INTEGRATED ANALYSIS OF WAULSORTIAN-TYPE BIOHERMS OF THE
LODGEPOLE FORMATION: STARK COUNTY, NORTH DAKOTA
AND BRIDGER RANGE, MONTANA

by

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Geology).

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ABSTRACT

Significant amounts of hydrocarbons have been produced in Stark County, North Dakota from Mississippian-aged carbonate mounds or bioherms within the Lodgepole Formation. These carbonate mounds have been compared and contrasted to Waulsortian mounds, which are found in the Lower Carboniferous (Tournaisian-Visean) throughout the northern hemisphere (Wilson 1975). While Waulsortian or Waulsortian-type mounds are characterized by their mud-rich and massive nature, the mounds in Stark County are noticeably different. Initial petrographic study of the Patterson #1-24 well (NESE Sec. 24 T. 139N R. 97W) in Stark County has shown that major constituents of the mounds include crinoids, brachiopods, and ostracods among other minor constituents. Porosity is minimal and is generally limited to intergranular and intragranular pore types. Outcrops of these mounds have been identified in two different mountain ranges in Montana. Two mounds are present in Swimming Woman Canyon of the Big Snowy Mountains in central Montana. Up to five mounds are located at two different locations within the Bridger Range of southwestern Montana.

Field work was done on two mounds that had been un-studied due to their remoteness at the southernmost tip of the Bridger Range Mountains. Data collected included dimensions of mounds, stratigraphic sections, facies associations, and systematic sampling both laterally and vertically. Data collected from this outcrop was used to compare and contrast observations made previously on outcrops that had been studied in great detail. In addition, these outcrop data were used to compare the Montana outcrop mounds to those that are producing significant amounts of hydrocarbons from the subsurface in Stark County, North Dakota.

Rocks from both the subsurface and outcrops were studied extensively (via core and hand samples) followed by petrographic thin section analysis. For each thin section acquired, grains
present, texture, cavity structures, cements, replacements, and porosity were noted. Of particular importance was developing a diagenetic history of these mounds. As such, the variety of cements present were noted and studied. Furthermore, cathodoluminescence microscopy was used to aid in distinguishing the different episodes of cementation that comprise the paragenetic history of these mounds.

A total of five distinct facies were observed at the Bridger Range outcrops. They are (1) a crinoid and fenestrate bryozoan mottle wackestone basal biostrome facies; (2) a skeletal wackestone to mud-rich packstone to grainstone to marine cemented boundstone inner core facies; (3) a crinoidal and bryozoan to mud-rich packstone to grainstone outer core facies; (4) a bryozoan and crinoidal mud-rich packstone to grainstone; and (5) an argillaceous mudstone to skeletal wackestone of the regional Lodgepole facies.

Comparing the outcropping mounds to the subsurface mounds, the previously studied mounds at Sacagawea Peak and Saddle Peak are dwarfed by the large mound complexes in Stark County. This difference in size is attributed to a smaller initial area upon which the Bridger Range mounds nucleated followed by a much earlier cessation of mound development (i.e., earlier drowning event) compared to the Stark County mounds.

The locations of mounds found in the subsurface coincide with areas that have abnormally thick Upper Bakken Shale. These areas of thick Upper Bakken Shale have been attributed to two-stage dissolution of the underlying Prairie salt, which ultimately may have allowed for the development of the subsurface Lodgepole mounds. Initial dissolution resulted in a paleotopographic low, where additional Upper Bakken Shale was deposited. The second stage of dissolution resulted in a paleotopographic high of the Upper Bakken Shale, forming an ideal site for nucleation of the Lodgepole carbonate mounds.
Based on petrographic studies, the Bridger Range outcropping mounds and the Stark County subsurface mounds were cemented early with pseudo-peloidal, radial-fibrous, and equant calcite cements. These cements allowed for minimal compaction and preservation of the mound core facies.
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ACKNOWLEDGEMENTS

There are a handful of people who I would like to thank for assisting me and supporting me through the thesis writing process. First, Dr. Steve Sonnenberg, for accepting me as a student and providing me with an interesting and thought-provoking project. His willingness to sit down and discuss ideas throughout the entire process was constant. Dr. Rick Sarg and Dr. Mary Carr, for both sitting down with me and discussing the various aspects of this project and offering thought-provoking ideas. Dr. John Humphrey, for his friendship, assistance with cathodoluminescence petrography, and thorough editing. Dr. Mark Longman for his engaging discussions that made me think about things I would not have otherwise considered.

The Colorado School of Mines Bakken Consortium, its leadership, my fellow members, and the numerous industry sponsors who make these studies possible.

My parents, Eric and Virginia, for their guidance, encouragement, and upbringing which has helped shape me to who I am today. My siblings, Karl, Jack, and Marie, for being, well, siblings. My grandfather, Joseph Mueller, who bestowed to his grandchildren the gift of a college education. Lastly, my close friends, for making my life outside of thesis writing enjoyable.
CHAPTER 1

INTRODUCTION

Discovery of hydrocarbon producing carbonate mounds within the Mississippian Lodgepole Formation (Figure 1.1) was in 1993 with the ConocoPhillips Dickinson State 74 wildcat well. This well, followed by subsequently drilled wells, initiated the play at Dickinson Field in Stark County, North Dakota. Significant production from the Lodgepole exists in Manitoba (Young and Rosenthal, 1991); however, prior to this discovery, the Lodgepole was known as a low volume, sporadic reservoir along the Nesson Anticline in the United States (LeFever and Anderson, 1984; Montgomery, 1995). Within two years, three additional fields had been discovered in Stark County, North Dakota, which targeted these carbonate mounds. The Lodgepole mounds were quickly referred to as Waulsortian mounds and later Waulsortian-type mounds. There is still debate as to whether or not they should be affiliated with the term ‘Waulsortian’ at all.

Carbonate mounds within the Lodgepole Formation have been studied in several outcrop locations in Montana. Two mounds are present in Swimming Woman Canyon of the Big Snowy Mountains in central Montana (Strickland et al., 1956; Merriam, 1958; Cotter, 1965, 1966; Smith, 1972a, 1972b, 1977, 1982; Winfrey, 1983; Smith and Custer, 1987; and Adams, 1999). Up to five mounds are found at two different locations within the Bridger Range of southwestern Montana, with three previously studied at Sacagawea Peak and two unstudied mounds at Saddle Peak (Stone, 1971, 1972; Smith, 1972a, 1972b). Of these five mounds in the Bridger Range, two had yet to be studied in any detail. Field work was conducted in August of 2015 to re-examine the three previously studied mounds at Sacagawea Peak, and to compare and contrast them with the two previously unstudied mounds at Saddle Peak. Data collected includes dimensions of mounds,
identification of facies, facies associations, and systematic sampling both laterally and vertically where possible. Data collected from this outcrop were then used to compare and contrast observations made to outcrops that have previously been studied in great detail. In addition, these outcrop data were used to compare the Montana mounds with those that are producing significant amounts of hydrocarbons in Stark County, North Dakota.

Subsurface core is available from a number of producing mounds in Stark County, North Dakota. Both facies and depositional geometries vary within these mounds. Comparison of subsurface mounds with outcrops from Montana allowed for a better understanding as to how these mounds may have formed. The locations of mounds in Stark County coincide with anomalously thick underlying Upper Bakken Shale. Using IHS Petra, the Upper Bakken Shale has been mapped throughout Stark County along with the locations of Lodgepole mounds. In mapping the mounds, a clean gamma-ray signature, characteristic of a clean limestone, made identifying mounds fairly simple.

Oils produced from these Lodgepole mounds are sourced from the underlying organic-rich Bakken shales. The hydrocarbons have similar compositions to that of the oils produced in Parshall field and Sanish field as noted by Jarvie (2000). Being sourced from the Bakken shales, these Lodgepole mounds must be considered, in effort to better understand the Bakken petroleum system in its entirety.

1.1 Objectives & Purpose

The purpose of this thesis work is to add valuable information that may help in determining how and why these carbonate mounds formed. This is done by studying both the depositional and diagenetic histories of both the outcropping mounds in Montana and the subsurface mounds in North Dakota. Comparing and contrasting outcropping mounds in Montana with subsurface
mounds in North Dakota will shed light on the conditions present at their respective locations throughout their respective histories. By studying the mounds in detail, their relationship to the Bakken petroleum system and how they aid in petroleum production can be better understood. Additionally, this work shows how and why the geometries of these mounds change from area to area.

Figure 1.1 Stratigraphic columns for both southwestern Montana and North Dakota showing time correlative units. Data from Sandberg et al. (1988), Sonnenberg (2016) pers. comm., and Lockwood (2016) pers. comm.
1.2 Waulsortian Terminology

Originally described by Dupont in 1863, the term “Waulsortian Phase” was used in reference to Upper Tournaisian and Lower Viséan limestones (Lees, 1961; 1964) exposed near the village of Waulsort in Belgium (Wilson, 1975; Lees, 2006). These massive lime mudstone bodies, characterized by their scattered crinoid and bryozoan fragments, in addition to their lens-like buildups and mounds, began to be recognized in other places outside of Belgium. Notably, they were found to occur in Western Europe (Ireland, France, England), and in North America (Texas, Oklahoma, New Mexico, and Montana) (Wilson, 1975). Based on their compositional and depositional similarities from continent to continent and outcrop to outcrop, the Waulsortian facies was referred to more and more. Delépine (1951) defined the Waulsortian facies as “…a reef limestone made of fine-grained calcareous mud, crinoidal debris, and even cherty beds here and there; but the main part is composed of massive, unstratified limestone, with blue or black ‘veins’; the central part of these veins consist of a great variety of fenestellids.”. Similarly, Lees (1964, p. 484) noted that “the lithological variation in Waulsortian limestones can be expressed in terms of their five main components: (1) calcite mudstone; (2) coarsely crystalline calcite mosaics (including Stromatactis and ‘reef tufa’); (3) in situ fenestillid Bryozoa; (4) crinoid, shelly and bryozoan debris; and (5) entire fossils other than Bryozoa”.

Lees and Miller (1985) studied the facies variation in Mid-Dinantian buildups from Europe and North America. This study may have been fueled by the use of the term “Waulsortian” from the 1960’s to present day as a catch-all classification for a variety of Paleozoic carbonate buildups, accumulations, reefs, knolls, facies, etc. (Lees and Miller, 1985). Consequently, Lees and Miller (1985) identified four component assemblages (termed A, B, C, and D) that could be used to compare the classic Waulsortian buildups in Belgium to those elsewhere in Europe and North
America that have similar component assemblages. It is recognized that the majority of Waulsortian buildups are of late Tournaissian and early Viséan age (Lees and Miller, 1995) (Figure 1.2). It is also noted that the buildups in Montana are early Tournaissian in age (Kinderhookian) (Smith 1972a, 1972b, 1982; Lees and Miller, 1995; Adams, 1999). With similarities to the classic Waulsortian buildups of Europe, Lees and Miller (1995) classified the buildups in Montana and North Dakota as “Waulsortian-type”.

Figure 1.2 Stratigraphic range of Waulsortian buildups from both Europe and North America. Lack of solid lines along left and right edges of shaded columns indicate doubt in position or range. Importantly, the buildups in Montana are confidently dated to be from the late Kinderhookian. Correlations are based on conodont and microfaunal data. Such data can be found in the original source. Modified from Lees and Miller (1995).

Bridges et al. (1995) observed a lack of consistency in which the terms ‘Waulsortian’, ‘Waulsortian-like’ and ‘non-Waulsortian’ were being used when discussing Early Carboniferous buildups. As a result, it was recommended that the types of Early Carboniferous buildups should be based on skeletal composition. In doing so, Bridges et al. (1995) proposed five types of buildups: (1) Fenestrate bryozoan-sponge spicule buildups; (2) crinoid-bryozoan buildups; (3)
crinoid-brachiopod-fenestrate bryozoan buildups; (4) coralgal-\textit{Aphralsyia} and bryozoan-coralgal buildups; and (5) trepostome-microthrombolite buildups.

While early studies of the Waulsortian facies suggested “reefs” as interpretations for their depositional geometries, Lees (1961, 1964) importantly noted that although rich in skeletal debris, the facies does not contain a ridged skeletal framework that one would typically associate with a reef. Consequently, the Waulsortian buildups are termed as “banks” by Lees and Miller (1995). They prefer this term as “Waulsortian accumulations did not necessarily form mounds and were not always muddy throughout”. Consequently, Lees and Miller (1995 p. 193) declared ”we propose to avoid the terms \textit{mound, mud-mound, bioherm,} and \textit{reef}”. Despite their efforts, Waulsortian buildups or Waulsortian-type buildups are still referred to as mounds or bioherms. Based on the American Geological Institute’s \textit{Glossary of Geology}, the terms ‘bank’, ‘bioherm’, ‘biostrome’, ‘mound’, and ‘organic mound’ are defined below:

\textbf{Bank:} (AGI, p. 56) “A limestone deposit consisting of non-fragmental skeletal matter, formed in place by organisms (such as crinoids and brachiopods) that lack the ecologic potential to erect a rigid, wave-resistant structure” (Nelson et al., 1962).

\textbf{Bioherm:} (AGI p. 73) “A mound-, dome-, lens-, or reef-like or otherwise circumscribed mass of rock built up by, and composed almost exclusively of, the remains of sedentary organisms (such as corals, algae, foraminifers, mollusks, gastropods, and stromatoporoids) and enclosed or surrounded by rock of different lithology” and “…often stresses the calcareous composition” (proposed by Cumings and Shrock (1928, p. 599) and defined by Cumings (1930, p. 207).
*Biostrome*: (AGI, p. 75) “A distinctly bedded and widely extensive or broadly lenticular, blanket-like mass of rock built by and composed mainly of the remains of sedentary organisms, and not swelling into a mound-like or lens-like form” (proposed by Cumings (1932, p. 334).

*Mound*: (AGI, p. 466) “An organic structure built by fossil colonial organisms, such as crinoids.”

*Organic Mound*: (AGI, p. 499) “Bioherm”.

It is important that these terms are defined as they will be used throughout this work. With these definitions taken into consideration, the Waulsortian or Waulsortian-type buildups will henceforth be referred to as bioherms and mounds, interchangeably. In addition, the appropriateness of referring to these bioherms or mounds as Waulsortian or Waulsortian-type will be discussed later.
CHAPTER 2
LOCATIONS OF STUDY AREAS

Research for this thesis was conducted at two distinct locations. The outcrop component was completed in the Bridger Range of southwestern Montana while the subsurface component was completed in Stark County of southwestern North Dakota.

2.1 Bridger Range, Montana

Waulsortian-type carbonate mounds within the Mississippian Lodgepole Formation outcrop in the Bridger Range of southwestern Montana. The Bridger Range is a subrange of the Rocky Mountains and is aligned generally north-south with an approximate length of 25 miles (40 km) (Figure 2.1). Two different outcrops of carbonate mounds have been identified within the Bridger Range over the past 50 years. Both groups are visible from the western side of the range, appearing as relatively lighter-colored lenses within the darker colored Lodgepole Limestone talus and scree near the ridge crest.

The first group can be found ¾ miles south-southeast of the tallest peak in the Bridger Range, Sacagawea Peak, at an elevation of 9,665 feet. These buildups can be accessed by driving 20 miles north on MT-86 from Bozeman on the east side of the Bridger Range and an additional 6 miles on Fairy Lake Road to the Fairy Lake Campground. From the campground, hiking along a 2 mile long trail with a 2,000 foot gain in elevation ends at Sacagawea Peak. Lastly, descending Sacagawea Peak along the ridge to the south-southeast, ascending the third tallest peak, Naya Nuki Peak, and crossing the saddle immediately south of this peak. The buildups are located on the west side of this saddle.

The second group of buildups are found approximately 7.5 miles south of the Sacagawea Peak buildups. More specifically, these buildups are found ¾ of a mile south of the fourth tallest
peak in the Bridger Range, Saddle Peak, at an elevation of 9,134 feet. The Saddle Peak buildups can be accessed by driving on the west side of the Bridger Range to the Middle Cottonwood Canyon trailhead. From the trailhead, hike along the Middle Cottonwood Canyon trail for approximately 6 miles, gaining 4,000 feet in elevation. Finally, summit Saddle Peak from the west and then descend the peak to the south along the ridge for ¾ of a mile. The buildups are located on the west side of the range with sparse tree cover along the base and around the sides of the buildups. Alternative routes to access this group of buildups include the longer and more arduous “College M” trail to the south, as well as reaching the ridge from the Bridger Bowl Ski Area to the north and descending along the ridge until Saddle Peak and subsequently the nearby buildups.

2.2 Stark County, North Dakota

The subsurface study area is located in Stark County, North Dakota and includes townships 140N-138N and ranges 97W-95W (Figure 2.2). The subsurface study area is approximately 400 miles east of the Bridger Range in southwestern Montana. Since the discovery in 1993, there have been eight distinct fields producing from the Waulsortian-type mounds of the Lodgepole Formation. They are the Eland, Dickinson, Duck Creek, Versippi, Subdivision, Stadium, Hiline, and Livestock fields (Figure 2.2). To date, over 60 million barrels of oil have been produced from these eight fields with 10 wells producing over 1 million barrels each (Table A.1).
Figure 2.1  (A) Index map of the Bridger Range of southwestern Montana. Left map shows general topography of the Bridger range with the Sacagawea Peak and Saddle Peak outcrop locations relative to the town of Bozeman. Map modified from Stone (1972). (B) Right aerial photomap shows the Bridger Ranger at nearly the same scale and highlights specifically the locations of these outcrops to one another.
Figure 2.2 Map of Stark County, North Dakota and the individual producing fields. Wells for this study are highlighted with red stars. Modified from Montgomery (1995).
In this chapter, an overview of the regional structural settings in addition to the regional stratigraphic settings will be discussed for both the Bridger Range in southwestern Montana and Stark County in North Dakota.

3.1 Regional Structural Setting – Bridger Range, Montana

In order to understand the stratigraphy of southwestern Montana, one must first consider the regional structural setting. The main structural framework of southwestern Montana was initially developed during the Precambrian (Poole and Sandberg, 1977). Sloss (1950) identified four particular elements that controlled sedimentation by their tectonic behavior during Paleozoic deposition. They include the Cordilleran miogeosyncline (i.e., the Paleozoic passive margin) to the west, Williston Basin to the east, Wyoming shelf to the south, and the Central Montana Trough (Figure 3.1).

Peterson (1981) noted that the paleostructural framework of western Montana was developed as early as the late Precambrian. This framework was present throughout geologic time and affected later Paleozoic sedimentation. From the late Proterozoic to early Cambrian, present day Montana was located along the western side of the passive North American continental margin. The margin remained passive until the late Devonian to early Mississippian, after which the western margin of North America converged with the Antler Orogenic Belt. The reasoning and method by which the North American margin converged has been discussed in great detail over the years; however, it is uniformly considered to be the Antler Orogeny. The Antler Orogeny resulted in a mountain range that extended for hundreds of miles north and south, and was initially formed hundreds of miles offshore of the Montana Platform (Figure 3.2).
Figure 3.1 Major structural elements in the Northern Rocky Mountains and Plains Region. Of particular interest is the Willison Basin to the east, Cordilleran miogeosyncline (i.e., the Paleozoic passive margin) to the west, Wyoming shelf to the south, and the Central Montana Trough. Roberts (1979).
As a result of the Antler Orogeny, the former continental shelf, which was present during the deposition of Silurian and Devonian strata, had been modified into the Antler orogenic highland (belt), a foreland basin, and western portion of the cratonic platform (Figure 3.3) (Poole and Sandberg, 1977).

The foreland basin, referred to as the Cordilleran miogeosyncline, was asymmetric with the axis trending north-south. The deepest part of the basin was located immediately adjacent to the Antler highlands and shallowed eastward toward the cratonic platform (Dorobek et al., 1991).
Figure 3.3 Generalized cross-section of North American continent and island-arc system resulting in the cratonic platform, foreland basin, Antler orogenic highland, and inner-arc basin during the late Devonian and Mississippian as a result of Antler orogenic deformation. Modified from Poole and Sandberg (1977).

Subsidence between the Antler highland and the Montana Platform was episodic and highly variable. Foreland basin development was initiated by the early to middle Devonian, while the Montana Platform did not begin to subside until the late Devonian. Dorobek et al. (1991) proposed several hypotheses for why this may have occurred. Earlier onset of subsidence in the foredeep may have been due to encroachment of the accretionary wedge within the Antler highland. Another possibility is that a pulse of Frasnian-Famennian tectonic subsidence on the Montana Platform resulted from a eustatic rise in sea level. Bond and Kominz (1991) estimated that sea level rise between Frasnian-Famennian time was approximately 100 meters. This is comparable to the Frasnian-Famennian subsidence reported by Dorobek et al. (1991). Consequently, Montana Platform subsidence may be related to a combination of both tectonics and sea-level rise (Dorobek et al., 1991). This episodic and highly variably subsidence on the Montana Platform is evidenced by the varying strata deposited during times of varying subsidence. Sediment that was deposited immediately following an increase in subsidence rate generally resulted in transgressive or
onlapping packages (e.g., Lodgepole Formation; Dorobek et al., 1991). Alternatively, sediment that was deposited following a decrease in subsidence rate generally resulted in regressive or offlapping packages (e.g., Mission Canyon Formation; Dorobek et al., 1991).

As previously mentioned, the paleostructural framework developed in the late Precambrian was present throughout deposition of Paleozoic strata in western Montana (Peterson, 1981). The structures that were most important in shaping the Paleozoic sediments included the Lemhi arch, Alberta shelf, Beartooth shelf, Belt Island complex, Boulder High, Coeur D’Alene Trough, Central Montana Trough, Big Snowy Trough, Ruby Trough, and the Muldoon Trough (Peterson, 1981). The Precambrian paleostructural framework is believed to have formed during a middle Proterozoic rifting event that allowed for formation of the Central Montana Trough and the Coeur D’Alene Trough (Figure 3.4) (Dorobek et al., 1991). The Central Montana Trough was an east-west trending belt of subsidence that connected the Williston Basin in the east to the Paleozoic passive margin to the west (Figure 3.2).

The Central Montana Trough and Coeur D’Alene Trough depocenters were bounded by east-west trending normal faults associated with this rifting and were reactivated during the Neoproterozoic (Dorobek et al., 1991). With the onset of the Antler Orogeny, these faults were once again reactivated and combined with differential subsidence, resulted in tectonic inversion of paleostructures. By the late Devonian, the Central Montana Trough had been inverted into the Central Montana Uplift (Figure 3.5). From the late Devonian through Mississippian time, continued differential compaction and tectonic inversion resulted in multiple depocenters with east-west trending axes (Figure 3.6). These depocenters remained through the Mississippian, during which Lodgepole deposition in the Bridger Range area occurred.
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Figure 3.5 Isopach map for the late Devonian (Frasnian to Famennian) strata. Most important feature to note is the location of the east-west trending Central Montana Uplift (CMU) in relative relation to that of the Central Montana Trough to the south shown in Figure 3.4. Modified from Peterson (1986) and Dorobek et al. (1991).
Figure 3.6 Isopach map for the Madison Group strata (early to middle Mississippian). Note the location of the late Devonian Central Montana Uplift in Figure 3.5. With tectonic inversion, the Central Montana Uplift then became the Central Montana Trough by the early to middle Mississippian. Modified from Peterson (1986) and Dorobek et al. (1991).
The Bridger Range area exposes approximately 27,000 feet of sedimentary rocks from Beltian to Holocene in age. The range forms part of the southwestern rim of the Crazy Mountain Basin and is bound to the west by the Gallatin Valley (McMannis, 1955). The exposed strata are generally eastward dipping and outcrop in an elongate, generally north-trending band that is present the entire length of the range. While Ordovician, Silurian, and Permian strata are not present, the rest of the Paleozoic sediment is exposed and is generally 5,000 feet thick (McMannis, 1955). Near Saddle Peak, the structure is uncomplicated, as the area is an undisturbed fault block between two major northwest-trending faults that cross the width of the Bridger Range (Stone, 1971). These major faults are high-angle reverse faults (McMannis, 1955) with the southern fault being visible from Sacagawea Peak. The rocks within this fault block generally strike at 025° and dip 40° to 65° (McMannis, 1955).

3.2 Regional Structural Setting – Stark County, North Dakota

The Williston Basin is an intracratonic, sag-type basin that developed during the Ordovician and experienced deposition throughout the Phanerozoic (Waters and Sando, 1987). The basin is relatively circular and contains nearly 16,000 feet of sedimentary rocks that range in age from Cambrian through the Tertiary. The basin is situated in the northern Great Plains of the United States and Canada and includes parts of North Dakota, South Dakota, Montana, and the Canadian provinces of Manitoba and Saskatchewan (Gerhard et al., 1990) (Figure 3.7). The basin is extremely large, covering an area of roughly 133,000 mi². The Waulsortian-type buildups found within the Lodgepole Formation are located in the central part of the Williston Basin, in Stark County of southwestern North Dakota (Figure 3.7).
Paleozoic sedimentation within the Williston Basin was closely related to the tectonic history of the western border of the North American craton (Peterson and MacCary, 1987). The central region of this Paleozoic depocenter was comprised of a stable core, the Canadian shield of Precambrian rocks, and the transcontinental arch (Figure 3.2). Underlying the basin are the Precambrian rocks of the Canadian Shield (Gerhard et al., 1990). West of the Williston Basin is the Central Montana Trough, bounded by the Cordilleran miogeosyncline further westward. West of the Cordilleran miogeosyncline is the Antler orogenic belt, which as discussed previously, actively grew during the middle Devonian (Figure 3.1). This growth resulted in a north-south trending system of thrusting, mountain building, and island growth that underwent multiple stages of development in the Paleozoic and Mesozoic (Peterson and MacCary, 1987).
During the early to middle Paleozoic, the transcontinental arch essentially separated the North American craton into eastern and western shelf provinces (Peterson and MacCary, 1987). The eastern portion of the Cordilleran shelf, adjacent to the transcontinental arch, is considered the northern Great Plains region. This region contains variety of paleostructural elements associated with the development and growth of the Cordilleran shelf, with the main element being the Williston Basin (Peterson and MacCary, 1987). The Williston Basin, originally a craton-margin basin or continental shelf basin, began subsiding in the Ordovician or late Cambrian (Peterson and MacCary, 1987). With deformation of the Cordilleran orogeny, and subsequent crustal additions to the western continental margin, the Williston Basin transformed into an intracratonic basin during the late Devonian to Mississippian time (Gerhard et al., 1990; Montgomery, 1995).

The Williston Basin itself is characterized by a number of important structural and tectonic elements. These elements include the Cedar Creek, Nesson, Billings, and Little Knife anticlines (Figure 3.8) (Montgomery, 1995). The basin remains undisturbed by major orogenic trends and consequently, the structures present within the basin are related to basement faulting. Sources for stresses that have resulted in these structures include two regional northeast-southwest trending lineaments, the Fromberg-Brockton zone to the north and the Colorado-Wyoming lineament to the south (Figure 3.9) (Montgomery, 1995).

These two left-lateral shears, or wrench fault trends, control the orientation of many other structural features found in the Williston Basin (Figure 3.10) (Gerhard et al., 1990). Particularly, these trends are believed to have been responsible for the generation of planes of basement fractures in the Williston Basin (Gerhard et al., 1990). These planes of weakness (i.e., basement fractures) became zones of weakness that subsequently controlled the later development of many of the present structural features observed within the Williston Basin (Figure 3.8) (Gerhard et al.,
Of the structures that were developed as a result of these trends, the dominant sense of motion was vertical uplift (Gerhard et al., 1990).

Figure 3.8  Map showing major structural and tectonic features in the United States portion of the Williston Basin extending from North Dakota, through South Dakota, and into eastern Montana. Particularly significant features to note are the Cedar Creek, Billings, and Little Knife anticlines in southwestern North Dakota. Additionally, the area of interest (Stark County, North Dakota) shown is highlighted in red towards southwestern North Dakota (modified from Gerhard and Anderson, 1988; Montgomery, 1995).
Figure 3.9  Map showing major northeast-southwest trending tectonic shear sets that formed the Central Rocky Mountain province in relation to the Williston Basin. Major shear sets include the Fromberg-Brockton Fault zone and the Colorado-Wyoming lineament to the south (Gerhard et al., 1990).

Figure 3.10  Generalized movement of Fromberg-Brockton fault zone to the north and the Colorado-Wyoming lineament to the south (modified from Gerhard et al., 1990).
3.3 Regional Stratigraphic Setting - Bridger Range, Montana

In the Bridger Range of southwestern Montana, Mississippian-aged strata is comprised of two formations that make up the Madison Group. They are the lowermost Lodgepole Formation and the overlying Mission Canyon Formation. The lowermost Lodgepole is subdivided into three members. They are the lowermost Cottonwood Canyon Member, overlying Paine Member, and uppermost Woodhurst Limestone Member (Figure 3.11) (Smith, 1977). The Lodgepole Formation conformably overlies the late Devonian to early Mississippian Sappington Member of the Three Forks Formation and is conformably overlain by the Mission Canyon Formation. The Lodgepole and Mission Canyon Formations in the Bridger Range represent continuous deposition through all of the Kinderhookean and perhaps the earliest Osagean (Laudon and Severson, 1953).

![Stratigraphic column](image)

Figure 3.11 Stratigraphic column of southwestern Montana. Data from Sandberg et al. (1988), Sonnenberg (2016) pers. comm., and Lockwood (2016) pers. comm.
3.3.1 Sappington Member of Three Forks Formation

The Three Forks Formation is comprised of three members, the lowermost Logan Gulch Member, the Trident Member, and the uppermost Sappington Member. The Sappington Member is late Devonian to early Mississippian in age. In the Bridger Range, it is comprised of three members that total approximately 72 to 81 feet in thickness (McMannis, 1955). These three members include: (1) a black, fissile, conodont-bearing shale 8-16 feet thick; (2) a pale-brown to yellow-brown, thick to medium-bedded, fine-grained siltstone that is generally vertically increasing in sand content and averaging 62 feet thick; (3) a dark-brown to black, silty shale or siltstone 2-3 feet thick (McMannis, 1955). The Sappington Member is the correlative equivalent to the Middle Bakken and Lower Bakken Shale members of Bakken Formation (Figure 1.1), which will be discussed in further detail in Section 3.4.1.

3.3.2 Lodgepole Formation

In the Bridger Range, the Lodgepole Formation varies from approximately 750 feet to 810 feet in thickness. It consists of generally dark-gray, thin to very thinly-bedded lime mudstones with intercalated calcareous shale partings that are 1-3 inches thick (McMannis, 1955). Above the basal contact with the underlying Sappington Formation, there are approximately 315 to 325 feet of dark gray to dark brown, thinly-bedded, fine-grained, brittle limestone. Above 315 to 325 of basal strata lies approximately 440 feet to 480 feet of pale yellow to brown, orange-brown, and gray-brown, thin-bedded, fine-grained limestones, alternating with medium to thickly-bedded, massive crystalline limestones (McMannis, 1955). Chert nodules are common in the lower section of the Lodgepole and are typically less than 2 inches thick though are laterally more extensive.

Significant to the Lodgepole Formation is the presence of Waulsortian-type carbonate mounds or bioherms. In the Bridger Range, these bioherms can have as much as 60 feet in
topographic relief and span over 500 feet in width. These bioherms are generally rich in crinoids and fenestrate bryozoans. There are five facies associated with the Bridger Range bioherms: (1) a crinoid and fenestrate bryozoan mottled wackestone basal biostrome facies, (2) a skeletal wackestone to mud-rich packstone to grainstone to marine cemented boundstone inner core facies, (3) a crinoidal and bryozoan to mud-rich packstone to grainstone outer core facies, (4) a bryozoan and crinoidal mud-rich packstone to grainstone flank facies, and (5), an argillaceous mudstone to skeletal wackestone of the regional Lodgepole facies. A much more detailed analysis of these bioherms will be discussed in detail in subsequent chapters.

3.3.2.1 Cottonwood Canyon Member

The lowermost Cottonwood Canyon Member of the Lodgepole Formation is correlative to the Upper Bakken Shale of the Bakken Formation in the Williston Basin (Figure 1.1 and Figure 3.11). It was originally considered the “dark shale unit of Devonian and Mississippian age” by Sandberg and Klapper (1967). The contact between the Cottonwood Canyon Member and the overlying Paine Member is generally considered to be conformable though may appear to be disconformable due to the abrupt change in lithology (Sandberg and Klapper, 1967).

3.3.2.2 Paine Member

In central and southwestern Montana, the Paine Member is characterized by thinly-bedded, fine to coarse-grained, dense, crystalline limestone that is separated by calcareous shale and shaly limestone (Sloss and Hamblin, 1942; Roberts, 1979). The basal Paine Member is distinguishable by its abundance of chert. In the Bridger Range, it may contain up to 30 percent dark-gray to yellow nodular chert (Laudon and Severson, 1953). The upper part of the Paine Member is thin to medium-bedded argillaceous dolomite and dolomitic limestone that is slightly less resistant to erosion than the overlying rocks (Roberts, 1979). The Kinderhook-Osage boundary is identified
on the basis of faunal collections at, or near the contact between the Paine Member and the Woodhurst Limestone Member (Sando and Dutro, 1974). Most importantly, the Waulsortian-type bioherms found in the Bridger Range are typically found within the Paine Member of the Lodgepole Formation.

3.3.2.3 Woodhurst Member

The Woodhurst Member conformably overlies the Paine Member and is predominately a light-colored, thickly-bedded, fine-grained limestone (Sando, 1967; Sando and Dutro, 1974; Roberts, 1979, Adams, 1999). The Woodhurst is commonly bioclastic, with the contact between the underlying Paine Member typically found at a lowermost detritus of crinoidal material (Sloss and Hamblin, 1942). This first crinoidal limestone records the initiation of cyclical alternation of crinoidal limestones (commonly oolitic) and shaly, predominantly fine-grained limestones (Sando and Dutro, 1974).

3.3.3 Mission Canyon Formation

The Mission Canyon Limestone conformably overlies the Lodgepole Formation and has a gradational contact. It varies in thickness from approximately 430 feet to 950 feet with measured sections in the Bridger Range varying between 870 feet and 950 feet thick (McMannis, 1955). It is generally a massive, pale yellow to brown, poorly bedded limestone that weathers to a light-gray cliff-former (McMannis, 1955; Stone, 1971). Crinoidal lime and dolomitic lime wackestones, minor oolitic and pelletoidal lime grainstones, and packstone are characteristic lithologies of the Mission Canyon Formation (Stone, 1972). In the Bridger Range, the Mission Canyon Formation is the Big Snowy Group.
3.4 Regional Stratigraphic Setting - Stark County, North Dakota

As mentioned previously, the Williston Basin contains nearly 16,000 feet of sedimentary rocks that range in age from Cambrian through the Tertiary. During the Paleozoic, the basin had evolved from a craton-margin basin or continental shelf basin into an intracratonic basin. This change resulted in significant changes in overall depositional regimes (Peterson and MacCary, 1987). This cratonic basin was characterized by a very gently-dipping carbonate ramp during the lower Mississippian, with the slope estimated to be less than one foot per mile (Lindsay, 1988). Within the Williston Basin, Mississippian-aged strata is comprised of three formations that make up the Madison Group. The Madison Group is more than 2000 feet thick in the central Williston Basin (Peterson and MacCary, 1987). They are the lowermost Lodgepole Formation, overlying Mission Canyon Formation, and the uppermost Charles Formation (Figure 3.12). The Madison Group is part of a major transgressive-regressive sequence that is associated with the Lower Kaskaskia sequence of the Late Devonian and the Upper Kaskaskia sequence of the Mississippian (Montgomery, 1995). The lowermost Lodgepole Formation conformably overlies the Late Devonian to Early Mississippian Bakken Formation in western North Dakota in the central Williston Basin (Peterson, 1984). The Bakken Formation thins away from the basin center along the southern, eastern, and western basin margins (Adams, 1999). Typically, the Bakken Formation unconformably overlies the Three Forks Formation. However, along basin margins, the Lodgepole Formation conformably overlies the Three Forks Formation, Birdbear Formation, and Duperow Formation. Throughout the Williston Basin, the Lodgepole Formation is conformably overlain by the Mission Canyon Formation.
3.4.1 Bakken Formation

The Bakken Formation is Late Devonian to Early Mississippian in age. The Bakken Formation as defined, is restricted to the subsurface of the Williston Basin in eastern Montana to western North Dakota in the United States and southern Saskatchewan to southwestern Manitoba in Canada. However, the correlative equivalents to the Bakken Formation are present in outcrops in Montana (Figure 1.1). The Devonian-Mississippian boundary is typically placed within the Bakken Formation, which disconformably overlies the upper Devonian Three Forks Formation.
(Peterson and MacCary, 1987). It is thickest in the center of the basin, attaining a total thickness of 140 feet (Meissner, 1978) and thinning to 0 feet along the southern, eastern, and western basin margins (Meissner, 1978; Adams 1999). The Bakken is divided into three members: (1) Upper Shale Member, (2) Middle Siltstone Member, and (3) Lower Shale Member (Figure 3.13).

![Stratigraphic column of the Bakken Formation with typical gamma ray and neutron density wireline log responses (Meissner, 1978).](image)

Figure 3.13 Stratigraphic column of the Bakken Formation with typical gamma ray and neutron density wireline log responses (Meissner, 1978).

Of the three members, the Middle Siltstone Member has the largest variability in thickness while the Upper and Lower Shale Members maintain a relatively consistent thickness. This is not the case in Stark County, however. In Stark County, the locations of Waulsortian-type mounds within the Lodgepole Formation coincide with anomalously thick intervals of Upper Bakken Shale (Figure 3.14).

The Upper and Lower Bakken shales are nearly identical in composition. They are dark-brown to black, organic-rich, non-calcareous, hard shales (Meissner, 1978). The shales were deposited in an anoxic marine environment that allowed for anoxic conditions to exist (Webster, 1984). With high TOC values, the Bakken shales have successfully generated abundant amounts of hydrocarbons that have sourced many different petroleum system within the Williston Basin.
3.4.2 Lodgepole Formation

The Lodgepole Formation is early Mississippian in age and is overlain by the Mission Canyon and Charles formations. Maximum transgression was recorded during the lower Lodgepole deposition, with the Lodgepole recording deeper water and starved-basin conditions (Lindsay, 1988). The Lodgepole Formation is generally a gray to dark gray argillaceous to shaley or silty, thin to medium-bedded limestone (Rose, 1976; Peterson and MacCary, 1987). Chert is present, though dispersed. The Lodgepole is thickest in the Williston Basin depocenters where it is 600-800 feet thick, thinning towards the basin margins (Gaswirth et al., 2010).

Similar to the Bridger Range Waulsortian-type bioherms, the mounds that produce significant amounts of hydrocarbons in Stark County, North Dakota are located within the
Lodgepole Formation. The mounds are similar to those of the Bridger Range, with their crinoidal and fenestrate bryozoan rich core facies. However, the Stark County mounds are much larger in aerial extent, with topographic reliefs of up to 350 feet and aerial extents of over 1 mile in diameter. Unique to Stark County, it is hypothesized that individual bioherms amalgamated into groups of bioherms, yielding the overall much larger geometries when compared to those of the Bridger Range. The facies and geometries of these Stark County bioherms will be discussed in greater detail in subsequent chapters.

3.4.3 Mission Canyon Formation

Commonly referred to as the Mission Canyon Limestone, the Mission Canyon Formation is generally a thickly-bedded to massive fossiliferous to oolitic carbonate (Peterson and MacCary, 1987). It was deposited on a gently dipping ramp during the Mississippian. The Mission Canyon carbonates record a shallowing of water depth with shoreline regression into the Williston Basin (Lindsay, 1988). This shallowing and regression ultimately led to the basin wide deposition of the Charles Formation evaporites.
CHAPTER 4
PREVIOUS WORK

There have been an abundance of studies pertaining to both the outcropping mounds in Montana as well as the subsurface mounds in Stark County, North Dakota. This chapter serves as an introduction to these studies.

4.1 Bridger Range, Montana

The Lower Mississippian limestones which overlay the Sappington Formation were originally known as the Madison Formation. After studies in the Little Rocky Mountains of north-central Montana, Collier and Cathcart (1922) defined the limestones as the Madison Group and subdivided it into a lower Lodgepole Formation and an upper Mission Canyon Formation. This group and formation nomenclature was extended into southwestern Montana by Sloss and Hamblin (1942). Sloss and Hamblin (1942) chose exposures along the Gallatin River in Logan, Montana as the location for the Madison Group type section. It was here that the Lodgepole Formation was subdivided into the Paine and Woodhurst members after terminology used by Weed (1900) in the Castle Mountains (McMannis, 1955).

McMannis (1955) is credited for his exhaustive compilation on the geology of the Bridger Range from 1950 to 1952. During this time, he focused on the overall stratigraphy and structural evolution of the range in great detail. His comprehensive work has been a fundamental building block in the geologic study of the Bridger Range ever since.

A variety of studies have focused on the buildups found within the Lodgepole Formation in the Bridger Range since the first discussion by Cotter (1965, 1966). Cotter (1965, 1966) focused on the buildups located at Swimming Woman Canyon in the Big Snowy Mountains of central
Montana. Particularly, Cotter (1965, 1966) analyzed the constituents, growth geometries, and diagenesis of the buildups.

Stone (1971) conducted the most detailed study of the buildups found at Sacagawea Peak in the Bridger Range to date. Over an eight week period, he photographed, collected samples, mapped, and measured sections for what he concluded are three individual bioherms. He identified five major limestone facies associated with the buildups; an inner core, outer core, basal biostrome, flank, and regional host. Stone’s work has been used as a foundation for many observations made in this author’s own study of the Lodgepole buildups in Montana.

Smith (1972a, 1972b) studied the buildups located at both Swimming Woman Canyon in central Montana and Sacagawea Peak in southwestern Montana as part of a regional study focused on the stratigraphy and petrology of the Lodgepole Formation.

4.2 Stark County, North Dakota

The carbonate mounds found in Stark County, North Dakota have been studied considerably more than the mounds which outcrop in Montana. Upon discovery in 1993, a handful of brief articles were published in geologic newsletters regarding the new play. The first of these articles described the location, production, and reservoir characteristics of Conoco’s Dickinson State #74 discovery well (Burke and Diehl, 1993). Additionally, Burke and Diehl (1993) discussed the potential methods by which the mounds were formed, modern analogues, as well as those which outcrop in Montana.

As exploration and production of mounds continued, additional publications provided updates on additional wells that were being brought online along with successes and failures of attempting to locate additional mounds (Burke and Diehl, 1995a, 1995b, 1995c, 1995d; O’Conner, 1995; Petzet, 1995a, 1995b). Other publications discussed the tectonic controls, (Schurr et al.,
and hypothesized about future potential (Brogdon et al., 1996). Facies descriptions from
several mound cores were discussed by Burke (1997) which parallel observations of the Bridger

LeFever et al. (1995) discussed a primary exploration for additional Stark County mounds
and of particular interest, noted that two-stage salt dissolution and collapse may have been a
possible mechanism for initiation of mound growth, which will be discussed in greater detail in
subsequent chapters (LeFever et al., 1995; LeFever and LeFever, 1995). An alternative
mechanism for mound initiation and growth was proposed by Longman (1996). Longman
hypothesized that “intersecting sets of regional fractures through sites of thick, organic-rich
Bakken shales could have provided places for the gas seeps and vent communities to develop”. It
is at these gas seeps and vent communities that Longman (1996) suggested the Stark County
mounds may have formed and eventually may have coalesced into composite complexes
(Longman, 1996).

Montgomery (1995, 1996) published arguably the most expansive, thorough, and detailed
study of the Lodgepole play in Stark County. Montgomery discussed the background, drilling
history, stratigraphy, depositional history, structural geology, tectonics, and overall petroleum
geology of the productive Lodgepole mounds. Young et al. (1998) published a study focused
specifically on the reservoir properties and producing characteristics of the mound.

The first study comparing outcrops to subsurface was completed by Adams (1999). This
study focused specifically on Dickinson field in an effort to compare and contrast the producing
mounds to the outcrops at Swimming Woman Canyon in central Montana.

Gaswirth et al. (2010) published a geologic assessment of the Lodgepole Formation as part
of the “Bakken-Lodgepole Total Petroleum System”. Their assessment focused on the petroleum
geology of the Lodgepole mounds in Stark County, North Dakota with an emphasis on source rocks, thermal maturity, and general reservoir characteristics.

Longman and Cumella (2016) revisited the Stark County mounds (particularly Eland Field) with a plethora of unpublished data provided by Duncan Energy. Their work detailed the overall history of Eland Field and how it has fared over the past twenty years. They acknowledged that many previous accounts of the mounds that outcrop in Montana describe excessive amounts of micrite and that these outcropping mounds may be considerably different than those in the subsurface in Stark County.

4.3 Big Snowy Mountains, Montana

Outcrops of the Mississippian-aged Lodgepole bioherms are also found at Swimming Woman Canyon in the Big Snowy Mountains of central Montana. At this location, there are three large bioherms that are in excess of 175 feet thick. They have been studied extensively in the past by Strickland et al. (1956); Merriam (1958); Cotter (1965,1966); Smith (1972a, 1972b, 1977, 1982); Winfrey (1983); Smith and Custer (1987); and Adams (1999).

Winfrey (1983), with funding from Amoco Production, studied the Swimming Woman Canyon outcrops in great detail. Winfrey thoroughly mapped the mounds and diligently analyzed the diagenesis from these mapped mounds. Winfrey was also the first to use cathodoluminescence as an aide in understanding the diagenesis of the mounds at Swimming Woman Canyon.

Adams (1999) analyzed the depositional and diagenetic characteristics of the Swimming Woman Canyon mounds and compared/contrasted them with the mounds associated with the prolific Dickinson Field in Stark County, North Dakota. With ample data provided by Conoco, Adams thoroughly described available core and thin sections in addition to utilizing cathodoluminescence and stable isotope analysis in her study of the mounds.
A variety of methods were utilized in this study. These methods include field work, describing core, subsurface mapping using HIS Petra, petrography, cathodoluminescence, and scanning electron microscopy.

5.1 Field Work

Two weeks of field work in the Bridger Range of Montana were completed in August of 2015. All data were personally collected and brought to Colorado School of Mines for further analyses. A total of four days were spent at the Sacagawea Peak outcrops and five days were spent at the Saddle Peak outcrops (Figure 2.1). At both locations, the outcrops were examined, measured, photographed, and sampled in detail. Where possible, stratigraphic sections were measured. At the Sacagawea Peak location, observations made were compared and contrasted to observations made previously by Stone (1971). The exposed bioherms at this location are lobate and have comparable geometries to one another (Figure 5.1).

The geometries of the exposed bioherms at the previously unstudied Saddle Peak are noticeably different. The remoteness of the Saddle Peak bioherms, located at the southernmost tip of the Bridger Range Mountains, is what had kept these mounds from being studied in the past. The northernmost bioherm (referred to as bioherm I) has a much more variable geometry compared to the bioherms located at Sacagawea Peak (Figure 5.2). Bioherm I and bioherm II were measured, though the severity of the terrain and geometries of the bioherms did not allow for exact measurements in all dimensions. As such, aerial photos were used in acquiring and recording dimensions of the bioherms.
Figure 5.1  Location of Sacagawea Peak outcrops. Latitude: 45°53'5.24"N and Longitude: 110°57'39.86"W.

Figure 5.2  Location of Saddle Peak outcrops. Latitude: 45°46'50.20"N and Longitude: 110°56'17.57"W.
5.2 Core Descriptions

A total of 7 cores from the subsurface mounds in Stark County, North Dakota are available for observation. One core, the Patterson #1-24, is stored locally at the United States Geological Survey (USGS) Core Research Center (CRC) in Lakewood, Colorado and was described for this study.

For the Patterson 1-24 well, a total of 15 petrographic thin sections had already been made. The remaining cores are stored at the North Dakota Geological Survey Core Library in Grand Forks, North Dakota. These include the Dickinson State A #83, Dickinson Kuntz #1-2, C.J. Steffan #2-2, C.J. Steffan #1-35, Kadramas #75, and the Knopik #1-11 cores (Table 5.1). For each of the cores stored in North Dakota, high-resolution photographs are available online. Additionally, some of these cores have petrographic thin sections already made and are also available online.

Figure 5.3 Location of 7 subsurface core in Stark County, North Dakota. Cores include the Paterson #1-24, Dickinson State A #83, Dickinson Kuntz #1-2, C.J. Steffan #2-2, C.J. Steffan #1-35, Kadramas #75, and the Knopik #1-11.
Table 5.1: List of seven core available for study with API number, location, TD, and intervals at which core is available from.

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<th>Well Name</th>
<th>API</th>
<th>Location</th>
<th>TD</th>
<th>Cored Interval (MD)</th>
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<td>9750'-9847', 9937'-9990'</td>
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<tr>
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<td>NWNW Sec 5-139N-96W</td>
<td>10080'</td>
<td>9956'-10016'</td>
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<td>10055'-10109'</td>
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<tr>
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<td>10350'</td>
<td>9947'-9989'</td>
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<tr>
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<td>9792'-9823', 9825'-9923', 9993'-10007', 10009'-10045'</td>
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<tr>
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<td>9750'-9770'</td>
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<td>10150'</td>
<td>9760'-9930'</td>
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</table>

5.3 Subsurface Mapping from Stark County, North Dakota

A Petra project was created and the Lodgepole-producing fields within Stark County were mapped. Wireline logs are currently available and additional well logs can be found on the North Dakota Industrial Commission (NDIC) website. A total of 77 rasterized logs were utilized. Once all available logs were retrieved, imported into Petra, and depth-registered, the mounds were mapped. Mapping allows one to see the abrupt thickness variations and the overall subsurface geometries of the mounds. Of particular interest is mapping the underlying Upper Bakken Shale and comparing mound locations relative to areas that have thicker Upper Bakken Shales.
5.4 Petrographic Analysis

Samples collected from outcrops were cataloged and sent to Weatherford Labs in Golden, Colorado in order to acquire petrographic thin sections. Nineteen standard 30 micron thick petrographic thin sections were made. The thin sections were impregnated with fluorescent-spiked, blue-dyed epoxy for use of the epifluorescence microscope and for easier identification of porosity. One half of the thin sections were stained with Alizarin Red S for easier discrimination between carbonate minerals. Of these thin sections, three are from the Sacagawea Peak outcrops and the remaining sixteen are from the Saddle Peak outcrops. All facies present in outcrop are represented by individual thin sections (Table 5.2). In addition to the petrographic thin sections made from outcrop samples, a total of fifteen petrographic thin sections from the Patterson #1-24 core were utilized (Table 5.3). For every thin section studied, each of the following were noted: skeletal grains present, non-skeletal grains present, texture, cavity structures, cements, replacement features, and porosity. Of particular interest is analyzing the diagenetic history of these mounds. As such, the variety of cements present were noted and studied in detail. Thin sections were analyzed using a Leica DM 2500P microscope in conjunction with a Leica DFC 450C digital camera.

Table 5.2 Table of nineteen thin sections made from samples collected from outcrops.

<table>
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<tr>
<th>Thin Section #</th>
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<th>Location</th>
<th>Bioherm #</th>
<th>Facies Present</th>
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</thead>
<tbody>
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Table 5.3 Table of fifteen thin sections from the Patterson #1-24 well available at the USGS in Lakewood, Colorado.

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5.5 Cathodoluminescence Petrography

Cathodoluminescence (CL) microscopy aided in distinguishing the different episodes of cementation in an effort to better understand the diagenetic history of the mounds. All CL work
was completed at Dr. David A. Budd’s lab at the University of Colorado at Boulder over a two-week span. A Leitz Ortholux microscope, in conjunction with a Technosyn 8200 MK II Cold Cathodoluminescence Unit was used for the CL petrography. An Olympus digital camera attached to the Leitz Ortholux microscope allowed for images to be acquired. Operating conditions for the MKII were an accelerating voltage of 12 kV, 0.05 torr of vacuum, and a beam current of 450 to 500 µA. Cathodoluminescence microscopy was completed on a total of 16 thin sections from both the outcropping mounds and subsurface mounds. It is important to recognize that the amount of luminescence observed in photos taken under cathodoluminescent conditions are heavily dependent upon the operating conditions of the equipment and amount of exposure time. Consequently, the amount of luminescence is relative from sample to sample, with exposure times ranging from 1/164th of a second to 21 seconds (Table A.2).

5.6 Scanning Electron Microscopy

Scanning electron microscopy (SEM) was used in an attempt to analyze the fine-grained cements present in outcrop samples, in addition to observing the effects of diagenesis at a high resolution. All SEM work was completed at the Colorado School of Mines over a two-day period using a newly acquired TESCAN MIRA3 LMG Schottky field emission-scanning electron microscope (FE-SEM). The microscope is equipped with a back-scattered electron (BSE) detector that detects the abundance of backscattered electrons, which is directly proportional to the mean atomic number of the materials being studied. Consequently, in a single BSE image collected, minerals with a higher overall atomic number (e.g., calcite) backscatter more electrons and therefore are relatively brighter than dolomite, which has a lower average atomic number.

The FE-SEM is also equipped with a Bruker XFlash 6/30 silicon drift detector for energy dispersive x-ray spectrometry (EDS). This EDS system allows for additional elemental analysis
and chemical characterization of a sample, and was utilized in quickly differentiating calcite from dolomite, quartz, iron-oxides, and other minor minerals present in samples.

Thin sections from outcrop were analyzed using the FE-SEM. Thin sections were prepped by washing with methanol to remove any oils that may have been present while handling. Once clean, they were then dried at 104°F for 10 minutes. The thin sections were then subjected to 0.001 millibars of vacuum and coated with a fine layer of carbon using a Cressington Carbon Coater.
The outcropping mounds in the Bridger Range of southwestern Montana and the subsurface mounds in Stark County, North Dakota were extensively mapped using a variety of techniques.

6.1 Outcrops - Bridger Range, Montana

Outcrops at two different locations within the Bridger Range of southwestern Montana were studied over a two-week period. Data collected in the field include vertical and lateral dimensions of mounds, photographs, stratigraphic sections (where possible), facies identification, collection of hand samples, and additional notes on any unique or distinguishing features.

6.1.1 Sacagawea Peak Outcrops

A total of four days were spent mapping the Sacagawea Peak bioherms. These bioherms were meticulously mapped by Stone (1971) over an eight-week period. Consequently, the four days mapping the Sacagawea Peak bioherms were spent comparing Stone’s observations to those made for this study.

A total of three bioherm cores are present at Sacagawea Peak, and are all located on the same stratigraphic level as noted by Stone (1971, 1972). The Lodgepole Formation at Sacagawea Peak is generally striking north-northwest at 025° and dipping at angles ranging from 70° to 75° to the east. Stone (1971, 1972) noted that the bioherms at Sacagawea Peak occur approximately 116 feet above the base of the Lodgepole Limestone. Of the three bioherms present at Sacagawea Peak, the northernmost bioherm, bioherm I, consists of 5 separate exposures and is believed to be connected below the scree (Figure 6.1). The middle bioherm, bioherm II, consists of two separate
exposures and is also believed to be connected below scree level. The southernmost of the three Sacagawea Peak bioherms, bioherm III, is a single continuous exposure.

Figure 6.1 Aerial photograph of bioherms I, II, and III located at Sacagawea Peak. Bioherm I is comprised of 5 separate exposures, bioherm II of two separate exposures, and bioherm III is comprised of a single exposure.

The three Sacagawea Peak bioherms vary in both thicknesses and breadth. Bioherm I was found to have a maximum stratigraphic thickness of 59 feet and a breadth of approximately 529 feet. Bioherm II is 24 feet thick and has a breadth of approximately 300 feet. Bioherm III was estimated at being 30 to 40 feet in maximum thickness and a breadth of approximately 500 feet (Stone 1971, 1972). Both Stone (1971, 1972) and this author acknowledge that all three of the
Sacagawea Peak bioherms are dome shaped with a planar base if restored to the original depositional positions. Furthermore, the bioherms are all concave downward at the point of their maximum stratigraphic thicknesses and have relatively planar bottoms (Figure 6.2).

![Photo of bioherms I, II, and III located at Sacagawea Peak looking southward. The bioherms are easily distinguished by their prominence from the surrounding Lodgepole Limestone and their distinct light-gray color.](image)

Figure 6.2  Photograph of bioherms I, II, and II located at Sacagawea Peak looking southward. The bioherms are easily distinguished by their prominence from the surrounding Lodgepole Limestone and their distinct light-gray color.

### 6.1.2 Saddle Peak Outcrops

A total of 5 days were spent mapping the Saddle Peak bioherms. Prior to this field work, these bioherms had never been studied in detail. Their existence was noted by Stone (1971), who had observed them from a distance and concluded that they may be Lodgepole bioherms. With
the aid of aerial imagery, two high-relief bodies were identified in the general area mentioned by Stone (1971), prior to field work.

There are two bioherms at the Saddle Peak location, bioherms I and II, respectively (Figure 6.3). Bioherm I is the northernmost of the two bioherms with bioherm II located 0.24 miles south of bioherm I. The bioherm-enclosing strata of the typical Lodgepole Formation at the Saddle Peak location is generally striking northward, ranging from 350° to 020° and dips nearly vertical, ranging from 75° to 87° to the east. The base of the bioherms is obscured by scree so it isn’t possible to determine their exact heights from the base of the Lodgepole.

Figure 6.3 Photograph of the Saddle Peak bioherms I and II taken from Saddle Peak looking southwards. Bioherm I is visible, though partially camouflaged by abundant pine trees. Bioherm II is easier to distinguish as it is relatively free of any vegetation.
Bioherm I has a maximum exposed thickness of approximately 74 feet and a breadth of approximately 146 feet. Bioherm II has a maximum exposed thickness of approximately 25 feet and a breadth of approximately 160 feet. Though similar in breadth, the maximum thicknesses are noticeably different between the two bioherms. This difference in thicknesses can easily be seen in plan view (Figure 6.4).

Figure 6.4 Plan view image of bioherms I and II. The high dip angle in the area makes it possible to see the cross-sectional geometry of the bioherms in plan-view photographs. Bioherms I and II are approximately the same width though bioherm I is much thicker at 74 feet compared to 25 feet in bioherm II.

This contrast in thickness is attributed to the more highly variable geometry of bioherm I compared to bioherm II. Bioherm II appears as a single, relatively lenticular body with the long axis in the north-south direction, while bioherm I appears as several bodies with the long axis generally in the north-south directions. The multiple exposures of bioherm I are believed to be due to weathering and erosion of a single lenticular body similar to that of bioherm II, over time. Evidence for this greater degree of weathering and erosion is the larger amount of vegetation
present on bioherm I. This vegetation includes trees in excess of 20 feet with complex root systems interacting with fractures present in the outcrop (Figure 6.6).

Similar to the Sacagawea Peak bioherms, the Saddle Peak bioherms are dome shaped in cross-sectional view (Figure 6.5). Additionally, the Saddle Peak bioherms also are all concave downward (or convex upward) at the point of their maximum stratigraphic thicknesses and have relatively planar bottoms. As stated previously, the bioherms at Sacagawea Peak occur approximately 116 feet above the base of the Lodgepole Limestone (Stone 1971). The exact height of the basal biostrome facies above the base of the Lodgepole Formation at the Saddle Peak outcrops, however, is unknown due to cover. Although, based on similarities between the Sacagawea and Saddle Peak outcrops, it is believed that the mounds at Saddle Peak are of similar stratigraphic height above the base of the Lodgepole Formation.

Figure 6.5 Aerial photograph looking directly down towards bioherm I. The generalized outline of the bioherm is highlighted with the top of the flank facies (green), top of the outer core facies (red), top of the inner core facies (blue) and the top of the planar basal biostrome facies (orange).
6.2 Subsurface – Stark County, North Dakota

Mapping within Stark County, North Dakota involved correlating horizons from the Lower Bakken Shale of the Bakken Formation through the Lodgepole Formation in a total of 77 rasterized
The primary logs used for correlation purposes were gamma ray (GR), density porosity (DPHI), and neutron porosity (NPHI). Mounds were most easily identifiable using GR logs, as a typical gamma ray response for the Lower Lodgepole is approximately 30-40 API units. While in the presence of a mound, the gamma ray response is approximately 5 API units (Figure 6.7).

The mounds in Stark County reach upwards of 300 feet in thickness. Based on wells with mound penetrations and offsets without mound penetrations, the margins of the mounds in Stark County have dips of upwards of 40 degrees. These steeply dipping margins, combined with depositional reliefs upwards of 300 feet, made locating mounds difficult initially.

Mapping the underlying Upper Bakken Shale is of particular interest when looking at the available subsurface data in Stark County. Particularly, the focus was on areas with anomalously thick Upper Bakken Shales, and their locations relative to the presence of overlying Lodgepole mounds. Mapping showed that generally, in the absence of an overlying Lodgepole mound, the Upper Bakken Shale maintained a relatively consistent thickness, ranging from 10 to 13 feet thick. In the presence of a Lodgepole mound, the underlying Upper Bakken Shale significantly increases in thickness from the typical 10 to 13 feet, up to 50 feet, although thicknesses are generally about double (Figure 6.8). With mound margins dipping upwards of 40 degrees and depositional reliefs upwards of 300 feet, these mounds can seemingly appear and disappear very quickly in the subsurface (Figure 6.9). This can be observed in Figure 6.10, where cross section A-A’ depicts four wells in the Dickinson Field area of Stark County, North Dakota. It is important to note that the A-A’ cross-section is datumed on the top of the Three Forks. This was done as the overlying Lower Bakken Shale and Middle Bakken members of the Bakken Formation have consistent thicknesses while the Upper Bakken Shale varies in thickness. Consequently, this cross-section
shows the important increase in thickness and maintains the consistent thicknesses of the underlying Middle Bakken and Lower Bakken Shale members.

Figure 6.7 Two petrophysical logs showing typical log responses of the typical Lodgepole (left) and when in the presence of a mound (right). Note lower API GR response in the mound facies.
Upper Bakken Shale Isopach

Figure 6.8  Upper Bakken Shale isopach map from Stark County, North Dakota. Typical Upper Bakken shale is 10 to 13 feet but significantly increases in thickness in the presence or near the overlying Lodgepole carbonate mounds (compare with Figure 6.9). Map was created using IHS Petra.
Figure 6.9 Lodgepole carbonate mound isopach map from Stark County, North Dakota. Color filled contours range from 140 feet to 360 feet thick. It is important to note the significant amount of interpolation by Petra in areas where there is little to no well control. This was dealt with by utilizing control points where it was known that no mounds are present, where no wells with logs were available. Map was created using IHS Petra.
Figure 6.10  Stratigraphic cross section A-A’ showing four wells in Dickinson Field. The four wells include (from southwest to northeast) Conoco’s Shjeflo-84, Conoco’s Kadramas-75, Conoco’s Dickinson State-74, and Conoco’s Filipi-76. The Shjeflo-84 and Filipi-76 did not produce from the Lodgepole while the Kadramas-75 and Dickinson State-74 have produced prolific amounts of oil. Note the distances between wells as well as the thickening of the underlying Upper Bakken Shale when the Lodgepole mound facies is present above. Cross section is flattened on the top of the Three Forks Formation.
The southwestern-most well, the Conoco Shjeflo-84, encountered 23 feet of Upper Bakken Shale and no Lodgepole mound. The next well, the Conoco Kadramas-75 well is 0.5 miles (northeast) from the Shjeflo-85, and has 43 feet of Upper Bakken Shale and 284 feet of overlying Lodgepole mound strata. Conoco’s Dickinson State-74 well is 0.57 miles northeast of the Kadramas-75, and is comparable to the Kadramas-75 well. The Dickinson State-74 encountered 40 feet of Upper Bakken Shale and 303 feet of overlying Lodgepole mound strata. The northeastern-most well in the cross-section, is Conoco’s Filipi-76 well, which is 0.54 miles east-northeast of the Dickinson State-74 well. The Filipi-76 is similar to the Shjeflo-84 well, with a more typical section of Upper Bakken Shale totaling 16 feet. Additionally, the Filipi-76 well did not encounter the Lodgepole mound strata. With this in mind, the Shjeflo-85 and Filipi-76 wells did not produce any hydrocarbons from the Lodgepole. The Kadramas-75 and Dickinson State-74, however, have produced 4.08 million barrels and 3.10 million barrels of oil, respectively (Table A.1).

While thickness variations of the Upper Bakken Shale and the presence of Lodgepole mounds are significant, it is also important to note the thicknesses of the Middle Bakken and Lower Bakken Shale. Particularly, there is little to no increase in thickness, regardless of whether a Lodgepole mound is present (Figure 6.10).

Trend surface residual mapping techniques were explored when mapping the subsurface mounds. Particularly, the technique was utilized when looking at the Upper Bakken Shale and its relationship with the underlying strata and overlying Lodgepole mounds where present. This technique of mapping can be used to show significant anomalies either above or below the generated trend surface. In this case, the goal was to significantly intensify the present day structure of the Upper Bakken Shale within Stark County (Figure 6.11). In doing so, a trend
surface is first made by fitting a generated surface to a set of subsurface contour data (i.e., Upper Bakken Shale depths) in IHS Petra using multiple linear regression (Figure 6.12). This trend surface shows a monoclinal dip towards the northwest. Next, a first-order residual surface is generated by subtracting the previously generated trend surface data from the subsurface contour data (Figure 6.13). A first order residual surface was chosen as the area of focus has a relatively small lateral extent and shows zero degrees of curvature compared to 2nd, 3rd, etc orders. This trend residual surface can either show positive or negative thicknesses. That is, if a subsurface contour data point is shallower than the trend surface, it will result in a positive thickness anomaly on the trend residual surface. Alternatively, if a subsurface contour data point is deeper than the trend surface, it will result in a negative thickness anomaly on the trend residual surface.

When comparing the generated trend residual surface (Figure 6.13) with the Lodgepole mound isopach map (Figure 6.9), there is generally an overlap of the positive thickness anomalies with the locations of overlying Lodgepole mounds. This is not surprising, as cross-sections have demonstrated the strong correlation between a thick Upper Bakken Shale and the presence of overlying Lodgepole mounds. Additionally, the trend residual surface shows that the Upper Bakken Shale, underlying the majority of the Lodgepole mounds, is a paleotopographic high compared to the surrounding typically northwesterly dipping Upper Bakken Shale. If the trend residual surface map were to show a negative thickness anomaly, it would be inferred that the Upper Bakken Shale is currently a “sag”; however, this is not the case.
Figure 6.11 Upper Bakken Shale structure map in Stark County, North Dakota. The Upper Bakken Shale is generally dipping to the northwest, though localized areas of variability are present in the center of the map. Contour interval = 25 feet.
Figure 6.12  Trend surface map of the Upper Bakken Shale structure in Stark County, North Dakota. The generated trend surface map calculated that the Upper Bakken Shale is dipping at an angle of 0.61° (resulting in a 32.2 foot increase in depth every 1 miles) and striking at approximately 290°. Contour interval = 25 feet.
Figure 6.13 Trend residual surface map of the Upper Bakken Shale structure in Stark County, North Dakota. The trend residual surface map shows significant positive thickness anomalies in the center of the map upwards of 50 feet. These positive thickness anomalies correspond to the locations of overlying Lodgepole mounds. Contour interval = 25 feet.
CHAPTER 7

FACIES

Five distinct facies were identified in the Sacagawea Peak and Saddle Peak outcrops. They are the basal biostrome facies, inner core facies, outer core facies, flank facies, and the regional Lodgepole facies (Figure 7.1). Their depositional geometries, textures, skeletal constituents, non-skeletal constituents, and associated muds are discussed in the following sections.

Figure 7.1 Generalized mound geometry and facies distributions of the Sacagawea Peak and Saddle Peak outcrops. Image is not to scale.

7.1 Basal Biostome Facies

The basal biostrome facies is a tan to light-brown to light-gray crinoid and fenestrate bryozoan mottled wackestone. The basal biostrome facies is unique to the Bridger Range and is found at both the Sacagawea Peak and Saddle Peak outcrops. No evidence of a basal biostrome or basal biostrome-like facies has been identified in the subsurface in Stark County, North Dakota.

The basal biostrome maintains a nearly constant thickness, ranging from four feet at the Sacagawea Peak outcrop to three feet at the Saddle Peak outcrop, which is nearly 7.5 miles away (Figure 7.2). The basal biostrome facies is present directly below the lower core facies of the bioherms and is underlain by the Paine Member of the Lodgepole Formation. The exact height of
the basal biostrome facies above the base of the Lodgepole Formation is unknown due to cover. This facies has a distinct weathering profile and is well indurated in outcrop. With these characteristics, it is easily differentiated from the overlying and underlying strata. Based on field observations, the basal biostrome always underlies the inner core facies in each of the three bioherms at Sacagawea Peak and the two bioherms at Saddle Peak.

![Photo of the basal biostrome facies from Bioherm II at Saddle Peak. Thin, undulatory bedding is easily observable and often breaks into one-inch thick sheets. Rock hammer for scale.](image)

Figure 7.2  Photo of the basal biostrome facies from Bioherm II at Saddle Peak. Thin, undulatory bedding is easily observable and often breaks into one-inch thick sheets. Rock hammer for scale.

The basal biostrome facies is rich in carbonate mud that is generally light-tan to dark-tan to brown in color. The facies is thinly bedded with fine laminae that are undulatory due to the abundant amount of intact fenestrate bryozoan fronds that were deposited parallel to bedding. In hand sample, the basal biostrome is mottled, with some portions more mud-rich, while adjacent portions are richer in skeletal debris (Figure 7.3).
Fenestrate bryozoan fragments are found in all basal biostrome samples and constitute the most common skeletal grains in the facies. Fenestrate bryozoan fronds appear as either isolated zooecia arranged linearly, or as chains of connected zooecia in cross-section (Figure 7.4). These fenestrate bryozoan fronds are oriented parallel to bedding, and as mentioned previously, give this facies an undulatory bedding pattern (Figure 7.4). Crinoid fragments are the second most abundant skeletal grains found in the basal biostrome facies and are typically large. Additional minor skeletal constituents include brachiopods, mollusks (gastropods and bivalves), arthropods (trilobites and ostracods), and very minor trepostome bryozoans. The majority of these minor skeletal fragments are disarticulated. While abundant in skeletal debris, non-skeletal constituents were not recognized, potentially due to recrystallization.

Figure 7.3 General fabric of the basal biostrome facies when looking at a single bedding surface in plan view. Note the overall light-tan color and mottled appearance with some areas being more mud-rich, and other having more abundant skeletal debris. Mechanical pencil for scale.
Figure 7.4 Photomicrographs of the basal biostrome facies from bioherm II at Saddle Peak. (A) This skeletal wackestone has a diverse assemblage of fossil fragments, though the most common are fenestrate bryozoans in addition to crinoid arm plates (c) and columnals (c). (B) Characteristic cross-sectional view through one of the many fenestrate bryozoans (fb) present in the basal biostrome facies. These bryozoan fronds are often undulatory and the carbonate mud surrounding them often reflects this wavy nature. (A) Outcrop sample B2-BS-2, plane polarized light, scale bar = 1mm and (B) Outcrop sample B2-BS-1, plane polarized light, scale bar = 1mm

7.2 Inner Core Facies

The inner core facies is light gray to dark gray. It varies considerably from skeletal wackestones to mud-rich packstones, grainstones, and marine-cemented boundstones. It is present at both the Sacagawea Peak and Saddle Peak outcrops. It is generally massive and bedding is not present.

The inner core facies is directly underlain by the basal biostrome facies and is overlain by the outer core facies. The inner core facies is massive at both the Sacagawea Peak and Saddle Peak outcrops. This massive nature allows for a distinct identification of the inner core facies from the similar overlying outer core facies. While all of the outcrops have experienced extensive weathering, some areas have been more affected than others. This made it difficult to distinguish the inner core facies from the outer core facies in some cases while in the field.
The most common skeletal constituents of the inner core facies are bryozoan and crinoid fragments. Bryozoans present include both trepostome and fenestrate types. Tips of trepostome bryozoan branches up to 2 mm in size are present and are easily identified by their outward-bending zoecial walls when cut through the long axis of a branch. Fenestrate bryozoans are common and are present as linearly arranged chains and individual transverse sections with thick zoecial walls with spine-like rims, and an open zoecial aperture (Figure 7.5). Additionally, solid cross bars (dissepiments or fenestrules) from fenestrate bryozoan are present. These intact fenestrate bryozoans are preserved within an early marine cement and are believed to be bound together during deposition, thus making them boundstones. Crinoid columnals up to 6 mm in diameter and crinoid arm plates are present throughout the inner core facies. Additional minor skeletal fragments include longitudinal fragments of crenulate brachiopod shells, ostracod shells, and mollusk fragments.

Non-skeletal constituents are rare in the inner core facies. Intraclasts of wackestones are present, though rare, in some samples. Intraclasts are typically well-rounded and have sharp boundaries with the surrounding packstones and grainstones where present. These sharp boundaries may be in the form of stylolites or a skeletal-grain to intraclast interface. The wackestone intraclasts contain small fragments of fenestrate bryozoans, minor crinoids, and minor ostracods.

With the variability in overall lithology of the inner core facies from mud-rich packstones to grainstones to boundstones, dramatic fluctuations in mud content are also present from thin section to thin section (Figure 7.5). Grainstone samples generally have a complete absence of mud while packstone samples contain significant amounts of mud. Other samples from the inner core
facies are grain-supported, though they have rounded clasts of fine-grained mud surrounded by the
grain-supported skeletal material.

![Image of photomicrographs](image)

Figure 7.5 Photomicrographs of the inner core facies from bioherm II at Saddle Peak. (A) Fenestrate bryozoan fronds are intact and were bound together during deposition by early marine cement. (B) The texture of the inner core facies can vary from boundstones (A) to mud-rich packstones (B). (A) Outcrop sample B2-IC-1, plane polarized light, scale bar = 1mm and (B) Outcrop sample B2-IC-1, plane polarized light, scale bar = 1mm

### 7.3 Outer Core Facies

The outer core facies is a light-gray to dark-gray crinoidal and bryozoan wackestone to mud-rich packstone to grainstone. It is present at both the Sacagawea Peak and Saddle Peak outcrops. Bedding is present within the outer core at the Sacagawea Peak outcrops, which made differentiation between the inner core and outer core facies quite simple. This was not the case with the Saddle Peak outcrops, as the outer core facies is a more massive to slightly bedded.

Because of the unique weathering and erosion profile of bioherm I at Saddle Peak, a considerable amount of time was spent trying to determine where to place the contact between the inner core and outer core facies. Consequently, it was important to look at not only the differences in bedding, but particularly at compositional differences between the two facies.
The outer core facies is similar to the inner core facies based on overall fabrics and their varieties. However, there are several differences between the two. In hand sample, the outer core facies appears to be overall fine-grained. Samples are typically light-gray to dark-gray on a fresh surface. The overall fabric of the rock appears to be very crystalline with minor large crinoid columnals present throughout. The most common skeletal constituents found in the outer core facies are fenestrate bryozoan fragments. As with other facies, fenestrate bryozoans can often be present as linearly arranged chains, as well as individual isolated transverse sections. Crinoids are the second most common skeletal constituent. Crinoid fragments include arm plates and columnals. Additional minor skeletal constituents include articulated and disarticulated ostracods, articulated and disarticulated bivalves, brachiopod spines, trilobite carapaces, and trepostome bryozoans are present, though rare. As with the inner core facies, non-skeletal constituents are rare in the outer core facies. One major difference between the outer core and inner core is the increased fauna diversity in the outer core. It is important to consider, however, that this observation is made based on a limited number of hand samples that were able to be retrieved.

While fine-grained carbonate mud is present in the outer core facies, it is significantly less than that of the inner core facies. Carbonate mud is found as disseminated material between regions of grain supported material (i.e., matrix). As with the inner core, some samples are predominately grainstone while others have a significant amount of grains in the presence of this disseminated carbonate mud (Figure 7.6). Additionally, similar to the inner core facies, some samples are abundant in early diagenetic calcite cement that will be discussed later. This cement bound the fenestrate bryozoans, crinoids, and other skeletal fragments at the time of deposition, resulting in boundstones (Figure 7.6). The boundstones that were built by these organisms experienced early cementation to enhance the nature of this facies’ fabric.
7.4 Flank Facies

The flank facies is a light to dark-gray bryozoan, crinoidal, mud-rich packstone to grainstone. The majority of grainstones present in the flank facies are typically comprised largely of crinoid fragments, and by historical definition, would be considered an encrinite. It is present at both the Sacagawea Peak and Saddle Peak Outcrops.

Generally, the flank facies in outcrop is thinnest at the crests of the mounds, when present, and thickens away from the crest and towards the edges of the mounds (Figure 7.1). Present at Sacagawea Peak, Stone (1971) noted that the flank facies was “present locally on the core tops as a bed less than one foot thick and increases to over 20 feet thick between bioherms II and III”. This change in thickness was also present at the Saddle Peak bioherms where the flank facies was present at the top of bioherm I as a 0.5 foot thick bed and increased in thickness up to

Figure 7.6 Photomicrographs of the outer core facies from bioherms II and I, respectively, at Saddle Peak. (A) Abundant fenestrate bryozoan fragments and crinoid debris make up this packstone. Note the presence of fine-grained mud in the top right as well as the disseminated mud in the center of the photomicrograph. (B) Early marine cemented boundstone comprised entirely of fenestrate bryozoan fronds (fb). Radial-fibrous cement surrounds frond and equant calcite cements fills voids (A) Outcrop sample B2-OC-1, plane polarized light, scale bar = 1mm and (B) Outcrop sample B1-OC-2, plane polarized light, scale bar = 1mm
approximately 10 feet between the two bioherms. However, the flank facies was not present on top of bioherm II based on lack of deposition as compared to weathering of the outcrop.

In hand sample, the flank facies is light to dark-gray in color. A weathered sample provides an adequate overview of the primary constituents due to the skeletal constituents being less likely to erode compared to the mud present. It is coarse grained with crinoid fragments reaching up to 8 mm in diameter with an average diameter of approximately 1 to 2 mm. On a fresh surface, the rock is crystalline, with minor preferential oxidization of skeletal constituents. Thin bedding is present in some samples.

Crinoid fragments are the most common skeletal constituents found within the flank facies (Figure 7.7). The crinoid fragments are generally columnals or arm plates. They are easily identifiable, as optically, they act as a single crystal of calcite and display unit extinction. Commonly, the internal micropores of the crinoid fragments are filled with micritic carbonate, resulting in a dusty or cloudy appearance. Upon closer magnification, this internal micritic carbonate within the pores is more uniformly oriented, resulting in a checkerboard appearance.

Fenestrate bryozoan fragments are the second most common skeletal constituent found within the flank facies. While considerably less abundant than crinoid fragments, fenestrate bryozoan fragments are commonly found in localized pockets. The fenestrate bryozoans are generally found as isolated zooecia. Intact and linearly arranged chains are present, though rare. Trepostome bryozoans are rare, though are present and are commonly present as transverse sections in thin sections cut perpendicular to bedding. Additional minor skeletal constituents include mollusks (gastropods and bivalves), brachiopods, and arthropods (trilobites and ostracods). While abundant in skeletal debris, the flank facies is lacking in non-skeletal constituents.
Mud content in the flank facies varies greatly from sample to sample. Where grainstones are present in the flank facies, mud is relatively rare and is only found in the interparticle voids between the numerous crinoid and rare fenestrate bryozoan fragments. Other samples of the flank facies that are mud-rich packstones, have a higher abundance of mud (Figure 7.8).

Figure 7.7 Photomicrographs of the flank facies from bioherm II at Saddle Peak. In this characteristic grainstone flank facies sample, the crinoid fragments are coarse and often sutured. (A) Outcrop sample B2-FF-1, plane polarized light, and (B) cross-polarized light, scale bars = 1mm

Figure 7.8 Photomicrographs of the flank facies from bioherm II at Saddle Peak. The variability of the flank facies from a crinoidal grainstone to a mud-rich packstone is easily seen. A wide variety of skeletal fragments are present. They include crinoids, fenestrate bryozoans, trilobite carapaces, brachiopods, ostracods, etc. (A) Outcrop sample B2-FF-2, plane polarized light, and (B) cross-polarized light, scale bars = 1mm
7.5 Regional Lodgepole Facies

The regional Lodgepole facies is made up of typical non-mound Lodgepole strata. It is considered as any and all Lodgepole strata that encompasses (both above and below) the mounds where present, or is deposited where mounds are not present. It is typically a gray to dark-gray argillaceous mudstone to skeletal wackestone.

In outcrop, the regional Lodgepole facies is thinly-bedded and weathers into flaggy scree that litters the mountainside. The fine-grained micrite that makes up the mudstones and wackestones is dark gray to charcoal in color.

Though most commonly a mudstone, wackestones containing a variety of skeletal debris are also present. The most common constituents are crinoids, brachiopods, and bryozoans, though ostracods and trilobite carapaces are also present in minor proportions. Very thin wispy shale laminae are also present. Aside from skeletal fragments, mudstones and wackestones of the regional Lodgepole facies are generally lacking in any non-skeletal fragments. However, fine-grained disseminated pyrite has been noted.

7.6 Subsurface Stratigraphy and Lithology

Three distinct facies are associated with the subsurface mounds in Stark County, North Dakota. They are the mound core facies, flank facies, and the regional Lodgepole facies. It is important to note that the characteristics of these facies are based on available core, core photos, thin sections, photomicrographs of thin sections, personal discussions with other scientists, and observations made by scientists in the past.

7.6.1 Mound Core Facies

The mound core facies is the facies that acts as the hydrocarbon reservoir for the producing Stark County mounds. It is a light-tan to light-gray to dark-gray skeletal grainstone to marine-
cemented boundstone. This early cementation allowed for a rigid framework that allowed for subsequent cementation to occur, occluding a large amount of primary porosity. Intervals from the mound core facies are present in several cores located at the North Dakota Geological Survey in Grand Forks, North Dakota. Of particular interest are the Knopik #1-11, Kadramas #75 cores as they have continuous intervals of the mound core and both prolific hydrocarbon producers. The mound core facies can be up to 300 feet thick in some areas and can be non-existent in other areas, depending on mound growth geometries. The mound core has a highly variable texture and generally, is comparable to the inner and outer core facies of the outcropping Bridger Range mounds.

Depositional geometries of the mound core facies vary from location to location. However, the facies is overall massive and poorly bedded. The more common massive character of the mound core facies can be characterized by the chaotic and disordered positions of skeletal debris. Localized portions are well-developed bedding, though this is not the typical appearance of this facies. Concentrated, coarse skeletal debris allows for easier identification of this bedding. The attitudes of bedding are generally horizontal, though minor and localized dips of up to 5° are noted.

The mound core facies varies in color considerably. It ranges from a light-tan to beige in the Knopik #1-11 core to a light and dark-gray in the Kadramas #75 core. Stromatactis structures and vugs are abundant in this facies and can be found to be extensively interconnected (Figure 7.9). These stromatactis structures are not present in any other facies (neither outcrop nor subsurface). The stromatactis structures typically have a semi-planar base and a digitate roof (Figure 7.9). Fenestrate bryozoan fronds that have been deposited perpendicular to growth position can often be seen through transverse sections showing their linear chains of zooecia.
Figure 7.9 Core photo from the Knopik #1-11well at a depth of 9761 feet. Stromatactis structures and vugs are common in the mound core facies. These voids provide a significant amount of the porosity present in the mound core. Core photo provided by the NDIC.

The mound core facies is abundant in skeletal debris. Crinoid fragments are the most common skeletal constituent present, with additional constituents including fenestrate bryozoans, brachiopods, gastropods, ostracods, rugose corals, and rare foraminifers. Crinoid fragments vary from very small fine-grained columnals or arm plates to large articulated stems. The fenestrate bryozoan fragments are not preserved in growth position, but rather the largely intact fronds are laying perpendicular to growth position. Many of the brachiopods are articulated and some remain open and are the sites of intraparticle porosity, while others have been completely infilled with cement. While not visible with the naked eye, ostracods are present and generally articulated, though fragments are also present (Figure 7.10). Intact rugose corals are visible in core, typically
as dense colonies, but also as solitary corals. Regardless, their overall abundance is minimal compared to the other skeletal constituents. Endothyrid foraminifers were present in the Knopik #1-11 photomicrographs available from the NDIC. While abundant in several thin sections in this core, they have not been observed in other cores, nor have they been observed in outcrop. Stone (1971) specifically stated that foraminifera are “notable in their absence” in his study of the Sacagawea Peak outcrop. This facies is devoid of any non-skeletal constituents.

Figure 7.10 Photomicrograph from the upper portion of the mound core facies in the Knopik #1-11 core. Several articulated ostracods with intraparticle porosity are cemented inside of a brachiopod fragment by equant marine calcite. This abundance of intraparticle porosity and skeletal material is typical of the skeletal grainstones of the mound core facies. Subsurface sample from the Knopik #1-11 well at a depth of 9766 feet, plane polarized light, scale bar = 0.5 mm. Photomicrograph provided by Mark Longman.

At first glance, it appears that there is abundant mud in the mound core. However, upon closer inspection one will see that this fine-grained material is actually very fine skeletal debris. With that in mind, mud is rare in the mound core facies. Its lack of presence was noted by Longman (1996) and Adams (1999). Additionally, unique to the mound core facies is the large
quantity of intraclasts within the overall massive framework of the mound core facies (Figure 7.11). These intraclasts are typically elongate and are fine-grained compared to the surrounding material. It has been noted by Longman (2016, pers. comm.), that these fine-grained intraclasts may be remnants of early microbially cemented “crusts”. These intraclasts are noted in their absence from the flank facies as well as the regional Lodgepole facies.

![Core photo from the Knopik #1-11 well at a depth of 9762 feet. Abundance of the light-gray, fine-grained, and tabular intraclasts within the overall coarser skeletal grainstone. Photo available online via the NDIC.](image)

**Figure 7.11** Core photo from the Knopik #1-11 well at a depth of 9762 feet. Abundance of the light-gray, fine-grained, and tabular intraclasts within the overall coarser skeletal grainstone. Photo available online via the NDIC.

### 7.6.2 Flank Facies

The flank facies of the subsurface mounds is comparable to the flank facies of the outcropping mounds in the Bridger Range of Montana. It ranges from a light to dark-gray skeletal wackestone to packstone to predominantly crinoidal grainstone with other minor skeletal constituents present. The flank facies is present through the Patterson #1-24 core and the Steffan
The flank facies is commonly bedded with alternating layers of coarse crinoid debris separated by more fine-grained skeletal debris. Thin shaly partings are abundant and commonly separate the coarse crinoidal grainstones from the more fine-grained wackestones and packstones (Figure 7.13). This facies is well bedded in many areas and is commonly found to be dipping away from the mound core. Bedding tends to be well preserved and dips high as 40° are not uncommon, though it is more commonly found to be dipping anywhere from 10° to 30° as recognized in core and dipmeter logs.

The flank facies is largely comprised of crinoid fragments. These fragments range in size from centimeter diameter columnals to millimeter and sub-millimeter diameter columnals. These columnals have been found to be articulated and in some case, upwards of 5 cm in length. Bryozoans are present and can commonly be seen in core. Particularly, fenestrate bryozoan fronds, which were deposited perpendicular to growth position, are present as they are commonly on the boundary where pieces of core are broken. Brachiopods are present, though are considerably less common than crinoids and bryozoans.

Very fine-grained chert is present within the flank facies. Particularly, it is present at the base of the Patterson #1-24 core. Here, it is found with the very fine-grained skeletal debris present, in addition to the very fine-grained carbonate mud, all of which is dipping at a low angle. Adams (1999) identified lenses of chert in her analysis of the Frenzel #79 core. Aside from this chert, no additional large quantities of chert are present in the Patterson #1-24 core. A single irregular nodule of disseminated pyrite is present approximately 1 inch from the basal contact with the
Upper Bakken Shale within the Patterson #1-24 core. The pyrite spans the entire width of the core slab and was the only observed instance of pyrite in the core (Figure 7.12).

The abrupt contact between the flank facies and the underlying Upper Bakken Shale can be seen in the Patterson #1-24 core (Figure 7.12). At this contact, the fine-grained crinoidal wackestone of the flank facies contains the nodular pyrite spanning the width of the core, overlying the black organic-rich Upper Bakken Shale.

Carbonate mud is present in the flank facies to varying degrees. It can clearly be seen within the steeply dipping and alternating skeletal wackestones and packstone beds in conjunction with the crinoidal grainstone beds (Figure 7.13). Longman (1996) observed “poorly sorted skeletal fragments in a micritic and argillaceous matrix” in his analysis of the Frenzel #79 core.

Figure 7.12 Core photo from the Patterson #1-24 well at a depth of 9974 feet showing the abrupt contact between the underlying Upper Bakken Shale and the overlying flank facies. The flank facies present at this contact is a crinoidal wackestone with abundant pyrite. The Upper Bakken Shale is black and organic-rich. Photo available online via the NDIC.
Figure 7.13  Core photo from the Patterson #1-24 well at a depth of 9947 feet showing dipping beds of crinoidal grainstones with abundant shaly partings. These shaly partings often mark boundaries between grainstones and the finer-grained wackestones and packstones. Photo available online via the NDIC.

7.6.3  Regional Lodgepole Facies

The regional Lodgepole facies in Stark County, North Dakota, mirrors that of the regional Lodgepole facies in outcrops of the Bridger Range. It is a gray to dark-gray to charcoal colored argillaceous mudstone to skeletal wackestone. Skeletal constituents include crinoids, bryozoans, brachiopods, and ostracods. Wispy shale laminae are also present (Figure 7.14). It acts as the seal for the mound core facies, which is the hydrocarbon reservoir in the producing Stark County mounds.

The Patterson #1-24 core contains one of the best preserved contacts with the regional Lodgepole facies and the underlying mound core facies (Figure 7.15). Here, the regional
Lodgepole mudstone is slightly dipping around 5°. It is interbedded with the same light colored and fine-grained microbial crusts that were present in the mound core facies.

Figure 7.14 Photomicrographs of the typical carbonate mudstones and skeletal wackestones of the regional Lodgepole facies from the Patterson #1-24 well. (A) Skeletal wackestone with homogeneous carbonate mud matrix. (B) Carbonate mudstone to wackestone with minor crinoid debris, (c) in addition to wispy shale laminae (wsl) throughout. (A) Subsurface sample 9783.5’, plane polarized light, and (B) Subsurface sample 9802.5’, plane polarized light, scale bars = 1mm.
Figure 7.15  Core photo from the Patterson #1-24 well at a depth of 9806 feet showing the contact between the regional Lodgepole facies and the underlying mound core facies. The slightly dipping dark carbonate mudstone of the regional Lodgepole facies is interbedded with the mound core facies. Photo available online via the NDIC.
CHAPTER 8
DIAGENESIS

The diagenesis of carbonate sediments includes all events that affect sediments from the
time of deposition at the sea floor, though burial, and into late subaerial exposure. In the following
chapter, detailed observations regarding diagenesis in both the outcropping mounds in Montana
and the subsurface mounds in North Dakota are described. Diagenetic aspects include cements,
stylolites, stromatactis structures, replacement silica, and dolomite. Methods used for observations
include optical petrology, cathodoluminescence petrography, scanning electron microscopy, and
observations made from core.

8.1 Cements

The precipitation of cements in carbonate sediments is a major diagenetic process and takes
place when the pore fluids present are supersaturated with respect to the cement phase and there
are no kinetic factors that can inhibit the precipitation of said cement (Tucker and Wright, 1990).
A variety of different types of cements are present in both the bioherms outcropping in Montana
and those in the subsurface of Stark County, North Dakota.

8.1.1 Outcrop

Radial-fibrous and equant-crystalline calcite cements are the two most common cement
types present. Radial-fibrous cement is present throughout all facies and is distinguishable by its
column to needlelike shape and perpendicular growth with respect to the substrate on which it
forms on. Additional diagnostic characteristics of radial-fibrous cement include a length to width
ratio of at least 6 to 1 (Folk, 1965) (Figure 8.1). This radial-fibrous cement is commonly found
coating skeletal grains and lining fractures. Cathodoluminescence in the Saddle Peak outcrops is
generally homogeneous. While samples may look interesting in transmitted light with the varying types of skeletal fragments and cements, this is not the case when looking under cathodoluminescence. Typically, the luminescence is moderate to dull with little variation throughout the samples. Skeletal grains with radial-fibrous cement are easily identified in transmitted light, although under cathodoluminescence, the fabrics are essentially obliterated by what is believed to be a single diagenetic event during which the fabrics were homogenized during recrystallization at some point (Figure 8.2).

Equant-crystalline mosaic calcite cement is common throughout all facies in both outcrops and in the subsurface (Figure 8.3). This cement is typically void-filling and pore-lining. Consequently, it is found filling in what was once interparticle porosity, intraparticle porosity, fractures, etc. This equant-crystalline cement is characterized by the generally equant and anhedral to subhedral crystals. Additionally, equant-crystalline calcite is characterized by its length to width ratio of less than 1.5 to 1 (Folk, 1965). These crystals increase in size, with the smallest crystals originating at the point of nucleation and increasing outwards from the point of nucleation (Figure 8.4). Equant calcite cement is often found surrounding skeletal grains that have coatings of radial-fibrous cement (Figure 8.5).

Pseudo-peloidal microcrystalline cement is present in both the inner core and outer core facies of the outcropping bioherms. This cement was noted by Longman and Cumella (2016) in their study of the subsurface mounds. By definition, peloids are allochems that are made of “cryptocrystalline or microcrystalline calcium carbonate with no restrictions on the size or origin of the grains”, (McKee and Gutschick, 1969). The pseudo-peloidal cement has a uniformly small particle size and relatively consistent shape and size (Figure 8.6 and Figure 8.7). Areas exist where the pseudo-peloidal cement is not as homogeneous in size and shape, though still believed to be
pseudo-peloidal, exhibiting a clotted texture. This cement is typically darker in color than the surrounding material and is often found in localized masses. While present in several outcrop samples, this type of cement is not particularly common when compared to the radial-fibrous and equant calcite cements that more commonly occur.

Syntaxial calcite overgrowth cements are abundant in the flank facies and less so in the inner and outer core facies of the Sacagawea Peak and Saddle Peak outcrops in the Bridger Range. These syntaxial overgrowths form around skeletal fragments that act as single crystals of calcite or are monocrystalline. Echinoderm fragments, specifically crinoid fragments, are the most common hosts for syntaxial overgrowths in the bioherms. These syntaxial overgrowths are in optical/crystallographic continuity with their skeletal hosts. Though optically continuous, the original crinoid host fragments are distinguished from the overgrowths by their darker and cloudy appearance in plane polarized light (Figure 8.8). In the grainstone portions of the flank facies, where the primary constituent is crinoid fragments, the syntaxial overgrowths converge with one another and their respective boundaries are more easily distinguishable (Figure 8.8). Fenestrate bryozoan and crinoid fragments with syntaxial overgrowths are surrounded by equant calcite cements as shown in plane-polarized light (Figure 8.9). Under cathodoluminescence, these skeletal fragments have a relatively dull luminescence. Luminescence of the fenestrate bryozoan fragments is homogeneous with the surrounding equant calcite cement. Alternatively, while crinoid fragments have a dull luminescence, they have thin, brightly luminescent rims (i.e., initial growth of syntaxial cements). Later portions of the syntaxial cements have uniform, moderate to dull luminescence (Figure 8.9).
Figure 8.1  Photomicrographs of radial-fibrous cement around a fenestrate bryozoan frond (fb) in the inner core facies. (A) Radial-fibrous (rf) cement grow perpendicular to the zooecial walls under plane polarized light. (B) The extent of the radial-fibrous cement is more easily observed under cross polarized light. Note the equant calcite (ec) cement surrounding the radial-fibrous cement in the rest of the photomicrograph. Outcrop sample B1-IC-1, (A) plane polarized light and (B) cross polarized light, scale bars = 500µm.

Figure 8.2  (A) Photomicrograph of a transverse section of a fenestrate bryozoan from the inner core facies taken in plane polarized light. The zooecia has been infilled with cement and the zooecial wall has been coated with radial-fibrous cement. (B) Photomicrograph taken under cathodoluminescence (CL) shows a relatively dull luminescence throughout, with very minor specks of moderate luminescence. Under CL, the boundary between the fenestrate bryozoan and the radial-fibrous rims are nearly indiscernible. Outcrop sample B1-IC-1, (A) plane polarized light and (B) plane polarized light under CL, scale bars = 100µm.
Figure 8.3 Photomicrographs of equant calcite cement in the inner core facies. Outcrop sample B1-IC-1, (A) plane polarized light and (B) cross polarized light, scale bars = 200µm.

Figure 8.4 Photomicrographs of a brachiopod spine with equant calcite cement infilling the once central canal void. The typical two-layer wall structure of a brachiopod spine, comprised of a thin and fibrous radially-oriented outer wall and a concentrically parallel inner wall is visible. Note the increasing crystal size from the inside of the walls towards the central canal. Outcrop sample B2-IC-2, (A) plane polarized light and (B) cross polarized light, scale bars = 100µm.
Figure 8.5  Photomicrographs of equant calcite cements in conjunction with radial-fibrous cement in the inner core facies. Skeletal fragments are commonly found with radial-fibrous cement rims and surrounding equant calcite mosaics. Outcrop sample B2-IC-1, (A) plane polarized light and (B) cross polarized light, scale bar = 200µm.

Figure 8.6  Photomicrographs of pseudo-peloidal micrite cement within the inner core facies. The peloidal micrite cement is surrounding fenestrate bryozoan fronds and is surrounded by equant calcite cement in areas. Outcrop sample B1-IC-1, (A) plane polarized light and (B) cross polarized light, scale bars = 1mm
Figure 8.7  Photomicrographs of pseudo-peloidal micrite cement found within the outer core facies. Pseudo-peloidal micrite cement is concentrated around and to the left of a crinoid fragment. The peloidal micrite cement is also bounded by equant calcite cement. Outcrop sample B1-OC-1, (A) plane polarized light and (B) cross polarized light, scale bars = 1mm.

Figure 8.8  Photomicrographs showing the abundance of syntaxial overgrowth cements associated with crinoid fragments in primarily the flank facies. Viewing under cross polarized light allows for easier identification of individual syntaxial overgrowths and their respective boundaries. Outcrop sample SAC-FF-1, (A) plane polarized light and (B) cross polarized light, scale bars = 1mm.
Figure 8.9  (A) Photomicrograph of crinoid fragments in transverse section through a fenestrate bryozoan frond from the flank facies taken in plane-polarized light. The crinoid fragments (hazy speckled areas) are encompassed by syntaxial overgrowth cements with the syntaxial overgrowth boundaries visible. (B) Photomicrograph taken under cathodoluminescence (CL) shows an overall dull luminescence with areas of moderate luminescence. Particularly, the crinoid fragments have thin rims of moderate luminescence indicating that initial rind of syntaxial cement is compositionally different than the remainder of the cement. Additionally, it is important to note the non-luminescent zooecial walls of the fenestrate bryozoan indicate that the bryozoan itself has not been diagenetically altered. The syntaxial overgrowth cement surrounding the crinoids and fenestrate bryozoan has a homogeneous dull luminescence, indicating that a single diagenetic event occurred. Outcrop sample B2-OC-1, (A) plane polarized light and (B) plane polarized light under CL, scale bars = 100µm.

8.1.2 Subsurface

Radial-fibrous cement is equally as common in the subsurface as it is in outcrops. A general observation made is that the radial-fibrous cement in the subsurface was found to have a larger maximum growth size compared to the smaller radial-fibrous crystals found in outcrop. Additionally, like the outcrops, radial-fibrous cements are commonly lining fractures, voids, and coating skeletal fragments (Figure 8.10).

Equant-crystalline calcite cement is also just as common in the subsurface as it is in outcrop. Coarse mosaics of this cement can be found in both the mound core facies and the flank facies of the subsurface. As observed in outcrop, the equant calcite cement is void-filling and pore-lining.
The continued growth of this cement ultimately led to a decrease in void space and subsequent porosity. The equant calcite cement is generally anhedral to subhedral.

Pseudo-peloidal microcrystalline cement is found in the subsurface mounds. It moderately abundant and considerably more abundant compared to the amount found in the outcropping mounds. This cement is similar to the pseudo-peloidal cement found in outcrop, though while it is found in localized masses in outcrop, it is observed as being much more dispersed in the subsurface (Figure 8.11). These pseudo-peloidal microcrystalline cements have been attributed to microbes that were present during the time of deposition (Longman, 1996; Morgan et al., 2012; Longman and Cumella, 2016). Morgan et al., (2012) noted that the mounds “do not exhibit classic microbial structures such as stromatolitic or thrombolytic forms”. However, they note that “the microbial signature within the mounds is in the form of small peloids that form a clotted texture”.

![Figure 8.10](image_url) Photomicrographs of what was once a larger open void that has since been infilled with predominantly radial-fibrous calcite cement, in addition to small equant calcite cement. Note that the void is horizontal and may have at one point been shelter porosity. Subsurface sample 9836’, (A) plane polarized light, and (B) cross polarized light, scale bars = 1mm.

The presence of syntaxial overgrowth cements in the subsurface is comparable with the amount present in outcrop. Syntaxial overgrowths are typical in the flank facies of the subsurface
mounds in addition to the inner and outer core facies. In areas of the subsurface where crinoid fragments are larger than those in outcrop, the syntaxial overgrowths are generally more restricted in their growth and do not extended far beyond the boundaries of the individual crinoid fragments (Figure 8.12) due to minor amounts of open pore space available.

Figure 8.11 Photomicrographs of microbially precipitated pseudo-peloidal cement. Subsurface sample from the Patterson #1-24 well at a depth of 9826 feet, (A) plane polarized light, and (A) – plane polarized light, scale bars = 1mm.

Figure 8.12 Photomicrographs showing syntaxial overgrowths on crinoid fragments that are in close proximity to one another. The syntaxial overgrowths are limited in breadth due to the neighboring fragments. Subsurface sample from the Patterson #1-24 well at a depth of 9937 feet, (A) plane polarized light and (B) cross polarized light, scale bars = 1mm.
8.2  Stylolites

Stylolites are present in both outcrop and in the subsurface. However, the amount of effects of stylolitization vary from outcrop to the subsurface.

8.2.1  Outcrop

Stylolites are equally common in both the inner and outer cores of the Bridger Range outcrops. These stylolites have allowed for concentration of insoluble organic matter along their irregular surfaces and are readily seen in thin section. In the inner core, stylolites are commonly found at boundaries between areas with predominantly equant marine calcite and areas that are much more fine-grained and mud-rich (Figure 8.13). Additionally, stylolites are commonly found to rim intraclasts of the skeletal wackestones that can be found in the inner core.

Figure 8.13  Photomicrograph of a stylolite within the outer core facies. Note the interface which the stylolite provides between the more equant calcite (center) and the fine-grained material. Outcrop sample B1-OC-3, plane polarized light, scale bar = 1mm.
8.2.2 Subsurface

Stylolites are more common in the subsurface based on observations. Additionally, the stylolites present in the subsurface tend to be larger with more insoluble material being concentrated within. As with the outcropping mounds, the subsurface mounds also have open porosity associated with the stylolites. This stylolitic-associated fracture porosity is not particularly significant though, overall, helps with the storage potential of hydrocarbons.

8.3 Stromatactis

Stromatactis and stromatactis-like structures are commonly associated with Waulsortian and Waulsortian-type mounds. Stromatactis has been defined by Heckel (1972) as “a spar filled cavity in calcilutite which has a typical flat to smoothly curved base and an irregular top that is not sheltered by rigid grains.” These stromatactis structures typically have a semi-planar base and a digitate roof.

8.3.1 Outcrop

Stromatactis or stromatactis-like structures often associated with Waulsortian or Waulsortian-type mounds were not observed at the Saddle Peak outcrops. Their absence was also noted by Stone (1972) from the Sacagawea Peak outcrops. Thin section analysis of outcrops samples also failed to reveal any stromatactis structures or evidence of past stromatactis structures. Their overall absence from outcropping mounds is significant as it is a major different between the outcropping mounds of the Bridger Range and the subsurface mounds of Stark County, North Dakota.
8.3.2 Subsurface

While not observed in outcrop, stromatactis and stromatactis-like structures are present in the subsurface mounds. In some locations, these structures are open and preserved, allowing for a significant amount of porosity. In other locations, the stromatactis and stromatactis-like structures are internally lined with radial-fibrous cement, destroying any porosity that may have been present (Figure 8.14).

![Figure 8.14](image)

Figure 8.14 Core photo from C.J. Steffan #1-35 well at a depth of 9855 feet. Visible at the top of the photos is a stromatactis cavity that has been partially infilled with radial-fibrous cement. A fraction of the original porosity associated with this stromatactis structure is still present. Photo available online via the NDIC.

8.4 Replacement Silica

Authigenic silica is found in both the outcropping and subsurface mounds. Where found, it has typically replaced calcite from skeletal fragments in varying amounts.
8.4.1 Outcrop

Chert is present in the basal biostrome, flank, and outer core facies of the Saddle Peak bioherms. The chert is microcrystalline quartz and is easily identified in thin section by its light tan to white color in plane-polarized light, and its high petrographic relief. In addition, it is distinguishable by its low first-order birefringence under cross-polarized light, resulting in conjunction with its salt and pepper appearance. Chert predominantly occurs as partial replacement of skeletal grains; however, rare patches of chert replacing equant calcite mosaics in the outer core facies are present. Crinoid columnals and arm plates constitute the most commonly skeletal grains replaced by chert (Figure 8.15). Replacement of calcite in crinoid fragments has in some cases preserved the micropores (Figure 8.16). Silicification and dolomitization occur in close proximity to one another though the relative timing between the two is unknown (Figure 8.17 and Figure 8.18).

Figure 8.15 Photomicrograph of a crinoid columnal that has undergone extensive silica replacement. The typical salt and pepper appearance of replacement silica under cross polarized light is highlighted in this photomicrograph. Outcrop sample B2-BS-1, cross polarized light, scale bar = 200µm.
Figure 8.16 Photomicrograph of silica replacement of a large crinoid fragment within the basal biostrome facies. Silica replacement is distinguishable by its high petrographic relief in thin section and by the low birefringence under cross polarized light. Outcrop sample B2-BS-1, plane polarized light, scale bar = 200µm.

Figure 8.17 SEM photomicrograph of skeletal fragment that has been preferentially replaced by both silica and dolomite. The silica replacement is concentrated around the rim while dolomitization is occurring towards the bottom of the grain and is coarser. Outcrop sample B2-IC-2, scale bar = 100µm.
Figure 8.18 SEM photomicrograph with energy dispersive x-ray spectrometry (EDS) elemental mapping. Using EDS, the elemental compositions of silica (green), calcium (purple), and magnesium (teal) are highlighted. With the highlighted elements and knowing the chemical formulas for calcite, dolomite, and quartz, these respective minerals can be mapped.

8.4.2 Subsurface

Chert is present throughout the subsurface mounds in a variety of forms. It commonly occurs in conjunction with crinoid fragments within the mound core facies, as well as within the flank facies where they have undergone extensive silica replacement. Additionally, very fine-grained chert is found within argillaceous mudstones of the typical Lodgepole facies (Figure 8.19). As with the outcropping silica, it is easily identified in petrographic thin sections by its salt and pepper appearance. No sponge spicules were observed in petrographic thin sections of subsurface mounds. However, this may be due to the dissolution of the silica associated with the sponge spicules, resulting in the chert that is observed in both thin sections and in core.
Figure 8.19 Photomicrographs showing fine-grained chert interbedded with an argillaceous mudstone. In other portions of this thin section, the chert is also interbedded with fine layers of skeletal debris. Subsurface sample from the Patterson #1-24 well at a depth of 9955 feet, (A) plane polarized light and (B) cross polarized light, scale bars = 1mm.

8.5  Dolomite

The amount of dolomite varies greatly between outcrop and subsurface. While dolomite is present in outcrop, it is regarded as a minimal amount compared to the subsurface.

8.5.1  Outcrop

Though present, dolomite occurs only rarely in the Sacagawea and Saddle Peak outcrops. The dolomite is generally isolated to the inner core facies and is commonly found as isolated rhombohedral crystals that are up to 80 microns in width (Figure 8.20). The majority of these dolomite rhombohedra have undergone some degree of dolomite dissolution, often resulting in a more stable dolomite rhombohedral core being the only remaining portion (Figure 8.21). Dolomite in the Saddle Peak outcrops is similar to that of the Sacagawea Peak outcrops, in which Stone (1972) considered dolomite to be “a component of minor volumetric importance”. Dolomite is
also observed filling in voids that were at one point open porosity (Figure 8.22). Dissolution of this void-filling dolomite is common.

Figure 8.20 Photomicrograph of several euhedral dolomite rhombohedra within the inner core facies. These particular dolomite crystals have experienced minor amounts of dolomite dissolution, as compared to the dolomite rhombohedron in Figure 8.21. Outcrop sample B2-IC-2, cross polarized light, scale bar = 1mm.

Figure 8.21 Photomicrograph of a remnant euhedral dolomite rhombohedron that has undergone some degree of dolomite dissolution within the inner core facies. The stable core remains, while the less stable outer core is no longer present. Dissolution of the outer core has allowed for the creation of secondary porosity. Outcrop sample B2-IC-2, plane polarized light, scale bar = 100µm.
Figure 8.22 SEM photomicrograph of a transverse section though a fenestrate bryozoan fragment that has been infilled with dolomite. The fine-grained, laminated, crenulated exterior of the zooecial wall is easily differentiated from the coarser surrounding calcite cement. The dolomite is filling in the zooecia and zooecial apertures. Some degree of dolomite dissolution has occurred, resulting in secondary porosity (black). Outcrop sample B2-IC-2, scale bar = 100µm.

8.5.2 Subsurface

While not common in outcrops, dolomite is prevalent in the subsurface mounds of Stark County. Particularly, baroque (saddle) dolomite is commonly found in the subsurface mounds. Baroque dolomite is distinct and easily identifiable with its curved crystal faces and undulose extinction. Baroque dolomite’s most common modes of occurrence are as (1) coarse void fills,
and (2) as a coarse replacement of precursor matrix limestone or dolomite (Moore and Wade, 2013). Baroque dolomite in the subsurface mounds is found as coarse void fills that can be sub-millimeter scale in thin section (Figure 8.23), and up to multiple centimeters in scale (Figure 8.24). Large baroque dolomite-filled vugs, like that in Conoco’s Kadramas #75 well (Figure 8.24), are common throughout the subsurface and can be observed in core photos available from the North Dakota Industrial Commission. Regardless of scale, this dolomite is found to be filling voids and reducing porosity over time.

![Photomicrograph from Conoco's Patterson #1-24 well at a depth of 9814 feet showing small-scale void-filling baroque (saddle) dolomite cements. Baroque dolomite is distinguishable by its undulose extinction and curved crystal faces. Thin section has been stained with Alizarin Red S. Subsurface sample from the Patterson #1-24 well at a depth 9814 feet, plane polarized light, scale bar = 1mm.](image)

Figure 8.23
8.6 Paragenetic Sequence

Choquette and Pray (1970) introduced the terms eogenetic, mesogenetic, and telogenetic for early near-surface, burial, and uplift/unconformity-related diagenetic processes, respectively. Stone (1971) used these terms in his synthesis of the diagenesis of the Sacagawea Peak bioherms of the Bridger Range. However, these terms are not generally used today. Instead, the terms “near surface”, “shallow burial”, “deep burial”, and “post uplift” are used.
It is clear that both the outcropping and subsurface mounds have undergone significant and varying degrees of diagenesis. These different diagenetic events significantly modified the types and distribution of porosity through time. Consequently, the paragenetic sequences for both the outcropping mounds and subsurface mounds will be considered.

8.6.1 Outcrop

The sequence of events for the outcropping mounds can be found in Table 8.1 below. Microbially precipitated carbonate cement was the first true binding agent for the skeletal debris accumulated on the mound cores. This microbially precipitated cement is in the form of peloidal to pseudo-peloidal clots that can either be very concentrated in areas, or dispersed (Figure 8.6 and Figure 8.7). Concurrently, radial-fibrous calcite cements were being precipitated from normal marine waters during mound growth. This radial-fibrous cement grew and coated grains with rims of isopachous cement. This encrustation is observed around the abundant fenestrate bryozoans (Figure 8.1 and Figure 8.5). This encrusting radial-fibrous cement grew perpendicular from the points of nucleation and in some circumstances, converged with nearby grains that also had encrusting radial-fibrous cement growing around them (Figure 8.5).

Syntaxial overgrowths of crinoid fragments are common and were formed near surface to shallow burial as evidenced by their inclusion-rich and dusty to cloudy appearances (Tucker and Wright, 1990, p. 352). Further evidence of near surface to shallow burial syntaxial overgrowths are the very thin moderately luminescent rims around crinoid fragments due to an early pore fluid that was enriched in manganese (Figure 8.9). These syntaxial overgrowths are common in the crinoidal grainstone flank facies, often encompassing entire grains and filling in any voids that may have been present at the time of deposition.
The drusy mosaics of equant-crystalline calcite may have formed in the near surface meteoric environment, in shallow burial stage, or a combination of both. These drusy mosaics are pore-filling and increase in crystal size towards cavity centers (Figure 8.1, Figure 8.3, and Figure 8.4). As small fractures formed, this equant calcite cement also filled small fractures as they propagated, likely during the burial stage (Figure 8.10 and Figure 9.4). The consistently increasing crystal size of the equant calcite cement as it fills cavities can be attributed to a single stage in which conditions did not vary dramatically.

Subhedral to euhedral dolomite rhombohedra are found as replacing fine-grained calcite matrix (Figure 8.21) and filling in voids (Figure 8.22). The exact timing of this dolomitization is uncertain, though it occurred sometime during shallow to deep burial stages. Chemical differences between inner and outer zones of individual dolomite rhombs are common and visible with CL microscopy. Following precipitation of dolomite, dissolution of the dolomite occurred. This dissolution may have been from saline waters rich in calcium. It is important to note that lack of calcite dissolution in the outcropping mounds. The chemical zoning of the individual dolomite crystals resulted in partial dissolution where the less stable outer cores dissolve and the more stable inner cores remain (Figure 8.21 and Figure 8.22). This preferential dissolution resulted in the conversion of unstable outer cores into secondary porosity that is still preserved.

Silicification, though it occurred, was not significantly pervasive. Where present, silicification is found to be replacing the calcite of large crinoid fragments where it ultimately preserves the original micropores (Figure 8.15 and Figure 8.16). The timing of this silicification is unclear given its scarcity. However, it is presumed to have precipitated in the late-shallow burial to deep burial stage.
Mechanical compaction occurred during the near surface stage of the deposition of the basal biostrome facies and later during the shallow to deep burial stages. Stylolites were produced in the mound core facies due to this mechanical compaction throughout the shallow and deep burial stages (Figure 8.13 and Figure 9.5). This is evidenced by the near surface and early cementation that lithified the material, during which compaction was minimal, followed by the eventual compaction that is now present. These stylolites transect the rock fabric, cutting across grains, cement, and matrix indiscriminately. The early precipitation of radial-fibrous cements around skeletal grains prevented significant amounts of mechanical compaction that, without these early cements, could have occurred in the inner and outer core facies. These stylolites are coated with insoluble residues and are the sites of secondary porosity.

With continued deep burial, and subsequent uplift due to the Laramide Orogeny, the Lodgepole mounds were subaerially exposed. With this exposure, the mounds underwent significant amounts of weathering, resulting in the present day outcrops.

Table 8.1 Sequence of events table for the outcropping Bridger Range mounds. Hashed lines indicate uncertain timing while solid lines indicate a more certain degree of timing for each particular event.
8.6.2 Subsurface

The early cementation of the subsurface mounds at the near surface stage in a normal marine environment in Stark County is similar to that of the outcropping mounds in the Bridger Range (Table 8.2). Microbially precipitated calcite cement was important, acting as a fine-grained binder for the abundant skeletal debris present during mound growth. Radial-fibrous calcite cements were precipitated in normal marine waters and quickly encrusted the abundant skeletal debris shortly after deposition. With the presence of stromatactis in the subsurface, these radial-fibrous cements were observed encrusting the internal vugs either partially or in some places, they completely line the vugs (Figure 8.14).

Fracturing occurred after the early cementation that occurred during the near surface and shallow burial stages. Many of these fractures filled and completely cemented (Figure 8.10). Dissolution of calcite occurred at some point during the shallow and deep burial stages. This dissolution increased secondary intraparticle porosity in skeletal debris that had previously been cemented with radial-fibrous and equant calcite cements during the near surface to shallow burial stages (Figure 9.6). It also created vuggy porosity (Figure 9.7) and allowed for enhanced fracture porosity in fractures that were once fully cemented (Figure 9.10).

Saddle (baroque) dolomite is pervasive in the subsurface. It is present as both small crystals (Figure 8.23) and large crystals (Figure 8.24) that are often void filling. Saddle dolomite can be considered a ‘geothermometer’, as it is indicative of elevated temperatures in which it is precipitated (60-150°C), as noted by Radke and Mathis (1980). The saddle dolomite precipitated during the deep burial stage and is a direct result of the elevated temperatures associated with burial. Individual dolomite rhombs are also present through the subsurface mounds. They are generally sub-millimeter scale and are euhedral to subhedral.
Solution compaction occurs in the shallow burial realm and has produced abundant stylolites. Secondary porosity is associated with these stylolites and the stylolite-associated fractures (Figure 9.9). Similar to the outcropping mounds, the early radial-fibrous and equant calcite cementation prevented significant amounts of compaction occurring in the mound core facies. The subsurface mounds were continuously buried with sediment and did not undergo any significant uplift and remained in the subsurface where they are observed today.

Table 8.2 Sequence of events table for the subsurface mounds in Stark County, North Dakota. Hashed lines indicate uncertain timing while solid lines indicate a more certain degree of timing for each particular event.

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CHAPTER 9

POROSITY EVOLUTION

During diagenesis, the mounds can either gain or lose porosity. Generally, with increasing depth of burial, there is generally a decrease in porosity (Tucker and Wright, 1990). However, processes such as dissolution and fracturing can later create porosity. The amount of porosity and types of porosity vary greatly between outcrop and subsurface. Generally, the outcrops have miniscule amounts of porosity compared to the porosity present in the subsurface.

9.1 Outcrop

Virtually all porosity that was present during time of deposition has since been filled in both the Saddle Peak and Sacagawea Peak outcrops. It is estimated that porosities of over 50% were common in the form of shelter porosity, intraparticle porosity, and interparticle porosity at the time of deposition. With the large abundance of fenestrate bryozoans, a large amount of this depositional porosity was shelter porosity. This porosity has since been filled with mosaics of equant calcite cement and radial-fibrous cement (Figure 9.1).

Gastropods, pelecypods, ostracods, brachiopods, and bryozoans account for the locations of the once abundant intraparticle porosity that was eventually filled with cement. The minor amount of porosity that remains is in the form of intraparticle and fracture porosity. The intraparticle porosity generally is found associated with fenestrate bryozoans. Specifically, the porosity present is located in the zooecia of the fenestrate bryozoans (Figure 9.2 and Figure 9.3). Fracture porosity is pervasive through nearly all mound facies present though in varying degrees (Figure 9.4). In some circumstances, it is difficult to determine whether or not the open fractures are an artifact of the thin section preparation or not.
When stylolites are present, porosity typically occurs along the boundaries of the stylolites. This stylolite-associated dissolution porosity is found along with porosity in the fractures (Figure 9.5). These types of porosities provide a significant amount of permeability in the mounds. It is important to note that while it allows for enhanced permeabilities, it is minimal compared to the amount present in the subsurface mounds of Stark County, North Dakota.
Figure 9.2 Photomicrograph of intraparticle porosity within an oblique section of a fenestrate bryozoan frond within the outer core facies. The porosity resides within the individual zooecia. Outcrop sample B2-OC-2, plane polarized light, scale bar = 200µm.

Figure 9.3: Photomicrograph of intraparticle porosity within a transverse section of a fenestrate bryozoan frond in the outer core facies. Individual zooecia such as shown above are the most common sites for remaining intraparticle porosity. Outcrop sample B2-OC-2, plane polarized light, scale bar = 100µm.
Figure 9.4  Photomicrographs of a large fracture that has been infilled with equant calcite cement in the outer core facies. Though heavily cemented, a minor amount of porosity still exists. Outcrop sample B2-OC-1, (A) plane polarized light and (B) cross polarized light, scale bars = 1mm.

Figure 9.5  Photomicrograph of stylolite-associated dissolution porosity within the outer core facies. This type of porosity is generally restricted to the inner and outer core facies. Outcrop sample B1-OC-3, plane polarized light, scale bar = 200µm.
9.2 Subsurface

Unlike the outcrops, the subsurface mounds in Stark County, North Dakota have a significant amount of preserved porosity. Types of porosity include intraparticle porosity, interparticle porosity, moldic porosity, vuggy porosity, dissolution porosity, and fracture porosity. The most common location for intraparticle porosity is within large brachiopods, ostracods, and the occasional rugose coral, as observed in core. Commonly, sites of the intraparticle porosity have had some degree of cementation occurring within the pores that diminishes the porosity to a certain extent (Figure 9.6). Interparticle porosity is present though not as common as intraparticle porosity (Figure 9.7). Moldic porosity is commonly observed in core, and less commonly observed in thin sections. Vuggy porosity is present in the subsurface mounds and absent from outcrop. The vugs can reach several centimeters in breadth (Figure 9.8) and can be found to be extensively connected. Large open fractures are present in the subsurface and are present within core. While some of these fractures may be filled with saddle dolomite, others remain open. In productive mounds, these large vugs and fractures appear to be filled with hydrocarbons. Montgomery (1995) described, “oil bleeding from all fracture and vug surfaces” from the productive Knopik #1-11 well. Vugs and fractures are interpreted to be highly connected, resulting in high permeability, and allow for the highly productive wells in Stark County. Similar to the outcrops, the subsurface mounds have stylolite-associated dissolution porosity (Figure 9.9). This porosity is present most commonly in the inner and outer core facies and is extensively connected. Dissolution porosity associated with stylolites in the subsurface is considerably more abundant than in outcrop.
Figure 9.6 Photomicrograph of a large articulated brachiopod with a considerable amount of intraparticle porosity. The brachiopod has had some internal cementation that has destroyed approximately half of the primary intraparticle porosity. The infilling cement is equant crystalline calcite. Subsurface sample from the Patterson #1-24 well at a depth of 9826 feet, plane polarized light, scale bar = 1mm.

Figure 9.7 Photomicrograph of abundant interparticle and minor intraparticle porosity within a skeletal grainstone. Large crinoid fragments are present with syntaxial overgrowths. An articulated ostracod on the right contains intraparticle porosity that has been partially occluded by internal cement. Subsurface sample from the Patterson #1-24 well at a depth of 9824 feet, plane polarized light, scale bar = 1mm.
Figure 9.8  Photomicrograph of vuggy porosity present in the Patterson #1-24 well. Subsurface sample from the Patterson #1-24 well at a depth of 9843 feet, plane polarized light, scale bar = 1mm.

Figure 9.9  Photomicrograph of stylolite induced dissolution porosity. Subsurface sample from the Patterson #1-24 well at a depth of 9843 feet, plane polarized light, scale bar = 1mm.
Results from cathodoluminescence study of the Patterson #1-24 well from Stark County, North Dakota are similar to the outcrops of the Bridger Range in Montana. Of the samples observed, they are generally homogeneous with a dull and rarely bright luminescence. As noted previously, the mounds in Stark County, North Dakota have a large amount of fracture porosity and permeability. This fracture porosity was present in both plane-polarized light and under cathodoluminescence (Figure 9.10). In plane-polarized light, the porosity is confined to the fracture. Under cathodoluminescence, the observed area has a relatively dull luminescence. Interestingly, there are areas with brighter luminescence. It is possible that at one point in time, the fracture was completely filled with calcite. As diagenesis continued, the fracture underwent partial dissolution, resulting in porosity.

Figure 9.10 (A) Photomicrograph from Conoco’s Patterson #1-24 well at a depth of 9843 feet showing a fracture filled with fibrous calcite cement growing perpendicular to the fracture wall. Open porosity is present within the fracture as seen in the light green areas. (B) Photomicrograph taken under cathodoluminescence (CL) shows the material around the fracture as having a dull luminescence. The open porosity is nonluminescent (black). Some of the fracture infilling cement has a moderate to bright luminescence. Consequently, at some point after the infilling of the fracture, the cement had undergone some degree of dissolution resulting in the fracture porosity observed. Subsurface sample 9843’, (A) plane polarized light and (B) plane polarized light under CL, scale bars = 100µm.
CHAPTER 10

DISCUSSION

In this chapter, a discussion of the previously described data, observations, and results is discussed. Table 10.1 below summarizes the general characteristics of both the outcropping mounds from the Bridger Range in southwestern Montana and the subsurface mounds from Stark County, North Dakota.

Table 10.1  Summarization of various component of both outcropping and subsurface mounds.

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<th>Component</th>
<th>Outcropping Mounds Bridger Range, Montana</th>
<th>Subsurface Mounds Stark County, North Dakota</th>
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<tr>
<td>Max. Thickness</td>
<td>74 feet (Saddle Peak) &amp; 60 feet (Sacagawea Peak)</td>
<td>300+ feet</td>
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<td>Max. Breadth</td>
<td>160 feet (Saddle Peak) &amp; 600 feet (Sacagawea Peak)</td>
<td>Multiple miles in diameter</td>
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<tr>
<td>Height Above Base of Lodgepole</td>
<td>Approximately 116 feet (Sacagawea Peak)</td>
<td>0 feet (Lie directly above Upper Bakken Shale)</td>
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<td>Mounds Underlain By</td>
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<td>Dolomite Dissolution</td>
<td>Occurred</td>
<td>No evidence that it occurred</td>
</tr>
<tr>
<td>Silicification</td>
<td>Rare-Moderately Common</td>
<td>Rare</td>
</tr>
</tbody>
</table>
10.1 Initiation of Mound Development

A combination of factors allowed the Lodgepole carbonate mounds to nucleate, and initiate mound development, resulting in the outcropping mounds of the Bridger Range in southwestern Montana and the subsurface mounds in Stark County, North Dakota.

10.1.1 Outcropping Mounds

During the early Mississippian, sediments were deposited on a carbonate ramp in southwestern and central Montana (Adams, 1999). This carbonate ramp was trending east-west and dipping towards the north in the Central Montana Trough (Figure 3.2). Stone (1971), suggests these outcropping Bridger Range mounds initiated in deep water, presumably below the photic zone. The photic zone is the depth of water that is exposed to sufficient amounts sunlight that allows for photosynthesis to occur. It is generally regarded as being the upper 70 to 90 meters of the ocean. Below the photic zone is the disphotic zone. This extends from the base of the photic zone to roughly 200 m and is where there is light (equal to or less than 1% of surface sunlight), though insufficient amounts for photosynthesis to occur. Stone (1971) noted “The Lodgepole Limestone bioherms formed in an environment below the zones of wave action and light penetration, in an open marine area of normal salinity or possibly slight restriction. Such an environment may likely have been subject to ocean bottom currents of unknown, but probably gentle intensity.” Stone (1971) did not go into detail as to how or why the basal biostrome formed. However, the character of the basal facies suggest that gentle ocean bottom currents moving around very minor paleotopographic highs and lows concentrated muds and allowed for invertebrates to thrive. Fenestrate bryozoans formed the initial colonies in the basal biostrome facies, though they were joined by colonies of crinoids and occasional brachiopods. These organisms stabilized sediment surfaces and ultimately resulted in a hard substrate that other
organisms could colonize. Wilson (1975) described a basal bioclastic wackestone pile, similar to the basal biostrome facies observed in outcrop, upon which many mounds develop. Wilson described this bioclastic pile as being formed by the mechanical accumulation of both fine and coarse sediment through currents and wave action. Furthermore, Wilson considered this basal bioclastic pile, “Probably the most important process localizing mound growth.” (Wilson, 1975 p. 367).

The outcropping mounds at both Sacagawea Peak and Saddle Peak of the Bridger Range are all underlain by this basal biostrome facies. This facies is unique to the Bridger Range and has not been identified in any other outcrop studies of the Swimming Woman Canyon mounds, nor in the subsurface. In her study of the Lodgepole mounds at Swimming Woman Canyon, Winfrey (1983) described a ‘submound facies’ that is a maximum of 20 feet in thickness and is a “yellow to pink, thinly bedded, skeletal-bearing crystalline dolomite that overlies the upper dark shale of the Cottonwood Canyon Member and directly underlies the mounds core facies.” This is distinctly different from the tan to light-brown to light-gray crinoid and fenestrate bryozoan mottled wackestones of the basal biostrome facies found at Sacagawea Peak and Saddle Peak in the Bridger Range, approximately 100 miles to the southwest.

The basal biostrome of the Bridger Range outcrops and the ‘submound’ facies of the Swimming Woman Canyon outcrop are both laterally extensive below the mounds. Stone (1971) noted that while the basal biostrome is extensive below the mounds, it is not present in a section he measured one mile north of the Sacagawea Peak outcropping mounds. In agreement with Stone (1971), data shows that these facies that underlie the mound cores may have acted as a substrate for mound growth. This is due to a distinctly different lithology of the basal biostrome, its lateral extent, and its presence below both the Sacagawea Peak and Saddle Peak bioherms.
It is important to consider that at Sacagawea Peak, the carbonate mounds are found approximately 116 feet above the base of the regional Lodgepole Formation (Stone, 1971). This is in contrast to the subsurface where the mounds occur at the base of the Lodgepole Formation. Because of abundant scree at the Saddle Peak outcrops, the heights of the mounds relative to the base of the Lodgepole Formation were unable to be determined.

10.1.2 Subsurface Mounds

Unlike the outcropping mounds, each studied subsurface mound in Stark County directly overlies an abnormally thick Upper Bakken Shale. Longman and Cumella (2016) referred to this additional package of Upper Bakken Shale as the ‘Extra Upper Bakken Shale’, though I refer to it collectively as the Upper Bakken Shale. The presence of overlying Lodgepole mounds in Stark County, North Dakota is directly related to the anomalously thick Upper Bakken Shale is directly below. A comparison of isopach maps from the Upper Bakken Shale and the Lodgepole mound facies shows that where the Upper Bakken Shale is thicker than the normal 10 to 15 feet, overlying Lodgepole mounds are present. As the Upper Bakken Shale thickens to double, or triple the normal thickness, the overall thickness of the mounds also increases. This thickening of the Upper Bakken Shale has long been associated with dissolution of the underlying Devonian Prairie salt, and is widely accepted (LeFever and LeFever, 1995; LeFever et al., 1995; Longman, 1995; Gaswirth et al., 2010; Longman and Cumella, 2016). Hundreds of feet of Prairie salts were deposited in both North Dakota and Montana, thinning towards the basin margins (Oglesby, 1988; LeFever et al., 1995). It is important to note that in mapping the Prairie salts, Oglesby (1988) showed that these salts were not deposited as far west as the Bridger Range in southwestern Montana. Rather, the depositional limit of the Prairie salts was approximately 250 miles to the east. With continued deposition of overlying Devonian strata, the Lower Bakken Shale and Middle Bakken members
were deposited regionally, followed by the first stage of Prairie salt dissolution (Figure 10.1a). In this first stage of dissolution, localized areas of the Prairie salt were removed by subsurface waters, resulting in large fluid-filled cavities within the surrounding Prairie salt. Over time, these fluid-filled cavities reached a point at which they could no longer withhold the overburden, after which the overburden collapsed. This collapse of the overburden into the fluid-filled cavities introduced additional energy which was dispersed elsewhere. Consequently, the cavity filling fluid was displaced from the cavity through fracture networks (LeFever et al., 1995). At the time of Upper Bakken Shale deposition, these syn-depositional collapse events were occurring, resulting in localized depressions, or sagging of the surface that the Upper Bakken Shale in Stark County was deposited on (Figure 10.1a,b). These localized paleotopographic lows, which resulted in an increase of accommodation space, allowed for the thickening of the Upper Bakken Shale that we see preserved in the subsurface.

Although the first stage of Prairie salt dissolution is widely accepted, what followed after is debated. One possibility is that after the localized first stage of Prairie salt dissolution that allowed for the thickening of the Upper Bakken Shale, a second stage of Prairie salt dissolution occurred (Figure 10.1c). While the first stage was localized, the second stage was more regional. This regional second stage of salt dissolution caused the area surrounding the localized thicker Upper Bakken to be paleotopographically lower, and the localized areas with thicker Upper Bakken Shales to be paleotopographically higher. LeFever and LeFever (1995) noted that the present day southern limit of the Prairie salt, located about 30 miles north of the producing Lodgepole mounds, has long been considered a depositional edge. However, after additional examination, they concluded that the southern edge is actually a result of regional dissolution. It
is possible that this second stage regional dissolution allowed for the gradual migration of the extent of the Prairie salt basinward, to the north, where it is present today.

It was on these localized Upper Bakken Shale paleotopographic highs, which are a result of two stages of Prairie salt dissolution, that the overlying Lodgepole mound growth was first initiated (Figure 10.1d). These Upper Bakken Shale paleo-highs are still present and can be seen as structural noses on a subsurface structure map of the Upper Bakken Shale (Figure 6.11). Additionally, with trend residual mapping, these structural highs are even more pronounced as positive relief (Figure 6.13). Cobb (2013) presented evidence for multi-stage collapse structures within the Bakken and Three Forks Formations associated with the underlying Prairie salt through extensive mapping. These multi-stage collapse structures resulted in localized structural inversions and thickness anomalies within these formations in Bottineau County, North Dakota, approximately 125 miles north of Stark County, North Dakota. Large basement faults were mapped and found to heavily influence Prairie salt dissolution and overlying thickness anomalies. Based on cross-sections and isopach maps, with these basement faults taken into consideration, Cobb (2013) concluded that the structural inversion observed in northern North Dakota occurred during Lodgepole time. With substantiated evidence for multiple stages of Prairie salt dissolution, resulting in localized structural inversions of the Bakken and Three Forks Formations in northern North Dakota, it is easy to consider that this may also be the mechanism for initiation of mound development in Stark County, North Dakota. This, combined with subsurface mapping of the Upper Bakken Shale, adds validity to this hypothesis.

Although the initiation of mound growth on localized paleo-highs is commonly suggested (Smith, 1977, 1982; LeFever and LeFever, 1995; LeFever et al., 1995; Sturm et al., 1997; Young et al., 1998; Adams, 1999; Gaswirth et al., 2010; Morgan et al., 2012), it has been hypothesized
that the mounds may have actually nucleated on Upper Bakken Shale paleographic lows (Gordon, 1995; Longman and Cumella, 2016).

Longman and Cumella (2016), with a plethora of previously un-published data, asserted that the subsurface Lodgepole mounds “…formed in depositional sags into which the underlying Upper Bakken Shale collapsed rather than on paleohighs.” (Longman and Cumella, 2016, p. 56). This was based largely on dipmeter data for wells within Eland Field. Longman and Cumella (2016) showed dipmeter data for three wells (the L.R. #1-10 and the Patterson #1-24, and the Ridl #1-11), with the first two being mound flank wells and the third being a mound core well. They concluded that with these dipmeter data, the Upper Bakken Shale of the mound flank wells is dipping toward the mound growth centers while the diverse dip directions of the mound cores are largely dipping in away from the mound centers of growth. This juxtaposition of Upper Bakken Shale dips with mound core dips and their relative position to one another resulted in their conclusion that the mounds formed in paleotopographic lows instead of paleotopographic highs.

Alternative to the two-stage Prairie salt dissolution theory, Longman and Cumella (2016) proposed a three stage model for Lodgepole mound formation. This three-stage theory was based on available cores, wireline logs, and image logs and is as follows:

Stage 1: Compaction waters were expelled onto the sea floor along fractures created by dissolution of the underlying Prairie salt to form springs, possibly warm, where calcium carbonate precipitated.

Stage 2: Continued growth of limestone precipitating around the springs created vertical relief on a microbially cemented hard substrate, much favored by crinoids and bryozoans. Their debris accumulated around the flanks of the mounds with dips opposite those of the underlying shales.
Stage 3: Numerous conical limestone mounds coalesced to form the Eland Field mound complex with diverse internal dips and up to 300 ft of vertical relief above the sea floor. At that point, the springs ceased flowing and eventually the micrite-rich “normal” Lodgepole argillaceous mudstones and wackestones capped the mound complex.

Their proposed first stage mirrors that of my hypothesized first stage of Prairie salt dissolution. The stage that resulted in an overall paleotopographic low, into which the Upper Bakken Shale was continuously being deposited. They added to this stage by hypothesizing that the fluid expelled during overburden collapse made its way to the sea floor via springs and was possibly warm, allowing for carbonate precipitation as the warm expelled waters meet the surrounding cooler water, using carbonate mounds in Yellowstone National Park’s Mammoth Hot Springs as a subaerial analog for this theory. These waters expelled at the subaerial Mammoth Hot Springs mounds are heated by a large, molten, underlying magma body in immediate vicinity (Bargar, 1978). There is no such evidence for any magma source of energy that would significantly thermally elevate the expelled fluids due to the first stage of Prairie salt dissolution in Stark County. Rather, one would expect the expelled fluids to be of a slightly warmer temperature due to the area’s geothermal gradient. It is important to keep in mind that Longman and Cumella (2016) merely considered that the expelled waters were “possibly” warm. With that, the exact difference in temperature between the expelled fluids and the surrounding seawater is unknown. However, based on the several hundred feet of strata between the Prairie salt and the Upper Bakken Shale, and assuming a typical geothermal gradient, the difference in temperature would not be significant. With no significant thermally elevated fluids, there would be minimal contrast in temperature between the expelled fluids and the surrounding seawater. Consequently, with no thermal contrast, calcium carbonate is less likely to precipitate out of solution.
Figure 10.1 Model for two-stage Prairie salt dissolution that allowed for mound growth in Stark County, North Dakota. (A) Deposition of the Prairie salt followed by additional Devonian strata followed by the Lower Bakken Shale, and Middle Bakken Shale. (B) First stage of localized Prairie salt dissolution limited to the Stark County, North Dakota area. During this first stage of dissolution, the Upper Bakken Shale was regionally deposited. In areas where salt dissolution was occurring, localized paleotopographic lows were created, resulting in an increase in accommodation space that allowed for a thicker section of Upper Bakken Shale to be deposited. (C) Second stage of Prairie salt dissolution was regional and resulted in the Upper Bakken Shale that was being deposited in the localized paleotopographic lows to be inverted into paleotopographic highs compared to the surrounding strata. (D) These paleotopographic Upper Bakken Shale highs were the sites of mound nucleation and the foundations upon which the Lodgepole carbonate mounds developed. (After Swenson, 1967).
It is necessary to consider the dipmeter data discussed by Longman and Cumella (2016). While these data show divergent dips between the Upper Bakken Shale and the overlying strata, it is important to recognize the spatial distribution between the L.R. #1-10, Ridl #1-11, and Patterson #1-24 wells. That is, these wells are merely single points within a roughly 6 mi² area. Additionally, these varying dips could possibly be attributed to the variability in the Prairie salt dissolution. Data suggest that the first stage of the Prairie salt dissolution was not homogeneous in rates across the entire area where the Lodgepole mounds are found. Instead, there were localized areas where the dissolution was occurring faster than neighboring areas, resulting in minor paleo-highs in an overall paleo-low during the time of Upper Bakken Shale deposition. By the second stage of Prairie Salt dissolution, the overall paleo-low was inverted, resulting in an overall Upper Bakken Shale paleo-high structure with localized areas of paleo-lows. These minor variations in paleotopography could have resulted in the variable dips shown in the dipmeter data. As mentioned previously, it is probable that these paleo-highs provided a foundation upon which organisms lived and grew.

With respect to Longman and Cumella’s (2016) seafloor springs, the concept of large quantities of fluids traveling vertically, through the hundreds of feet of strata separating the Prairie salt and the Upper Bakken Shale was suggested. Instead, it would be more reasonable that the fluids associated with salt dissolution would be more likely to move horizontally through units, as compared to traveling vertically. Oglesby (1988), concluded that the process of Prairie salt dissolution in North Dakota and Montana occurred from the top and downward, with the formations overlying the Prairie Formation supplying the aquifer waters responsible for dissolution. With that being said, we know that fractures are pervasive in the subsurface mounds and are extremely permeable. However, fracture networks or conduits in the strata between the Prairie
salt and Upper Bakken Shale, large enough to move massive amounts of water necessary to precipitate the amount of calcium carbonate present in the subsurface mounds have yet to be seen. Additionally, the expelled waters would be expected to have a very large amount of dissolved salts. These expelled waters would be relatively dense and be less likely to move vertically and be more easily moved horizontally.

10.2 Mound Growth

A brief discussion regarding how both the outcropping mounds and the subsurface mounds continued to grow and their characteristics of growth are considered below.

10.2.1 Outcropping Mounds

With the stabilized substrate of the basal biostrome facies, additional invertebrates lived, thrived, and eventually succumbed to their inevitable deaths. Their skeletal debris accumulated and was quickly cemented and lithified, resulting in the inner core facies. Along with the skeletal debris, carbonate mud was being deposited. Early cementation allowed for fenestrate bryozoan fronds to remain intact and result in some degree of shelter porosity. This shelter porosity was quickly filled in by additional marine cement (Figure 7.5). During early mound growth, intraclasts of skeletal wackestones were deposited sporadically throughout the inner core facies. These intraclasts may have been as a result of portions of the mound that were less firm than the surrounding areas and consequently more prone to any ocean-bottom currents that were present. With continued growth, the mounds both aggraded and prograded. As the mounds aggraded, faunal diversity and abundance increased. This increase in diversity and abundance is attributed to the increase in relative amount of light. This diversification is observed in the outer core facies where trilobites, ostracods, pelecypods, and other invertebrates were more numerous than compared to the inner core facies. With this increased abundance and diversification, the
deposition of intraclasts ceased within the outer core facies. This is presumably due to the overall higher abundance of skeletal debris compared to muds that helped hold all of the sediment together, with or without the presence of any ocean bottom currents.

Penecontemporaneously with deposition of both the inner and outer core facies, debris was being shed off of the flanks of the mounds. This debris was comprised largely of crinoid fragments, possibly due to their predominant cylindrical shape acting as a wheel and being more susceptible to transport. However, fenestrate bryozoans and other minor skeletal constituents were also transported down along with the crinoid fragments. The sediment of the flank facies was principally cemented by early radial-fibrous and equant calcite cement, void of any microbial precipitated carbonate.

The outcropping mounds in the Bridger Range grew to a maximum thickness of 74 feet, and lateral extents up to 500 feet, considerably smaller in size than the Lodgepole mounds in Stark County, North Dakota. The mounds in Swimming Woman Canyon on central Montana however, grew upwards of 150 feet high (Winfrey, 1983; Adams, 1999).

10.2.2 Subsurface Mounds

Many different depositional models for Lodgepole mound growth have been proposed in a number of different studies. Of these different models, a variety of water depths have been suggested for mound growth, though many agree that they began growing well below storm wave base and below or near the photic zone. The subsurface mounds are assumed to have started growing below or near this photic zone boundary due to the lack of calcareous algae, as well as their relative location on the carbonate ramp (Longman, 1996; Longman and Cumella, 2016). It is in this low-light environment that the subsurface Lodgepole mounds may have first began to grow.
Data agrees with the widely accepted concept that, with carbonates, topography often begets topography. The inherited paleotopographic highs were sites for colonies of crinoids and fenestrate bryozoans to thrive. Additional invertebrates were present, crawling around as mound development continued. The sediment deposited as a result of these organisms resulted in a firm substrate upon which additional invertebrates could thrive.

Individual mound growth centers were quickly cemented and lithified. The cements were a combination of early marine radial-fibrous cement, as well as calcium carbonate precipitated by microbes (Lees and Miller, 1985; Monty, 1995; Pratt, 1982; Longman, 1996; Morgan et al., 2012; Longman and Cumella, 2016). This microbial precipitation of microcrystalline carbonate is typically peloidal or clotted and is present in the mound core facies. This cement is considered automicrite (James and Wood, 2010), as it is produced in place, generally on a substrate, and is an important binding agent with respect to these mounds.

As the mounds aggraded, the tops of the mounds reached relatively shallower water depths. With this decrease in depth, the waters became more oxygenated. Within these more oxygenated waters, faunal diversity and abundances increased upwards (Montgomery, 1995; James and Wood, 2010). As the mounds continued growing, debris was being shed towards the flanks of the mounds. This crinoid-rich debris ultimately led to deposition of the flank facies that is pervasive around the mounds. No significant amount of microbially precipitated mud is found in the flank facies, as it consists principally of packstones and grainstones that are largely comprised of crinoid fragments. The mounds grew upwards and outwards, with dips reaching up to 40 degrees on the mound flanks. With continued aggradation and progradation, individual mound growth centers eventually coalesced into large mound complexes, with continued microbial precipitation of carbonate and
early marine cement holding the skeletal material together (Montgomery, 1995; Young et al., 1998; Longman and Cumella, 2016).

With continued aggradation, the mounds encountered high energy currents associated with storms. With this newly introduced energy, the early microbially cemented crusts of the mound core were broken up and transported very short distances as intraclasts (Figure 7.11). These intraclasts present in the mounds are a result of the mechanical breakup of the early lithified microbial crusts and are found close to their place of origin. Wilson (1975) added that “…mounds commonly begin growth below wave base and build up into it…” (Wilson, 1975, p. 367). Though these mounds may have made it into the photic zone, there is no calcareous algae preserved.

10.3 Cessation of Mound Development

Certain factors caused the mounds to abruptly quit developing. These factors are considered for both the outcropping mounds and subsurface mounds below.

10.3.1 Outcropping Mounds

After an unspecified amount of time, mounds in the Bridger Range abruptly quit developing and were enveloped in the Paine Member of the Lodgepole Formation. This abrupt cessation of development is attributed to continued transgression during the Kinderhookian, effectually drowning the mounds with the increased water depth. Evidence for this deeper water can be found in the facies of the Lodgepole Formation. Following drowning, there was an overall regression during the Osagean stage that allowed for deposition of the Woodhurst Member of the Lodgepole Formation. This was deposited on top of the Paine Member, which had enveloped the Lodgepole carbonate mounds. During deposition of the Woodhurst Member, sea level was fluctuating and cyclic regression-transgression sequences were recorded in an overall regression (Frazier and Schwimmer, 1987). It is possible that the presence of the flank facies deposited on
top of the mounds can be attributed to the newly introduced marine conditions during drowning. These conditions were favorable for crinoid colonies to thrive and with continued drowning, these conditions no longer existed. On the other hand, the presence of this capping flank facies could be attributed to the amount of erosion that has occurred and where the present day outcrops are relative to the crests of their original deposition structure.

10.3.2 Subsurface Mounds

After reaching heights of over 300 feet, growth of the subsurface mounds in Stark County, North Dakota abruptly ended. The mounds in Stark County were ultimately drowned by a significant sea-level transgression, which allowed Lodgepole clinoforms to both aggrade and prograde towards the basin center. Transgression reached a maximum in the uppermost Devonian to Early Mississippian during deposition of the lower Lodgepole Formation (Montgomery, 1995). This transgression resulted in deposition of shelf-to-basin carbonates of the Lodgepole Formation, followed by regression that led to the shallow-shelf and tidal-flat environments of the overlying Mission Canyon Formation and restricted Charles Formation (Montgomery, 1995). With aggradation and progradation, the Lodgepole mounds were encapsulated within argillaceous mudstones of the regional Lodgepole facies. This drowning of the Lodgepole mounds completely and abruptly caused the thriving carbonate factory to shut down, as documented by the abrupt change in facies.

Figure 6 of Longman and Cumella (2016) shows a regional south-to-north stratigraphic cross section focused on the Lower Bakken Shale through the top of the Lodgepole Formation. This cross-section places the Lodgepole mounds along foresets of Lodgepole clinoforms that are delineated by regional correlations in logs. The tops of the mounds are nearly coeval with the topset of the lowermost Lodgepole clinoforms. Alternatively, with their proposed third stage of
mound formation, Longman and Cumella (2016) suggested that mound growth was terminated by the suspension of fluids flowing through seafloor springs. They attributed the interfingering of the regional Lodgepole facies with the mound core facies visible in the Patterson #1-24 core (Figure 7.15) to episodic “last-gasp” fluid expulsion events.
CHAPTER 11

CONCLUSIONS

1) The presence of two previously un-studied Lodgepole carbonate bioherms, approximately 7.5 miles south of the Sacagawea Peak bioherms studied by Stone (1971), is confirmed.

2) Five distinct facies were observed at the Bridger Range outcrops. They are (1) a crinoid and fenestrate bryozoan mottled wackestone basal biostrome facies, (2) a skeletal wackestone to mud-rich packstone to grainstone to marine cemented boundstone inner core facies, (3) a crinoidal and bryozoan to mud-rich packstone to grainstone outer core facies, (4) a bryozoan and crinoidal mud-rich packstone to grainstone flank facies, and (5), an argillaceous mudstone to skeletal wackestone of the regional Lodgepole facies.

3) The mounds at Sacagawea Peak and Saddle Peak are dwarfed by the large subsurface mound complexes in Stark County, North Dakota. This difference in size is attributed to a smaller initial area upon which the Bridger Range mounds nucleated, followed by a much earlier cessation of mound development (i.e., earlier drowning event) compared to the Stark County mounds.

4) The Bridger Range outcropping mounds and the Swimming Woman Canyon mounds both have a basal substrate upon which mound growth was initiated, while the subsurface Stark County mounds do not.

5) The Stark County subsurface mounds formed at the base of the Lodgepole Formation while the outcropping Bridger Range mounds formed over 100 feet above the base of the Lodgepole Formation.

6) The Stark County subsurface mounds may have developed as a result of two-stage Prairie salt dissolution. These stages of dissolution allowed for thickening of the Upper Bakken Shale into
an area of salt withdrawal, resulting in positive paleotopography upon which the Lodgepole mounds nucleated.

7) The Bridger Range outcropping mounds and the Stark County subsurface mounds were cemented early with microbial, radial-fibrous, and equant calcite cements. These cements allowed for minimal compaction during later burial, and subsequent preservation of the mound core facies.

8) Void-filling saddle (baroque) dolomite is pervasive in the Stark County subsurface mounds and absent from the Bridger Range outcropping mounds.

9) With the knowledge that very small Lodgepole carbonate mounds exist (i.e., Bridge Range outcrops), there may be potential for additional mounds present in the subsurface of the Williston Basin.
CHAPTER 12
RECOMMENDATIONS FOR FUTURE WORK

While this study was as encompassing and thorough as possible, in hindsight, there are a number of things that could have been done differently (or additionally), and may have resulted in different conclusions. This chapter addresses these in the form of recommendations and considers what could be done in moving forward with this study.

1) Utilize a field assistant for any outcrop work within the Bridger Range. Had there been a field assistant, more samples could have been acquired and brought back to CSM for study. With additional field samples, a more thorough representation of the outcropping mounds would have been achieved.

2) Consider the subsurface mounds from a regional scale as well as a local scale. The regional structure of the area surrounding Stark County, North Dakota is sure to hold many keys to understanding how initiation of these Lodgepole carbonate mounds occurred. Particularly, why the first stage of Prairie Evaporite dissolution occurred as a localized phenomenon in Stark County, North Dakota.

3) Incorporate additional core and thin sections from the NDIC in Grand Forks, North Dakota. While core photos are available for a number of cores from the North Dakota Industrial Commission, they are no substitute for seeing the core in person. Consequently, a trip to Bismarck, North Dakota would have been beneficial. Additionally, it may have been worth searching for non-public data held by current well operators for added insight into the subsurface mounds.

4) Cut additional thin section from the Patterson #1-24 well. Specifically, have the thin sections cut at both the basal and upper contacts that are present in the core to better understand the
nature of these contacts. By better understanding these preserved contacts, one may better understand how and why these mounds initiated and why they ceased developing.

5) Compare and contrast the outcropping mounds in the Bridger Range in southwestern Montana to those in Swimming Woman Canyon in central Montana. Use previous work by Winfrey (1983), and Adams (1999), and undertake possible additional fieldwork for these comparisons.
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APPENDIX A

Table A.1  Wells producing from the Lodgepole carbonate mounds in Stark County, North Dakota that had have had a cumulative production of 1MMBO or greater. Wells are listed by descending cumulative oil production. Cumulative production data is from date of completion until January 2016. Data collected from IHS Enerdeq.

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<th>Location</th>
<th>Completion Date</th>
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<td>4,102,533</td>
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<td>139N 97W 23 NE NE</td>
<td>1995-03-20</td>
<td>4,413,228</td>
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</tr>
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Table A.2  Operating conditions present for each sample studied with cathodoluminescence. Includes thin section number, image number, location, magnification, exposure time for photo, and type of light conditions present for each photo taken.

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