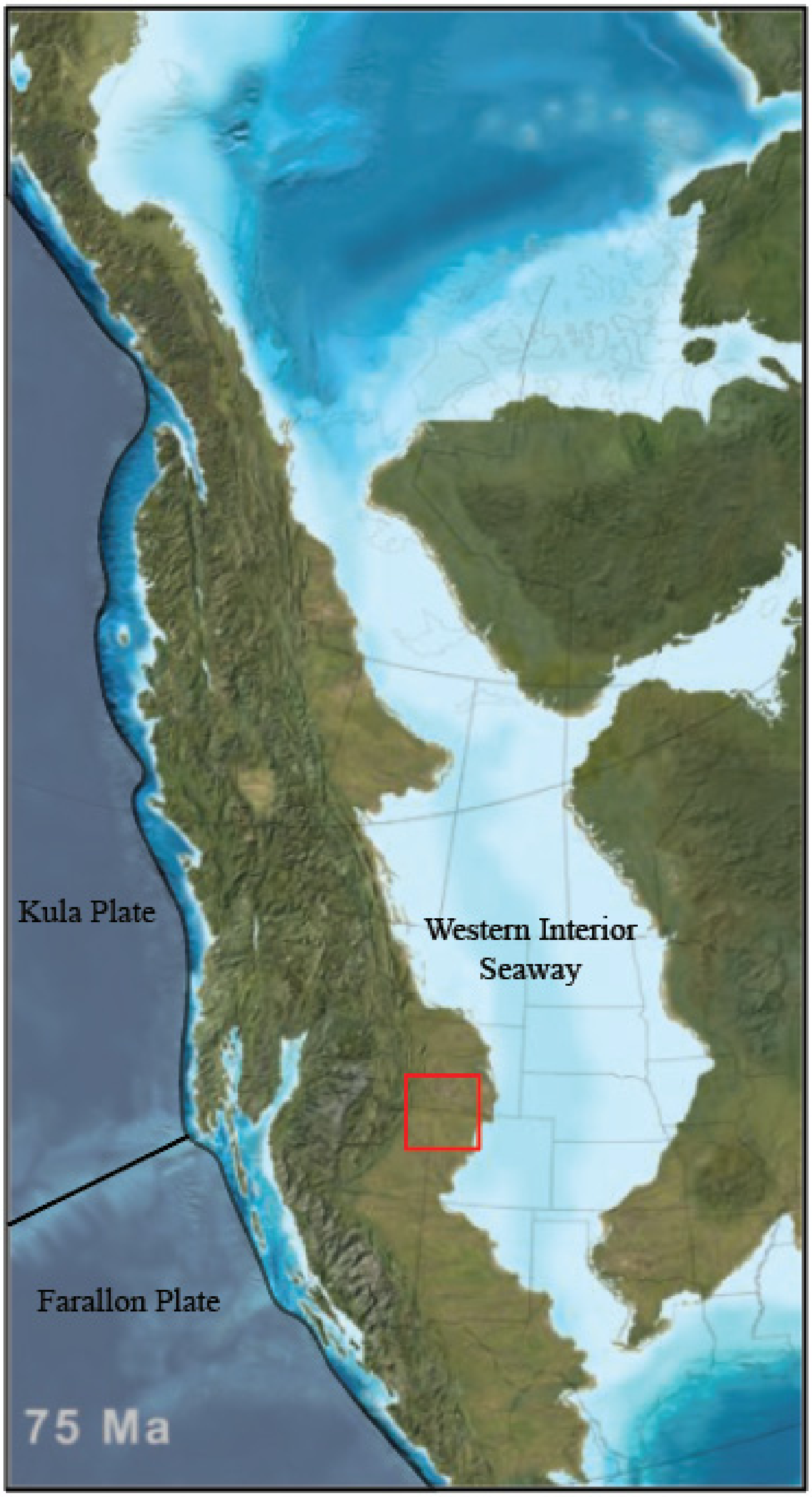


Figure 5. Paleogeographic map of the Late Cretaceous (75 Ma) outlining the Kula and Farallon oceanic plates being subducted underneath the North American continental plate causing the Sevier fold and thrust belt. Globally high sea levels filled in the foreland basin east of the mountain belt creating the Western Interior Seaway. Area of interest shown within the red box. Modified from Leva-Lopez and Steel (2010) and Blakey (2018).

subsidence along the eastern edge of the Sevier fold and thrust belt (English and Johnston, 2004; Leva-Lopez and Steel, 2015). This marked the start of the transition from the Sevier orogeny to the Laramide orogeny. The Laramide orogeny is characterized by thick-skinned faulting that caused complex patterns of subsidence creating local depocenters adjacent to large basement-cored arches and anticlinal features and lasted until the Paleocene (55 Ma; Cross, 1986; Roehler, 1990; English and Johnston, 2004; Gomez-Veroiza and Steel, 2010). Specifically, the greater Green River basin was then segmented into smaller sub-basins (i.e., Green River basin, Washakie sub-basin, Sandwash sub-basin) that were separated by arches and anticlines (i.e., Rock Springs uplift, Uinta Mountain uplift, Cherokee Arch; Figure 1; Mederos et al., 2005).

The Trail Member fluvial system transported sediments from the Willard and Absaroka thrust sheets of the Sevier fold and belt and from early onset of the Uinta Mountain uplift to the Western Interior Seaway to the east (Figure 1; DeCelles and Mitra, 1995; Leary et al., 2015). Specifically, the Trail Member was active during the late Campanian (approximately 78-75 Ma) as the area saw a decrease in Sevier orogenic activity (Devlin et al., 1993; DeCelles, 1994; DeCelles and Mitra, 1995; Gomez-Veroiza and Steel, 2010). Although the exact beginning of the Laramide orogeny is debated, evidence within the greater Green River basin suggests that early Laramide orogenic movement occurred during the deposition of the Trail Member. Evidence includes the observation that movement along normal faults around the Rock Springs uplift that occurred during the deposition of the Ericson Sandstone (Martinsen et al., 1999; Mederos et al., 2005; Leary et al., 2015). Detrital zircon U-Pb ages from the Uinta Mountains suggest that the uplift provided significant amounts of sediment to the Ericson Sandstone in areas just north of the Uinta Mountains (such as the Flaming Gorge and Clay Basin field areas; Leary et al., 2015).

Continued emergence of Laramide-related structures through the Paleocene caused the Trail Member to be exposed at the surface (Cross, 1986).

Stratigraphy

The late Campanian Ericson Sandstone forms the fluvial-dominated portion of the 3rd order regressive to transgressive Mesaverde Group (Figure 6; Pedersen and Steel, 1999). In the Rock Springs uplift area, the Mesaverde Group comprises the following formations (in ascending order): Blair Formation, Rock Springs Formation, Ericson Sandstone, and Almond Formation (Figure 6). The Blair Formation, the oldest formation in the Mesaverde Group, represents a marine environment from nearshore to offshore deposits (Douglass and Blazzard, 1961). The Rock Springs Formation, which sits unconformably below the Trail Member of the Ericson Sandstone, represents a coastal plain environment (Martinsen et al., 1999; Pedersen and Steel, 1999). Within the upper Rock Springs Formation, two intertonguing units, the McCourt and Gottsche Tongues, were utilized in this study for identifying the contact between the Rock Springs Formation and the Trail Member (Figure 7). The McCourt Tongue can be easily identified and traced throughout the field areas as a laterally continuous, massive bleached sandstone interpreted as marine shoreface deposits (Pedersen and Steel, 1999). The Gottsche Tongue, or uppermost unit of the Rock Springs Formation, can be identified by mud-rich strata with isolated fine-grained sandstone channels that represent a non-marine and brackish water coastal plain environment (Pedersen and Steel, 1999). In the field, the Gottsche Tongue is a slope former that separates the McCourt Tongue and Trail Member sandstones with a visible erosional contact.

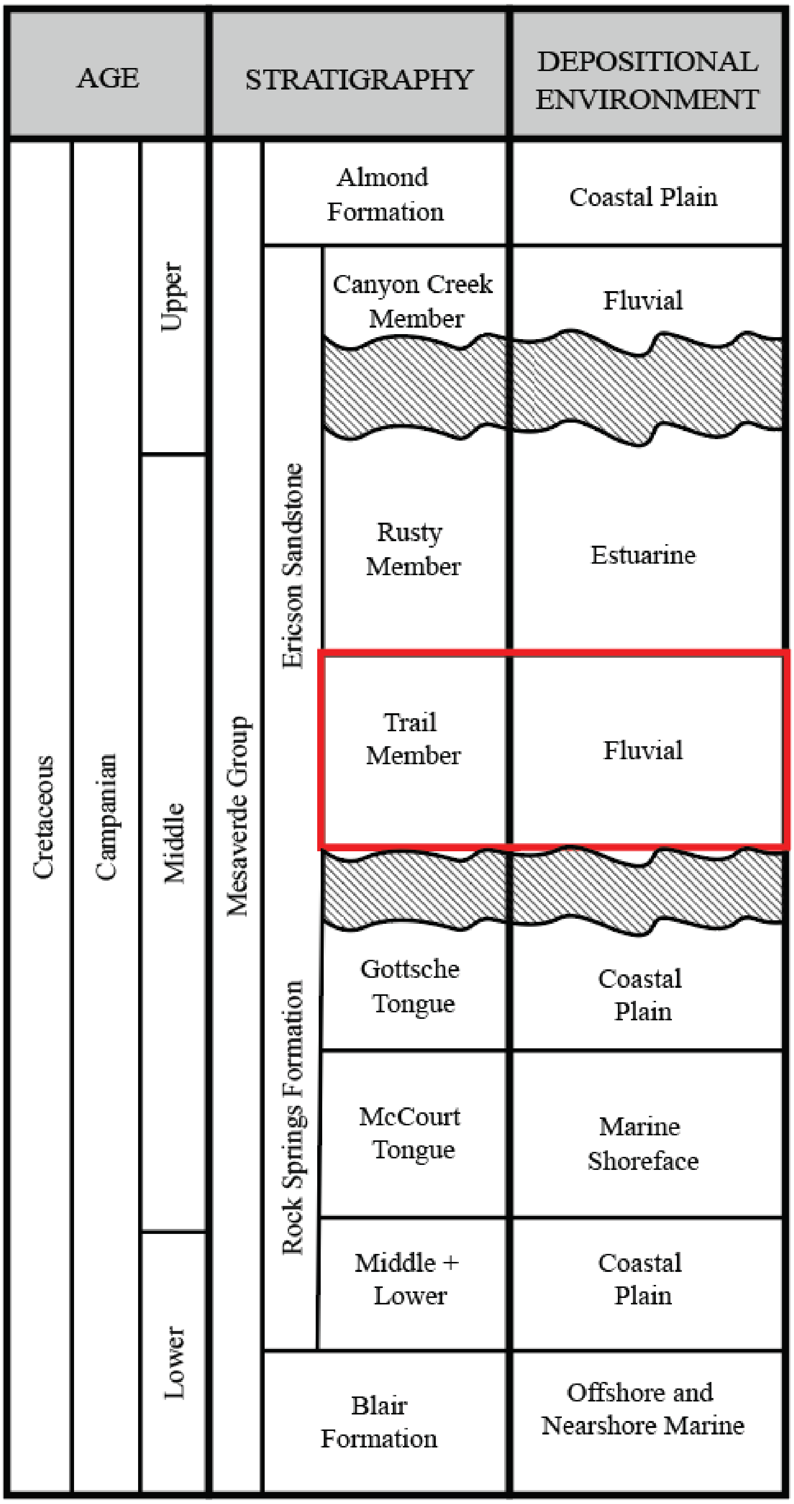


Figure 6. Generalized stratigraphic column (not to scale) of the Mesaverde Group and relevant units in the Rock Springs uplift area with interpreted depositional environments. The Trail Member, focus of this study, is outlined in red. Unconformities in the area are shown with dashed lines. Modified from Martinsen et al. (1999) and Gomez-Veroiza and Steel (2010).

The Ericson Sandstone includes the following three members (is ascending order): the Trail Member, the Rusty Member, and the Canyon Creek Member (Figure 6). The lowermost Trail Member sits unconformably above the Rock Springs Formation. The Trail Member is characterized by multi-story, multi-lateral, fine- to coarse-grained lensoidal sandstones with minor mud interbeds (Figure 7; Martinsen et al., 1999; Leary et al., 2015). The Trail Member represents a high NTG fluvial environment that transported sediments from west to east. In the three field areas and subsurface, the Trail Member ranges significantly in thickness from 45 m to 180 m, and thickens overall towards the basin. The Rusty Member lies conformably above the Trail Member and interfingers with the upper Trail Member (Figure 6). The Rusty Member has a greater proportion of mud-rich strata than the other two members of the Ericson Sandstone and ranges in thickness from 100 m to 120 m in the Flaming Gorge and Clay Basin areas (Figure 7; Leary et al., 2015). The mud-rich strata dominate this member in outcrop, with isolated fine-grained lensoidal sandstones within the mud-rich slopes. The Rusty Member is interpreted to

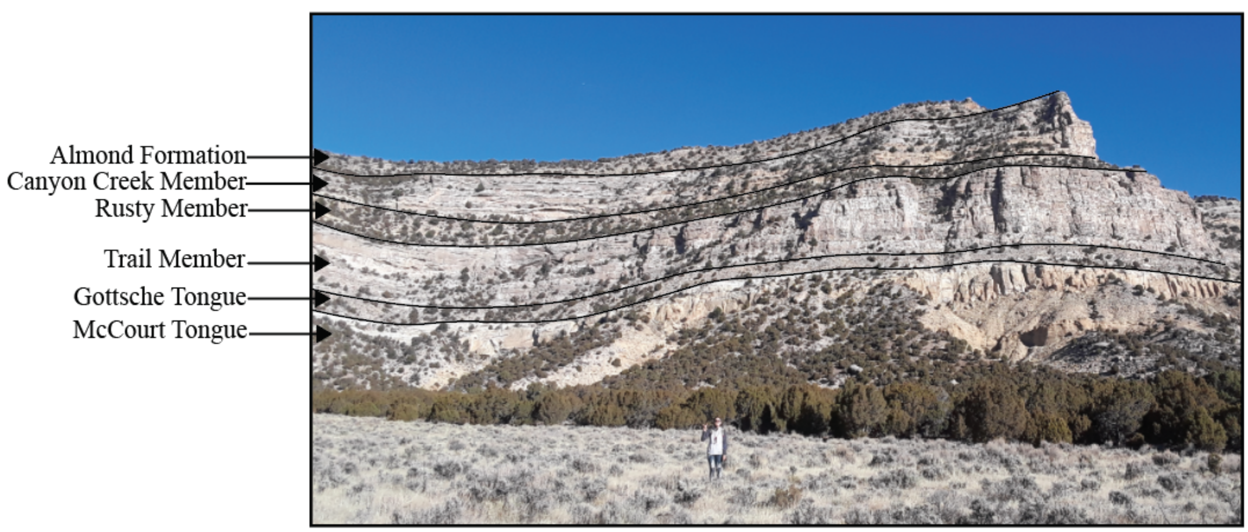


Figure 7. Annotated picture showing Mesaverde Group stratigraphy in the Clay Basin locality. The lower Rock Springs Formation and Blair Formation are not present above the surface in this area.

have been an estuarine environment with fluvial and distributary channels cutting into the finer-grained overbank deposits (Martinsen et al., 1999; Leary et al., 2015). The uppermost member of the Ericson Sandstone is the Canyon Creek Member, which is also targeted as a hydrocarbon reservoir (Figure 6; Wyoming Oil and Gas, 2019). The Canyon Creek Member lies unconformably above the Rusty Member and can be identified by the distinct change from mud-rich to sand-rich strata that is similar in appearance to the Trail Member (Figure 7). The Canyon Creek Member ranges in thickness from 40 m to 60 m in the Flaming Gorge and Clay Basin field areas (Leary et al., 2015). The Canyon Creek Member is represented by sandstones that are coarser-grained than those of the Trail and Rusty Members and represents a highly amalgamated fluvial system.

The uppermost formation of the Mesaverde Group is the Almond Formation (Figure 6). The Almond Formation lies conformably above the Canyon Creek Member of the Ericson Sandstone and is targeted and produced hydrocarbons. Most of the Almond Formation represents a seaward shift in facies because it has been interpreted to represent a coastal plain environment, while the upper Almond Formation represents a shallow marine environment (Kieft et al., 2011).

Methods

Measured Sections

Eleven sections of the Trail Member outcrops were measured using a Jacob's staff in the three field areas (4 sections – Flaming Gorge, 5 sections – Clay Basin, 2 sections – Northern Colorado; Figure 8). Each measured section started at the McCourt Tongue of the upper Rock Springs Formation, which is identified by the laterally continuous, massive bleached fine-grained

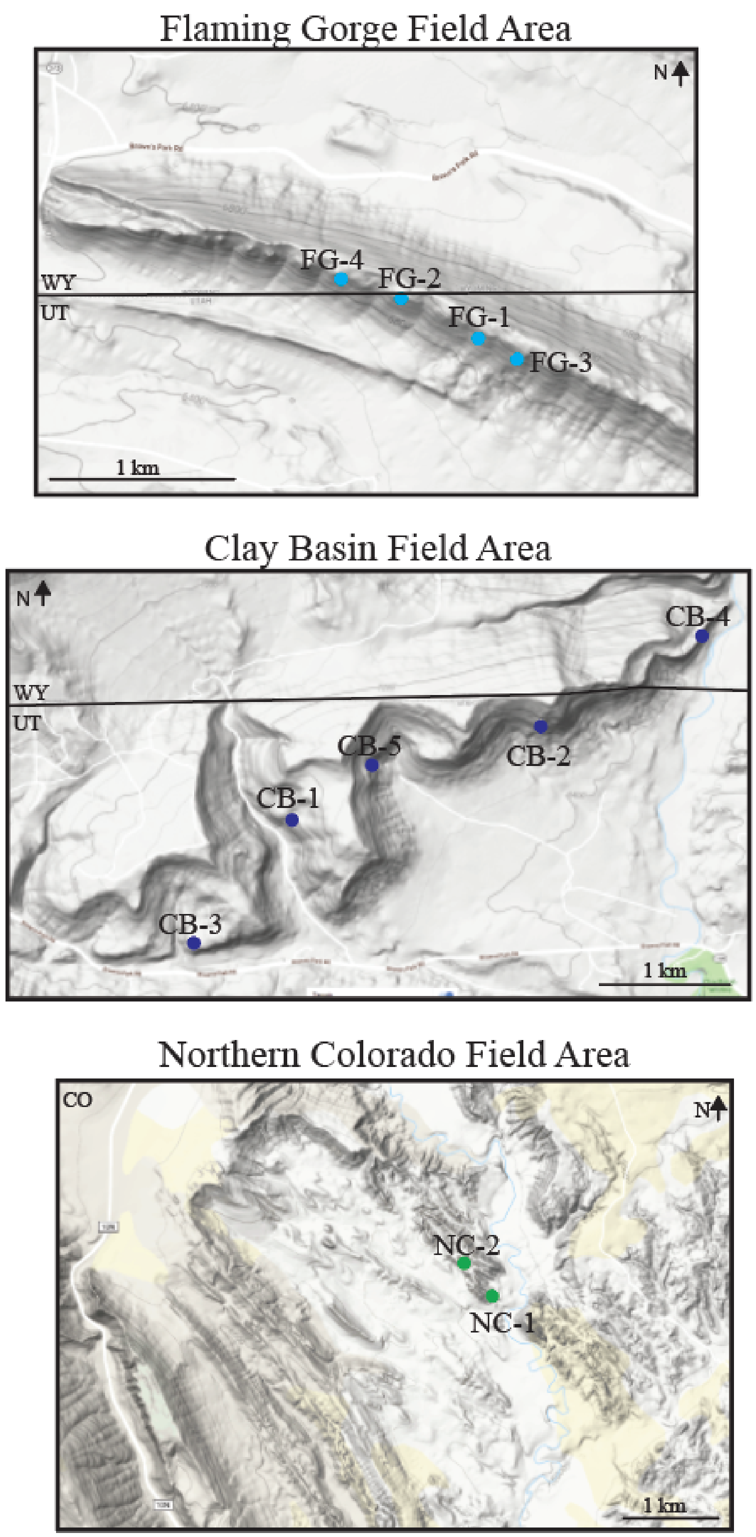
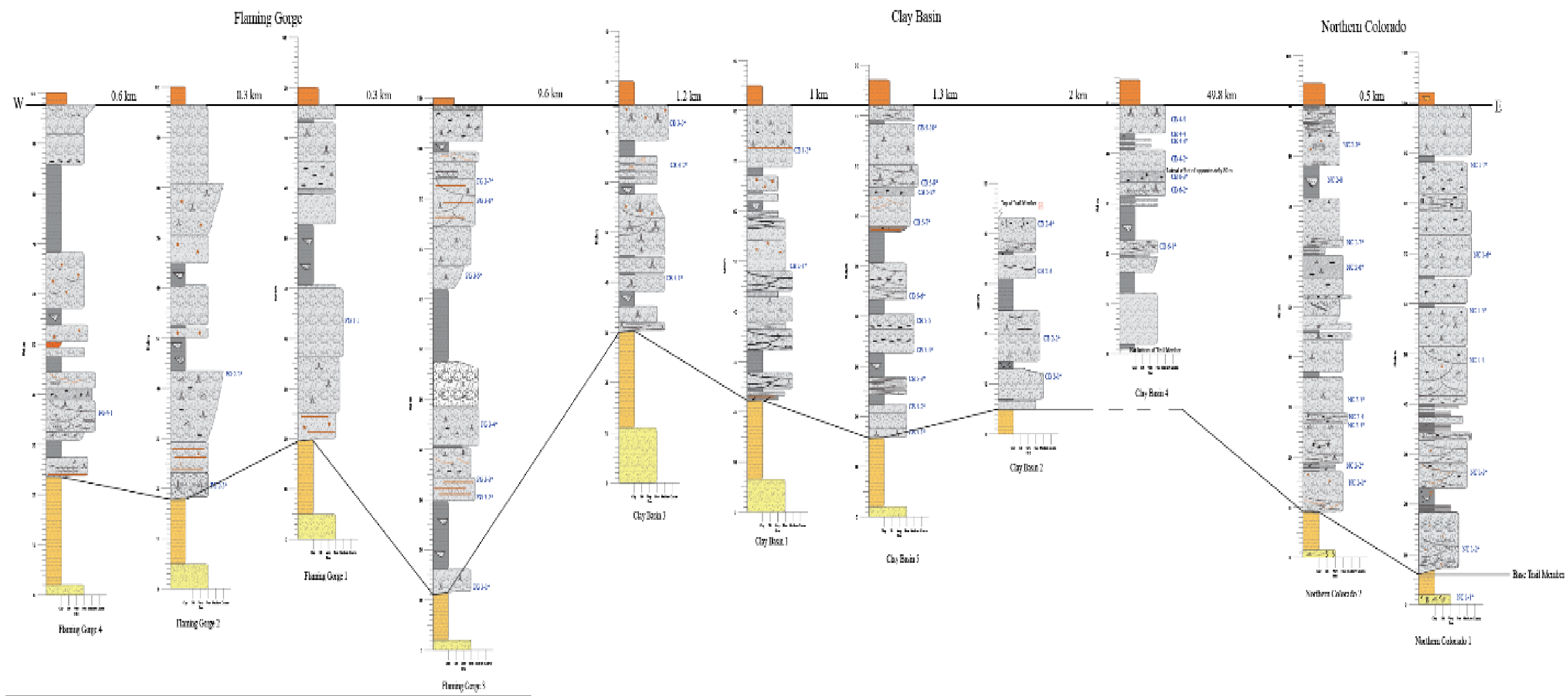


Figure 8. Location maps for each of the three outcrop field areas with the location of each measured stratigraphic columns. Refer to Figure 3 for location of the field areas.

sandstone, and each section ended at the contact of the Trail and Rusty Members with the exception of CB-2 and CB-5 due to lack of accessibility. Each section was measured and described with respect to variability in grain size, sedimentary structures, interpreted facies association, color, and degree of amalgamation. All measured section were digitized for easy visualization and placed within a west to east correlation panel (Figure 9). Additionally, hand samples were collected throughout each measured section with notes recording location, grain size, and facies association. A total of fifty-three samples were collected from the three field areas and selected samples were used for porosity, permeability, and thin section analyses (Table 1).

In two of the field areas (Clay Basin and Northern Colorado), a scintillometer (RS-230 BGO Super-SPEC Gamma-Ray Scintillometer) was used on one section each (CB-5 and NC-2) to help correlate outcrop data to the well logs. Readings were taken for uranium, thorium, and potassium radioactivity in the formation, along with a total composite. The output data (Table 2) was used to calculate pseudo-gamma ray values using the following API equation ($API = (19.6*K) + (8.1*U) + (4*Th)$). The acquisition time for each scintillometer reading was 30 seconds and these measurements were taken at interpreted lithologic breaks. Scintillometer data acquisition was not done in even increments, but was extrapolated between readings that represent facies changes.



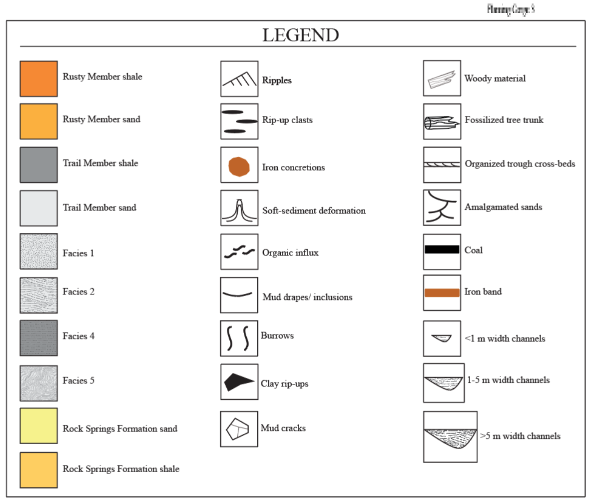


Figure 9. Measured stratigraphic columns within a west to east correlation panel with the top of the Trail Member as the datum. Cross section represents 65 km of depositional dip from the furthest west of proximal stratigraphic column moving towards the basin. Measured sections begin at the McCourt Tongue of the Rock Springs Formation and end at the Trail/Rusty Member contact. Hand sample ID's and locations are placed on each stratigraphic column. Hand samples ID's with an asterisk (*) indicate samples with porosity and/or permeability data. Refer to Figures 3 and 8 for regional and section locations.

Outcrop Hand Samples					
Sample #	**Facies**	**Grain Size**	**Porosity**	**Permeability**	**Thin Section**
Flaming Gorge					
FG 1-1*	2	Medium			
FG 2-2	2	Coarse	X	X	X
FG 2-3	2	Fine	X	X	X
FG 3-1	2	Fine	X	X	
FG 3-2	2	Fine - Medium	X	X	
FG 3-3	2	Fine - Medium	X	X	
FG 3-4	2	Medium	X	X	X
FG 3-5	2	Very Fine	X	X	
FG 3-6	1	Fine - Medium	X	X	
FG 3-7	1	Fine - Medium	X	X	X
FG 4-1	2	Medium - Coarse	X	X	
Clay Basin					
CB 1-1	1	Fine	X	X	X
CB 1-2	2	Coarse		X	
CB 2-1	1	Medium	X	X	X
CB 2-2	2	Fine - Medium	X	X	X
CB 2-3*	1	Medium			
CB 2-4	1	Fine	X	X	
CB 3-1	2	Medium	X	X	X
CB 3-2	1	Fine			X
CB 3-3	2	Medium		X	X
CB 4-2	2	Medium	X	X	
CB 4-3	3	Very Fine	X	X	
CB 4-4*	4	Silt			
CB 4-5*	2	Coarse			
CB 5-1	1	Fine	X	X	X
CB 5-2	1	Fine	X	X	
CB 5-3	1	Fine	X	X	X
CB 5-4	2	Medium	X	X	X
CB 5-5*	2	Medium			
CB 5-6	1	Fine	X	X	
CB 5-7	2	Fine - Medium	X	X	
CB 5-8	5	Medium	X	X	X
CB 5-9	2	Medium - Coarse	X	X	X
CB 5-10	2	Medium	X	X	
CB 6-1	2	Fine	X	X	
CB 6-2	2	Medium	X	X	
CB 6-3	5	Medium	X	X	
Northern Colorado					
NC 1-1	Rock Springs	Very Fine	X	X	
NC 1-2	2	Fine	X	X	
NC 1-3	2	Medium	X	X	X
NC 1-4*	2	Medium			
NC 1-5	2	Medium	X	X	X
NC 1-6	2	Medium		X	
NC 1-7	2	Medium	X		
NC 2-1	2	Fine	X	X	
NC 2-2	1	Very Fine	X	X	X
NC 2-3	2	Fine	X	X	X
NC 2-4*	2	Medium - Coarse			
NC 2-5	2	Fine	X	X	
NC 2-6	5	Fine	X	X	X
NC 2-7	2	Fine	X	X	
NC 2-8*	4	Silt			
NC 2-9	2	Very Fine - Fine	X		

Table 1. Outcrop hand sample table indicating sample #, facies association, grain size, porosity, permeability, and thin section analyses. Sample ID's with an asterisk (*) indicates the sample was too damaged for additional analyses (i.e. porosity and permeability tests) within the lab.

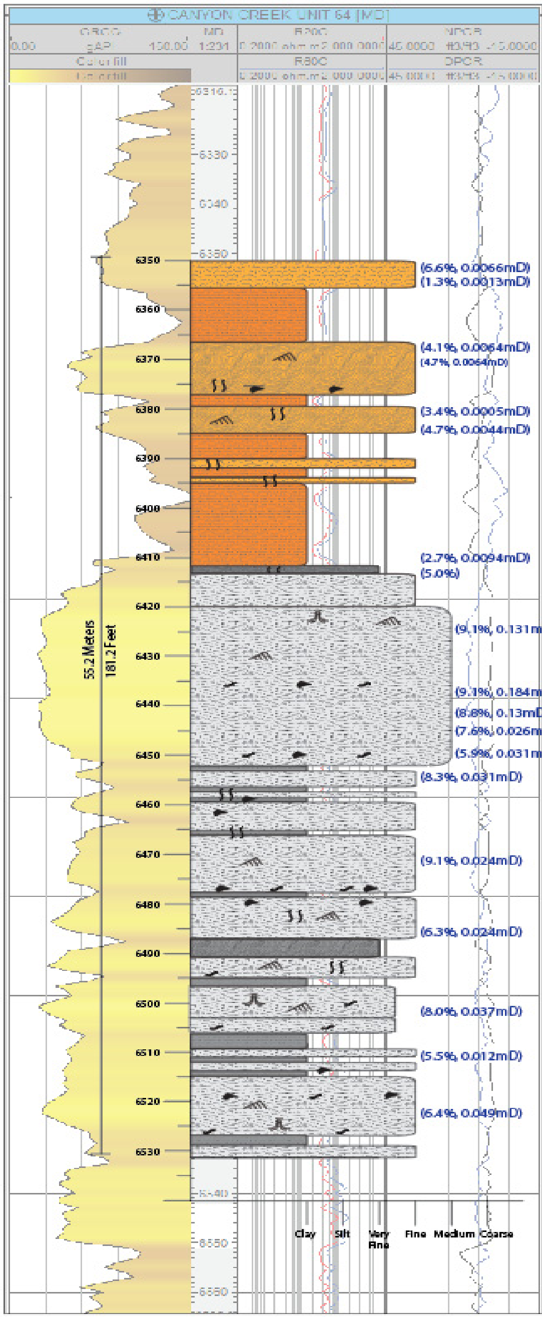
Clay Basin 5		
Depth (m)	Facies	GR (API)
63.5	2	32.8
61.9	5	19.6
55.8	2	33.7
55.2	4	94.2
42.9	2	17.7
37.1	2	20.9
31.9	2	17.6
24.3	1	34.9
22.8	1	23.7
19.8	1	32.4
15.6	1	26.4
0	McCourt Tongue	59.3

Northern Colorado 2		
Depth (m)	Facies	GR (API)
88.2	2	142.7
86.3	4	106.2
81.4	2	88.4
74.7	4	98.7
68.2	2	51.5
63.5	2	57
61.1	3	75.6
60.2	2 5	39.6
51.7	2	74.1
48.2	2	65.5
43.7	2	62
32.9	2	45.4
29.9	2	37.4
26.9	2	63.9
22.9	2	52.8
18.9	2	55.1
18.4	3 4	8.6
10.4	2	74.1

Table 2. Scintillometer data from two measured sections (CB-5 and NC-2) with the recorded locations (m) and facies association.

Core and Well Logs

Core and well logs were provided by Dominion Energy, but are publicly available through the Wyoming Geological Survey. The core and well log data were provided from wells within the Canyon Creek and Trail producing fields. The core was taken from the Canyon Creek Unit 64 producing well and is located at the Utah Geological Survey (UGS) core lab in Salt Lake City, UT. The core was described in detail and eighteen and seventeen porosity and permeability data points and gamma ray data were measured (Figure 10). The core gamma ray was used to depth adjust and overlay the core description over the corresponding well log (Figure 10). The well log data received from twelve producing wells included gamma ray, resistivity, and porosity (Figure 11). Tops were picked for the three members (Trail, Rusty, and Canyon Creek) of the Ericson Sandstone in addition to the Rock Springs Formation using primarily gamma ray signatures. Trail thicknesses were acquired using the top and bottom picks and NTG values were calculated using a gamma ray cut off of 70 API based on outcrop sandstone facies scintillometer readings (Figure 11).



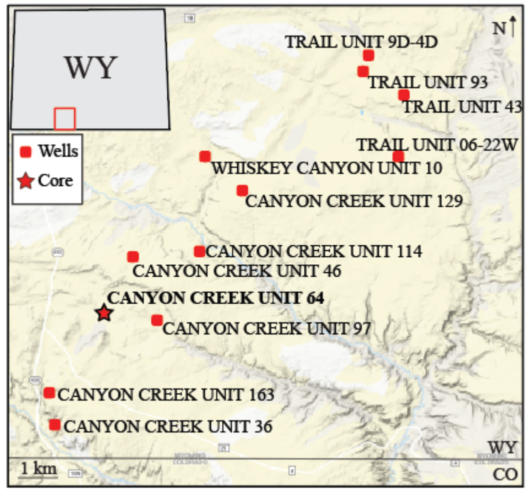


Figure 10. Canyon Creek Unit 64 core description overlain on gamma ray, resistivity, and porosity well logs. Core description was shifted to fit well log curves. The top 63.4 ft (19.3 m) is interpreted to be the Rusty Member and is shown by the orange color, while the remaining 117.8 ft (35.9 m) are interpreted to be the Trail Member and is represented by the grey color. See Figure 9 for legend.

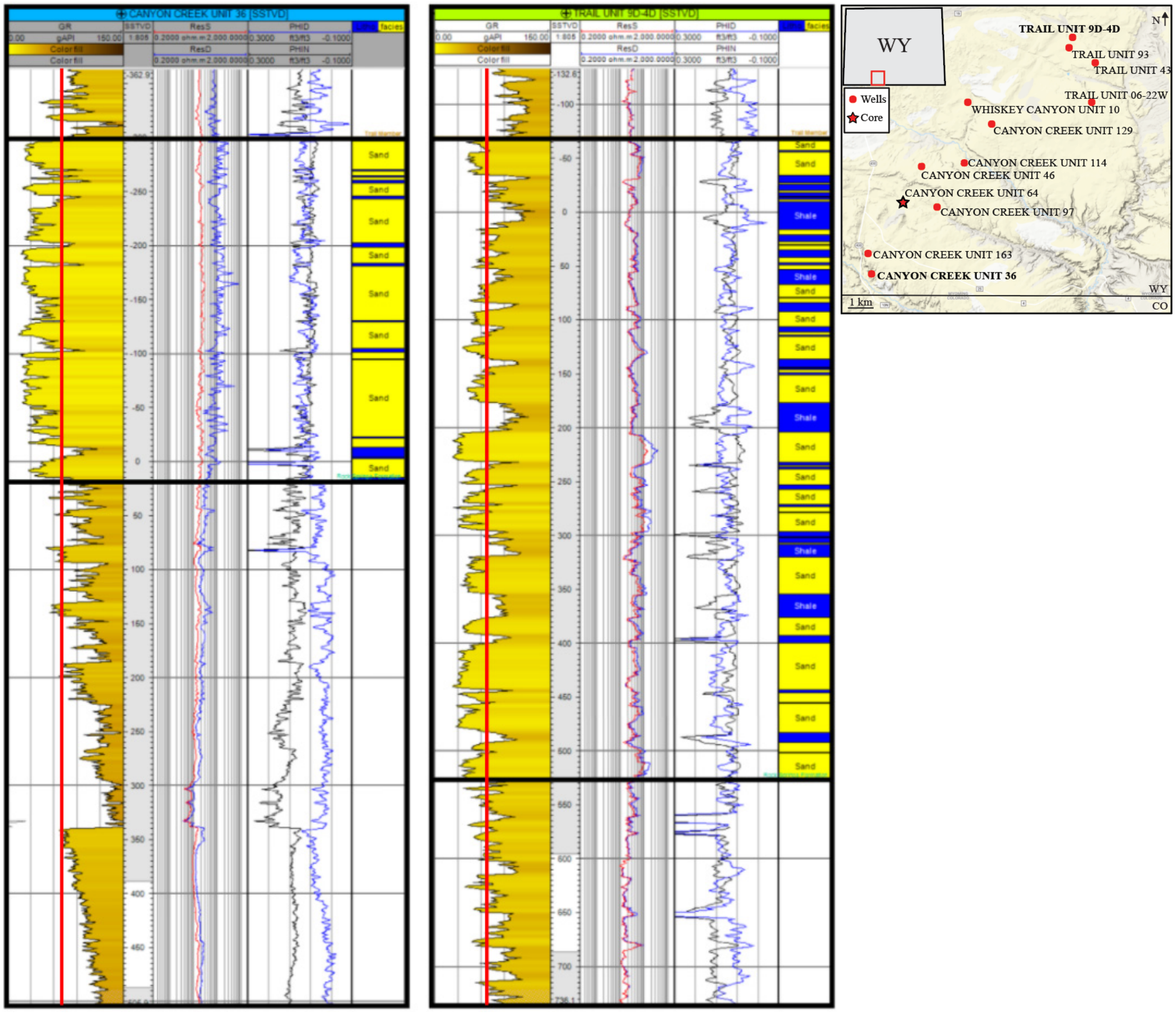


Figure 11. Examples of well data (i.e. gamma ray, resistivity, and porosity logs) from two wells located on the most southwest (left) and northeast (right) corners of the Canyon Creek and Trail fields. The black lines represent the top and bottom contacts of the Trail Member. The gamma ray cut off used to determine sand versus shale is shown by the red line with the calculated results shown in the right well log track. The blue represents shale and the yellow represents sand.

Porosity and Permeability

Porosity and permeability values were measured from hand samples collected in each of the measured sections. First, 1-inch core plugs were made from each of the outcrop samples using a drill press. The core plug was cut down to the proper length using a tile saw. Measurements and calculations, including height, width, weight, and volume were recorded for each of the core plugs. The core plugs were then placed inside the Ultra-Pore 300 Porosimeter and Ultra-Perm 500 Permeameter at the Brigham Young University Sedimentology Laboratory. A total of forty-two samples were used for porosity measurements and forty-one samples were used for permeability measurements.

Thin Sections

Outcrop and subsurface thin sections were used to determine composition and grain characteristics, including sorting, roundness, contacts, diagenetic features, and pore types. Fifty-one thin sections from the Canyon Creek Unit 64 core were made available through Dominion Energy and twenty thin sections were made from selected outcrop samples. Pelcon point-counting software was used to count 300 points with 1.5 mm spacing per thin section to determine composition and these data were plotted on a QFL (Quartz-Feldspar-Lithic) ternary diagram to identify how samples compare/contrast in relation to facies associations, field areas, and subsurface to outcrop. The core thin sections were also assigned facies associations consistent with those developed in the field areas in order to compare outcrop to subsurface.

Photogrammetry

A DJI Phantom 3 Professional drone was used to take high-resolution pictures of the Trail Member in Clay Basin and Northern Colorado. The edited pictures were imported into the Agisoft Photogrammetry software, which creates 3-D photogrammetric panels (Figure 12). To reduce processing time, three photogrammetric panels were created for Clay Basin and two panels for Northern Colorado. The three Clay Basin photogrammetric panels spanned a total of 5.8 km and the Northern Colorado photogrammetric panels spanned 0.4 km. These high-resolution 3-D models allow for quantitative characterization of channel forms and channel clusters. Channels and channel clusters were outlined within Agisoft and the width and depth for each channel or channel cluster was measured (Figure 12). Channels were characterized as either a low or high accommodation category based on the depth-to-width ratio (Figure 12). In Clay Basin, 3,115 channels were identified in Agisoft, with 445 classified as low accommodation and 2,670 as high accommodation. In Northern Colorado, 127 channels were identified with 27 channels classified as low accommodation and 100 as high accommodation.

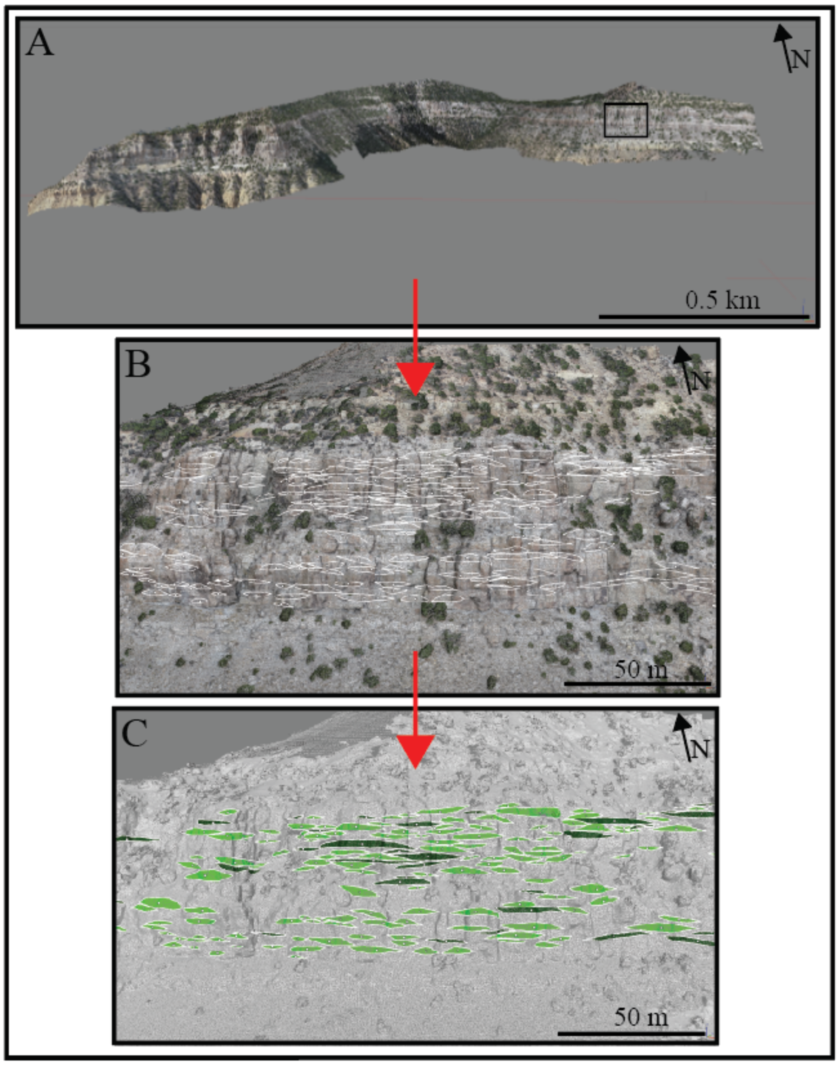


Figure 12. Photogrammetric workflow within the Agisoft software for the Clay Basin West panel. A. Pictures from the DJI Phantom 3 Professional drone are stitched together to create a 3-D dense cloud model. B. Channels and channel clusters were outlined (white polygons). C. Measurements (width and depth) were recorded for each channel/channel cluster and the ratio was used to categorize the channels as low accommodation (dark green) or high accommodation (light green).

Geocellular Facies Modeling

Facies modeling was conducted for the Trail Member fluvial system using Schulmberger's Petrel software platform. Three photogrammetric point clouds (including all points and interpreted channel points) from Clay Basin and one photogrammetric point cloud from Northern Colorado were imported into Petrel with an interpreted facies property and used as control data for static facies modeling. Within each model, the point sets were decimated in order to increase the efficiency and decrease the processing time of the model. A grid was created by defining top and bottom surfaces that correspond respectively with the top and bottom contacts of the Trail Member (Figure 13). The final model was built with a layer thickness of approximately 5 m. In the x, y direction (map view), the final grid is 10 m x 10 m. Channel and background facies were upscaled into the grid, which served as the control data for the facies modeling (Figure 13).

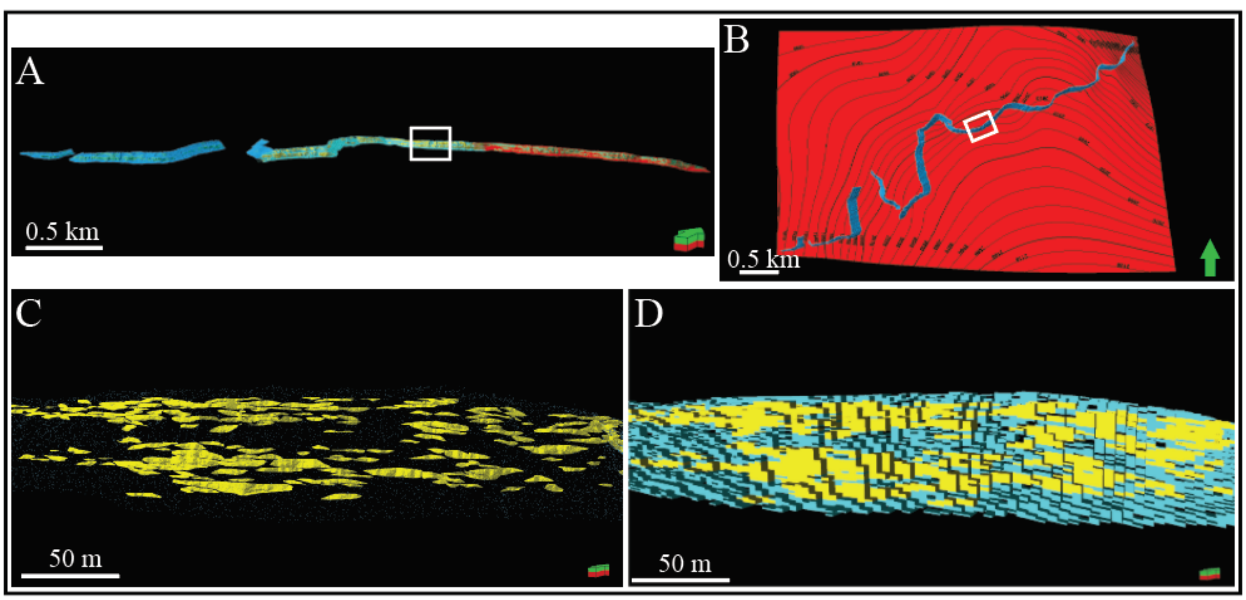


Figure 13. Clay Basin Petrel static model workflow. A. Three Clay Basin photogrammetric panels with background points (blue, green, and red) and channel points (yellow) were imported from Agisoft. B. Bottom (pictured) and top Trail structure maps were created with outcrop control (blue). C. Zoomed-in picture showing the background (blue) and channel (yellow) points. D. Background and channel points upscaled.

The 3-D facies modeling was done using the object modeling stochastic method. Object modeling allows for the characterization of geologic objects (in this case, channels) by defining distributions for the geometries and dimensions of the objects (Falivene et al., 2006). The object modeling parameters were taken from modern analogues (i.e., Susitna River, AK), outcrop photogrammetric data, and previous research on the Trail Member by Leary et al. (2015; Figure 14; Table 3). Specifically, the amplitude (sinuosity) and wavelength were determined by studying modern analogues of the Trail Member fluvial system. The Susitna River in southern Alaska is a predominately braided river that evolves into a meandering river downstream as the gradient shallows and sediment source is farther away (Leary et al., 2015; Figure 14). The Susitna River is sourced from the Alaskan Range and flows approximately 180 km into the Cook Inlet (Figure 14). Although this river is sourced from glacial water, there are several similarities to the Trail Member. Both rivers are close to mountain ranges and flow into the ocean within a couple hundreds of kilometers. Amplitude and wavelength measurements were made along the Susitna River using Google Earth. The channel width and thickness data for the model were retrieved from channel measurements made with Agisoft from the Trail Member outcrops. The orientation parameters were taken from Leary et al. (2015) in which paleocurrent data recorded showed a north-east trend flowing away from the Uinta Mountain uplift.

Petrel Model Input Parameters			
Model Dimensions	10m x 10m x 5m		
# of Layers	14		
NTG (%)	75		
	Min	**Average**	**Max**
Orientation (°)	60	75	90
Amplitude (m)	1000	1500	2000
Wavelength (m)	4000	5000	6000
Channel Width (m)	10	15	150
Channel Thickness (m)	5	7	13.5
Temporal Trends	Fit Curves to Histogram (see Figure 37)		

Table 3. Petrel 3-D object modeling input parameters.

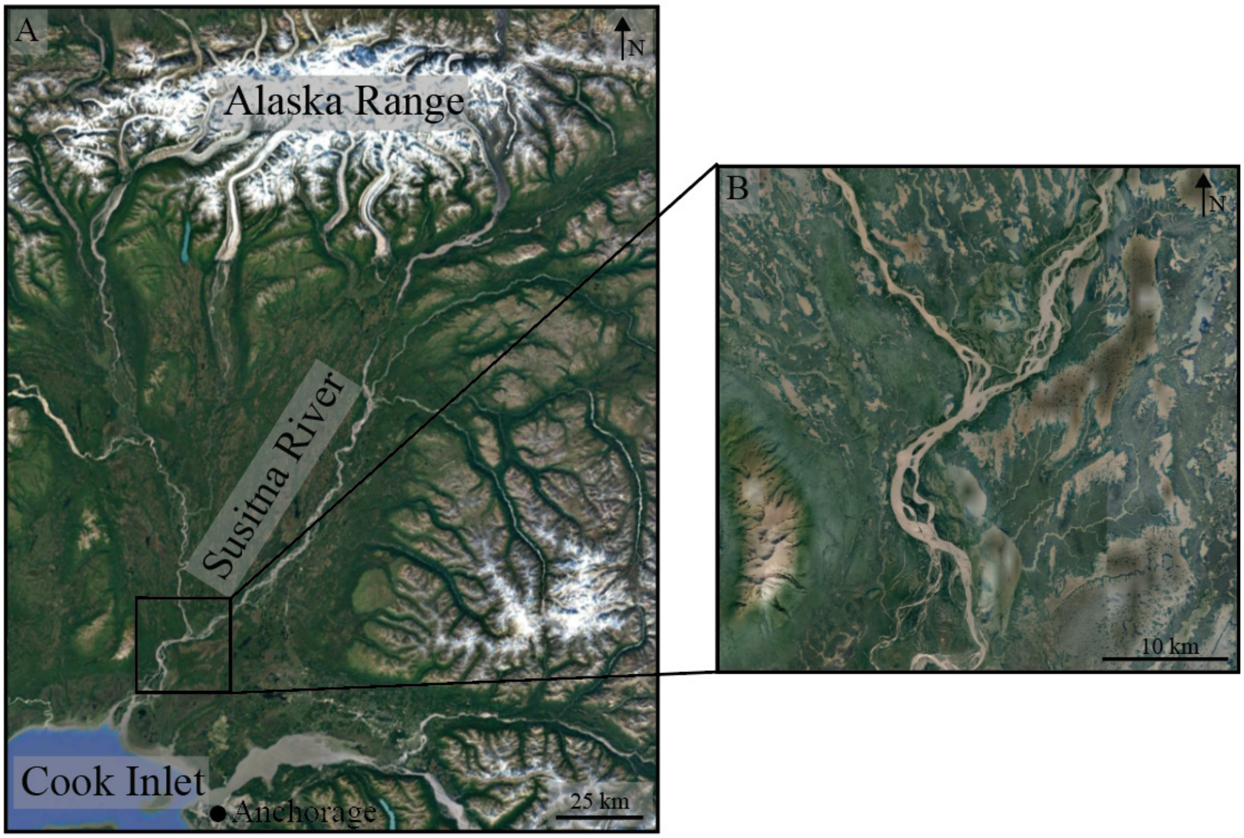


Figure 14. Susitna River modern analogue. A. The Alaskan Range sources the sediment for the Susitna River to transport towards the Cook Inlet. B. The Susitna River is a braided river that transitions to a more meandering river system down dip. Measurements (amplitude and sinuosity) were made in Google Earth for inputs in the Petrel model.

Results

Facies

A total of five main facies (Facies 1-5), along with two sub-facies (Facies 2a-3a), were observed from the three outcrop locations. Facies associations were identified and distinguished based on grain size and dominant sedimentary structures. Facies 1, 2, 2a, and 5 are characterized as reservoir sandstone facies while Facies 3, 3a and 4 are characterized as baffles or barriers to fluid flow. Twenty thin section were made from outcrop samples from the three field areas and Facies 1, 2 and 5. All facies exhibited rounded to sub-angular grains and point to linear grain contacts (Figure 15). Compositionally, quartz is the most dominant grain type, making up an average of 71.6% of all the outcrop samples analyzed. Quartz overgrowths are present in all samples and are much more common in the subsurface (Figure 15). Lithics are present and common in each of the samples making up an average of 28.4% in all outcrop samples. Feldspars were rare in all samples with an average of 0.2%. Forty-two outcrop samples were measured for porosity and forty-two outcrop samples were analyzed for permeability (Table 4). All of the reservoir facies (Facies 1, 2, and 5) exhibit similar average porosity values ranging from 24.2 % to 25.7%. Average permeability values varied throughout the reservoir sandstone facies ranging from 556.3 mD to 823.9 mD.

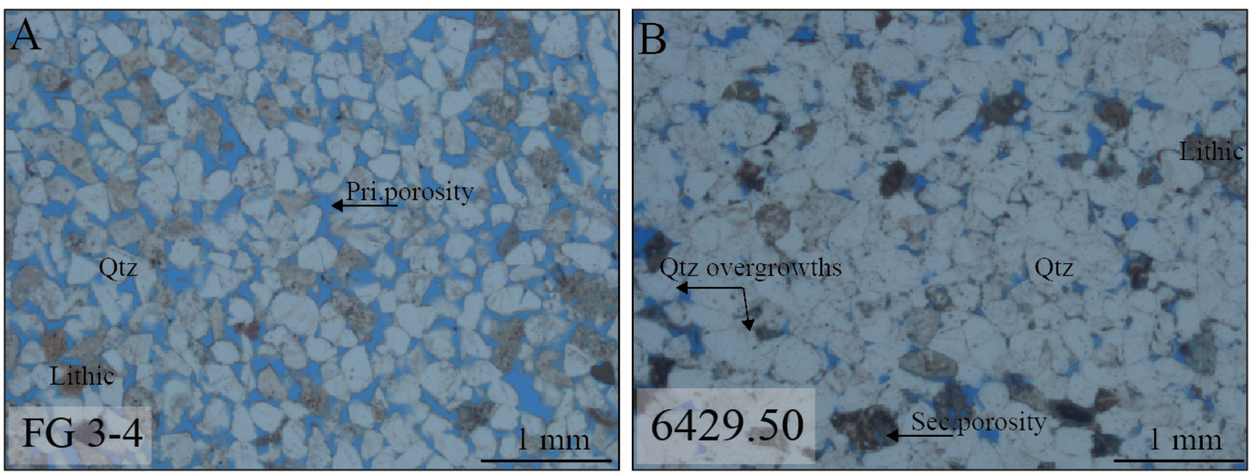


Figure 15. Two thin section photomicrographs of Facies 2 (fine- to coarse-grained trough cross-bedded sandstone) comparing outcrop and subsurface. A. Facies 2 photomicrograph from hand sample FG 3-4. Notations show examples of a quartz and lithic grain as well as primary porosity (intergranular) seen in blue between the grains. Grain contacts are dominantly point to linear. B. Facies 2 photomicrograph from the subsurface at 6429.5 ft. Notations show examples of a quartz and lithic grain, quartz overgrowths, and secondary porosity (intragranular) within a lithic grain. Burial and overgrowths have decreased primary porosity and increased linear to concave grain contacts.

Outcrop Porosity and Permeability Data			
Sample	**Facies**	**Porosity Average (%)**	**Permeability Average (mD)**
Flaming Gorge			
FG 1-2	2	22.9	84.26
FG 2-2	2	23.6	688.5
FG 2-3	2	22.0	227.6
FG 3-1	2	26.0	736.8
FG 3-2	2	24.4	686.4
FG 3-3	2	20.7	353.8
FG 3-4	2	22.9	650
FG 3-5	2	25.2	927
FG 3-6	1	23.4	606.8
FG 3-7	1	20.7	66.65
FG 4-1	2	21.7	790.4
Clay Basin			
CB 1-1	1	26.5	829.6
CB 1-2	2	30.1	
CB 2-1	1	24.7	334.4
CB 2-2	2	28.4	1050
CB 2-4	1	18.9	5.086
CB 3-1	2	30.4	803.8
CB 3-3	2	29.8	
CB 4-2	2	22.8	1700
CB 4-3	3	17.0	23.22
CB 5-1	1	24.5	1300
CB 5-2	1	24.7	933.2
CB 5-3	1	25.7	397.6
CB 5-4	2	27.7	2076
CB 5-6	1	26.6	798.8
CB 5-7	2	25.1	964
CB 5-8	5	22.2	49.82
CB 5-9	2	27.0	1040
CB 5-10	2	28.8	1024
CB 6-1	2	26.0	2416
CB 6-2	2	21.8	1318
CB 6-3	5	24.0	1362
Northern Colorado			
NC 1-2	2	25.5	49.96
NC 1-3	2	28.9	785
NC 1-5	2	27.2	40.56
NC 1-6	2	31.4	
NC 1-7	2		1040
NC 2-1	2	22.1	74.44
NC 2-2	1	26.3	290.4
NC 2-3	2	29.6	647
NC 2-5	2	21.9	676.6
NC 2-6	5	27.9	1060
NC 2-7	2	26.9	640.4
NC 2-9	2		36.46

Table 4. Porosity and permeability data for outcrop hand samples with facies association and field area location.

Within the subsurface (Canyon Creek Unit 64 core), Facies 1, 2, 3, and 4 were observed and described within the 117.8 ft (35.9 m) section of Trail Member. Thirty-six Trail Member thin sections were made available by Dominion Energy for point counting analysis. All facies exhibited rounded to sub-angular grains. Grain contacts shift to mainly linear and concave with rare point contacts suggesting higher compactional pressure (Figure 15). Compositionally, the subsurface Trail Member is the most mature with an average of 82.1% quartz and 17.9% lithics. Feldspars were rare in the subsurface as well (0.01% average). Lithic grains have undergone mechanical compaction surrounding nondeformed quartz grains, quartz overgrowths are much more prevalent, and these effects reduce primary intergranular porosity (Figure 15). Twelve porosity and eleven permeability values from Facies 2 and 3 of the Trail Member were made available. Average porosity values range from 5.8% to 8.2% with average permeability values ranging from 0.028 mD to 0.073 mD (Table 5). Overall, the core and subsurface respectively have much lower porosity and permeability values than that of the outcrop samples.

Whole Core Porosity and Permeability Data			
Depth (ft)	Facies	Porosity (%)	Permeability (mD)
Rusty Member			
6351.7	2	6.6	0.0066
6355	2	1.3	0.0013
6367.3	2	4.1	0.0076
6370.3	3	4.7	0.0064
6380.5	3	3.4	0.0005
6382.4	3	4.7	0.0044
Trail Member			
6413.1	3	5	
6424.3	2	9.1	0.131
6439.4	2	9.1	0.184
6442.4	2	8.8	0.13
6444.6	2	7.6	0.026
6449.3	2	5.9	0.031
6454.8	2	8.3	0.018
6471.7	2	9.1	0.024
6486.3	3	6.3	0.024
6502.4	2	8	0.037
6511.2	3	5.5	0.012
6523.8	3	6.4	0.049

Table 5. Porosity and permeability values from the interpreted Rusty and Trail Members from the Canyon Creek Unit 64 core with associated facies.

Facies 1: Massive Sandstone

Facies 1 is a fine- to medium-grained bleached massive sandstone unit (Figure 16). This facies is rarely exposed in the field areas, but is present in all locations and within the core. Rare soft-sediment deformation occurs within this facies as well as occasional weakly defined parallel bedding planes. Facies 1 is the most compositionally mature reservoir facies, with an average of 80% quartz and 20% lithics in all outcrop samples (Figure 17; Table 6). Thin section analysis shows that these sandstones are moderately- to well-sorted, grains are rounded to sub-angular, and grain contacts are point to linear (Figure 16). Pore types within Facies 1 are predominantly primary intergranular with some secondary porosity from leached lithic grains (Figure 16). Ten hand samples characterized as Facies 1 were collected and analyzed for both porosity and permeability. Facies 1 has a similar average porosity (24.2%) compared to the other reservoir facies (Facies 2 and 5; 25.7% and 24.7% respectively) and has an average permeability of 556.3 mD (Figure 18; Table 7).

In the Canyon Creek Unit 64 core, Facies 1 is present although it is not common. Facies 1 is similar to that found in outcrop as a fine-grained massive sandstone unit, however thin section analysis shows that burial forces decrease the amount of primary intergranular porosity present and grain contacts are dominantly linear to concave (Figure 16). Quartz overgrowths occur more frequently in quartz-rich areas and in the subsurface (Figure 16). Overall, Facies 1 is interpreted to have been deposited quickly as evidenced by the lack of sedimentary structures and could represent crevasse splays along the edge of a river system.

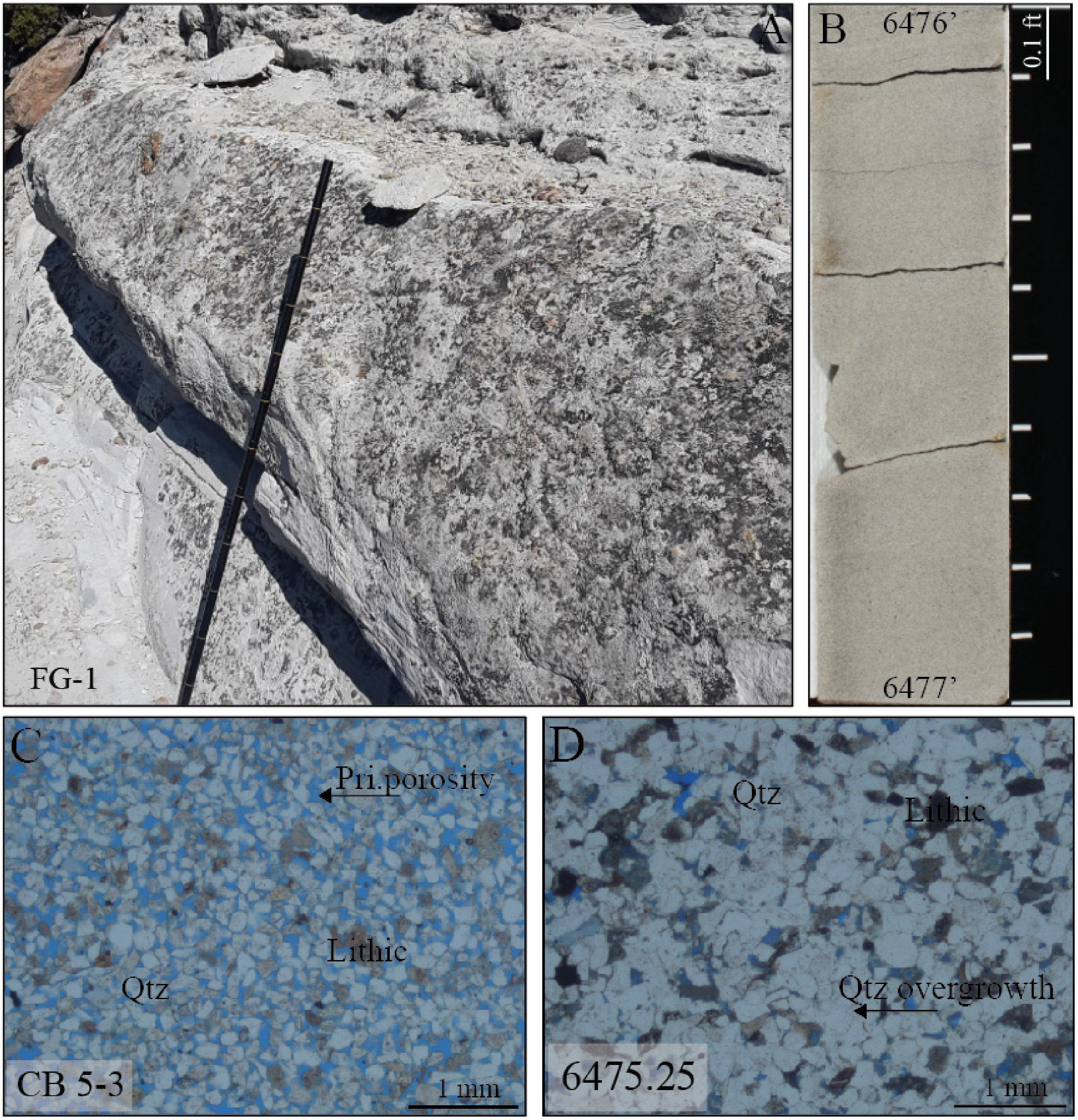


Figure 16. Examples of Facies 1 (massive fine-grained sandstone) from the outcrop and subsurface. Notations on photomicrographs show grain and porosity types and any diagenetic features. A. Picture taken at Flaming Gorge section 1 (FG-1) showing an outcrop example of Facies 1. Jacob staff for scale with each yellow mark representing 10 cm. B. Picture taken of the core (6476' – 6477') showing the nature of Facies 1 within the core. C. Photomicrograph taken from a hand sample taken from Clay Basin section 5 (CB-5). Note the well-sorted and quartz-rich nature of Facies 1. D. Photomicrograph taken from the core showing the reduced primary porosity and increased grain contact.

Outcrop Facies Composition Data					
QFL	Min (%)	Max (%)	Average (%)	Standard Deviation (%)	# of Samples
Facies 1					
Quartz	63.2	88.1	80.0	8.8	8
Lithics	11.9	36.8	19.9	8.8	8
Facies 2					
Quartz	44.9	79.1	66.9	10.6	10
Lithics	20.9	55.1	33.1	10.6	10
Facies 5					
Quartz	60.6	62.1	61.3	1.1	2
Lithics	37.9	39.4	38.7	1.1	2

Table 6. Outcrop facies composition (quartz and lithic) data from point counting of 20 thin sections. Feldspars were not included due to the rare appearance within the thin sections.

Outcrop Porosity Statistics				
Min (%)	Max (%)	Average (%)	Standard Deviation (%)	# of Samples
Facies 1				
18.9	26.6	24.2	2.57	10
Facies 2				
20.7	31.4	25.7	3.17	28
Facies 3				
17.0	17.0	17.0	0.00	1
Facies 5				
22.2	27.9	24.7	2.92	3

Outcrop Permeability Statistics				
Min (mD)	Max (mD)	Average (mD)	Standard Deviation (mD)	# of Samples
Facies 1				
5.1	1300.0	556.3	410.95	10
Facies 2				
36.5	2416.0	797.3	588.11	28
Facies 3				
23.2	23.2	23.2	0.00	1
Facies 5				
49.8	1362.0	823.9	687.20	3

Table 7. Outcrop porosity and permeability statistics based on facies associations.

Rusty Core Composition Data					
QFL	Min (%)	Max (%)	Average (%)	Standard Deviation (%)	# of Samples
Facies 2					
Quartz	72.8	90.9	81.1	6.1	7
Lithics	9.1	27.2	18.9	6.1	7
Facies 3					
Quartz	72.6	84.1	76.8	5.1	4
Lithics	15.9	27.4	23.2	5.1	4
Facies 4					
Quartz	71.6	75.8	74.0	2.0	4
Lithics	24.2	28.4	26.0	2.0	4
Total					
Quartz	71.6	90.9	78.1	5.6	15
Lithics	9.1	28.4	21.9	5.6	15

Trail Core Composition Data					
QFL	Min (%)	Max (%)	Average (%)	Standard Deviation (%)	# of Samples
Facies 1					
Quartz	75.3	89.9	79.8	6.0	5
Lithics	10.1	24.7	20.1	5.9	5
Facies 2					
Quartz	73.0	92.4	82.1	4.8	22
Lithics	7.6	27.0	17.9	4.8	22
Facies 3					
Quartz	77.5	90.3	83.4	3.8	9
Lithics	9.3	22.5	16.6	3.8	9
Total					
Quartz	73.0	92.4	82.1	4.7	36
Lithics	7.6	27.0	17.9	4.7	36

Table 8. Rusty and Trail Member composition data compiled from Canyon Creek Unit 64 core thin sections. Facies were identified and characterized from the core description (see Figure 10).

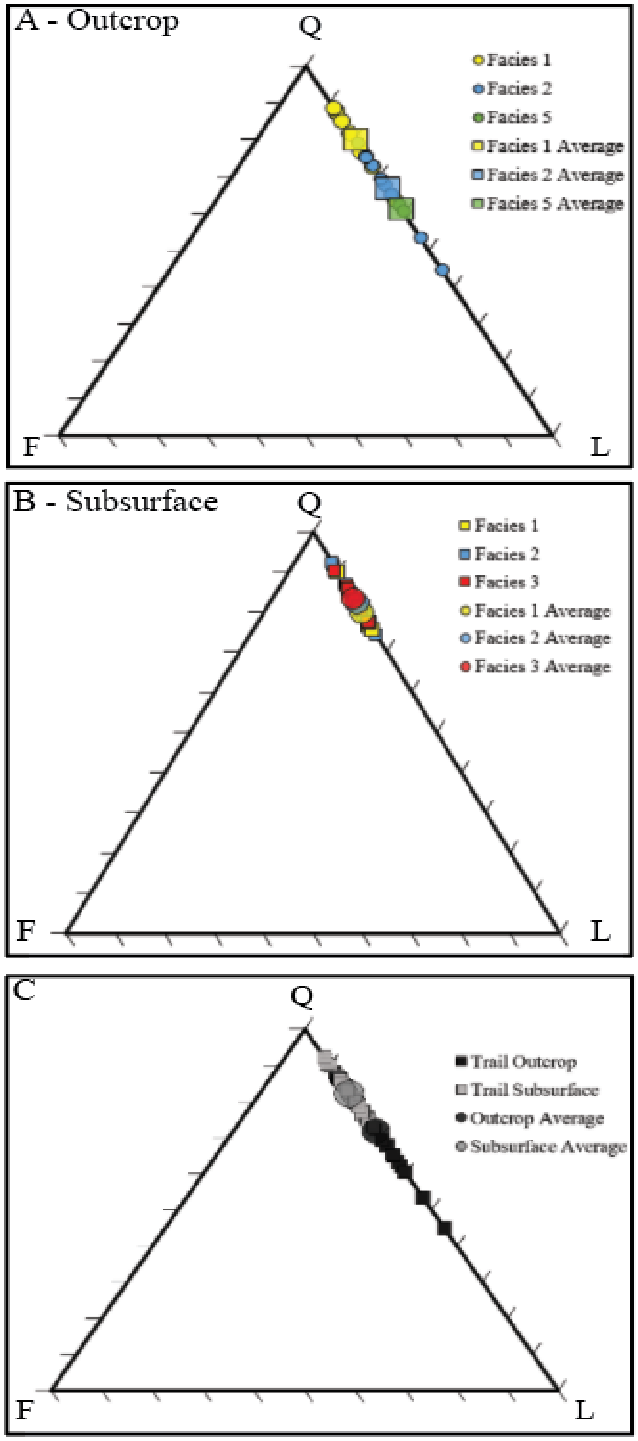


Figure 17. Facies QFL diagrams for both outcrop and subsurface composition data. A. QFL ternary diagram showing Facies 1, 2, and 5 from outcrop samples with each facies average. Facies 1 is the most compositionally mature, followed by Facies 2 and 5. B. QFL ternary diagram displaying Facies 1, 2, and 3 from subsurface samples with each facies average. B. QFL ternary diagram comparing the compositions of the Trail Member outcrop and subsurface. The subsurface is more compositionally mature than the outcrops.

Facies 2: Trough Cross-Bedded Sandstone

Facies 2 is a fine- to coarse-grained trough cross-bedded sandstone (Figure 19). It is the most dominant facies within the Trail Member and is observed throughout all field areas and in the subsurface. The trough cross-bedding exhibits both well- and weakly-defined bedding surfaces. These bedding surfaces are found throughout and the weakly-defined bedding surfaces are commonly associated with soft-sediment deformation. Soft-sediment deformation is common throughout Facies 2. Ripple-laminations are found throughout, and planar-laminations are rarely observed. Mud drapes are infrequently observed between or within channel forms. The geometry of the beds can vary from lensoidal (i.e. individual channels) to amalgamated lensoidal blocks of strata (i.e. multiple channels or channel clusters). The bottom of channels tend to cut into other preexisting channel or into muddier intervals and clay rip-up clasts are common along the base of the channels. Burrows (possibly *Teredolites*) were only seen once in Clay Basin (CB-2 section), while burrows occur more frequently in the Northern Colorado locality and in the core.

Compositionally, Facies 2 is less mature than Facies 1 with an average of 66.9% quartz and 33.1% lithics from ten outcrop samples (Figure 17; Table 6). Thin section analysis indicates that Facies 2 is poor- to moderately well-sorted, grains are rounded to sub-angular, and grain contacts are point to linear (Figure 19). Facies 2 porosity is characterized by mainly primary intergranular porosity with secondary intragranular porosity from the leaching of increased amounts of lithic grains (Figure 19). Twenty-eight outcrop samples were used in porosity and permeability measurements. Facies 2 has the highest average porosity at 25.7% and the average permeability records at 797.3 mD (Figure 18; Table 7).

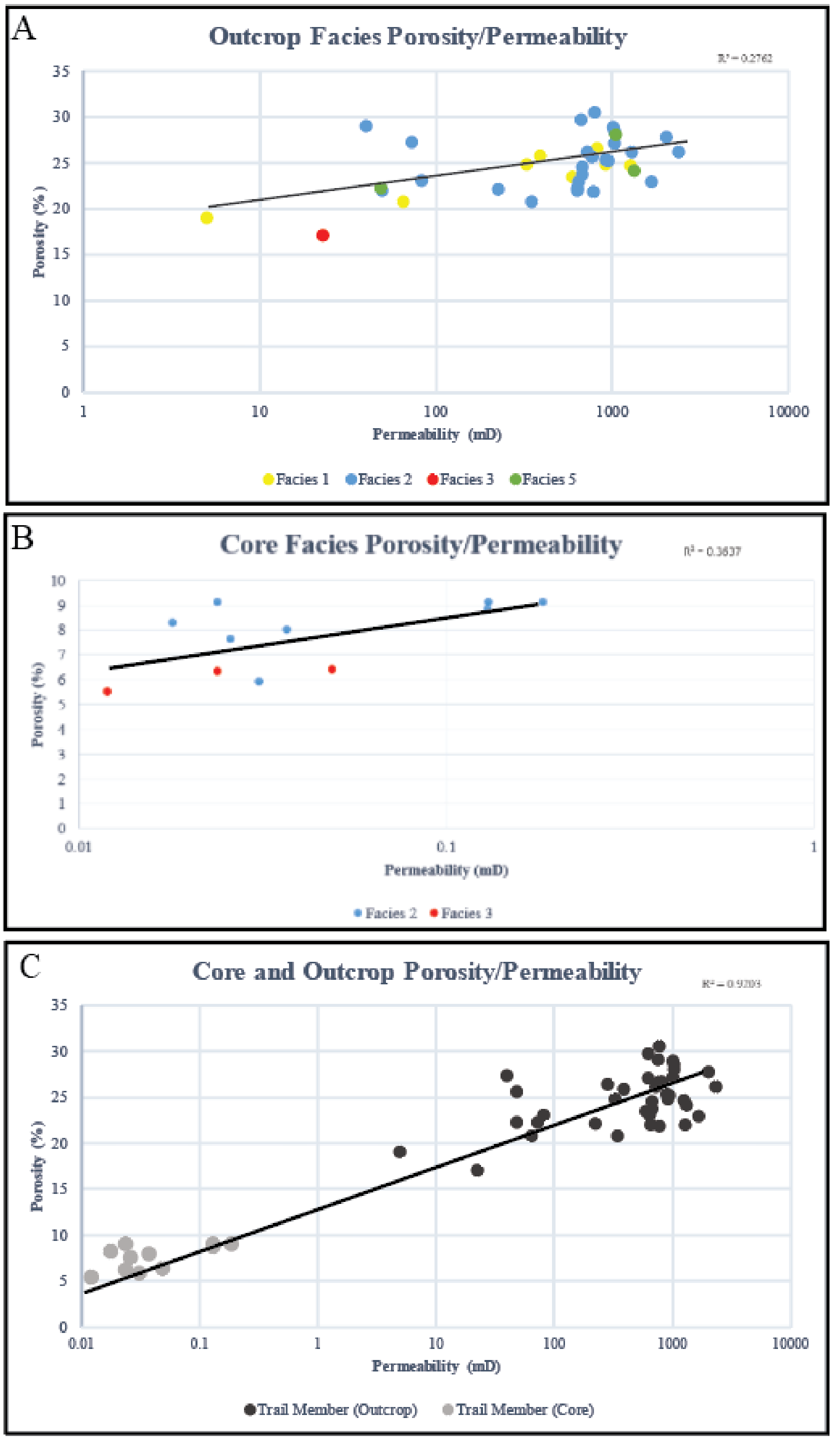


Figure 18. Facies porosity (%) versus permeability (mD) graphs. A. Outcrop porosity and permeability data based on facies. Facies 2, on average, has the highest porosity and permeability. B. Subsurface porosity and permeability data showing Facies 2, again, has the highest average. C. Trail Member outcrop and subsurface porosity and permeability values. Outcrop data has consistently higher porosity and permeability values than the core, which has good porosity, but poor permeability.

Within the subsurface, the Canyon Creek Unit 64 core exhibited well-defined trough cross-bedded and ripple-laminated sandstones with common mud drapes along the ripples (Figure 19). Burrows and coal fragments are present and clay rip-up clasts were deformed due to burial compaction. Compositionally, Facies 2 in the subsurface is more mature with an average of 82.1% quartz and 17.9% lithics (Figure 17; Table 8). Burial pressure has decreased the amount of primary intergranular porosity and grain contacts are dominantly linear to concave (Figure 19). Quartz overgrowths occur more frequently within areas of quartz-dominated grains. The average porosity and permeability from Facies 2 within the subsurface are 8.2% and 0.073 mD showing a decrease from the outcrop (Figure 18; Table 9). Facies 2 is interpreted as fluvial lateral accretion sets and fluvial channel dune sets.

Trail Member Subsurface Porosity Statistics				
Min (%)	Max (%)	Average (%)	Standard Deviation (%)	# of Samples
Facies 2				
5.9	9.1	8.2	1.10	8
Facies 3				
5.0	6.4	5.8	0.67	4

Trail Member Subsurface Permeability Statistics				
Min (mD)	Max (mD)	Average (mD)	Standard Deviation (mD)	# of Samples
Facies 2				
0.018	0.184	0.073	0.07	8
Facies 3				
0.012	0.049	0.028	0.02	3

Table 9. Subsurface Trail Member porosity and permeability statistics based on facies associations.

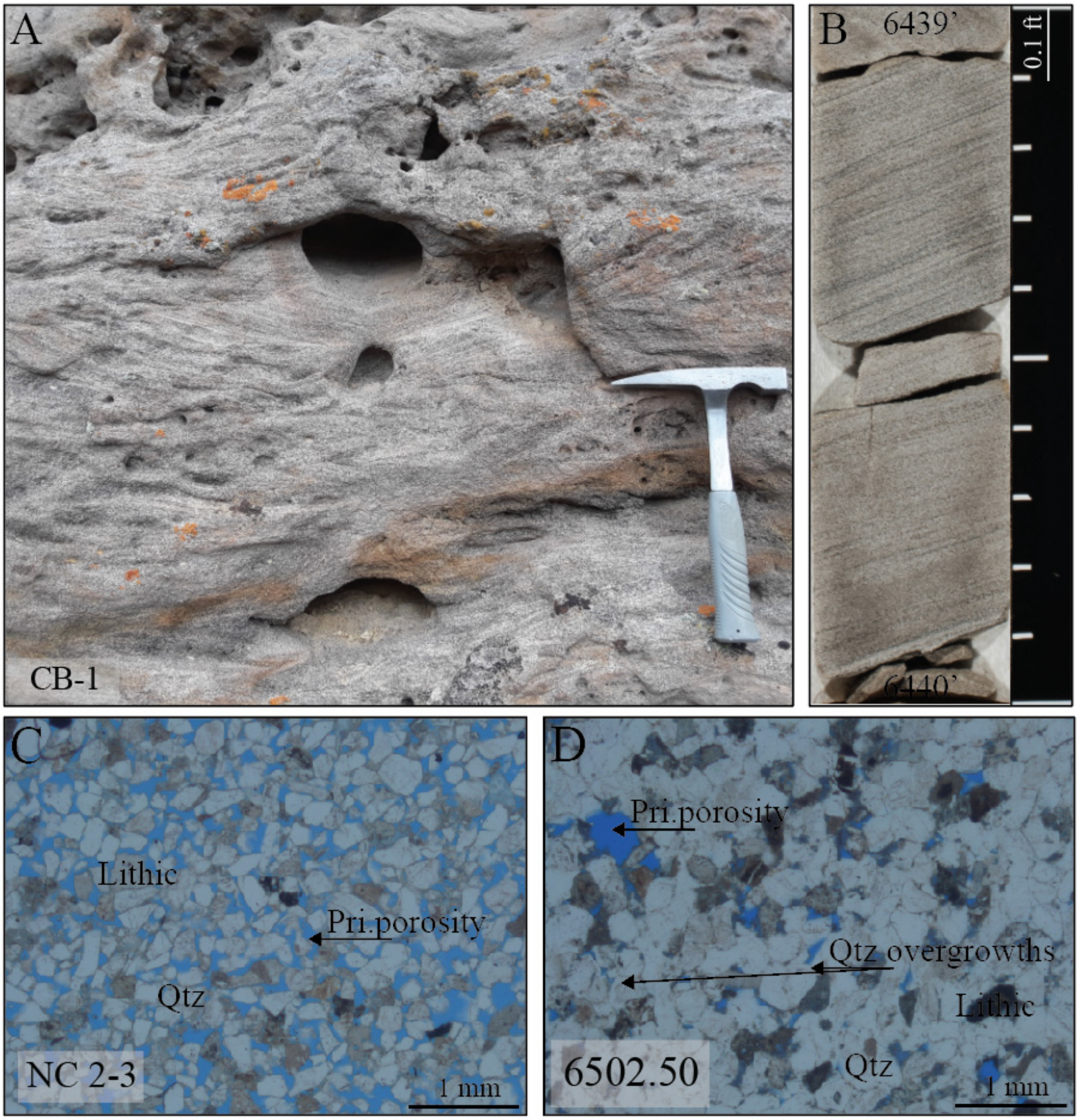


Figure 19. Examples of Facies 2 (fine- to coarse-grained trough cross-bedded sandstone) from the outcrop and subsurface. Notations on photomicrographs show grain and porosity types and any diagenetic features. A. Picture taken at Clay Basin section 1 (CB-1) of trough cross-beds and medium-sized grains. Rock hammer for scale. B. Picture taken of the core (6439 ft. – 6440 ft.) showing trough cross-beds in the subsurface. C. Photomicrograph taken from a hand sample taken in the Northern Colorado locality (NC-2). D. Photomicrograph taken from the core (6502.5 ft.) showing increased quartz overgrowths and decreased porosity.

Facies 2a: Organic-rich Trough Cross-Bedded Sandstone

Facies 2a is found exclusively in the Northern Colorado locality and can be distinguished from Facies 2 by the presence of terrestrial woody material, coal flecks, burrows, mud cracks, and larger clay rip-up clasts (Figure 20). Similar to Facies 2, Facies 2a is a fine- to coarse-grained trough cross-bedded sandstone. Individual channels seem to be more prevalent in this area. Additionally, two fossilized tree trunks (60 to 70 cm in diameter) were found in Northern Colorado (Figure 20). Facies 2a is interpreted as fluvial lateral accretion sets and fluvial channel dunes that cut into organic-rich overbank material. This fluvial system does not appear to avulse as frequently due to the increased amount of preserved organic material.

Figure 20. Examples of Facies 2a located in Northern Colorado. A. Mud cracks within a fine-grained sandstone. Pencil for scale. B. One of two 60-70 cm diameter fossilized tree trunks. C. Examples of woody material and casts. Pencil for scale.

Facies 3: Heterolithic Sandstone and Mudstone

Facies 3 is comprised of heterolithic interbedded sandstone and mudstone (Figure 21). This facies is rarely found in the Clay Basin and Flaming Gorge measured sections, but is found more commonly in Northern Colorado. The sandier beds commonly consist of fine-grained, parallel- to ripple-laminated sandstones that can be a few 10's of centimeters thick, and are rarely massive. The mudstone layers can also be a few 10's of centimeters thick and have parallel- to ripple-laminated throughout. Facies 3 seems to be laterally discontinuous as Facies 1 and Facies 2 are commonly eroding into the finer-grained layers. Porosity and permeability measurements from an outcrop sandstone interbed show the lowest average values from the outcrop samples at 17% and 23.2 mD (Figure 18; Table 7).

In the Canyon Creek Unit 64 core, heterolithic sandstone and mudstone is present, however a main difference is the extensive amount of deformation that exists in the core (Figure 21). Coal fragments are found throughout in an unorganized manner and stylolites are present. Composition data from the subsurface indicates that Facies 3 is the most mature with an average of 83.4% quartz and 16.6% lithics (Figure 17; Table 8). Thin sections indicate that Facies 3 is finer-grained and sorting varies from moderate to poor (Figure 21). Quartz overgrowths are not as common possibly due to the increased clay content. Subsurface average porosity and permeability values are lower than Facies 2 with 5.8% and 0.028 mD indicating a tight reservoir (Figure 18; Table 9). Due to the interbedded nature of Facies 3, it is interpreted to represent fluvial marginal deposits.

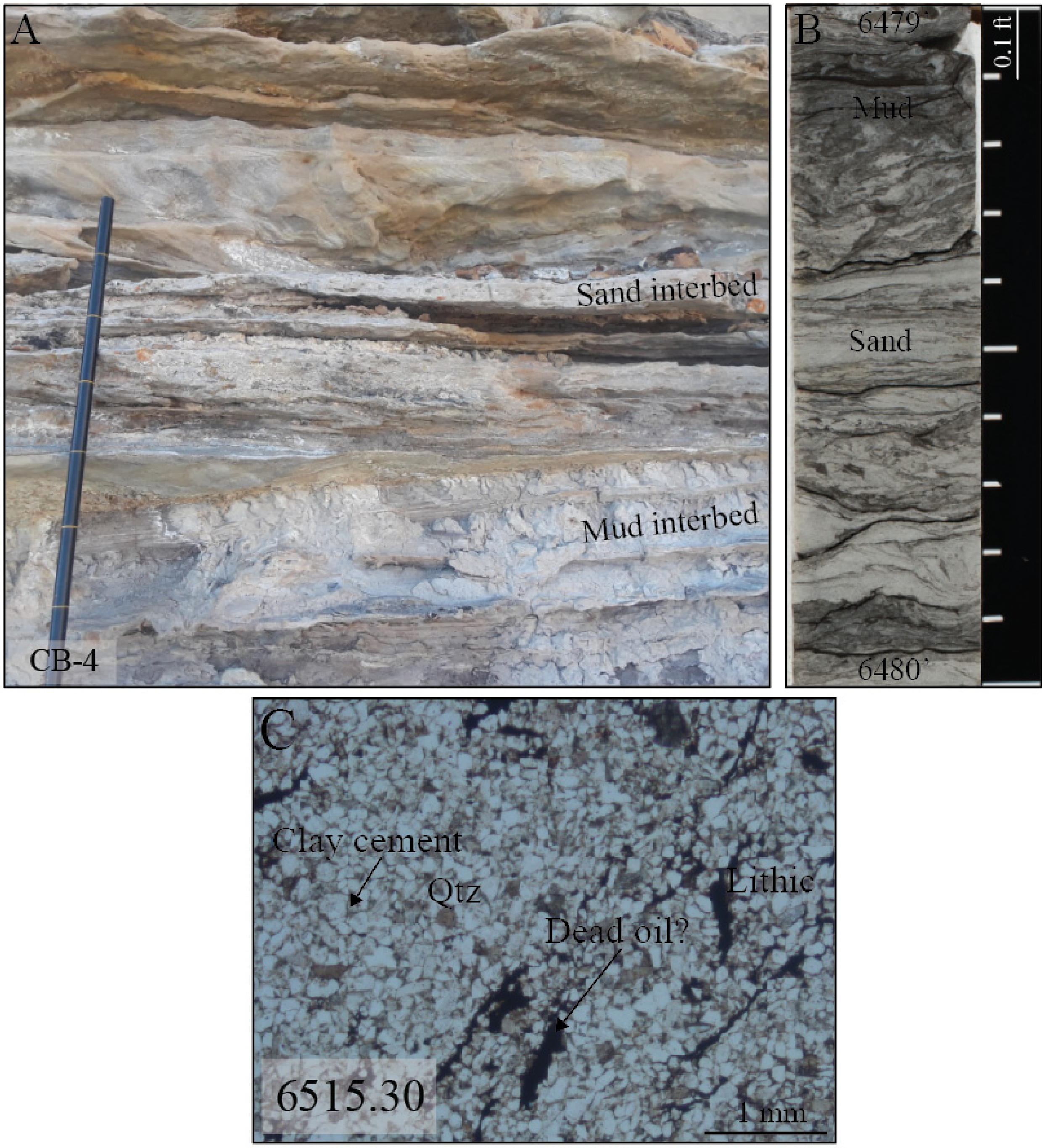


Figure 21. Examples of Facies 3 (Heterolithic sandstone and mudstone) from outcrop and subsurface. A. Picture taken at Clay Basin section 4 (CB-4) showing the sandstone and mudstone interbeds of Facies 3. Jacob staff for scale with each yellow mark representing 10 cm. B. Picture taken of the core (6479 ft. – 6480 ft.) showing sandstone and mudstone layers, however the layers are distorted. C. Photomicrograph taken from the core (6515.3 ft) showing no porosity, majority quartz grains, clay cement between the grains, and possible dead oil.

Facies 3a: Heterolithic Sandstone and Mudstone with Organics

Facies 3a is found in the Northern Colorado locality and within the core and can be distinguished from Facies 3 by the presence of organic material. Specifically, heterolithic sandstones and mudstones in Northern Colorado and the core have layers of woody material, such as wood casts and coal flecks with increased bioturbation. Facies 3a is interpreted to be a marginal fluvial deposit with increased organic material.

Facies 4: Mudstone

Facies 4 is a laminated sandy siltstone to mudstone (Figure 22). Covered slope in the measured sections is also categorized as Facies 4. The laminated sandy siltstone to mudstone beds vary in thickness from a few 10's of centimeters to several meters. Generally, it consists of parallel-laminated beds, and can contain ripple-laminations. Additionally, clay rip-up clasts and coal flecks are commonly found. The laminated sandy siltstone to mudstone is laterally continuous, but can be limited laterally due to Facies 1 and Facies 2 eroding into the finer-grained strata. The covered portions range in thickness from 1 m to 17.6 m with an average of 5 m and are laterally continuous. It is common to see isolated Facies 1 and Facies 2 sandy channels within the covered slopes. Facies 4 is found within the Canyon Creek Unit 64 core with thicknesses of a few 10's of centimeters (Figure 22). Facies 4 is interpreted to represent the overbank environment within a fluvial system.

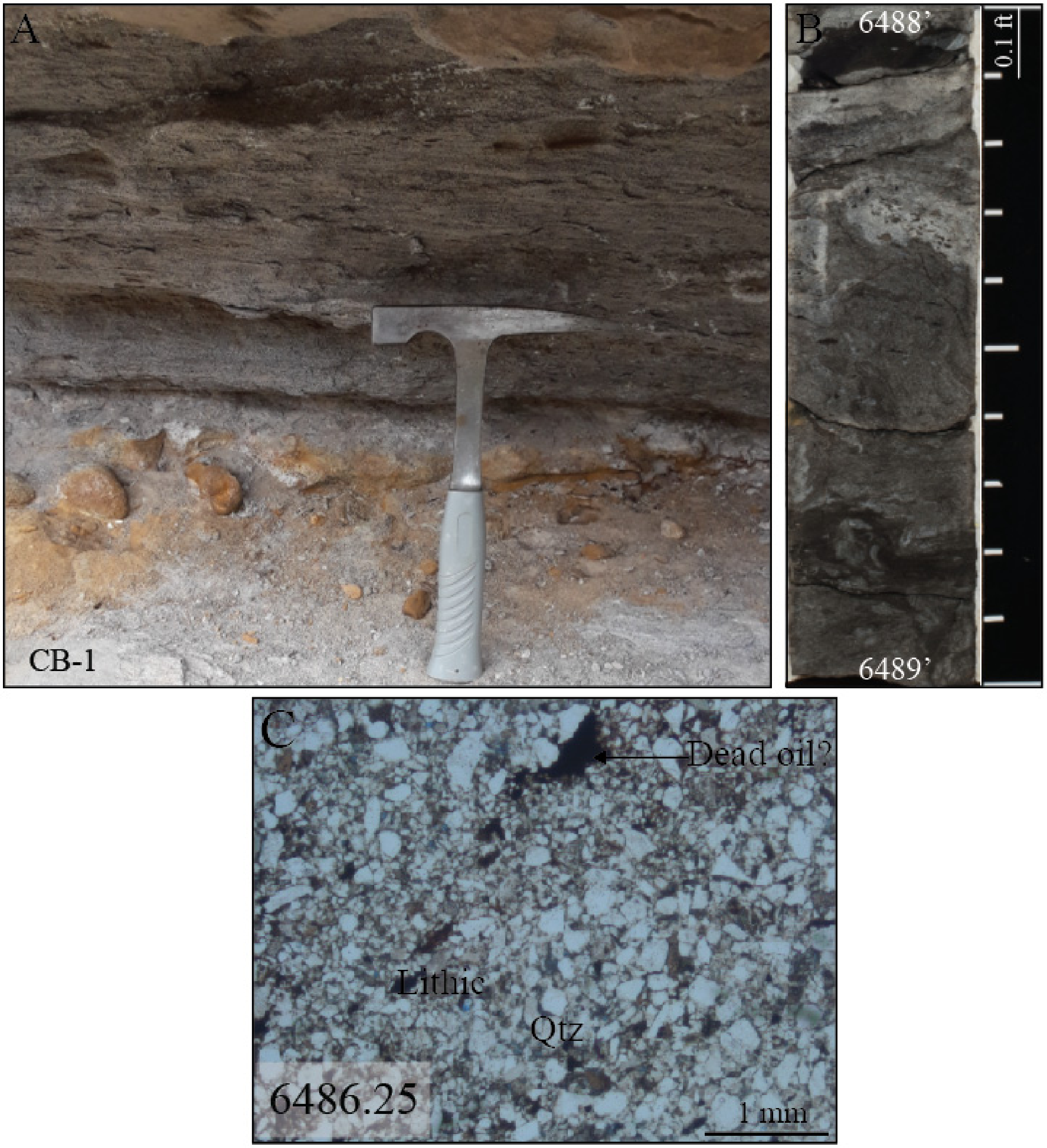


Figure 22. Examples of Facies 4 (laminated sandy siltstone to mudstone). A. Picture taken at Clay Basin section 1 (CB-1) showing the recessive nature of Facies 4 with a hammer for scale. B. Picture taken of the core (6488 ft – 6489 ft) showing the dark, finer-grained nature of Facies 4 with some distortion of the layers. C. Photomicrograph taken fron the core (6486.25 ft) showing very little porosity, majority of quartz grains, poorly sorted, clay cement in between the grains, and possible dead oil.

Facies 5: Unorganized Sandstone

Facies 5 is a highly unorganized medium- to coarse-grained sandstone. Facies 5 is found in all three field areas, but was not recognized in the core. Soft-sediment deformation including flame structures causes the highly unorganized nature of Facies 5 (Figure 23). Large (approximately 1-5 cm thick) mudstone and clay rip-up clasts are scattered throughout the facies, unlike the basal-concentrated rip-up clasts seen in Facies 2. The lateral and vertical extent of Facies 5 varies. Beds of Facies 5 range in thickness from 1.6 m to 7.1 m and can vary in lateral extent from a few meters wide to less than a meter wide. Compositionally, Facies 5 is the least mature facies with an average of 61.3% quartz and 38.7% lithics (Figure 17; table 6). Thin sections showed that Facies 5 is the least well sorted reservoir facies with moderate to poor sorting and porosity types include primary intergranular porosity and secondary intragranular porosity from leached lithic grains (Figure 23). Three outcrop samples indicate average porosity and permeability measurements of 24.7% and 823.9 mD (Figure 18; Table 7). Porosity averages are similar to Facies 1 and 2 and Facies 5 has the highest average permeability. The coarse-grained, unorganized nature of Facies 5 indicates high energy flow events potentially representing flooding events.

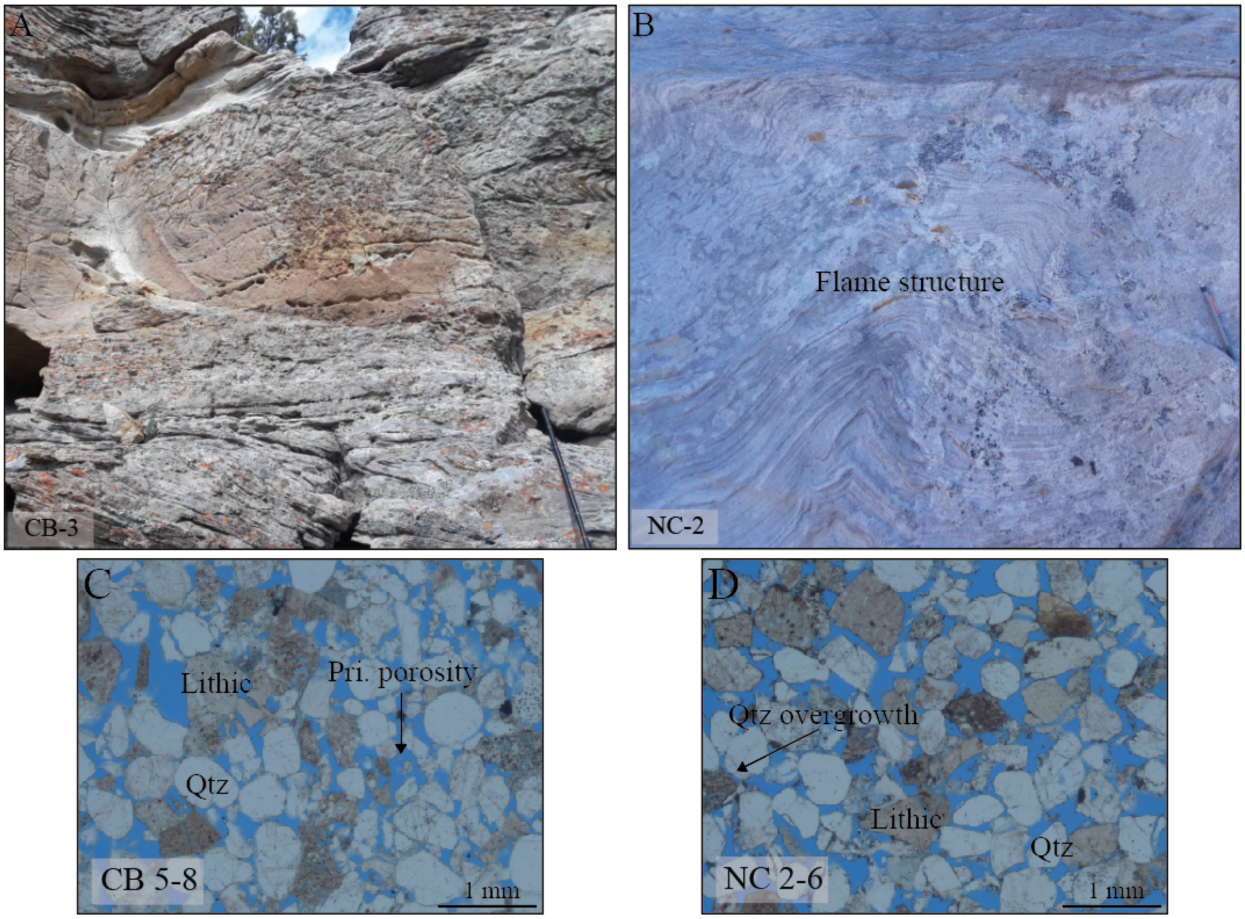


Figure 23. Examples of Facies 5 (medium- to coarse-grained highly unorganized sandstone). A. Picture taken at Clay Basin section 3 (CB-3) showing abundant soft-sediment deformation in a coarse-grained sandstone. Jacob staff for scale with each yellow mark representing 10 cm. B. Picture taken at Northern Colorado section 2 (NC-2) showing a flame structure within a medium-grained bleached sandstone. See pencil for scale. C. Photomicrograph taken of CB-5 thin section showing the poor sorting, quartz and lithic sandstone with primary porosity. D. Photomicrograph taken from NC-2 section showing poor sorting, minor quartz overgrowths, and mainly primary porosity.

Rusty Member

The upper portion (63.4 ft or 19.3 m) of the Canyon Creek Unit 64 core was described and interpreted to be the Rusty Member, which lies above the Trail Member (Figure 10). A total of fifteen thin sections were used to analyze Facies 2, 3, and 4 that were observed within the Rusty Member. Compositionally, the Rusty Member is slightly less mature than that of the Trail Member with an average of 78.1% quartz and 21.9% lithics (Figure 24; Table 8). Six porosity and permeability measurements were made available throughout the Rusty Member portion of the core. Average porosity (4.1%) and permeability (0.0045 mD) are both lower than that of the Trail Member core (Figure 24; Table 10).

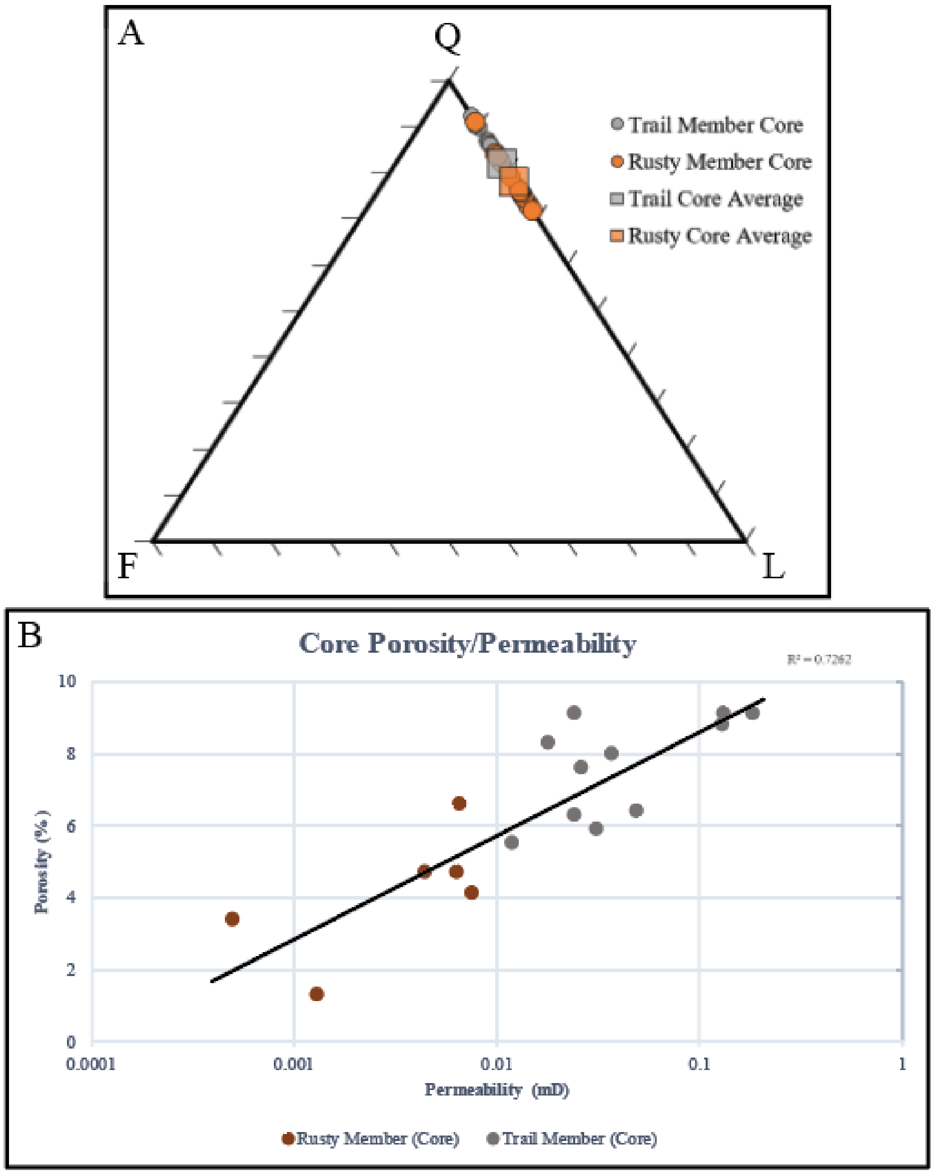


Figure 24. QFL diagram and porosity versus permeability graph showing Rusty and Trail Member data from the core. This data helped with the interpretation that the top portion of the core is the Rusty Member. A. QFL ternary diagram comparing the Trail and Rusty Members within the subsurface. The Trail Member is on average more compositionally mature than the Rusty Member. B. Porosity and permeability data from the Rusty and Trail Members. The Rusty Member has consistently lower porosity and permeability values.

Subsurface Porosity Statistics				
Min (%)	Max (%)	Average (%)	Standard Deviation (%)	# of Samples
Whole Core				
1.3	9.1	6.3	2.2	18
Rusty Member				
1.3	6.6	4.1	1.7	6
Trail Member				
5.0	9.1	7.4	1.5	12

Subsurface Permeability Statistics				
Min (mD)	Max (mD)	Average (mD)	Standard Deviation (mD)	# of Samples
Whole Core				
0.0005	0.1840	0.0408	0.0541	17
Rusty Member				
0.0005	0.0076	0.0045	0.0030	6
Trail Member				
0.0120	0.1840	0.0605	0.0588	11

Table 10. Subsurface Trail and Rusty Member porosity and permeability statistics.

Spatial Trends

Proximal Trail Member (Flaming Gorge and Clay Basin)

Flaming Gorge and Clay Basin are located north of the Uinta Mountain uplift and south of the Rock Springs uplift. Thin section analyses from outcrop samples of Facies 1, 2, and 5 indicate that Flaming Gorge is the least mature field area with an average of 64.3% quartz and 35.7% lithics (Figure 25; Table 11). Eleven Clay Basin samples averaged 73.8% quartz and 26.1% lithics (Figure 25; Table 11). Measured porosity and permeability data from Flaming Gorge show an average of 23% and 528.9 mD from eleven hand samples (Figure 26; Table 12). Clay Basin has higher average porosity and permeability values than Flaming Gorge with 25.4% and 969.8 mD averages from twenty-one samples (Figure 26; Table 12). Both porosity and permeability increase from Flaming Gorge to Clay Basin. Net-to-Gross (NTG) shows the amount of reservoir quality sand (net) versus the total thickness of the Trail Member interval. NTG was calculated for each measured section by defining Facies 1, 2, and 5 as reservoir sandstones (net) and Facies 3 and 4 as mud (non-net). Flaming Gorge and Clay Basin have similar average NTG of 75%, with a range of 63.3% (CB) to 85.1% (FG; Figure 27; Table 13).

Outcrop Location Composition Data					
QFL	Min (%)	Max (%)	Average (%)	Standard Deviation (%)	# of Samples
Flaming Gorge					
Quartz	53.4	75.4	64.3	9.0	4
Lithics	24.6	46.6	35.7	9.0	4
Clay Basin					
Quartz	44.9	87.1	73.8	12.5	11
Lithics	12.9	55.1	26.1	12.5	11
Northern Colorado					
Quartz	60.6	88.1	72.4	11.1	5
Lithics	11.9	39.4	27.6	11.1	5

Table 11. Composition data from outcrop samples based on field locations.

Outcrop Porosity Statistics				
Min (%)	Max (%)	Average (%)	Standard Deviation (%)	# of Samples
Flaming Gorge				
20.7	26.0	23.0	1.73	11
Clay Basin				
17.0	30.4	25.4	3.50	21
Northern Colorado				
21.9	31.4	26.8	3.05	10
Total				
17.0	31.4	25.1	3.26	42

Outcrop Permeability Statistics				
Min (mD)	Max (mD)	Average (mD)	Standard Deviation (mD)	# of Samples
Flaming Gorge				
66.7	927.0	528.9	295.62	11
Clay Basin				
5.1	2416.0	969.8	655.27	19
Northern Colorado				
36.5	1060.0	485.5	401.27	11
Total				
5.1	2416.0	721.6	556.87	41

Table 12. Outcrop porosity and permeability statistics based on field locations.

Outcrop NTG Data			
Section Name	Gross Thickness (m)	Net Thickness (m)	NTG (%)
Flaming Gorge			
FG-1	66.7	53.0	79.5
FG-2	77.9	66.3	85.1
FG-3	78.6	62.4	79.4
FG-4	74.1	47.6	64.2
Clay Basin			
CB-1	59.0	47.4	80.3
CB-2*	38.1	30.1	79
CB-3	45.2	37.2	82.3
CB-4*	48.2	30.5	63.3
CB-5	66.0	48.7	73.8
Northern Colorado			
NC-1	92.5	81.9	88.5
NC-2	80.9	70.2	86.8

Outcrop NTG (%)			
Min	Max	Average	Standard Deviation
Flaming Gorge			
64.2	85.1	77.1	8.97
Clay Basin			
63.3	82.3	76.2	8.72
Northern Colorado			
86.8	88.5	87.7	1.20
Total			
63.3	88.5	78.8	8.61

Table 13. Outcrop NTG data and statistics based on field locations.

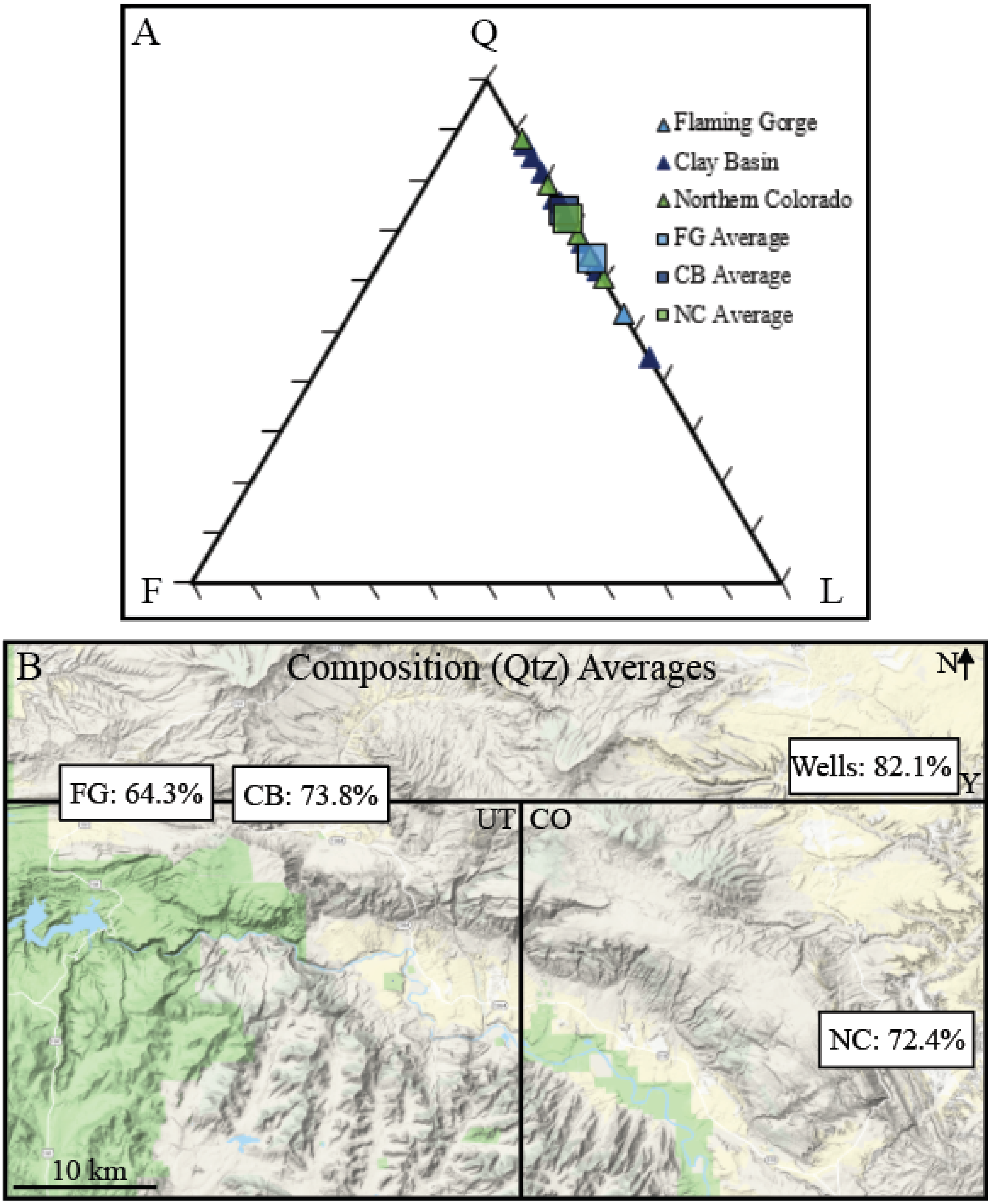


Figure 25. Spatial composition data for the four localities (Flaming Gorge, Clay Basin, Northern Colorado, and wells). A. QFL ternary diagram comparing location composition data. Averages of sandstone Facies 1, 2, and5 are the least mature in Flaming Gorge followed by Northern Colorado and Clay Basin. B. Quartz averages show an increase towards the basin, specifically towards the wells.

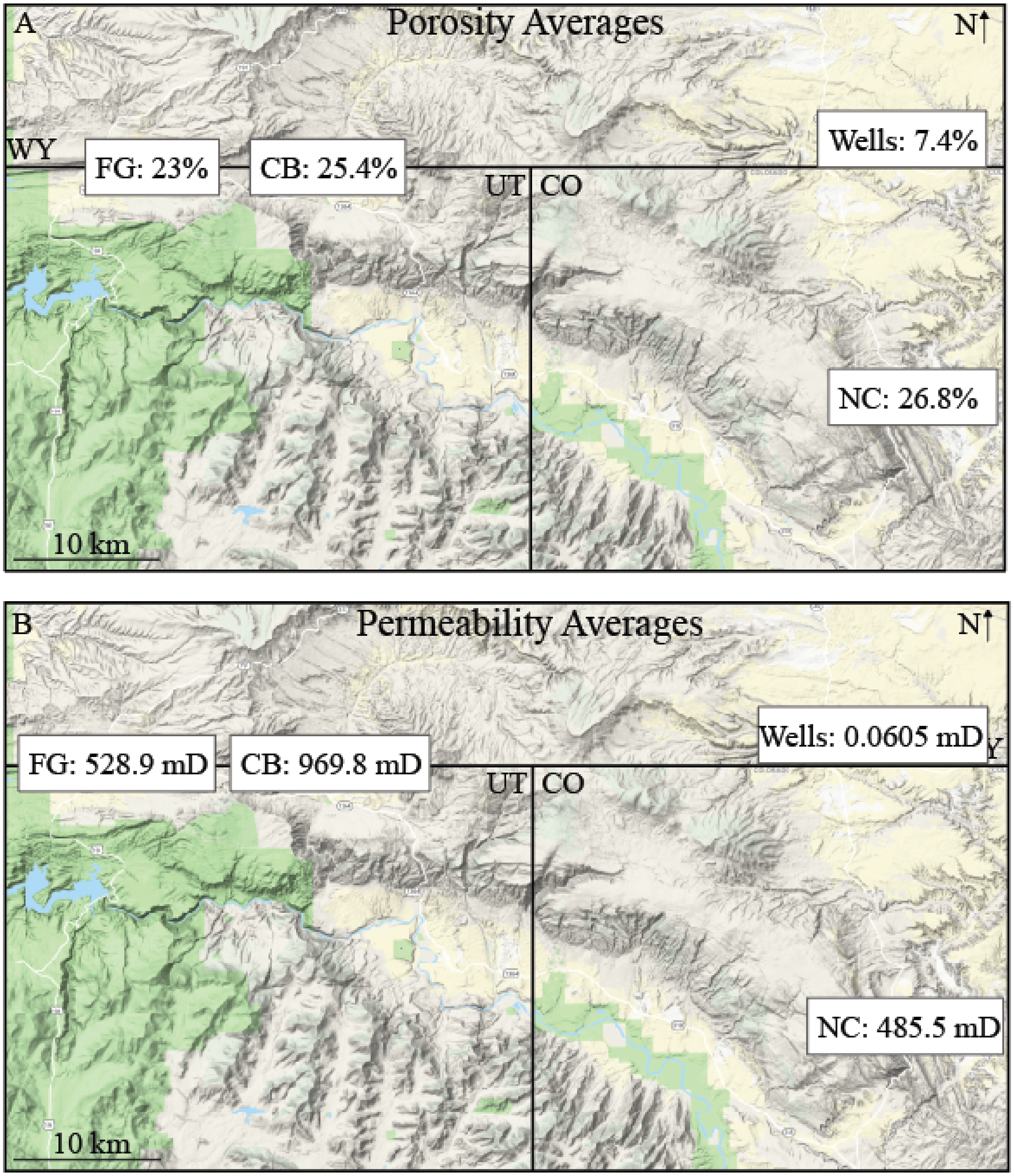


Figure 26. Maps showing porosity and permeability locality averages along depositional dip. A. Porosity averages for each locality. Outcrop locations show a general increasing trend towards the basin, while the wells have a significantly lower porosity average. B. Permeability averages for each locality. There is a decreasing trend towards the basin in permeability. The well data shows a very tight reservoir.

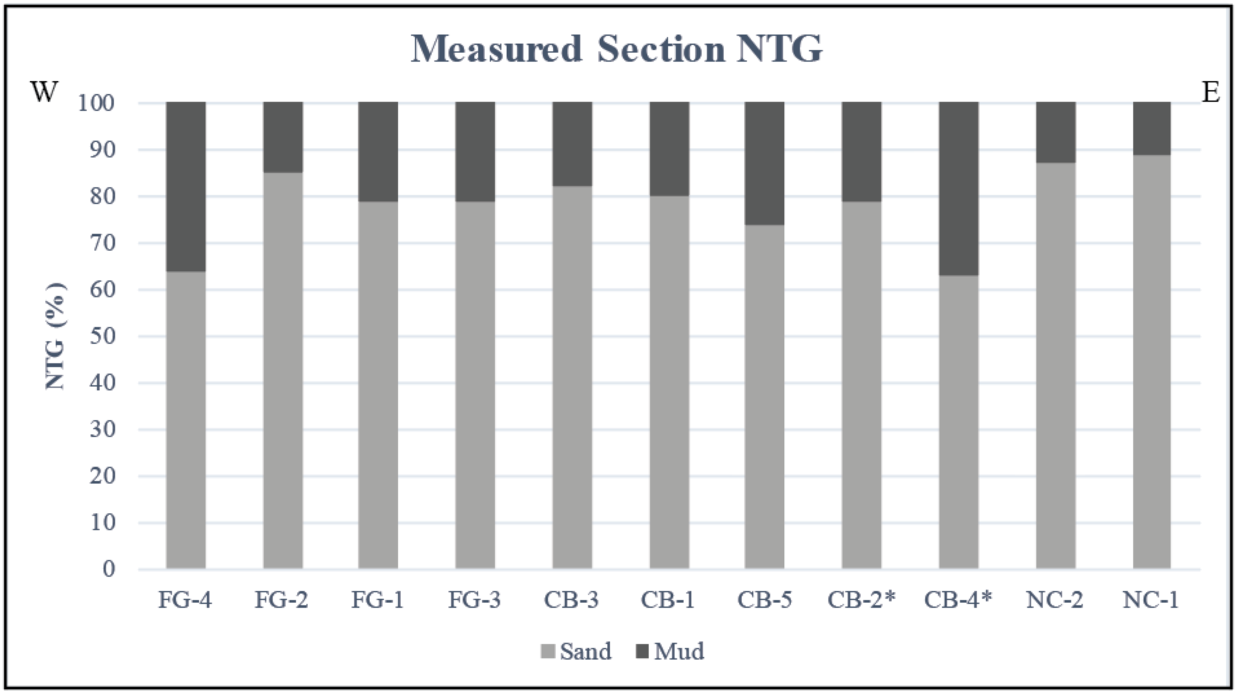


Figure 27. Measured section NTG panel from the most proximal section (FG-4) towards the basin (NC-1) over approximately 65 km. Sand was calculated by assigning Facies 1, 2, and 5 as reservoir sandstones and Facies 3 and 4 as mudstones or barriers to flow. CB-2 and CB-4 are not complete sections of the Trail Member. Refer to Figures 3 and 8 for location maps.

Photogrammetric panels allow for observations of fluvial architecture on a broader scale and for channel sandstones to be outlined and measured. To assist in processing time, three photogrammetric panels were created for Clay Basin. In Clay Basin, 3,115 channels were outlined along the 5.8 kilometer transect. Channel depths ranged from 0.3 m to 13.5 m with an average of 1.8 m (Figure 28; Table 14). Channel widths ranged from 2.1 m to 148 m with an average of 13.1 m (Figure 28; Table 14). Channels were categorized as high versus low accommodation based on their stacking patterns in the field, which is consistent with a division based on depth-to-width ratio. A depth-to-width ratio of less than 0.10 resulted in the channel points being categorized as low accommodation, while a ratio greater than 0.10 was categorized as high accommodation. The 445 channels classified as low accommodation in Clay Basin ranged in channel depths from 0.3 m to 11.4 m with an average of 1.58 m (Table 14). The widths for low accommodation channels ranged from 4.3 m to 148 m with an average of 19.2 m (Table 14). The 2,670 channels categorized as high accommodation in Clay Basin ranged in channel depths from 0.4 m to 13.5 m with an average of 1.84 m (Table 14). Channel widths for high accommodation in Clay Basin ranged from 2.1 m to 63.3 m with an average of 12.1 m (Table 14). Overall, low accommodation channels had a lower average in channel depth, but a higher average in channel widths. Additionally, locations of low and high accommodation channels based on this channel did not result in a clear trend.

Clay Basin Channel Depth			
Min (m)	Max (m)	Average (m)	Standard Deviation (m)
Low Accommodation			
0.32	11.4	1.6	1.1
High Accommodation			
0.37	13.5	1.8	1.0
All Channels			
0.32	13.5	1.8	1.0

Clay Basin Channel Width			
Min (m)	Max (m)	Average (m)	Standard Deviation (m)
Low Accommodation			
4.3	148.0	19.2	13.5
High Accommodation			
2.06	63.3	12.1	6.7
All Channels			
2.06	148.0	13.1	8.4

Table 14. Clay Basin channel depth and width statistics from the channels that were identified and measured within Agisoft.

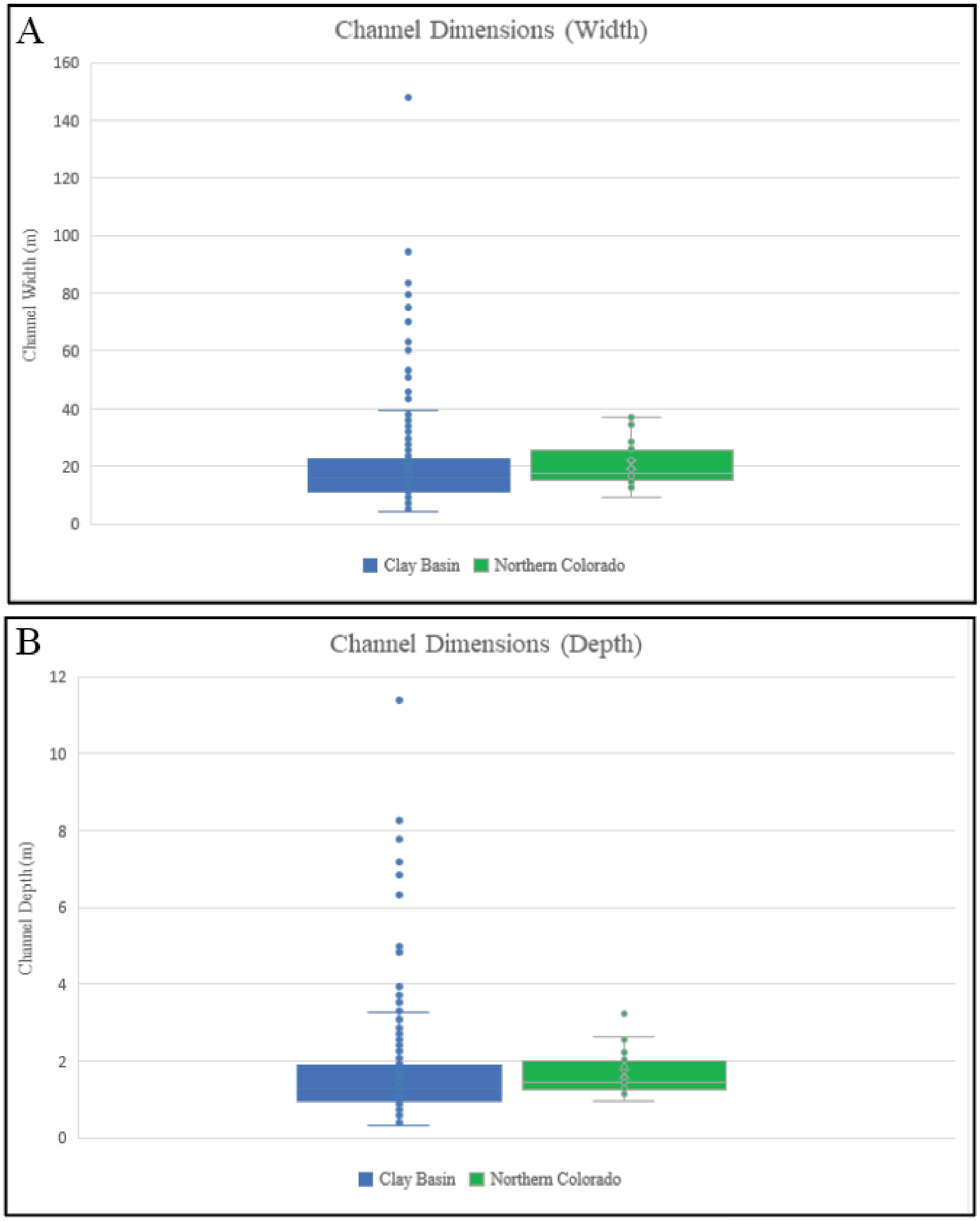


Figure 28. Channel dimension (width and depth) range charts comparing Clay Basin and Northern Colorado. A. Channel width range plots show Clay Basin on average has smaller channel widths, however, the range is much larger than for Northern Colorado. B. Clay Basin and Northern Colorado have similar channel depths with Clay Basin having a larger range in values.

From the photogrammetric panels, it is observed that Clay Basin has a high NTG and the sandier areas create large sandstone cliffs, while muddier areas form slopes. In addition, the photogrammetry assisted in definition of three zones showing temporal changes within the Trail Member at Clay Basin (Figure 29). The Upper and Lower Trail zones of the Trail Member are characterized by laterally continuous amalgamated sandstone units, while the Middle Trail zone one of the Trail Member is characterized by vertically stacked, amalgamated channels that are bounded laterally by muddier sediments represented by slopes on the scale of 100s of meters wide (Figure 29). Twelve thickness measurements for each of the three zones were made using Agisoft in four main locations throughout Clay Basin. The Lower Trail zone ranges in thickness from 13 m to 30.2 m with an average of 21.3 m (Table 15). The Middle Trail zone ranges in thickness from 11.4 m to 23.3 m with an average of 17.7 m (Table 15). The Upper Trail zone ranges in thickness from 12 m to 22.6 m with an average of 18 m (Table 15). Additionally, measurements were made in the Middle Trail zone to determine widths of vertically stacked channel complexes and widths of muddier intervals. The sand-rich vertically stacked channel intervals within the Middle Trail zone ranged from 205 m to 290 m with an average of 244 m (Table 15). The mud-rich intervals within the Middle Trail zone ranged from 119 m to 335 m with an average of 224 m (Table 15). The mud-rich intervals have a larger variation in width.

The three Clay Basin point cloud sets, which included both channel and background points, were imported from Agisoft to Petrel. The imported channel and background data were defined as sand (channel points) and shale (background points) in order to define the original point set NTG, which for Clay Basin is 31.3%. The original point set was then upscaled to the 10 m x 10 m x 5 m model grid and the resulting NTG increased to 60.5%. Based on NTG values from measured sections in Clay Basin, a 75% NTG was input into the original facies model parameters. The resulting model had a final NTG value of 74.5% (Figure 30).

Petrel data analysis shows the distribution of sand (channel) versus shale (background) within each of the 14 defined zones (each zone is 5 m thick). This allows for the observation of any field area-wide temporal trends. In the upscaled 10 m x 10 m x 5 m grid, the 14 zones showed the same Upper and Lower Trail sand-rich zones that were defined in the photogrammetry reflected by higher sand proportions (Figure 31). The Middle Trail zone shows a lower sand-to-shale proportion (NTG) also seen in the photogrammetry. The facies model data analysis also shows the general trend of sand-rich strata in the Upper and Lower Trail zones with less sand in the Middle Trail; however, the model smoothed that curve, so that it is not as prominent as in the upscaled cell data analysis (Figure 31).

Clay Basin Zone Thickness		
Upper Trail Zone (m)	**Middle Trail Zone (m)**	**Lower Trail Zone (m)**
Clay Basin West 1		
15.1	21.2	22.2
15.7	23.2	30.2
Clay Basin West 2		
12	22.5	13
21	16.6	16.1
20	16.1	19.2
Clay Basin West 3		
20.2	14.7	20.5
21.3	15.6	20.2
20.8	17	21.6
22.6	16.9	20.8
Clay Basin East 1		
17.1	11.4	26.3
12.9	23.3	22.3
17.7	13.6	23

Clay Basin Middle Trail Zone Widths	
Sand-rich Intervals (m)	**Mud-rich Interval (m)**
Clay Basin West 1	
	296
Clay Basin West 3	
238	117
Clay Basin East 1	
290	147
205	335

Table 15. Clay Basin Upper, Middle, and Lower Trail zone measurements. See figure 29 for a location map. Width measurements were taken only in the Middle Trail.

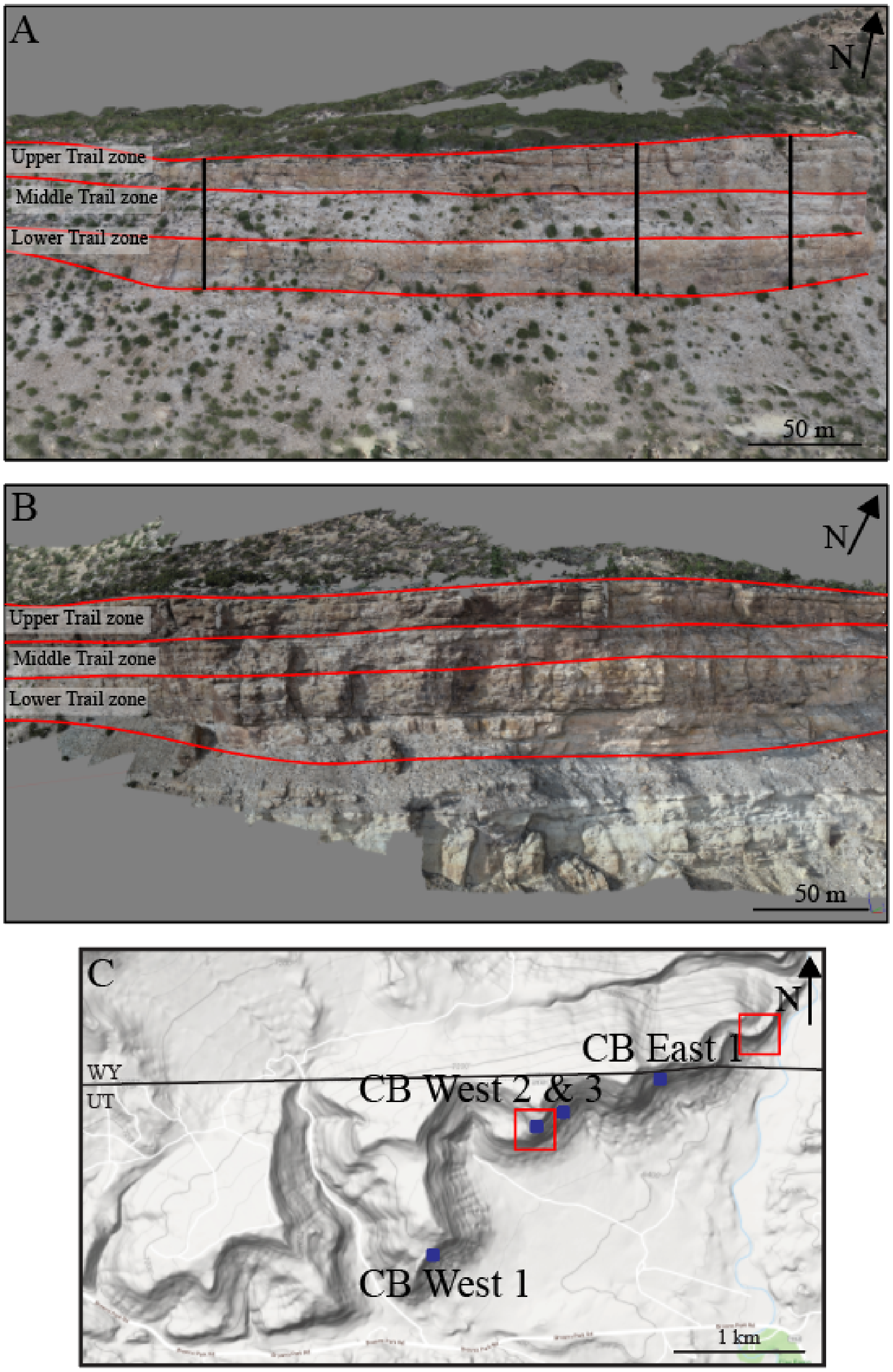


Figure 29. Pictures from Clay Basin photogrammetric panels with annotations showing the Upper, Middle, and Lower zones. Black lines indicate where thickness and width measurements of the three zones were taken. A. Red lines indicate boundaries for the three zones. In this area, the Middle Zone is represented by a slope-former. B. In this area at Clay Basin, the Middle Zone is represented by a cliff-former of vertically stacked channels. C. Location map of the four areas were measurements were taken of the three zones with outlined boxes showing the locations of the panels shown in A and B.

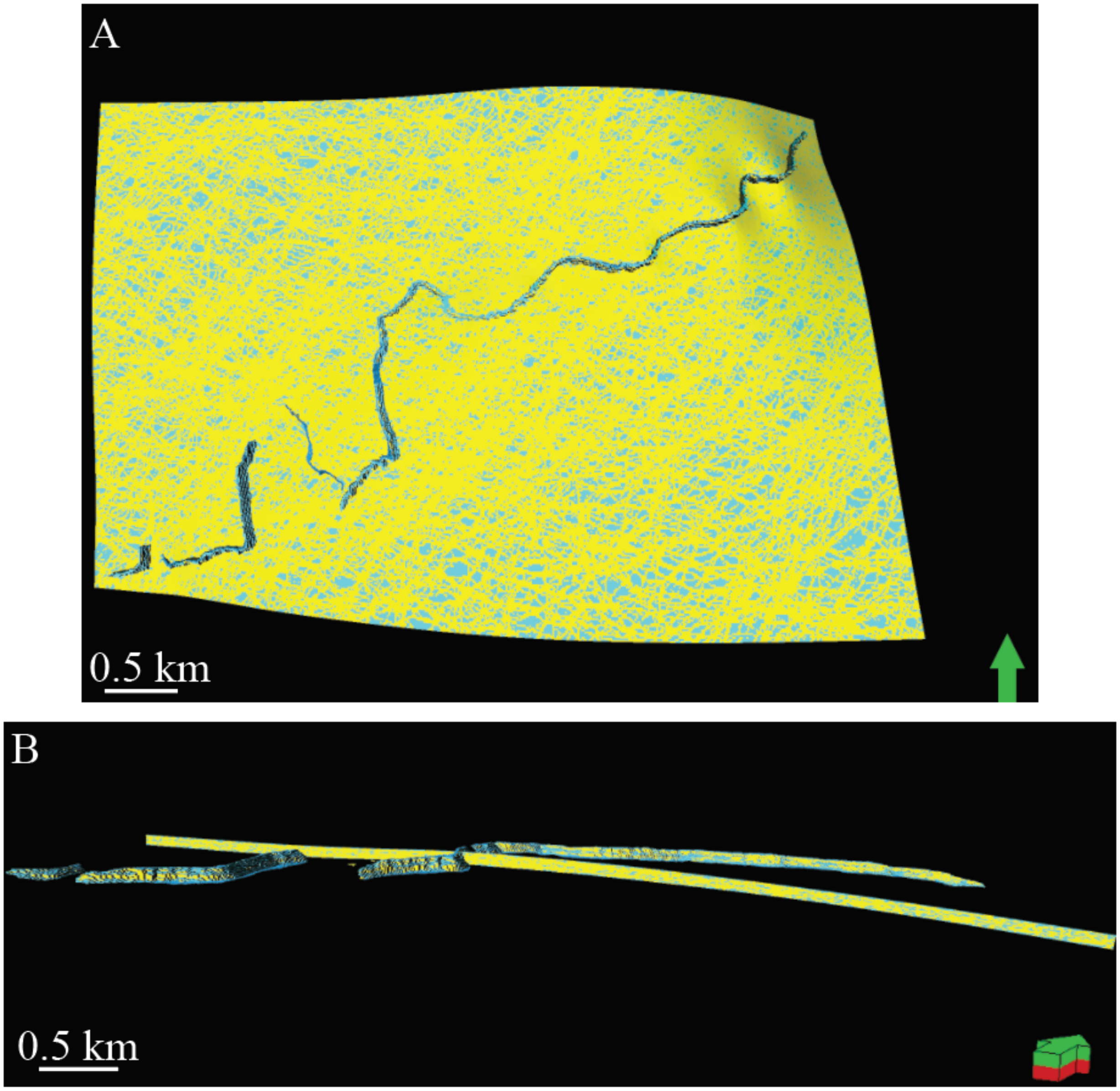


Figure 30. Clay Basin 10 m x 10 m x 5 m Petrel 3-D model with a 74.5% NTG. Background facies or shale is blue, while channels or sandstone are yellow. A. Map view images showing the outcrop control and fluvial sandstone channels. B. Cross sectional view showing outcrop control and how the sand behave spatially from the outcrop.

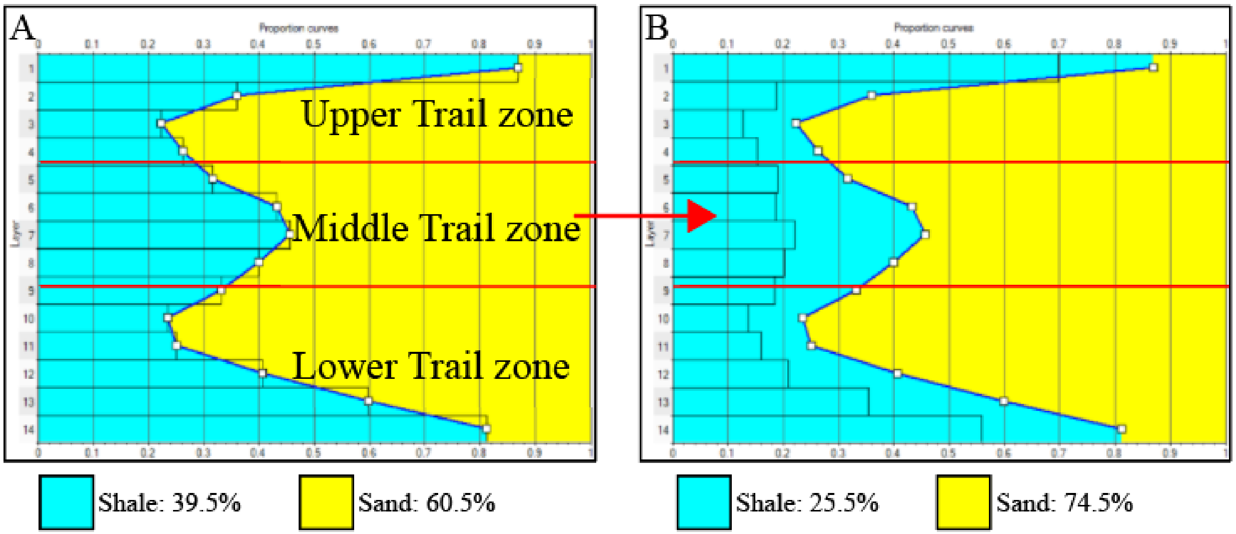


Figure 31. Petrel data analysis results for upscaled cells (A) and after property modeling (B). The 14 layers represent the 5 m thick zones through the Trail Member. The bar graphs show the proportion of sand to shale. In both the upscaled and property modeling graphs show the Upper and Lower sand-rich zones that were defined in photogrammetry. The Middle Zone is still sand-rich, but has a larger proportion of mud.

Distal Trail Member (Northern Colorado)

The Northern Colorado locality is located to the east and basinward of the Flaming Gorge and Clay Basin localities. Thin sections show that sandstone Facies 1, 2, and 5 have an average quartz content of 72.4% and 27.6% lithic content (Figure 25; Table 11). Porosity and permeability data show an average of 25.1% and 485.5 mD within Northern Colorado based on ten (porosity) and eleven (permeability) samples (Figure 26; Table 12). The two measured sections in Northern Colorado ranged from 86.8% to 88.5% NTG with an average of 87.7% (Figure 27; Table 13).

In Northern Colorado, two photogrammetric panels were created and spanned 0.4 km. Channels were outlined and measured along the sand-rich west side. 127 channels were outlined on the west side. Channel depths ranged from 0.9 m to 5.6 m with an average of 2.4 m (Figure 28; Table 16). Channel widths ranged from 6.8 m to 37.1 m with an average of 16.7 m (Figure

28; Table 16). The 27 low accommodation channels ranged in channel depths from 0.9 m to 3.2 m with an average of 1.7 m (Table 16). Channel widths for low accommodation ranged from 9.4 m to 37.1 m with an average of 20.6 m (Table 16). The 100 high accommodation channels ranged in depth from 0.9 m to 5.6 m with an average of 2.6 m and channel widths ranged from 6.8 m to 28.6 m and averaged 15.6 m (Table 16).

Northern Colorado Channel Depth			
Min (m)	Max (m)	Average (m)	Standard Deviation (m)
Low Accommodation			
0.94	3.2	1.7	0.5
High Accommodation			
0.97	5.6	2.6	1.0
All Channels			
0.94	5.6	2.4	1.0

Northern Colorado Channel Width			
Min (m)	Max (m)	Average (m)	Standard Deviation (m)
Low Accommodation			
9.41	37.1	20.6	7.3
High Accommodation			
6.83	28.6	15.6	4.8
All Channels			
6.83	37.1	16.7	5.8

Table 16. Northern Colorado channel depth and width statistics from the channels that were identified and measured within Agisoft.

Unlike Clay Basin, Northern Colorado shows a more defined change in fluvial architecture laterally rather than vertically (Figures 32 and 33). The west side of Northern Colorado shows more defined lensoidal channel forms that are not as amalgamated as those seen in Clay Basin (Figures 32 and 33) . The east side of Northern Colorado, approximately 0.4 km from the west side, does not have many visible sandstone channels and is dominantly slope-forming indicating muddier sediments. Therefore, no channels were picked along the east side of Northern Colorado.

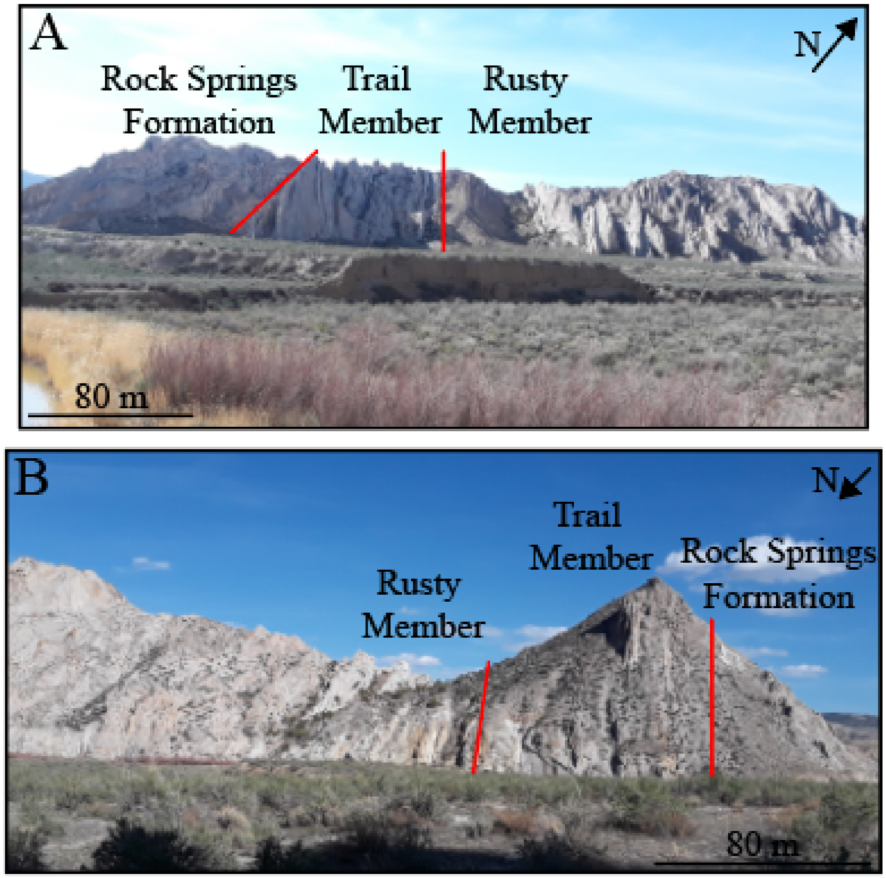


Figure 32. Pictures showing the vertical dipping nature of the beds at the Northern Colorado locality. A. Picture of the west side and sand-rich Trail Member. B. Picture of the east side of Northern Colorado showing mud-rich strata.

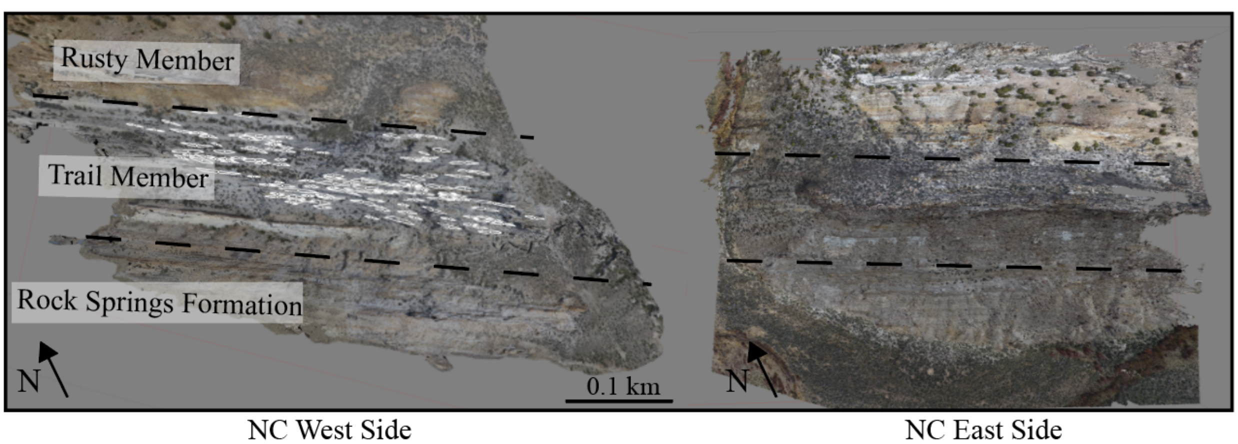
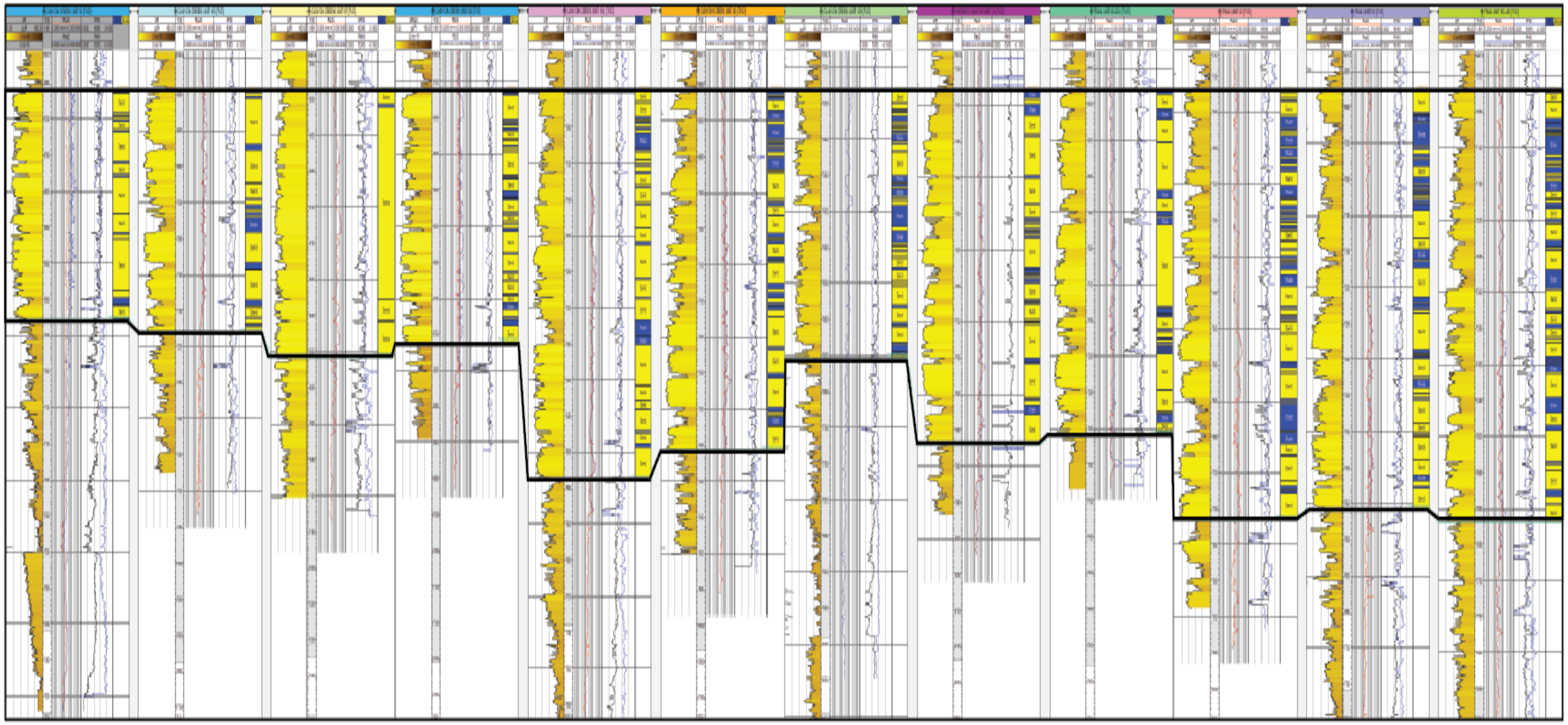


Figure 33. Photogrammetric panels showing lateral variability within the Northern Colorado locality. Bird's eye view (cross sectional view due to vertical dipping beds) of the sand-rich west side showing channel picks (white polygons) versus the east-side mud-rich Trail Member. The west and east sides are separated by 0.3 kilometers.

Subsurface Trail Member (Canyon Creek and Trail Fields)

Fifty-one thin sections were provided by Dominion Energy for point counting. Each thin section was assigned a facies association based on the core description. All facies have similar percentages of quartz (ranging from 79.8% to 83.4%) and lithic grains (16.6% to 20.1%). The core thin sections have a narrower compositional distribution than the outcrop samples and are more compositionally mature than the outcrop with an average of 82.1% quartz. Primary porosity estimated from point counting is greatly reduced in the subsurface due to compaction and more abundant quartz overgrowths. Twelve porosity and eleven permeability samples were provided by Dominion Energy and were taken from the core. The Trail Member within the subsurface has an average porosity of 7.4% and an average permeability of 0.0605 mD indicating a tight reservoir. The core and subsurface respectively have much lower porosity and permeability values than those of the outcrop samples.

The thickness of the Trail Member in the subsurface is highly variable and ranges from 97 m to 182 m with a general thickening trends towards the northeast over approximately 15 km (Figure 34; Table 17). Subsurface net-to-gross calculations were done by implementing a gamma ray cut off of 70 API. This cut off was determined by utilizing the scintillometer data from CB-5 and NC-2 sections and associated facies. Gamma ray values less than 70 API were considered net (sand), while values greater than 70 API were considered non-net (mud). The average NTG of the subsurface Trail Member is 76%, while ranging from 60% to 99% (Figure 35; Table 17). As the Trail Member thickens towards the northeast in the Trail and Canyon Creek fields, there is a general decrease in the same direction of NTG.



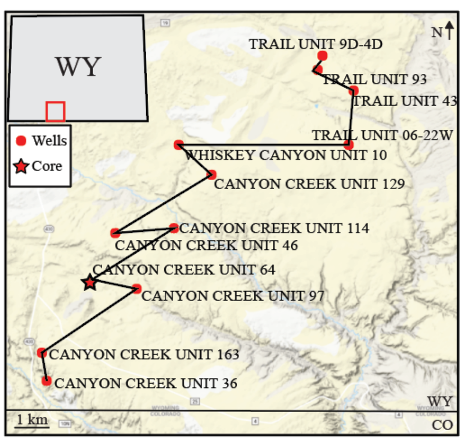


Figure 34. Cross section of the subsurface Trail Member using twelve wells. The bottom and top Trail Member contacts are outlined in black. The cross section shows the Trail Member thickening towards the northeast. Datum: Trail Member top.

Well Data (GR <70 API)				
Well Name	**Total Thickness (m)**	**Sand (m)**	**Mud (m)**	**NTG (%)**
CANYON CREEK UNIT 36	96.9	86.5	10.4	89.3
CANYON CREEK UNIT 163	102.5	81.2	21.3	79.2
CANYON CREEK UNIT 97	152.3	150.0	2.3	98.5
CANYON CREEK UNIT 64	106.5	85.5	21.0	80.3
CANYON CREEK UNIT 114	164.9	131.7	33.1	79.9
CANYON CREEK UNIT 46	152.2	104.2	47.9	68.5
CANYON CREEK UNIT 129	112.5	70.6	42.0	62.7
WHISKEY CANYON UNIT 10	149.7	120.2	29.5	80.3
TRAIL UNIT 06-22W	144.9	116.7	28.3	80.5
TRAIL UNIT 43	180.7	109.2	71.6	60.4
TRAIL UNIT 93	176.5	120.9	55.6	68.5
TRAIL UNIT 9D-4D	181.8	118.7	63.1	65.3

Well NTG (%) Statistics			
Min	**Max**	**Average**	**Standard Deviation**
60.4	98.5	76.1	11.33

Table 17. Trail Member subsurface thickness and NTG data for each well and statistics for all wells.

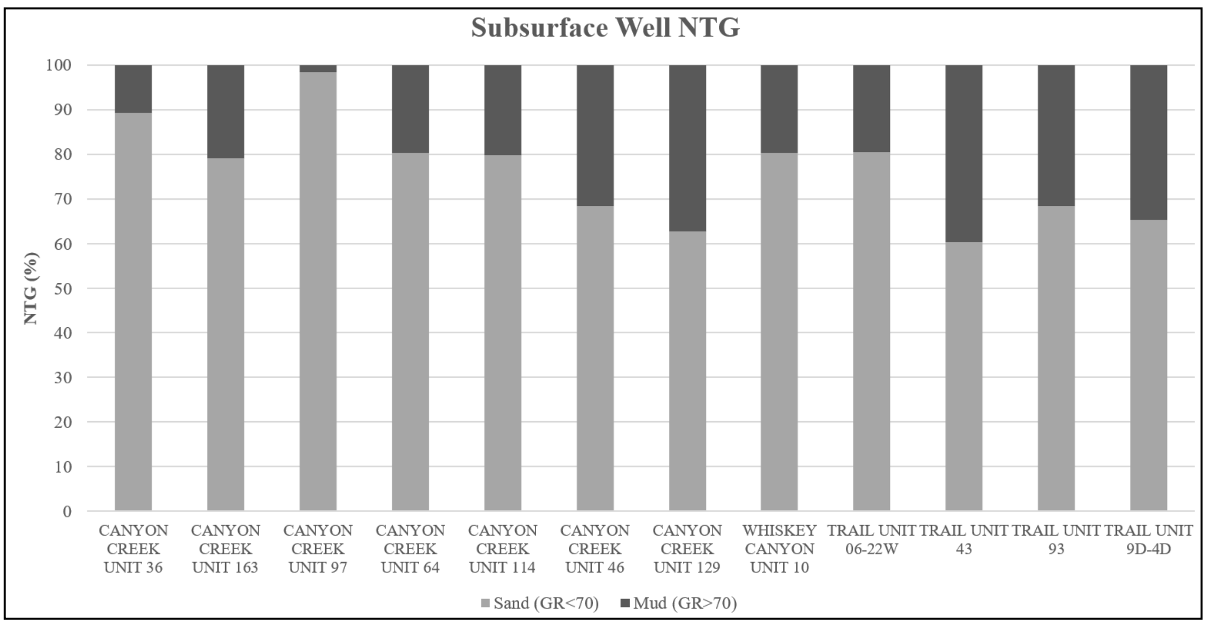


Figure 35. Calculated NTG of the subsurface Trail Member from the well logs in the Canyon Creek and Trail fields. This NTG panel shows a 15 km transect from the southwest towards the northeast. This panel shows a general decrease in NTG towards the northeast.

Large-scale Spatial Trends

Spatially, trends can be seen throughout the Trail Member from the proximal Flaming Gorge and Clay Basin field areas towards the distal Northern Colorado and subsurface areas. Compositionally, quartz averages increase towards the basin from 64.3% (FG) to 82.1 (Subsurface; Figure 25). Clay Basin and Northern Colorado have similar quartz averages of 73.8% (CB) and 72.4% (NC), however Clay Basin has a wider range from 44.9% to 87.1% quartz than that of Northern Colorado that ranges from 60.6% to 88.1%. Outcrop porosity values increase towards the basin from 23% (FG) to 26.8% (NC; Figure 26). Subsurface porosity values are consistently lower than the field areas at an average of 7.4%. Outcrop permeability does not have a clear trend as porosity does, however it seems to have a general decrease towards the basin. Flaming Gorge and Clay Basin vary from 528.9 mD (FG) to 969.8 mD (CB) with Northern Colorado having the lowest outcrop average at 485.5 mD (NC; Figure 26). The subsurface permeability is again consistently much lower than outcrops with an average of 0.0605 mD. Burial forces compact the Trail Member decreasing both porosity and permeability. Outcrop NTG increases towards the basin from Flaming Gorge (77.1%) and Clay Basin (76.2%) to Northern Colorado at (87.7%; Figure 27). The wells have a similar NTG average of Flaming Gorge and Clay Basin at 76.1%, however the wells range significantly more from 60% to 99% (Figure 35). Photogrammetric analysis shows that Clay Basin shows more abrupt temporal changes while Northern Colorado and the subsurface show more rapid spatial changes.

Discussion

Clear trends are seen over 65 km from the Flaming Gorge area into northwestern Colorado. The Flaming Gorge and Clay Basin localities represent a more proximal part of the Trail fluvial system and share many commonalities. The Northern Colorado locality shows clear differences and represents more distal facies associations within the Trail sediment routing system. Similarities and differences between the three outcrop localities provides important information about the fluvial dynamics of the system, as well as indications of possible tectonic and eustatic activity during the time of deposition.

Proximal Trail Member (Flaming Gorge and Clay Basin)

Modern fluvial systems consist of several components that can be preserved in the record including the fluvial channel (thalweg) deposits, channel and point bars, crevasse splays, and flood plain deposits. Complete fluvial channel and pointbar deposits in the rock record can often be identified by generalized fining-upwards repetitive sequences characterized by the following succession: scoured surfaces with rip-up clasts lining the bottom (channel-floor lag), trough cross-bedded sandstone (channel-bed dunes or lateral accretion sets), planar-laminated sandstone (foreset beds), rippled-laminated sandstone, and mudstone (flood plain; Figure 36; Cant and Walker, 1976; Rust, 1978). This complete fluvial channel succession preserved in the rock record indicates lateral migration of a fluvial system allowing the channel to fill with fine sediment as it migrates away. During times of rapid and/or frequent avulsion, the uppermost portions of this succession are often eroded away (McLaurin and Steel, 2006).

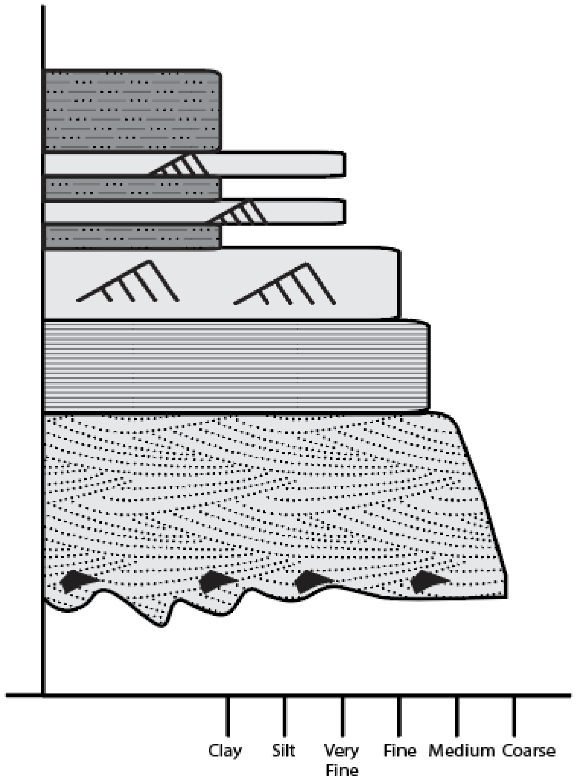


Figure 36. Generalized complete fluvial channel succession. From bottom to top, scoured surface with rip-up clasts (channel floor lag), trough cross-bedded sandstone (channel bed dunes and/or lateral accretion sets; Facies 2), planar-laminated sandstone (foreset bars), ripple-laminated sandstone, heterolithic sandstone and mudstone (marginal fluvial; Facies 3), and mudstones (flood plain; Facies 4). This succession represents a decrease in flow energy.

The Trail Member in the Flaming Gorge and Clay Basin field areas is dominated by trough cross-bedded sandstones of Facies 2. Facies 2 represents the lower fill of the channel thalweg including channel-floor lag (rip-up clasts) and channel-bed dunes or lateral accretion sets (trough cross-beds) forming in strong, unidirectional currents within the lower portion of the channel (Cant and Walker, 1976; Rust, 1978; Bridge, 2006; Leary et al., 2015). There is appreciable variability in the expression of trough cross-bedding within Facies 2 of the proximal Trail Member. Trough cross-bed sets that have clear upper and lower bounding surfaces probably represent a well-established dune system, while trough cross-bed sets that are randomly oriented and have common soft-sediment deformation suggest variability in flow amount, fluid saturation, and channel movement indicative of more flashy discharge and less organization overall. The lack of abundant planar- and ripple-laminated sandstones (tops of channel deposit sequences) throughout Flaming Gorge and Clay Basin indicates frequent lateral channel migration and avulsion within a highly mobile, high-energy fluvial system (McLaurin and Steel, 2006). Although not seen commonly within the Flaming Gorge and Clay Basin field areas, Facies 1 (massive fine-grained sandstones) is interpreted to represent the rapid deposition of sediments under upper flow-regime conditions, such as flooding events (Miall, 1978; Leary et al., 2015). Specifically, these events can cause levees to breach and crevasse splays to form and deposit laterally discontinuous massive, well-sorted sediments, such as Facies 1. The finer-grained facies (Facies 3 and 4) that represent marginal fluvial and overbank low flow-regime deposits are not abundant in the more proximal Trail Member localities, suggesting frequent lateral migration and avulsion that erodes and reworks the muddier sediments. The compositionally immature and coarser-grained sediments of Facies 5 (medium- to coarse-grained soft-sediment deformed sandstones) suggest occasional high-energy flow events causing bank failure or rapid deposition of highly saturated coarser-grained sediments causing flame and other soft-sediment structures (Mills, 1983). This facies is somewhat common, suggesting higher flow energy and highly fluid saturated events, such as flooding events that transport coarser-grained sediments down dip.

The Trail Member in Flaming Gorge and Clay Basin represents a sand-rich, highly amalgamated fluvial system. The Trail Member ranges in thickness from 45 m to 78 m with NTG ranging from 63.3% to 85.1%. The Trail Member is thinner here than in the more distal Northern Colorado outcrops, and is also thinner than calculated subsurface thicknesses in the Canyon Creek and Trail fields to the east. Compositionally, Flaming Gorge and Clay Basin have averages of 64.3% and 73.8% quartz from all outcrop samples (Facies 1, 2, and 5). The compositional average of Facies 1, 2, and 5 of Clay Basin is similar to that of Northern Colorado, however the quartz percentages from Clay Basin (44.9% to 87.1% range more than within Northern Colorado (60.6% to 88.1%). Facies 3 and 4 are less commonly preserved between channels in Flaming Gorge and Clay Basin adding to the sand-rich nature of the Trail Member in these locations. The coarse-grained, immature Facies 5 (average 61.3% quartz) is found more frequently in the more proximal locations. Flaming Gorge and Clay Basin also lack the preserved organic material, burrows, and woody material that are commonly found in Northern Colorado. These data suggest that the fluvial system is highly mobile resulting in sand-rich strata and closer to the sediment source the sandstones are more compositionally immature (Figure 37).

The early onset of the Uinta Mountain uplift located just south probably supplied a significant amount of sediments to the Flaming Gorge and Clay Basin localities, which helps explain the compositionally and texturally immature nature of preserved channel sandstones. Also, the uplift increased the sediment supply to the Trail Member on a more regional basis, which would have assisted in filling available accommodation more rapidly causing the fluvial system to avulse more frequently. This caused the fluvial channels to erode and transport the finer-grained sediments (Facies 3 and 4) further down system resulting in more sand-rich strata.

Photogrammetric models from Clay Basin shows three zones with distinct fluvial stacking patterns: Upper and Lower Trail zones (laterally amalgamated sandstones) and a Middle Trail zone (vertically stacked sandstones). Martinsen et al. (1999) described the nature of the stacking patterns of the Rusty and Canyon Creek Members of the Ericson Sandstone. Fluvial vertical and lateral stacking patterns observed by Martinsen et al. (1999) are seen on a finer-scale within the Trail Member indicating both allogenic and autogenic forcings. The Upper and Lower Trail zones are characterized by 18 m to 21.3 m (Upper and Lower Trail zone averages) thick

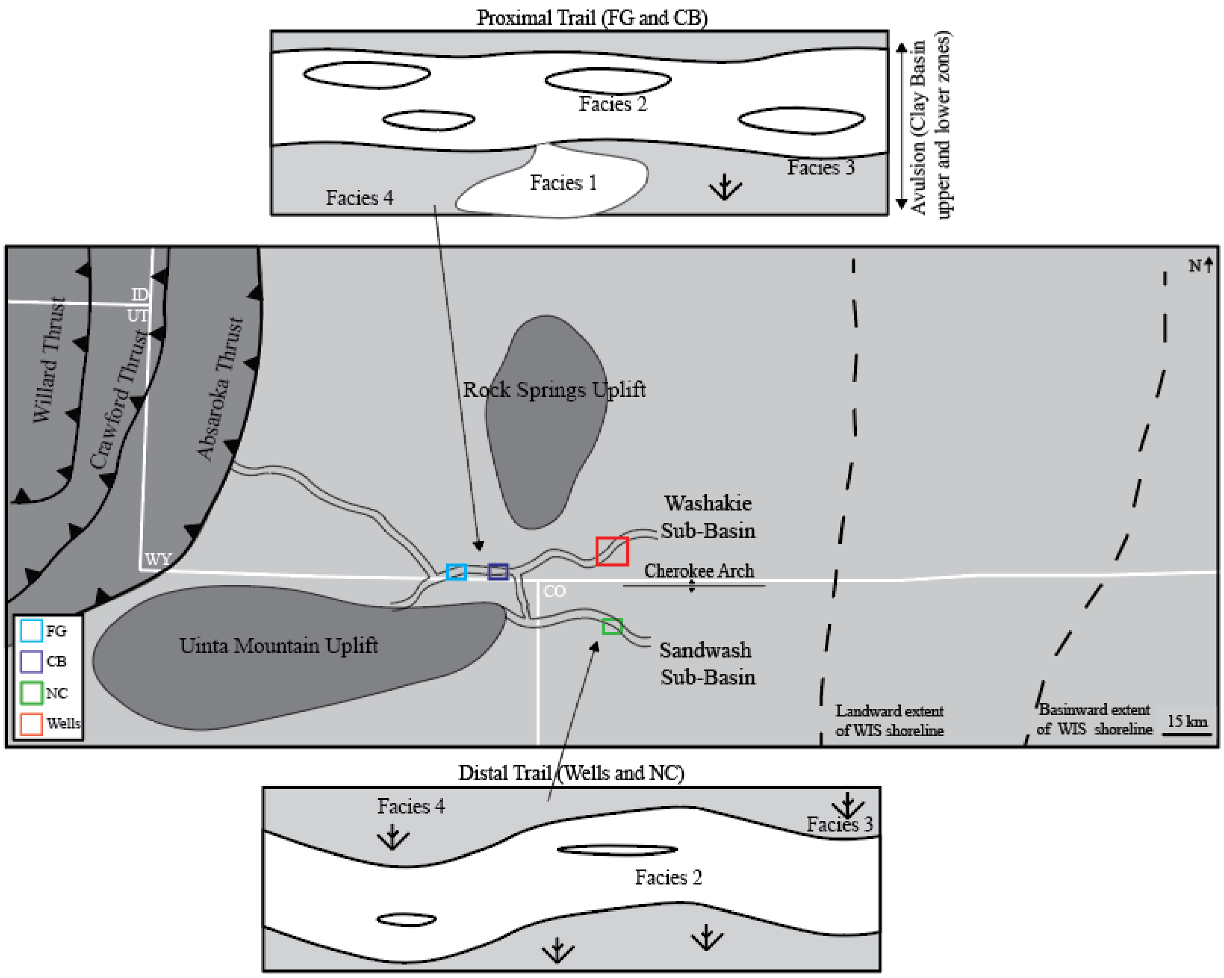


Figure 37. Regional scale depositional environment model of the Trail Member. The map shows the two main sediment sources of the Trail Member (Sevier fold and thrust belt and Uinta Mountain uplift). The Western Interior Seaway (WIS) shoreline landward and seaward extents during the Trail Member deposition are shown. On a finer-scale, the proximal and distal Trail Member fluvial channel systems are shown with locations of associated facies. Modified from DeCelles (2004), Nichols and Fisher (2007), and Gomez-Veroiza and Steel (2010).

laterally continuous amalgamated sandstone cliffs. The Middle Trail zone of the Trail Member, however, shows more vertically stacked channel complexes (average 17.7 m thick) that are separated by finer-grained intervals that are represented by slopes. The Lower Trail zone of laterally stacked amalgamated channels suggest an environment of relatively low accommodation, where the system is highly mobile and avulsing frequently to find available space. The Middle Trail zone indicates higher accommodation as the system had available space allowing for the fluvial system to build up on itself instead of migrating laterally resulting in laterally isolated, thick packages of sandstone. The Upper Trail zone of the Trail Member in Clay Basin is similar to the Lower Trail zone suggesting lower accommodation and a laterally accreting fluvial system.

The vertical variability in the Trail Member suggests that controls on sediment supply and accommodation varied appreciably during the deposition of the Trail Member. Martinsen et al. (1999) suggest that possible allogenic mechanisms that could cause the abrupt changes in fluvial architecture within a formation include local tectonic events, climatic changes, or eustasy. Prominent eustatic influence on the Trail Member at Clay Basin is unlikely due to the distance from the shoreline and lack of marine influenced sedimentary structures. At the landward extent of the Western Interior Seaway during the time of Trail deposition, it was located approximately 140 km east of Clay Basin and at the basinward extent the shoreline was located approximately 230 km east of Clay Basin (Gomez-Veroiza and Steel, 2010). Climate changes could have influenced the sediment supply in the local area. A change towards a wet climate could cause increased erosion and transportation of sediments, which would cause accommodation to be filled more rapidly and avulsion to occur more frequently as is seen in the Upper and Lower Trail zones in Clay Basin. A drier climate would decrease the rate of erosion and transportation and therefore decrease the sediment supply to the fluvial system. Significant climate changes, however, are not seen throughout the Cretaceous. Hay (2008) suggests that Cretaceous climate was warm and equable and not easily disturbed. Therefore, the most probable driver for temporal changes in fluvial architecture in the proximal Trail Member strata of Flaming Gorge and Clay Basin is local tectonics. Local tectonics that could be influencing the Trail Member in these field areas include the Uinta Mountain uplift to the south and the Sevier fold and thrust belt to the west (Figure 37; DeCelles and Mitra, 1995). Provenance work from Leary et al. (2015) suggests that sediments within the Trail Member are being sourced mainly from the Willards thrust with the Absaroka thrust and Uinta Mountains as secondary sources of sediment. The deposition of the Upper and Lower Trail laterally amalgamated sandstone zones suggest that the rate of uplift and/or thrusting periodically increases, which then increases the amount of sediment available to be transported. This increase in sediment supply would quickly fill the available accommodation due to local subsidence from the uplift, causing the fluvial channels to avulse and move laterally. In the Middle Trail zone, vertical amalgamation and laterally isolated channel complexes suggest that the rate of uplift and/or thrusting slowed, decreasing the amount of sediment and allowing the fluvial system build vertically with less frequent avulsion. The Middle Trail zone allows for the observation of how a fluvial system reacts without the influence of allogenic processes.

Distal Trail Member (Northern Colorado)

The Trail Member in the Northern Colorado field area also consists of predominantly Facies 2 sandstones with channel-floor lag (rip-up clasts) and channel-bed dunes (trough cross-beds). In contrast to the more proximal Flaming Gorge and Clay Basin field areas, the upper portion of the fluvial channel succession (planar- and ripple-laminated sandstones) is more commonly preserved within Facies 2 in Northern Colorado. The addition of two sub-facies (Facies 2a and 3a) acknowledges the appearance and increase in organic material found throughout. Facies 2a (organic-rich fine- to coarse-grained trough cross-bedded sandstone) and 3a (organic-rich heterolithic sandstone and mudstone) contain a significantly higher amount of organic material and sedimentary structures that suggest a lower flow regime and a more established flood plain, where organic material is locally abundant and flow conditions allow for some preservation. Coal flecks, mud cracks, woody material, wood casts, burrows, and two fossilized tree trunks were identified within these two sub-facies. Although they are not abundant along the west side, the finer-grained facies (Facies 3, 3a, and 4) are preserved more frequently in between channels and the channels do not erode as deeply into the muddier intervals. This suggests less frequent and/or less erosive power due to lower flow energy. Facies 5 is present in this area, however, it is not observed as commonly as in Clay Basin and Flaming Gorge. Therefore, the Trail Member in Northern Colorado appears to represent a lower energy system within a lower accommodation setting. Nichols and Fisher (2007) demonstrate how facies and fluvial architecture change down dip within a fluvial distributary system. The medial zone described by Nichols and Fisher (2007) shares common features with those observed in Northern Colorado, such as more preserved floodplain deposits, less channel erosion, and finer-grained sediments. This suggests that the fluvial system has encountered a reduced river discharge, a decrease in gradient, and is a more prominent meandering system.

Channels were outlined and measured along the west side of the Northern Colorado locality. The width:depth ratio at Northern Colorado (7.7) is slightly wider than the average at Clay Basin (7.5). This is consistent with a lower energy, more distal interpretation, although they are not statistically distinct populations. Unlike Clay Basin, photogrammetric analysis shows a rapid lateral change in NTG from the west to the east side of the field area rather than defined temporal changes. The west side (where NC-1 and NC-2 were measured) is more sand-rich than the east side, which is largely a mud-rich interval with isolated sand bodies. The rapid change (0.4 km) from sand-rich to mud-rich strata could indicate a possible incised valley fill (Figure 38). During lowstand, an incised valley forms with possible early deposition of sediments. As the sea level transgresses, sediments are locally focused within the incised valley and deposited creating a high NTG area next to a low NTG area (Figure 38). This could account for the higher NTG average at Northern Colorado and the rapid lateral change. This suggests that more distally, the Trail Member is being more influenced by allogenic eustatic changes rather than tectonic changes as was seen in Flaming Gorge and Clay Basin.

Distal Trail Member (Subsurface)

The Canyon Creek Unit 64 core shows the bottom portion of the Rusty Member and top

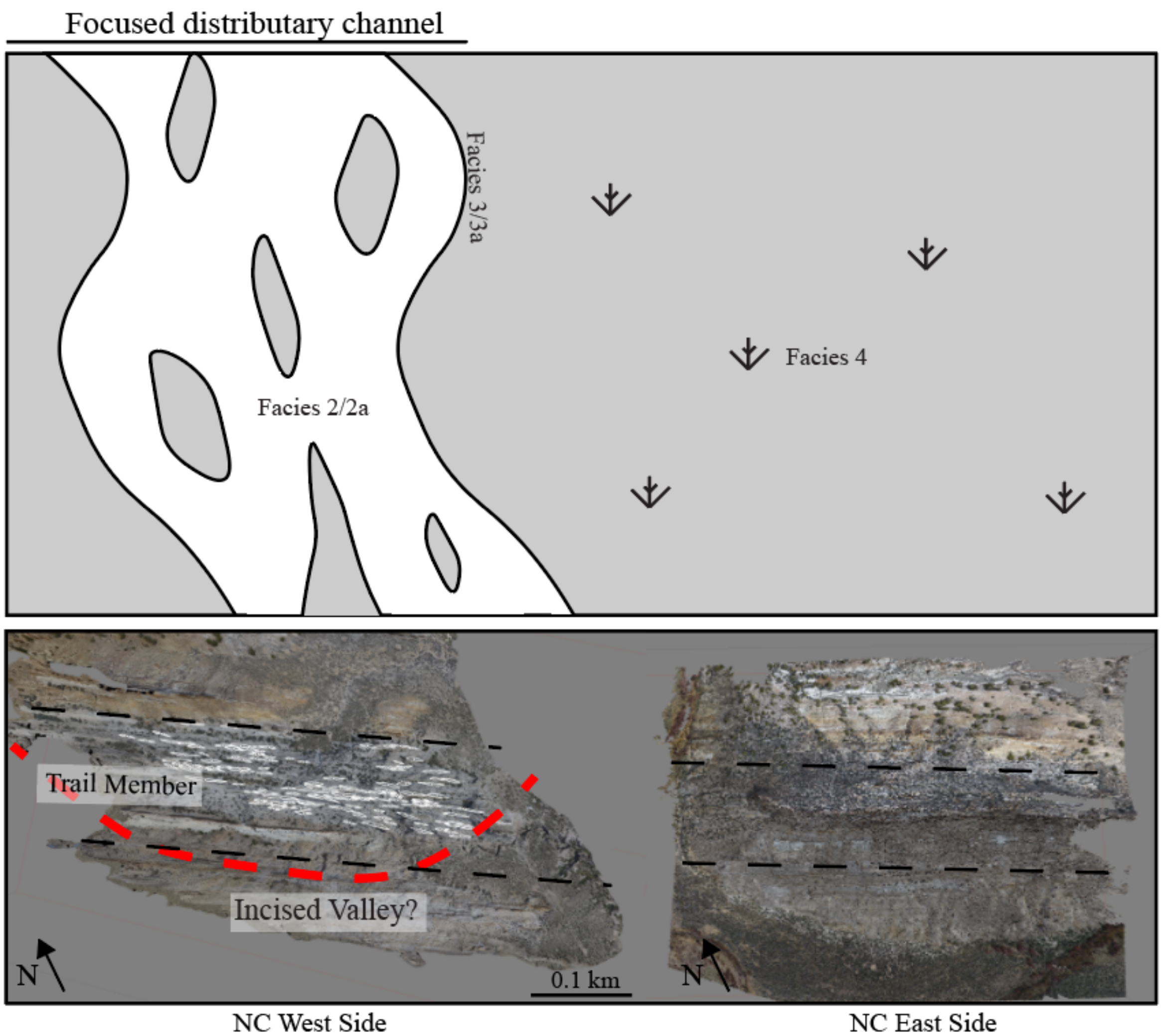


Figure 38. Depositional environment model of the Northern Colorado locality. The photogrammetric panels show lateral variability from the sand-rich strata on the west side to the mud-rich strata on the east side. The depositional model shows an established flood plain that deposited the mud on the right (east) with a focused distributary channel on the left (west), which could represent incised valley fill that is focusing the sand. This model is not to scale and does not represent paleocurrent directions.

of the Trail Member. Interpretation of the contact between the Rusty and Trail Member is based on the increase of mud-rich facies at the top of the core, as well as consistently lower porosity and permeability values. Facies 1, 2, 3, and 4 occur within the Trail interval of the core. Specifically, a more complete fluvial channel succession is apparent within Facies 2 as trough cross-bedded sandstones transition into ripple-laminated sandstones showing a decrease in flow regime. There is also an increase in heterolithic fine-grained sandstone and mudstone (Facies 3), that includes areas of the core that have been deformed and disturbed. It is common to observe coal flecks, increased organic material, and increased bioturbation indicating a more established flood plain that is not being eroded as frequently as in the more proximal field location (FG and CB). Subsurface thin section data indicates that the Trail Member is more compositionally mature (82.1%) in the subsurface than the more proximal outcrops. The increased transport distance led to stable minerals (i.e. quartz) to be preferentially preserved while unstable minerals (i.e. lithics) were subjected to disaggregation and dissolution. Compaction due to increased burial is apparent shown by deformed and compressed mud-rich rip-up clasts, decreased primary porosity, and an increase in linear and concave grain contacts.

Connectivity of reservoir quality sandstones and the nature of the fluvial system in the subsurface were analyzed using thickness and NTG data from twelve well logs spanning 15 km from the southwest to the northeast. Within the Trail and Canyon Creek field, the Trail Member interval thickness ranges from 96.9 m to 181.8 m and increases towards the northeast. The NTG has the opposite trend as NTG decreases towards the northeast, showing more frequent preservation of mud-rich marginal and overbank facies between sand intervals. This suggests

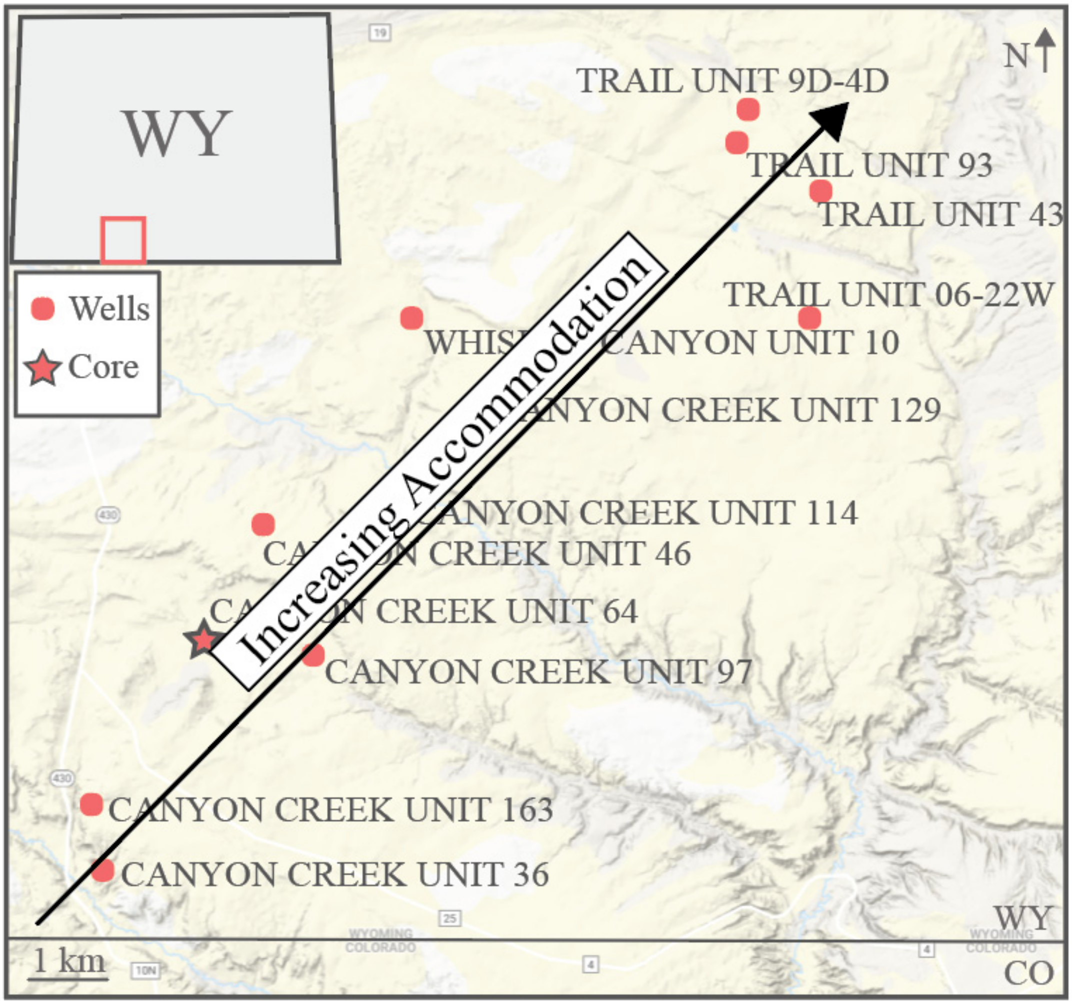


Figure 39. Well location map with the interpretation of increasing accommodation towards the northeast determined from the Trail Member thickening while NTG decreases towards the northeast.

that accommodation increased towards the northeast rapidly allowing for the Trail Member to double in thickness over 15 km (Figure 39). This area may be influenced from either tectonic or eustatic allogenic processes. Tectonically, the area may have been influenced by early subsidence of the Laramide-aged Washakie sub-basin. From the southwest to the northeast, the location of the wells are trending away from the Cherokee Arch into the margins of the Washakie sub-basin (Figure 40). The strata towards the northeast is then affected by the creation of additional accommodation that allows for more sediment to be deposited and for finer-grained

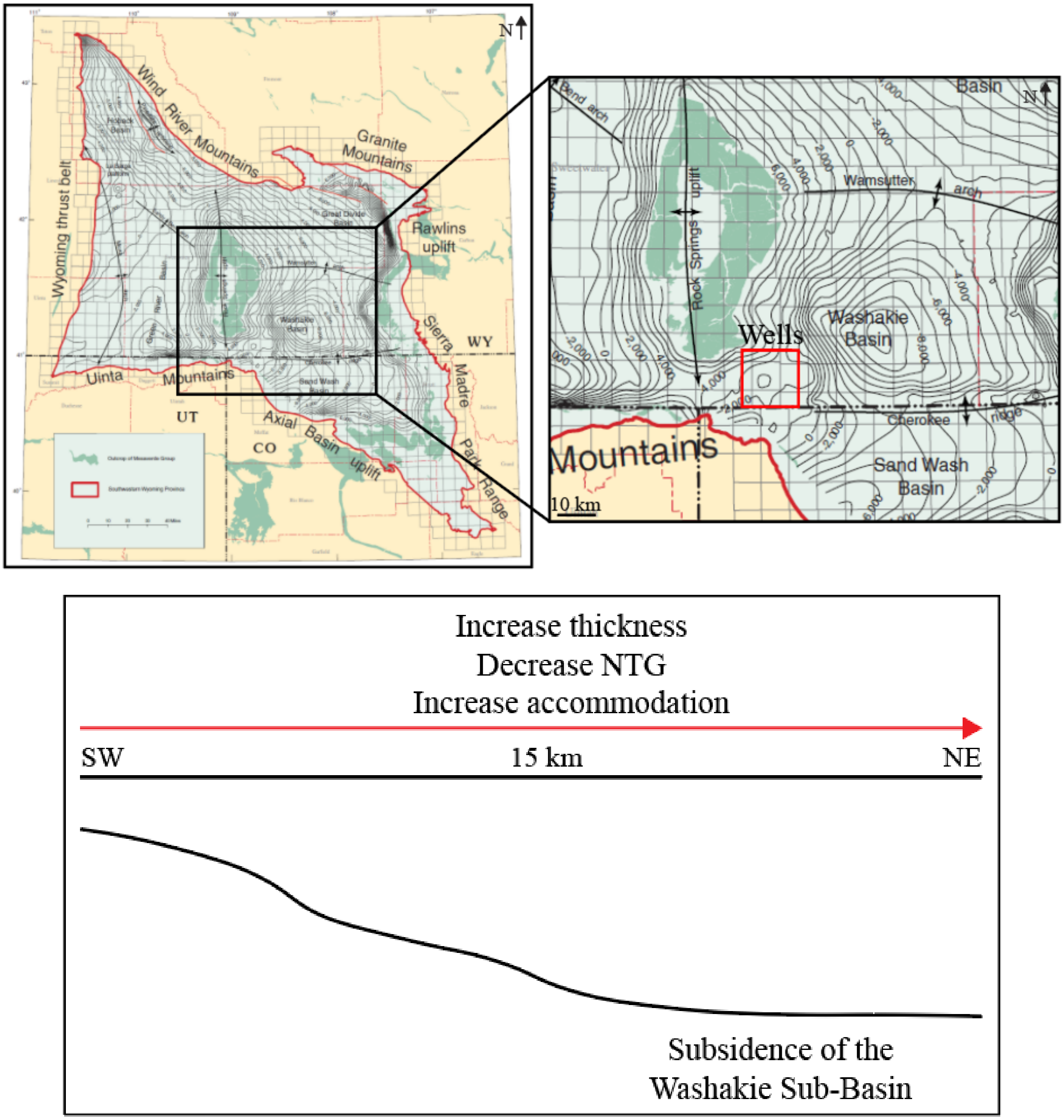


Figure 40. Map and cross section showing the Washakie sub-basin subsiding towards the east creating additional accommodation. The Trail Member then thickens and increases the preservation of finer-grained facies due to the increase in accommodation from subsidence. Modified from Wyoming Oil and Gas (2019).

facies (Facies 3 and 4) to be preserved preferentially. Eustatic changes could have created an incised valley during the lowstand, which was then filled during the transgressive systems tract. The increased thickness and decreased NTG could indicate the wells are located along the margins of an incised valley fill (Figure 41). The Trail Member thickens and accommodation increases as the system enters an incised valley. These possible interpretations suggest that Trail Member deposition did not occur in a simple proximal to distal transect, but was influenced by possible tectonic and eustatic influences.

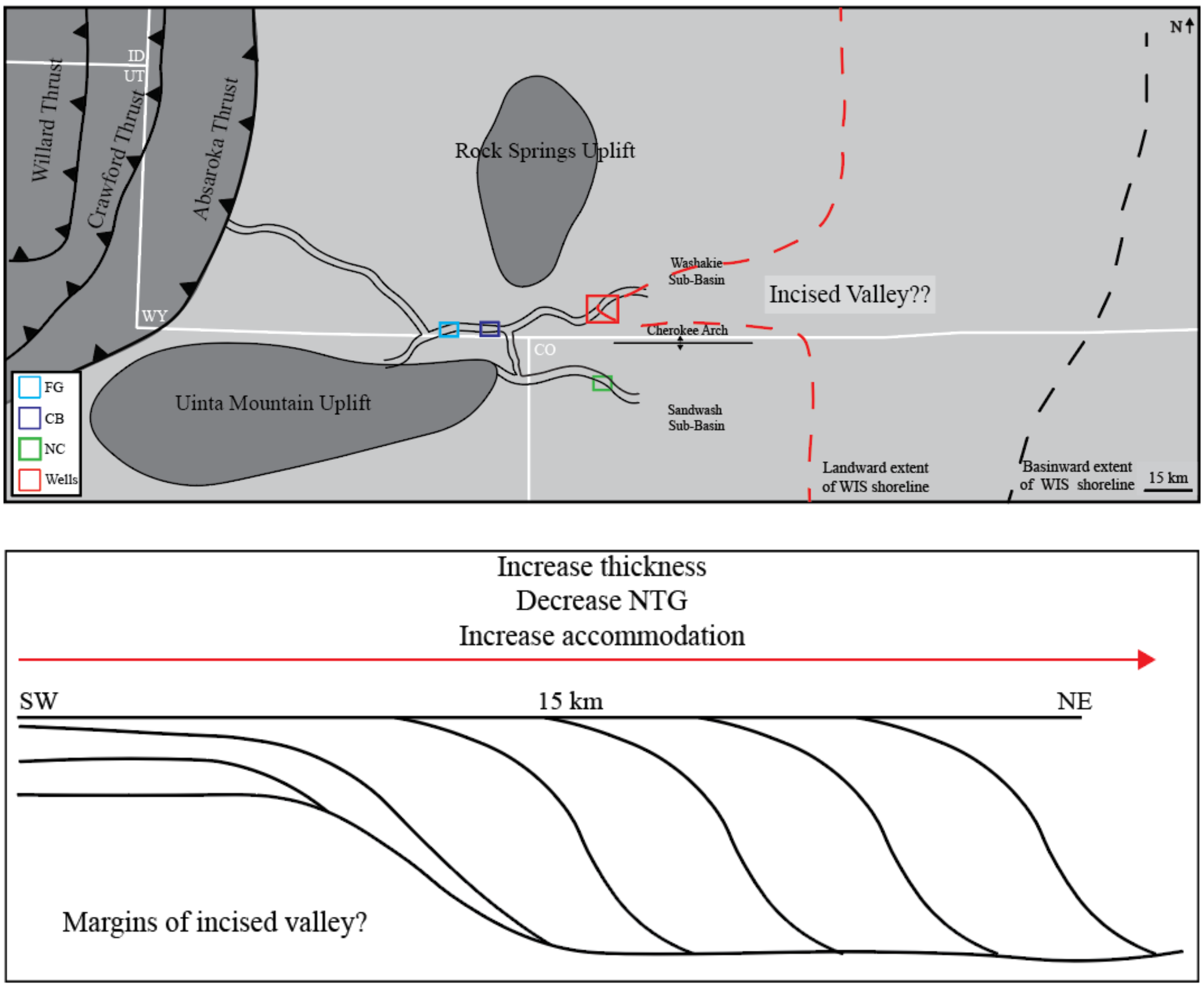


Figure 41. Map and cross sectional view of a possible incised valley influencing the rapid change in accommodation seen in the well logs. Modified from DeCelles (2004), Nichols and Fisher (2007), and Gomez-Veroiza and Steel (2010).

Reservoir Potential

The Trail Member fluvial system is currently a producing hydrocarbon reservoir. Porosity and permeability data from the three field areas show good reservoir quality with high average for both porosity and permeability (FG: 23% and 528.9 mD; CB: 25.4% and 969.8 mD; NC: 26.8% and 485.5 mD). Thin sections show little evidence of compaction, minor quartz overgrowths and quartz-rich grains. Surficial weathering and absent burial forces could be influencing the higher porosity and permeability values as the outcrop does not correlate well with the porosity and permeability data taken from the subsurface (Subsurface: 7.4% and 0.0605 mD).

Thin sections show that porosity and permeability within the Trail Member are affected by diagenetic processes that caused quartz overgrowths and the dissolution of lithic grains. Quartz overgrowths are found in both outcrop and core thin sections; however, they are much more extensive in the subsurface due to deeper burial away from the margins of the basin. In both outcrop and subsurface, quartz overgrowths occur more frequently associated with larger grains (upper fine to coarse) and do not occur in areas with clay cement. Edman (1986) suggests that syntaxial quartz overgrowths in the Ericson Sandstone occur early in the diagenetic history due to the presence of euhedral crystal suggesting growth during times when the pore spaces are still open. Clay cement is found to have filled in pore space in between the grains. Edman (1986) suggests that the clay cement filled in pore space early in the Trail Member's diagenetic history, although after the majority of the quartz overgrowths occurred. Clay cement and quartz overgrowths decreased the porosity within the reservoir sandstones. Later in the diagenetic history, however, dissolution of the clay cement and lithic grains caused the formation of secondary intragranular porosity. This would have increased the porosity in the reservoir, however permeability may not have increased because intragranular porosity does not connect pore spaces as well as primary intergranular porosity. Subsurface data indicates low to good porosity (5% to 9.1%) and very low permeabilities (0.0120 to 0.1840 mD) indicating a very tight reservoir. Therefore, hydraulic fracturing is a potential means to increase the permeability in the subsurface during hydrocarbon production.

Facies 1, 2, and 5 are the identified reservoir intervals in the Trail Member. Facies 3 and 4 represent baffles or barriers to flow of hydrocarbons due to the increased amount of mud and impermeable layers. Connectivity of the reservoir quality facies decreases in the field areas from Flaming Gorge and Clay Basin to Northern Colorado. The connectivity of channel sandstones relates to the fluvial architecture with Flaming Gorge and Clay Basin. The Upper and Lower Trail zones indicates sufficient lateral connectivity, however these zones are not as connected vertically. The Middle Trail zone with vertically stacked channels has the potential to connect the Lower and Upper Trail zones, however a large portion of the Middle Trail zone is dominated by the muddier intervals that act as a barrier to fluid flow. The 3-D Petrel facies model vertical proportion curve also shows the Upper and Lower Trail sand-rich zones, with a more mud-rich Middle Trail zone that still has a significant proportion of sand. The 3-D model shows areas of the sand-rich Middle Trail zone that connects the Upper and Lower Trail zones and can create a migration pathway for hydrocarbons. A major set-back to the model, however, is that it cannot map the finer layers of mudstones (Facies 3 and 4) that can act as a barrier to fluid flow and it may be overestimating the sand:shale ratio on the vertical proportion curve. This could cause a more optimistic result for the amount of reservoir potential sandstone and how much it is connected. This then simplifies migration pathways for hydrocarbons and decreases the time in which it takes the reservoir to be charged with hydrocarbons, when in reality the system is much more complex. Mitigation for this limitation includes using more detailed data such as well logs and creating a more detailed and finer-scaled model that can be influenced by the thin layers of Facies 3 and 4 that were observed in the field.

Connectivity of reservoir quality sandstones within Northern Colorado tend to be less than that of Clay Basin and Flaming Gorge. Although a high NTG system, the sand channels are more isolated and less connective than the more proximal Trail Member. The increase of mud intervals separating sandstones acts as barriers and will decrease the chance of the sandstones being in pressure communication, leading to difficult drainage of this as a reservoir compared to the more source proximal outcrops to the west. Photogrammetry and the vertical nature of the Trail Member has preferentially eroded finer-grained facies (Facies 3 and 4) leaving more isolated sand channels.

Conclusions

This study shows important changes in the nature of the Trail Member fluvial system along 65 km of depositional dip. Twelve wells, including one with core data, located north of the Northern Colorado field area were used to compare the subsurface to outcrop and observe the nature of the Trail Member in the subsurface. Photogrammetric analysis shows three distinct zones within the Trail Member at Clay Basin. The Upper and Lower Trail zones are comprised of laterally continuous, amalgamated sandstone units that represent an environment of lower accommodation and/or increased sediment supply. This suggests increased movement from local tectonics, such as the Uinta Mountain uplift and thrusting within the Sevier fold and thrust belt. The Middle Trail zone is characterized by vertically stacked, amalgamated sandstone units that are laterally bound by mud-rich slopes. This zone suggests higher accommodation that allows for autogenic processes to determine the channel stacking pattern as local tectonics decreased in rate of movement.

Within the Northern Colorado field area, organic material and upper fluvial channel succession facies and sedimentary structures are more commonly preserved than in the more proximal locations (FG and CB). The fluvial architecture shows more isolated sand channels with thin fine-grained material in between the channels. This, along with the organic material and observed sedimentary structures, indicates that the fluvial system is more distally located and transitioning into a more distributary channel system. Photogrammetry shows a rapid change of the Trail Member from sand-rich on the west side to mud-rich on the east side within 0.4 km. The rapid lateral change suggests an incised valley fill that concentrated sand in one area. This indicates a change from more tectonically-influenced to more eustatic-influenced system. The twelve wells and core also indicate the preservation of flood plain material and a decrease in flow energy in a more basinal position, similar to Northern Colorado. The subsurface Trail Member increases in accommodation within 15 km towards the northeast indicating possible early subsidence of the Washakie sub-basin or the Trail Member is being influenced by an additional incised valley.

The Trail Member serves as a hydrocarbon reservoir and produces within the Trail and Canyon Creek natural gas fields. Facies 1, 2, and 5 serve as reservoir quality sandstones (Facies 1: 24.2% and 556.3 mD; Facies 2: 25.7% and 797.3 mD; Facies 5: 24.7% and 823.9 mD). Porosity and permeability values do not correlate well between the outcrop and subsurface (Subsurface: 7.4% and 0.0605 mD). Volumetrically, Facies 2 forms the majority of the reservoir. Porosity data shows an increase towards the basin, while permeability does not exhibit as clear of a spatial trend but overall decreases towards the basin. Connectivity of reservoir quality sandstones appears to decrease towards the basin, although it still remains quite high as seen in NTG of Northern Colorado and the wells). Overbank mud-rich deposits are more frequently preserved between channel sandstones as seen in Northern Colorado and in the subsurface. Petrel modeling shows good lateral connectivity in Clay Basin along the Upper and Lower Trail zones, however they are not well connected vertically, except where vertically stacked channels within the Middle Trail zone are present. Thin, fine-grained material (i.e. mud drapes) can act as a barrier to fluid flow and is not represented in the Petrel model, but is seen in outcrop and core. Overall, the Trail Member is a high NTG fluvial system that serves as a reservoir for hydrocarbons, but does evolve to a lower energy system with more prominent mud intervals down dip.

The Trail Member within the greater Green River basin shows important depositional dip changes from the more proximal Flaming Gorge and Clay Basin localities into northwestern Colorado and towards the Washakie sub-basin in the subsurface. Three zones within Clay Basin (Lower, Middle, Upper) show finer temporal changes in autogenic channel clustering that are effected by allogenic (tectonic) drivers. These data suggest early Laramide structures (Uinta Mountain uplift) are influencing the deposition of Trail Member strata along with the waning Sevier fold and thrust belt. In Northern Colorado, preserved finer-grained material, more common occurrences of low flow regime sedimentary structures (i.e. mud cracks, ripple-laminations), and slightly wider channels are indicative of a lower energy fluvial system further into the basin. The rapid and distinct lateral change from sand-rich to mud-rich strata with Northern Colorado suggests incised valley fill indicating a change in allogenic drivers from tectonics to eustatic changes. Trail Member subsurface strata represents an environment similar to that of Northern Colorado of a lower energy fluvial system. The rapid (15 km) increase in accommodation towards the northeast is indicative of possible early subsidence of the Washakie sub-basin or the system is on the margins of an incised valley fill. This suggests that tectonics and sea-level can be influencing the fluvial architecture towards the basin. The Trail Member serves as an important analogue for fluvial systems near active tectonics and shorter distances from the sediment source to the basin throughout geologic time.

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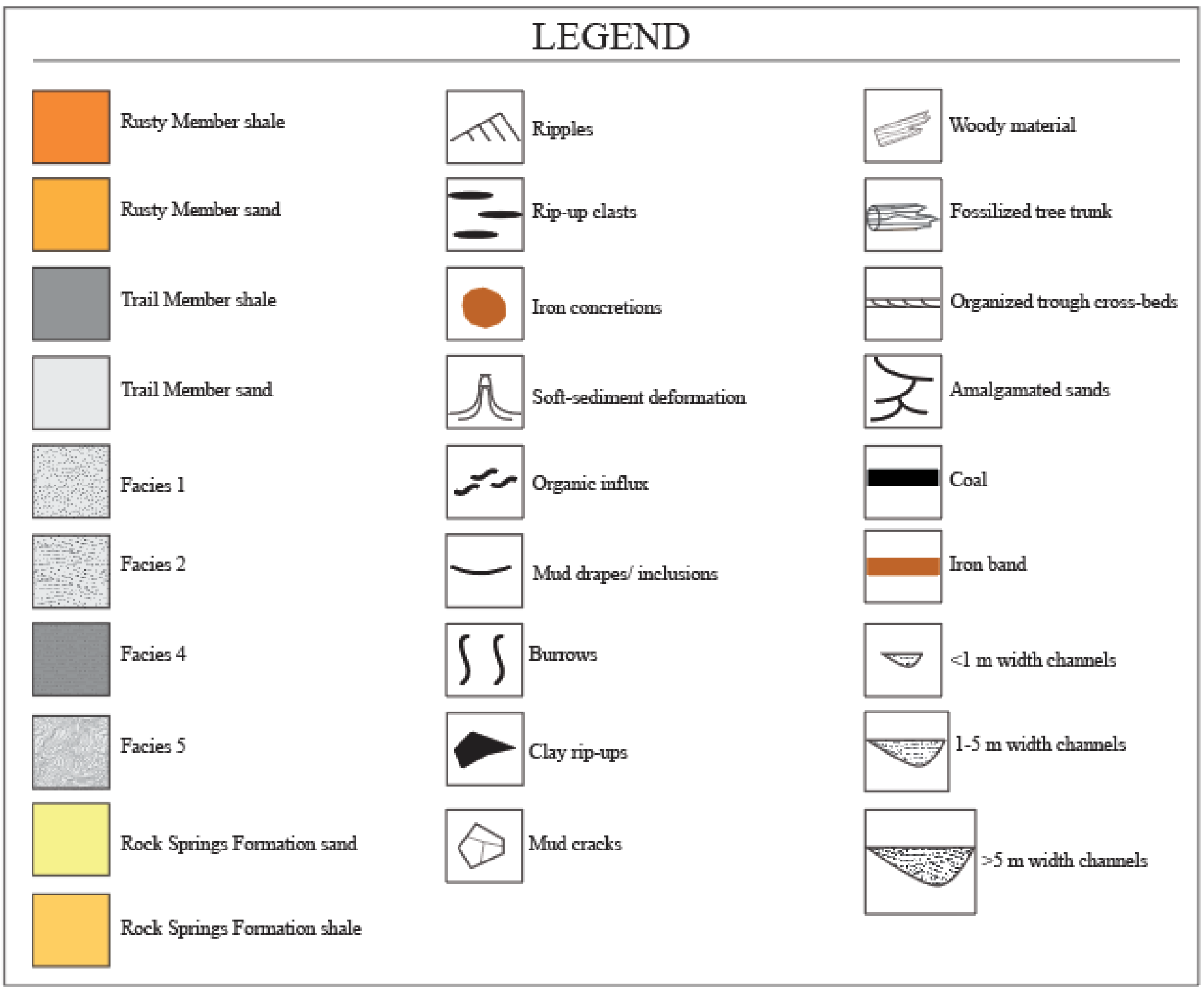
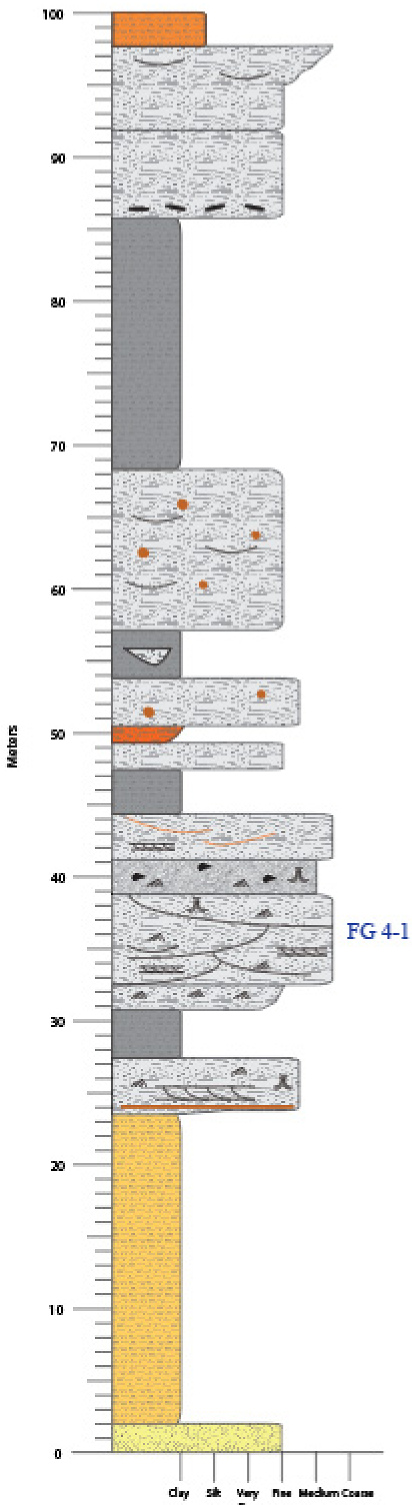
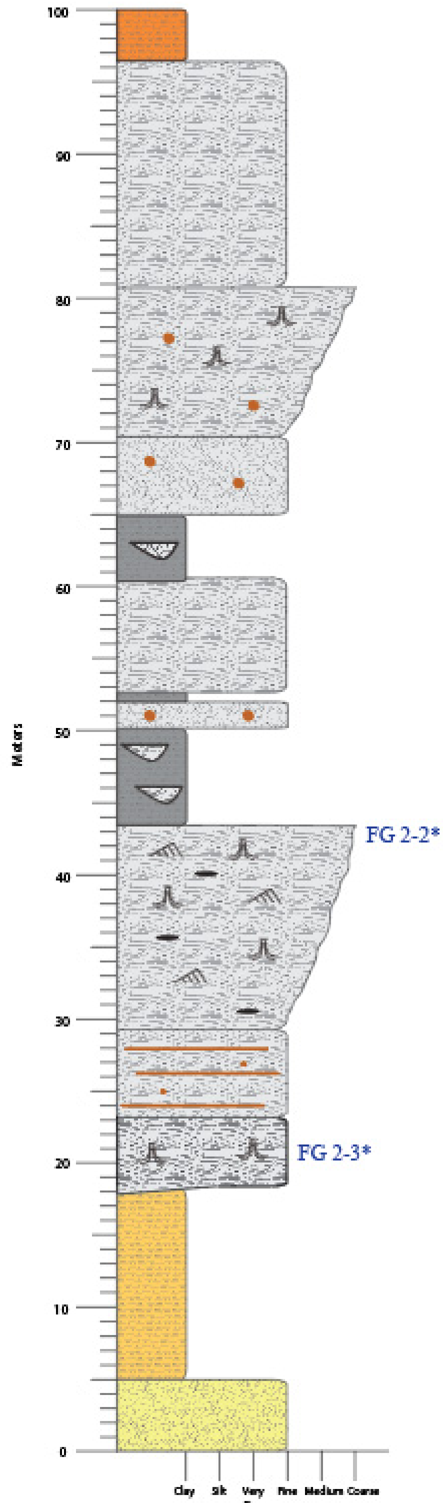
Appendix

The following are the eleven measured sections from Flaming Gorge, Clay Basin, and Northern Colorado. Each measured section records lithology, sedimentary structures, facies association, and hand sample location. Hand sample ID's with an asterisk (*) indicate samples that underwent porosity and permeability analyses. The measured sections will be placed in order from west to east.

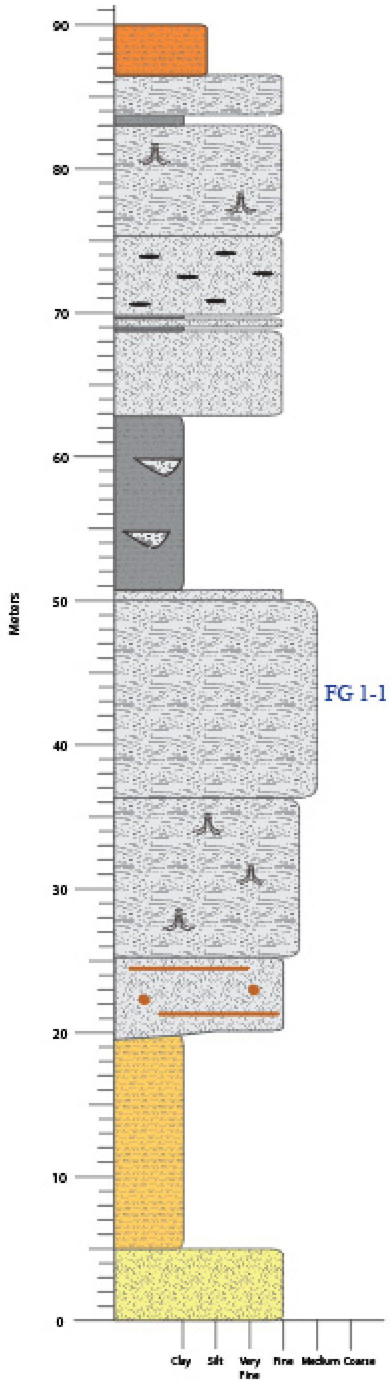




Flaming Gorge 4



Flaming Gorge 2



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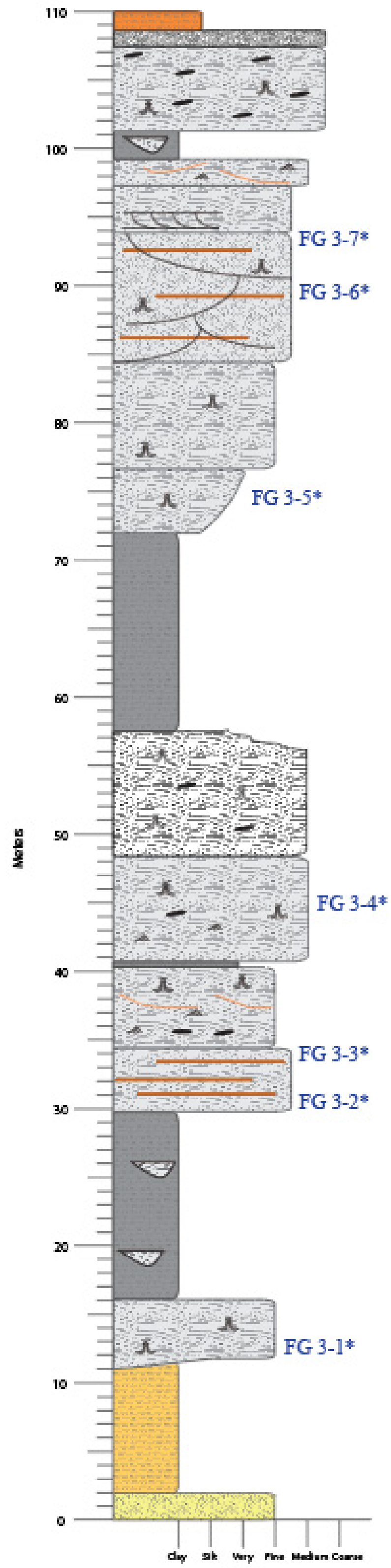

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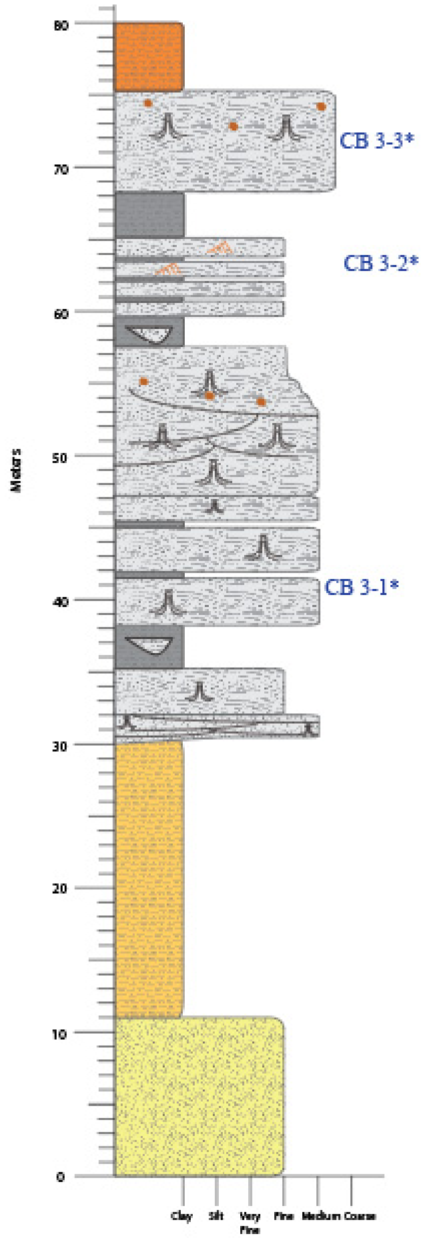
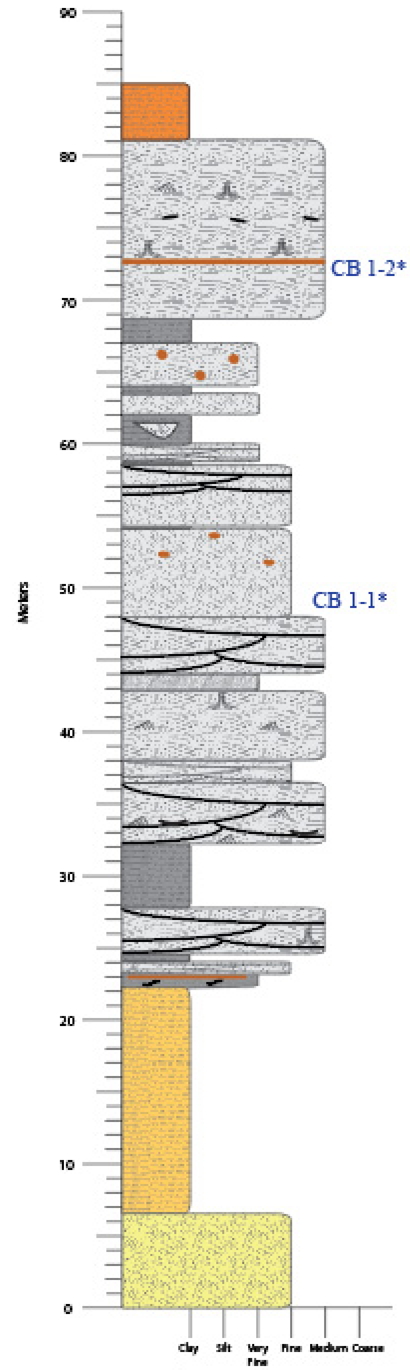
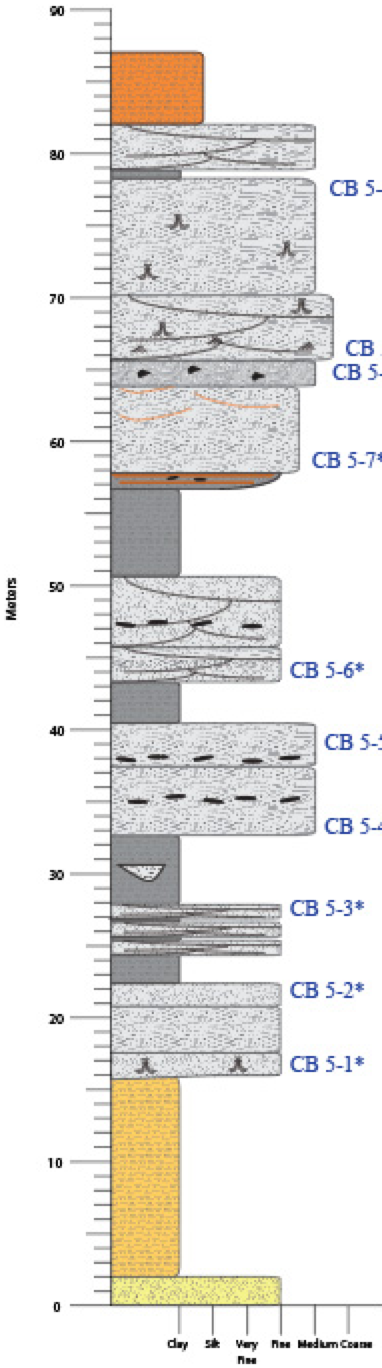


Clay Basin 3



Clay Basin 1



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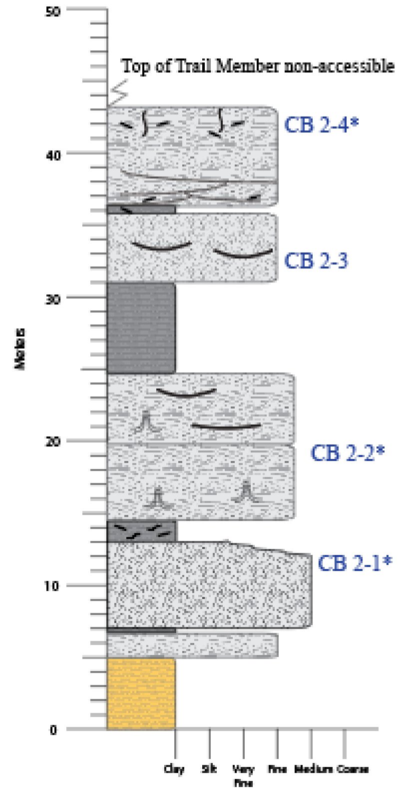

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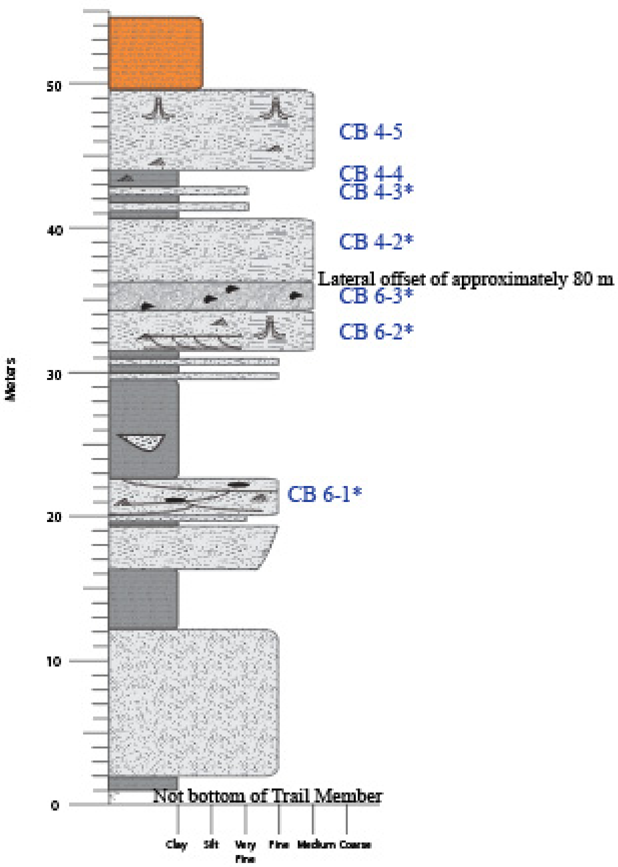

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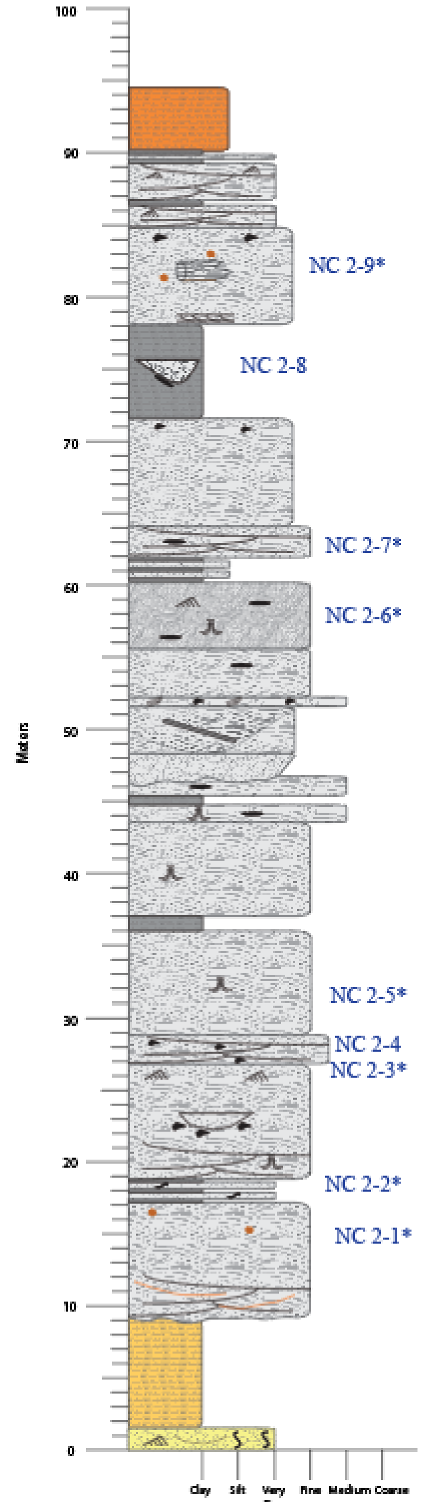
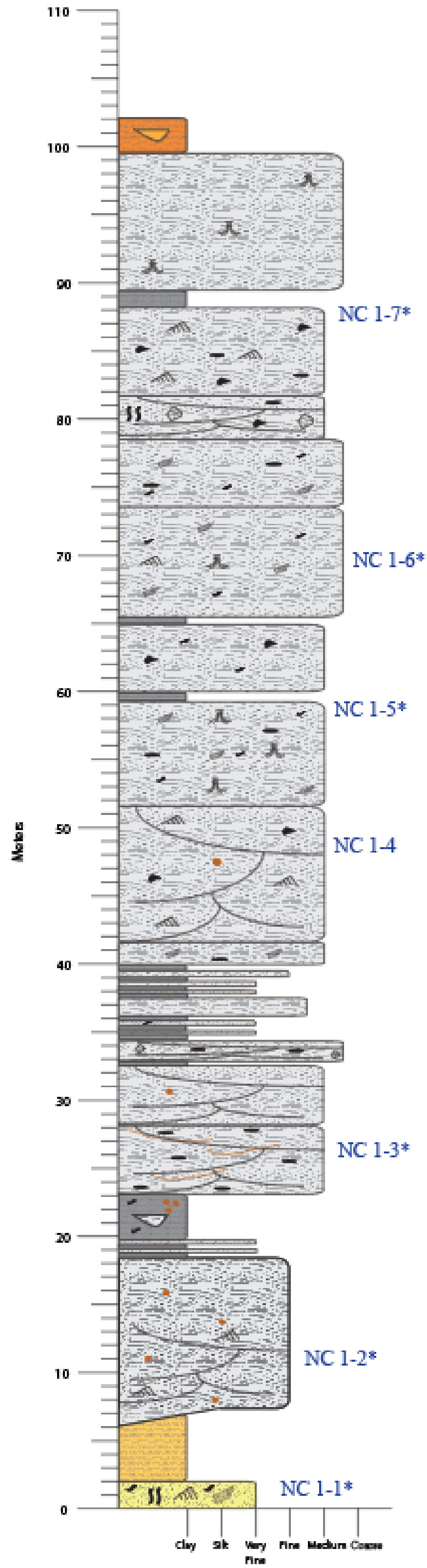


Northern Colorado 2



Northern Colorado 1