Carbonate Lake Deposits in the Fluvial Bridger Formation of the Greater Green River Basin, Wyoming

A thesis presented to
the faculty of
the College of Arts and Sciences of Ohio University

In partial fulfillment
of the requirements for the degree
Master of Science

Audrey A. Blakeman
August 2014

© 2014 Audrey A. Blakeman. All Rights Reserved.
This thesis titled
Carbonate Lake Deposits in the Fluvial Bridger Formation of the Greater Green River Basin, Wyoming

by

AUDREY A. BLAKEMAN

has been approved for
the Department of Geological Sciences
and the College of Arts and Sciences by

Elizabeth H. Gierlowski-Kordesch
Professor of Geological Sciences

Robert Frank
Dean, College of Arts and Sciences
ABSTRACT

BLAKEMAN, AUDREY A., M.S., August 2014, Geological Sciences

Carbonate Lake Deposits in the Fluvial Bridger Formation of the Greater Green River Basin, Wyoming

Director of Thesis: Elizabeth H. Gierlowki-Kordesch

The Eocene Bridger Formation is the uppermost fluvial unit exposed in the lacustrine Greater Green River Basin of southwestern Wyoming. It is characterized by thick sequences of siliciclastic mudstones, sandstones, and thin limestones; the limestones have been interpreted previously as transgressive lake deposits linked to the upper Laney Member of the Green River Formation, an overfilled lake deposit. The stratigraphic interval studied is in the Bridger B unit in the Devil’s Playground Quadrangle; it included the Golden Bench Limestone and five unnamed limestone units immediately above and below it. These limestones are not laterally continuous and have variable thicknesses though they appear to have lateral continuity from aerial photographs. Ground truthing of the discontinuity of limestones and their relationship to their associated mudstones and sandstones in the Bridger B suggest deposition instead in the distal floodplains of an anastomosing river system that flowed toward the upper Laney Member lake.
This work is dedicated to my son, Orion. That little smile keeps me going.
ACKNOWLEDGMENTS

This work was supported by generous grants from the Geological Society of America, the American Association of Petroleum Geologists, the Society for Sedimentary Geology, the Ohio University Geological Sciences Alumni Association, and the Kerry Kelts Student Research fund.

Additional thanks are in order for Dr. Elizabeth Gierlowski-Kordesch for being a spectacular advisor and pushing me to work hard but not to do so at the expense of time spent with my son. She kindled my interest in lacustrine sedimentology and inspired me to see a fantastic project through to the end, and I am deeply indebted to her. Dr. David Kidder and Dr. Daniel Hembree deserve thanks for being helpful and wonderful committee members; they both provided excellent suggestions and diverse viewpoints that aided in making this thesis as clear as possible to people who are not intimately acquainted with the topic of carbonate lake deposits on anastomosing river floodplain.

Finally, I extend thanks to my mother, Judy Hogge, and my husband, Brandon Blakeman for always supporting me in my academic endeavors. They have given me the space to work and endless encouragement; without them none of this would have been possible.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Dedication</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>List of Tables</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>List of Figures</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Chapter 1: Introduction</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>Chapter 2: Literature Review of Anastomosing Rivers and Associated Floodplain Deposits</td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>Modern examples of anastomosing rivers</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>Examples of anastomosing rivers in the sedimentary record</td>
<td></td>
<td>29</td>
</tr>
<tr>
<td>Anastomosing rivers with associated carbonate</td>
<td></td>
<td>36</td>
</tr>
<tr>
<td>Model for carbonate deposition on anastomosing river floodplains</td>
<td></td>
<td>51</td>
</tr>
<tr>
<td>Chapter 3: Regional Geology of the Greater Green River Basin, Wyoming</td>
<td></td>
<td>54</td>
</tr>
<tr>
<td>Chapter 4: Stratigraphy and Sedimentology of the Bridger Formation</td>
<td></td>
<td>57</td>
</tr>
<tr>
<td>Stratigraphy of the Bridger Formation</td>
<td></td>
<td>57</td>
</tr>
<tr>
<td>Chapter 5: Methods</td>
<td></td>
<td>71</td>
</tr>
<tr>
<td>Field Work</td>
<td></td>
<td>71</td>
</tr>
<tr>
<td>Chapter 6: Results and Lithofacies Interpretation</td>
<td></td>
<td>77</td>
</tr>
<tr>
<td>Sedimentologic Results</td>
<td></td>
<td>79</td>
</tr>
<tr>
<td>Descriptions of limestone beds</td>
<td></td>
<td>79</td>
</tr>
<tr>
<td>Lithofacies descriptions</td>
<td></td>
<td>97</td>
</tr>
<tr>
<td>Lithofacies type 1: Massive micrite</td>
<td></td>
<td>97</td>
</tr>
<tr>
<td>Lithofacies type 2: Marlstone</td>
<td></td>
<td>98</td>
</tr>
<tr>
<td>Lithofacies type 3: Iron-rich micrite</td>
<td></td>
<td>99</td>
</tr>
<tr>
<td>Lithofacies type 4: Silty mudstone</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Lithofacies type 5: Massive sandstone</td>
<td></td>
<td>102</td>
</tr>
<tr>
<td>Lithofacies type 6: Trough cross-bedded sandstone</td>
<td></td>
<td>103</td>
</tr>
<tr>
<td>Chapter 7: Discussion and Interpretation of Paleoenvironment</td>
<td></td>
<td>107</td>
</tr>
<tr>
<td>Discussion of previous interpretations of floodplain lake origin</td>
<td></td>
<td>107</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Page

Table 1: Descriptions of carbonate microfacies present in the Morrison Formation, east-central Colorado. Modified after Dunagan (2000).................................................................43

Table 2: Sedimentologic descriptions of layers a-d of the carbonate unit in the Catskill Magnafacies exposed in the Davenport Center quarry in southern New York. Taken from Demicco et al. (1987)........................................................................................................... 46

Table 3: Sedimentologic descriptions of Bridger B limestone beds .........................96

Table 4: Summary of lithofacies types, affiliated limestone unit(s), and paleoenvironmental interpretations .................................................................106
LIST OF FIGURES

Page

Figure 1. Generalized depiction of the Greater Green River Basin and the location of the Bridger Basin, in Sweetwater County, Wyoming ........................................ 13

Figure 2. Stratigraphic representation and depositional paleoenvironments of the Greater Green River Basin. ........................................................................................................... 14

Figure 3. Stratigraphic representation of the Bridger Formation. ........................................ 16

Figure 4: Channel pattern of an avulsion belt. The levee encasing the main channel is breached and new channels form perpendicular to it, into the floodbasin areas. ........ 21

Figure 5: 3-D view of sedimentary facies within an anastomosing river system, including incised channels, high, stable levees, and protected distal floodbasin marshes and lakes. ................................................................................................................................. 22

Figure 6: Inset shows geographic location of the Magdalena River. Large picture shows anastomosing channel patterns and wetland areas (stipple areas) within the basin ...... 27

Figure 7: Block diagram illustrating the Magdalena River system and zones of deposition within the Magdalena foreland basin ................................................................. 28

Figure 8: Schematic of the Powder River during the Paleocene, illustrating a configuration of anastomosing and braided rivers within a low-gradient basin floor.... 34

Figure 9: Map showing localities of Catskill Magnafacies exposure.............................. 35

Figure 10: Depiction of sedimentation localities in the Upper Freeport Formation, western Pennsylvania, illustrating areas in which carbonate deposition can occur on anastomosing river floodplains.................................................................................. 39

Figure 11: Photographs of sedimentologic features within the Catskill Magnafacies carbonate unit ............................................................................................................... 47

Figure 12: Stratigraphic depiction of the units within the GGRB, including the Green River Formation and the Bridger Formation ......................................................... 56

Figure 13: Stratigraphy of the Bridger Formation, indicating marker beds within Bridger units A-E .................................................................................................................. 58

Figure 14: Correlation between the lower Bridger Formation A and B (Tbb) and the upper Laney Member of the Green River Formation (Tgl) based on Ar$^{39}$/Ar$^{40}$ ratios in the Church Buttes Tuff (CB) shown in red box ........................................................................ 61
Figure 15: Distribution of Bridger B limestones in the Bridger Basin, SW Wyoming. Inset shows distribution within the Devil’s Playground area.

Figure 16: General stratigraphic representation of the stratigraphic interval of interest in the middle Bridger B.

Figure 17: Order of depositional events resulting in the lithofacies association in the Bridger B, in order from times 1-4.

Figure 18: Stratigraphic correlation of upper Bridger B units within the Bridger Basin, SW Wyoming. Compiled by Buchheim et al. (2000).

Figure 19: Mapping area in the central portion of the Devil’s Playground 7.5’ Quadrangle.

Figure 20: Sedimentologic sections produced from the stratigraphic study interval, corresponding to labeled locations in Figure 19.

Figure 21: Photographs of the Lucerne limestone bed.

Figure 22: Isopach map of the distribution and thickness of the Lucerne limestone bed in the study area.

Figure 23: Photographs of Holmes Crossing limestone bed.

Figure 24: Isopach map of the distribution and thickness of the Holmes Crossing limestone bed in the study area.

Figure 25: Photographs of the Lost Dog limestone bed.

Figure 26: Isopach map of the distribution and thickness of the Lost Dog limestone bed in the study area.

Figure 27: Photographs of the Golden Bench limestone.

Figure 28: Isopach map of the distribution and thickness of the Golden Bench limestone bed in the study area.

Figure 29: Photographs of the Spaceport limestone bed. A. Outcrop photo showing massive character.

Figure 30: Photographs of the Anvil Draw limestone bed.
Figure 31: Isopach map of the distribution and thickness of the Anvil Draw limestone bed in the study area

Figure 32: Photograph of trough cross-bedded sandstone lithofacies

Figure 33: Model depicting the three types of lakes and their relationship to the creation of accommodation space within a basin versus sediment and water input

Figure 34: Depiction of a meandering river floodplain showing depositional zone I-IV.
CHAPTER 1: INTRODUCTION

The Lower Eocene Bridger Formation is the uppermost fluvial unit exposed in the lacustrine Greater Green River basin (GGRB) of Wyoming, which includes the famous Green River Formation (Brand et al., 2000; Buchheim et al., 2000 Bohacs et al., 2003). The distribution of facies across the GGRB has only recently been addressed in detail through chronology (dating of layers), sedimentology, and geochemistry (Smith et al., 2008; Davis et al., 2009). The fluvial-lacustrine sediments of the Bridger Formation, are interpreted as the floodplain associated with the southern margin of Lake Gosiute (Brand et al., 2000). However, the connection with the main lake sequence of the central part of the GGRB is still largely unknown.

Smith et al. (2008) and Davis et al. (2009) correlated the fluvial Bridger Formation in the southwestern part of Wyoming (Figure 1) with the lacustrine upper Laney Member, composed of carbonates, mudstones, and sandstones, in west-central Wyoming. The upper Laney Member is the uppermost freshwater lake deposit (with associated fluvial facies) of the Green River Formation (Figure 2) (Bohacs et al., 2003; Smith et al., 2008; Davis et al., 2009). The dynamics of the connection between the upper Laney Member and the Bridger Formation in southwestern Wyoming, including the facies distribution and paleoenvironmental interpretation, need to be better refined.
Figure 1. Generalized depiction of the Greater Green River Basin and the location of the Bridger Basin, in Sweetwater County, Wyoming. Modified after Murphey and Evanoff (2011).
Figure 2. Stratigraphic representation and depositional paleoenvironments of the Greater Green River Basin. Box depicts the interfingering of the lacustrine Laney Member with the fluvial lower Bridger Formation. Modified after Bohacs et al. (2003).

The Bridger Formation, exposed within the Bridger basin (see Figure 1), is characterized by thick sequences of fine-grained siliciclastic mudstones, sandstones, and limestones. The source of these thick mudstones are interpreted as eroded volcanic sediments, originally sourced from volcanic episodes in the Absaroka volcanic field near
Yellowstone National Park and the Challis volcanic field in Idaho, both to the north of the GGRB (after Bradley, 1964; McIntyre, 1982; Moye et al., 1988; Burns et al., 1995; Harlan et al., 1996; Horner et al., 1996; Hiza, 1999; Buchheim et al., 2000; Feeley et al., 2002; Murphey and Evanoff, 2011). Eruptions from these volcanic fields deposited ash across the region (after Smith, 2008); this ash was weathered and fluvially transported into the Bridger Basin by rivers likely originating in the Uinta Thrust Front immediately to the south. The Bridger Formation is subdivided into five units, labeled A-E, that crop out in various portions of the Bridger Basin (Brand et al., 2000; Buchheim et al, 2000; Murphey and Evanoff, 2011). Detailed work on the relationship of the Bridger Formation to the main units of the lacustrine-fluvial Green River Formation to the north has only begun with the correlation of the Bridger Formation to the upper Laney Member of the Green River Formation (Smith et al. 2008; Davis et al., 2009) through Ar$^{39}$/Ar$^{40}$ dating. A focus on the limestones of the Bridger Formation may shed light on their relationship to the limestones of the upper Laney Member to the north. This study concentrates on the limestones documented in Unit B of the Bridger Formation.

Seven thin freshwater limestones are found interbedded with the siliciclastic sediments of the lower Bridger B (Blacks Fork Member) (Brand et al., 2000; Buchheim et al., 2000) just west of the Flaming River Gorge in southwestern Wyoming, approximately 28 miles south of the town of Green River (Figure 3). Buchheim et al. (2000) mapped the mid-upper and upper Bridger B unit, including three of the limestone layers: the unit underlying the Lower Turtle Layer, the Golden bench limestone, and the unit associated with the Black Mountain Turtle layer (Figure 3) in a small portion of the
Devil’s Playground Quadrangle (USGS) west of the Flaming Gorge along the Black Mountain.

Figure 3. Stratigraphic representation of the Bridger Formation. Inset shows the units within the Bridger B, and the limestones that were mapped by Buchheim et al. (2000) are highlighted in yellow. Modified after Murphey and Evanoff (2011) and Buchheim et al. (2000).

Buchheim et al. (2000) suggested that the limestones are laterally extensive but vary widely in composition and thickness at various localities throughout the Bridger basin. The variation was attributed to a series of lakes occupying the basin during the
Bridger epoch (Buchheim, 2000). Brand (2007) also interpreted the Bridger B limestones as massive, basin-wide carbonate units. Lateral continuity was assumed rather than documented via inspection of limestone distribution on topographic maps from limited study areas of exposure during the mapping of the associated turtle-bearing units; no sedimentologic descriptions or detailed ground truthing across the outcrop area was completed. Brand (2007) proposed that these limestones were deposited in a shallow Lake Gosiute, and refuted previous suggestions (Brand et al., 2000) that Lake Gosiute had, by Bridger time, disappeared and been replaced by later lakes. Unfortunately, Buchheim et al. (2000) and Brand (2007) provide insufficient evidence regarding the nature and extent of the limestones. The units were not studied in the detail needed to conclusively determine their depositional origin.

An alternate hypothesis exists for the deposition of the limestone units in the Bridger Formation. The carbonates could have been deposited on the floodplain of an anastomosed river system; the Bridger Formation with its interbedded limestones associated with channel sandstones could simply represent carbonate-rich fluvial input into floodplains adjacent to Lake Gosiute (after Gierlowski-Kordesch et al., 2013). According to Weedman (1988; 1994) and Valero Garcés et al. (1997), carbonate deposition can occur in these anastomosing river systems containing sandstones, mudstones, and even coal in some cases. Carbonate deposition is possible within the floodbasins, which are protected from frequent bedload sedimentary input by high and stable levees; only suspended and dissolved load reach these areas during flood events when levees are not breached. These anastomosing floodbasins provide ideal isolated settings for the precipitation and settling of ultra-fine carbonate particles, especially with
a carbonate-rich source area (Valero Garcés et al., 1997; Gierlowski-Kordesch et al., 2013).

A closer look at the limestones is necessary to determine the depositional origin of the Bridger B in the Devils Playground Quadrangle (USGS). Are they the product of floodplain deposition within an anastomosing river system, or were these limestones deposited as part of a transgression of lake sediments correlated with the upper Laney Member of the Green River Formation?
CHAPTER 2: LITERATURE REVIEW OF ANASTOMOSING RIVERS AND ASSOCIATED FLOODPLAIN DEPOSITS

There are currently four types of recognized fluvial systems: meandering, braided, seasonal tropical and subtropical, and anastomosing. Each are characterized by distinct sedimentary patterns, ranging from those found in the high-bedload channel deposits of the braided system to the dominantly suspended-load successions of the anastomosing river (Fielding et al., 2009; 2011; Miall, 2010; Makaske, 2001). The most easily recognized in the sedimentary record are those that are most common (and subsequently most studied) in the modern: meandering and braided rivers. Anastomosing rivers are difficult to identify in the geologic record because their deposits can resemble those of meandering rivers, but are very important in developing a greater understanding of the processes that occurred in the fluvial systems, marginal-marine, and marginal-lacustrine settings of the past.

An anastomosing river is a fluvial system comprised of multiple channels that are concomitant—generally a main channel and smaller, secondary channels—sequestered by high stable levees that bound and protect interchannel floodbasins (Makaske, 2001). The interchannel floodbasins encompass broad areas and provide quiet protected settings for fine-grained sedimentation to take place (North et al., 2007). These rivers are typically found in humid foreland basins and in coastal areas where the groundwater table is high and the gradient is exceptionally low. The low gradient and high base level are necessary components responsible for maintenance of anastomosis in these rivers systems as well as for the characteristic sedimentation patterns. Consequently, anastomosing rivers are only sustainable as long as the spring line is at or near the surface (Valero...
Garcés et al., 1997; Gierlowski-Kordesch et al., 2013). Sedimentation patterns in these fluvial systems are predominantly driven by suspended load, with the vast majority of bedload deposition occurring within the confines of the narrow channel belts (Nadon, 1994). Anastomosing channel belts are formed by aggradational processes, resulting in high levees bounding narrow, deeply incised channels with very low width/thickness ratios (Gibling, 2006).

Avulsions are the driving mechanism for new channel formation in anastomosing rivers, occurring when channels become inundated with sediment and can no longer be contained by the high levees that bound them (Figure 4) (North et al., 2007). This results in a levee breach, and as the old channel is filled in, a new one must form to compensate. Very little channel migration occurs in anastomosing river systems, however, due to the stability of the natural levees (Makaske, 2001).
Figure 4. Channel pattern of an avulsion belt. The levee encasing the main channel is breached and new channels form perpendicular to it, into the floodbasin areas. Taken from Makaske (2001).

Four main depositional environments exist in anastomosing river systems, each with a distinct set of sedimentary features (Figure 5): channels, levees, crevasse-splays, and interchannel floodbasins (Nadon, 2004). Channels are depositionally similar to meandering rivers; they are sand-dominated and showcase the coarsest deposits in an anastomosing system. Levees are high and stable, consisting of finer muds. Crevasse splays are small channel deposits that form perpendicular to the main channel and spill into floodbasins as avulsions occur or during flooding (Makaske, 2001). Floodplain sediments are deposited in the quiet overbank settings that are protected from frequent bedload input; they therefore contain very fine-grained deposits, often including
laminated muds, clays, and in some instances, carbonates (Schneider et al., 1984; Nadon, 1994; Cooley and Schmitt, 1998; Valero Garcés et al., 1997; Gebhardt et al., 2000; Makaske, 2001).

Figure 5. 3-D view of sedimentary facies within an anastomosing river system, including incised channels, high, stable levees, and protected distal floodbasin marshes and lakes. Taken from Nadon (1994).

Aggradational processes that typify these settings dictate the type of channel deposits for anastomosing rivers. They feature bedload sedimentary deposition of grain sizes varying from gravels to silts, but generally consist mostly of sand-sized particles (Makaske, 2001). Aggradational processes within the channels result in unusually thick channel successions confined in relatively narrow channel bodies that exhibit planar
tabular cross-bedding as a result of sand waves. These sand bodies grade laterally into
the finer-grained deposits of the natural levees (Makaske, 2001). Channel bodies are
characteristically deposited in a multi-storey fashion, and are represented in the
stratigraphic record as ribbon-like sand bodies with width/thickness rations of less than
60 interspersed throughout the predominately mudstone facies of the levee and
floodbasin deposits (Gibling, 2006). They contain stratified sands that are deposited on
thin point bars during lateral accretion, just as in meandering river systems. Point bars are
best defined on very mature channels, as the most mature channels have a higher
tendency toward meandering (Makaske, 2001).

Levees in anastomosing river systems are unlike their counterparts in meandering
river types due to the aggradational properties and avulsion-dominated channel formation
(Nadon, 1994). These levees are tall and wedge-shaped, observed to be up to four meters
thick and are laterally as much as two kilometers wide. Levee deposits taper gradually
into interchannel floodbasin deposits, and appear abruptly alongside channel sandstones.
These features are composed primarily of sand- and silt-sized sediment that is usually
laminated. Avulsion belt deposits, a record of changing river patterns, may underlie the
natural levee deposits (Makaske, 2001). The stability of the natural levees can be
attributed in part to high degrees of cohesion with the fine-grained sediment, but also are
deeply affected by the binding effects of vegetation. Roots aid in sediment consolidation,
consequently helping to forestall riverbank erosional processes (North, 2007; Gibling and
Davies, 2012).

Crevasse splays are lenticular bodies in cross-section and can be quite thick (up to
three meters). These deposits coarsen upward, from silt to coarse sand, and are usually
topped by a thin, fining upward sequence. Cross-lamination and high-angle cross-bedding are sedimentary deposits typical of crevasse splays (Makaske, 2001), and they may exhibit pedogenic reworking (Nadon, 1994). Crevasse splays often bridge the sedimentary gap between levee deposits and the successions of the quiet stable floodbasins. Crevasse splays occur where water level breaches the natural levee system; narrow channels are incised into the levee providing a conduit between the main channel and the floodbasin. This is the main mechanism for delivering bedload into the floodbasins.

Crevasse splays are essentially tiny fluvial to deltaic systems; they have a lobate geometry, interposed between fine-grained interchannel floodbasin deposits (Makaske, 2001). In rare cases, crevasse splay channels may erode through the floodbasin deposits and divert a significant amount of flow away from the main channel belt. The formation of new channels this way is an example of the avulsive processes that drive anastomosing rivers. The usual result of crevasse splays, however, is that they become inundated with sediment to be reclaimed by vegetation and continue as part of the levee wall (Makaske, 2001).

Stable interchannel floodbasins are the defining feature of anastomosing river systems, making them highly unusual by comparison to their more common fluvial counterparts. Concave-up in nature, their bounding surfaces are topographically higher than the anastomosing channels, but the concave nature results in lower floodbasin topography (North, 2007). They are protected from bedload sedimentary input from anabranching channels by the high levees and are, as a result, dominated by suspended load sedimentation into marshes, mires, and lakes (Makaske, 2001). These are laterally
extensive depositional environments and are often pedogenically re-worked, with soil
types ranging from poorly-developed Entisols to well-developed Vertisols (Nadon,
1994).

Marshes and lakes within floodbasins are the primary recipients of suspended
load sedimentation (see Gierlowksi-Kordesch et al. 2013), while the mires are typically
too distal to the channels to receive much in the way of sedimentary input. Mire deposits
can be laterally extensive and contain large volumes of peat, making ancient
anastomosing river systems good candidates for coal production, although they are short-
lived (Makaske, 2001). Marshes are swampy areas that experience heavy plant and
animal bioturbation. They are composed primarily of organic-rich materials and muddy
sediment that may be laminated in the absence of bioturbation activity (Makaske, 2001).

Modern examples of anastomosing rivers

The upper reaches of the Columbia River, in British Columbia, Canada, are a
classic modern example of an anastomosing river system. It is a highly developed system
situated in a humid, proximal montane environment; there are six channels flanked by
stable levees, surrounding distinct interchannel floodbasins. Channel fills in the Columbia
River range from gravels to silts, but are predominately composed of sand-sized material.
These sand bodies are up to twelve meters in thickness and display planar tabular cross-
bedding in their deposits. Planar tabular cross-bedding in this system is a result of sand
wave migration within the channels. Classic multi-storey successions that fine upward
indicate flood cycles during channel aggradation (Makaske, 2001).
The levee deposits in the Columbia River are high and stable, up to four meters thick, tapering gradually into the interchannel floodbasins. Levees are composed of fine, laminated silt and sand, in addition to coarser, delta-like crevasse splays. Floodplain deposition consists of mires, marshes, and lakes; organic muds, peat, and laminated fines, as well as heavy bioturbation by plants and animals are found in these locations. The floodplains are localities that undergo passive deposition of fine-grained suspended sediments (Makaske, 2001).

The Magdalena River in Colombia, South America also provides a modern example of sedimentation in an anastomosing river system (Figure 6) (Smith, 1986). Situated in a tectonically active foreland basin that is up to 25 kilometers wide, the middle reaches of the Magdalena River contains extensive wetlands and stable channels (Figure 7). The gradient is exceptionally low, ranging between 9.5 and 12.4 cm/km (Smith, 1986); low gradients are an essential component in developing anastomosing conditions (Valero Garcés et al., 1997). Low gradient, coupled with high groundwater baseline, results in lakes and wetland environments covering between 80-90% of the floodplain in the basin, with the rest being accounted for by channels, levees, and splays (Smith, 1986). Smith (1986) draws a parallel between basin subsidence and river type, suggesting that anastomosing rivers occur as basin subsidence outpaces sediment aggradation. The basin in which the Magdalena river resides is at equilibrium with regard to subsidence versus aggradation; if subsidence slowed, meandering conditions will prevail as they do in the northern reaches of the Magdalena as it approaches the Caribbean coast (Smith, 1986).
Figure 6. Inset shows geographic location of the Magdalena River. Large picture shows anastomosing channel patterns and wetland areas (stipple areas) within the basin. Taken from Smith (1986).
Smith (1986) describes the sedimentology of various deposits within the Magdalena River system, including channels, crevasse splays, levees, and wetlands. Channel deposits are characterized by moderately- to well-sorted, medium-grained sand with abundant organic material; deeper channels can contain larger sediment and rip-up mud clasts. Sharp basal erosional boundaries separate the channel bodies from underlying mud facies. A 20:1 width-depth ratio for channels in this system is inferred based on cross-sectional profiles of a major channel called Mompos.

Crevasse splay channels in the Magdalena River recognized by Smith (1986) are up to 10 meters deep and up to 100 meters wide; some of the larger examples extend to
lengths of ten kilometers into the surrounding floodplains. Deposits from splay channels are composed of medium-grained sands interbedded with muds. Natural levees are narrow and densely vegetated in the Magdalena River, with a composition of silty mud interbedded with fine sandy layers. They range in width from 100 meters, where associated with growing channels, to four kilometers in channels that are becoming infilled (Smith, 1986). Channels in anastomosing systems are stable for long periods, and with time, they build alluvial ridges above the floodplain. As channels are infilled with sediment and ridges continue to accrete, channels are destabilized until avulsions occur through crevasse splay formation. This is the process that drives new channel formation (Smith, 1986).

Smith (1986) generalizes floodplain deposits into wetlands. These consist of vegetated marshes, swamps, and shallow lacustrine bodies floored by mud. The northern half of the basin in which the Magdalena River resides is covered by floodplains predominately inundated by lakes and the southernmost portion is mostly composed of marshy or swampy environments.

Examples of anastomosing rivers in the sedimentary record

The uppermost Campanian to upper Maastrichtian St. Mary River Formation (SMRF) in Alberta, Canada, provides an ancient example of anastomosis; it is composed of lenticular sandstone bodies distributed throughout finer-grained sediment and can be used to define sedimentology in other anastomosing river successions (Nadon, 1994). Four facies associations within the St. Mary River Formation are described: large sandstone lenses, small sandstone lenses, sandstone/siltstone sheets, and overbank fines.
The four facies associations are interpreted as representing the entire suite of depositional environments in an ancient anastomosing river system, ranging from channel fills to floodplain deposits.

The first facies association of the SMRF is the large sandstone lenses, interpreted as main fluvial channel deposits. They are single to multi-storey, lenticular sandstone bodies that exhibit trough cross-bedded to horizontally laminated sandstone with \textit{in situ} tree trunks, intraclasts, and shells (Nadon, 1994). The \textit{in situ} tree trunks are especially interesting, as they verify the interpretation of anastomosis in these river systems. In a meandering system, lateral channel migration would not allow trees to remain in place. The only explanation for this phenomenon is that an avulsion occurred, resulting in sudden burial of a tree, leaving it in place (Nadon, 1994).

The second facies association of the SMRF comprises small sandstone lenses, characterized by heavily rooted, vertically-accreted sandstone conduits that are perpendicular to the main channel. These small sandstone lenses are more rare than the large sandstone lenses of the first facies association. Paleocurrent analyses confirm that these sandstone bodies trend perpendicular to the larger ones, providing the basis for interpretation as crevasse splay channels (Nadon, 1994).

Fining-upward sandstone and siltstone sheets comprise the third facies association of the SMRF, containing significant bioturbation, root structures, and massive texture to ripple cross-lamination. Paleoflow directions in these sheets, as in the previous facies association, are perpendicular to the main channel bodies, suggesting that these facies represent crevasse splay deposits (Nadon, 1994).
Finally, the fourth facies association of the SMRF is comprised of the overbank fines. This facies association exhibits a range of sedimentary structures from lamination to bioturbation and pedogenic re-working. Thinly laminated sediments are interpreted to represent deposition in floodplain lakes, while heavily bioturbated and pedogenically re-worked successions are broadly categorized as marsh deposits (Nadon, 1994).

The Paleocene Fort River Formation, encompassing portions of northeastern Wyoming and southeastern Montana, is an economically important coal-bearing deposit (Johnson and Pierce, 1990). It also provides insight into variable depositional patterns throughout an ancient anastomosing system.

Johnson and Pierce (1990) divide the Tongue River Member of the Fort River Formation into five depositional groups: type A sandstone, type B sandstone, type C sandstone, gray mudrock, and carbonaceous shale and coal. Type A sandstone is fine-grained and deposited in lenticular bodies with concave-up basal erosion surfaces. These bodies exhibit large-scale trough cross-beds and are up to 10 meters in thickness. In local areas, fossilized plant remains and fragments of mudrock are present. Johnson and Pierce (1990) designate type A sandstones as deposits from ancient anastomosing channels; the lenticular geometry of these bodies suggests deposition through accretion of a lateral and vertical nature. The type A sandstone deposits occur in single bodies, but are more commonly found deposited in a multistoried fashion as much as 17 m in thickness composed of up to four distinct channels. These sandstones also occur in aggregates of single- and multistoried types that are laterally extensive for distances of several kilometers. Type B sandstones are rare and exhibit unclear geometries. These bodies are generally found below type A sandstones in the form of fragmental slump blocks.
associated with the cut banks of type A deposits. Type B sandstones are series of thin, alternating units of sands and mudstones with carbonaceous laminae that commonly appear in abrupt contact with other lithofacies (Johnson and Pierce, 1990). Johnson and Pierce (1990) interpret type B sandstones as levee deposits and attribute their paucity to erosion by rapid lateral evolution of channels. The remaining slump blocks were protected due to emplacement beneath the channel bodies.

Type C sandstones are described by Johnson and Pierce (1990) as tabular deposits composed of fine-grained sand ranging in thickness from 0.3 to 2m, wedged between units composed of finer-grained material. These have abrupt basal contacts and lack sedimentary structures, except for rare instances of trough cross-bedding in the lower sections. Fossilized plant material is abundant in type C sandstones and rhizolith structures are apparent in the uppermost region in some examples. Johnson and Pierce (1990) designate type C sandstones as crevasse splay deposits. Tabular geometry, the presence of pedogenic features, and the abrupt appearance of these bodies within finer grained sediment lend to this conclusion.

The gray mudrock facies described by Johnson and Pierce (1990) is a collection of siltstone, claystone, shale, and mudstones that are interbedded with one another. This lithofacies contains abundant carbonaceous plant material and many horizons of rhizostructures; it is found to exhibit either blocky or fissile cleavage. Fossilized turtles are present in addition to preserved botanical structures such as fruits and leaves. This gray mudrock lithofacies is interpreted by Johnson and Pierce (1990) to be the product of deposition in a floodplain environment due to overbank flooding in an anastomosing river system. The final lithofacies identified by Johnson and Pierce (1990) in the Tongue River
Member is carbonaceous shale and coal; these are rich in plant material and are interpreted as the depositional representation of Paleocene swamps.

Johnson and Pierce (1990) postulate that part of their study area in the Tongue River Member of the Fort River Formation reflects the depositional style of sandy braided streams, and that the other reflects that of an anastomosing river system. Channel deposits are arrayed in a multi-storey fashion with sharp contacts separating them from finer-grained sediments of interchannel basins above and below. These considerations, in addition to the abundance of tabular crevasse-splay sandstones, draw a parallel with modern observances in anastomosing systems, such as those in the lower Saskatchewan River in Canada. A depositional model has been created that illustrates the setting in which the Tongue River Member may have been deposited (Figure 8). It includes an extensive alluvial plain along the Powder River basin. The water table was at or above the surface in an area with a very low gradient. Anastomosing rivers are supposed to have resulted from avulsions away from sandy braided rivers identified in the study area (Johnson and Pierce, 1990).
Figure 8. Schematic of the Powder River during the Paleocene, illustrating a configuration of anastomosing and braided rivers within a low-gradient basin floor. 1, 2, and 3 represent study areas within the Tongue River Member. After Johnson and Pierce, 1990.

The Upper Devonian Catskill Magnafacies, located in New York, also provides an example of anastomosing rivers in the sedimentary record (Figure 9). Gordon and Bridge (1987) describe and interpret units throughout the Catskill Magnafacies, which they divide into two groups: interbedded mudstone-sandstone units and sandstone bodies.

The sandstone bodies are composed of fine-medium grained sands that exhibit large-scale trough cross-bedding and, rarely, ripple cross-lamination. These have sharp erosional bases above underlying strata. Laterally extensive for up to hundreds of meters,
the sandstone bodies display multi-storey geometries with erosion surfaces between and fining-upward tendencies within the storeys (Gordon and Bridge, 1987).

Figure 9. Map showing localities of Catskill Magnafacies exposure, studied by Gordon and Bridge (1987). Numbers represent individual outcrops.

Sandstone-mudstone beds are composed predominately of mottled blocky mudstones that are interbedded with shales, siltstones and some sandstone. Mudstones and siltstones contain desiccation cracks and other features indicative of subaerial
exposure, such as raindrop impressions, root traces, and pedogenic slickensides. Large- and small-scale trough cross-bedding, planar lamination, and plant material occur in the sandstone units in these beds. Sandstones also exhibit lenticular geometries (Gordon and Bridge, 1987).

Gordon and Bridge (1987) interpret the deposits of the Catskill Magnafacies as a series of shallow rivers up to hundreds of meters wide migrating along alluvial plains within a foreland basin. Blocky mottled mudstones are interpreted as paleosols on floodplains, and siltstones as deposits in small lakes and floodbasin drainage conduits. Sandstones predominately represent paleochannels, but also crevasse splays and natural levees.

Anastomosing rivers with associated carbonate

Lake sedimentation within anastomosing river floodbasins is of great interest due to the variance of preserved sediments and the different mechanisms that produce them. In general, laminated clays and silts comprise the majority of floodbasin lake successions, but, similar to the marshes, can be heavily bioturbated and/or pedogenically reworked (Makaske, 2001; Nadon, 1994; North, 2007). The most unusual aspect of interchannel floodbasin lakes is that they provide optimal settings for carbonate deposition when sourced by waters rich in carbonate (Valero Garcés et al., 1997; Gierlowski-Kordesch et al., 2013). This is the only river type that allows for carbonate deposition on its floodplain due to the unique geometry provided by deeply incised channels separated from the floodplain by high, stable natural levees that prevent frequent bedload fluvial input into floodbasin lakes (Weedman, 1988; 1994; Gierlowski-Kordesch et al., 2013).
According to Valero Garcés et al. (1997), anastomosing river floodplains typically contain sandstones, mudstones, and coal, but carbonate deposition can and does occur. Since the floodplains are protected from frequent bedload sedimentary input by high and stable levees, they provide ideal settings for the precipitation and settling of ultra-fine carbonate particles from suspended and dissolved load.

The most important factor in achieving carbonate deposition in an anastomosing river system is a carbonate-rich source area. Climate, in these cases, is not the driving factor in carbonate deposition, as carbonate lakes have been reported everywhere from Antarctica through the tropics (Gierłowski-Kordes et al., 2013). Hydrology is key to the production of carbonate; as long as groundwater and surface water input is saturated with respect to calcium carbonate, derived from calcium-rich rocks in the provenance, and as long as siliciclastic sedimentation is low, carbonate can precipitate (Gierłowski-Kordes et al., 2013).

It is well documented that anastomosed rivers are dependent on a high regional groundwater table (Valero Garcés et al., 1997). The floodplains of anastomosing rivers contain lakes and marshes, as the environment exists below the regional spring line, especially in distal foreland basin alluvial settings (Gierłowski-Kordes et al., 2013.).

Typical anastomosed river floodplain successions are composed of fine-grained siliciclastic sediment (Nadon, 1994; North, 2007). This occurs in cases where siliciclastic input is high and precludes carbonate precipitation where there is little carbonate provenance. Gierłowski-Kordes et al. (2013) proposes a model that indicates two necessary conditions that allow carbonate deposition within the floodbasins of an anastomosing river floodplain. First, there must be a carbonate-rich provenance that
allows for an incursion of carbonate-rich waters to be delivered to floodbasin lakes via suspended load in surface water (Gierlowski-Kordesch, 2013). Secondly, the sites of deposition must be isolated and protected from influxes of siliciclastic sediment via bedload input.

Valero Garcés et al. (1997) documents an example of carbonate floodplains in a perennial anastomosing river system in the Upper Freeport Formation of western Pennsylvania (Figure 11). The Upper Freeport, of Pennsylvanian age, was deposited in the northern Appalachian basin and is composed of claystones, shales, coals, sandstones, and limestones comprising four facies associations (A-D) and twelve facies, three of which are mainly carbonate.

Association A is a rudstone-limestone association, interpreted by Valero Garcés et al. (1997) as having been deposited in a marginal lacustrine or marsh setting within interchannel floodbasins. Association B is composed of laminated limestones and rudstones, with interpreted origins in the littoral and sublittoral zones of floodplain lakes. Laminated limestones, interpreted as the result of deposition in offshore lake environments, compose Association C. Finally, Association D is composed of siliciclastics and coals, interpreted to represent deposition in pond and marsh settings on the alluvial plain.

Valero Garcés et al. (1997) suggest that carbonate facies in the upper Freeport Formation were deposited from suspended and dissolved load in topographically-low areas of the anastomosing river system where bedload input from channels was minimized by channel levees. This allowed for calcium carbonate in the suspended and dissolved load to precipitate in quiet floodplain lakes (see Figure 10).
Figure 10. Depiction of sedimentation localities in the Upper Freeport Formation, western Pennsylvania, illustrating areas in which carbonate deposition can occur on anastomosing river floodplains. Taken from Valero Garcés et al. (1997).
Carbonates in the Upper Freeport Formation are divided into five lithofacies: rudstone, matrix-supported breccia, laminated micrite, laminated clay-rich micrite, and banded to massive micrite. Rudstones are massive or bedded, clast-supported palustrine limestones that generally do not exceed 25 cm in thickness. The clasts are composed of cm-sized bone fragments and oncolites and are cemented with micritic calcite. Matrix-supported breccias range in thickness up to 20 cm and are composed of angular clasts. They are heavily pedogenically modified and brecciated. Laminated micrites are up to 1.5 m in thickness and are highly fossiliferous; they contain ostracodes, bivalves and organic plant fragments. Laminated clay-rich micrites range in thickness up to 1 m and contain fragmented ostracodes and plant material. Banded to massive micrites are massive limestones that are up to 1 m thick and contain peloids, rare ostracodes, and rare bones (Valero Garcés et al., 1997).

Flores and Hanley (1984) document another example of limestone bearing anastomosing river deposits in the Paleocene Upper Tongue River Member of the Fort Union Formation in Wyoming. The deposits are broken down into four facies: lake-crevasse delta and channel, crevasse splay and channel, interchannel basin areas, and a coquina limestone.

The lake-crevasse delta and channel facies is composed of mudstones, siltstones, and shales, in addition to lenticular deposits of limestones and sandstones. The lake portion of this facies consists of limestones, shales, and mudstones. The limestones are of particular interest as they are clay-rich micrites that pinch out laterally and appear to be randomly oriented throughout the vertical succession. Coals and carbonaceous shales are also present in this facies. The lake-crevasse delta facies grade laterally into extensive
channel sandstones—up to eight km wide. Large lobate crevasse-splay deposits are associated with the channel sandstones (Flores and Hanley, 1984).

Flores and Hanley (1984) discuss the mechanism for limestone deposition in the lake-crevasse delta and channel facies, citing their abrupt changes in thickness and increased uniformity with greater distance from channel sandstones. This geometric arrangement suggests that periods of lower detrital influx, and amount of distance from the detrital input, from channels dictated the precipitation of carbonate.

The crevasse splay and channel facies in the Upper Tongue River Member are up to 60 meters thick and are composed of mostly siliciclastic rocks, such as mudstones, sandstones and siltstones with minor intervals carbonaceous shales and coals. The siliciclastic rocks commonly appear in coarsening-upward packages representative of crevasse splay deposits. Less common is the appearance of fining-upward, ripple cross-laminated sandstones, reaching thicknesses of ten meters that represent channel fills. These appear as independent units or cross-cut crevasse splay bodies, and are replaced laterally by levee and floodplain deposits (Flores and Hanley, 1984).

The channel and interchannel facies also contains mostly siliciclastic materials ranging from sandstones to shales. The sandstones are cross-bedded and range in thickness from 15 to 44 meters and are up to three km wide; they have lenticular geometries and appear as lenses separated from one another by four or more km (Flores and Hanley, 1984). Flores and Hanley (1984) determine that at least four of these channel bodies are coeval; these grade laterally into finer materials deposited in crevasse splays, levees, and interchannel lake bodies. Thick channel fills allude to vertical aggradation.
with little lateral migration in interconnected channels; these channels are separated by interchannel lakes and coal-producing floodbasin swamps (Flores and Hanley, 1984).

The coquinoid limestone unit is the uppermost unit in the Tongue River Member, composed of massive limestone with abundant gastropod fragments. Flores and Hanley (1984) theorize that this extensive, massive unit was deposited in a “true” lake body as a shallow lake replacing the anastomosing river system.

Studies of the Jurassic Morrison Formation provide insight into the sedimentology of fluvio-lacustrine carbonates preserved in foreland basins, in what were likely anastomosing river systems. In the Western Interior basin, in east-central Colorado, successions of lacustrine, fluvial, and associated floodplain deposits make up the Morrison Formation, composed of a series of interbedded siltstones, mudstones, sandstones and mottled paleosols (Dunagan, 2000).

Dunagan (2000) describes substantial differences in sedimentologic features within the carbonate units and divides them into eight microfacies: microbialites, skeletal mudstone-wackestone, peloid skeletal mudstone-wackestone, ooid packstone-grainstone, micritic mudstone, intraclast wackestone-grainstone, and carbonaceous packstone. All are interpreted as lacustrine carbonates deposited in either marginal or offshore lake environments based on their respective sedimentologic features (Table 1).

The marginal lacustrine microfacies contain abundant peloids, detrital quartz, and mud rip-up clasts, with some ripple marks, ripple cross-lamination, and plant fragments. All are fossiliferous, with gastropods, ostracodes, and bivalves being common in marginal settings and fish and algal material common in open lacustrine depositional settings (Dunagan, 2000).
Table 1


<table>
<thead>
<tr>
<th>Microfacies</th>
<th>Major Depositional features</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonaceous packstone</td>
<td>Diffuse lamination, pyrite</td>
<td>Marginal Lacustrine</td>
</tr>
<tr>
<td>Intraclast wackestone-grainstone</td>
<td>Peloids and green mudstone rip-up clasts; rare dark intraclasts; minor ooids and volcanic shards; chert; detrital quartz; pyrite</td>
<td>Marginal Lacustrine</td>
</tr>
<tr>
<td>Micritic mudstone</td>
<td>Starved ripple of detrital quartz and peloids; halite, gypsum, and trona pseudomorphs; plant fragments; detrital quartz; volcanic shards; pyrite</td>
<td>Marginal Lacustrine</td>
</tr>
<tr>
<td>Ooid packstone-grainstone</td>
<td>Minor ripple marks; dinuturbation and trackways; nuclei composed of quartz, bone, ooids, and bioclasts</td>
<td>Marginal Lacustrine</td>
</tr>
<tr>
<td>Peloidal skeletal mudstone-wackestone</td>
<td>Rare plant fragments, oncoids, and bone debris; rounded to elliptical peloids and dark rare intraclast; minor green mudstone rip-up clasts; Magadi-type cherts; gypsum pseudomorphs; pyrite; detrital quartz</td>
<td>Marginal Lacustrine</td>
</tr>
<tr>
<td>Peloidal skeletal mudstone-grainstone</td>
<td>Minor cross-lamination; laminae of alternating grainstone and packstone; gypsum pseudomorphs; Magadi-type cherts; rounded to elliptical peloids; minor intraclasts; pyrite; detrital quartz</td>
<td>Marginal Lacustrine</td>
</tr>
<tr>
<td>Skeletal mudstone-wackestone</td>
<td>Minor intraclasts and detrital quartz; Magadi-type cherts; diffuse to bioturbated laminae</td>
<td>Open Lacustrine</td>
</tr>
<tr>
<td>Microbialites</td>
<td>Minor intraclasts and detrital quartz; Magadi-type cherts; diffuse to bioturbate laminae; composite microbial biostromes (planar, wrinkled, laterally-linked, and columnar stromatolites)</td>
<td>Open Lacustrine</td>
</tr>
</tbody>
</table>
Dunagan (2000) interprets the carbonate microfacies in the Morrison Formation of east-central Colorado as having been deposited in wide shallow lakes surrounded by immense mudflats, with minor deposits of mudstone and siltstone, all bordering alluvial environments. A more likely interpretation is that these carbonates were deposited in floodbasin lakes within an anastomosing river system (after Valero Garcés, 1997; Gierlowski-Kordesch et al., 2013).

Dunagan (2000) identifies the Western Interior basin as a wide shallow basin and through the presence of microbialites suggests a high groundwater table. Low gradients with water tables at or near the surface are optimal settings for anastomosing rivers with fine sediment bedloads to exist (Valero Garcés et al., 1997; Gierlowski-Kordesch et al., 2013). The large volume of mudstone in the marginal lacustrine zone, coupled with a much smaller presence of sandstone and siltstone fits the model for anastomosing river systems with anabranched channels and crevasse splays (rare sandstones), high stable levees (minor siltstones and abundant mudstones), and floodbasins including lakes (abundant mudstones and carbonates), as described in Makaske (2001), North et al. (2007), and Valero Garcés et al (1997).

Cooley and Schmitt (1998) interpret fluvial deposits in the Morrison Formation just north of Bozeman, Montana as those of an anastomosing river system. Fluvial deposition occurred in the study area in a subsiding foreland basin during the Jurassic, depositing a succession of mudstones, sandstones, limestones, coals, and conglomerates. Sandstones are trough cross-bedded to ripple cross-laminated, interpreted as channels and crevasse splays. The mudstones exhibit sheet-like geometries and range from laminated to massive; these are interpreted as overbank fines deposited in interchannel floodbasins.
The limestones are small lenticular bodies that range between 5 and 20 cm in thickness, interpreted as the depositional product of small floodbasin ponds or lakes (Cooley and Schmitt, 1998).

The channel deposits in the Morrison Formation at this site showed no evidence of lateral mobility and they exhibit the low width/thickness ratio typical of anastomosed river systems. Paleocurrent measurements highlight a general northward paleoflow direction, but individual channel bodies trended in slightly different directions. Overbank mudstones compose greater than eighty percent of overall lithofacies occurrences, also typical of anastomosing rivers (Cooley and Schmitt, 1998).

The Catskill Magnafacies (Gordon and Bridge; 1987) contains freshwater carbonates on anastomosing river floodplains (Demicco et al., 1987). The Catskill Magnafacies is predominantly composed of siliciclastic mudstones and sandstones (Gordon and Bridge, 1987), but a minor carbonate unit (one of many) is described in southern New York. Demicco et al. (1987) document the exposure of these carbonate beds in a quarry near Davenport Center, situated within a succession of siliciclastic units, including sandstones interpreted as channel bodies and mottled mudstones interpreted as floodplain paleosols. Demicco et al. (1987) postulate that the described carbonate unit was deposited as the result of suspended load sedimentation in a floodplain lake in the interchannel floodbasin of the Catskill anastomosing system. This carbonate unit is a 0.4-0.5 meter thick and is comprised of dolomitic mudstone that occurs in four traceable intervals that extend the length of the quarry (labeled a-d), separated by heavily desiccated zones that were preserved as carbonate breccias (Demicco et al., 1987). The sedimentologic descriptions for layers a-d are provided in Table 2 and Figure 11.
Table 2

*Sedimentologic descriptions of layers a-d of the carbonate unit in the Catskill Magnafacies exposed in the Davenport Center quarry in southern New York. Taken from Demicco et al. (1987).*

<table>
<thead>
<tr>
<th>Carbonate Layer</th>
<th>Sedimentary Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Olive gray. Contains mm-scale flat and wave laminae composed of either peloids or mudstone. Also apparent mudcracks up to 50mm in vertical length and defined desiccation-related polygons. Contorted vertical tubes lined with mudstone around sparite cores or filled with exclusively by meniscate-structure mudstone.</td>
</tr>
<tr>
<td>b</td>
<td>Massive and fenestral peloidal wackestone with uncommon mm-scale laminae composed of peloids, dolomitic mudstone, and spar-filled vertical tubes. Ostracode fragments interspersed throughout layer, increasing in concentration toward the top. Where massive, abundant horizontal and vertical burrows are present up to 100 mm in length and 10 mm in diameter; smaller tubes filled with sparite, larger tubes have laminated fillings/linings with sparite cores.</td>
</tr>
<tr>
<td>c</td>
<td>Olive Gray. Massive with rare laminae. Common meniscate dolomitic mudstone-filled burrow tubes up to 15 mm wide and 0.15 m long. Upper 1/3 of interval contains dense network of horizontal cracks broken by vertical mudcracks; cracks are filled with finely laminated mudstone.</td>
</tr>
<tr>
<td>d</td>
<td>Olive Gray. Massive with rare laminae. Common meniscate dolomitic mudstone-filled burrow tubes up to 15 mm wide and 0.15 m long. Upper part of d contains up to 10% fine- to medium-grained quartz sand.</td>
</tr>
</tbody>
</table>
Figure 11. Photographs of sedimentologic features within the Catskill Magnafacies carbonate unit (scale bar is 5 cm long in A,B,C,D, and G). A. Suite of layers a-d. B. Layer a showing large compacted mudcracks (arrow). C. Section of layer a showing its bedding plane. D. Layer b depicting rare laminae, burrow tubes, and upper brecciated surface. E. Thin section of layer b depicting alternating peloidal and mudstone laminae and vertical tubes (arrow). F. Thin section depicting mottled mudstone with calcispheres. G. Layer c. Laminated horizontal cracks, symmetrically arranged at arrow. Taken from Demicco et al. (1987).
Demicco et al. (1987) postulate that this carbonate unit accumulated during a period of reduced siliciclastic input within an interchannel lake or marsh as clay-sized particles in cyanobacterial mats. The presence of vertical tubes representing filamentous algal material, horizontal cracks preserved between laminae, and the stromatolitic appearance of the lamination support a carbonate paleoenvironment with occasional desiccation. It is suggested that the laminae composed of peloidal silt resulted from bedload suspension in mild currents with heavy bioturbation and the abundance of ostracodes and large burrows in layer b indicating quiet subaqueous paleoconditions between drying events.

The Maastrichtian to Paleocene aged North Horn Formation in Price Canyon in east-central Utah affords another example of an ancient anastomosing system associated with limestone beds. It is situated in a small basin that resulted from Laramide uplifts in the region during the late Campanian through the Eocene and that is bound by a thrust belt and the San Rafael Uplift (Olsen, 1995). Olsen (1995) identifies four intervals of the North Horn Formation within Price Canyon: a lacustrine interval at the base, an amalgamated sandstone interval, and middle fluvial interval, and an upper fluvio-lacustrine interval. Of particular interest is the lower lacustrine interval to the sedimentologic similarities it shares with anastomosing systems.

Olsen (1995) describes the basal lacustrine interval of the North Horn Formation as a 20-60 meter thick unit that alternates between beds of sandstone, mudstone, and limestone. The mudstones include an abundance of fossilized bivalve and gastropod remains, and the limestones are highly fossiliferous and include substantial quantities of
sand and finer-grained siliciclastic detritus. Discontinuous sandstone bodies within the fine sediments that exhibit basal trough cross-bedding and fining upward tendencies are interspersed throughout the basal lacustrine interval. Paleocurrents are unidirectional within individual sandstones, but as a group there is no distinct directional trend. The upper portion of the basal lacustrine interval is overlain by pedogenically-modified mudstones. Lenticular, fining-upward sandstone bodies that show evidence for lateral accretion are encased within the mudstone intervals.

Interpretation of the basal lacustrine interval of the North Horn Formation by Olsen (1995) suggests that this interval represents a shallow perennial lake of limited size that experienced little fluctuation in water depth. The thin sandstones are postulated to represent storm deposits or sheetfloods, and the thick sandstones developed from channels with alluvial fans prograding into the lake basins.

It is likely, based on sedimentologic descriptions provided by Olsen (1995), that the basal lacustrine interval of the North Horn Formation actually represented an anastomosing fluvial system and that the shallow lacustrine facies were interchannel floodbasins. The thin sandstones are likely resultant from crevasse splays from the main channel. Crevasse splays are cross-bedded and laterally discontinuous, usually bound on all sides by floodplain sediment (Makaske, 2001). Pedogenically reworked mudstones documented by Olsen (1995) are consistent with natural levee settings or floodplains; both of these settings can be subject to pedogenesis during subaerial exposure (Stevaux and Souza, 2004). Multiple channels are apparent in the North Horn Formation, these having moderate sinuosity (Olsen, 1995); this too is consistent with an interpretation of
anastomosing rivers. Channels in these river types exhibit lenticular geometries and often fine upward into mudstone (Stevaux and Souza, 2004).

Another example of carbonate deposition in anastomosing river systems is documented in the Pennsylvanian Wettin Member of the Rothenburg Formation in the Saale Basin in eastern Germany (Schneider et al., 1984; Gebhardt et al., 2000). The Wettin Member is composed of sandstone lenses, red mudstones, coals, and silty limestones. The carbonates are bituminous and laminated and contain abundant fossils; these include fish, bivalves, and ostracodes. The mudstone lithofacies includes ostracodes, insects, plant material, and the egg cases of freshwater sharks (Schneider et al., 1984).

A final example of anastomosing river carbonates is documented in Gierlowski-Kordesch et al. (2013) in the Pennsylvanian to Permian, upper Conemaugh, Monongahela, and Dunkard Groups located in southeastern Ohio. These groups contain successions of siliciclastic rocks that are interpreted as floodplain, lake, and channel deposits in addition to floodplain palustrine to lacustrine limestones. Limestones exhibit a range of sedimentary features that indicate palustrine or lacustrine origin. The Arnoldsburg limestone is thickly laminated and contains brecciated palustrine features. The Fishpot Limestone is pedogenically modified, containing abundant root traces filled with micrite cement as well as spar-filled ostracodes. The Pittsburgh Limestone contains root traces with clay cutans and a sparry-calcite fill, as well as disrupted stromatolites containing root traces. Finally, the Sewickley Limestone is a clastic carbonate-cemented with micrite (Gierlowski-Kordesch et al., 2013).
Model for carbonate deposition on anastomosing river floodplains

According to Gierlowski-Kordesch et al. (2013), there are two basic criteria that must be met in order to precipitate carbonate on a siliciclastic river floodplain. First, waters must be Ca-rich; calcium is obtained from the erosion of pre-existing rocks in the provenance. Second, there must be areas isolated from siliciclastic input for extended periods to allow for precipitation of carbonate. Braided and meandering rivers may experience influxes of Ca-rich waters, but they contain no isolated areas that provide locations for carbonate deposition. In braided rivers, ephemeral ponds develop in depressions resulting from cut-and-fill erosion, but these exist only during periods of low flow and only for very brief time periods. Meandering rivers deposit siliciclastics on floodplains during flood events and the amount and distribution of pedogenic alteration of these sediments is dependent on sedimentation rate and distance from the river channel (Kraus, 1999; Kraus and Aslan, 1999). The oxbow lakes that form from meander bend cutoff on these types of floodplains receive siliciclastic input during all flood events (Wren et al., 2008; Bos 2010), since they are hydrodynamically connected to flow in the main channel and are not isolated (Cittero and Piégay, 2009). Thus, oxbow lakes cannot precipitate carbonate, as verified by the lack of carbonates on these river floodplains in the sedimentary record (Gierlowski-Kordesch et al., 2013).

Anastomosing rivers, however, provide ideal settings for carbonate accumulation in interchannel floodbasins because bedload siliciclastic input into these areas only occurs in the event of crevasse splay formation during levee breaches. Groundwater sedimentary input via dissolved load into floodbasin lakes is insufficient to explain the accumulations of carbonate, as anastomosing rivers exist below the regional spring line
and minimal topography occurs in distal floodplain regions of this river type. The hydrologic regime thus does not allow for the development of springs or seeps as a source of groundwater input. This indicates that surface water input from a Ca-rich provenance must provide the calcium required for limestone deposition in these floodbasin lakes (Gierlowski-Kordesch et al., 2013).

In order to confirm these controls on carbonate accumulation in a river floodplain, Gierlowski-Kordesch et al. (2013) first cataloged more than 130 Phanerozoic fluvial systems from the literature to observe what kind of rivers in the geologic record accumulated carbonate lake deposits on the floodplain. Data from each of the 130 Phanerozoic fluvial systems from the literature were analyzed for width/thickness ratios in order to determine fluvial classification with anastomosing being less than 60, and meandering ranging between 61 and 250 (Gibling, 2006). Within the 130 fluvial examples, 57 anastomosing river deposits contained carbonate lakes with associated carbonate provenance while 66 anastomosing river deposits did not have carbonate lake deposits nor carbonate provenance. Only 13 meandering river deposits were recognized in the geologic record and none contained carbonate lake deposits with eight examples containing carbonate in the provenance and five examples without. It was concluded that anastomosing rivers are the only fluvial type that can sustain carbonate deposition on their floodplains when carbonate rocks are present in the source area. This supports the conclusion that anastomosing river floodplains can accumulate carbonate lakes within their isolated floodplains in the presence of a source area containing limestones that contribute Ca-rich drainage waters. The hypothesis that Ca-rich surface water input is the necessary mechanism to deliver carbonate into floodbasin lakes was tested by
Gierlowski-Kordesch et al. (2013) in the Stewart Quadrangle of Athens County, Ohio, by using the carbonate bodies found within a succession of Pennsylvanian rocks interpreted as an anastomosing river system (Nadon et al., 1998). With the calculated volume of six limestone layers within the Stewart Quadrangle, a numerical model was generated to compare the Ca transported in the modern Hocking River, located in the Stewart Quadrangle, with the volume of Ca in six limestone bodies of the interpreted Pennsylvanian anastomosing river system preserved in the Stewart Quadrangle. This numerical model tested whether enough Ca could be delivered via dissolved and suspended load by surface water to allow for thick carbonate deposition over the short lifespan, 10-1000’s of years, on anastomosing river floodplain lakes (Gierlowski-Kordesch et al., 2013).

Modeling of the river water surface input showed that it can indeed deliver the necessary Ca required for precipitation of thick limestone bodies in floodplain lakes of anastomosing river systems within a 100-1000 year period, based on the comparisons between the Ca load of the Hocking River and the Ca content of the Pennsylvanian limestones. When adjustments to the numerical model were made to test whether deposition from springs (groundwater) could instead be the source for the Ca in the Pennsylvanian floodplain carbonate lakes, it was found that in order for a limestone layer of the same thickness as those in the Stewart quadrangle to precipitate, that the time period for accumulation would need to be at or in excess of 100,000 years—far longer than the lifespan of a river floodplain lake (Demicco et al., 1987; Gierlowski-Kordesch et al., 2013).
CHAPTER 3: REGIONAL GEOLOGY OF THE GREATER GREEN RIVER BASIN, WYOMING

The Greater Green River Basin (GGRB) is a foreland basin controlled by Laramide and Sevier tectonics that encompasses a large area of southwestern Wyoming. Beginning in the late Cretaceous and extending through the Eocene, the Sevier fold-thrust front to the west coupled with Laramide orogenic uplift to the east produced a series of intermontane basins, including the GGRB (Smith et al. 2008). The GGRB is divided into four subbasins separated from one another by the Rock Springs Uplift: the Washakie, Sand Wash, Great Divide, and the Bridger (Chetel and Carroll, 2010). The Bridger Basin is the southernmost subbasin, located adjacent to the Uinta Mountains of northeastern Utah (see Figure 1) (Smith et al., 2008; Murphey and Evanoff, 2011).

During the Eocene, Lake Gosiute occupied the GGRB resulting in a succession of sedimentary units that reflect a cyclic pattern of lake stages as local tectonic controls and climatic influence changed basin dynamics (Carroll and Bohacs, 1999). Lacustrine sedimentary successions evolved from the initial fluvial conditions during basin origin. Lake deposits changed from overfilled to balanced-filled to underfilled lake types and then back to balanced-filled to overfilled before the basin fill culminated in a final stage of fluvial deposition during the middle to late Eocene (Figure 12). Volcaniclastic sediments were fluvially transported into the basin from the south and west, originating from Absaroka and Challis volcanic episodes to the north (Zonneveld et al., 2003; Chetel and Carroll, 2010), contributing to the siliciclastic successions of the fluvial Bridger Formation, the final infill of the GGRB.
The GGRB deposits represent a balance between hydrology, subsidence, and sediment supply throughout the life of the basin. The initial fluvial depositional stage in the GGRB is represented in the lower Eocene Wasatch Formation, as sediment and water supply far outpaced accommodation space. Basin subsidence then increased, as sediment and water supply remained high, resulting in overfilled lake deposition of the Luman Tongue of the Green River Formation. As subsidence continued to increase and outpace sediment and water input into the basin, a balanced-filled lake stage was recorded in the deposits of the Tipton Member of the Green River Formation; balanced-filled lakes fluctuate from open to closed hydrology. Subsidence outpaced sediment input following the balanced-filled stage, resulting in a underfilled saline lake deposit reflected in the Wilkins Peak Member, famous today for its trona deposits (Smoot, 1983). After the Wilkins Peak, subsidence began to slow, allowing the cycle to reverse with Lake Gosiute growing progressively fresher in the balanced-filled, lower Laney Member to the once again overfilled lake represented by the upper Laney Member. The Bridger Formation represents the final fluvial stage in the basin fill succession (Figure 12) (Bohacs et al., 2000; 2003; Pietras et al., 2003; Bohacs, 2012).
Figure 12. Stratigraphic depiction of the units within the GGRB, including the Green River Formation and the Bridger Formation. Lake type descriptions: OF=overfilled, UF=underfilled, BF=balance-filled. Taken from Pietras et al. (2003).

This research focuses on the connection between the lacustrine upper Laney Member of the Green River Formation and the fluvial Bridger Formation, specifically on the depositional origin of the carbonate floodplain deposits of the Bridger.
CHAPTER 4: STRATIGRAPHY AND SEDIMENTOLOGY OF THE BRIDGER FORMATION

Stratigraphy of the Bridger Formation

The Bridger Formation, located in the Bridger subbasin of the GGRB, is of great interest to the paleontologic community due to its abundance of vertebrate fossils (Murphey and Evanoff, 2011). These include crocodilians, fish, primates, cats, tapirs, and equine and bovine ancestors, among many others (Murphey and Evanoff, 2007).

The Bridger Formation is subdivided into five units, labeled A-E, exposed in various portions of the Bridger Basin (Brand et al., 2000; Buchheim et al., 2000; Murphey and Evanoff, 2011) (Figure 13). These are subdivided around various marker beds and broken into intervals according to fossil content (Murphey and Evanoff, 2011). Bridger A is the lowermost interval; at approximately 200 feet in thickness, it is comprised of carbonate-rich shales and tuff beds, and combined with the Bridger B make up the Blacks Fork Member—the lowermost Member of the Bridger Formation (Matthew, 1909; Murphey and Evanoff, 2011). The Bridger B, which makes up the middle to upper Blacks Fork Member, is the focus of this study. This unit reaches a thickness of approximately 450 feet and is composed primarily of mudstones and sandstones interbedded with thick limestone units (Matthew, 1909). The base of the Bridger B is constrained by the Lyman limestone, the middle by the Church Butte Tuff, and the upper section by the Black Mountain Turtle Layer (Murphey and Evanoff, 2011).
Figure 13. Stratigraphy of the Bridger Formation, indicating marker beds within Bridger units A-E. Modified after Murphey and Evanoff, 2011.
The middle to mid-upper Bridger Formation is designated as the Twin Buttes Member; this includes Bridger units C and D. The Bridger C is approximately 300 feet thick and is divided into three sections—lower, middle and upper—by the Sage Creek limestone at its base, the Soap Holes limestone at the base of the middle, and the upper section is basally bounded by the Henry’s Fork tuff. Bridger D is also delineated into three sections by the Lonetree limestone at its base, the Blue Sheet Sandstone at its middle, and the Upper White limestone at the base of the upper unit. Bridger D is comprised predominately of tuffs; it is 350 feet thick (Matthew, 1909; Murphey and Evanoff, 2007, Murphey and Evanoff, 2011).

Unit E of the Bridger Formation is the uppermost unit, designated as the Turtle Bluff Member. It is basally constrained by the Basal E limestone and capped by the Behunin Reservoir Gypsum Bed. Bridger E is the thickest unit—approximately 500 feet—composed of tuffs and ash intervals (Matthew, 1909; Murphey and Evanoff, 2011).

The connection between the Bridger Formation and the main units of the Green River Formation have just begun to be addressed in detail with the correlation of the Bridger Formation to the upper Laney Member of the Green River Formation (Smith et al., 2003; Murphey and Evanoff, 2007; Carroll et al., 2008; Smith et al., 2008; Davis et al., 2009) through dating of ash tuffs. Murphey and Evanoff (2007) report Ar$^{40}$/Ar$^{39}$ isotopic ages for the Church Buttes Tuff, a tuff bed located in the stratigraphic middle of the Bridger B succession (see Figure 14). The approximate depositional age of the Bridger B is 47.96 ± 0.20 Ma. The Church Buttes Tuff was also sampled by Smith et al. (2008) and found, using Ar$^{39}$/Ar$^{40}$ isotope ratios, to have an approximate age of 48.6 ±
0.31 Ma. Isotopic ages reported in each study are close enough to be considered in relative agreement. The isotope data reported by Smith et al. (2008) was used to demonstrate both chronostratigraphic and lithostratigraphic correlations between the upper Laney Member of the Green River Formation to the Blacks Fork Member of the Bridger Formation, Bridger B (Figure 14) (Smith et al., 2008). An analcite tuff in the upper Laclede Bed of the upper Laney Member was found, also using Ar\textsuperscript{39}/Ar\textsuperscript{40} isotope ratios, to have an approximate age of 48.94 ± 0.12 Ma (Smith et al., 2003; Carroll et al., 2008). The combination of isotopic age data found through analyses of tuff beds in the Bridger Formation and upper Laney Member of the Green River Formation provide convincing evidence that Lake Gosiute was in existence at the time of Bridger deposition. The relationship between the fluvial Bridger Formation lacustrine upper Laney Member may be elucidated by a detailed focus on Bridger B limestones.
Figure 14. Correlation between the lower Bridger Formation A and B (Tbb) and the upper Laney Member of the Green River Formation (Tgl) based on Ar$^{39}$/Ar$^{40}$ ratios in the Church Buttes Tuff (CB) shown in red box. Modified after Smith et al. (2008).

Stratigraphy of the middle Bridger B

The middle interval of the Bridger B is the focus of this study (Figures 15 and 16). This interval of the Bridger B is composed primarily of silty mudstones with interbedded thin limestone and sandstone units. Its lower boundary is an unnamed limestone, less than 1 m thick, associated with the Lower Turtle Layer, named for the
abundant accumulation of turtle fossils. The middle of this interval is denoted by the Golden Bench limestone bed, a limestone that is generally less than 1 m thick; it is separated from the Lower Turtle layer by approximately 40 m of finer-grained siliciclastic rock units. The upper boundary of the middle Bridger B is a limestone associated with the Black Mountain Turtle layer, another turtle-rich claystone; this limestone is also generally less than 1 m in thickness. The Golden Bench limestone is separated from the Black Mountain Turtle layer by approximately 30 m of fine-grained siliciclastics.

*Sedimentology of the middle Bridger B*

The sedimentology of the Bridger B has only recently been addressed in detail. Buchheim et al. (2000) compiled stratigraphic sections of the Bridger B at 23 locations within the Bridger Basin (Figure 15) and walked between 3 and 4 km of the interval between the Black Mountain Turtle layer and the Lower Turtle layer (Figure 16), in order to more closely examine lateral variations in the lithologic units.
Figure 15. Distribution of Bridger B limestones in the Bridger Basin, SW Wyoming. Inset shows distribution within the Devil’s Playground area. Red box shows the mapping area examined in this study. Mapped by Buchheim et al. (2000).
Figure 16. General stratigraphic representation of the stratigraphic interval of interest in the middle Bridger B. It predominately is composed of mudstone and siltstone underlain by a limestone immediately below the Lower Turtle layer, divided at the middle by the Golden Bench Limestone, and capped by the Black Mountain Turtle layer. The red box indicates approximate interval mapped in this study. Modified after Buchheim et al. (2000).
Buchheim et al. (2000) identified four major lithofacies within the Bridger B interval that were examined in outcrops and hand samples, including (1) cross-beded sandstone, (2) thin-bedded sandstone-siltstone, (3) claystone, and (4) limestone. The cross-beded sandstone lithofacies is composed of poorly sorted, green-gray, fine- to medium-sized sandstone interspersed with silt and clay sized particles. It is mineralogically mature, composed primarily of clays derived from weathered volcaniclastics. This lithofacies is generally structureless, but has trough cross-beding in some of the sandstone units. The cross-beded sandstones are interpreted as channel bodies that range in thickness from 4 to 10 m, but generally do not exceed 6 m.

The thin-bedded sandstone-siltstone lithofacies contains green-gray clay, silt, and fine- to medium-sized sand of volcaniclastic origin. Silty claystones in this association exceed 3 m in thickness, while sandstone thicknesses are variable between 0.15-2 m. The sandstone bodies are described as laterally continuous bodies contained within large mudstone successions. Rarely, small channels dissect the thin-bedded sandstone lithofacies. This lithofacies is commonly structureless and contains turtle fossils.

The claystone lithofacies are successions of clay and silt-sized units, up to a few meters in thickness, which contain an abundance of vertebrate fossils. The sediment is composed of weathered, volcaniclastic clay minerals that preserve many soft-sediment deformation structures and uncommon bioturbated intervals. The claystone lithofacies is cut by several shale intervals that do not exceed 2 cm in thickness. The limestone lithofacies is notable for its variable thickness over short distances. It ranges in thickness up to 1 m, but fluctuates over areas as small as 100 m. Limestones in this lithofacies exhibit micritic textures and do not preserve any sedimentologic structure. They are
mineralogically composed of calcimicrite and contain variable siliciclastics. The bench below the Black Mountain Turtle layer, for instance, is a silica-rich unit in the Black Mountain area. Tufa, stromatolites, ostracodes, and plant impressions are common, but not always present in the limestone beds (Buchheim et al., 2000).

Previous Paleoenvironmental Interpretations

Buchheim et al. (2000) interpreted the depositional environment of each lithofacies in the Bridger B—claystone, limestone, thin bedded sandstone and siltstone, and the crossbedded sandstone—and categorized deposition into a sequence of events corresponding to four time intervals related to influxes of volcaniclastic materials (Figure 17). The limestone lithofacies was deposited during Time 1 and again during Time 4 after siliciclastic input subsided. The depositional origin of the limestone lithofacies was interpreted as sedimentation in a shallow, extensive, fresh-to brackish-water lake with a low topographic gradient that occupied the southern area of the Bridger Basin. This interpretation is supported by the presence of shallow-lacustrine fauna—gastropods, stromatolites, ostracodes, and bivalves—and by the observation that the limestones are continuous instead of grading northward into deeper-water lacustrine facies (Buchheim et al., 2000). During Time 2, the claystone lithofacies was deposited within the Bridger “lake” as a fluvial-lacustrine sedimentation event. This system prograded into the lake and abruptly covered the limestone lithofacies as an incursion of volcaniclastic sediment took place following volcanic eruptions to the north and west (McIntyre, 1982; Moye et al., 1988; Burns et al., 1995; Harlan et al., 1996; Horner et al., 1996; Hiza, 1999; Feeley et al., 2002). The mineralogy of the claystone lithofacies indicates that it developed from
the weathering of volcanic ash (Buchheim et al., 2000.) Factors that contribute to an interpretation of a lacustrine origin for the claystone lithofacies include the presence of lacustrine fauna, the paucity of channel deposits—there are some, but they are very uncommon—and the presence of extensive organic-rich intervals. Rare channels in the claystone lithofacies are commonly affiliated with crevasse splays and overbank floodplain deposits (Buchheim et al., 2000).

The claystone lithofacies gradually transitions into the thin-bedded sandstone and siltstone lithofacies, interpreted by Buchheim et al. (2000) to represent fluvial deposition in the form of crevasse splays and ponded floodplains. The thin-bedded sandstone and siltstone lithofacies contains channel deposits interpreted to have prograded over great distances into an extremely shallow lake, similar to those observed in modern Africa at Lake Turkana. Buchheim et al. (2000) support the interpretation of shoestring channel sands prograding into a shallow lake by pointing to abrupt lateral changes in facies from channel sands to lacustrine claystone, though it is also mentioned that the same facies change might occur in a situation where overbank flooding fills ephemeral ponds or lakes. The former hypothesis was chosen because the channels were uncommon and confined within lacustrine claystones. Buchheim et al. (2000) assert that the cross-bedded sandstone lithofacies was deposited by large meandering rivers on a floodplain environment, pointing to woody fragments and pebble-sized sediment in defense of this interpretation. Deposition of the cross-bedded sandstone lithofacies occurred over the later portion of Time 2 and all of Time 3. The succession begins to repeat at Time 4 as siliciclastic input into the basin slows and as basin subsidence resumes, resulting in new limestone deposition in a shallow lake.
Figure 17. Order of depositional events resulting in the lithofacies association in the Bridger B, in order from times 1-4. Time 1: shallow lake occupies the Bridger Basin, depositing lacustrine limestone. Time 2: an influx of volcaniclastics begins to fill in the Bridger lake resulting in deposition of claystone and rare channels. Time 3: the Bridger lake is completely filled by volcaniclastic material and meandering rivers deposit crossbedded sandstones. Time 4: subsidence resumes and volcaniclastic input slows, facilitating the development of new limestone-bearing lakes. After Buchheim et al., (2000).
Brand (2007) offers a more general interpretation of the Bridger B succession. The Laney Member is representative of a shallow overfilled Lake Gosiute that periodically overflowed and deposited the Bridger Limestones when inundated with volcanoclastic materials. Following limestone deposition in the Bridger Formation, subsidence would resume in the main body of Lake Gosiute and produce a deeper overfilled lake. The limestones, according to Brand (2007), resulted simply from the expansion and contraction of Lake Gosiute over the Bridger floodplain.

Evanoff (2014, Northern Colorado University, personal communication) offers another depositional interpretation for the middle Bridger B. He suggests that the Bridger Basin was regularly inundated with volcanic ash from the Absaroka and Challis volcanic fields to the north (after McIntyre, 1982; Moye et al., 1988; Burns et al., 1995; Harlan et al., 1996; Horner et al., 1996; Hiza, 1999; Feeley et al., 2002) resulting in fluvially-deposited volcanoclastic units that were transported into the basin from the west and traveled toward the Uinta thrust front to the south. Such high volumes of volcanoclastic sediment, responsible for Bridger B claystones, precluded the presence of common channels. Limestones were deposited simply in a series of highly alkaline lakes that were exclusively fed by groundwater and that Lake Gosiute was not in existence at the time of deposition.

The existing interpretations based on the sedimentology of the middle Bridger B are inconsistent with general sedimentology. The main questions about these interpretations include: (1) Can an overfilled lake experience such wide fluctuations in its shorelines (over 40 km)? (2) Is there sedimentologic evidence to support a system of
groundwater-fed alkaline lakes within a fine-grained siliciclastic floodplain? (3) Is there enough sedimentologic evidence for a meandering river system within the Bridger B unit? (4) Why do carbonate lakes form easily within the influence of a siliciclastic fluvial floodplain?
CHAPTER 5: METHODS

In order to determine whether the limestones of the Bridger Formation were deposited as a transgressive arm of Lake Gosiute or as carbonate lakes upon an anastomosed river floodplain feeding into Lake Gosiute, detailed field work is needed first to characterize the limestones within a designated field area.

Field Work

The Devil’s Playground 7.5’ Quadrangle (USGS), located approximately 40 miles south of Green River, Wyoming, has extensive exposures of the Bridger B, as documented by Buchheim et al. (2000) (see Figure 15). The map and sedimentologic sections constructed by Buchheim et al. (2000) (Figures 15 and 18) were used as a core area for this fieldwork and were re-examined in order to elucidate the relationships among the limestones exposed within the quadrangle and those associated with Lake Gosiute to the north.
Figure 18. Stratigraphic correlation of upper Bridger B units within the Bridger Basin, SW Wyoming. Compiled by Buchheim et al. (2000).
In order to understand the depositional setting of the limestones of the Bridger Formation, this study focused on the limestone beds in the stratigraphic interval of the middle Bridger B from immediately below to approximately 2 m above the Golden Bench limestone (Figure 16) in an approximately 1.5 km² area in the center of the Devil’s Playground 7.5’ Quadrangle (Figure 19). The Golden Bench limestone was identified based on its proximity to the Black Mountain Turtle Layer (BMTl); the BMTl was recognized by its abundance of vertebrate fossil material. As observed in Figure 16, the Golden Bench limestone is the first limestone stratigraphically below the BMTl, so it was assumed in the field that the limestone immediately below the BMTl must be the Golden Bench. Its golden color confirmed this assessment.

The stratigraphic interval studied included the Golden Bench Limestone and five unnamed or undocumented limestone units immediately above and below it. Fluctuation in thicknesses was recorded for each of these units and their areal distributions were documented by tracing each throughout the designated map area until the limestone pinched out. Names were assigned to the previously unidentified limestone units to simplify discussion. Samples were collected from each limestone at various localities throughout the map area for visual comparison and for use in petrographic analyses. The areal extent of the limestone beds in this interval as well as their thickness and detailed petrography were targeted.

Eleven sedimentologic sections (see Figure 20; labeled A through K) throughout this study area were measured to understand how these limestone beds are interrelated within this Bridger B interval. The sites of sedimentologic sections were chosen based on good exposure and easy accessibility of the limestone units for accurate measurements;
locations were also chosen to provide a general cross-section of the study area. The sections were used to illustrate the distribution of the limestone units as they pinched in and out, as well as to describe adjacent rock types in order for a better interpretation of the depositional paleoenvironment. Correlation of these sections was not based directly on one layer, as is customary. Since none of the limestones are continuous across the entire study area, correlation was solely based on ground truthing the relationships of each limestone layer to its adjacent limestone layers, both above and below. Isopach maps were constructed from these data, using the program Surfer 7.0, to gauge the areal extent of each layer within the study area for possible continuous extent to the north towards the age-correlated outcrops of the upper Laney Member of the Green River Formation.
Samples collected in the field were used to produce eighteen thin sections from the limestones in the study area: five of the Golden Bench limestone, five of the marlstone immediately below the Golden Bench called the Lucerne, and two each of the four remaining limestones. The unofficial names, stratigraphic position, and description of each limestone are listed in the following chapter. The emphasis on thin section
selection from the Golden Bench and the Lucerne limestone beds was because they comprised all three of the carbonate lithofacies types discussed in the following chapter, while all the other limestones comprised one facies type. Thin sections were analyzed using an optical microscope for fossil content, sedimentary features, and sedimentary textures.
CHAPTER 6: RESULTS AND LITHOFACIES INTERPRETATION

Eleven sedimentologic sections were measured that depict the stratigraphic relationships of the limestone beds to one another and their overall distributions; for simplicity, the unnamed limestone beds were named for local landmarks. The stratigraphic positions of all the limestone beds from oldest to youngest in the studied Bridger B interval include Lucerne, Holmes Crossing, Lost Dog, Golden Bench, Spaceport, and Anvil Draw (Figure 20).

The limestones comprise three lithofacies types: massive micrite, marlstone, and iron-rich micrite. Fine-grained siliciclastics, which are the most common sediments in the study area, additionally compose three lithofacies types: silty mudstone, massive sandstone, and trough cross-bedded sandstone. Discussion of lithofacies types with their accompanying limestone bed(s) (or lack thereof) and respective paleoenvironmental interpretations are simplified in Table 4 after the discussion of limestone sedimentology and lithofacies types that follows.
**Figure 20.** Sedimentologic sections produced from the stratigraphic study interval, corresponding to labeled locations in Figure 19. This figure shows the stratigraphic position of each of the limestone beds, separated by fine-grained siliciclastic sediments.
Sedimentologic Results

Descriptions of limestone beds

The limestone beds of the studied Bridger B interval (Figure 20) are described here from oldest to youngest, including: 1) Lucerne, 2) Holmes Crossing, 3) Lost Dog, 4) Golden Bench, 5) Spaceport, and 6) Anvil Draw. A summary of sedimentologic characteristics follows in Table 3.

Lucerne limestone bed

The Lucerne limestone bed is the lowermost limestone bed in the stratigraphic study interval. It is gray in color and has fissile or platy texture on weathered surfaces. This limestone is a very clay-rich unit that reacts poorly with 3% hydrochloric acid. It contains abundant preserved plant impressions as well as rare iron-replaced insect and arachnid fossils. In thin section, the Lucerne limestone bed is classified as a marlstone and is structureless; it contains preserved plant organic matter (Figure 21). The Lucerne ranges in thickness from 16 to 46 cm, but is generally approximately 40 cm thick throughout most of its exposure and is situated along the eastern margin of the study area (Figure 22); it pinches out abruptly at its northernmost extent and is replaced by a silty claystone unit.
Figure 21. Photographs of the Lucerne limestone bed. A. and B. illustrate the platy character of the Lucerne in outcrop. Hammer is 11 inches long, and notebook is 5x8 inches. C. Thin section photograph of the Lucerne showing micritic texture and preserved plant organic matter. D) Photograph of preserved arachnid.
Figure 22. Isopach map of the distribution and thickness of the Lucerne limestone bed in the study area. Contour interval measured in cm.

Holmes Crossing limestone bed

The Holmes Crossing limestone bed is a micritic limestone that is gray on fresh surfaces and ranges in color from gray to tan on weathered surfaces. It has a massive blocky character in outcrop and ranges in thickness from 14 to 33 cm, with an average of
approximately 20 cm thick. It lacks sedimentary features in hand sample, but abundant spar-filled to clay-filled microtubules, interpreted as rhizoliths, are observed in thin section (Figure 23). The Holmes Crossing Limestone bed is located only in the northern portion of the study area (Figure 24).
Figure 23. Photographs of Holmes Crossing limestone bed. A. Holmes Crossing limestone in outcrop, showing massive texture. Notebook is 5x8 inches. B. Thin section photo showing micritic texture with spar-filled microtubules (circled in red) and clay-filled microtubules (circled in black), interpreted as rhizoliths.
Lost Dog limestone bed

The Lost Dog limestone bed is a micritic limestone that ranges in thickness from 7 to 30 cm; its approximate thickness is generally around 20 cm. It has a massive blocky
character in outcrop and is gray on fresh surfaces. It ranges in color from gray to tan on weathered surfaces. In outcrop and in hand sample, the Lost Dog limestone lacks sedimentary structure or features, but in thin section algal spores and spar-recrystallized ostracodes are observed (Figure 25). The Lost Dog limestone bed is situated in the northeastern portion of the study area only (Figure 26).
Figure 25. Photographs of the Lost Dog limestone bed. A. Massive character of the Lost Dog limestone in outcrop. Hammer is 11 inches long. B. Thin section photograph showing general micritic texture. C. Thin section photograph showing algal spore in the Lost Dog limestone.
Figure 26. Isopach map of the distribution and thickness of the Lost Dog limestone bed in the study area. Contour interval measured in cm.

Golden Bench limestone bed

The Golden bench limestone bed, as identified by Buchheim et al. (2000) is a massive micritic limestone that exhibits a highly variable thickness ranging from 10 to 53
cm. On fresh surfaces the Golden Bench is gray, but on weathered surfaces it exhibits a range of color from gray to tan to reddish gold. Its outcrop character is also variable; it is massive and blocky (massive micrite), but it commonly exhibits a cavity-rich weathering pattern (iron-rich micrite). Cavities are generally roundish and range in diameter from millimeters to several centimeters. In some localities this weathering pattern is accompanied by igneous clasts, molds of vertebrate bones, and/or tufa-coated logs eroding out of the exposure. In thin section, the Golden Bench lacks sedimentary structure or features, except for algal spores (Figure 27). The Golden Bench is aerially constrained to the eastern portion of the study area; it is pinches out abruptly to the north (Figure 28) in the direction of the correlated exposures of the upper Laney Member.
Golden Bench Limestone Bed

Figure 28. Isopach map of the distribution and thickness of the Golden Bench limestone bed in the study area. Contour interval measured in cm.

Spaceport limestone bed

The Spaceport limestone bed is a gray micritic limestone that ranges in thickness from 15 to 20 cm. In outcrop is has a massive blocky character that lacks sedimentary
structures. Spar and clay-filled microtubules, interpreted as rhizoliths, are observed in thin section (Figure 29). The Spaceport limestone is a very localized limestone bed, with less than 100 m of outcrop exposure; it is situated in the upper-central portion of the study area.
Figure 29. Photographs of the Spaceport limestone bed. A. Outcrop photo showing massive character. Pick is 25 inches long. B. Thin section photograph showing micritic texture. Note spar-filled microtubules, interpreted as rhizoliths (circled). C. Thin section photograph showing clay-filled and clay-lined microtubules interpreted as rhizoliths with cutans.
Anvil Draw limestone bed

The Anvil Draw limestone bed is the uppermost limestone in the stratigraphic study interval. It is a micritic limestone that ranges in color from gray on fresh surfaces to gray or tan on weathered surfaces. The Anvil Draw limestone bed ranges in thickness from 10-30 cm and exhibits a massive blocky texture in outcrop that lacks sedimentary structures. In thin section it contains spar-filled microtubules, interpreted as rhizoliths (Figure 30). The Anvil Draw Limestone bed is situated in the northeastern portion of the study area only (Figure 31).
Figure 30. Photographs of the Anvil Draw limestone bed. A. and B. Massive blocky texture in outcrop. Hammer is 11 inches long, and Brunton compass is approximately 4x3 inches. C. Thin section photograph illustrating massive micritic texture. Note abundant spar-filled microtubules, interpreted as rhizoliths, two of which are circled in red.
Figure 31. Isopach map of the distribution and thickness of the Anvil Draw limestone bed in the study area. Contour interval measured in cm.
Table 3.
Sedimentologic descriptions of Bridger B limestone beds

<table>
<thead>
<tr>
<th>Limestone bed</th>
<th>Lithofacies type</th>
<th>Color</th>
<th>Texture</th>
<th>Thickness (cm)</th>
<th>Sedimentary features</th>
</tr>
</thead>
</table>
Lithofacies descriptions

The six limestones in addition to the fine-grained siliciclastics that compose the majority of sedimentary deposits in the Bridger B are constrained to six lithofacies types: 1) massive micrite, 2) marlstone, 3) iron-rich micrite, 4) silty mudstone, 5) massive sandstone, 6) large-scale trough cross-bedded sandstone. Descriptions and interpretations follow.

*Lithofacies type 1: Massive micrite*

*Description*

The massive micrite lithofacies is the most extensive carbonate lithofacies type, comprising five of the limestone beds: 1) Holmes Crossing, 2) Lost Dog, 3) Golden Bench, 4) Spaceport, and 5) Anvil Draw (Table 3). It is made up of massive limestones lacking sedimentary structures. This lithofacies type contains ostracodes, algal spores, and microtubules. The microtubules are mm-scale and filled with sparite; some are lined with clays.

*Interpretation*

The massive micrite lithofacies is interpreted as a limestone of shallow lacustrine origin. Water depth is inferred based on the presence of ostracodes and microtubules interpreted as rhizoliths. Ostracodes inhabit shallow lacustrine areas (Buchheim, 2000). The microtubules are root casts, voids left behind as roots decayed that were later filled with sparry calcite cement (Klappa, 1980; Freytet and Plaziat, 1982; Retallack, 1988; 2001). In rare cases, the root casts exhibit clay linings around the sparry calcite cements,
interpreted as cutans (Figure 29). These s root voids were lined with clayey sediment during illuviation processes (Retallack, 2001; Gierlowksi-Kordesch, 1991; Gierlowksi-Kordesch et al., 2013).

In the Pennsylvanian Upper Freeport formation (see Chapter 2), there are limestones interpreted as the product of deposition in floodplain lakes of an anastomosing river system (Valerio Garcés et al., 1997). These include massive micritic limestones containing rare ostracodes and bones, similar to the massive micrite lithofacies in the Bridger B. Demicco et al (1987) document four limestone intervals in the Catskill Magnafacies, also interpreted as anastomosing river carbonates. Some of those limestones share commonalities with the limestones of the Bridger B, including spar-filled tubules and fragmented ostracodes. Limestones in both examples are laterally constrained and associated with floodplain mudstone lithofacies types.

**Lithofacies type 2: Marlstone**

*Description*

The Lucerne Limestone bed (Figure 21; Table 3) composes the marlstone lithofacies. It is a clay-rich, fissile micritic limestone that contains abundant plant impressions, preserved plant organic matter, and rare fossilized insects and arachnids.

*Interpretation*

The marlstone lithofacies is interpreted as a shallow lacustrine limestone with high clay content. Shallow origin is inferred by the presence of plant impressions, insects, and arachnids (Schneider et al., 1982). The high clay content likely resulted from an
influx of volcaniclastic sediment entering the region from volcanic events to the north and west (McIntyre, 1982; Moye et al., 1988; Burns et al., 1995; Harlan et al., 1996; Horner et al., 1996; Hiza, 1999; Feeley et al., 2002).

As discussed in Chapter 2, Valero Garcés et al. (1997) describes laminated clay-rich micrites containing plant material in an interpreted anastomosing river in the Pennsylvanian Upper Freeport Formation that share a similar clay content with this marlstone lithofacies type. Clay-rich micrites are also identified in the Upper Tongue River Member of the Fort Union Formation that pinch out laterally over short distances on a floodplain (Flores and Hanley, 1984); this description is similar to the lateral discontinuity of the Lucerne limestone bed (Figure 22). Both examples are interpreted as floodplain carbonates in an anastomosing river floodbasin setting (Flores and Hanley, 1984; Valero Garcés et al, 1997).

**Lithofacies type 3: Iron-rich micrite**

**Description**

The Golden Bench Limestone (Figure 27) contains two lithofacies: iron-rich micrite and massive micrite. A portion of the Golden Bench Limestone in a limited zone located in the central sector of the study area is a very dense, iron-rich micritic limestone that contains many cavities. *In situ* igneous clasts are rare on exposed surfaces and smaller cavities originally may have contained igneous clasts since many can be found at the base of the outcrop. Also larger cavities are casts and molds of vertebrate fossils. The Golden Bench limestone contains spar-filled tubules that are centimeters in length and millimeters wide distributed randomly across the layer. The portion of the Golden Bench
limestone designated as the iron-rich micrite lithofacies is differentiated from the portions designated as massive micrite lithofacies by its inclusion of vertebrate fossils, igneous clasts, cavity-rich weathering pattern, and its golden hue. Its massive micrite lithofacies is present in the rest of the study area and contains all the features described for this lithofacies (type 1).

Interpretation

The iron-rich micrite lithofacies is interpreted as a shallow lacustrine environment similar to that of the massive micrite lithofacies. The spar-filled tubules are interpreted as rhizoliths (Klappa, 1980; Freytet and Plaziat, 1982; Retallack, 1988). This lithofacies type differs in that it contains abundant casts of vertebrate fossils (see Figure 27) within the more golden portion of the exposed layer that are interpreted as a possible death assemblage. Similar death assemblages are documented in limestones on anastomosing river floodplains in the Jurassic Morrison Formation in Utah (Richmond and Morris, 1996; Suarez et al., 2007). The iron-rich micrite lithofacies also contains igneous clasts that are assumed to provide the elevated iron content that gives the Golden Bench limestone its “golden” hue.

Lithofacies type 4: Silty mudstone

Description

The silty mudstone lithofacies is the most widespread lithofacies type, composing the majority of Bridger B sedimentary succession studied. It was not examined in great detail for two reasons. One, the limestones were the main focus of this study, and two, a
fresh exposure of this lithofacies was difficult to obtain. The Devil’s Playground quadrangle consists mostly of badlands-style topography and the silty mudstones have undergone intense weathering. The intense erosion of the silty mudstones makes detailed sedimentology nearly impossible without the aid of heavy machinery to remove the outer materials to reach fresh outcrop. This lithofacies, where examined, is composed of massive green-gray mottled claystone interspersed with silt-sized sediments. It has a distinctive popcorn weathering pattern that lends the Bridger B its badlands topography. The silty mudstone lithofacies contains turtle fossils but commonly lacks bedload sedimentary structures. Rarely, it exhibits a platy texture with fine cm-sized tubules composed of clays. Also rarely, preserved carbonized plant matter occurs.

Interpretation

The silty mudstone lithofacies is interpreted as a floodplain deposit, based on its relationship to the other lithofacies types and its sedimentary features. The cm-sized tubules are interpreted as rhizoliths (Klappa, 1980; Freytet and Plaziat, 1982; Retallack, 1988), but no pattern indicating well-defined soil horizons was apparent. The massive texture is interpreted as pedogenic modification, while the inclusion of preserved organic plant matter supports this conclusion.

Anastomosing river floodplains can include marshy areas that contain vertebrate fossils and plant material—often coal—due to standing water and abundant vegetation (Nadon, 1994; Valero Garcés et al., 1997). This lithofacies type contains abundant turtle fossils and carbonized plant material, suggesting a similar environment of deposition (Schneider et al., 1982; Johnson and Pierce, 1999). Pedogenic modification is also
common in floodplain environments due to subaerial exposure and abundant vegetation (Nadon, 1994). The Bridger B in this study interval is observed to contain rare fine tubules interpreted as rhizoliths (Retallack, 1988; 2001) within a platy-fissile textured silty mudstone that differs from the surrounding silty mudstone. This is interpreted as an Entisol due to its textures and lack of defined soil horizons (Retallack, 1988; 2001).

The five other lithofacies types are found interbedded within the silty mudstone lithofacies, with the silty mudstone dominating the lithofacies association in volume. In a fluvial system, particularly an anastomosing system, floodplain fines are expected to far exceed other lithofacies types due to their large areal extent relative to channel and levee bodies (Nadon, 1994). Siltstones and/or mudstones are a sedimentary feature common to all anastomosing river systems described in the literature as overbank fines from suspended load sedimentation away from channels (Flores and Hanley, 1984; Smith, 1986; Gordon and Bridge, 1987; Johnson and Pierce, 1990; Nadon, 1994; Valero Garcés, et al., 1997; Cooley and Schmitt, 1998; Dunagan, 2000; Makaske, 2001).

Meandering river systems also contain overbank fines (Zwolinski, 1992), fine-grained sediments that accumulate on meandering floodplains (Kraus, 1999: Kraus and Aslan, 1999).

**Lithofacies type 5: Massive sandstone**

*Description*

The massive sandstone lithofacies is uncommon in occurrence; it is composed of red and purple mottled fine-grained sand. It is massive (structureless) and ranges in
thickness from 10-20 cm. This single unit below the Golden Bench limestone (section G in Figure 20) is in abrupt contact above and below with silty mudstones.

*Interpretation*

The massive sandstone lithofacies is interpreted as the distal portion of a crevasse splay deposit, based on its relationship to surrounding lithofacies types. It is interbedded with the silty mudstone lithofacies interpreted as floodplain deposits, is not laterally continuous or traceable over any great distance, and lacks sedimentary features. According to O’Brien and Wells (1986) and Nadon (1994), crevasse splays are wedge-shaped and the distal portions are thin and structureless. Crevasse splays abruptly lap onto floodplain sediments, including those deposited in floodbasin lakes in anastomosing river systems. (O’Brien and Wells, 1986; Nadon, 1994).

*Lithofacies type 6: Trough cross-bedded sandstone*

*Description*

The trough cross-bedded sandstone lithofacies is the most localized lithofacies type, occurring only in Section I (Figure 20). It is composed of fine-grained, red to green mottled sandstone that is 82 cm thick. This sandstone lacks fossils but contains trough cross-sets that are decimeters in scale (Figure 32). Paleocurrent measurements indicate flow was in a southeasterly direction.
Figure 32. Photograph of trough cross-bedded sandstone lithofacies. Cross-bedding highlighted in red. This photograph corresponds with sedimentologic section I in Figure 21.

**Interpretation**

The trough cross-bedded lithofacies is interpreted as a crevasse splay deposit. This interpretation is based on its relationship to surrounding strata; it is common for crevasse splay deposits, especially in the distal portion of the splay, to be sandwiched between floodplain fines (Makaske, 2001). This is the case in the Bridger B study interval, as seen in Section I (figure 20). This lithofacies is interpreted as a crevasse splay due to its lack of lateral continuity or traceability throughout the mapping area.
Nowhere else was a thick, lenticular cross-bedded sandstone observed to suggest that this sandstone is part of a channel deposit. As crevasse splays are essentially miniature fluvial deltas that prograde away from channels into floodbasins in anastomosing river systems, high-angle cross-bedding is a common sedimentary structure (Flores and Hanley, 1984; Johnson and Pierce; 1990; Nadon, 1994; Cooley and Schmitt, 1998; Makaske, 2001). Crevasse splay deposits also occur in meandering river deposits, but preservation depends on sedimentation rate since the splays can be incorporated into floodplain soils (Kraus, 1999; Kraus and Aslan, 1999).
Table 4.

Summary of lithofacies types, affiliated limestone unit(s), and paleoenvironmental interpretations.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Name</th>
<th>Limestone Bed(s)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>massive micrite</td>
<td>Holmes Crossing, Lost Dog, Golden Bench, Spaceport, Anvil Draw</td>
<td>floodbasin lake</td>
</tr>
<tr>
<td>2</td>
<td>marlstone</td>
<td>Lucerne</td>
<td>floodbasin lake</td>
</tr>
<tr>
<td>3</td>
<td>iron-rich micrite</td>
<td>Golden Bench</td>
<td>floodbasin lake</td>
</tr>
<tr>
<td>4</td>
<td>silty mudstone</td>
<td>none</td>
<td>floodbasin</td>
</tr>
<tr>
<td>5</td>
<td>massive sandstone</td>
<td>none</td>
<td>crevasse splay</td>
</tr>
<tr>
<td>6</td>
<td>trough cross-bedded sandstone</td>
<td>none</td>
<td>crevasse splay</td>
</tr>
</tbody>
</table>
CHAPTER 7: DISCUSSION AND INTERPRETATION OF PALEOENVIRONMENT

The Bridger B in the study area is divided into six lithofacies: 1) massive micrite, 2) marlstone, 3) iron-rich micrite, 4) silty mudstone, 5) massive sandstone, and 6) trough cross-bedded sandstone (Table 4). These lithofacies, interpreted as floodbasin lake, floodplain marsh, and crevasse splay deposits are combined in a lithofacies association best attributed to the distal floodplain areas in an anastomosing river system.

In order to defend this interpretation, it is necessary to first address in detail the questions raised by previous interpretations of the Bridger B: (1) Can an overfilled lake experience such wide fluctuations in its shorelines (over 40 mi)? (2) Is there sedimentologic evidence to support a system of groundwater-fed alkaline lakes within a fine-grained siliciclastic floodplain? (3) Is there enough sedimentologic evidence for a meandering river system within the Bridger B unit? (4) Why do carbonate lakes form easily within the influence of a siliciclastic fluvial floodplain?

Discussion of previous interpretations of floodplain lake origin

Brand (2007) interpreted the Bridger Formation as reflective of a shallow, overfilled Lake Gosiute that expanded onto an extensive floodplain as it was inundated with volcaniclastic sediment; he speculated that when volcanism ceased subsidence recommenced in the main body of the lake. Renewed subsidence resulted in a deeper overfilled lake that contracted and exposed Bridger sediments. The limestones of the Bridger formation were supposed to have been deposited during the many expansions of Lake Gosiute, and limestone deposition ceased with lake contraction.
Brand acknowledged that Lake Gosiute existed at the time of Bridger deposition as is consistent with interpretations of the upper Laney Member of the Green River Formation as an overfilled lake (Bohacs et al., 2003). The main question to be addressed with this interpretation is “Can an overfilled lake expand over great distances?” The site of this study area is located approximately 40 miles south of the main exposed body of the Green River Formation.

Overfilled lakes do not expand over great distances. There are three different lake types based on accommodation, and sediment and water input: underfilled, balanced-filled, and overfilled (Figure 33) (Bohacs et al, 2003; 2012). In an underfilled lake, accommodation always exceeds sediment and water supply into the basin resulting in the possibility for dramatic fluctuations in lake level, though never overcoming the sill due to subsidence. This results in a closed hydrology, where more sediment and water enters the basin than is expelled at surface (not including groundwater) (Bohacs et al., 2003; Bohacs, 2012).

A balanced-filled lake is a lake that experiences fluctuations in the creation of accommodation versus the input of sediment and water. Water level in these lake types are near the sill level, allowing for alternations in open and closed hydrology. At times subsidence outpaces water and sediment supply creating a closed lake and, at other times, water and sediment supply outpace subsidence and exceed the sill level, resulting in an open hydrology (Bohacs et al., 2003; Bohacs, 2012).

An overfilled lake is one in which water and sediment supplies exceed the creation of accommodation. These lakes are always at sill level, and have an open hydrology. When hydrology is open the same volume of water entering a lake is leaving
it, so lake levels are stable and do not experience wide fluctuations (Bohacs et al., 2003; Bohacs, 2012).
Figure 33. Model depicting the three types of lakes and their relationship to the creation of accommodation within a basin versus sediment and water input. Underfilled lakes have high accommodation with low sediment and water input; they are hydrologically closed. Balance-filled lakes are intermediate, alternating between open and closed hydrology. Overfilled lakes are hydrologically open; they have low accommodation and high water and sediment input. Once an overfilled lake is completely filled with sediment, it becomes a fluvial system. After Bohacs et al. (2003).
If the upper Laney Member of the Green River Formation represents an overfilled lake (Carroll and Bohacs, 1999; Bohacs et al., 2003), it is simply not possible for it to experience dramatic fluctuations in lake level, especially not a fluctuation so extreme as to submerge an area 40 miles away from the main lake body. The idea that Brand (2007) proposes, that an inundation with volcaniclastic sediments resulting in expanding lake levels, can be explained differently. If an overfilled lake is inundated with large volumes of sediment, the lake does not expand but rather disappears and is replaced by a fluvial system—in this case the Bridger Formation (Bohacs et al., 2003). The Bridger Formation has long been identified as fluvial in origin (Buchheim et al., 2000; Bohacs et al., 2003; Murphey and Evanoff, 2011) and it does not require dramatic fluctuations in the level of an overfilled lake to explain the limestone deposition.

The distribution of the thin freshwater limestones in the study area shows that they are locally constrained. The Holmes Crossing, Lost Dog and the Anvil Draw limestone beds were located in the northern portion of the mapping area (Figures 24, 26, and 31, respectively) and thus cannot be conclusively shown to be discontinuous to the north without further research. The Lucerne and Golden Bench limestone beds (Figures 22 and 28, respectively), however, were found to be discontinuous to the north. They were observed pinching out abruptly into floodplain fines in a northerly direction, verifying that they do not continue to the north and are not extensions of the main body of Lake Gosiute.

Evanoff (University of Northern Colorado, personal communication, 2014) suggests that the Bridger Basin was inundated with high volumes of volcaniclastic sediment fluvially deposited by rivers that traveled from west to south toward the Uinta
Thrust Front. This volume of volcaniclastic sediment, responsible for the massive quantities of silty mudstone in the study area, precluded the presence of common channels. Due to this unusual depositional situation, the Bridger B in the studied interval was reduced to a series of groundwater-fed lakes in a marshy setting.

The major question that arises with this interpretation is: “Is there sedimentologic evidence to support a system of groundwater-fed alkaline lakes within a fine-grained siliciclastic floodplain?” Mudstones have very low permeabilities and flow is very limited (Dewhurst et al., 1999). If limestones within the Bridger B were deposited in groundwater-fed lakes, there would need to be a source of Ca in their immediate vicinity. These lakes are deposited in siliciclastic mudstone units (Buchheim, 2000; Brand 2007; Murphey and Evanoff, 2011) and there are no immediate sources of Ca-rich material below (Nelson et al., 2009) There is, however, a carbonate source in the provenance—Permian limestones eroded from the Uinta thrust front to the south (Hansen, 1969; Smith et al., 2008). Smith et al. (2008b) also document a Ca source in the provenance surrounding the GGRB during the Eocene in uplifted Precambrian basement rocks. If the Permian limestones in the subsurface would be the source for the carbonates, how would groundwater flow against gravity in a distal floodplain to reach the surface as ascending springs? Ascending springs occur under unusual circumstances in the presence of structural features such as folds and lineaments, when hydrodynamic flow barriers allow groundwater to flow opposite the force of gravity (Renaut et al. 2002, 2012). There is no evidence of structural deformation required for ascending spring development in the Bridger Formation (Dickinson et al., 1988).
Another consideration of hydrology is the presence of crevasse splays, noted both within this study and in Buchheim et al. (2000). Crevasse splays are avulsions from fluvial bodies (Nadon, 1994; Valero Garcés et al., 1997; Makaske, 2001, Buchheim et al., 2001; Gierlowski-Kordesch et al, 2013), suggesting that there was at least one channel in the immediate vicinity of the study area. Groundwater fed lakes cannot contain cross-bedded sand if they do not experience bedload sedimentation (after Rosen, 1994). These crevasse splay deposits are interbedded with silty mudstones and in one case situated immediately below a limestone unit (Section I, figure 20), suggesting deposition within an active fluvial system.

The lack of stromatolites is another piece of evidence against groundwater-fed carbonate lakes. Elsewhere in the Bridger Formation—the upper Bridger B and the Bridger C for example—stromatolites are abundant (Murphey, 1995; Buchheim, 2000; Murphey and Evanoff, 2011), but they are conspicuously absent from this middle Bridger B study interval. Stromatolites typically form at groundwater seeps at the regional spring line (Hillaire-Marcel and Casanova, 1987; Gierlowski-Kordesch et al., 2013). The absence of stromatolites in the limestones of the study interval suggests that these limestones were not deposited at the regional spring line in groundwater-fed lakes. The absence of spring deposits (stromatolites, travertine, etc.) supports the conclusion that these lakes must have received the majority of their water input from surface water, not groundwater.

Buchheim et al. (2000) discarded the idea that the middle Bridger B represented an anastomosing river system due to the paucity of channel bodies, and instead interpreted the limestones of the Bridger B as floodplain deposits on a meandering river
floodplain. Murphey (1995) and Evanoff (2014) claim that there is a channel with a southerly paleoflow direction to the west of this study area, although this is based solely on personal communication and is not documented anywhere in the literature. The question that arises with this interpretation is: “Is there enough sedimentologic evidence for a meandering river system within the Bridger B unit?”

No channels were observed in the study area, though floodplains can be a telling depositional environment when it comes to interpreting river type when channels are lacking. Flooding is a common occurrence in meandering river systems and floodplain deposition occurs in four zones around the channel body (Figure 34) (Zwolinski, 1992). In zone 1, immediately adjacent to a channel, flooding events result in sand sheets. In zone 2, mud and clay coat the floodbasin areas; stagnant water allows for the settling of suspended clays and silts. Zone 3 occupies the distal areas of floodbasins contain few depositional products due to very slow flow. Finally, zone 4 is situated on the highest topographic extent of meandering river floodplains and deposition occurs there during extreme flood events (Zwolinski, 1992).
Figure 34. Depiction of a meandering river floodplain showing depositional zone I-IV. Zone 1 is immediately adjacent to the channel and receives the most frequent, and largest grained sedimentary input. Zone 2 is the location of fine-grained sedimentation following flooding events. Zone 3 represents the distal floodplain and receives rare little sedimentary input due to low and infrequent flow. Zone 4 represents floodplain terraces where sedimentation only occurs during catastrophic flooding events. After Zwolinski (1992).

A sedimentologic section of a meandering river deposit, from stratigraphic low to high, generally appears as follows. Basal lag conglomerates are deposited as erosion into a floodplain commences, followed by planar laminations from higher flow. Trough cross-
bedded, medium- to coarse-grained sands are deposited in the main body of a channel and in crevasse splays. Crevasse splays onto floodplain areas are common due to unstable levees that contain higher concentrations of sand than mud-sized sediment. Immediately above the trough cross-bedded sands is finer-grained, sand and silt-sized sediment that exhibit ripple cross-laminations from lower flow regimes, topped by massive or laminated muds deposited on floodplains (Bjorlykke and Avseth, 2010). This is the classic fining upward succession of meandering rivers (Miall, 2010).

Since the Bridger B in the studied interval lacks channel deposits, it is difficult to reject a meandering river interpretation on the basis of sedimentology as meandering and anastomosing rivers share similar sedimentary characteristics on floodplains. The channel body to the west of the study area mentioned by Murphey (1995) and Evanoff (2014) can not be conclusively classified as a meandering channel, as there is no documented sedimentologic evidence to classify it as such. It seems unlikely that a channel could flow in a southerly direction, as in order to do so it would need to flow against gravity from low to high topography as it approached the Uinta Thrust Front to the south of the Bridger B depositional area. This channel may instead represent a crevasse splay from a main channel in an anastomosing river system; crevasse splays can be extensive and would explain the anomalous flow direction. More study is needed to determine the origin of this channel, as it remains undocumented.

One difference between the depositional products of meandering and alternative river types is that while meandering rivers commonly have extensive floodplains bearing swamps and oxbow lakes, these areas are sites of silt and mud deposition. These areas receive frequent siliciclastic input because the channels lack high stable levees to protect
floodbasins during flooding events. (Zwolinski, 1992). Carbonate deposition cannot occur on meandering river floodplains for this reason (Gierlowski-Kordesch et al., 2013) because protected areas are needed to accumulate carbonate. The thin freshwater limestones suggest a different interpretation.

If the limestones of the Bridger B are inconsistent with interpretations that they are an extension of the upper Laney Member lake to the north, are sediments of groundwater fed lakes, or are sediments on the floodplain of a meandering river system, the question remains: “Why do carbonate lakes form easily within the influence of a siliciclastic fluvial floodplain?” Gierlowski-Kordesch et al. (2013) proposed and tested a model that explains the deposition of carbonates on otherwise siliciclastic floodplains in an anastomosing river system. Two essential components are 1) Ca-rich provenance, and 2) a quiet area away from frequent siliciclastic input to allow carbonate to precipitate. In an anastomosing river system, high stable levees protect floodplain lakes and ponds from frequent bedload sedimentary input, receiving mostly suspended-load sediments from channel bodies (Valero Garcés et al., 1997; Gierlowski-Kordesch et al., 2013). This allows for the settling of ultra-fine carbonate particles delivered into floodbasin lakes via surface water input. Gierlowski-Kordesch et al. (2013) tested this hypothesis modeling carbonate accumulation in a floodplain using the Ca output of the Hocking River in Athens County, Ohio, which has a provenance rich in Pennsylvanian limestones. It was discovered that large volumes of carbonate can be delivered via fluvial surface water that can accumulate in the short lifespan (100s-1000s of years) of a floodplain lake.
Paleoenvironmental Interpretation of the middle Bridger B in the Devil’s Playground Quadrangle

The previous interpretations of the middle Bridger B are not consistent with the results of this study. The limestones are not continuous to the north, so they were not deposited as part of an expansion of Lake Gosiute. Also, the upper Laney Member represents an overfilled lake and that lake type does not experience large fluctuations in lake level (Bohacs et al., 2000; 2003; Bohacs, 2012). Lack of sedimentologic evidence of groundwater input in addition to the presence of fluvial sedimentary features such as crevasse splay deposits, does not support an interpretation of groundwater-fed lakes.

Anastomosing rivers typically occupy foreland basins with low topographic gradients and high regional groundwater tables (Makaske, 2001; Gierlowski-Kordesch et al., 2013). The Greater Green River Basin is a series of broken foreland basins controlled by Sevier and Laramide tectonics through the middle Eocene (Smith et al., 2008), and the Bridger subbasin had a low topographic gradient (Buchheim et al., 2000). The absence of spring deposits in the study area implies that the basin floor was below the regional spring line during the time of middle Bridger B (after Gierlowski-Kordesch et al., 2013), or perhaps that the topography was not high enough to be conducive to spring development.

The presence of lacustrine limestones interbedded with floodplain deposits is inconsistent with a meandering river interpretation, as there is no mechanism to explain carbonate deposition in an area frequently inundated with siliciclastic sediment during flooding events (Gierlowski-Kordesch et al., 2013). As there are no channel deposits in the immediate vicinity of the study area, one cannot base an interpretation on a
width/thickness ratio of channel bodies, so the floodplain deposits must be used to determine the type of fluvial origin for Bridger B sediments. Floodplains without carbonates are sedimentologically similar and are therefore indistinguishable between in meandering and anastomosing river systems; both river system types contain abundant paleosols and crevasse splays (Nadon, 1994; Kraus and Hasiotis, 2006) so their presence is not a good indicator of river type. The presence of carbonates in the study area is the main line of evidence to support an alternative interpretation of an anastomosing river system. Anastomosing rivers are the only river type that contain protected interchannel floodbasins to allow carbonate to precipitate away from siliciclastic input (Gierlowski-Kordesch et al., 2013).

Clearly, the limestones of the middle Bridger B in the Devil’s Playground quadrangle are the result of deposition in the distal areas of an anastomosing river floodplain that fed into Lake Gosiute to the north. The silty mudstone lithofacies is compatible with an interpretation of floodplain deposits. It is structureless, contains carbonized plant material and rhizoliths, and is associated with fluvial crevasse splay deposits, consistent with interpretations of anastomosing river floodplains presented in Nadon (1994) and Valero Garcés et al. (1997).

The massive sandstone and trough cross-bedded sandstone lithofacies types are locally constrained and not laterally traceable. The thin massive sandstone lithofacies lacks sedimentary structures and is interbedded with the interpreted, fine-grained floodplain sediments, accordant with an interpretation of the distal portion of a crevasse splay (O’Brien and Wells, 1986). The trough cross-bedded sandstone is situated above fine-grained floodplain sediments and overlain by a lacustrine limestone, the Golden
Bench limestone bed, exhibiting high-angle trough cross-bedding commonly associated with crevasse splay (Nadon, 1994; Makaske, 2001).

The massive micrite, marlstone, and iron-rich micrite lithofacies are interpreted as a series of shallow floodbasin lakes on an anastomosing river system. They were deposited in a freshwater lacustrine to palustrine paleoenvironment based on its inclusion of ostracodes, vertebrate fossils, algal spores, root traces, and the absence of desiccation features. Localized distributions of the limestone bodies and their homogeneous internal textures suggest that they were deposited in small lakes or ponds rather than in large lakes (Alonso-Zarza and Wright, 2010; Gierlowski-Kordes et al., 2013).

According to Gierlowski-Kordes et al. (2013), carbonate deposits do not only form in the floodbasin areas of anastomosing river systems, but are a valuable tool in distinguishing anastomosing rivers from their fluvial counterparts in the sedimentary record. Carbonates are unable to precipitate in other fluvial systems due to the absence of high stable levees that prevent channel migration and frequent overbank input of siliciclastic materials into floodbasin lakes. Only anastomosing rivers have levees that are high and stable enough to prevent frequent bedload siliciclastic input into floodbasin lakes where protected and quiet lacustrine areas allow carbonate deposition to proceed.
CHAPTER 8: SUMMARY

During the early Eocene, the GGRB was occupied by Lake Gosiute, which experienced fluctuations in lake level as a result of a changing tectonic setting. By Bridger time in the middle Eocene, volcanic activity was occurring to the north and west and depositing ash across the region (after Smith et al., 2008). This ash was fluvially transported into the GGRB, and as sedimentation began to overtake creation of accommodation space, the main body of Lake Gosiute became an overfilled lake confined to the northern portion of the GGRB (Bohacs et al., 2003). As a result of these frequent influxes of volcanoclastic and reduced subsidence in the southern areas of the GGRB compared to the north (Beck et al., 1988), the Bridger Basin was filled in along the margins and was transformed into a watershed containing fluvial systems that fed into Lake Gosiute from the south and west (Zonneveld et al., 2003).

The succession of mudstone, sandstone, and thin limestone in the study area of the Bridger Basin is interpreted as the depositional sediments in the distal floodplains of a river system that fed into Lake Gosiute from the south, travelling into the basin from the uplifting Uinta Thrust Front. A regional setting with low topographic gradient (Bohacs et al., 2003) and a lack of large microbialites implies that Bridger B sediments were deposited below the regional spring line in a distal fluvial setting. Sandstones are massive to trough cross-bedded units that are pedogenically modified and areally constrained; these are interpreted to represent crevasse splays off of a main channel into the distal floodplain (after Makaske, 2001). Silty mudstones are the dominant lithofacies in the study area, these being thick packages of silt- and clay-sized sediment that lacks bedload sedimentary structure and rarely contain poorly-developed paleosols. These are
interpreted as floodplain deposits of an anastomosing river based on their relationship to other lithofacies and due to their sheer abundance; floodplain fines make up greater than eighty percent of sediments in an anastomosing river system (Cooley and Schmitt, 1998). A floodplain interpretation is consistent with observations in the study area, including paleosol development in the mudstones that contain turtle fossils and carbonized plant material compatible with a marshy setting.

The sedimentation rate on this distal floodplain is inferred to have been very high due to frequent incursions of volcaniclastic materials. Sedimentation rates are inferred by the presence of floodplain Entisols, which are very poorly developed paleosols with lifespans on the order of 10s-100s of years (Retallack, 2001). As observed paleosols are poorly developed in the Bridger B study area, it can be assumed that high sedimentation rates prevented the soils from advancing beyond the Entisol stage. There are rhizoliths in the silty mudstones and also in the thin limestones, but these units are in very abrupt contact with one another and the roots do not penetrate the boundaries between the two. This indicates that sedimentation occurred frequently, because soil development did not have time to penetrate into the limestones below the mudstones and mix the sediments further.

The thin limestone beds of the Bridger B were deposited as shallow lakes in the distal portions of the floodplain areas. Abundant plants and a rich vertebrate fauna occupied these lakes and surrounding areas in a humid climate—as evidenced by abundant turtle fossils in the floodplain deposits as well as an apparent death assemblage in the Golden Bench limestone containing crocodilian fossils discussed in Chapter 6. Murphey and Evanoff (2011) document frogs, crocodilians, and even primate fossils in
the GGRB during the Bridger. The Bridger B limestones lack desiccation features, implying that the lakes in which they were deposited were perennially wet; this assertion is also bolstered by the presence of freshwater ostracodes and reptile and amphibian fossils that allow an assumption of low salinity. Plant impressions and root traces in the limestones lend to an interpretation of shallow water depth.

The presence of limestones is a major criterion in interpreting the river floodplain of the Bridger B as part of an anastomosing river system (Gierlowski-Kordesch et al., 2013). Carbonate lakes on floodplains need hydrodynamically isolated areas to accumulate Ca away from siliciclastic input and require a carbonate-rich provenance as a source for surface water input containing Ca-rich suspended and dissolved load. Therefore, the limestone layers of the studied Bridger B succession represent short-lived lakes in the interchannel floodbasins of an anastomosing river. Inference of a high sedimentation rate for this Bridger B distal anastomosing floodplain is also based on a comparison with limestones in the Stewart Quadrangle in Athens County, Ohio. The six Pennsylvanian limestones in the Stewart Quadrangle documented in Nadon et al. (1998) and Gierlowski-Kordesch et al. (2013) are thick limestones interpreted as floodplain lake deposits on an anastomosing river floodplain. The numerical model presented in Gierlowski-Kordesch et al. (2013) calculated that these thick limestones, commonly meters in thickness, could be deposited on an order of 100s of years. Bridger B limestones are thin limestones, never exceeding 0.5 m in thickness, suggesting frequent interruption of carbonate sedimentation as siliciclastic volcanic materials were delivered into the basin. When the influx of volcaniclastic sediments ceased, carbonate precipitation was permitted to resume resulting in a succession of carbonate floodplain
lakes interbedded with silty mudstone floodplain deposits within these floodbasins. The high sedimentation rate of volcaniclastic sediments resulted in “muddy” micritic limestones, some with high clay contents, as in the Lucerne Limestone.

The Bridger B in the study area simply represents the distal floodplain areas, away from main channel bodies, of an anastomosing river system that fed into Lake Gosiute during the middle Eocene Major transgressions in an overfilled lake cannot occur and are unnecessary to explain the interbedding of the limestone lithofacies within the siliciclastic lithofacies of the Bridger B. There is no evidence for a groundwater origin for these limestones, either as microbialites or over time—the sedimentation rate was too high to allow enough time for carbonate deposition to occur exclusively from groundwater in distal fluvial setting. According to the modeling of carbonate accumulation within floodbasins of anastomosing river systems in Gierlowski-Kordesch et al. (2013), a carbonate deposition through groundwater in distal fluvial settings would far exceed the lifetime of these floodplain lakes.

Finally, and most importantly, the presence of limestones precludes an interpretation of any river type except anastomosing rivers because anastomosing rivers are the only river types that have high stable levees to protect interchannel floodbasins from siliciclastic input. Anastomosing rivers are the only river type that have interchannel lakes protected by these levees and are provided with a quiet setting for carbonate deposition to proceed.
CHAPTER 9: CONCLUSIONS

• The Bridger Formation located in the Greater Green River Basin of southwestern Wyoming is divided into 5 subunits, labeled A-E. The middle Bridger B, located stratigraphically between the Lower Turtle layer and the Black Mountain Turtle layer along the base of Black Mountain in the Devil’s Playground Quadrangle is the focus of this study. This interval contains five previously unnamed limestone beds in addition to the Golden Bench limestone, named for simplicity in order from oldest to youngest: 1) Lucerne, 2) Lost Dog, 3) Holmes Crossing, 4) Golden Bench, 5) Spaceport, and 6) Anvil Draw.

• These limestones in addition to sandstones and silty mudstones in the study area make up six lithofacies types: 1) massive micrite, 2) marlstone, 3) iron-rich micrite, 4) silty mudstone, 5) massive sandstone, and 6) trough cross-beded sandstone.

• Depositional setting for each lithofacies type based on sedimentary features and lithofacies relationships are interpreted as: 1) floodbasin lake, 2) floodbasin lake, 3) floodbasin lake, 4) fluvial floodplain, 5) crevasse splay, 6) crevasse splay.

• Previous interpretations are inconsistent with the findings of this study. Limestone deposition resulting from an expansion of the Laney Member lake to the north is not likely as it is an overfilled lake; those lake types do not experience significant lake level fluctuations. Also, this study found that the limestone bodies are discrete and not laterally continuous in a northerly direction toward the main body of Lake Gosiate. There is also no evidence to support a groundwater-fed lake hypothesis, as stromatolites and spring deposits are conspicuously absent; they are
present during later phases of Bridger deposition. There is also no evidence of ascending springs that would provide a mechanism for groundwater to travel against gravity as a mechanism to provide carbonate to groundwater-fed lakes from below. A meandering river depositional hypothesis does not provide a mechanism for carbonate deposition on a floodplain frequently inundated with siliciclastic sediment during flooding events.

- The middle Bridger B in the study area is interpreted in this study as floodplain deposition in an anastomosing river system. Only anastomosing rivers with their high stable levees and floodbasins protected from bedload siliciclastic input from channels can provide a setting conducive to carbonate precipitation within lakes.

- Carbonate from a Ca-rich source area, carried in surface waters, provides the Ca necessary to precipitate carbonate in floodbasin lakes.
REFERENCES


