Geologic mapping of exhumed, mid-Cretaceous paleochannel complexes near Castle Dale, Emery County, Utah: On the correlative relationship between the Dakota Sandstone and the Mussentuchit Member of the Cedar Mountain Formation

Amanda Elizabeth MacKay Sorensen
Brigham Young University - Provo

Follow this and additional works at: https://scholarsarchive.byu.edu/etd

Part of the Geology Commons

BYU ScholarsArchive Citation
https://scholarsarchive.byu.edu/etd/2727

This Thesis is brought to you for free and open access by BYU ScholarsArchive. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of BYU ScholarsArchive. For more information, please contact scholarsarchive@byu.edu, ellen_amatangelo@byu.edu.
Geologic mapping of exhumed, mid-Cretaceous paleochannel complexes near Castle Dale, Emery County, Utah: On the correlative relationship between the Dakota Sandstone and the Mussentuchit Member of the Cedar Mountain Formation.

Amanda E. Sorensen

A thesis submitted to the faculty of Brigham Young University in partial fulfillment of the requirements for the degree of Master of Science

Dr. Brooks B. Britt, chair
Dr. Bart J. Kowallis
Dr. Thomas H. Morris

Department of Geological Sciences Brigham Young University
June 2011

Copyright © 2011 Amanda Sorensen
All Rights Reserved
ABSTRACT

Geologic mapping of exhumed, mid-Cretaceous paleochannel complexes near Castle Dale, Emery County, Utah: On the correlative relationship between the Dakota Sandstone and the Mussentuchit Member of the Cedar Mountain Formation.

Amanda E. Sorensen
Department of Geological Sciences, BYU
Master of Science

Numerous well-preserved, exhumed paleochannels in the Morrison, Cedar Mountain and Dakota Sandstone formations are exposed east of Castle Dale, Utah. These channels consist primarily of point bar complexes and scattered, low sinuosity channels. To determine the vertical and lateral relationships of these channels within the Cedar Mountain and Dakota Sandstone formations, a 1:24,000 scale geologic map covering ~140 km² was created showing the fluvial sandstones.

In the study area the Cedar Mountain Formation consists, from bottom to top, of 2.5-10 m of Buckhorn Conglomerate Member equivalent units, ~80 m of the Ruby Ranch Member, and ~30 m of the Mussentuchit Member. The Dakota Sandstone consists of conglomeratic to sandy, meandering channel fills within the Mussentuchit Member. The Ruby Ranch-Mussentuchit member contact is diagnosed as the top of a laterally extensive, ~10 meter thick, maroon paleosol with calcrete horizons and root traces. When deeply weathered the contact is discernable as a shift from maroon mudstone to a pale green-white, silty mudstone. Like the balance of the Mussentuchit Member overbank deposits, the white-green mudstone is rich in smectitic clays.

In the southern one-third of the mapped area, Ruby Ranch Member sandstones are thin, discontinuous channel segments surrounded by floodplain deposits. In the middle to northern area, point bar complexes dominate, some of which are laterally amalgamated. Flow direction data from four meander complexes and a low sinuosity channel indicate an average northeast flow. Dakota Sandstone channels all of which are within the Mussentuchit Member also flowed to the northeast but point bar complexes are both more numerous and more laterally continuous than in the Ruby Ranch Member, indicating deposition in an area with less accommodation space than during Ruby Ranch Member time.

The data indicate the Dakota Sandstone consists exclusively of fluvial sandstones encased within the Mussentuchit Member of the Cedar Mountain Formation. Therefore, these units are coeval and simply different facies of the same depositional system. Consequently the Mussentuchit Member is considered a member facies of the Dakota Formation.

Keywords: exhumed paleochannel, point bar complex, Cedar Mountain Formation, Dakota Sandstone, Mussentuchit Member, Ruby Ranch Member
ACKNOWLEDGEMENTS

I would like to thank my husband for all his support day and night. Also I’d like to thank my brother David MacKay for his willing help in the field. I am particularly grateful for the direction, aid and patience given by my thesis advisor Dr. Britt and the support given by Dr. Kowallis and Dr. Morris. Without the geology department and very generous donors to the department, the opportunity to complete this master’s degree would not have been possible.
TABLE OF CONTENTS

ABSTRACT ........................................................................................................................................ 1

1 INTRODUCTION .......................................................................................................................... 2

1.1 Objectives ................................................................................................................................ 3

1.2 Background ................................................................................................................................ 3

1.2.1 Paleotectonic Setting ........................................................................................................ 3

1.2.2 Stratigraphy ........................................................................................................................ 5

1.2.2.1 Cedar Mountain Formation .................................................................................... 8

1.2.2.2 Dakota Sandstone ..................................................................................................... 10

1.2.2.3 Alluvial Sequence Stratigraphy ............................................................................ 11

1.2.3 Exhumed Channels ......................................................................................................... 13

1.3 Study area and methods ...................................................................................................... 14

2 RESULTS AND DISCUSSION ............................................................................................... 16

2.1 Geologic Map ....................................................................................................................... 16

2.1.1 Buckhorn Conglomerate and Yellow Cat Member .................................................... 16

2.1.1.1 Data ........................................................................................................................ 16

2.1.1.2 Discussion .............................................................................................................. 17

2.1.2 Ruby Ranch Member .................................................................................................... 19

2.1.2.1 Data ........................................................................................................................ 19

2.1.2.2 Discussion .............................................................................................................. 20

2.1.3 Mussentuchit Member and Dakota Sandstone .......................................................... 21

2.1.3.1 Data ........................................................................................................................ 21

2.1.3.2 Discussion .............................................................................................................. 23

2.2 Exhumed Channels and Point Bar Complexes ............................................................ 26

2.2.1 Paleochannel Parameters ............................................................................................ 26

2.2.2 Paleochannel Flow ....................................................................................................... 27

2.2.2.1 Discussion .............................................................................................................. 27

2.3 Mussentuchit Member and Dakota Sandstone Relationship ........................................... 29

2.4 Tectonic and Sequence Stratigraphic Implications ............................................................ 32

3 CONCLUSIONS ........................................................................................................................ 33

REFERENCES ................................................................................................................................... 35

TABLE ................................................................................................................................................ 48

Table 1: Flow parameters based on the measured radius of curvature in meters ...................... 48

FIGURES ............................................................................................................................................ 49

Figure 1: Index map ...................................................................................................................... 49

Figure 2: Foreland basin model ................................................................................................ 50

Figure 3: Regional early to mid-Cretaceous stratigraphic history ........................................... 50
Figure 4: The three types of terrestrial sequence bounding unconformities ........................................51
Figure 5: Point bar depositional model ........................................................................................................52
Figure 6: Measured section of the upper Morrison, Cedar Mountain and Mussentuchit/Dakota formations ........................................................................................................................................54
Figure 7: Map showing the sandstones preserved in the Ruby Ranch Member and the Mussentuchit Member/Dakota Sandstone ........................................................................................................................................54
Figure 8: Alluvial sequence stratigraphy for the Upper Morrison Formation, Buckhorn Conglomerate and equivalents, Ruby Ranch Member and Mussentuchit Member/Dakota Sandstone ........................................................................................................................................55
Figure 9: Isolated Ruby Ranch Member channel sandstone, looking to the southeast .............................56
Figure 10: Lateral accretion in a Ruby Ranch Member point bar complex ...............................................56
Figure 11: The Ruby Ranch-Mussentuchit member contact .....................................................................57
Figure 12: Vertical relationships between Dakota Sandstone channels and the Mussentuchit Member of the Cedar Mountain Formation .........................................................................................................................58
Figure 13: Ruby Ranch Member and Mussentuchit Member/Dakota Sandstone paleoflow direction ........................................................................................................................................59
Figure 14: Radius of channel meander curvature histograms .....................................................................60
Plate 1: Geologic Map ........................................................................................................................................61
ABSTRACT

Numerous well-preserved, exhumed paleochannels in the Morrison, Cedar Mountain and Dakota Sandstone formations are exposed east of Castle Dale, Utah. These channels consist primarily of point bar complexes and scattered, low sinuosity channels. To determine the vertical and lateral relationships of these channels within the Cedar Mountain and Dakota Sandstone formations, a 1:24,000 scale geologic map covering ~140 km² was created showing the fluvial sandstones.

In the study area the Cedar Mountain Formation consists, from bottom to top, of 2.5-10 m of Buckhorn Conglomerate Member equivalent units, ~80 m of the Ruby Ranch Member, and ~30 m of the Mussentuchit Member. The Dakota Sandstone consists of conglomeratic to sandy, meandering channel fills within the Mussentuchit Member. The Ruby Ranch-Mussentuchit member contact is diagnosed as the top of a laterally extensive, ~10 meter thick, maroon paleosol with calcrete horizons and root traces. When deeply weathered the contact is discernable as a shift from maroon mudstone to a pale green-white, silty mudstone. Like the balance of the Mussentuchit Member overbank deposits, the white-green mudstone is rich in smectitic clays.

In the southern one-third of the mapped area, Ruby Ranch Member sandstones are thin, discontinuous channel segments surrounded by floodplain deposits. In the middle to northern area, point bar complexes dominate, some of which are laterally amalgamated. Flow direction data from four meander complexes and a low sinuosity channel indicate an average northeast flow. Dakota Sandstone channels all of which are within the Mussentuchit Member also flowed to the northeast but point bar complexes are both more numerous and more laterally continuous.
than in the Ruby Ranch Member, indicating deposition in an area with less accommodation space than during Ruby Ranch Member time.

The data indicate the Dakota Sandstone consists exclusively of fluvial sandstones encased within the Mussentuchit Member of the Cedar Mountain Formation. Therefore, these units are coeval and simply different facies of the same depositional system. Consequently the Mussentuchit Member is considered a member facies of the Dakota Formation.

1 INTRODUCTION

The Cretaceous Cedar Mountain Formation and Dakota Sandstone are economically important because they are gas reservoirs in the Uinta Basin (Currie et al., 2008) and are yielding new vertebrate fossils (Kirkland et al., 1997; Eberth et al., 2006; Garrison et al., 2007; Mori, 2009; Shapiro et al., 2009; MacDonald et al., 2010; Taylor et al., 2011). There is considerable argument about the number and nature of the contained faunas and the environments in which they lived and were preserved (Rushforth, 1971; Tschudy et al., 1984; Kirkland et al., 1997; Eberth et al., 2006; Garrison et al., 2007; Kirkland and Madsen, 2007; Suarez et al., 2007; Mori, 2009; Shapiro et al., 2009). They also represent a time of transitioning climates from relatively more arid to increasingly humid. Finally, they represent a transition from terrestrial to marine depositional environments in the Cordilleran foreland basin with the encroachment of the Western Cretaceous Interior Seaway from southeast to northwest.

Typically, the top of the Cedar Mountain Formation has been identified as the mudstones below the first buff sandstone, which is defined as the base of the Dakota Sandstone (Stokes, 1944, 1952; Young, 1965). However, due to the discontinuous nature and variable stratigraphic position of the basal Dakota Sandstone in different parts of the Colorado Plateau, it has been proposed that the Mussentuchit Member and Dakota Sandstone are coeval (Kirkland et al., 1997;
The relationship of the upper Cedar Mountain Formation (the Mussentuchit Member) with the Dakota Sandstone has been unclear. East of Castle Dale, Utah (Figure 1), an array of well-preserved paleochannels occurs in the Morrison, Cedar Mountain Formation and Dakota Sandstone. Previous studies to the southeast of the study area described exhumed channels in the Morrison (Derr, 1974) and Cedar Mountain formations (Harris, 1980), but none in the Dakota Sandstone. Mapping these exhumed channels and deciphering member contacts may provide greater clarity as to their chronostratigraphic relationship. This clarity may, in turn, provide further insights into the paleotectonics, paleoclimate, and depositional environments of the local cordilleran foreland basin.

1.1 Objectives
The objectives of this thesis are to: (1) generate a geologic map of the Cedar Mountain Formation, Dakota Sandstone and their associated sandstones east of Castle Dale, Utah; (2) describe the fluvial deposits represented by exhumed channels and point bar complexes; (3) better determine the relationship between the Mussentuchit Member of the Cedar Mountain Formation and the Dakota Sandstone; and (4) interpret the implications for the paleoclimatic and paleotectonic setting.

1.2 Background

1.2.1 Paleotectonic Setting
In the study area, the Cedar Mountain Formation and Dakota Sandstone were deposited in a predominantly fluvial system during the mid-Cretaceous (Aptian-Cenomanian) (Yingling, 1987; Yingling and Heller, 1992; Currie, 1997; Aubrey, 1998; Garrison et al., 2007; Mori, 2009). These formations, along with overlying marginal marine and marine strata were deposited in the Cordilleran foreland basin east of the Sevier orogenic belt (DeCelles and Currie, 1996; Currie
This trough-like basin formed as a result of crustal loading along the eastward propagating thrust belt of the Sevier orogeny, which depressed the lithosphere east of the front to form a north-south trending foreland basin (Jordan, 1981). Evidences for this foreland basin are provided by Early to Late Cretaceous strata that are thickest and coarsest parallel to the west margin of the basin near the thrust front and, fluvial drainages that flow to the northeast (Yingling, 1987; Aubrey, 1989; Yingling and Heller, 1992; DeCelles and Currie, 1996; Currie, 1997; Currie, 1998; Currie, 2002).

There is disagreement as to the time of origin of the Sevier orogeny. Historically, its initiation is dated to the Middle to Late Jurassic (Spieker, 1946; Eardley, 1960; Armstrong and Oriel, 1965; Wiltschko and Dorr, 1983). However, some (Yingling, 1987; Yingling and Heller, 1992; Jordan, 1981; DeCelles, 1994) argued for an Early-Cretaceous initiation of the orogeny because, unlike the balance of the Cedar Mountain Formation and other formations in the foreland basin, the Late Jurassic Morrison Formation and Early Cretaceous Buckhorn Conglomerate of the Cedar Mountain Formation do not thicken to the west. This disparity in timing and configuration was addressed by the formulation of a kinematic model that divided an ideal foreland basin into four depositional zones (Figure 2) – the wedgetop, foredeep, forebulge, and backbulge (Kauffman, 1977; DeCelles and Giles, 1996; DeCelles and Currie, 1996). DeCelles and Currie (1996) and Currie (1997; 1998) proposed that the Late Jurassic Morrison Formation and Early Cretaceous Buckhorn Conglomerate were deposited in the backbulge – a hypothesis that calls for a westward thinning, rather than thickening of strata. Eastward migration of the forebulge resulted in the basal Cretaceous unconformity and subsequently, following a post-Morrison Formation hiatus of about 25 Ma (Greenhalgh and Britt, 2007), the balance of the Cedar Mountain Formation and the Dakota Sandstone were both deposited in the
foredeep and forebulge (DeCelles and Currie, 1996). In Utah, the thickest Early to Late Cretaceous foredeep deposition is in the Gunnison Plateau region (Yingling, 1987; Yingling and Heller, 1992). In the San Rafael area, the two formations were likely deposited in the foredeep toward the forebulge (Figure 2) (DeCelles and Currie, 1996; Currie, 1997; 1998).

It is suggested that most sediment for Cedar Mountain Formation and Dakota Sandstone deposition was derived from the Sevier thrust belt to the west and to a lesser degree, the Mogollon highlands to the south (Currie, 2002; Uličný, 1999; Dickinson and Gehrels, 2008). Fluvial systems within the Morrison, Cedar Mountain and Dakota Sandstone formations generally flowed to the northeast and drained into a marine embayment opening to the north that extended approximately to the U.S.-Canadian boundary, until the Late Cretaceous when rising sea levels flooded the foreland basin (DeCelles, 2004). Ultimately, the non-marine formations in central Utah were buried for more than 75 million years. Laramide uplift and related erosion in the late Cenozoic exhumed the channels and current climate has allowed for their preservation (Williams, et al., 2007).

Concerning the paleoclimate, palynomorphs and macroflora from the Dakota in southern Utah indicate a tropical or subtropical paleoclimate (Agasie, 1969; May and Traverse, 1971). Climate models for the mid-Cretaceous Western Interior of North America (Glancy et al., 1986) suggest that summer months were relatively dry and cyclonic storm tracks moved onto the eastern slopes of the Sevier Orogenic Belt producing higher precipitation during the winter months (Gustason, 1989).

1.2.2 Stratigraphy
The stratigraphic nomenclature of the Cedar Mountain Formation and Dakota Sandstone has evolved over time (see Figure 3). The Dakota “Group” was described first by Meek and Hayden
(1862) in Nebraska and later with post Burro Canyon rocks by Coffin (1921). However, there is still argument as to whether it is valid to perpetuate the name “Dakota” from the eastern side of the Western Interior Cretaceous Seaway to the western side (Young, 1960). Initially, strata now included in the Cedar Mountain Formation were grouped with the Morrison Formation (Eldridge 1894; Lee, 1920) with the Dakota Sandstone marking the upper limit. This was unquestioned until Knowlton (1920) recognized angiosperm plants in Lee’s (1920) upper Morrison Formation. The earliest angiosperms could be no older than Cretaceous in age and Knowlton (1920) removed the conglomerate and upper shale from the Morrison Formation placing them in the Dakota “Group”. However, these changes were not adopted until Stokes (1944, 1952) recognized the Buckhorn Conglomerate and the Cedar Mountain Formation as Lower Cretaceous and formally recommended a change in nomenclature. He also suggested that the Buckhorn Conglomerate is part of the Cedar Mountain Formation because it is discontinuous and generally too thin to map separately (Stokes, 1952). A few years later, Young (1960) defined the “Dakota Group” as predominantly non-marine basal Cretaceous deposits of the Colorado Plateau with the lower formation being the Cedar Mountain, which is characterized by non-carbonaceous mudstones. For the upper formation, which was known by various names, including “Dakota Sandstone”, “Dakota(?)” and “Dakota” and characterized by carbonaceous mudstones, coals, conglomerates and sandstones, he proposed a new name, the Naturita Formation. He renamed this unit because the relationship of these units in Colorado, Utah, and surrounding states could not be physically related to the type locality of the Dakota Sandstone in Nebraska. In the same paper, Young (1960) suggested that the name Burro Canyon Formation, which Stokes (1944, 1952) had proposed for basal non-carbonaceous mudstone strata east of the Colorado River, be dropped and considered those strata to be the Cedar Mountain Formation. He supported these
recommendations with a type section (Young, 1965) however the terminology did not come into common use. Later, Craig (1981) stated that grouping the Burro Canyon Formation with the Cedar Mountain Formation, upgrading Dakota to group status, and replacing the name Dakota Sandstone with the name Naturita Formation disregarded significant lithologic differences and would be too major of a redefinition. Craig (1981) followed the Cedar Mountain Formation definition of Stokes (1944, 1952) (i.e., with a basal Buckhorn Conglomerate and the upper Shale Member). Kirkland et al. (1997) proposed subdividing the Cedar Mountain Formation into the Buckhorn Conglomerate, Yellow Cat, Poison Strip, Ruby Ranch and Mussentuchit members. However, they (Kirkland et al., 1997) cautioned that the Mussentuchit Member might be coeval with the Dakota Sandstone.

Soon thereafter, Aubrey (1998) proposed that the Buckhorn Conglomerate Member should be included in the Morrison Formation because (1) a widespread, well-developed calcrete overlies the Buckhorn Conglomerate and marks the Morrison-Cedar Mountain formation contact when the Buckhorn Conglomerate is not present and (2) because the Buckhorn Conglomerate and Brushy Basin members appear to locally interfinger. Roca and Nadon (2007) supported Aubrey’s interpretation and presented additional evidence that the Buckhorn Conglomerate and Morrison Formation are part of the same genetic package. The evidence consisted of soft sediment deformation of the Morrison Formation by overlying Buckhorn Conglomerate. However, other authors (Mori, 2009; Greenhalgh, 2006; Greenhalgh and Britt, 2007, Kirkland and Madsen, 2007) considered the Buckhorn Conglomerate to be Cretaceous in age and part of the Cedar Mountain Formation. Greenhalgh and Britt (2007) rejected Roca and Nadon’s (2007) interpretation because they consider the deformed strata identified by Roca and Nadon (2007) to be Yellow Cat Member of the Cedar Mountain Formation, not the Morrison Formation. Finally,
in the latest interpretation of basal Cedar Mountain Formation members, Greenhalgh (2006) and Greenhalgh and Britt (2007) suggested that the Buckhorn Conglomerate, Yellow Cat, and Poison Strip members interfinger and represent an early Albian fill of valleys incised into the Morrison Formation. They also proposed that the paleosol complex noted by Aubrey (1998) overlies these paleovalley fills as well as Morrison Formation, where it was not incised. Finally, Greenhalgh and Britt (2007) and Mori (2009) recognize three primary stratigraphic “sequences” within the Cedar Mountain Formation, namely, from bottom to top (1) the Yellow Cat, Poison Strip, Buckhorn Conglomerate members which are early Albian paleovalley fills, (2) the Albian Ruby Ranch Member, and (3) latest Albian to early Cenomanian Mussentuchit Member.

1.2.2.1 Cedar Mountain Formation

The Cedar Mountain Formation is the most widespread mid-Cretaceous stratigraphic unit in Utah and western Colorado (Kirkwood, 1976; Sprinkel et al., 1992; Currie, 1997; Currie, 2002). The formation consists primarily of fluvial/lacustrine and alluvial sediments indicative of poor drainage and low relief in the cordilleran forebulge and thins from the west to the east (Currie, 1998; Currie, 2002). The formation overlies the Brushy Basin Member of the Morrison Formation. Lithologic and pedogenic features have been described across the Morrison and Cedar Mountain formation boundary in Utah, including in the San Rafael Swell (Greenhalgh, 2006). The sandstones and conglomerates within the Cedar Mountain Formation represent channel and point bar deposition and the mudstone and siltstones represent the overbank deposition (Yingling, 1987; Currie, 1998; Currie, 2002). Temporally, the formation spans approximately 25 million years, from the early Aptian, no older than 122-124 Ma (Mori, 2009; Greenhalgh, 2006) to the Albian-Cenomanian boundary (98.39 ± 0.07 Ma) (Cifelli et al., 1997; Garrison et al., 2007). Ludvigson et al. (2010) calculated ages of 119.4 Ma from the Ruby Ranch
Member supporting the date obtained by Mori (2009) and Greenhalgh (2006). Recently, Sames et al. (2010) concluded that the basal Cedar Mountain Formation is much older than the radiometric ages indicate, dating back to the Berriasian-Valangian (~140 Ma). This conclusion is based on their ostracod data and dinosaur fauna that Kirkland and Madsen (2007) postulated is significantly older than other Cedar Mountain Formation dinosaur faunas. In light of the radiometric ages, and the speculative nature of the dinosaur correlations, we follow the radiometric ages cited above for the Cedar Mountain Formation.

The evolution of the stratigraphic history of the Cedar Mountain Formation is shown in Figure 3. Our study follows the hypothesis of Greenhalgh and Britt (2007), in which the Buckhorn, Yellow Cat and Poison Strip members are considered different facies of the same prograding clastic wedge and therefore are all members of the Cedar Mountain Formation. The Ruby Ranch Member overlies these basal units and is characterized by abundant caliche horizons that often weather into nodules and paleosols developed in silty mudstones. These paleosols indicate a semiarid monsoonal climate with intervals of time that recorded low rates of deposition (Stokes, 1944; Kirkland et al., 1997; Elliott et al., 2007). The Mussentuchit Member is distinguished by a shift to highly smectitic clays (Kirkland et al., 1997). Garrison et al. (2007) noted a laterally continuous sandstone at the base of the unit in the type locality at Mussentuchit Wash. This sandstone coincides with a freshwater limestone in the Price River area (Garrison et al., 2007). Widespread sandstones in the upper 20-30 meters of the Mussentuchit Member have long been assigned to the Dakota Sandstone (Stokes, 1952; Young, 1960; Craig, 1981; Kirkland et al., 1997). The lowest occurrence of a significant sandstone is used to mark the base of the Dakota Sandstone. Most of these sandstones appear to be essentially conformable with related
fine-grained sediments. It has been suggested that these sandstones are coeval with, and represent channel facies, of the Mussentuchit Member (Kirkland et al., 1997; Mori, 2009).

1.2.2.2 Dakota Sandstone

The Dakota Sandstone, formation or group, is generally defined as Cretaceous non-marine deposits or transitional beds deposited along the lower alluvial plain or shoreline of the invading Cretaceous Sea (Yingling and Heller, 1992; Kirkwood, 1976; Ryer et al., 1987; Pierson, 2009). The Dakota Sandstone is typically composed of sandstone, conglomerate and mudstone. Generally these are interpreted to be tidally influenced fluvial deposits, channel fills, and depending on the location, shallow marine deposits (Kirkwood, 1976; Ryer et al., 1987). In the San Rafael region, the Dakota Sandstone typically overlies the Cedar Mountain Formation. However, to the south it overlies progressively older Jurassic, Triassic and Paleozoic rocks, (Aubrey, 1989; Pierson, 2009; Kirschbaum and McCabe, 1992). Thus, the Dakota Sandstone incises into these underlying formations creating a regional unconformity. This regional unconformity formed due to local uplift and a drop in sea level at the end of the Early Cretaceous (late Albian) (Aubrey, 1989; 1998). The drop in sea level created paleovalleys followed by a relative sea level rise where “Dakota” sandstones filled the paleovalleys.

The Dakota Sandstone has been divided into three informal members: first, the basal laterally continuous fluvial sandstone; second, carbonaceous shales and channel sandstones with coal; and third, marine influenced sandstones (Peterson, 1969). However, the Dakota Sandstone deposits are highly variable and at times pinch out completely (Eaton et al., 1990). According to Eaton et al. (1990) and Yingling (1987) the Dakota Sandstone in the study area is non-marine. Within the study area Tidwell and Hebbert (1992) described the false tree fern Tempskya from
what we consider the Mussentuchit Member. They postulated that the depositional setting and environment was similar to the current day Everglades.

1.2.2.3 Alluvial Sequence Stratigraphy

Sequence stratigraphy, the study of genetically related facies within a chronostratigraphic framework and sequence boundaries, is primarily utilized in marine and marginal marine areas where sedimentary packages are controlled by relative sea level (Mitchum et al., 1977; Wilgus et al., 1988; Van Wagoner et al., 1990). A number of studies, however, attempt to apply sequence stratigraphic principles to continental strata by focusing on changes in accommodation space, which may or may not be due to changes in sea level (Shanley and McCabe, 1994; Olsen et al., 1995; Currie, 1997; Cleveland et al., 2007, Roca and Nadon, 2007, Currie et al., 2008). In an alluvial/fluvial setting such as in the Morrison, Cedar Mountain, and Dakota Sandstone formations, accommodation is controlled by the equilibrium stream profile and base level (Shanley and McCabe, 1994; Currie, 1997). Variations in sea level, sediment supply, stream discharge, intrabasin tectonism and/or climate may readjust the equilibrium profile of a stream and affect the accommodation space on the alluvial/fluvial plain (Currie, 1997).

Rather than using terms such as lowstand and highstand, which are related to changes in sea level, Currie (1997) adopted the terms degradational, transitional and aggradational because they are related solely to increases and decreases in accommodation. An aggradational systems tract occurs when there is an increase in accommodation. Typically with an increase in accommodation, there is a change from a low sinuosity braided to high sinuosity anastomosing and meandering channel morphology, the floodplain is stabilized, and more fine-grained material is preserved. High rates of aggradation create channel segments that are isolated vertically and laterally by overbank material. During late stages of an aggradational systems tract, where the
rate of increasing accommodation begins to slow, the fluvial channels tend to transition from isolated to more amalgamated sandstones. A degradational systems tract occurs when there is a decrease in accommodation. The decrease in accommodation may result in sediment bypass, valley incision, an increase in coarse-grained material, and low sinuosity braided channel morphologies that are thin and widespread. If incision occurs, channel bodies will likely be restricted to paleovalleys (Currie, 1997).

Sequences are bounded by unconformities and there are three main types (see Figure 4). Type 1 unconformities develop during major reductions in accommodation space and are exemplified by valley incision. Type 2 unconformities are associated with a minor decrease in accommodation and result in widespread shallow erosion. Lastly, Type 3 unconformities form because of localized to subregional uplift within a basin (Posamentier et al., 1988; Currie, 1997).

By dividing up depositional sequences bounded by unconformities into systems tracts Currie (1997) was able to assign the Upper Jurassic-Lower Cretaceous rocks into four depositional sequences, two of which are in the Cedar Mountain Formation and Dakota Sandstone. His LK-1 sequence is represented by the Buckhorn Conglomerate and the LK-2 by the rest of the Cedar Mountain Formation bounded on top by the unconformity at the base of the Dakota Sandstone. However, we do not recognize the sequence boundary at the base of the Dakota and propose that in the study area the top of the LK-2 sequence is bounded by the unconformity at the Ruby Ranch-Mussentuchit member contact. Despite this alternative interpretation we use Currie’s (1997) alluvial sequence stratigraphic model to divide the Cedar Mountain Formation and Dakota Sandstone into systems tracts and sequences. However, it is appropriate to use traditional sequence stratigraphy nomenclature with the Dakota Sandstone as sea-level begins to control deposition with the incoming Western Interior Cretaceous Seaway.
1.2.3 Exhumed Channels

This is not the first study on exhumed paleochannels in east-central Utah. Derr (1974) described exhumed fluvial channel fills in the Brushy Basin Member of the Morrison Formation near Green River, Utah. Later, Harris (1980) studied exhumed channels in the Cedar Mountain Formation approximately 11 km southwest of Green River. Following the discovery of curvilinear features on Mars, Williams et al. (2007; 2009) used the exhumed channels described in the aforementioned studies as terrestrial analogs. In another study, the fracture patterns in these channel sands were analyzed to determine whether the fracture orientation changes with the orientation of the channel sands (Lorenz et al., 2006). These studies provide an understanding of the Cedar Mountain and Morrison formation exhumed channels in a relatively localized area. Numerous stratigraphic, sedimentologic, and paleontologic studies have been completed on the Cedar Mountain Formation (including Eberth et al., 2006; Garrison et al., 2007; Currie, 1998) but none recognize the point bar complexes described in our study. However, a number of workers have reported on point bar assemblages in other locations. Exhumed meander scrolls in the Western Desert of Egypt were mapped with 1:20,000-scale aerial photographs from which measurements of curvature radius and mean scroll spacing were made (Brookes, 2003). Based on the information gathered from the field and photos, he calculated discharge and sinuosity for the streams. Smith (1987) studied similar features in the Karoo Formation of South Africa and reconstructed the morphology and depositional environment of the Permian Reiersvlei Sandstone. Using other exhumed Permian point bars, Edwards et al. (1983) determined paleochannel geometry and flow patterns in north-central Texas. Like Brookes (2003), they used aerial photographs to determine radius of curvature. However, Edwards et al. (1983) focused more on sedimentary features and structures. A point bar complex facies model was developed for an exhumed Quaternary channel in the Ganga Plain, India (Singh et al., 1998). Using these
papers as models, we apply similar methods to exhumed channels east of Castle Dale, Utah (Figure 5).

1.3 Study area and methods

The area of study is located on the Colorado Plateau, along the western flank of the San Rafael Swell east of Castle Dale, Utah (Figure 1) and covers some 140 km². The area is accessible in the north by the Green River Cut-off Road, in the south by the Sand Bench Loop and small, unmarked Jeep trails. This location was chosen because of the abundance of well-preserved channel segments and point bar complexes in the Morrison, Cedar Mountain and Dakota Sandstone formations. Additionally, this area was selected for mapping because the Buckhorn Conglomerate and the Yellow Cat Member of the Cedar Mountain Formation are both present. Recently, a thick paleosol was identified (Mori, 2009) that marks the contact of the Ruby Ranch and Mussentuchit members and better facilitates mapping.

Mapping was done using Cardinal Systems Virtual Reality (VR1 and VR2) software, which allows detailed mapping of the point bar complexes, associated sandstone channels and their contacts in a precise, detailed three-dimensional environment. Mapping utilized 1:40,000 and 1:20,000 scale black and white stereo photographs and 1:30,000 scale color infrared aerial photographs obtained from the USDA and BLM. Multiple sets were utilized because of insufficient coverage in the 1:20,000 scale photographs. The photos were scanned at high resolution (800-1000 dpi) and assigned relative and absolute orientations. This permits the program to create a 3D model onto which precise mapping of the contacts, fluvial sandstones, and the relative stratigraphic positions of the point bar complexes can be placed. Color infrared photos were used primarily to map contacts. Black and white photos were used for mapping the sandstones.
Fieldwork was conducted to collect architectural and other sedimentological data on significant channels and to determine contacts between members and formations. A Bushnell Onix 400 GPS was used to mark data locations where information such as flow direction measurements, pictures, contacts, measured sections, etc. were taken.

Channel mapping focused on digitally tracing the exhumed channels and point bar complexes from stereo photos using VR1 and VR2 software. Member and formational boundaries were also mapped based on descriptions from Greenhalgh and Britt (2007) and Mori (2009). We utilized the 3D visualization program to interpolate contacts from known locations as determined in the field. From the aerial photos of point bar complexes, their radius of curvature was measured for use in paleofluvial calculations. Radius of curvature is measured by superimposing circles of known radii on the outermost point bar of the complex following Brookes (2003). These data were then entered into equations (section 2.2.1) to determine paleofluvial estimates.

A stratigraphic section (Figure 6) was measured from the top of the Morrison Formation to the top of the Dakota Sandstone using a clinometer and Jacob’s staff to provide baseline lithologic data and thicknesses of significant lithosomes. The location of this stratigraphic section is indicated by S1 in Figure 1. Sand to Mud ratios were calculated using data from this measured section and the Long Walk Quarry section from Mori (2009).

The data derived from the field and the 3D visualization software were compiled and finalized in ArcMap to visually communicate the fluvial architecture of Cedar Mountain Formation and the Dakota Sandstone (Plate 1).
2 RESULTS AND DISCUSSION

2.1 Geologic Map

Strata in the mapped area (Figure 1) include the Jurassic Entrada, Curtis, Summerville, Morrison, and Cretaceous Cedar Mountain, Dakota Sandstone and Mancos Shale formations (Figure 7 and Plate 1). The Cedar Mountain Formation, its members, and the Dakota Sandstone were mapped in detail. The contacts were determined largely in the field. All other contacts are based on color changes in the aerial photos and the geologic map of the Huntington 30’ x 60’ quadrangle Carbon, Emery, Grand and Uintah Counties, Utah (Whitkind, 1988). In the study area the Buckhorn Conglomerate/Yellow Cat, Ruby Ranch and Mussentuchit members of the Cedar Mountain Formation are present. The Cedar Mountain-Morrison formational contact has been mapped along with the Ruby Ranch-Mussentuchit member contact. Sandstones of the Ruby Ranch Member and Mussentuchit Member that are at a mappable scale are also included. The sandstones above the Ruby Ranch-Mussentuchit member contact, traditionally referred to the Dakota Sandstone, are mapped as part of the Mussentuchit Member. The Mussentuchit Member/Dakota Sandstone contact with the overlying Mancos Shale is estimated because alluvium obscures much of the contact.

2.1.1 Buckhorn Conglomerate and Yellow Cat Member

2.1.1.1 Data

In the field area, a 0-10m thick Buckhorn Conglomerate crops out north of the Green River Cut-off Road on Little Cedar Mountain. It fines upwards, and is typically composed of cobble to sand size chert clasts. It is generally cemented with calcite. Occasional sandstone lenses of cross-bedded, medium to coarse sands are interbedded with the conglomerate. The conglomerate appears to cut into and rework sediment in the underlying variegated silty to fine-grained sandstones and mudstones of the Morrison Formation. In plan view, there are few discernable
channels in the Buckhorn Conglomerate within the study area. No paleoflow data from this unit were collected in our study.

The classic Buckhorn Conglomerate pinches out just north of the Green River Cut-off road but the horizon extends to the south as an approximately 2-m-thick, highly mottled, silty mudstone with common chert pebbles (Figure 6). The basal one-third is a slope forming, predominantly fine to medium sandstone with abundant chert pebbles up to 1.5 cm in diameter. The sand fraction is mostly quartz with common chert lithics. The upper portion of the unit is a medium to coarse sandstone with abundant chert grains, which are often clustered in stringers up to 2 cm thick.

The upper portion of this basal unit of the Cedar Mountain Formation is typically overprinted by a calcrete/silcrete. A calcrete is defined as terrestrial, near surface, secondary calcium carbonate accumulations in soil profiles, bedrocks and sediments. In contrast a silcrete is dominated by secondary silica accumulations (Watts, 1980; Wright, 1991; Retallack, 2001; Alonso-Zarza, 2003). The secondary calcium carbonate and silica fragmented the matrix into angular clasts that weather out in relief. In the study area south of the Green River Cut-off road, this Buckhorn Conglomerate equivalent is too thin to map at a 1:24,000 scale. Nevertheless, the unit occurs throughout the study area.

2.1.1.2 Discussion

Taken together, the Buckhorn Conglomerate and its coeval mudstones, sandstones, and calcrete/silcrete comprise the basal unit of the Cedar Mountain Formation. These basal sediments of the Cedar Mountain Formation often fill incisions into, and are largely composed of materials reworked from, the underlying Brushy Basin Member of the Morrison Formation (Eberth et al., 2006, Britt et al., 2009, Greenhalgh and Britt, 2007). Incised areas are recognizable by the
absence of a deep paleosol that marks the top of the Morrison Formation (Greenhalgh and Britt, 2007).

The Buckhorn Conglomerate, in the strict sense, was interpreted as a braided fluvial system (Currie, 1997; Currie, 1998) that flowed to the northeast (Yingling, 1987; Currie, 1998) and filled a paleovalley incised into the Morrison Formation. Currie (1998) mapped the Buckhorn Conglomerate focusing on a 30 m thick outcrop near the Utah-Colorado border within Dinosaur National Monument. He considered this the main Buckhorn Conglomerate drainage trunk. In the Green River-Moab region there are no significant conglomerates at or near the base of the Cedar Mountain Formation. However, the Buckhorn Conglomerate’s lateral equivalents, the Yellow Cat and Poison Strip Sandstone members and one or more calcrete horizons are present (Greenhalgh and Britt, 2007).

The chert-rich, brecciated sandstone, Buckhorn Conglomerate equivalent, is interpreted to be sandstone altered and fragmented by pedogenic or groundwater cementation processes. This resulted in a calcrete/silcrete that marks, or is just above, the Cedar Mountain-Morrison formation contact south of the Green River cut off road. Greenhalgh et al. (2007) also identified this unit in the San Rafael Swell area and called it the Yellow Cat Member. The unit is typically massive with few discernable sedimentary structures. This is most likely due to the subsequent calcic pedogenic alteration that led to the deposition of the chert stringers and brecciated appearance. It is possible that the sandstone portion of the unit was deposited in fluvial feeder systems to the Buckhorn Conglomerate trunk fluvial system (Greenhalgh and Britt, 2007). Alternatively, in a system of cobbles and gravels, the sandstone could represent an overbank facies of the same system. Some authors use this calcrete as evidence of the Buckhorn Conglomerate being older and part of the Morrison Formation (Aubrey, 1998; Roca and Nadon,
However, it is likely that the paleosol above the Buckhorn Conglomerate represents soil development that was contemporaneous with the alteration of the sandstones creating the calcrete/silcrete.

Currie (1997) placed the Buckhorn Conglomerate and calcrete in a sequence stratigraphic framework. He determined that a type 1 unconformity develops where a paleovalley cuts down into the underlying Morrison Formation. The Buckhorn Conglomerate represents the degradational and transitional systems tract infilling the incised valley and the calcrete/silcrete likely represent a type 3 unconformity, when the area was uplifted by the migrating forebulge. I suggest that the paleosol marking the top of the Morrison Formation is a type 2 unconformity created by a lack of deposition. This unconformity is then incised (type 1 unconformity) as the degradational lower Buckhorn Conglomerate downcuts, reworks and infills. The upper Buckhorn Conglomerate then becomes more of a transitional systems tract. Finer material and thin laterally continuous sandstones are deposited and eventually replaced and displaced by the calcrete/silcrete (Figure 8). This calcrete/silcrete represents a type 3 unconformity caused by the migration of the flexural forebulge (Currie, 1997) which causes pedogenic and groundwater alteration of the transitional thin laterally continuous sandstones and the upper Buckhorn Conglomerate.

### 2.1.2 Ruby Ranch Member

#### 2.1.2.1 Data

Above the Buckhorn Conglomerate and the correlative Yellow Cat Member calcrete/silcrete complex is the Ruby Ranch Member. This member is a dull maroon colored silty-mudstone with resistant carbonate horizons and thin, fining upward sandstones ranging from 0.2 to 4 m thick. In the measured section (Figure 6) the Ruby Ranch Member is approximately 80 m thick. The thin
sandstones tend to be fine grained and the thicker ones (1-3 m thick) cross-beded, fining upward, predominantly medium to fine grained with a conglomerate base. In aerial photos these thicker sandstones crop out as broad, curvilinear, nested sets of fining upward sandstones (Figure 9 and 10). These sandstones are highly discontinuous and are isolated between fine-grained siltstones and mudstones.

Fractured cemented carbonate horizons within the dull maroon silty mudstones, weather into spheroidal “nodules” that drape the slopes and are a defining feature of this unit. The Ruby Ranch Member is capped by a 10 m thick mudstone that is a distinct reddish/dark purple color (Figure 11). When this upper horizon is freshly exposed, root traces and resistant fractured carbonates are apparent (Mori, 2009).

2.1.2.2  Discussion

The Ruby Ranch Member of the Cedar Mountain Formation is interpreted as a fluvial unit with overbank deposits overprinted by calcic paleosols (Kirkland et al., 1997). The carbonate horizons that weather to nodules are likely of pedogenic (caliche) origin, possibly groundwater cementation of permeable alluvium (Currie, 1997; Greenhalgh and Britt, 2007), or lacustrine carbonates (Garrison et al., 2007; Ludvigson et al., 2010). Caliches or calcretes are calcium carbonate cemented zones that develop from percolating waters in the B horizon of soils in semi arid to arid climates and are enhanced by high evaporation rates (Elliott et al., 2007). The abundant caliche or calcrete horizons in the Ruby Ranch Member are interpreted as evidence of wet and dry cycles in a semiarid environment (Kirkland et al., 1997).

The curvilinear nested sets of sandstones are interpreted herein to represent laterally accreted, fining upward sandstones deposited in point bar complexes of meandering streams (Figure 5 and Figure 9). Sedimentary features within the sandstone support this interpretation.
Cross-bedded sandstones fine upwards and display a conglomerate/gravelly base as shown in the model (Figure 5). The point bar complex sandstones are more extensive in the middle part of the mapped area (Figure 7 and Plate 1) than in the southern or northern parts of the map. In the southern reaches of the study area, small isolated channel sandstones (Figure 9) are exposed but broad exposures of scroll sets are absent or not preserved. In the sequence stratigraphic framework these Ruby Ranch Member isolated sandstones and overbank mudstones are representative of an aggradational or highstand systems tract (Figure 8).

Masters et al. (2004) reported a dinosaur-bearing, anastomosing/braided river channel within the Ruby Ranch Member at Dinosaur National Monument. The site, however, has been reassessed and the channel is within the Mussentuchit Member of the Cedar Mountain Formation (Chure, et al., 2010).

The 10 m-thick maroon mudstone with probable root traces and carbonate nodules that caps the Ruby Ranch Member in the study area is interpreted as a well-developed paleosol. The thickness of this paleosol indicates it represents a significant unconformity (Figure 6). The dark maroon color is a stark contrast with the immediately overlying, light-colored smectitic clay-rich sediments of the Mussentuchit Member, making the paleosol an excellent marker bed.

### 2.1.3 Mussentuchit Member and Dakota Sandstone

#### 2.1.3.1 Data

In the study area, the Mussentuchit Member consists primarily of carbonaceous, smectitic mudstones often gray in color. These mudstones are interbedded with yellow sandstone units that have been traditionally assigned to the Dakota Sandstone. Mapping shows the sandstones to be amalgamated, sheet-like bodies made up of laterally accreting sinuous sandstones and uncommon linear sand bodies. Smaller sandstone channels and meander sets are visible on the
ground but they were not mapped because they are not visible in the aerial photographs and they would not show up at the mapped scale.

Unconformably overlying the well-developed, maroon paleosol capping the Ruby Ranch Member is a green/grey muddy siltstone with little smectitic clay. This unit grades into an approximately 1 m thick, smectitic, clay-rich, pale green mudstone that in turn grades into a dark green-blue mudstone. These mudstones are easily distinguishable from those of the Ruby Ranch Member by the popcorn-like weathering texture of the smectitic clays and the absence of caliche “nodules”. The exception is a single thin, fractured, carbonate-cemented horizon that weathers into nodules a couple meters above the base of the Mussentuchit Member. There are paleosols in the Mussentuchit Member (Garrison et al., 2007), but they are not as extensive as the paleosol that caps the top of the Ruby Ranch Member and marks the Ruby Ranch-Mussentuchit member contact.

Where the section was measured (Figure 6) there are two major sandstones within the Mussentuchit Member. The lowest of these sandstones is 20 m above the base of the member. The base of this sandstone consists of a roughly 15 cm thick conglomerate beneath approximately 1.5 m of fine-to medium-grained, upward fining, cross-bedded sandstone. This sandstone downcuts slightly into the underlying mudstone. Above the first sandstone, in the measured section, is another dark green-blue-grey mudstone/siltstone, about 1.4 m thick, which is similar to the basal mudstones of the Mussentuchit Member, with a weathered ‘popcorn’ texture. A fine-to medium-grained sandstone, similar to the basal sandstone, at least 1.7 m thick, overlies the smectitic mudstone/siltstone. Neither of the sandstones includes marine macrofossils or tidal deposits that would indicate a direct marine influence. However, the sandstones often include carbonaceous materials, including rare, thin, discontinuous coal beds.
Based on a thin section from the lowest of the two sandstones, which is typical of this lithology in the area, the sandstones tend to be well-sorted, medium-to fine-grained sandstone with less than 5% silt or clay. The composition is primarily quartz with approximately 40% feldspar and lithics. At the base of the laterally accreting sandstones/point bars, coarse sands and conglomerates are typical. Ripples are rare and occasionally a topset and its corresponding forset bed are recognizable (Brookes, 2003).

The contact between the sandstones and the overlying Mancos Shale was not observed in the study area because it is covered by alluvium/colluvium. Therefore, the nature of this contact remains to be determined.

2.1.3.2 Discussion

The Mussentuchit Member is not always differentiated from the Ruby Ranch Member or the Dakota Sandstone and it is only recently that the Mussentuchit and Ruby Ranch members have begun to be mapped separately (Doelling and Kuene, 2009). Currie et al. (2008) did not include the Mussentuchit Member in their stratigraphic column but include it in the Ruby Ranch Member of the Cedar Mountain Formation. This leads to placing the Ruby Ranch Member – Dakota Sandstone boundary at the base of the first sandstone. The Mussentuchit Member is not always present; although, in some locations, it is present but has not been documented. For example, in the Moab region, Mori (2009) recognized the Mussentuchit Member and the paleosol at the contact with the Ruby Ranch Member for the first time.

The Mussentuchit Member is differentiated from the Ruby Ranch Member by a shift to smectitic-rich, carbonaceous mudstones and siltstones above the paleosol at the Ruby Ranch-Mussentuchit member contact (Kirkland et al., 1997; Garrison, 2007; Mori, 2009). Sandstones
above this contact are more laterally continuous than those in the Ruby Ranch Member. However, they thin and thicken locally (Figure 12) and the basal sandstone, historically considered the base of the Dakota Sandstone (Stokes, 1952; Young, 1960; Craig, 1981; Kirkland et al., 1997), is not a single unit, but distinct sandstone bodies. Thus, different sandstone bodies represent the basal sandstone in different locations (Young, 1960, 1965).

The Dakota Sandstone was first subdivided by Peterson (1969) in the Kaiparowit plateau into three informal members: first, a basal fluvial laterally continuous sandstone; second, carbonaceous shales and channel sandstones with coal; and third, the marine-influenced sandstones (Gustason, 1989, Uličný, 1999; Kirschbaum and McCabe, 1992). In the Uinta Basin the Dakota Sandstone has been divided into two sequences (Vaughn and Picard, 1976; Currie, 2002; Currie et al., 2008; Pierson, 2009) the first is composed of fluvial sandstones, conglomerates and overbank deposits. The second sequence is composed of similar lithologies but the upper part exhibits a marine influence. Based on these descriptions, the “Dakota” in the area of this study is different from the Dakota Sandstone to the north and south. In the study area, I saw no features such as, macrofossils or tidal deposits, which would indicate a direct marine influence. Although, the classic oyster bearing beds are not present in this area, the carbonaceous shale and coals could represent a higher water table. This suggests deposition is in part controlled by an increase in sea-level.

The recognition of directly marine-influenced Dakota Sandstone to the north and south, and the absence of marine markers in the study area is puzzling. Aubrey (1989) described the Dakota Sandstone in the southeastern Colorado Plateau. He postulated that the southern margin of the Plateau was uplifted and tilted before the deposition of the Dakota Sandstone this explains angular unconformities in some areas. In our mapped area, the first and third informal members
of the Dakota Formation, as described by Gustason (1989) are also not present. Eaton et al. (1990) and Yingling (1987), who did field work in the San Rafael Swell, support this conclusion. A marine influence to the north and to the south and a lack of marine facies here suggests that there was a local high in this area during deposition. Locally, the sandstones in the Mussentuchit Member, or the middle Dakota Sandstone member, appear to incise into the lower mudstones where the fluvial channels thicken, however, there does not appear to be a regional unconformity at the base of the Dakota sandstones. This implies that there is a relationship between the unconformity at the base of the Mussentuchit Member and that of the Dakota Sandstone in other areas. For this reason, the “Dakota” sandstones have been mapped as part of the Mussentuchit Member. The relationship between the Dakota Sandstone and Mussentuchit Member of the Cedar Mountain Formation is analyzed below in section 2.3.

The fines preserved in the Mussentuchit Member suggest a significant increase in accommodation after the erosional period represented by the underlying unconformity. This is similar to the fine-grained sediment preserved in the older Ruby Ranch Member. However, one major difference between the Ruby Ranch Member and the Mussentuchit Member/Dakota Sandstone is that the sandstones are more laterally extensive and amalgamated. This implies less accommodation or extensive winnowing of existing sediments. Therefore, the Mussentuchit Member/Dakota Sandstone probably represents either a transitional or late aggradational systems tract in the sense of Currie (1997). Above these sandstones is the Tununk Shale Member of the Mancos, which is marine. Thus, the contact between the uppermost sandstone and the marine shale is a marine flooding surface and would be a considered either an aggradational systems tract or a highstand systems tract.
Another major difference between the Ruby Ranch and Mussentuchit member deposits is a lack of calcretes that weather and drape the slopes, and the abundance of smectitic clays, carbonaceous material and volcanic ashes in the Mussentuchit Member. This suggests a significant climate change, from semi-arid to humid, due to the encroaching Western Interior Cretaceous Seaway, along with an increase in volcanic activity (Kirkland et al., 1997; Garrison et al., 2007).

2.2 Exhumed Channels and Point Bar Complexes

2.2.1 Paleochannel Parameters

In the study area, there are over 30 point bar complexes that can be identified from 1:20,000 scale photographs. Of these, the radius of curvature was estimated from 7 in the Ruby Ranch Member and 13 in the Mussentuchit Member. The average radius of curvature measured from the aerial photos in the Ruby Ranch Member is 231 m ($\sigma = 55$) and in the Mussentuchit Member it is 201 m ($\sigma = 87$) (Table 1). Bankfull widths were estimated for these scroll sets using the formula (Table 1);

$$W_b = 0.71R_c^{0.89}$$ (Williams, 1986).

$R_c$ is the mean radius of curvature and $W_b$ is the bankfull width. This model assumes that sinuosity, which is the ratio between channel length and meander belt axis, is greater than or equal to 1.70. We have also made the assumption that the outermost scrolls or point bars are most representative of the system because inner scrolls tend to be less circular and represent early stages of meander growth (Brookes, 2003). Bankfull depth is also estimated with radius of curvature using the equation (Table 1);

$$D_b = 0.085R_c^{0.66}$$ (Williams, 1986).
Using the results of the above equations $W_b/D_b$ ratios and bankfull cross-sectional areas ($A_b$) are calculated (Table 1);

$$A_b=0.067R_c^{1.53} \text{ (Williams, 1988).}$$

The average bankfull width from the Ruby Ranch Member point bar complexes equals 90 m ($\sigma = 19$) as compared to 79 m ($\sigma = 30$) from the Dakota Sandstones in the Mussentuchit Member. Bankfull depth equals 3.1 m ($\sigma = 0.5$) and 2.8 m ($\sigma = 0.8$), the ratio between bankfull width and depth is 29 ($\sigma = 1.8$) and 28 ($\sigma = 2.8$) and, bankfull cross-sectional areas 283 m$^2$ ($\sigma = 97$) and 240 m$^2$ ($\sigma = 155$) respectively (Table 1).

2.2.2 **Paleochannel Flow**

Paleochannel flow direction was measured from four point bar complexes in the Ruby Ranch Member and from ten point bar complexes in the Mussentuchit Member (Figure 1). In the Mussentuchit Member there were typically fewer reliable surfaces for these types of measurements and four of the ten surfaces have <11 measurements. The data is grouped by member/formation and plotted in rose diagrams (Figure 13). The average flow direction for the Ruby Ranch Member is $32^\circ$ ($\sigma = 18.19$) and in the Mussentuchit Member is $72^\circ$ ($\sigma = 11.63$). The flow direction is more variable and scattered in the sandstones of the Ruby Ranch Member.

2.2.2.1 **Discussion**

The flow parameters and direction data can aid in understanding the type of fluvial deposition. The data collected from the Ruby Ranch and Mussentuchit members are very similar and the differences are statistically insignificant particularly when considering the assumptions and errors associated with each equation. Radius of curvature, was used to calculate directly and indirectly each of the other parameters. There does not appear to be a considerable difference between the point bar complexes in the Ruby Ranch and the Mussentuchit members. The T test
result of 0.358 for the radius of curvature data indicates that the differences are insignificant. High accommodation space allows for deposition of more fines (Shanley and McCabe, 1994), and may explain the abundant overbank deposits (~ 5 % sand to mud ratio based on thickness in the stratigraphic section) preserved in the Ruby Ranch Member as compared to the Mussentuchit Member (~ 16 % sand to mud ratio). The sandstones in the Mussentuchit Member/Dakota Sandstone tend to be more variable and have radii of curvature both lower and higher than those in the Ruby Ranch Member (Figure 14). On average however, those of the Mussentuchit Member are lower. This may suggest that they are deposited in a meandering stream system with less accommodation causing higher variation in meander size including both well developed meanders and “less sinuous” sections. This is supported by the way the point bar complexes are amalgamated and form more sheet-like sandstones. In addition, the greater proportion of sand to fines (~16 %), as compared to the Ruby Ranch Member deposits (~5 %), suggests that there is less accommodation space and a great proportion of fines are bypassing the depositional area. Both the Mussentuchit Member, including the “Dakota” sandstones, and the Ruby Ranch Member have sand to mud ratios less than 20%. This suggests a suspended load and a high sinuosity meandering fluvial system (Galloway and Hobday, 1983; Morris and Richmond, 1992).

The average flow direction derived from the field gives a general northeast (Figure 13) vector for sandstones in both the Ruby Ranch Member and Mussentuchit Member/Dakota Sandstone, which is consistent with the literature (Yingling, 1987; Yingling and Heller 1992; Currie, 1998; Roca and Nadon, 2007). There are, however, slight differences between the flow direction data of the Mussentuchit Member/Dakota Sandstone and the Ruby Ranch Member sandstones. There is greater spread in the Ruby Ranch Member data (σ = 87) vs. Mussentuchit
Member data \((\sigma = 55)\). This lends support to the interpretation that the channels in the Ruby Ranch Member migrated more broadly with higher sinuosity (Roux, 1992) and greater accommodation space. The abundance of large scroll bar sets indicate the Ruby Ranch and Mussentuchit member fluvial channels were deposited in meandering river systems in an area with substantial accommodation space allowing for the preservation of abundant fines. The paleoflow and radius of curvature data supports that interpretation. However, these data may suggest that the Mussentuchit Member channels were deposited in an environment with less accommodation space than the Ruby Ranch Member.

2.3 Mussentuchit Member and Dakota Sandstone Relationship

From the time the Cedar Mountain Formation was divided into members, it was speculated that the Mussentuchit Member should be included in the Cedar Mountain Formation (Kirkland et al., 1997; Garrison et al., 2007; Greenhalgh and Britt, 2007; Mori, 2009). It is also questioned whether the name Dakota Sandstone applies to rocks deposited west of the Western Interior Cretaceous Seaway (Young, 1960; Craig, 1981; Gustason, 1989; Yingling, 1987; Greenhalgh and Britt, 2007). Young (1960) recognized three main sandstone units in the “Dakota” each which constitute the basal sandstone unit in a part of the Colorado Plateau. To resolve this issue he suggested the Cedar Mountain Formation and Dakota Sandstone be considered part of the “Dakota Group” but proposed separating the more carbonaceous rock and calling it the “Naturita Formation”. His suggestions were not widely adopted. Under his definition the currently defined Mussentuchit Member would have been part of this “Naturita Formation” although this was not illustrated in his type section (Young, 1965). Kirkland et al. (1997) and Mori (2009) suggest that the Mussentuchit Member and Dakota Sandstone may be coeval but do not delve any further. The recognition of the thick paleosol between the Ruby Ranch and the Mussentuchit members
indicates a significant unconformity between the two members. Missing time is up to 10 million years from ~113 Ma (Mori, 2009) to ~97 Ma (Cifelli et al., 1999; Garrison et al., 2007; Ludvigson et al., 2010). This significant hiatus relationship indicates that the Mussentuchit Member may be more closely related time wise to the Dakota Sandstone than the rest of the Cedar Mountain Formation.

There is other evidence that may imply a coeval nature for the Mussentuchit Member and Dakota Sandstones. In southern Utah the Encinal Canyon Member is the basal member of the Dakota Sandstone. Generally the associated mudstones of the Encinal Canyon Member can be distinguished by color from those of the Burro Canyon Formation which is correlative to the Cedar Mountain Formation east of the Colorado River (Aubrey, 1989). The mudstones of the Encinal Canyon Member of the Dakota Sandstone are grayer in color than the somewhat varicolored mudstones in the Ruby Ranch Member of the Cedar Mountain Formation. Garrison et al. (2007) described the Mussentuchit Member as a light gray-to-gray slope-forming mudstone, which is similar to the description of the Encinal Canyon Member of the Dakota Sandstone.

Earlier it was discussed that the lower and upper informal Dakota Sandstone members are not present in this study area, implying a local high existed during deposition (Yingling, 1989; Eaton et al., 1990). Also, briefly discussed, is that the amount of erosion occurring at the base of the Dakota Sandstone varies with location. Eaton et al. (1990) also mentioned that there are times when there is no sandstone between the Cedar Mountain Formation and the Mancos Shale. I suggest that the Encinal Canyon Member of the Dakota Sandstone is a facies equivalent of the Mussentuchit Member of the Cedar Mountain Formation and that the members may also be similar in age. Additionally, the unconformity at the Ruby Ranch-Mussentuchit member contact
and the “regional” unconformity at the base the Dakota Sandstone noted by other authors (Aubrey, 1989; Currie et al., 2008) appear to be the same. Because the lower informal “Dakota” member is not present locally I suggest that it is correlative to the Mussentuchit Member. A type I unconformity only developed where there was a paleovalley. The paleosol at the Ruby Ranch-Mussentuchit member contact began developing during a time of low accommodation, or degradation and in other areas this unconformity is represented by incision into lower strata and then infilling with the basal Dakota Sandstone unit (Figure 8). However, like the Buckhorn Conglomerate, this basal unit was not deposited everywhere. After deposition of the degradational lower conglomerate sandstones, a transitional systems tract continued filling paleovalleys. The Mussentuchit Member mudstones and siltstones represent the aggradational systems tract deposited during a phase of increased accommodation space. The sandstones in our study area represent the informal “middle member” of the Dakota Sandstone (Eaton et al. 1990). These sandstones represent a late aggradational systems tract related to decreasing accommodation. Thus, sandstone deposits become laterally continuous and thin while fines bypassed the study area (Figure 8). An alternative sequence stratigraphic interpretation is that the paleosol at Ruby Ranch-Mussentuchit member contact and incised valleys represent a falling stage or lowstand systems tract. The Mussentuchit Member and Dakota Sandstone represent a transgressional systems tract with the coals and carbonaceous mudstones indicating an increase in sea-level. And finally the deposition of the Mancos Shale would represent a high stand systems tract. One downfall to this interpretation is that it does not explain the apparent decrease in accommodation from the base of the Mussentuchit Member to the top of Dakota Sandstones within the Mussentuchit Member.
Ages for the Dakota Sandstone in this general area range from Albian to middle Cenomanian (Gustason, 1989; Pierson, 2009). Palynomorphs from the Dakota Sandstone indicate that the lower Dakota Sandstone sequence is Albian in age and the upper Dakota Sandstone is late Albian – early Cenomanian (Currie et al., 2008). Together, these ages suggest the unconformity separating these two units of the Dakota Sandstone is restricted to the late Albian. Radiometric dates of $97.0 \pm 0.1$ Ma (Cifelli et al., 1999) and 96.7 Ma (Garrison et al., 2007) in Emery county indicate the lower Mussentuchit Member is equivalent in age to the Dakota Sandstone, that is, Albian to Cenomanian in age, which correlates better with ages from the Dakota Sandstone.

The sandstones typically assigned to the Dakota Sandstone, and the Mussentuchit Member mudstones are interpreted to be coeval and different facies of the same system. If the Dakota Sandstone cannot be correlated with the type section in Nebraska, one option is to elevate the Mussentuchit Member to formational status and include in it sandstones previously assigned to the local Dakota Sandstones. The simplest option, however, is to consider the Mussentuchit as a member or facies of the Dakota Sandstone and it is the option followed here.

2.4 Tectonic and Sequence Stratigraphic Implications

During the deposition of the Cedar Mountain and Dakota formations deposition and accommodation was dominantly controlled tectonically in the mid-Cretaceous foreland basin. This is supported by the time span of sequences indicating that they are 3rd order sequences which are principally controlled by intrabasin tectonism (Coe, 2002).

The one new datum that affects the tectonic and sequence stratigraphic interpretations is the thick paleosol at the top of the Ruby Ranch Member, which represents a significant unconformity between the Ruby Ranch and Mussentuchit members. Because these are 3rd order
sequences we assume that this unconformity is related to a change in accommodation space resulting from changes in the fold and thrust belt. One possibility is that the paleosol could be a function of where shortening on the Canyon Range thrust is ending and being transferred to the beginning Pavant thrust (DeCelles and Coogan, 2006). This could cause a decrease in the loading and therefore decrease the flexural subsidence occurring in the basin leading to less accommodation, erosion and by-passed sedimentation.

Sequence stratigraphically, this paleosol indicates that there is a significant unconformity that represents a sequence boundary between the Ruby Ranch and Mussentuchit members supporting the conclusion that the Mussentuchit is coeval with the Dakota Sandstone and not a member of the Cedar Mountain Formation.

3 CONCLUSIONS
Based on the data we make the following conclusions:

• The Ruby Ranch Member sandstones were deposited in a meandering fluvial system with high accommodation space indicating the facies belong to an aggradational systems tract that allowed for the preservation of fines in overbank deposits leading to vertically and laterally isolated channels. This is also supported by radius of curvature and flow direction data.

• The Mussentuchit Member/Dakota Sandstone sandstones were also deposited in a meandering fluvial system however, with less accommodation space. This may indicate that the facies belong to a late aggradational systems tract causing the sandstones to be more laterally continuous and amalgamated.
• The paleodrainage direction for the Ruby Ranch Member and the fluvial channels in the Mussentuchit Member/Dakota Sandstones package is to the northeast.

The Dakota Sandstone and the Mussentuchit Member are coeval and different facies of the same system and the Mussentuchit Member should be considered a member or facies of the Dakota Sandstone. The recognition that the Mussentuchit Member is part of the Dakota Sandstone package is significant because provides powerful new model for the interpretation of sequence stratigraphic packages and their contained floras/faunas within the Cretaceous foreland basin of Utah.
REFERENCES


Meek, F.B., and Hayden, F.V., 1862, Description of new Lower Silurian (primordial), Jurassic, Cretaceous, and Tertiary fossils, collected in Nebraska Territory...with some remarks on the rocks from which they were obtained: Proceedings of the Academy of Natural Sciences of Philadelphia, v. 13, p. 419-420.


Mori, H., 2009, Dinosaurian faunas of the Cedar Mountain Formation with detrital zircon ages for three stratigraphic sections and the relationship between the degree of abrasion and U-Pb LA-ICP-MS ages of detrital zircons [M.S. thesis]: Brigham Young University, Provo, Utah, 102 p.


Table 1: Flow parameters based on the measured radius of curvature in meters. A T test shows that the difference between the Ruby Ranch and the Mussentuchit members is statistically insignificant. However, the average is higher in the Ruby Ranch Member but more variable in the Mussentuchit Member sandstones (= Dakota Sandstones). This could suggest the Ruby Ranch Member was dominated by meandering streams, with higher sinuosity, where the Mussentuchit Member was also dominated by meandering fluvial systems but with less accommodation resulting in greater sinuosity and point bar size variability. ID #’s correspond with labels in Figure 1.

<table>
<thead>
<tr>
<th>Formation</th>
<th>ID #</th>
<th>Radius of Curvature</th>
<th>Bankfull Width</th>
<th>Bankfull Depth</th>
<th>Wb/ Db</th>
<th>x-sectional area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mussentuchit</td>
<td>M11</td>
<td>370</td>
<td>137</td>
<td>4.2</td>
<td>33</td>
<td>569</td>
</tr>
<tr>
<td>Mussentuchit</td>
<td>M5</td>
<td>230</td>
<td>90</td>
<td>3.1</td>
<td>29</td>
<td>275</td>
</tr>
<tr>
<td>Mussentuchit</td>
<td>M4</td>
<td>100</td>
<td>43</td>
<td>1.8</td>
<td>24</td>
<td>77</td>
</tr>
<tr>
<td>Mussentuchit</td>
<td>M3</td>
<td>98</td>
<td>42</td>
<td>1.8</td>
<td>24</td>
<td>75</td>
</tr>
<tr>
<td>Mussentuchit</td>
<td>M4</td>
<td>190</td>
<td>76</td>
<td>2.7</td>
<td>28</td>
<td>205</td>
</tr>
<tr>
<td>Mussentuchit</td>
<td>14</td>
<td>200</td>
<td>79</td>
<td>2.8</td>
<td>28</td>
<td>222</td>
</tr>
<tr>
<td>Mussentuchit</td>
<td>15</td>
<td>260</td>
<td>100</td>
<td>3.3</td>
<td>30</td>
<td>332</td>
</tr>
<tr>
<td>Mussentuchit</td>
<td>M7</td>
<td>120</td>
<td>50</td>
<td>2.0</td>
<td>25</td>
<td>102</td>
</tr>
<tr>
<td>Mussentuchit</td>
<td>M9</td>
<td>320</td>
<td>120</td>
<td>3.8</td>
<td>31</td>
<td>456</td>
</tr>
<tr>
<td>Mussentuchit</td>
<td>20</td>
<td>280</td>
<td>107</td>
<td>3.5</td>
<td>31</td>
<td>372</td>
</tr>
<tr>
<td>Mussentuchit</td>
<td>13</td>
<td>120</td>
<td>50</td>
<td>2.0</td>
<td>25</td>
<td>102</td>
</tr>
<tr>
<td>Mussentuchit</td>
<td>M8</td>
<td>170</td>
<td>69</td>
<td>2.5</td>
<td>27</td>
<td>173</td>
</tr>
<tr>
<td>Mussentuchit</td>
<td>M6</td>
<td>160</td>
<td>65</td>
<td>2.4</td>
<td>27</td>
<td>158</td>
</tr>
<tr>
<td>Mussentuchit Mean</td>
<td></td>
<td>201</td>
<td>79</td>
<td>2.8</td>
<td>28</td>
<td>240</td>
</tr>
<tr>
<td>Mussentuchit Median</td>
<td></td>
<td>190</td>
<td>76</td>
<td>2.7</td>
<td>28</td>
<td>205</td>
</tr>
<tr>
<td>Mussentuchit Mode</td>
<td></td>
<td>120</td>
<td>50</td>
<td>2.0</td>
<td>25</td>
<td>102</td>
</tr>
<tr>
<td>Mussentuchit Standard deviation</td>
<td></td>
<td>87</td>
<td>30</td>
<td>0.8</td>
<td>2.8</td>
<td>155</td>
</tr>
<tr>
<td>Ruby Ranch</td>
<td>RR5</td>
<td>280</td>
<td>107</td>
<td>3.5</td>
<td>31</td>
<td>372</td>
</tr>
<tr>
<td>Ruby Ranch</td>
<td>RR2</td>
<td>210</td>
<td>83</td>
<td>2.9</td>
<td>29</td>
<td>239</td>
</tr>
<tr>
<td>Ruby Ranch</td>
<td>RR4</td>
<td>290</td>
<td>110</td>
<td>3.6</td>
<td>31</td>
<td>392</td>
</tr>
<tr>
<td>Ruby Ranch</td>
<td>10</td>
<td>270</td>
<td>104</td>
<td>3.4</td>
<td>30</td>
<td>352</td>
</tr>
<tr>
<td>Ruby Ranch</td>
<td>RR3</td>
<td>220</td>
<td>86</td>
<td>3.0</td>
<td>29</td>
<td>257</td>
</tr>
<tr>
<td>Ruby Ranch</td>
<td>RR1</td>
<td>220</td>
<td>86</td>
<td>3.0</td>
<td>29</td>
<td>257</td>
</tr>
<tr>
<td>Ruby Ranch</td>
<td>RR6</td>
<td>130</td>
<td>54</td>
<td>2.1</td>
<td>26</td>
<td>115</td>
</tr>
<tr>
<td>Ruby Ranch Mean</td>
<td></td>
<td>231</td>
<td>90</td>
<td>3.1</td>
<td>29</td>
<td>283</td>
</tr>
<tr>
<td>Ruby Ranch Median</td>
<td></td>
<td>220</td>
<td>86</td>
<td>3.0</td>
<td>29</td>
<td>257</td>
</tr>
<tr>
<td>Ruby Ranch Mode</td>
<td></td>
<td>220</td>
<td>86</td>
<td>3.0</td>
<td>29</td>
<td>257</td>
</tr>
<tr>
<td>Ruby Ranch Standard deviation</td>
<td></td>
<td>55</td>
<td>19</td>
<td>0.5</td>
<td>1.8</td>
<td>97</td>
</tr>
<tr>
<td>T test</td>
<td></td>
<td>0.358</td>
<td>0.341</td>
<td>0.309</td>
<td>0.258</td>
<td>0.449</td>
</tr>
<tr>
<td>Overall Average</td>
<td></td>
<td>212</td>
<td>83</td>
<td>2.9</td>
<td>28</td>
<td>255</td>
</tr>
</tbody>
</table>
Figure 1: Index map. A) Shows the relation of the study area to the United States, B) In relation to Utah, C) Location in Emery County in relation to the San Rafael Swell, D) Close up showing an outline of the mapped area. Labels S1, S2, S3 indicate locations of measured sections. S2 and S3 are from Mori (2009). The blue numbers in squares are locations where flow direction was measured in the Ruby Ranch Member and correspond to the labels in Figure 13. Green numbers in squares are locations where flow direction was measured in the Mussentuchit/Dakota sandstones and also correspond to the flow diagrams in Figure 13. The arrows display the average flow direction for each channel. The orange star represents the location in Figure 11.
Figure 2: Foreland basin model. There are four depositional zones, the 1) wedge-top, 2) foredeep, 3) forebulge and 4) back-bulge. It is postulated that the Morrison Formation and Buckhorn Conglomerate were deposited in the back-bulge. The Jurassic – Cretaceous unconformity is due to eastward migration of the forebulge and the Cedar Mountain Formation and Dakota Sandstone were deposited in the foredeep and forebulge (DeCelles and Giles, 1996; DeCelles and Currie, 1996).

Figure 3: Regional early to mid-Cretaceous stratigraphic history. From Mori (2009) using (Stokes, 1952; Kirkland et al., 1997; Aubrey, 1998; Roca and Nadon, 2007; Burton et al., 2006; Greenhalgh and Britt, 2007).
Figure 4: The three types of terrestrial sequence bounding unconformities as defined by Currie (1997). A) The Type 1 unconformity is due to a reduction in accommodation that caused valley incision. B) The Type 2 unconformity is caused by a minor reduction in accommodation and results in coarse-grained deposits and poorly developed soil and alteration horizons. C) The Type 3 unconformity is developed by uplift in the basin that caused abandonment of the preexisting flood plain. Soil formation and alteration may occur and once accommodation development resumes overlying sediments may onlap the topographic high. From Currie (1997).
Figure 5: Point bar depositional model. Adapted from Railsback (2002).
Figure 6: Measured section of the upper Morrison, Cedar Mountain and Mussentuchit/Dakota formations. The location is shown in Figure 1 as S1. c=clay, s=silt, vf=very fine sand, f=fine sand, m=medium sand, c=coarse sand, cg=conglomerate.

Figure 7: Map showing the sandstones preserved in the Ruby Ranch Member and the Mussentuchit Member/Dakota Sandstone. The orange line represents the Morrison-Cedar Mountain Formation contact. The red line represents the Ruby Ranch-Mussentuchit member contact. The dashed blue line represents the estimated Mussentuchit Member/Dakota Sandstone-Mancos Shale contact. Southern sandstones in the Ruby Ranch Member are dominantly thin channel segments. Those in the middle of the mapped area are well-developed point bar complexes laterally and vertically encased in overbank mudstones and siltstones. In the Mussentuchit Member/Dakota Sandstone the sandstones are more laterally continuous and amalgamated than those in the Ruby Ranch Member.
Figure 8: Alluvial sequence stratigraphy for the Upper Morrison Formation, Buckhorn Conglomerate and equivalents, Ruby Ranch Member and Mussentuchit Member/Dakota Sandstone. A) Shows what is seen in this field area with no major unconformity at the base of the Dakota Sandstone. B) Shows how what was observed in this field area relates to regionally when the lower member of the Dakota Sandstone is present and represents a significant unconformity. Adapted from Currie (1997) and Greenhalgh and Britt (2007).
Figure 9: Isolated Ruby Ranch Member channel sandstone, looking to the southeast. The dotted white line represents the edge of the exhumed channel. The Ruby Ranch-Mussentuchit member contact is in the lower right hand corner. Flow direction of the channel is highly variable but averages east-northeast (in the distance the channel bends to the northeast). Locality RR6 in Figure 1.

Figure 10: Lateral accretion in a Ruby Ranch Member point bar complex. Locality RR1 in Figure 1.
Figure 11: The Ruby Ranch-Mussentuchit member contact. A) Excellent exposure located at latitude 39.16259° N longitudes -110.935275° (orange star in Figure 1). Note reddish columnar peds or root traces on either side of author. B) Moderately weathered exposure immediately east of outcrop in A. C) typical slope-forming outcrop of the contact, as exposed 250 m south of A. A drape of alluvium obscures the contact in the middle of the photo.
Figure 12: Vertical relationships between Dakota Sandstone channels and the Mussentuchit Member of the Cedar Mountain Formation. A) Overview of Ruby Ranch, Mussentuchit members and Dakota Sandstone outcrops east of the S2 marker in Figure 1. White rectangles indicate the positions of photographs in B and C. B) Detail of three fluvial sandstones separated by carbonaceous mudstones. These sandstones illustrate the problem faced in determining the lower bounding surface for the Dakota Formation when the contact is defined as “the lowest sandstone”. C) Detail of two fluvial sandstones. The lower sandstone is 20 m wide and the upper sandstone ranges from 0.5 m to 5 m thick.
Figure 13: Ruby Ranch Member and Mussentuchit Member/Dakota Sandstone paleoflow direction. RR=Ruby Ranch, M=Mussentuchit. The larger rose diagrams are averages for all Ruby Ranch Member (31.9°, NE) and Mussentuchit Member/Dakota Sandstone (71.7°, ENE) flow direction. The red arrow and arc represent the flow direction with the standard deviation. Labels correlate to those in Figure 1.
Figure 14: Radius of channel meander curvature histograms. The radius of a superimposed circle is used to measure the best-preserved, outermost point bar in a complex. A) Ruby Ranch Member point bar complexes have an average of 231m. B) Mussentuchit Member point bar complexes have an average of 201m but a larger size range (120 to 380 m).