[PS]Preliminary Facies Analysis, Regional Sequence Stratigraphy and Distribution of Stratigraphically Controlled Mechanical Units of the Middle and Upper Williams Fork Formation, Piceance Basin, Colorado*

Michele Wiechman[1] and Jennifer L. Aschoff[1]

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[1]Department of Geology and Geological Engineering, Colorado School of Mines, Golden, CO (mwiechma@mymail.mines.edu)

Abstract

The Piceance Basin, northwest Colorado, is home to one of the most important basin-centered tight-gas accumulations in North American. A wide range of geologic controls is responsible for the variation in gas production from the heterogeneous, low permeability reservoirs here, but these controls are not well understood. Outcrop-to-subsurface stratigraphic correlation and detailed analysis of facies can elucidate potential stratigraphic controls on geographic and stratigraphic zones with better gas production. The objectives of this project are to:(1) characterize the specific types of fluvial and marine facies in the middle and upper Williams Fork Formation, (2) delineate the regional distribution of, and transitions between these depositional facies, (3) determine mechanical properties in these facies that affect fractures and (4) disentangle potential relationship between depositional and mechanical properties of the facies that may control gas production. Here, we present the first phase of the project including preliminary regional sequence-stratigraphic framework for the middle and upper Williams Fork Formation. The database focuses on outcrop data and consists of eight new detailed (10cm scale) measured sections, five published sections, six outcrop gamma-ray profiles, detailed facies and channel geometry descriptions, 3D channel dimension analysis, paleocurrent data and well-logs that were used to build regional cross-sections that identify regional stratigraphy. Thirty-one lithofacies were distinguished and grouped into six assemblages: (1) high-sinuosity, meandering fluvial, (2) isolated, low-sinuosity anastomosed fluvial, (3) tidally influenced fluvial, (4) estuarine, (5) regressive marine shoreline, and (6) transgressive marine shoreline barrier systems. The fluvial facies tend to be laterally extensive with variations in channel type throughout the basin while marine and tidal facies show lateral discontinuity in the northwestern sections of the Basin. Remote measurement of actual channel dimensions provides insight into potential controls on fracture development in various facies. Initial observations suggest that the anastomosed fluvial and marine shoreline facies have the most fractures with varying intensity in the facies. Future work will build on the array of detailed facies, sequence-stratigraphic context and fluvial channel dimensions to understand relationships between facies, fractures, and production from tight-gas sandstones.

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Wiechman, M.L and Aschoff, J.L
Department of Geology and Geological Engineering, Colorado School of Mines, Golden, CO 80401

1. Abstract

The Piceance basin, Northwest Colorado, is home to one of the most important basin-centered tight-gas accumulations in North American. A wide range of geologic controls are responsible for variation in gas production from the heterogeneous, low permeability reservior here, but these controls are not well understood. Out-crop-to-subsurface stratigraphic correlation and detailed analysis of facies can elucidate potential stratigraphic controls on geographic nd stratigraphic zones with better gas production. the objectives of this project are to: (1) characterize the specific types of fluvial and marine facies in the middle and upper Williams Fork Formation, (2) delineate the regional distribution of, and transitions between these depositional facies, (3) determine mechanical properties in these facies that affect fractures and (4) disentangle potential relationships between depositional and mechanical properties of the facies that may control gas production. Here, we present the first phase of the project including preliminary regional sequence-stratigrahic framework for the middle and upper Williams Fork Formation. The database focuses on outcrop data and consists of 8 new detailed (10cm scale) measured sections, 5 published sections, 6 outcrop gamma-ray profiles, detailed facies and channel geometry descriptions, 3D channel dimension analysis, paleocurrent data and well-logs that were used to build regional cross-sections that identify regional stratigraphy. Twenty-nine lithofacies were distinguished and grouped into six assemblages: (1) high-sinuosity, meandering fluvial, (2) isolated, low-sinuosity anastomosed fluvial, (3) tidally influenced fluvial, (4) estuarine, (5) regressive marine shoreline, and (6) transgressive marine shoreline barrier systems. The fluvial facies tend to be laterally extensive with variations in channel type throughout the basin while maarine and tidal facies show lateral discontinuity in the northwestern sections of the Basin. Remote measurement of actual channel dimensions provides insight into potenital controls on fracture development in variou facies. Initial observations suggest that the anastomosed fluvial and marne shoreline facies have the most fractures with varying intensity in the facies. Future work will build on the array of detailed facies, sequence-stratigraphic context and fluvial channel dimensions to understand relationshipds between facies, fractures, and production from tight-gas sandstones.

2. Scientific Questions

1. What was the basin-scale configuration and connection of depositional systems withing a sequence-stratigraphic framework? And, what were the type of depositional systems and their orientation?

2. Do the region-scale sedimentation trends help predict higher-than-average permeability zones?

3. Can sedimentation patterns be used to define trends in potential mechanical units that affect fracture development? If so, in which units and their distribution in the basin?

3. Geologic Background

Figure 1:

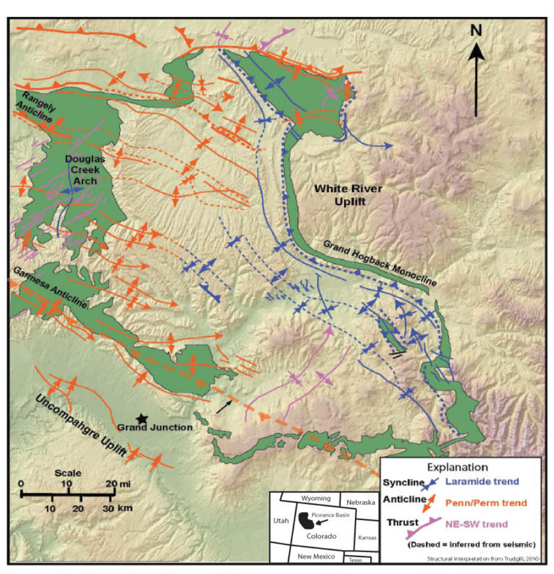

Figure 1: Map showing major structural features of the Piceance Basin, northwestern Colorado. Green shows the outcrop distribution of the Upper Cretaceous Williams Fork. (Modified from Trudgill, 2010)

Figure 2:

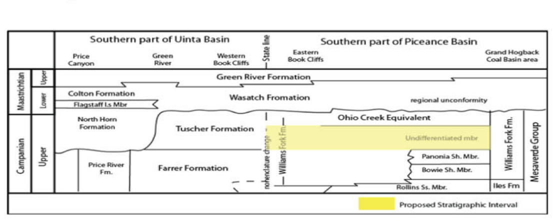

Figure 2: Stratigraphic column of the southern Uinta and Piceance Basins with pertinent stratigraphic units and their corresponding nomenclature. The Utah/Colorado state line corresponds with a name change from the middle and upper Williams Fork Formation to the Tuscher Formation. Interval of study is highlighted. (Modified from Hettinger and Kirschbaum, 2002)

Figure 3:

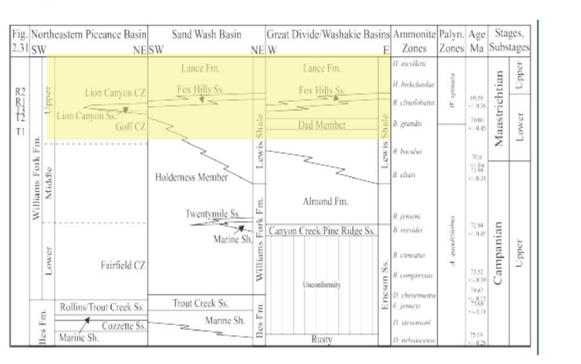

Figure 2: Regional stratigraphy of northwestern Colorado and southern Wyoming during the upper Campanian and Masstrichtian times. Interval of study is highlighted. (Modified from Cobban et al., 2006)

Figure 4:

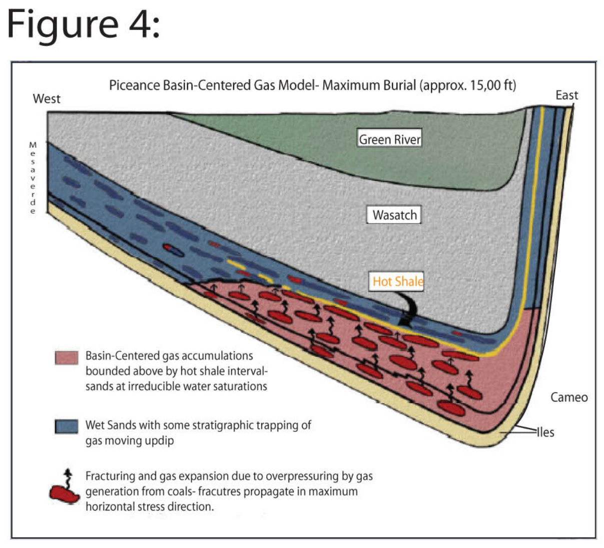

Figure 4: Schematic diagram of the Piceance Basin centered gas model. Maximum burial (approx 15,000 ft) allows for gas generation within the Illes and lower Williams Fork Formation. Fracturing within the Williams Fork Formation and gas expansion allows for movement of natural gas to sandstones within the middle and upper Williams Fork. (Modified from Cumella, 2008)

4. Methods

1. Define key Lithofacies, their porosity/permeability characteristics and sequence-stratigraphic context

2. Assign potential mechanical properties to lithofacies based on fracture types, spacing and abundance within each facies

3. Identify actual channel dimensions using remote data and geological interpretation programs

4. Petrological analysis of core samples to identify sequence-stratigraphic surfaces and sediment provenance.

5. Construct an outcrop-based, basin-scale stratigraphic framework based on outcrop and well log data.

5. Preliminary Datasets

Outcrop Dataset

* 6 Outcrop measured sections
*4 Outcrop Gamma Ray profiles
*30 Facies
* 6 Associations
* Paleocurrent data
*8 additonal outcrop profile sections identified

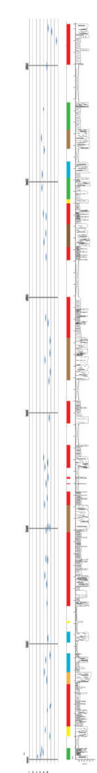

Figure 5: Outcrop meassured section from middle and upper Williams Fork Formation outcrops mear Meeker, Colorado. 10cm profile scale, outcrop gamma ray prfile, and facies associations identified

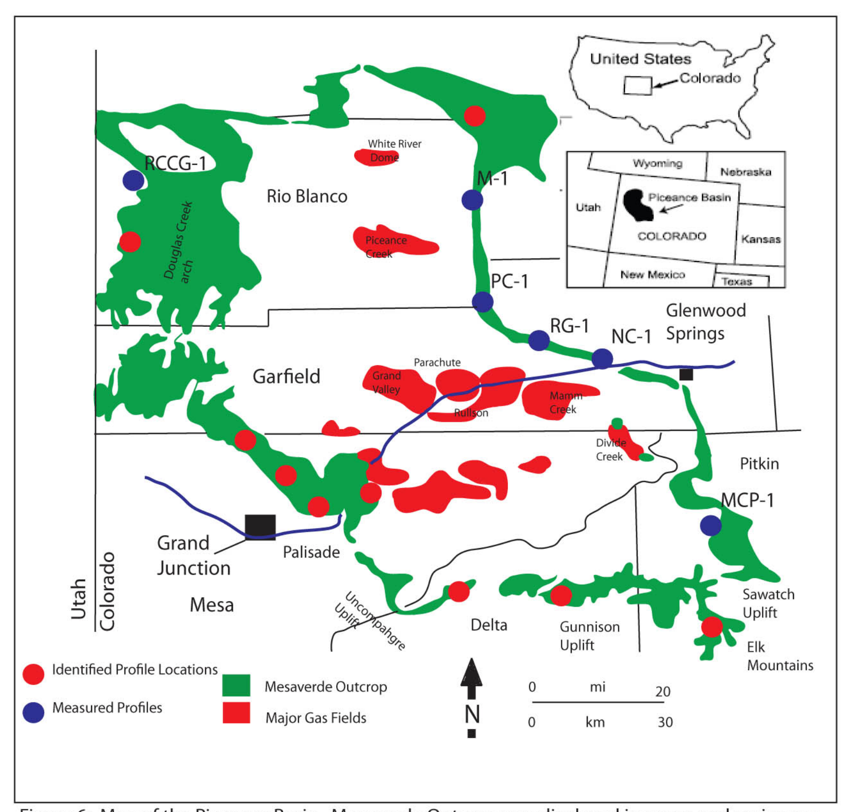

Figure 6: Map of the Piceance Basin. Mesaverde Outcrops are displayed in green and major gas fields are identified in red. Prevously measured outcrop profiles and future locations of measured profiles are identified. (Modified from Foster, 2010; Cole and Cumella, 2003)

Subsurface Dataset

* Over 6000 wells
*Over 200 wells with digital data
*Lower Williams Fork Formation sequence-stratigraphic framework.

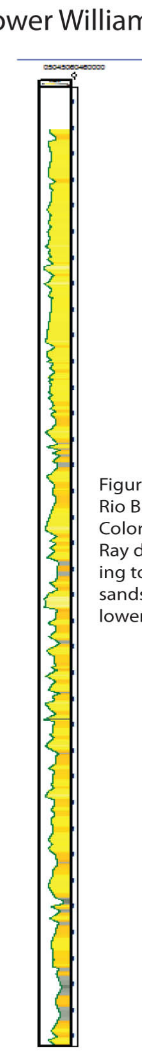

Figure 7: Gas producing well from Rio Blanco County, Piceance Basin, Colorado. Normalized digital Gamma Ray data is displayed with Geoshading to display the contrast between sandstones, shales, and coals of the lower Williams Fork.

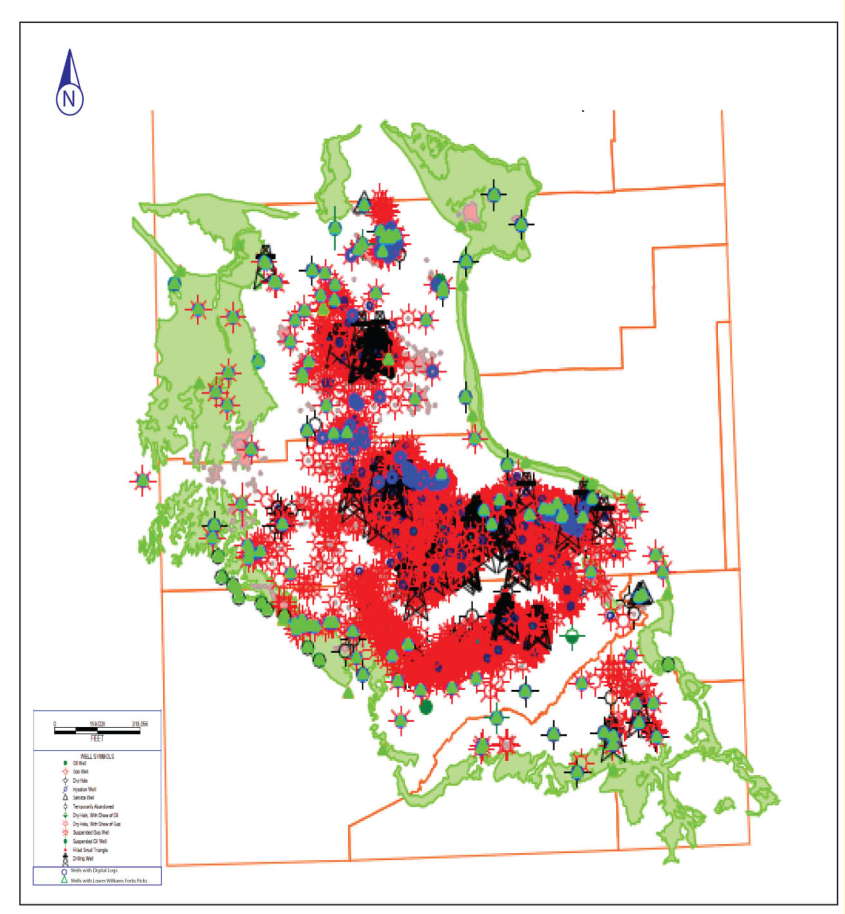

Figure 7: Map of the Piceance Basin. Mesaverde Outcrops are displayed in green and wells within the data base are posted. Wells with digital data are highlighted along with wells that were used to create a sequence-stratigraphic framework within the lower Williams Fork Formation.

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Wiechman, M.L and Aschoff, J.L

Department of Geology and Geological Engineering, Colorado School of Mines, Golden, CO 80401

6. Facies Analysis

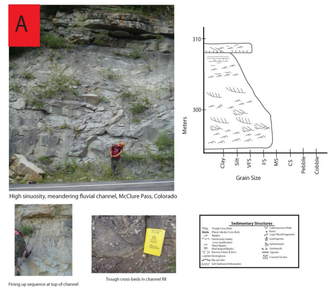
Fluvial Facies Identified in Stratigraphic Sections		
Facies	Description	Interpretation
1	Semi-continuous, irregular based, .3-.5m thick, thickens as move laterally, tan to grey sandstone, very fine grained to fine grained, Climbing current-ripple cross-laminations, Biotrubation at top, high lithic content.	Channel fill, high-sinuosity, meandering fluvial
2	Continuous, flat-based, 5-10m thick, amalgamated lenses of sandstone, lenticular, large scale planar-tabular cross-stratification with mud-drapes,ripples towards top of lenses, homogeneous fine grained.	Multilateral channel fill complex, Low-sinuosity meandering fluvial
3	Continuous, irregular based, .020-.030m thick, light grey mud with silty sand, horizontally laminated with small scale ripples towards top.	Distal floodplain deposits, meandering fluvial
4	Discontinuous, irregular based, dark grey lenticular sandstone, current-ripple cross-laminations with carbaneous mud-drapes.	Cravas splay of a high-sinuosity, meandering fluvial
5	Semi-continuous, irregular based 3-5m thick, amalagamated lenses of tannish grey sandstone, lenses seperated by silty mud with mud rip-up clast, current-ripple cross-lamination, trough cross-bedding towards base of lenses. Soft Sediment Deformation	Multistory channel fill complex, low-sinuosity anastomosed fluvial
6	Semi-continuous, flat based, .5-2m thick shale and sandstone, interbedded dark grey clay and silt with isolated lenses of structureless sandstone, trace tree toots, burrows, and petrified wood, mud rip-up clast seen above sandstone.	Floodplain deposits, meandering fluvial
7	Continuous, irregular basal contact, 2-5m thick, lenticular sandstone, surfaces overlain by larger interbedded cobble size clast of mud rip-up, clast current-ripple cross-lamination, in other parts of basin climbing current-ripple cross-stratification is seen, variable size trough cross-stratification, fining upward	Channel fill, low-sinuosity anastomosed fluvial
8	Semi-continuous, moderatly irregular based, .5-1.5mm thick (variable by location), tan grey very fine grained sandstone to medium grained sandstone, fining upward, lateral accretion sets with mudchips/ mud drapes on accretation set, current-ripple cross-lamination with mud drapes in some areas, petrified wood also possible	Top of channel fill, low-sinuoisty anastomosed fluvial
9	Semi-continuous to continuous, flat based, 3-5m thick, tan red fine grained sandstone with coarser boundaries, lateral accretation sets, rip-up clast and coarser grained current-ripple cross-laminations at base that increase in steepness as move up, trough cross-bedding. Soft sediment deformation. Fingers of interbedded mud/shale that increase in density as move upward. 24% Quartz, 70% feldspar, 5% lithcics	Channel fill, high-sinuosity, meandering fluvial
10	Discontinuous, irregular based, .5-1m thick, tan sandstone, current-ripples cross-laminations with muddrapes, low to upper fines, fining upward.	Floodplain deposits
11	Semi-continuous, irregular based, varying thickness .5-3m thick, dark tan to maroon sandstone, coarser grained, mud rip-up clast at base, fining upward, current-ripple cross-laminations with muddrapes, large scale trough cross-bedding, interbedded with fingers of mudstone/ silty clay shale.	Channel fringe, high-sinuoisty meandering fluvial
12	Semi-continuous to Discontinuous, irregular based, .5-1m thick, dark grey and black mud rip-up clast conglomerate, clast .010-.08m in size.	Alvusion channel, low-sinuosity anastomosed fluvial
13	Semi-continuous, irregular based, 5-10m thick, tan sandstone, lateral accretation sets, soft sediment deformation, mud rip-up clast at base, upper fine grained, trough cross-bedding, current-ripple cross-lamination with mud drapes, planar-tabular cross-stratification.	Channel fill, low-sinuosity anastomosed fluvial
14	Semi-continuous, flat based, tannish grey siltstone to fine grained and laminated with current-ripple cross-lamination, mud chips, interbedded 0-.1 thick sandstone, medium grained with trough cross-bedding.	Channel fringe, low-sinuoisty anastomosed fluvial
15	Discontinuous, irregular basal contact, 0.5m-1m algulmated lenses, upper fine grained to medium grained, fines upward to silt, soft sediment deformation, mud rip-up clast at base of lenses, trough cross-bedding, small scale ripple laminations, thick packages of *Teredolites* Ichnofacies	Channel fill, low-sinuosity anastomosed fluvial

Marine and Shallow Marine Facies Identified in Stratigraphic Sections		
Facies	Description	Interpretation
16	Semi-Continuous, sharp basal contact, thickly bedded, 3-5m, ripple cross-lamination, planar tabular cross-stratification, upper fine grained,possible hummocky-swelly cross-stratification coarsing upward, 60% feldspar, 30% quartz, and 10%lithics	Middle marine shoreface
17	Continuous, gradational contact from below, thinnly bedded, grey siltstone to very fine grained sandstone with hummocky cross-strata	Shallow marine, upper shoreface
18	Continuous, irregular based, 0.20-1m, tan to red, clay to very fine-grained sandstone, structureless, *Inoceramus* and *Brachiopods* bivalve stratified layer (concave down) , thin layer of gypsum	marine, lower shoreface
19	Continuous, thinnly bedded interbedded sand and fine silt, .03-.05m, where sedimentary structures preserved see wave ripples, soft sediment deformation, moderate concertation of *Skolithos* trace fossils, layer of gypsum	Shallow marine, upper shoreface

Tidal Facies Identified in stratigraphic Sections		
Facies	Description	Interpretation
20	Continuous, flat-based, .030-.050m thick, greenish-grey structureless mudrock with interbedded local lenses of ripple cross-laminated sands that are .050m thick, local flaser bedding at top of interval with localized bidirectional ripples, soft sediment deformation, clay coarsing up to very finegrained sandstone. 70% Quartz, 10% feldspar, and 20% lithics.	Tidal flats
21	Semi-continuous, irregular based, .010-.020m thick, tan to grey sandstone, very fine grained to fine grained, planar-tabular cross-lamination drapped with mud and carbaneous material, herringbone structure, Subrounded .10% Quartz, 15% feldspar, and 15% lithics.	Lower tidal flats
22	Discontinuous, irregular based, .005-.010m thick, tan, very fine grained to fine grained sandstone, constant grading, current-ripple cross-laminations with mud drapes, local mud rip-ups	Cravas splay of a high-sinuosity, meandering fluvial
23	Continuous, flat-based,dark grey shales, clay with minor silt, grades up to a mudstone and silt, structureless, soft sediment deformation, variable organic	Tidal flats
24	Semi-continuous, irregular based,coarsens upwards from loaded clay and silt to very fine grained tan sandstone, flaser bedding at base with trough cross-stratification as move towards top of sandstone, 0% Quartz, 30% feldspars, 10% lithics	Tidal delta
25	Discontinuous, flat basal and top contacts, .015-.020m thick, very fine grained, symetrical current-ripple cross-lamination.	mouth bar-estuarine
26	Semi-continuous, flat-based, 2-4m thick, amalgamated lenses of sandstone, tan to grey, very fine grained, coarsing upward within lenses, Trough cross-stratification towards top of lense, planar-tabular cross-stratification at base, ripples with carbaneous mud-drapes, soft sediment deformation. root traces at top of facies	Eustraine channel fill
27	Continous, flat-based, tan/red shale due to the sand, interbedded thin sand with slight planar-tabular cross-stratifcations. Shale has coal like apperance but does not break like coal	Edge of Upper flow regium sand flat, Estuarine
28	Continuous, moderate flat based, dark grey mudstone and interbedded black shales, lenticular, mud rip-up clast at basal contact, wood and root traces.	Tidally Influenced-anastomosed fluvial
29	Semi-continuous, gradual basal contact, 1-3m thick, tannish grey sandstone, lateral accretation sets, large scale trough cross-bedding with mud-rip up clast., planar-tabular cross-stratification, small scale climbing current-ripple cross-lamination, flazer bedding, hummocky.	Tidally Influenced-meandering fluvial
30	Semi-Continuous, tan to red color, fine to very fine-grained sandstone,lenticular, rip-up clast at very base, orientientated wood fragments, trough cross-bedding, planar-tabular cross-stratification, Teredolites (elongate cyclindrical burrows into a wood substrate) burrows perserved.	Delta Channel

7. Facies Associations

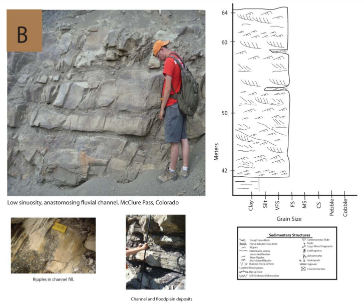
Symbol	Interpretation	Description	Associated Facies	Fracture Intensity
A	High-sinuosity, meandering fluvial	Semi-continuous, irregular based units, 1 to >25 m thick, tan to light grey, current ripple cross-laminated sandstone. Locally interbedded with structureless sometimes rooted mudstones. Coarse sand to mud rip-up conglomerate near base of scalloped lenticular sandstone bodies. Typically has a fining up trend, however can have a blocky stacking pattern. Lateral accretion sets, with cross trough and planar trabular strata. Interbedded fine grains are structureless to horixontal lamination, locally interbedded coals. Root traces, woody/plant material are commonly found.	1,2,3,4,5,6,8,9,10, 11,12	high fracture intensity
B	Isolated, low-sinuosity anastomosed fluvial	Discontinuous to semi-continuous, irregular based units, 1 to > 7m, tan to light grey, lenticular-shaped, fine to medium sandstone. High clay clast concentration and woody fragments near base of scalloped surfaces. Typically has thicker interbedded clay and silt to very fine grained sandstone packages with root traces/ woody debris. Current ripple laminations, planar-tabulr stratification, trough cross-laminations can be seen.	5,7,8,9,10,11,12,1 3,14, 15	moderate fracture intensity
C	Tidally Influenced fluvial	Semi-continuous, flat based with locally irregular based beds, lenticular-shaped, 1-15m, light tan to grey with dark grey and black interbedded, wavey/flaser bedded with high presence of muddrapes, bidirectional ripple cross clminations are preserved. Teredolites burrows perserved at base of channels. Typically showing a coarsing upward pattern.	21,24,25,26,27,28, 29	low facure intensity
D	Estuarine, tidally influence delta, nearby swamps	Semi-continuous, flat based, 1-10 m thick, very fine to fine grained, flaser/wavy/lenticular bedding with muddraped, bidirectional planar tabular and trough cross strat, Typically show an overal coarening up pattern.	20,21,22,23,24,25, 26,30	low fracuture intensity
E	Regressive marine shoreline	Continous, flat based, 3-5 m thick, fine to medium grained sandstones. Hummocky-swelly cross-stratification seen, coarsing upward pattern.	16,18,19	moderate fracture intensity
F	Transgressive marine shoreline barrier	Continous, flat based, 1 to >4m, silt to fine sandstone. Hummocky-swelly cross strata to structureless. Variable concentrations of Inoceramus and Brachipods bivalves, and Skolithos trace fossils	17,18,27,29	low fracture intensity



High sinuosity, meandering fluvial channel, McClure Pass, Colorado

Fining up sequence at top of channel

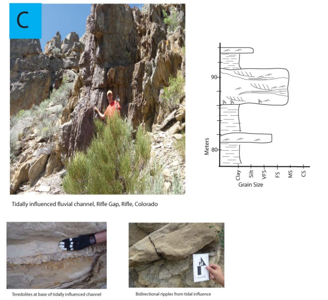
Trough cross-beds in channel fill



Low sinuosity, anastomosing fluvial channel, McClure Pass, Colorado

Ripples in channel fill.

Channel and floodplain deposits



Tidally influenced fluvial channel, Rifle Gap, Rifle, Colorado

Teredolites at base of tidally influenced channel

Bidirectional ripples from tidal influence

Estuarine, tidally influenced delta, Piceance Creek, Colorado

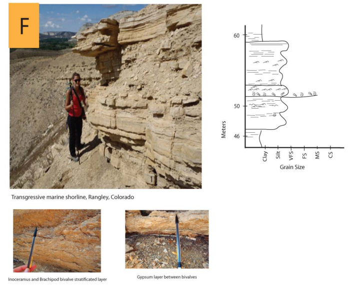
Bi directional ripples and mud deposits during slack periods

Top of delta sequence

Regressive marine shoreline, Rangley, Colorado

Hummocky stratification

Hummocky/Swelly stratification

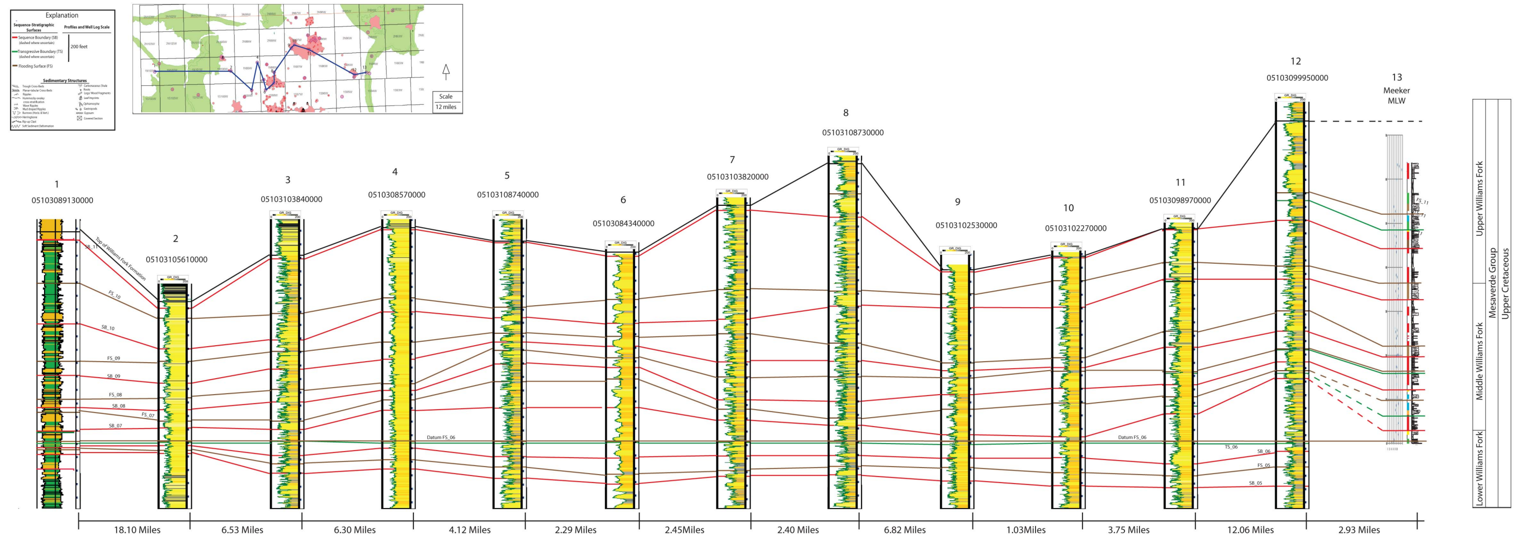


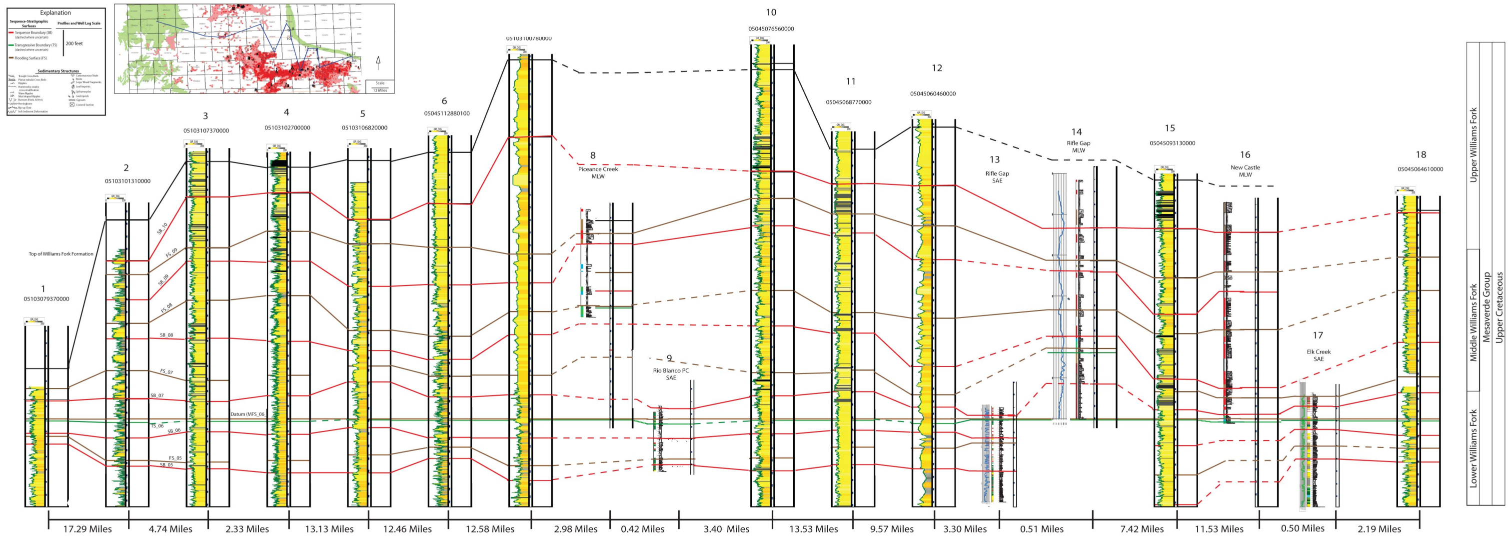
Transgressive marine shorline, Rangley, Colorado

Inoceramus and Brachipod bivalve stratificated layer

Gypsum layer between bivalves

8. Preliminary Correlations





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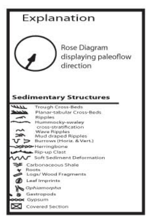
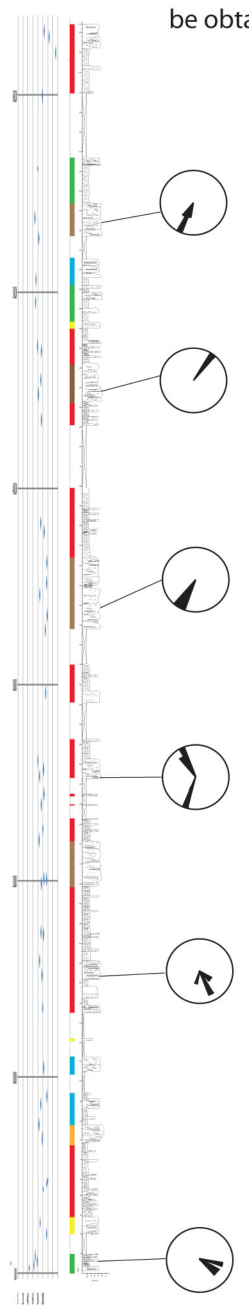
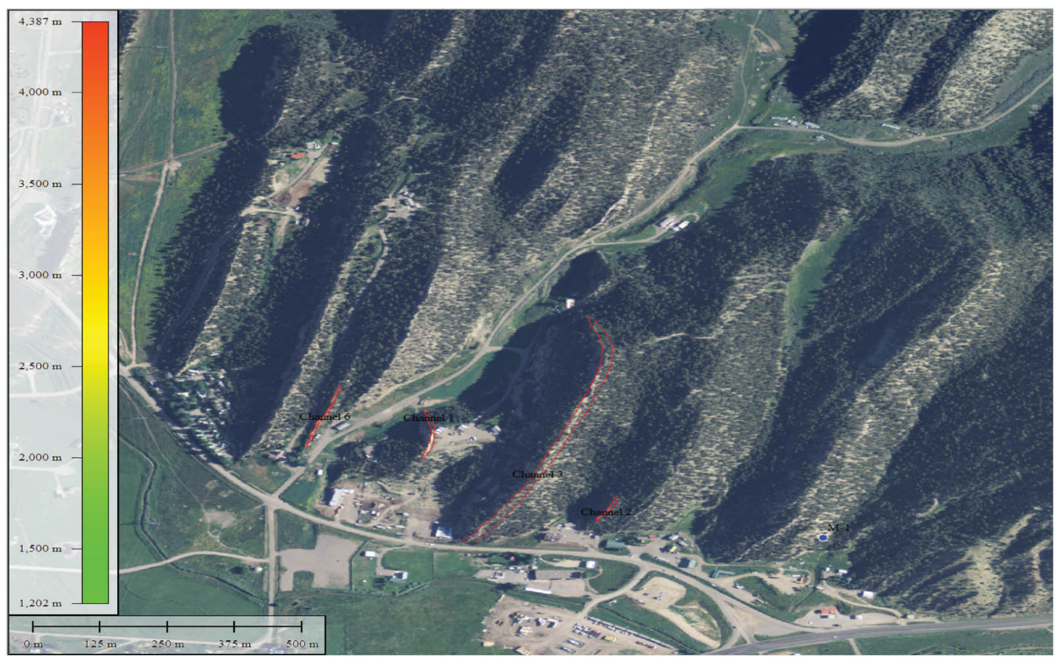
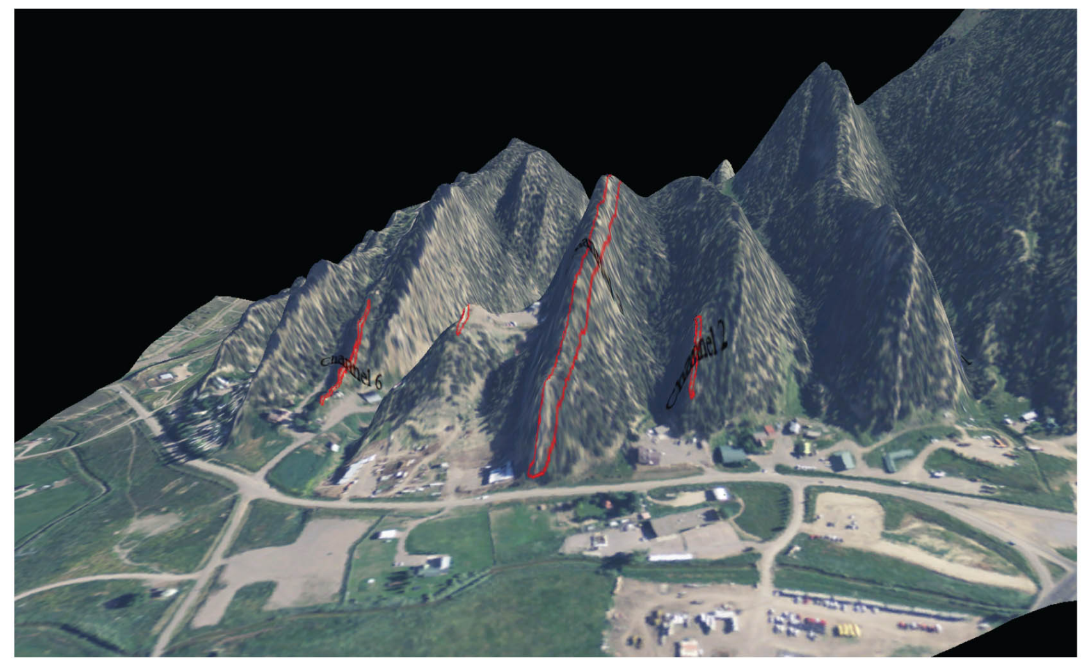
9. Actual Channel Dimensions- Workflow



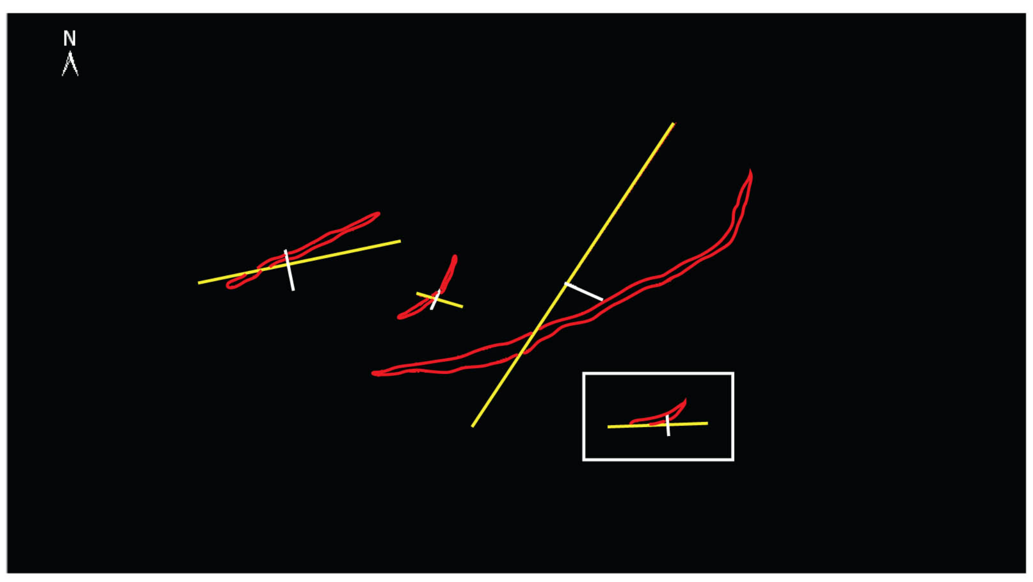
Measuring channel dimensions in the field can only give us an apparent size, however using paleocurrents and a variety of programsactual dimensions can be obtained

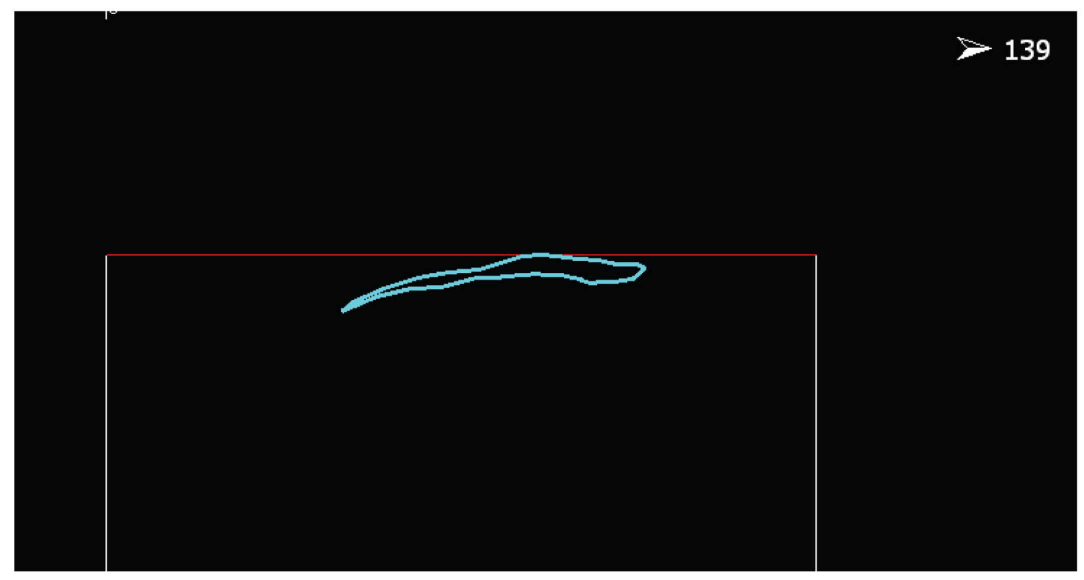






Using a mapping software, such as GlobalMapper, and high resolution DEM and aerial photos it is possible to pick out individual channel bodies or channel complexes. This allows us to determine the apparent channel dimensions, much like in the field. When combined with elevation data, the channel boundries can be placed into a structural software package and the actual channel dimensions can be determined.





Bringing the apparent channel dimensions and elevation data into a structural modeling program such as Move allows us to determine the actual channel dimensions before erosion. By applying the paleocurrents measured in the field it is possible to project the channels onto a section that is perpendicular to flow. This projection allows us to determine the actual channel dimensions instead of the apparent dimensions that are normally measured in the field.

10. Conclusions

*Detailed litofacies analysis aids identification of high frequency flooding surfaces that enhance correlation.

*Study supports the suggestion that the Williams Fork Formation changes from meandering fluvial systems to anastomosed systems.

*Fluvial facies are laterally extensice with variations in channel types while marine and tidal facies show lateral discontinuity in the northwestern sections of the Piceance Basin.

*Thinning in the middle and upper Williams Fork possible due to uplift of the Uinta Mountains and movement on the Uncomprage Uplift.

*Initial observations suggest the anastomosed fluvial, meandering fluvial and marine shoreline facies have the most fractures with varying intensity in the facies.

* Determining actual channel dimensions gives us a better understanding of the size of reservoirs and their extent in the subsurface.

11. Future Work

*Continue measuring stratigraphic profile sections, along with obtaining outcrop gramma-ray (GR) data, in the northwest, southwest, and southeast margins of the Piceance Basin.
6-9 new sections

*Continue to combine stratigraphic profiles with GR to recognize key sedimentary packages and bounding surfaces from outcrop to correlate into the basin using PETRA.

*Obtain fracture measurments in the field including; fracture type, spacing, and orientation.

*Petrographic analysis from Core to determaine Provenance and reservior heterogenity.

*Obtain channel dimensions throughout the Piceance Basin using remote software workflow presented above.

*Combine depositional isopach maps and production data to determain relationships between depositonal zones and facies to production maps to determine if zones we believe to be productive are extensive throughout the basin.

*Combine depositional isopach maps and and fracture occurence maps to determine mechanical properties that control gas production.

12. References

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