

REGIONAL OUTCROP CORRELATION
OF THE NIOBRARA FORMATION
NORTHWESTERN COLORADO

by
Kelly Bruchez

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Golden, Colorado

Date _____

Signed: _____
Kelly Bruchez

Signed: _____
Dr. Stephen A. Sonnenberg
Thesis Advisor

Golden, Colorado

Date _____

Signed: _____
Dr. John D. Humphrey
Professor and Head
Department of Geology and Geological Engineering

ABSTRACT

The purpose of this research was to measure, describe, and correlate the Niobrara Formation in northwestern Colorado using four outcrop measured sections: New Castle, Wolcott, Kremmling, and Delaney Buttes. All four outcrops are located on the margins of their respective basins (Piceance, Eagle, Middle Park, and North Park basins) creating reference sections with nearby well logs. The study interval is the Juana Lopez calcarenite to the basal Pierre Shale (Mancos Shale).

Once all the data was collected several major observations were made. There is a distinct lithology change in the Juana Lopez calcarenite from south to north across the study area. The chalks and marls of the Smoky Hill Member of the Niobrara Formation thicken from east to west from the Denver-Julesburg Basin to the Piceance Basin. The changes in thickness and lithology of the study interval are interpreted to have been caused by the Transcontinental Arch. Disappearance of ammonites and foraminiferal biozones are evidence of an unconformity exists at the base of the Juana Lopez. Thinning of the Storm King Mountain Shale from New Castle to Kremmling is evidence of a subtle unconformity at the base for the Fort Hays Limestone. The topographic profile of the Transcontinental Arch is not well understood. The changes in thickness and lithology of the study interval indicate movement along the Arch during time of deposition. The thinning observed in the Storm King Mountain Shale indicates a vertical relief of up to 200 feet for the Arch. The vertical relief of the Arch could have restricted clastic sediment to the west side of the Arch.

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CHAPTER 1

INTRODUCTION

The Niobrara Formation was deposited in the Western Interior Cretaceous seaway (Figure 1.1) over a period of 6 million years from Late Turonian to Early Campanian time (Roberts and Kirschbaum, 1995; Locklair, 2007; Kauffman, 1977; Obradovich, 1993; Scott and Cobban, 1964). From east to west across Colorado the Niobrara Formation displays a major change in lithology as limestones and chalks in eastern Colorado give way to calcareous and clay-rich shales in western Colorado (Figure 1.2) (Sonnenberg, 2011; Longman et al., 1998). Lateral changes in lithology are mainly caused by the proximity to the source of detrital clay and silt in the west.

There is little information available documenting lithofacies within and below the Niobrara Formation in northwestern Colorado. The lithology changes occur over a large distance making nomenclature difficult to assign. Fisher et al. (1985) compared western Colorado Fort Hays Limestone and Juana Lopez calcarenite sections at New Castle and Wolcott to several Front Range sections. However, most of the correlations of Fisher et al. (1985) pertain mostly to biostratigraphy, biofacies, and do not correlate above the Fort Hays Limestone. The gross lithologic changes occur over a large vertical and horizontal distance making them difficult to observe.

1.1 Purpose and Scope

The purpose of this research was to measure, describe, and correlate the Niobrara Formation in northwestern Colorado using four outcrop measured sections: New Castle, Wolcott, Kremmling, and Delaney Buttes. All four outcrops are located on the margins of their respective basins (Piceance, Eagle, Middle Park, and North Park basins) (Figure 1.3, 1.4

and 1.5). The study interval includes the Juana Lopez Formation to the basal Pierre Shale (Mancos Shale).

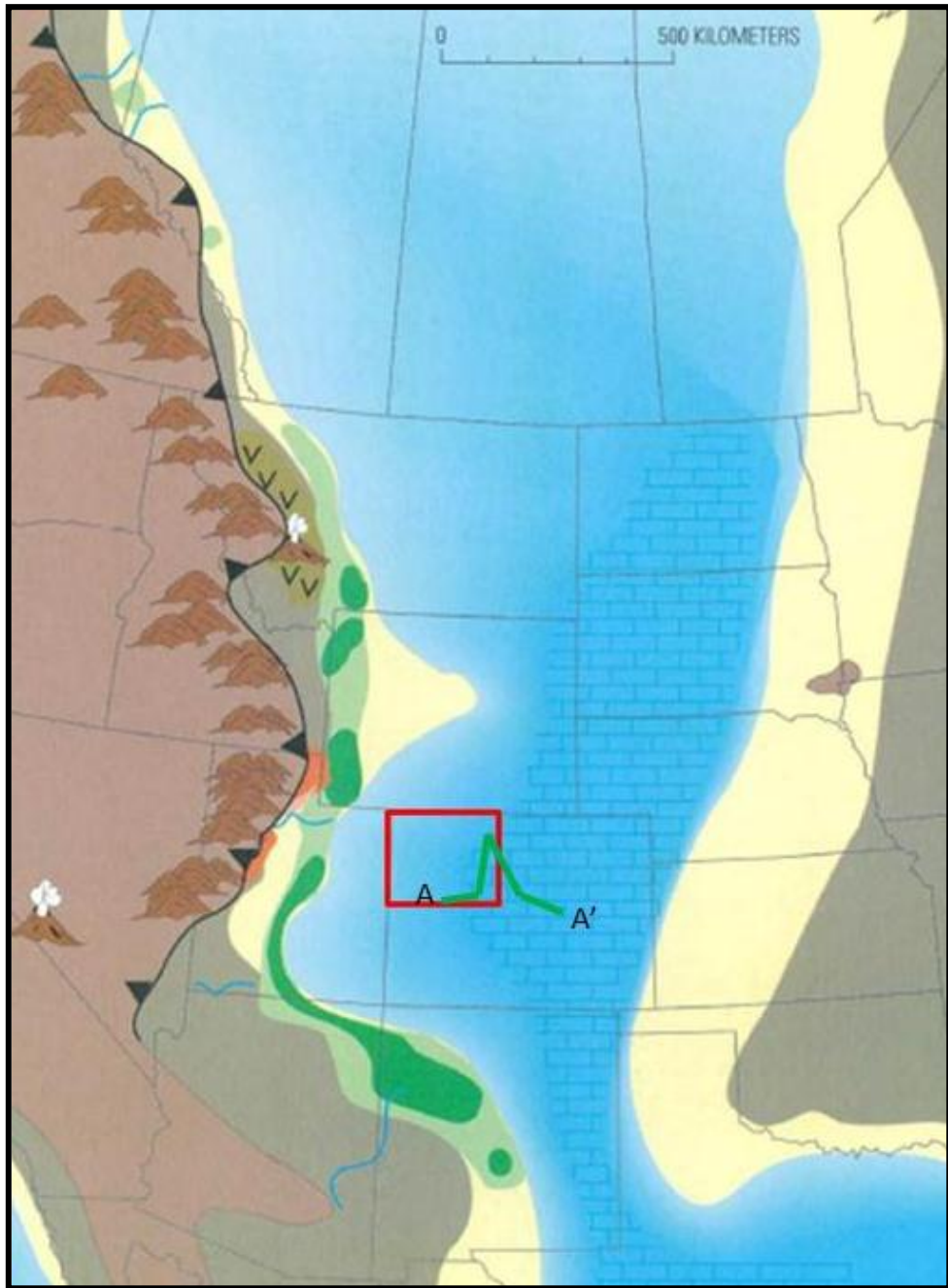


Figure 1.1 Paleogeographic reconstruction of the Cretaceous seaway during the Coniacian-Santonian time (from Roberts and Kirschbaum, 1995). Red box is the study area. Green line represents Plate 1A, 1B, and 7 line of section.

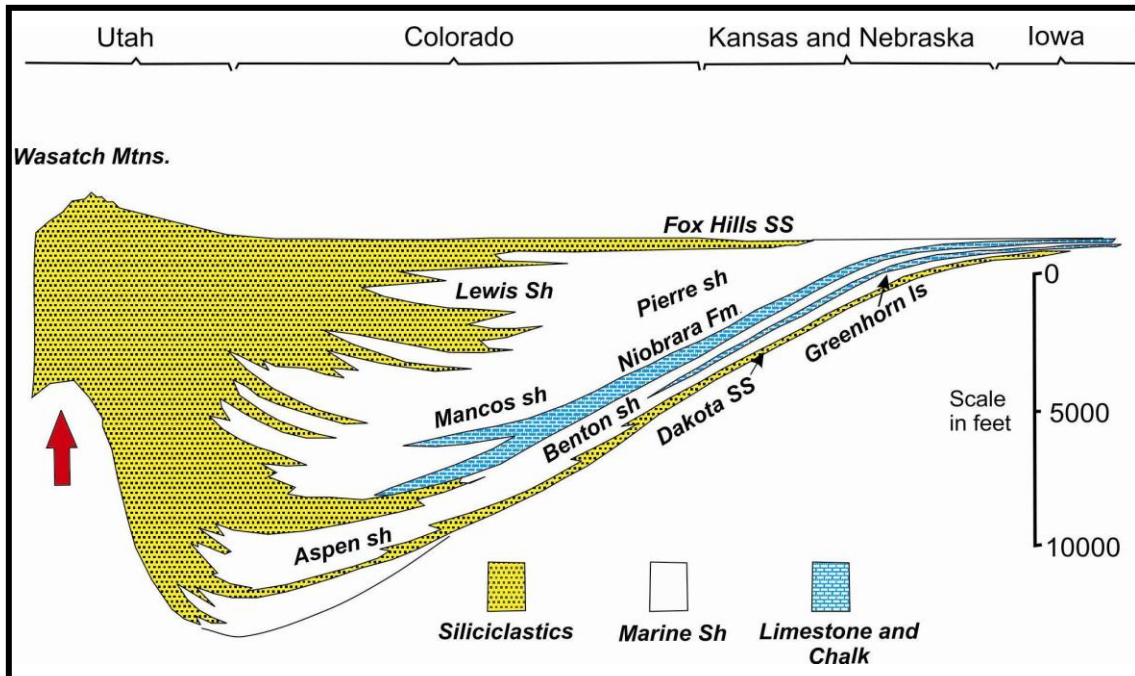


Figure 1.2. Schematic cross-section across the Western Interior Cretaceous Basin (modified from Kauffman, 1977). Note the increasing siliciclastic content from east to west (Sonnenberg, 2011).

A secondary purpose of this study was to compile a reference measured section and a surface GR profile for the eastern Piceance, Eagle, Middle Park, and North Park basins. A reference well log was compiled for the Piceance, Eagle, Middle Park, and North Park basins by using a nearby subsurface well log. In some instances the nearest well log was up to 30 miles away.

The Juana Lopez was used as a regional tie-in because of its very distinct appearance in outcrop, well logs, and is present at each of the four locations. The top of the study interval is the basal Pierre Shale or Mancos Shale. It is difficult to determine the exact contact between the Niobrara Formations and the Pierre Shale in outcrop. Typically there is a change in topography near the contact due to the change in lithology from the Pierre Shale to the Niobrara Formation. On subsurface well logs the top of the Niobrara Formation is marked by an increase in resistivity.

1.2 Outcrop Locations

The outcrop measured sections were chosen for three reasons: 1) outcrop quality, 2) proximity to current exploration (location), and 3) little to no research has been completed on the outcrops (Figures 1.3, 1.4 and 1.5). First, the measured sections are from the best outcrops within the study area. The Niobrara inherently weathers to poor exposures, so finding well exposed sections of the entire interval can be difficult. Second, the outcrops are located near current Niobrara exploration. Current exploration provided the subsurface well log data needed to tie measured sections back to the subsurface.

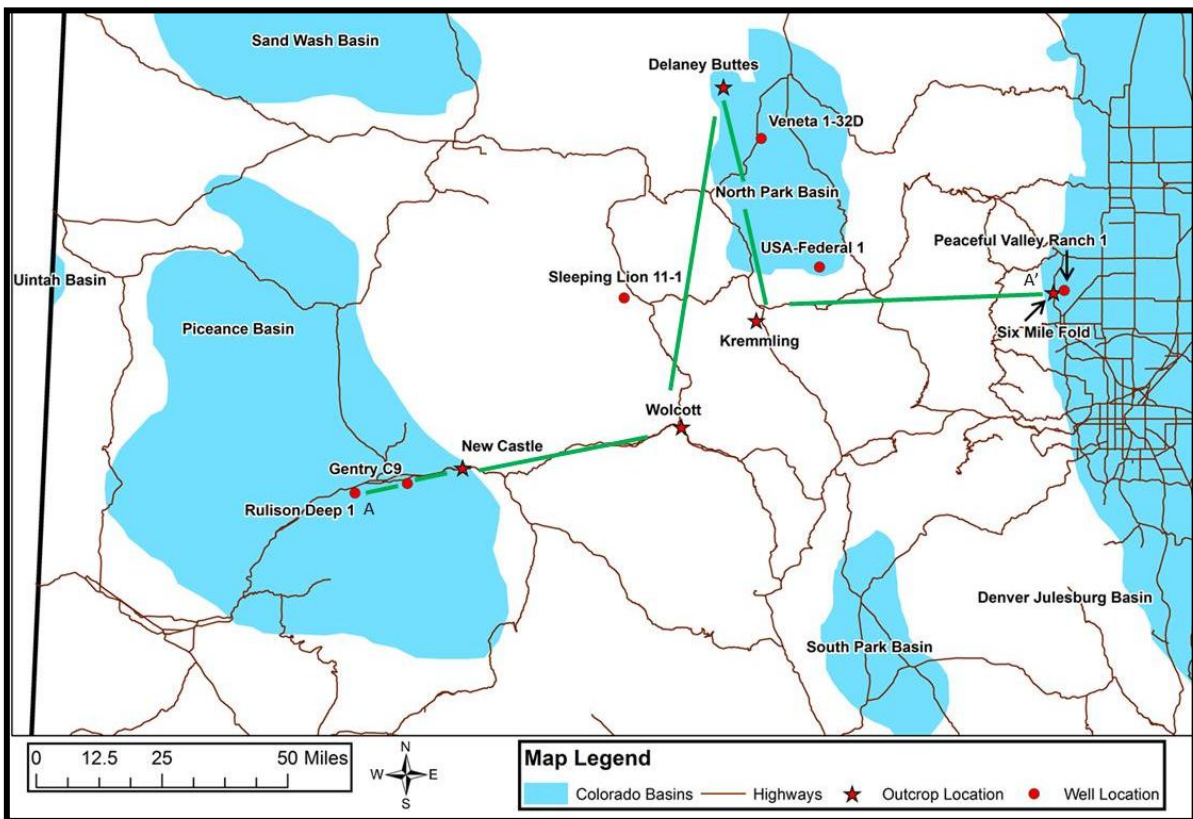


Figure 1.3. Map of the major Colorado basins and Oil & Gas fields from the Colorado Oil and Gas Conservation Commission (COGCC) website. Outcrop study locations are shown as red stars the locations of the wells used shown as red circles (note the relative location to Six Mile Fold). Also shown are the major freeways. Green line represents Plate 1A, 1B, and 7 line of section.

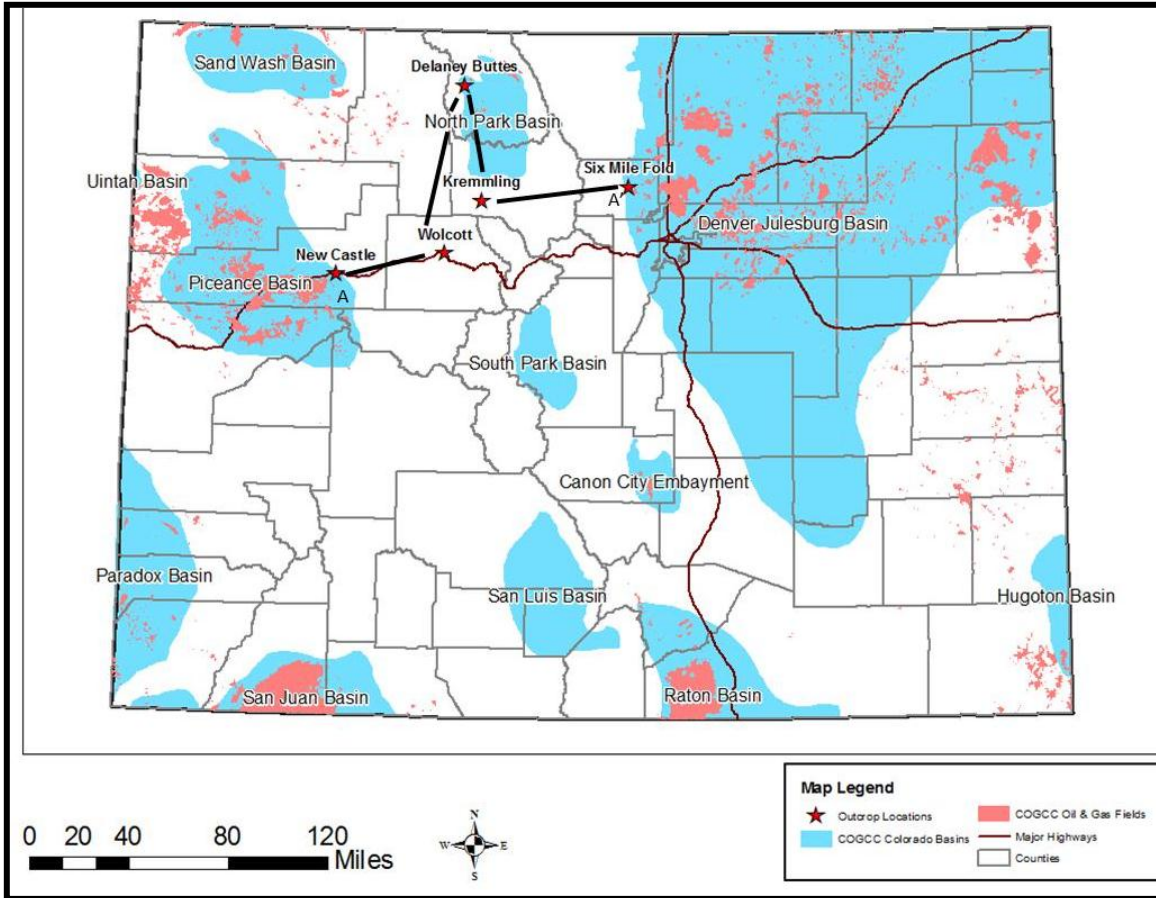


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The proximity of outcrops to the subsurface also allows for future studies to be conducted and easily tied back to the subsurface. Finally, there has been little to no research completed for each of the four measured sections. The measured sections are intended to be used as reference studies for future research.

1.3 Previous Research

The Niobrara Formation was named by Meek and Hayden in 1862 at the type location along the Missouri River in Knox County, Kansas (Mallory, 1977). Meek and Hayden (1862) defined the Niobrara Formation as lead-gray calcareous marl that weathers to white or chalky limestone. The Niobrara in the Rocky Mountain region is similar to the type location, but

contains an increasing amount of siliciclastic content and a decreasing amount of limestone and chalk content from east to west (Figure 1.1) (Mallory, 1977; Sonnenberg, 2011; Longman et al., 1998). On subsurface well logs the top of the Niobrara Formation can be distinguished in the thick Upper Cretaceous shale sequence by a noticeable increase in the resistivity log response (Plate 1a and 1b) (McAuslan, 1959). The increase resistivity is caused by an increase in carbonate content and, possibly, cemented fractures (Saterdal, 1955; Vincelette and Foster, 1992). The carbonate content is primarily composed of coccolith rich fecal pellets and inoceramids (Hattin, 1974). The coccoliths were concentrated as fecal pellets by herbivorous planktonic organisms that fed mainly on coccolithophorids (Hattin, 1974).

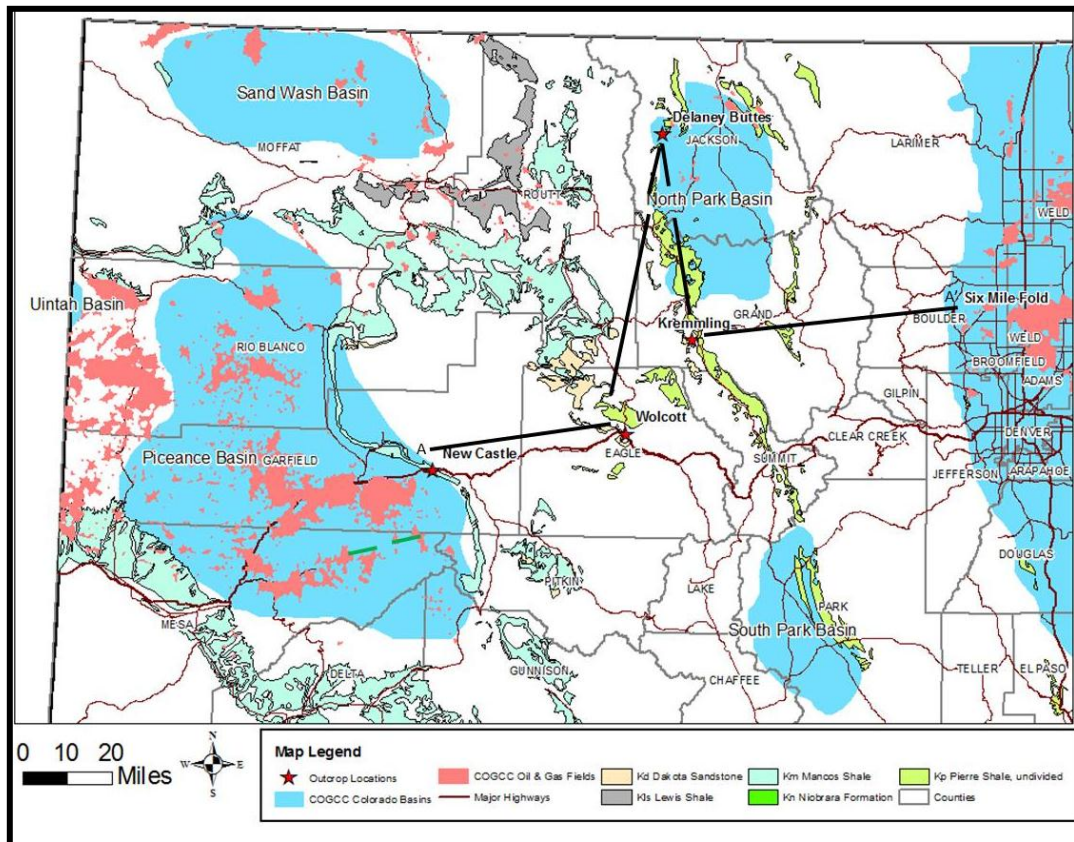


Figure 1.5. Map of greater northwestern Colorado showing import Cretaceous units mapped by the U.S.G.S. Outcrop study locations are shown as red stars (note the relative location to Six Mile Fold). Also shown are the counties and major roads. Black line represents Plate 1A, 1B, and 7 line of section.

Cobban and Reeside (1952a, 1952b) laid the basic stratigraphic framework for many studies by assigning ages to Cretaceous marine and non-marine rocks across several structural basins. Weimer (1959, 1960) contributed a great deal to the early understanding of stratigraphic and chronologic concepts. King (1965) measured nearly three dozen outcrops around Colorado and northern New Mexico focusing on the biostratigraphic zonation of the Fort Hays Limestone. Both Kent (1968) and Von Holdt (1978) measured multiple outcrop sections of the Niobrara Formation in northwestern Colorado focusing on the biostratigraphy. Izett (1973) mapped the Kremmling Quadrangle area in great detail creating a biostratigraphic column highlighting the faunal zones found in the Cretaceous System (Plate 2). Von Holdt (1978) in conjunction with Kauffman and Hattin (1982) proposed the type locality for the Storm King Mountain Member of the Mancos Shale be New Castle Colorado based on microfauna studies. Kauffman (1967, 1969, 1977, 1984, and 1985) continued previous work on the Niobrara Formation and Cretaceous Western Interior Seaway by including tectonic and eustatic controls. Kauffman also contributed to the understanding of the paleoecology and paleoceanography of the Cretaceous Western Interior Seaway. Dunn (1992) focused on the nannofossil biostratigraphy of the Fort Hays Limestone at Wolcott. Cushman (1994) focused on the palynostratigraphy of the Mancos Shale in western Colorado. Fisher et al. (1985) concentrated on the biofacies associated with the hemicyclothem of the Niobrara. Kuzniak (2009) concentrated on the stratigraphy, geochemistry, and petrophysics of the Lower Mancos Shale pertaining to Douglas Creek Arch. Charzynski (2010) focused on the stratigraphy, geochemistry, and petrophysics of the Niobrara Formation within the North Park Basin.

A review of the literature revealed that there was no published reference measured section of the Niobrara Formation in northwestern Colorado. The Rocky Mountain Association of Geologists (RMAG) Research Committee (1978) published regional subsurface cross-sections across Colorado. However, the published cross-sections are very large scale and do not subdivide the Niobrara Formation out into formal subunits or intervals. Finn and Johnson (2005) looked at the Niobrara petroleum system for the Greater Green River Basin but none of the work was ever tied back to outcrops. There was a need for reference measured sections of the Niobrara Formation in northwestern Colorado: thus the focus of this thesis.

1.4 Stratigraphy of the Niobrara Formation

The stratigraphy of the Niobrara Formation in northwestern Colorado is rather complex. West of the Denver-Julesburg Basin the lithologies change which caused problems correlations and nomenclature changes. To complicate the issue there are differing views of what point does the naming convention need to change for the Niobrara and underlying stratigraphy; much of which is beyond the scope of the discussed research. Only previously published nomenclature was used in this paper; no new names were added.

O'Boyle (1955) did not recognize the Niobrara Formation as a member of the Mancos Formation. Fisher (2007) divided the Mancos into several members including the Niobrara equivalent. For the purpose of this research the Niobrara has been broken down into two members, the Fort Hays Limestone and Smoky Hill Members. Kuzniak (2009) had less stratigraphic resolution than Fisher (2007) because Kuzniak used fewer intervals for the Lower Mancos Shale. The proposed nomenclature for the discussed research subdivides the Niobrara Formation into the Fort Hays Limestone Member and the Smoky Hill Member

(Figure 1.6). The Smoky Hill Member is further divided into six intervals. The six intervals proposed are Lower Marl, Lower Chalk, Middle Marl, Middle Chalk, Upper Marl, and Upper Chalk (Figure 1.6).

System	Series	Stage	Proposed Nomenclature		
CRETACEOUS	LATE	CAMPANIAN	MANCOS OR PIERRE SHALE		
		SANTONIAN	UPPER CHALK	SMOKY HILL MEMBER	NIOBRARA FORMATION
			UPPER MARL		
			MIDDLE CHALK		
			MIDDLE MARL		
			LOWER CHALK		
			LOWER MARL		
		CONIACIAN	FORT HAYS LIMESTONE MNR.		
			STORM KING MOUNTAIN SHALE		
			JUANA LOPEZ		
		TURONIAN	DAKOTA FORMATION		
					MANCOS FORMATION

Figure 1.6. Proposed stratigraphy of the Niobrara Formation in northwestern Colorado. Red outline indicates the study interval.

1.5 Biostratigraphy of the Niobrara Formation

Plate 2 is a biostratigraphic column highlighting the faunal zones found in the Cretaceous System in northwestern Colorado. Izett et al. (1971) mapped the Pierre Shale near Kremmling Colorado and correlated to the east and west. Izett et al. (1971) combined their work with the work previously completed by Cobban and Reeside (1952a, and 1952b) creating biostratigraphic zonation for northwestern Colorado. Plate 2 combines the work of Izett and Barclay (1973) who mapped the Kremmling area with the work King (1965) who focused on the biostratigraphic zonation of the Fort Hays Limestone. Von Holdt (1978) in conjunction with Kauffman and Hattin (1982) proposed the type locality for the Storm King Mountain Member of the Mancos Shale be New Castle Colorado based on microfauna studies. Dune (1992) documented the calcareous nannofossil assemblages in an effort to determine the nannofossil biostratigraphy and paleoecological conditions of the Fort Hays Limestone at Wolcott. Dune (1992) expanded on Von Holdt's (1978) work at Wolcott.

1.6 Data Used in Study

The outcrops that were measured in this study are partially or entirely located on public land. Prior permission was obtained for outcrops located on private land. The subsurface well log data was taken from the Colorado Oil and Gas Conservation Commission (COGCC) website. Surface Gamma Ray readings were collected with a hand held scintillometer on one-foot increments.

CHAPTER 2

METHODS AND INTERVALS

2.1 Methods of Measured Sections

Prior to measuring each section, a specific series of basic systematic field techniques were used to obtain an overall understanding of the outcrop. The first step was to locate the Juana Lopez calcarenite and Fort Hays Limestone for the basal tie-in of the measured section. The second step was to methodically “walk through” entire interval gathering a basic understanding of the outcrop. The third step was to locate the contact between the upper Niobrara Formation and the basal Pierre, or Mancos Shale. The unique weathering of the upper Niobrara and the basal Pierre due to similar lithology make it difficult to locate the exact contact. A combination of color change, slope change, vegetation change and overall weathering was used to determine the of the upper contact for this study based on overlying lithology of the Pierre Shale from U.S.G.S published literature and mapping (Izett et al., 1971; Izett et al., 1973). Finally, a Jacob staff and Brunton compass were used to measure the thickness of each outcrop by projecting the local dip every five feet. Orange flagging with the footage from the base of the section was placed every five feet so that the section could be described accurately and repeatedly.

After the each section was measured the surface Gamma Ray profile was obtained by using a hand-held RS-125 SuperSpec scintillometer. Surface readings were collected on a 1 foot increment for every measured section. The SuperSpec was set on a 30 second assay time and the data was collected in nano-grays per hour (nGy/hr). For the portion of the outcrops that were covered by slope and where trenching was not an option surface GR data was not collected.

2.2 Interpreted Intervals

The descriptions of the interpreted intervals are a compilation of numerous factors. Published U.S.G.S and C.G.S maps and descriptions were first reviewed to develop a basic field description (Izett and Barclay, 1973). Once each of the interpreted intervals was located in the field a revised description was then compiled for reference. As more sections were measured in greater detail the field descriptions improved and a facies chart was developed (Table 2.1). Figure 2.1 A-G are photos of each of the facies observed in the measured sections.

2.2.1 Frontier Sandstone or Codell Sandstone

The Codell Sandstone or Frontier Sandstone is characterized by fine to medium-grained, hummocky and cross-bedded sandstone interpreted as storm deposits. The usage of Codell Sandstone or Frontier Sandstone terminology is highly debated in northwestern Colorado and is only used as a marker to help locate the Juana Lopez. Von Holdt (1978) used the Codell Sandstone terminology at Wolcott, CO. Izett and Barclay (1973) mapped the interval as the equivalent to the Juana Lopez Member of the Mancos Shale in southwest Colorado.

2.2.2 Juana Lopez “calcarenite” fossiliferous sandstone

The Juana Lopez interval is characterized by ripple cross-laminated, small scale trough cross-stratification, silty to sandy, gray, fetid, crystalline limestone that contains abundant marine mollusk shells and some small fish teeth (Lidke, 1998; Hubert, 1954; Stauffer, 1953; Wanek, 1953). The Juana Lopez weathers to a brownish color. Fresh surfaces have a very strong fetid odor. The Juana Lopez contains three ash beds ranging from one to three inches thick. The Juana Lopez typically is well exposed in outcrop due to the

calcarenite being very resistive to erosion. The Juan Lopez typically has a sharp basal contact with the Codell Sandstone.

2.2.3 Storm King Mountain Shale

The Storm King Mountain Shale is characterized by silty, dark gray non-calcareous shale containing thin ash beds and scattered inoceramids fragments throughout the interval (Von Holdt, 1978). The Storm King Mountain Shale upper contact with the Fort Hays Limestone is gradational while the lower contact with the Juan Lopez Calcarenite is sharp. The Storm King Mountain Shale is typically moderately exposed in outcrop forming gentle to moderate slopes. The Storm King Mountain Shale is organic rich contains more the 3 weight percent TOC, scattered Inoceramus and lacks benthic foraminifera which suggests deposition occurred under low oxygen conditions (Von Holdt, 1978).

2.2.4 Niobrara Formation

The Niobrara Formation is composed of two members: the Fort Hays Limestone Member and the Smoky Hill Member. For the purpose this research the Smoky Hill member was subdivided into six intervals (Figure 1.6).

2.2.4.1 Fort Hays Limestone Member of the Niobrara Formation

The Fort Hays Limestone is characterized by tan to grey, very fine-grained, micritic to chalky, bioturbated, well-cemented, crystalline limestone. The Fort Hays Limestone is characterized by rhythmic oscillations of thick, lighter-colored, organic lean, high carbonate, blocky beds and thinner, weaker, grey shale interbeds (Izett and Barclay, 1973). Fragments and whole specimens of several species of Inoceramus bivalves are present. The Fort Hays is a prominent ledge former in outcrops resulting in excellent exposures. The Fort Hays contains a two inch ash at the base.

2.2.4.2 Smoky Hill Member of the Niobrara Formation

The Smoky Hill Member is broken down into six alternating intervals: Lower Marl, Lower Chalk, Middle Marl, Middle Chalk, Upper Marl, and Upper Chalk (Figure 1.6). The Smoky Hill Member is characterized by cyclically bedded calcareous shales, marls, and chinks that are recognized by weathering to silver, light- to dark-gray and brownish-gray, calcareous shale and very light gray, dense, conchoidal-fracturing, sparsely fossiliferous limestone. The Smoky Hill member has numerous ash beds throughout the interval.

Lower, Middle and Upper Marls are recognized in this study are characterized by medium to dark-gray, laminated, very fissile, weathers to platy chips. The marls tend to form slopes and may be covered by vegetation. Lower, Middle and Upper Chinks are recognized in this study are characterized by interbedded light to medium-gray, fissile, platy chink, shaly limestone, and dense, blocky- to massive-weathering limestone beds. The chink intervals tend to form large ledges or ridges.

2.2.5 Pierre Shale/Mancos Shale

The Mancos (Pierre) Shale is characterized by silty-shale that overlies the Niobrara Formation. The basal Mancos Shale (Pierre Shale) can be slightly calcareous. On well logs an increase in the resistivity log indicates the contact between the Pierre and Niobrara. In outcrop the contact is typically poorly exposed. It is difficult to distinguish the exact contact between the basal Mancos and upper Niobrara because the lithologies are very similar. The basal Mancos tends to form gentle slopes while the upper Niobrara forms small “flat spots” in the topography due to the change in lithology.

2.3 Observed Facies

The facies observed in the measured sections are based on texture, lithology, and grain size that can be seen with the naked eye and a 10x power field hand lens. No thin sections or SEM images were used in this study. No XRD was used to determine lithology. Hydrochloric acid was used to determine if certain shales had any carbonate content. Shale that did not effervesce under acid was interpreted to be non-calcareous.

Table 2.1 Chart showing the description of the interpreted facies observed in the research interval.

Facies	Description	Figure
"Calcarenite" Fossiliferous Sandstone	thinly, hummocky and unevenly laminated, silty to sandy, fetid, crystalline limestone that contains abundant marine mollusk shells and some small fish teeth, weathers to gray to brownish in color, fresh surface have a distinct fetid odor, very dense in outcrop, only the broken up shell fragments effervesce under acid	2.1 A
Limestone	tan to gray, very-fine grained, micritic, highly bioturbated - featureless, very well cemented, contains abundant fragments and whole specimens of several species of the Inoceramus, fractures concoidally, very dense in outcrop, strong effervescence under acid	2.1 B
Blocky Chalk	gray, very-fine grained, micritic, highly bioturbated - featureless, well cemented, contains abundant fragments and whole specimens of several species of the Inoceramus, slightly less dense than the Limestone facies, strong effervescence under acid	2.1 C
Platy Chalk	finely laminated, weathers to 1/8" thick chips, moderate to strong effervescence under acid	2.1 D
Impure Chalk	laminated but has a blocky like appearance, contains some silt, moderate to strong effervescence under acid	2.1 E
Calcareous Shale	dark gray in color, weathers to small chips, mild effervescence under acid	2.1 F
Dark Gray Non-Calcareous Shale	dark gray, weathers to black ships, does not effervesce under acid	2.1 G

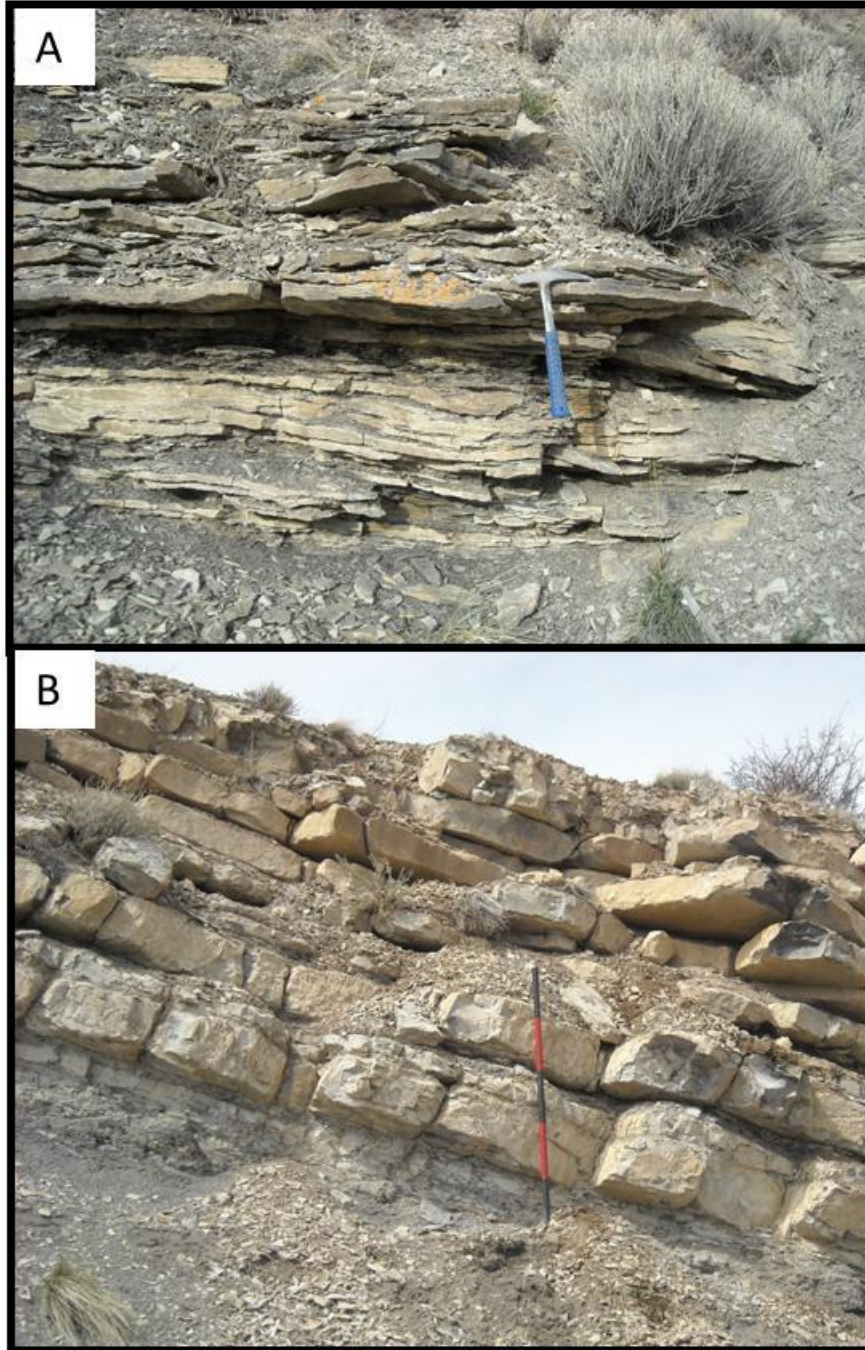


Figure 2.1 A and B. Pictures of observed facies for the measured sections. Figure 2.1 A (top) = Juana Lopez calcarenite at Kremmling, Figure 2.1 B (bottom) = Fort Hays Limestone at Kremmling. See Table 2.1 for the description for each facies.

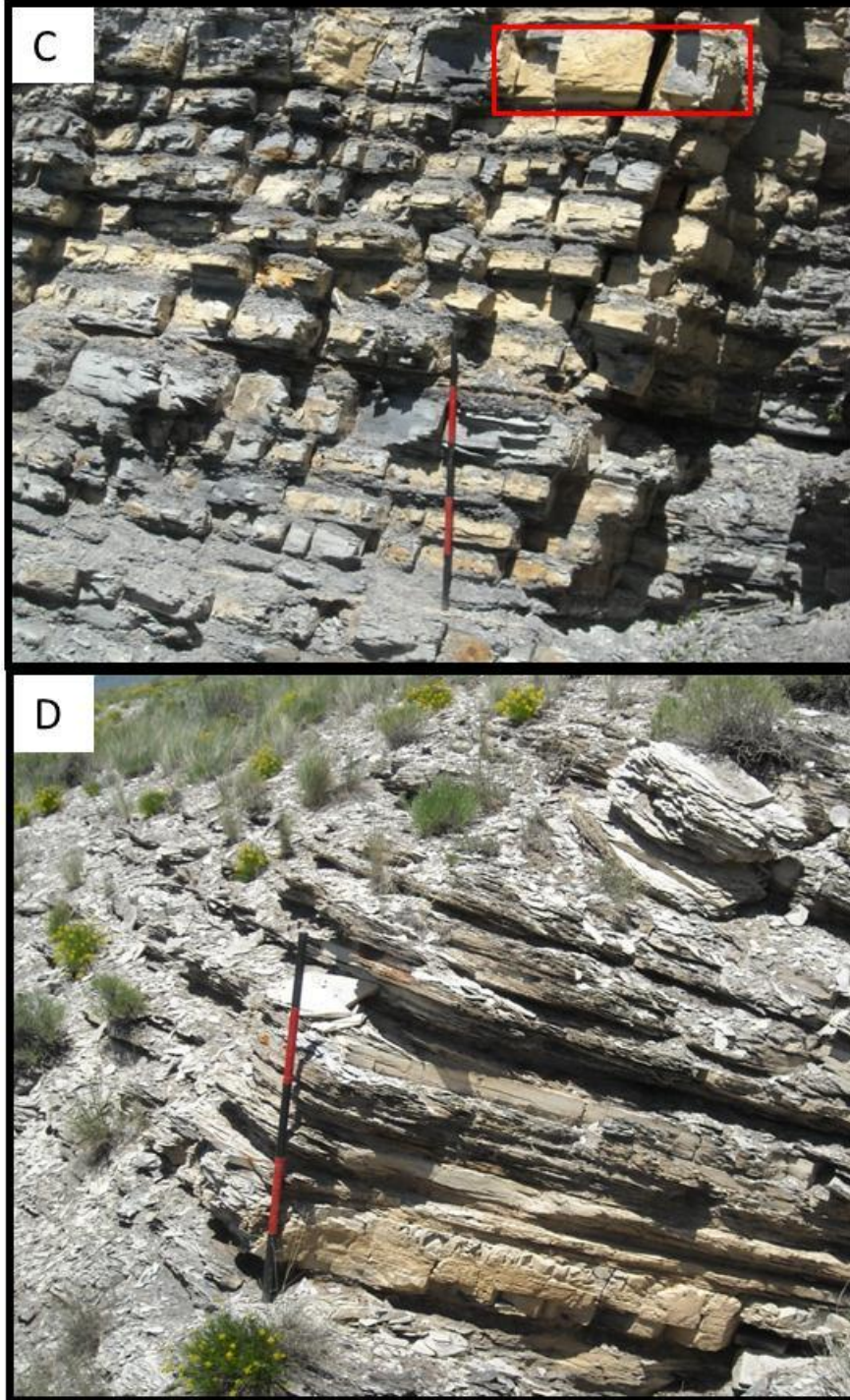


Figure 2.1 C and D. Pictures of observed facies for the measured sections. Figure 2.1 C (top) = red box is blocky chalk (Chalk 1) at Kremmling, Figure 2.1 D (bottom) = platy chalk (Chalk 3) at Kremmling. See Table 2.1 for the description for each facies.

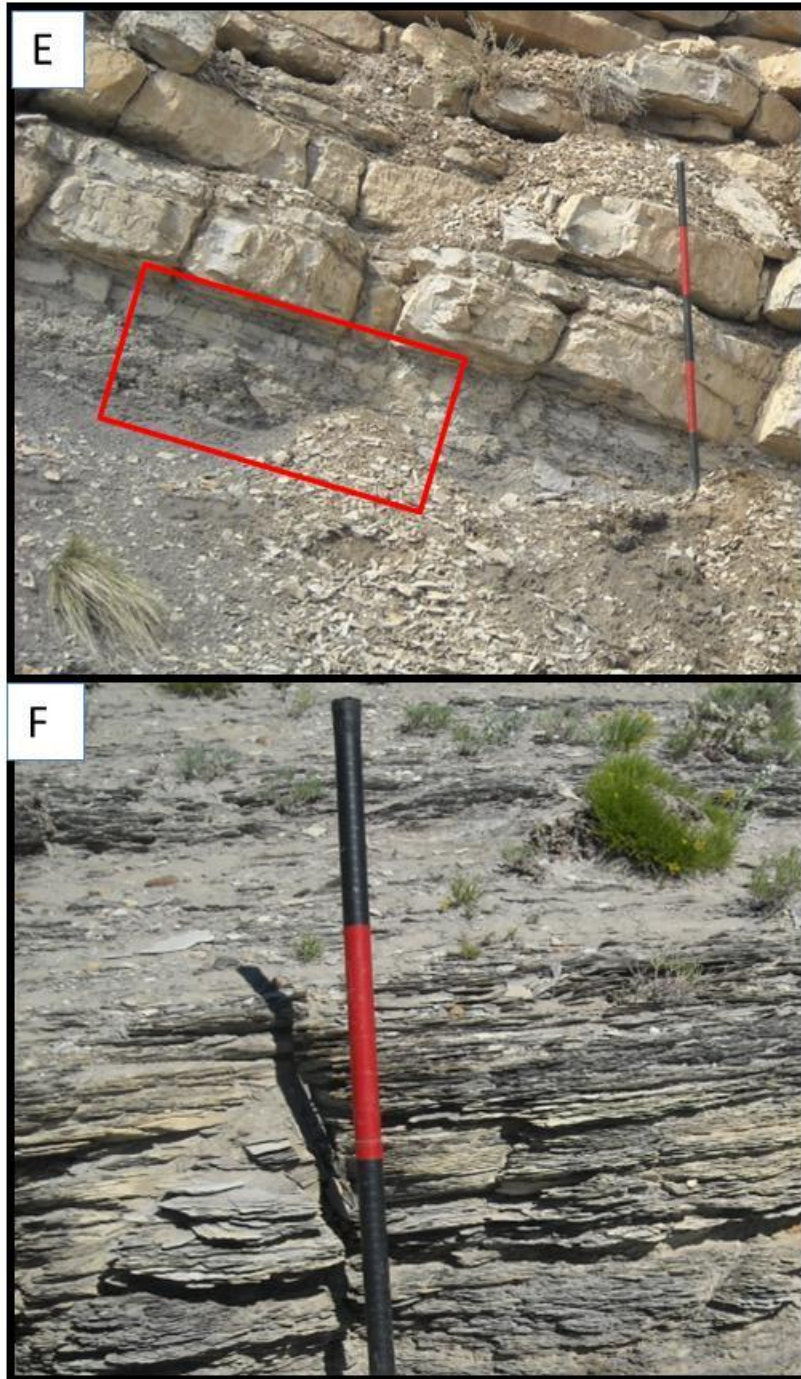


Figure 2.1 E and F. Pictures of observed facies for the measured sections. Figure 2.1 E (top) = impure chalk (lower portion of the Fort Hays limestone) at Kremmling, Figure 2.1 F (bottom) = calcareous shale (Marl 2) at Delaney Buttes. See Table 2.1 for the description for each facies.



Figure 2.1 Pictures of observed facies for the measured sections. Figure 2.1 G (top) = Dark gray non-calcareous shale (Storm King Mountain Shale) at Wolcott. See Table 2.1 for the description for each facies.

2.4 Reference Well Logs

Plate 1A/1B is a cross-section from eastern Piceance Basin to the western edge of the Denver-Julesburg Basin showing the thickness change of the Niobrara Formation Across the western and central portion of Colorado. The wells used in Plate 1A/1B, the reference cross-section, are listed in Table 2.2. The wells used in Plate 1A/1B were the closest wells to the measured sections that had full log coverage of the Niobrara. Gamma Ray (GR) and deep resistivity (ILD) logs were used to create Plate 1A/1B because the GR and ILD were the

most common logs found on the Colorado Oil and Gas Conservation Commission (COGCC) website. The GR and ILD log signatures have the most detail and definition over the study interval allowing for easy correlations. Interval transit time was used as a proxy for ILD for the Tiger Oil USA-Federal 1.

2.5 Summary

The facies descriptions were based on field observations and previously published literature. The Juana Lopez calcarenite and Fort Hays Limestone have lithologic characteristics that are easy to recognize in the field. The Storm King Mountain Shale lies between the Fort Hays and Juana Lopez allowing for easy location in the field and is described as a dark brownish to black silty shale. The Smoky Hill Member is difficult to separate into the six interpreted intervals.

The entire Smoky Hill Member contains significant amount of carbonate. Determining the relative carbonate content between the six facies proved difficult at first but become easier as more outcrops were measured and more observations were made. Weathering appeared to affect individual facies differently based on the interpreted carbonate content. The resistive limestones and chalks weathered to blocky beds that form ledges. The platy chalks and calcareous shales formed small ridges and steep slopes. Based on the field descriptions and the surface GR profiles the Smoky Hill Member was broken down into six intervals (Figure 1.6)

The logs used to create to Plate 1A/1B were all taken from the COGCC website. Several wells logs had to be digitized because to LAS files were not present. The combination of GR and ILD allowed for correlation of the Niobrara Formation from the Piceance to the Denver-Julesburg basin.

Table 2.2. Table listing the wells used in Plate 1A/1B with location and basin information.

Operator	Well Name	API	Location	Basin	Total Depth (FT)
Williams Production Company	Rulison Deep 1	05045068770000	2-6S-94W	Piceance	14278
Antero Resources	Gentry C9	05045152710000	17-6S-92W	Piceance	13,678
Egeria Oil Company	Sleeping Lion 11-1	05107061810000	11-1N-85W	Eagle	4444
EOG Resources	Vaneta 1-32D	05057064670000	32-7N-80W	North Park	8,192
Tiger Oil Company	USA-Federal 1	05049060140000	31-3N-78W	Middle Park	5819
Hasz Energy and Development	Peaceful Valley Ranch 1	05013062410000	29-2N-70W	Denver-Julesburg	3,824

CHAPTER 3

OUTCROP MEASURED SECTIONS

3.1 Measured Sections

The four measured sections are located on the edges of the eastern Piceance, Eagle, Middle Park and western North Park basins. The location of the outcrops provides a reference measured section for each basin in the study area (Figure 1.3). For each measured section scintillometer data was collected on a 1 foot increment where excessive slope material was not encountered.

3.1.1 New Castle (Plate 3)

The measured section at New Castle is located in section 34-T5S-R90W approximately 3 miles to the east of the town of New Castle exit off I-70 (Plate 3). The outcrop is on the north side of I-170 along Highway 6 frontage road. The Niobrara Formation is approximately 800 feet thick at New Castle based on nearby subsurface well logs. Only 400 feet of the Niobrara is exposed along the frontage road. The upper 400 feet is covered by slope and ancient Colorado River alluvium. The Niobrara Formation at New Castle is dipping at about 45 degrees to the southwest. The Juana Lopez, Storm King Mountain Shale, Fort Hays and Lower Smoky Hill are all very well exposed along the Highway 6 frontage road. Since the outcrop is dipping 45 degrees and is in the lower portion of the valley floor the exposure is partially covered to the north by ancient Colorado River alluvium making the outcrop difficult to access by foot. The exposure can be observed from the edge of the frontage road with ease but foot access is somewhat problematic. Figure 3.1 is a Google Earth image showing the line of transects that was used to measure the section.

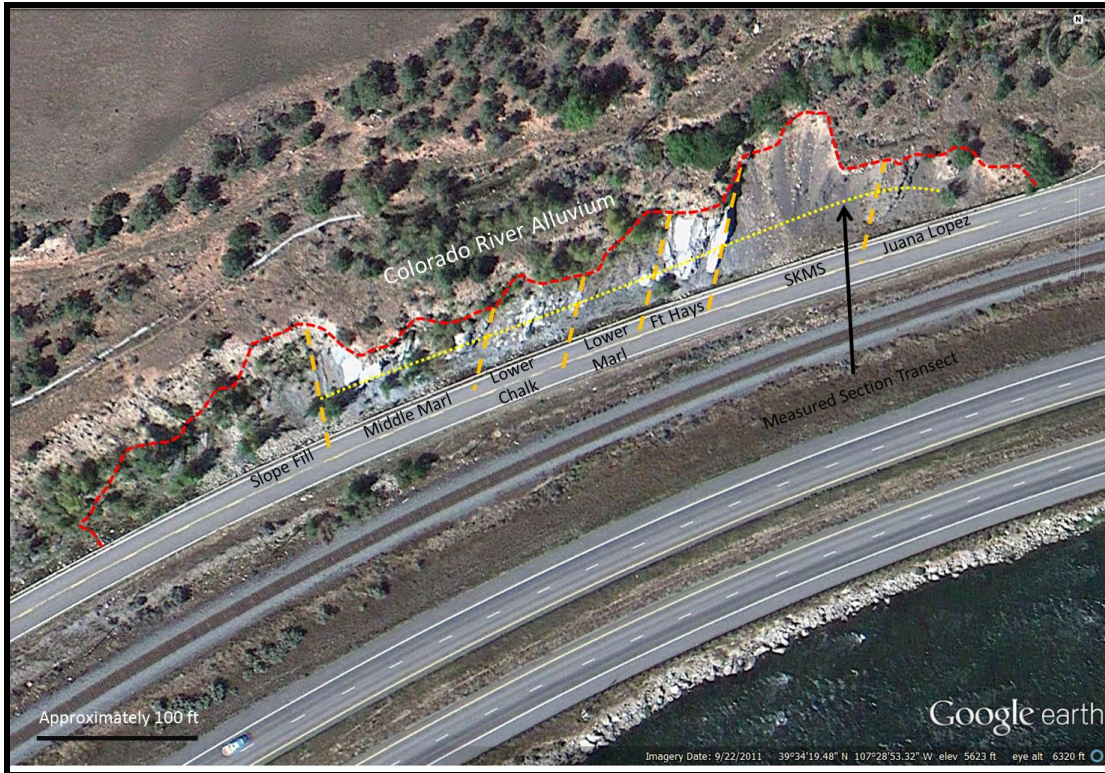


Figure 3.1. Google Earth image showing the measured section transect for Juana Lopez, Storm King Mountain Shale, Fort Hays, Lower Marl, Lower Chalk, and Middle Marl at New Castle located in section 34-T5S-R90W.

The measured section at New Castle is 410 feet thick (Plate 3). However, it is interpreted that the Niobrara Formation is closer to 800 hundred feet thick, based on nearby well logs, with the upper portion being covered by slope material and trenching was not an option. The Gentry C9 reference well is located about 15 miles to the west of the outcrop location (Figure 1.3). The Gentry C9 was drilled by Antero Resources in 2008 to a measured depth of 13,678 ft. The Niobrara Formation is approximately 1,012 feet thick in the Gentry C9. The logs for the gentry C9 show a very good correlation to the outcrop at New Castle even though the Niobrara is closer to 800 feet thick at New Castle. The Rulison Deep 1 drilled by Williams Production in 1994 was used as a secondary reference well to show the thickness change of the Niobrara from New Castle to the eastern portion of the Piceance Basin.

Plates 3 and 7 shows the increase in resistivity log response at the top of the Niobrara Formation due to an increased amount of carbonate content (Saterdal, 1955). The thinly bedded nature of the Niobrara Formation can produce an erratic GR and ILD log signature. The Fort Hays Limestone is composed of thinly bedded calcareous shales and slightly thicker, yet still thinly bedded, biomicritic limestones. The alternating sequence of calcareous shales and limestones give the Fort Fays a unique log and outcrop character.

3.1.2 Wolcott (Plate 4)

The measured section at Wolcott is located in two different locations. The lower portion of the Niobrara Formation, Storm King Mountain Shale, and Juana Lopez is located in section 15-T4S-R83W north of I-170 and to the east of Highway 131 behind the Gallegos Corporation building (Figure 3.2A). The upper portion is located in section 5-T4S-R83W approximately 2 miles to the northwest along Mill Creek Road and Horse Mountain Road, west of Highway 131 (Figure 3.2B). The contact between the Mancos Shale, or Pierre Shale, and Niobrara is poorly exposed and is interpreted to be at the intersection of Mill Creek Road and Horse Mountain Road. The Niobrara Formation at Wolcott is approximately 500 feet thick (Plate 4). The majority of the upper portion is exposed along Mill Creek Road with some of the interval covered by slope. The Niobrara is dipping approximately 10 degrees to the east at both exposures. The lower portion is very well exposed facing southerly. The upper portion is moderately exposed facing westerly. Due to recent road construction along Mill Creek Road the Niobrara outcrop have been much improved. Both exposures are only covered by slope fill in two small places.

The reference well log for the Wolcott measured section is the Sleeping Lion 11-1 drilled by Egeria Oil Company in 1993 (Figure 1.3).

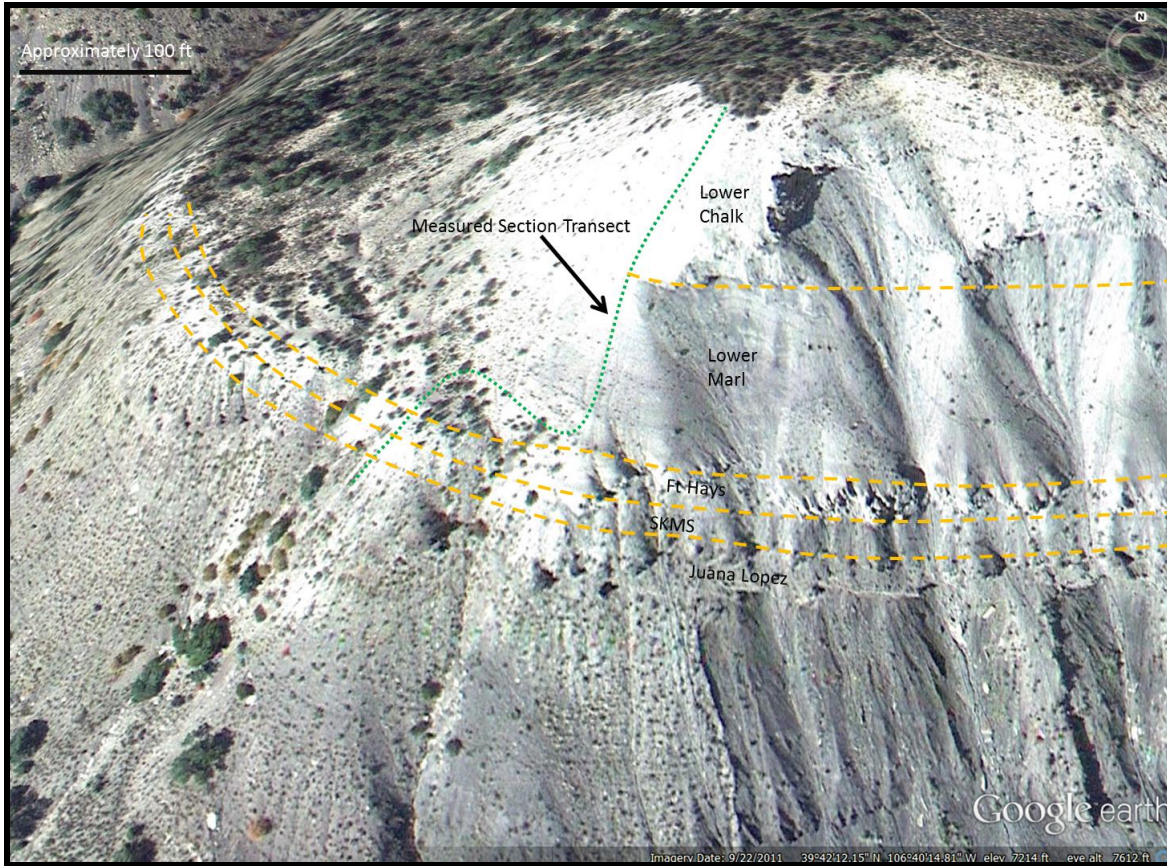


Figure 3.2A. Google Earth image showing the measured section transect for the Juana Lopez, Storm King Mountain Shale, Fort Hays, Lower Marl, and Lower Chalk at Wolcott located in section 15-T4S-R83W.

The well is 29 miles to the north of the outcrop. This well was used as the reference well because the Sleeping Lion 11-1 is the closest well with logs over the study interval. The Sleeping Lion 11-1 contains a much thicker Storm King Mountain Shale than what is present at Wolcott (Plate 4). The thickening of the Storm King Mountain Shale is interpreted to be caused by the location of the Transcontinental Arch. The Sleeping Lion 11-1 is located to the north of the arch while the Wolcott outcrop sits directly on top of the Arch. Thinning of the Niobrara Formation occurs over the crest of the Arch.

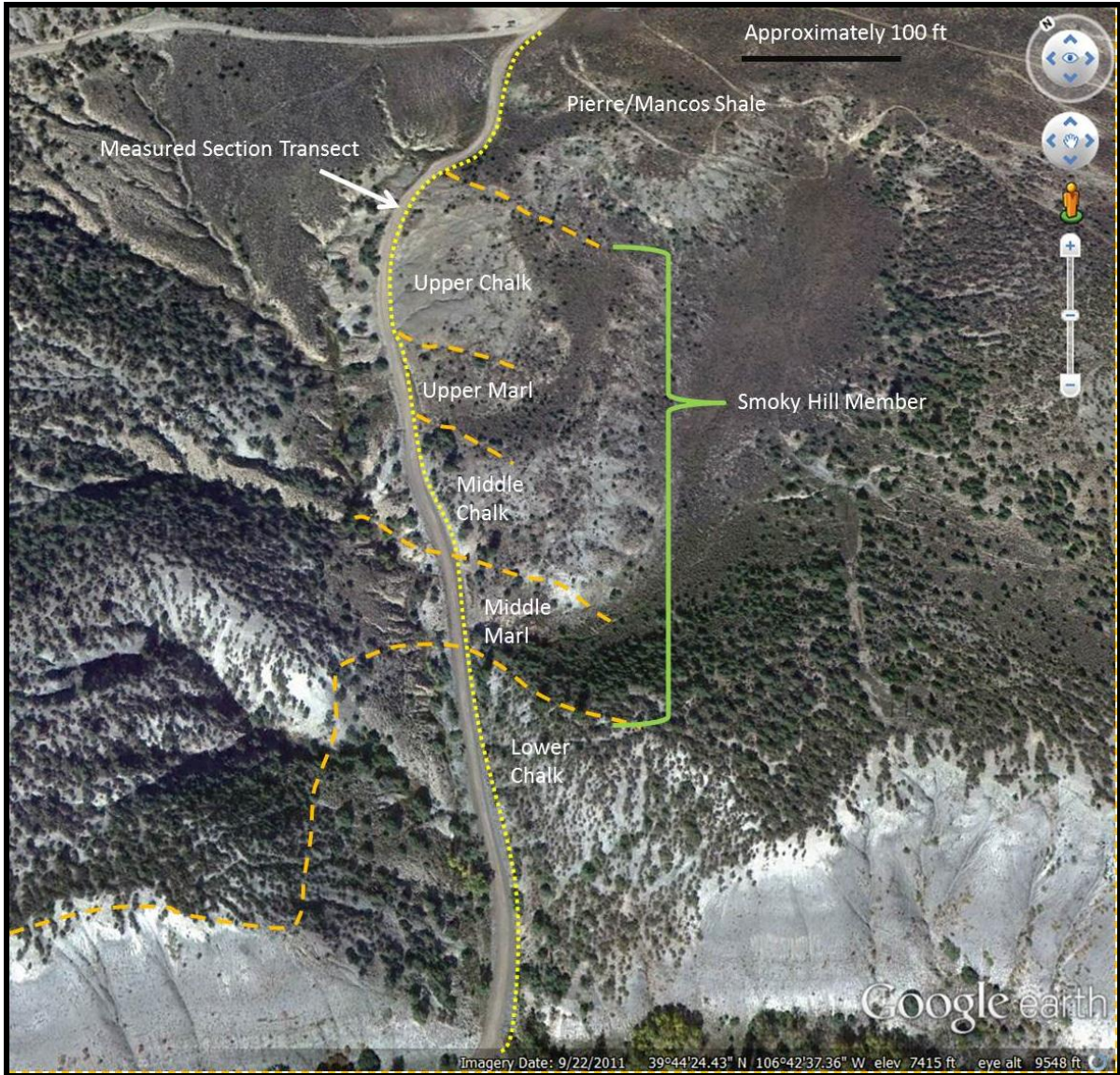


Figure 3.2B Google Earth image showing the measured section transect for Lower Chalk, Middle Marl, Middle Chalk, Upper Marl, and Upper Chalk at Wolcott along Mill Creek Road located in section 5-T4S-R83W.

3.1.3 Delaney Buttes (Plate 5)

The measured section at Delaney Buttes is located at the Odd Fellows recreation area in section 6 and 7-T8N-R81W. The Odd Fellows recreation area is approximately 3 miles west of Delaney Buttes reservoir. The Niobrara Formation outcrop is located one-half mile to the south of County Road 20. The Niobrara Formation is approximately 680 feet thick at Delaney Buttes (Plate 5). The Niobrara has large intervals that are covered by slope which

results in large gaps in the measured sections and surface Gamma Ray profile. The large portions of the outcrop covered by slope are interpreted to be the Lower Marl, Middle marl, and Upper Marl due to marls being less resistive to erosion than chalks. The Delaney Buttes outcrop contains areas that are interpreted to be faulted and highly fractured. Below the Lower Marl the dips are between 10-12 degrees to the northeast. Beginning at the lower Chalk the formation dips begin to increase to 45, 60, and in some cases the beds are slightly overturned. An interpreted fault is located about 50 feet below the contact of the Lower Marl and Lower Chalk where a grove of trees and shrubs are growing in a linear fashion. Figure 3.3 is a Google Earth image of the Delaney Buttes outcrop showing the measured section transect. In the Lower Chalk interval there are linear weathering features that appear to be micro faults with little to no displacement.

The thickness of the Niobrara Formation in the western North Park Basin is close to 700 feet. The reference log for the western North Park Basin is the Vaneta 1-32D (NENE of section 32-7N-80W) is located approximately 10 miles to the southeast from the outcrop location (Plate 1A/1B). The Vaneta 1-32 D shows a very distinct Juana Lopez and Fort Hays which correlates very well to the surface GR profile. The Storm King Mountain Shale is very thin and difficult to correlate on well logs but is characterized by a high GR and low ILD log signature. The Smoky Hill Member does not have the same well log character in the Vaneta 1-32 as it appears to in the other well logs. The marls and chalks do not appear to be as distinguishable by high or low resistivity log response. The muted log character of the Smoky Hill member indicating that the depositional environment fluctuated less in North Park than the other basins in this study. The location of the reference well log and outcrop to

the Transcontinental Arch played a large role in the carbonate and clastic sediment that was deposited.

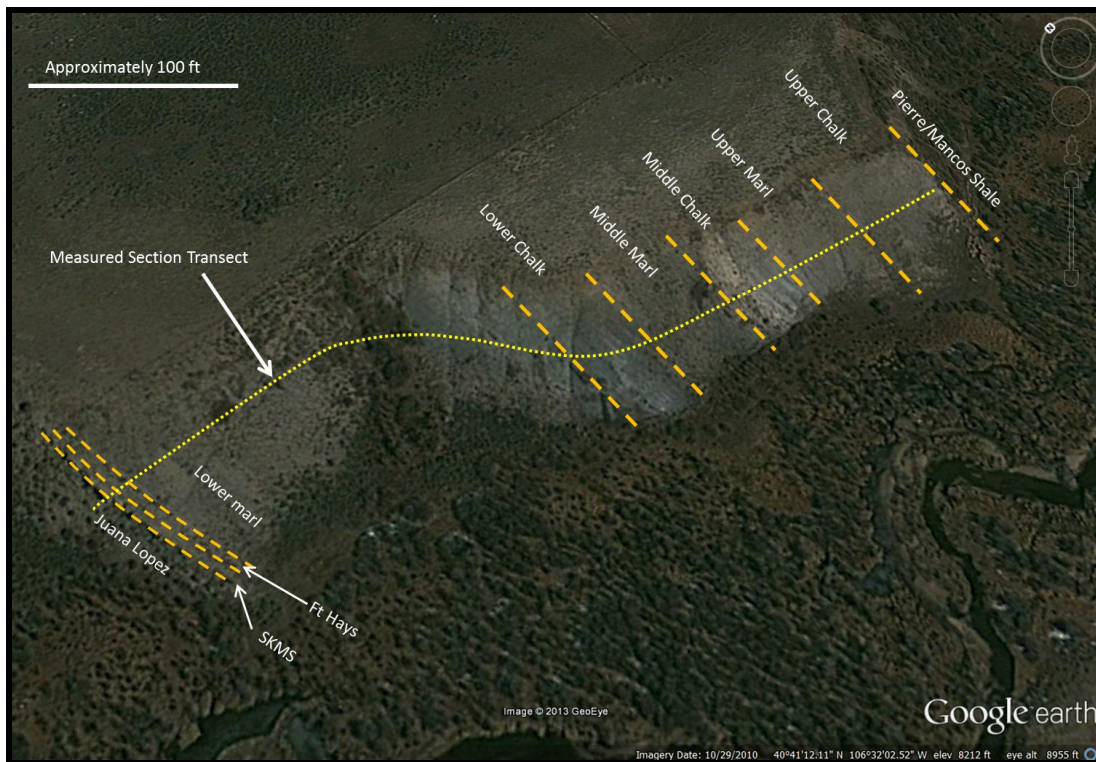


Figure 3.3 Google Earth image showing the measured section transect for the Niobrara Formation at Delaney Buttes located in section 6 and 7-T8N-R81W.

3.1.4 Kremmling (Plate 6)

The measured section at Kremmling is located is two different locations. The Juana Lopez calcarenite, Storm King Mountain Shale and Fort Hays Limestone are located in section 30-T1N-R80W on BLM land to the north of Trough Road, 1 mile west of Highway 9 (Figure 3.4A). The Smoky Hill interval is located in section 32-T1N-R80W along the Blue River at Blue Valley Ranch where exposures are best (Figure 3.4B). The contact with the Pierre Shale is best exposed in the SW1/4 Sec. 33-T1N-R80W., just east of Highway 9 (Izett et al., 1971). The Niobrara Formation at Kremmling is approximately 390 feet thick (Plate 6). Only the upper most 10-20 feet of the Niobrara is covered by slope which is debatable due to the lower 10 feet of the Pierre Shale being calcareous shale (Izett et al., 1971). The exposures

of the Niobrara at Kremmling are dipping approximately 10 degrees to the east facing southeasterly. The Juana Lopez calcarenite, Storm King Mountain Shale and Fort Hays Limestone are all very well exposed at Trough Road due to erosion from a small creek. The exposure of the Juana Lopez and Fort Hays is poor at Blue Valley Ranch because the outcrops are located in the bottom of the valley. The Lower Marl and above are extremely well exposed at Blue Valley Ranch because the Blue River has kept the outcrop cleaned during high runoff years.

The USA-Federal 1 drilled by Tiger Oil Company in 1978 was used as the reference well log for the Kremmling measured section (figure 1.3). The USA-Federal 1 is the closest well the measured section. The Kremmling measured section lies just to the west of the Williams Range Thrust which places the Precambrian Boulder Creek Granodiorite above the Cretaceous Pierre Shale. Finding a well log that had not been cut by the Williams Range Thrust fault proved difficult and no major faults were observed at either exposure of the Niobrara at Kremmling. The USA-Federal 1 well contains a interval transit time and GR logs. The interval transit time was used as a proxy for resistivity because denser-more resistive strata tend to have a higher velocities, and faster interval transit times. The Juana Lopez and Fort Hays have a much faster interval transit time than the marls and shales allowing for somewhat easy correlations.

3.2 Hand-Held Surface Scintillometer (GR)

A hand-held RS-125 SuperSpec scintillometer was used to collect surface Gamma Ray readings on a 1 foot increment for every measured section. The SuperSpec was set on a 30 second assay time. The surface GR readings were taken in nano-Grays per hour (nGy/hr) which is a unit of absorbed radiation.

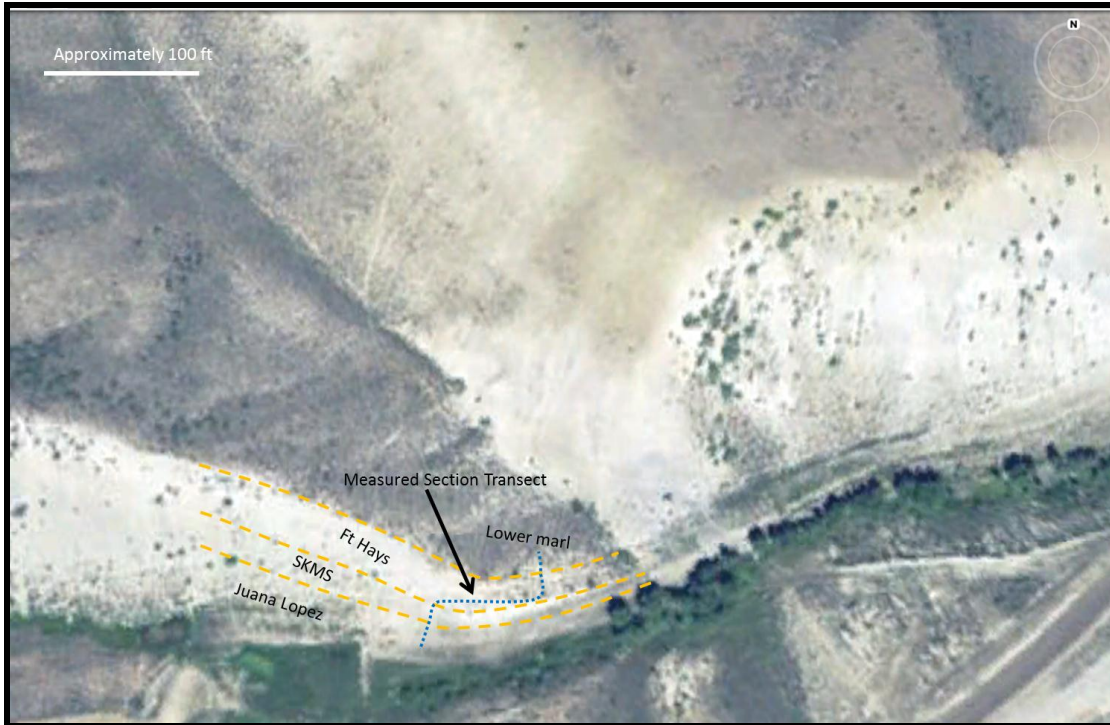


Figure 3.4A Google Earth image showing the measured section transect for Juana Lopez, Storm King Mountain Shale and Fort Hays Kremmling along the Trough Road located in section 30-T1N-R80W.



Figure 3.4B Google Earth image showing the measured section transect for Fort Hays through the Upper Chalk at Kremmling along the Blue River located in section 32-T1N-R80W.

The surface GR readings measured the amount of radiation being emitted from the measured sections. The radius of the investigation of the hand-held RS-125 SuperSpec scintillometer is approximately two inches. There is a small margin of error in the surface GR readings due to the radius of investigation which is why the readings were taken on a one foot increment. The data was first imported and plotted in Microsoft Excel to make sure there was no erroneous data. The data was then imported into Petra and depth shifted to the measured section footages creating a surface GR profile for each measured section.

The New Castle surface GR profile (Plate 3) covers approximately 400 feet of the study interval. Data was not collected over the upper portion of the study interval because of excessive slope material. The Wolcott surface GR profile (Plate 4) covers 430 feet of the study interval. The contact between the Niobrara and the Pierre/Mancos Shale is covered by excessive slope not allowing for the upper portion of the study interval to be collected. The Delaney Buttes surface GR profile (Plate 5) only covers a small portion of the study interval. The Kremmling surface GR profile (Plate 6) covers 380 feet of the study interval.

For all four measured sections (Plates 3, 4, 5 and 6) the surface GR profile ties very well to the measured sections. The surface GR signature correlates very well with the expected signature for carbonates, shales, and sandstones. The Fort Hays Limestone has a very blocky clean GR signature while the Storm King Mountain Shale has a very dirty signature. The surface GR profile also correlates well to the nearby subsurface reference well logs that show a very clean carbonate GR signature and a very dirty GR signature for the Storm King Mountain Shale. The chalk intervals have a slightly cleaner GR signature than the marls which have a subdued GR log signature.

3.3 Summary

After measuring and comparing the four outcrops there are several regional characteristics of the measured sections that are apparent (Plates 1, 7). The first being the lithologic change in the Juana Lopez calcarenite from the southwest at New Castle to the northeast at Delaney Buttes. The Juana Lopez loses a significant amount of shale and silt and contains an increasing amount of sand and broken shell fragments at Delaney Buttes than is present at New Castle and Wolcott. The lithology change of the Juana Lopez is observed in the GR and ILD log character. The GR log decreases while ILD log increases showing the change in lithology from south to north for the Juana Lopez as a result of the increased amount of sand and shell fragments. Second, there is a large thickness change of the Storm King Mountain Shale from New Castle to Delaney Buttes. The Storm King Mountain Shale is 100 feet thick at New Castle but is only a few feet thick at Delaney Buttes. There no change in lithology of the Storm King Mountain Shale between New Castle and Delaney Buttes. The log character for the Storm king Mountain Shale is consistent over the study area; the GR and ILD logs appear suppressed and lack definition. The Fort Hays Limestone undergoes a major thickness change from New Castle to Delaney Buttes. The Fort Hays Limestone is close to thirty feet thick at New Castle containing the typical thick blocky limestones and interbedded shales. The Fort Hays is only 5 feet thick with two small limestone beds present at Delaney Buttes. The log character of the Fort Hays is very consistent over the study interval. The Fort Hays Limestone has a low GR and high ILD log signature and has a blocky appearance on logs which mimics its shape in outcrop.

CHAPTER 4

DISCUSSION, CONCLUSIONS AND FUTURE WORK

4.1 Discussion

The Niobrara Formations exhibits a major change in lithology as limestones and chalks in eastern Colorado give way to calcareous and clay-rich shales in western Colorado (Figure 1.2) (Sonnenberg, 2011; Longman et al., 1998). The thickening observed in the marls and chalks from east to west is likely caused by increasing amount of clastic influx to the west. The marls and chalks were correlated based on gross high or low resistivity logs. The high resistivity log character of the chalks in the Denver-Julesburg Basin was correlated to the west based on relative high resistivity log character packages in each well. The marls were correlated based on low resistivity log character packages. Since no mineralogical data was used in this study the marls and chalks were correlated based on the relative high or low resistivity log response on a per well basis. The chalks and marls become increasingly thicker to the west. The carbonate factory was in the east with clastics diluting the carbonate production in the west. Plate 1 and 7 show that the Niobrara Formation significantly increases in thickness from the Denver-Julesburg Basin to the Piceance Basin. The lateral facies changes and increase in thickness from east to west of the Niobrara is due to the proximity of clastic influx. The carbonate content slowly decreases from east to west as the carbonate production is being diluted and suppressed by detrital clay. The limestones and chalks are being diluted by clastic sediment resulting in the lateral facies change and increase in thickness.

Plate 2 shows an unconformity at the base of the Fort Hays Limestone and at the base of the Juana Lopez and are emphasized by missing faunal zones (Fisher et al., 1985).

The presence of these unconformities raises several questions: 1.) Is the lithology change of the Juana Lopez caused by erosion or clastic influx? 2.) Is the thinning of the Storm King Mountain Shale onto the Transcontinental Arch caused by erosion? 3.) What was the profile of the Transcontinental Arch? 4.) What is the influence of tectonics on the Transcontinental Arch? 5.) Is there ponding of sediments on the northwestern side of the Transcontinental Arch?

The Juana Lopez exhibits a change in lithology from south to north across the Transcontinental Arch. With the presence of an unconformity at the base of the Juana Lopez the changes in lithology could be caused by erosion over the Arch resulting in a condensed section with an increased amount of sand and shell fragments. The increased amount of sand and shell fragments from south to north also indicates a possible proximal source of sand present at the time of deposition. A combination of clastic influx from the northwest and erosion most likely resulted in the lithology change of the Juana Lopez from south to north across the study area.

The facies change from the Storm King Mountain Shale up to the Fort Hays Limestone is gradual and does not distinctly indicate the unconformity mapped by Izett and Barclay (1973). However, the change in lithology from the organic rich non-calcareous Storm King Mountain Shale to the Fort Hays Limestone is very significant indicating a major change in depositional environment. The thinning of the Storm King Mountain Shale could be caused by the unconformity at the base of the Fort Hays. Plate 2 shows missing foraminiferal, ammonite, and inoceramid biozones within the upper portion of the Storm King Mountain Shale (Fisher et al., 1985). The unconformity at the base of the Fort Hays is very subtle. The thinning of the Storm King Mountain Shale is most likely a result from the

combination of a lack of accommodation space and erosion across the Transcontinental Arch. The significant thinning of the Storm King Mountain Shale indicates that Transcontinental Arch had a pronounced profile. The SKMS thickens to nearly 200 feet at Ridgeway, Colorado (Von Holdt, 1978) indicating that the Arch may have had up to 200 feet of vertical relief.

The symmetry and overall shape of the Transcontinental Arch is not very well understood. Sevier Orogeny tectonics could have played a large role the profile of the Arch during deposition of the study interval. Periods of thrusting and loading to the west potentially resulted in dynamic changes in the Arch causing erosion, non-deposition and changes in accommodation space. During periods when thrusting and crustal loading was at high, large amounts of sediment would be shed into the basin creating a “ponding” of sediments on the western side of the Arch. The ponding of sediments could also potentially explain why the carbonate factory to the east was so productive. The relative location of the each outcrop on the Transcontinental Arch has a large influence on the amount of carbonate content and the overall thickness of the Niobrara Formation (Figure 4.1). Outcrops located on the top of the arch tend to have more carbonate content, thinner, than outcrops located closer to the edge of the arch. Kremmling has the highest interpreted carbonate content while Delaney Buttes has the lowest. Figure 4.1 shows that Kremmling is located on the top of the arch while Delaney Buttes is located on the edge of the arch.

Changes in paleogeography of the Cretaceous seaway (Figure 4.2 A-E) play a large role in the lithological changes observed in the Juana Lopez calcarenite and Niobrara Formation within the study area (Cushman, 1994). Changes in the Cretaceous shoreline from Late Turonian through Latest Campanian are responsible for the lithologic changes observed in

the study area. The Juana Lopez contains an increasing amount of sand and broken shell fragments from south to north. The shoreline changed through time resulting in areas with higher clastic content. From east to west across Colorado the Niobrara Formation displays a major change in lithology as limestones and chalks in eastern Colorado give way to calcareous and clay-rich shales in western Colorado (Figure 1.2) (Sonnenberg, 2011; Longman et al., 1998). Lateral changes in lithology are mainly caused by the proximity to the source of detrital clay and silt in the west. As the lateral facies change occurs from east to west across Colorado the thickness of the Niobrara Formation triples due to the increased amount of clastic influx.

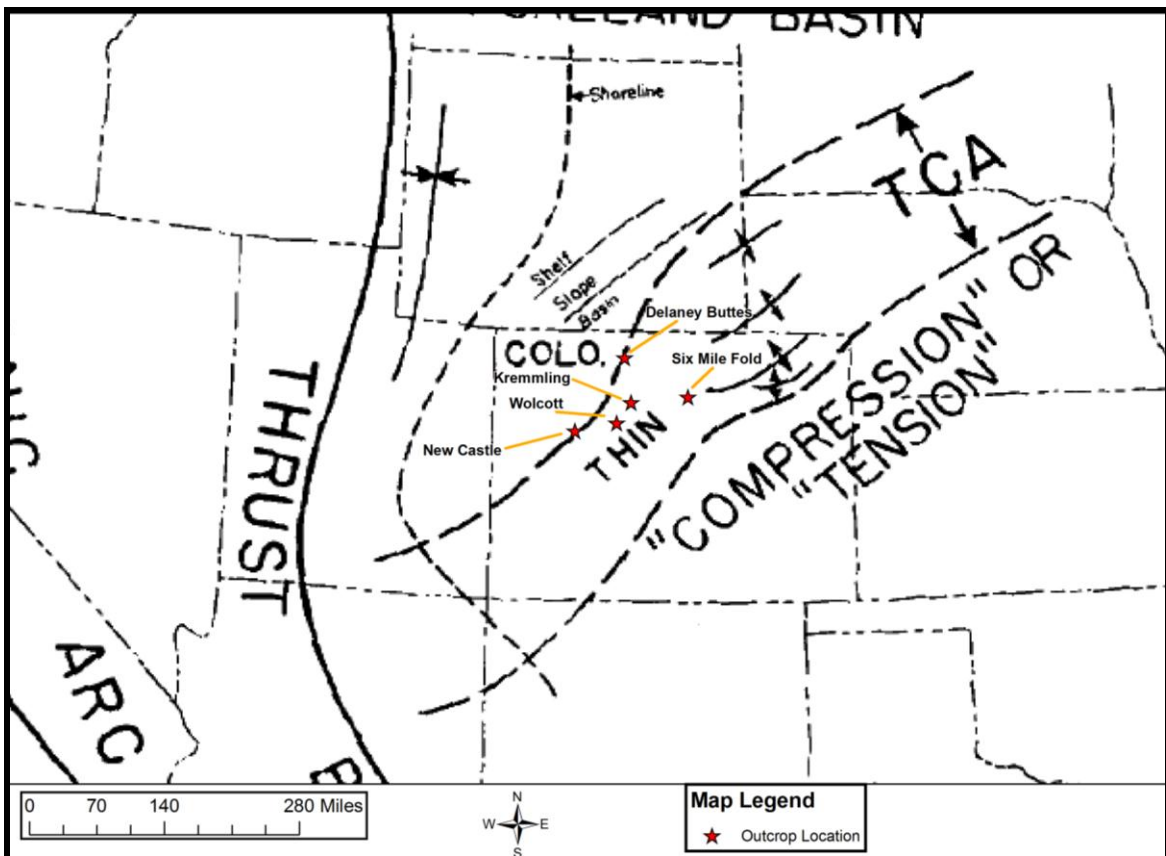


Figure 4.1. Map of the western United States showing the location of the measured sections in relation to the Transcontinental Arch (after Weimer, 1978).

The clastic influx diluted the carbonate content and resulted in a much thicker section. The Fort Hays Limestone exhibits a lateral facies change by grading into the non-calcareous Storm King Mountain Shale in southwestern Colorado. The Transcontinental Arch also played a large role in lateral facies change. The Transcontinental Arch was trending northeast-southwest creating a “high ridge” through central Colorado. Outcrops that were deposited on the crest of the arch have higher interpreted carbonate content than outcrops that were deposited off the crest of the arch. Carbonate production was greater on the crest of the arch than off the crest due to warmer water temperature and less clastic influx to hinder carbonate production. The increased amount of carbonate content on top of the Arch could also have been caused by clastics being trapped in the basin on the west diluting the carbonate production.

4.2 Conclusions

The measured sections in this study show major thickness and lithologic changes in the study interval from New Castle to Delaney Buttes. Over the course of approximately 150 miles the Juana Lopez calcarenite becomes less shaley and more sand rich retaining its distinct fetid smell and abundant broken shell fragments. The Storm King Mountain Shale thins from New Castle to Delaney Buttes. The lithology of the SKMS does not change from basin to basin. The Fort Hays Limestone thins significantly from the south to the north. At New Castle there are ten limestone beds greater than one foot thick while at Delaney Buttes there are only two ten inch thick limestone beds. The Niobrara Formations thins from nearly 800 feet at New Castle to 360 feet at Six Mile Fold

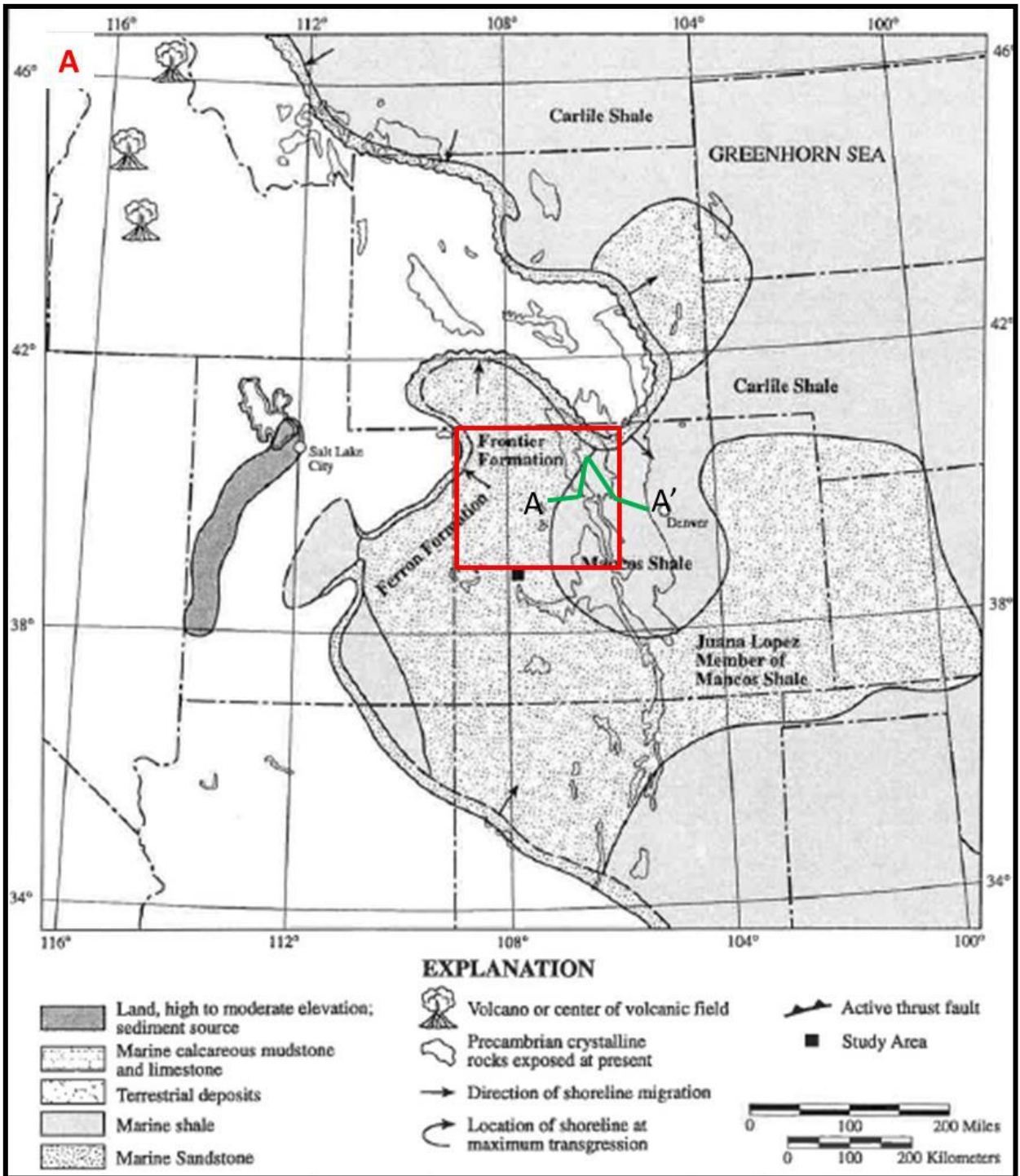


Figure 4.2 A. Regional paleogeography during middle Late Turonian. Northwestern Colorado was located in an embayment of the Greenhorn Sea and the Frontier delta reached its maximum extent. Small black square was Cushman's study area. Red box is the current study area (from Cushman, 1994; McGookey et al., 1972). Green line represents Plate 1A, 1B, and 7 line of section.

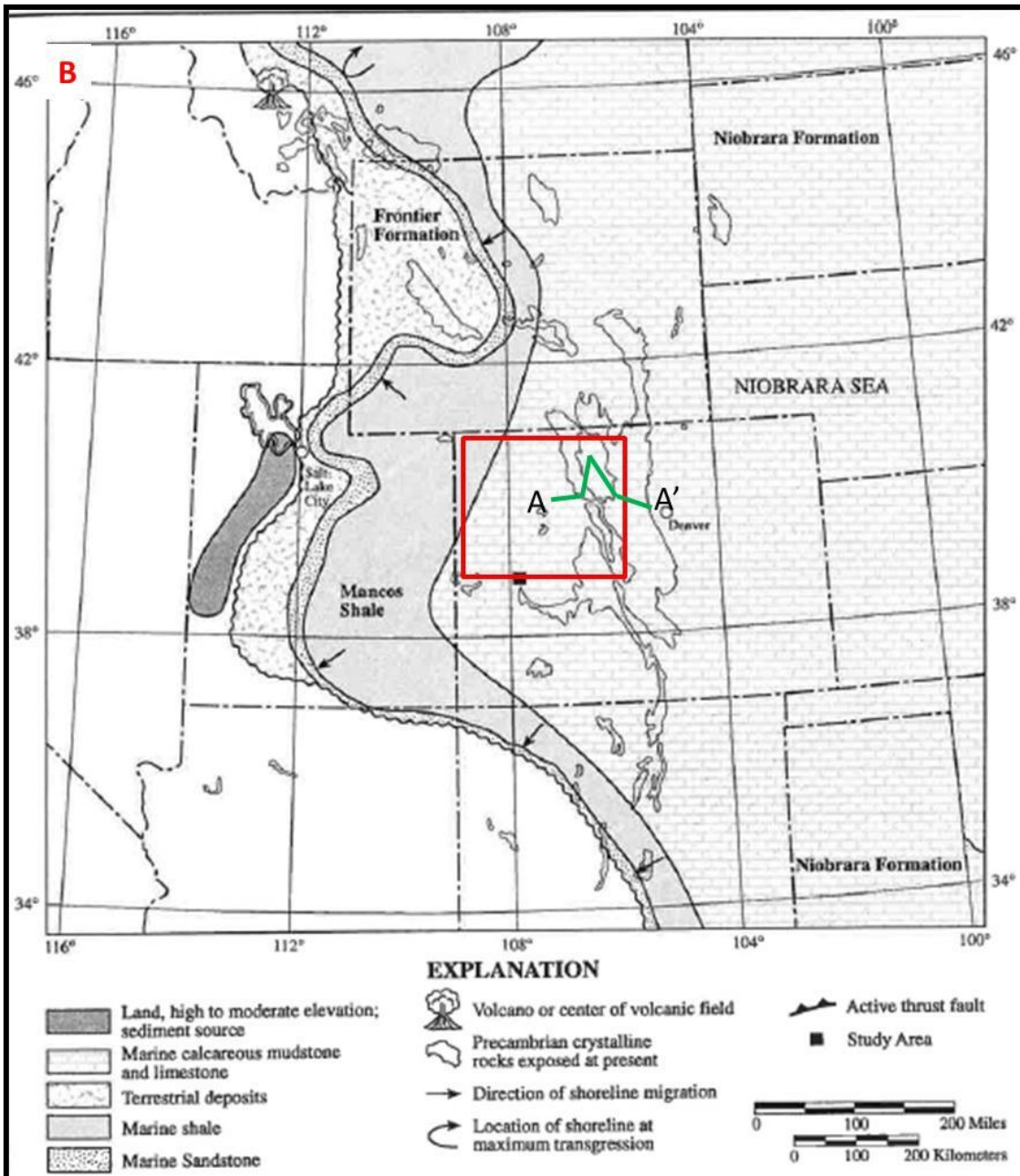


Figure 4.2 B. Regional paleogeography during Early Coniacian. The Frontier delta was foundering in western Wyoming. Small black square was Cushman's study area. Red box is the current study area (from Cushman, 1994; McGookey et al., 1972). Green line represents Plate 1A, 1B, and 7 line of section.

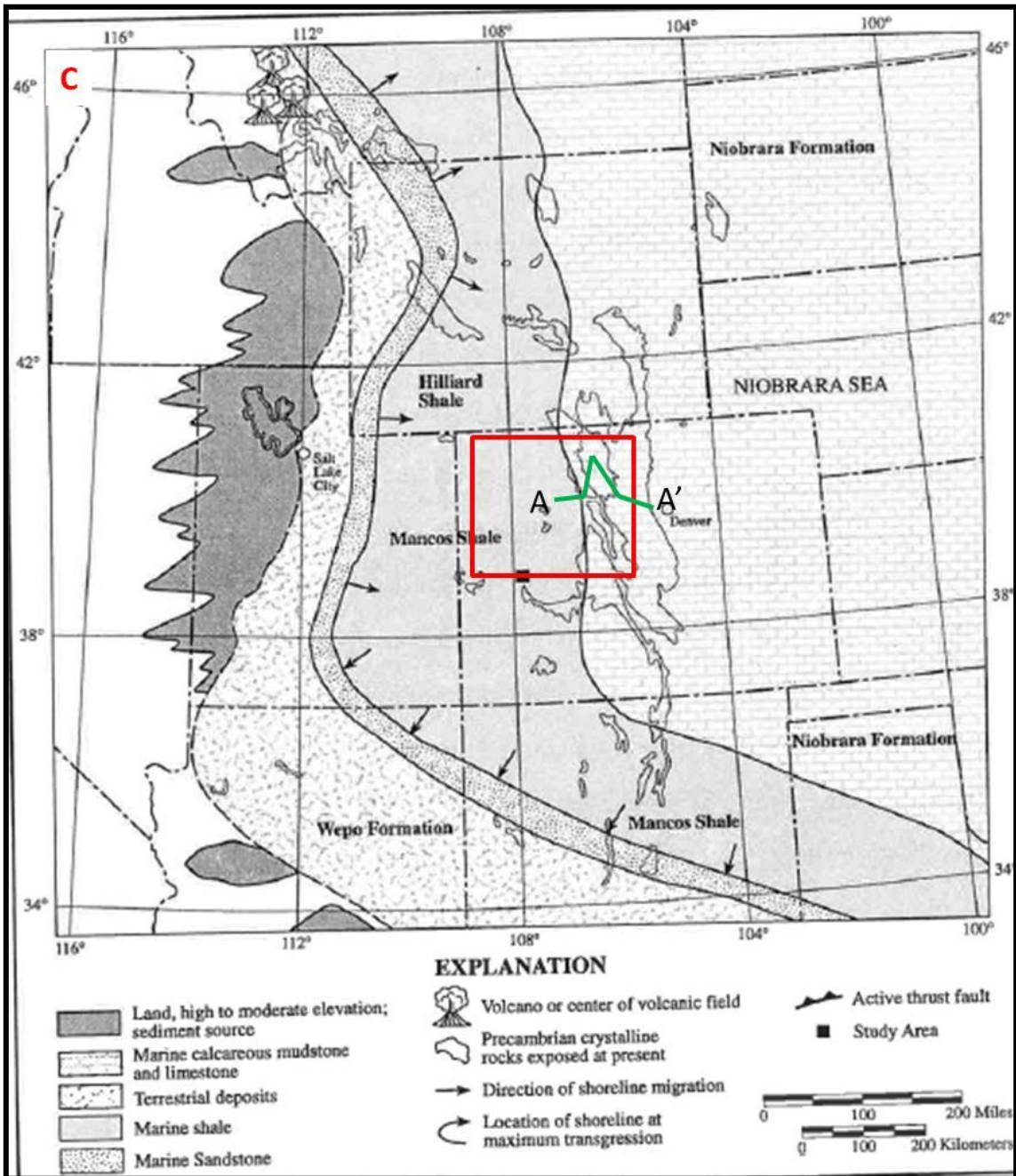


Figure 4.2 C. Regional paleogeography Late Santonian. Regional uplift began during this time in western Utah and southern Idaho. Small black square was Cushman's study area. Red box is the current study area (from Cushman, 1994; McGookey et al., 1972). Green line represents Plate 1A, 1B, and 7 line of section.

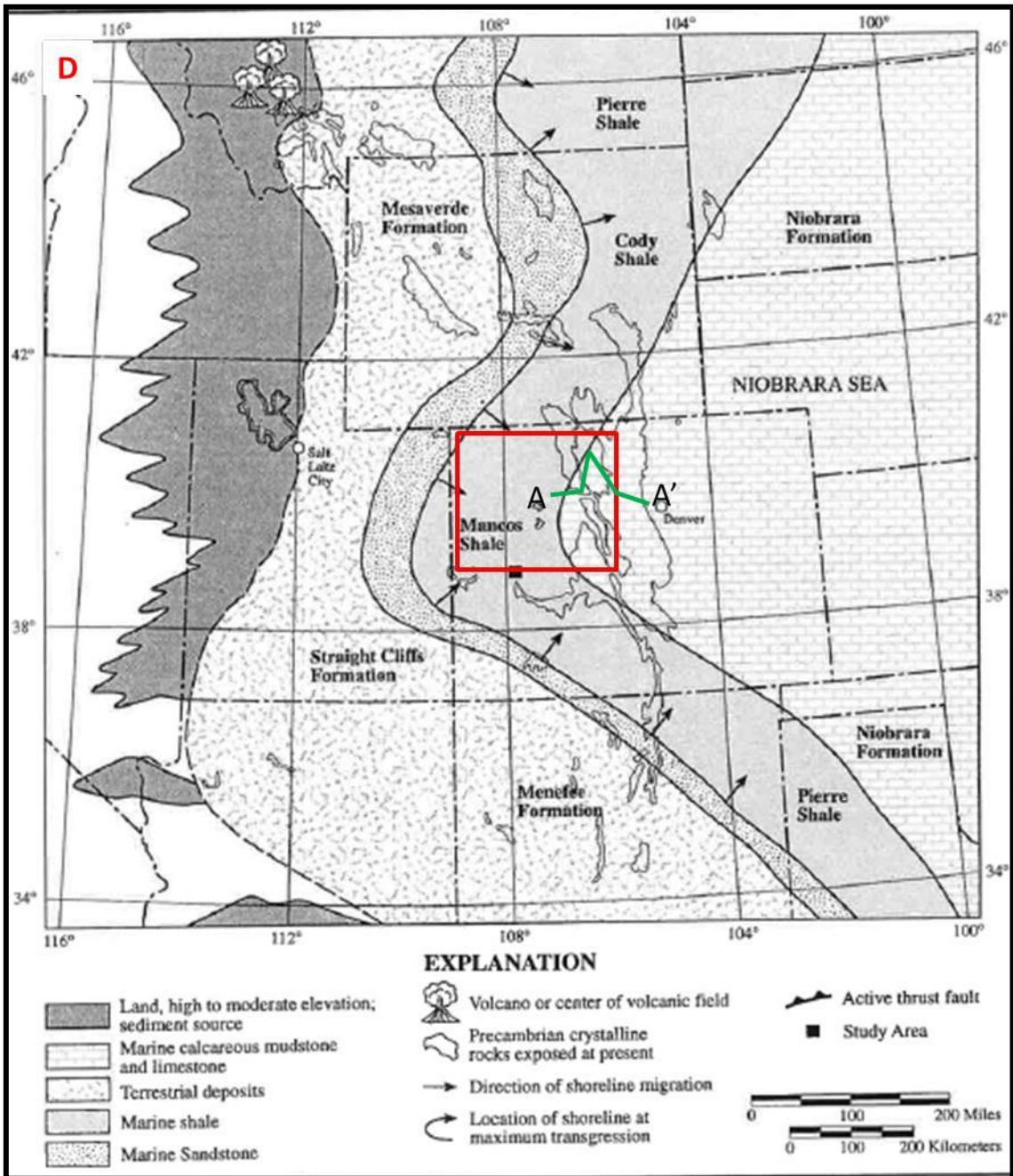


Figure 4.2 D. Regional paleogeography during Late Early Campanian. The Niobrara Sea regressed during this time as regional uplift continued to the west. Small black square was Cushman's study area. Red box is the current study area (from Cushman, 1994; McGookey et al., 1972). Green line represents Plate 1A, 1B, and 7 line of section.

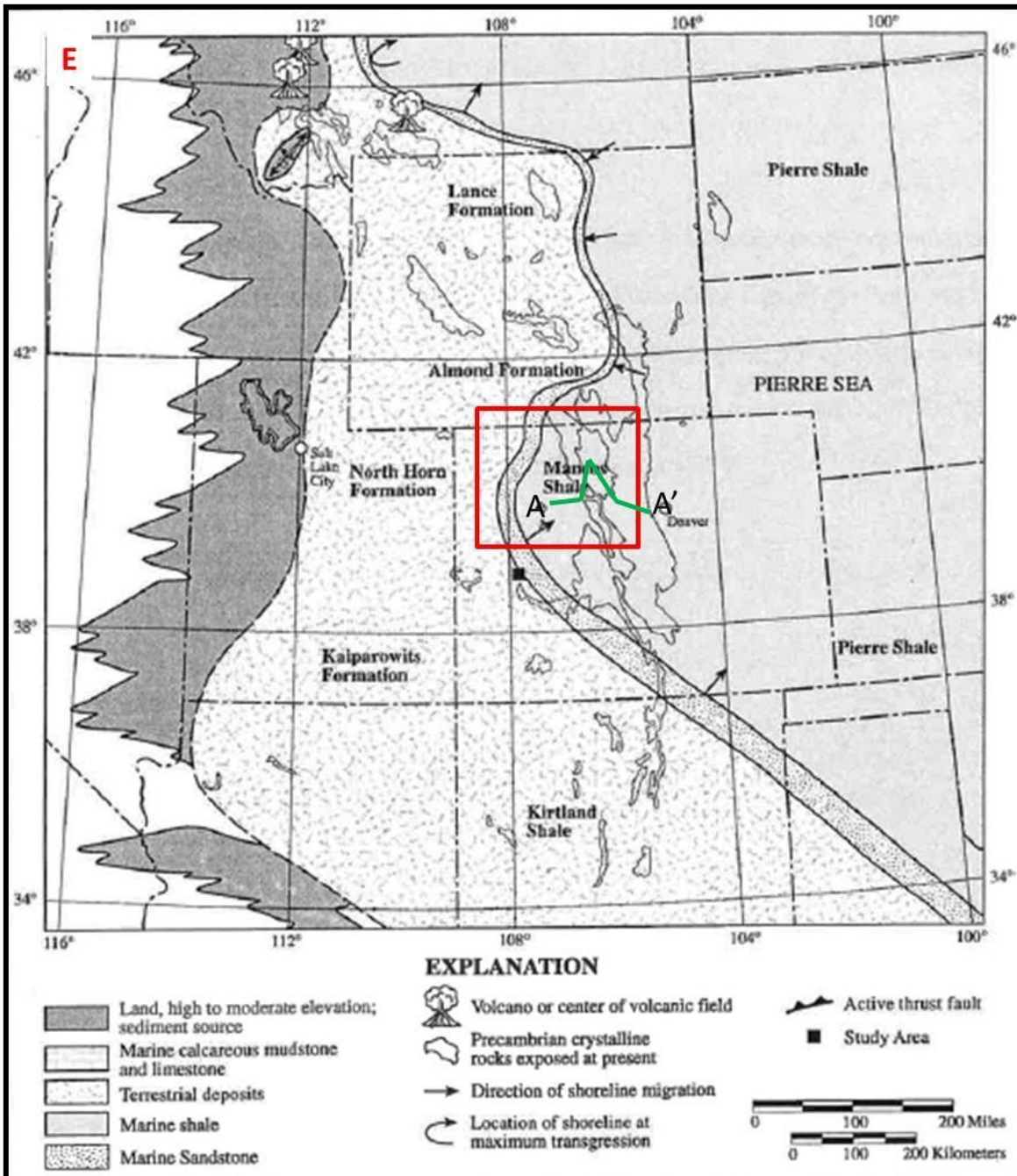


Figure 4.2 E. Regional paleogeography during the Latest Campanian. Northwestern Colorado was located along the shore of the Pierre Sea. Small black square was Cushman's study area. Red box is the current study area (from Cushman, 1994; McGookey et al., 1972). Green line represents Plate 1A, 1B, and 7 line of section.

4.3 Future Work

Composite but relatively basic measured type sections of the Juana Lopez calcarenite, Storm King Mountain Shale, and Niobrara Formation are presented in this research study. The measured sections need future work to help better understand the Niobrara Formation in northwestern Colorado. The measured sections are intended to be reference studies for future work. A more detailed measured section and analysis of the Juana Lopez and Storm King Mountain are needed in order to better understand the changes in the Fort Hays and Smoky Hill within the study area. Future studies focusing on the ash beds found in this study are needed to better understand how correlative the Niobrara is from one basin to the next. Future work is needed focusing on the thickness change of the study interval from south to north in an effort to better understand the role the Transcontinental Arch played in deposition in northwestern Colorado.

The lithologic changes observed in the Juana Lopez and lateral facies changes in the Niobrara Formation are not well understood. An XRD and a petrographic study focusing on the facies changes from the Denver-Julesburg to the Piceance Basin would provide enormous insight for better understanding the changes that are occurring. The chinks in the Denver-Julesburg Basin laterally grade into marls in the Piceance Basin. Thin sections of the Juana Lopez from northwestern Colorado would help classify and understand the source of the Juana Lopez. Thin sections of the marls and chinks in northwestern Colorado would provide important data needed for better understanding how the facies are changes from east to west and north to south.

The U.S.G.S took a surface core of the Niobrara Formation near Delta, Colorado. I believe the same should be done near Wolcott, Colorado. Wolcott lies in a “blank spot” of

data just south of the North Park Basin and northeast of the Piceance Basin. Kremmling is surrounded by basins that have a plethora of subsurface data for the Niobrara Formation. Taking a surface core of the Juana Lopez Calcarenite, Storm King Mountain Shale, and Niobrara Formation at Kremmling would provide enormous amount of data for the blank between basins. The data could be used to tie the Piceance Basin to the Denver-Julesburg, North Park, and Sand Wash Basins.

LIST OF ACRONYMS

Abbreviation	
SKMS	Storm King Mountain Shale
J. Lo.	Juana Lopez
GR	Gamma Ray
U.S.G.S	United States Geological Survey
C.G.S	Colorado Geological Survey

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Appendix A. Supplemental Electronic Files

Supplemental File	Description
Plate 1A	Plate 1A is a reference well cross-section from west to east with a datum on the Fort hays Limestone.
Plate 1B	Plate 1B is a reference well cross-section from west to east with a datum on the Niobrara Formation.
Plate 2	Plate 2 is a biostratigraphic column from USGS at Kremmling, CO.
Plate 3	Plate 3 is a measured section of the Niobrara Formation at New Castle, CO.
Plate 4	Plate 4 is a measured section of the Niobrara Formation at Wolcott, CO.
Plate 5	Plate 5 is a measured section at Delaney Buttes, CO.
Plate 6	Plate 6 is a measured section of the Niobrara Formation at Kremmling, CO.
Plate 7	Plate 7 is a compiled cross-section of the reference wells and measured sections from west to east.

Plate 1A is a reference well cross-section from west to east with a datum on the Fort hays Limestone. Plate 1B is a reference well cross-section from west to east with a datum on the Niobrara Formation. Plate 2 is a biostratigraphic column from USGS at Kremmling, CO. Plate 3 is a measured section of the Niobrara Formation at New Castle, CO. Plate 4 is a measured section of the Niobrara Formation at Wolcott, CO. Plate 5 is a measured section at Delaney Buttes, CO. Plate 6 is a measured section of the Niobrara Formation at Kremmling, CO. Plate 7 is a compiled cross-section of the reference wells and measured sections from west to east.