STRATIGRAPHY, DIAGENESIS AND FRACTURE CHARACTERIZATION OF THE
UPPER DEVONIAN THREE FORKS FORMATION IN MONTANA, WYOMING
AND SOUTH DAKOTA

by
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The Three Forks Formation could yield as much as 2 billion barrels of petroleum (NDGS, 2010) in the Williston basin. Previous outcrop studies date from the 1960s leave this formation almost uninvestigated in modern sedimentologic and stratigraphic terms.

The aim of the current work is to provide regional correlation of lithofacies, interpret environments of deposition, and to document fracture distribution and trends in the Formation based on nine outcrops in Wyoming, Montana and South Dakota, and a core from the Big Horn basin. The proposed stratigraphic correlation of the Three Forks Formation shows lateral and vertical facies changes based on both outcrops and a core.

Key stratigraphic surfaces are recognized from the core data and traceable throughout the study area in a well and outcrops. These major stratigraphic surfaces are a sequence boundary at the base of the Three Forks, a transgressive surface in the middle part of the Three Forks, and a sequence boundary at the top of the formation. Six interpreted facies associations are, from the shallowest to the deepest: (1) supratidal sabkha; (2) upper intertidal mud flat; (3) lower intertidal mud flat; (4) back-barrier lagoon deposits; (5) tidal bar (open marine) and (6) subtidal transgressive lag.

The supratidal sabkha has a shallowing-upward stacking pattern. Mosaic, nodular anhydrite together with reddish and greenish dolomicrosparstone are dominant. The upper intertidal mud-flat facies association is composed of pinkish-grey, yellow laminated dolomicrosparstone with shrinkage cracks, rip-up elasts, loading structures, fenestral porosity. Lower intertidal mud-flat to shallow subtidal facies association is composed of laminated yellow dolomicrosparstone. Lagoon deposits are massive dolosparstone with anhydrite nodules. The tidal bar facies association consists of yellow bioturbated dolosparstone. The supratidal transgressive lag facies association shows abandoned conodonts, plant debris and well-rounded quartz. The upper intertidal deposits dominate the lower and the middle parts of the Three Forks, whereas, the upper part is dominated by the back-barrier, lower intertidal and occasional open marine deposits.

Diagenetic features include four episodes of dolomitization, anhydrite precipitation and cementation, compaction, dedolomitization, dissolution. Reflux
dolomitization is interpreted to be the main mechanism to form dolostones in the study area. Porosity ranges from 0% to 15%. It was formed due to dolomitization and dissolution by meteoric waters during exposure and erosion in the late Devonian time.

An average number of 100 fractures were measured in each of the locations. Outcrops show hinge parallel and hinge perpendicular fractures. Fracture patterns were described and compared with fracture distribution in the overlying Bakken Formation. Fractures have predominant NE, NW and N-S strikes. Angle between fracture planes is usually of 70 degrees. General spacing between major fractures of similar direction is 20 cm and less. Laminated dolomicrosparstones of the intertidal facies, and massive dolosparstones of the back-barrier facies show most of the fractures. Many fractures go through the whole Three Forks Formation and extend into the Madison Formation.
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CHAPTER 1
INTRODUCTION

1.1 Importance

The Three Forks Formation is an important hydrocarbon play in Williston basin. According to a recently completed study by the North Dakota Geological Survey and Department of Mineral Resources, the Three Forks Formation could yield as much as 2 billion barrels of petroleum, enhancing the sustainability of the Bakken resource play over time. Currently, there are 181 wells drilled in the Three Forks Formation, confirming that it will be an important part of the overall Bakken petroleum system. Previous outcrop studies date from the 1960’s, and leave this Formation almost uninvestigated in modern sedimentologic and stratigraphic terms. The aim of the current work is to provide regional correlation of lithofacies, and to document fracture distribution and trends in the Formation based on ten outcrop sections in Wyoming, Montana and South Dakota. The work incorporates previous core studies in the Williston Basin itself, and a core from the Big Horn Basin that is adjacent to a number of the outcrop locations and has been described and correlated to the outcrops.

Fracture analysis of the Three Forks Formation has not been done and is important to understanding reservoir quality of this low porosity and permeability formation. Fracture patterns observed in outcrops are compared to fracture distribution in the overlying Bakken Formation, and to regional subsurface fracture trends. This study may help in future development of the Three Forks Formation.

1.2 Research Objectives and Purposes

The first goal of the current research is to describe and interpret the lithofacies distribution and diagenesis of the Three Forks Formation based on outcrops and core studies of previous studies, as well as one additional available core. The second goal is to develop a fracture distribution model for the Three Forks Formation.

The specific objectives of this research are to:
1) Construct a stratigraphic framework and make a lithofacies correlation in the Three Forks Formation, including data from both cores and outcrops.

2) Interpret the environments of deposition, and relate them to the facies relationships within the Three Forks.

3) Describe diagenetic changes within the different lithofacies.

4) Propose a fracture distribution model for the Three Forks Formation.

This study hopes to predict reservoir compartmentalization and reservoir quality, integrated with a fracture distribution model.

1.3 Previous Work

There have not been many outcrop studies of the Three Forks Formation. Previous work was done in the 1950-1960’s. There have been studies on subsurface correlation, both in the USA and Canada. No work has been done on fractures in the Three Forks Formation.

Baillie (1955), in his paper ‘Devonian System of the Williston basin’ described stratigraphy and depositional environments of the Canadian equivalent of the Three Forks Formation called the Qu’Appelle Formation. He correlated a number of cores in Canada, North Dakota and Montana with outcrops in Canada. The studied area was divided into several smaller ones such as the Manitoba shelf, and the Dakota shelf, and each area was described in detail.

Sandberg and Hammond (1958), in ‘Devonian System in Williston basin and Central Montana’ showed the stratigraphy of the southern part of the Williston basin. They correlated a number of wells and a type outcrop location in Logan, Montana, and proposed a map of the distribution of Devonian rocks. The Three Forks Formation is present in North Dakota, in the very northern part of South Dakota, in the western part of Wyoming, and is present in Montana with the exception of its southern part.

Later, in 1967 Sandberg and Klapper published a research paper entitled ‘Stratigraphy, Age, and Paleotectonic Significance of the Cottonwood Canyon Member of the Madison Limestone in Wyoming and Montana’. In this paper they described and correlated outcrops and wells. They divided the Three Forks Formation into three
members, from the base upward: the Sappington, the Trident and the Logan Gulch members. The Sappington Member, found locally at the top of the Three Forks Formation, is composed of fine to coarse sandstone and has been termed the Sanish in the subsurface of the Williston Basin. Sandberg proposed a map of the distribution of each of the Three Forks members.

Dumonceaux (1984), in her thesis, titled ‘Stratigraphy and Depositional Environments of the Three Forks Formation (Upper Devonian), Williston basin, North Dakota’ described the facies variation and depositional environments within the Three Forks Formation. She described four facies within the Formation that range from supratidal to sublittoral (Figure 1.1). Due to the presence of anhydrite, Deumonceaux interpreted the formation to be deposited in arid climate conditions, and concluded that cyclic transgressions and regressions caused lateral migration of depositional environments, resulting in a complex facies stacking patterns.

Berwick (2008), in his Master’s thesis, ‘Depositional Environments, Mineralogy, and Sequence Stratigraphy of the Late Devonian Sanish Member (Upper Three Forks Formation), Williston Basin, North Dakota’ identified five different lithofacies and made a correlation of cores from the northern part of the Williston basin. Facies A is a pale red, dolomitic shale with common shale clasts and discontinuous lenses of very fine to fine-crystalline dolomite. Facies B is a gray, calcareous dolomite. Facies C is a highly deformed and brecciated, silty dolomite and gray-green shale. Facies D is a silty dolomite and shale. Facies E is a slightly silty dolomite that is burrowed to extensively bioturbated. Towards the northern basin margin, he showed thinning and truncation of the Three Forks. His study agrees with Dumonceaux (1984) on the interpretation of depositional environments (Figure 1.2).

Gantyno (2010), in his Master’s thesis, ‘Sequence Stratigraphy and Microfacies Analysis of the Late Devonian Three Forks Formation, Williston Basin, North Dakota and Montana, U.S.A.’ addressed the lateral distribution, vertical variation and depositional environments of the Three Forks Formation. He described the stratigraphy in a sequence stratigraphic framework, and defined lithofacies and microfacies. He identified eleven lithofacies and five facies associations that were deposited in five different depositional settings: (1) upper supratidal sabkha; (2) lower
supratidal sabkha; (3) upper intertidal mud flat; (4) lower intertidal mud flat; and (5) open marine. The depositional model that Gantyno (2010) developed is shown in Figure 1.3. Diagenetic features in nine analyzed microfacies include dolomitization, anhydrite precipitation and cementation, compaction, clay cementation, dissolution and pyritization.

Angster (2010), in his research ‘Fracture analysis of the Bakken Formation, Williston Basin: Field Studies in Little Rocky Mountains, Big Snowy Mountains MT, and Beartooth Mountains WY’ described regional and local fracture distribution in the Bakken Formation. This study will expand that study to include fracture analysis of the Three Forks Formation.

Figure 1.1 Depositional model for the Three Forks Formation (Dumonceaux, 1984).
Figure 1.2 Depositional model of the Three Forks Formation (Berwick, 2008).
Figure 1.3 Depositional environment model (A) and lateral facies change interpretation (B) of the Three Forks Formation (Gantyno, 2010).
CHAPTER 2
BACKGROUND

2.1 Regional Setting

Regional setting plays a key role in the initial deposition and later development of the Three Forks Formation. Regional setting includes location, structure, stratigraphy and geologic history of the area.

2.1.1 Location of the Study Area

Ten outcrop locations were described and studied in this project (Figure 2.1) (see Appendix A for exact locations). Six locations are in Wyoming. Two of the Wyoming outcrops are in the northern part of the Absaroka Range - a western locality near the town of Cooke City in the Yellowstone National Park, and an eastern one near the town of Cody, in Shoshone Canyon. Well 25-M LBB is located in the southern part of the Absaroka Range – Pan Am Petroleum, Township 47N, Range100W, Section 12, quarter NESWNE, and API 4902905098. Two outcrops were described in the Bighorn Mountains, on the eastern and western edges of Cottonwood Canyon. A fifth location is in the southern part of the Beartooth Mountains, in Clarks Fork Canyon.

Figure 2.1. Map of the study area with geologic structures (in brown lines), locations of the described outcrops (yellow squares) and a well (dark-blue star). Boundary of the Williston basin is shown (blue line) (modified from Google Maps).
Two outcrops have been described in Montana. The southernmost one is located in the northern part of the Beartooth Mountains, in the Gallatin Forest, near the town of Big Timber. The second location is in the Big Snowy Mountains, near Lewistown, close to the Crystal Lake campground.

Two outcrops are in South Dakota, in the Black Hills. The first one is in the north, near the town of Deadwood; the second one is in the southeast, near the town of Rapid City.

2.1.2 Structure

Many of modern structural elements within the studied area derive from Precambrian shear zones that have been retained as zones of weakness. The study area is underlain by two Precambrian geologic provinces: the Trans-Hudson Orogen and the Churchill hinterland (Figure 2.2). Later in the Paleozoic there was rearrangement of blocks causing wrench–fault tectonics (Brown, 1984). Sales (1968), Stone (1969) and Brown (1987) suggest that the wrench-fault tectonics, expressed in vertical movement along fracture zones, had the most control over Paleozoic deposition. Block junctions have been termed lineament zones. Blocks can move periodically and in different directions through time.

There are three major Paleozoic structural blocks with minor internal blocks separated by lineament zones (Figure 2.3). The Alberta block is separated from the Cedar Creek block in the south by the Poplar lineament zone, and is bounded by the Sweetgrass lineament zone on the west. The Williston block is defined by the Devil Lake lineament zone on the east, Wyoming lineament zone on the south, and is separated from the Cedar Creek block by the Cedar Creek lineament zone (Brown, 1987).

Major Paleozoic and younger paleo-structures in the study area follow the pattern of these lineaments, and Precambrian weaknesses (Figure 2.4). The Wyoming shelf occupied southern Montana and the greater part of Wyoming during Paleozoic and early Mesozoic time. The central Montana Trough was actively subsiding during Precambrian time, and continued subsiding with various degrees of intensity later in geologic history.
Figure 2.2. Tectonic map showing time of the first major deformation of structural provinces and orogens. Study area is shown in black square (Williams et al, 1991)
The Alberta shelf occurs north of the central Montana Trough in southern Alberta and western Saskatchewan during the Paleozoic and Mesozoic. The Beartooth shelf bordered the central Montana trough from the south and extends into the northern part of Wyoming. The central Montana uplift was very active in the Devonian, and probably originated in the Cambrian (Peterson, 1981).

**2.1.3 Stratigraphy of the Williston Basin and Adjacent Areas**

In south-central Montana and north-central Wyoming, the Upper Devonian formations are shelf facies deposited between the basin and the shoreline, and lithologically, are almost identical to shelf facies along the southern and eastern margins of the Williston basin in North and South Dakota (Sandberg and Hammon, 1958). The Williston basin contains almost a complete section of sedimentary rocks, starting from late Cambrian through the Neogene. In the early Paleozoic, northwestern North Dakota became a depocenter with decreasing thickness of sediments towards the basin margins. Deposition of carbonate rocks started in the early Paleozoic and changed to
Figure 2.4. Regional paleostructure during Paleozoic time (Brown, 1984).
dominantly clastic deposition in the late Paleozoic (Peterson, 1987). The Paleozoic sedimentary column consists of four sequences of transgression and regression (Sloss, 1963). Upper Devonian rocks were deposited during the maximum transgression of the Devonian seaway, and they extend across most of Montana, through central to western Wyoming and westward. The Middle and Upper Devonian rocks have a southern limit in Montana (Brown, 1984). There are several places where Devonian is thin or absent. This is the zone near the central Montana Uplift and a northwest-trending zone along the Sweetgrass Arch. The Devonian in the Williston Basin is a cyclic sequence composed of both carbonate and clastic rocks.

**The Upper Devonian Birdbear (‘Nisku’) Formation**

This formation is the final carbonate-evaporate cycle of Devonian (Figure 2.5). It is divided into two units. The lower unit is composed of bedded, peloidal lime mudstone, and bedded to massive dolomite. The upper unit is massive bedded dolomite, breccia, and anhydrite. The Formation was deposited in subtidal to supratidal environments (Peterson and MacCary, 1987).

**Upper Devonian Three Forks Formation**

The Three Forks Formation unconformably overlies the Birdbear, and is a regressive sequence, consisting of mixed marine and nonmarine red and green shales, siltstones, sandstones, carbonates and evaporites (Peterson, 1987). Its thickness varies from a few feet to approximately 240 feet. Westward from the Williston basin in north central Montana, the lower Three Forks Formation becomes more anhydritic, and represents the eastern tongue of the upper part of the Potlatch anhydrite (Brown, 1984).

Regional distribution of evaporate beds and solution breccias in the Three Forks Formation, and underlying Birdbear Formation indicates a platform interior environment immediately east of the north-south trending belt of carbonate bank facies buildups in western Montana. It supplied a westward hydrodynamic gradient that enabled high magnesium evaporitic shelf waters to move westward during periods of low sea level, resulting in early dolomitization (Peterson, 1981).

The deposition of the Three Forks Formation was followed by uplift and removal of all or part of the formation, and later by rapid transgression and deposition of black shales and silty dolomites of the Bakken Formation (Thompson, 1961).
Lower Mississippian Bakken Formation

The Bakken Formation consists of three members: upper and lower organic-rich black shales, and a middle silty dolostone, and limestone member (LeFever et al., 1991). The Bakken represents two transgressive-regressive cycles of sedimentation (Meissner et al., 1984).

2.1.4 Geologic History

The Williston basin is an early Paleozoic intracratonic sedimentary basin. Devonian deposition in the basin was influenced the most by uplift along the Transcontinental Arch, which oriented the seaway to the north in middle Devonian time (LeFever, 1992) (Figure 2.6).
The Three Forks Formation accumulated in the restricted environments of a shallow epeiric sea with deeper areas and paleohighs inherited from Precambrian zones of weaknesses in the basement (Brown, 1984). Paleohighs include the Black Hills Uplift, the Big Horn Mountains and a paleo Absaroka Uplift in Wyoming (Figure 2.4). To the west from Montana there was an Antler Foreland basin resulting from the eastward thrusting of the Antler allochthon. The Montana Trough crosses Montana in the east – west direction, with the Central Montana Uplift at its eastern end, at the location of the modern Big Snowy Mountains. In North Dakota, the gently subsiding Williston Basin was connected to the Alberta Basin. Whether the Williston Basin was connected with the Antler Foreland basin through the Montana Trough is not well understood (Peterson, 1981). In late Devonian time the area was uplifted and a regional unconformity was formed followed by a regional transgression and accumulation of the Bakken shale. Several later tectonic events probably influenced the final erosional distribution of the Three Forks Formation. They include (1) the middle Carboniferous Ouachita-Marathon orogeny in the southwestern part of US, related to the formation of the Pangaea supercontinent, (2) the Sevier orogeny in the late Jurassic that was produced by subduction of the oceanic Farallon Plate underneath the continental North American Plate, and (3) the Laramide orogeny in the late Cretaceous – early Tertiary time when the Kula and Farallon Plates subsided underneath the North American Plate at a shallow angle (Willis, 1999).

2.1.5 Bakken Petroleum System

The Bakken Petroleum System is of Mississippian-Devonian age. It includes the Three Forks, the Bakken, and the Lodgepole formations. A petroleum system consists of source rock, and all genetically related hydrocarbon accumulations. The upper and lower Bakken members are source beds, and the Three Forks, the Lodgepole and all the members of the Bakken are reservoirs (Figure 2.5). All reservoirs are low-porosity and permeability. The Bakken and Three Forks are enhanced by natural fractures, due to the brittle nature of the formations (Sonnenberg, 2010). The petroleum system has formed a continuous type of accumulation in the deeper part of the Williston basin (Sonnenberg, Pramudito, 2009).
Figure 2.6. Paleogeographic maps. Subduction zones and associated orogenic belts (dashed red). A: The North American craton was open to the southwest (yellow arrow), and the Williston and Alberta basins were connected (W-A) in the Late Devonian. B: In the early Mississippian, the Alberta basin (AB) and the Williston (WB) basin were separated by the Sweetgrass Arch (SA) and the Transcontinental Arch (TA) supplied sediment from the southeast. Modified by Berwick, 2008 from http://--jan.ucc.nau.edu-rcb7-namD360.jpg.
The Bakken shale is mainly a type II kerogen, with rare admixture of type I. The shale is not thermally mature everywhere in the Williston basin, most prominently in the eastern part of it.

The Bakken Formation is estimated to have recoverable 3.65 billion barrels of oil, 1.85 trillion cubic ft of associated/dissolved natural gas, and 148 million barrels of natural gas liquids by the USGS. According to the NDIC, the Three Forks is estimated to have 1.9 billion barrels of recoverable reserves.

2.2 Location of Outcrops

Nine outcrop locations and one well location were used for this thesis. Their locations are shown on the Figure 2.1. This section summarizes the general geology and provides detailed locations for each measured section.

2.2.1 Beartooth Mountains and Absaroka Range

The Beartooth Mountain Range is part of the Rocky Mountain front in Montana and Wyoming. The Clark Fork River is its southern boundary with the Absaroka Range. This river forms Clarks Fork Canyon where the Clarks Fork section is located (Figure 2.7, Appendices A and B). It is along the Canyon Road, which is the west branch of the US 120 road. GPS coordinates of the outcrop are N44°51’8”, W109°18’13”. These mountains consist of an uplifted core of Precambrian rocks with younger sediments on the flanks. The eastern side is an overthrust along the Beartooth fault with steeply dipping to overturned beds (Figure 2.8). The core of the structure was formed during Precambrian tectonics and reactivated in Paleozoic and Mesozoic times. Beartooth thrust was formed in the Late Cretaceous –Early Tertiary time as a result of a Laramide orogeny (Hughes, 1933). The fault decreases southward and terminates in Clarks Fork Canyon. There is 5 m of the Three Forks Formation and 12m of the Bakken Formation exposed in the canyon, overlain by the Madison Formation above, and underlain by the Birdbear Formation.

To the north and the west, the Crazy Mountain basin bounds the Beartooth Mountains. There, the Crazy Mountain syncline was deformed by the uplifted granitic core of the Beartooth massive, forming steep, partly faulted flanks (Foose, 1961). In the northwest, southeast of the town of Livingston is an outcrop in the Gallatin National
Forest (Figure 2.9). It is located on the southern slope of the Baker Mountain, to the west of the Main Boulder Road. GPS coordinates are N45°31'58'', W110°12'58''. In this location there is 30 m of the Three Forks Formation, overlain by the Bakken Formation and underlain by the Birdbear Formation.

Figure 2.8. Cross – section AA’. Location of the cross-section is shown on the Figure 2.7. Modified after Hughes, 1933.

Figure 2.9. Geologic map of the northwestern Beartooth mountains, with location of the Gallatin Forest outcrop (black dot), north is up. Legend is on the Fig. 2.11 (Foose, 1961).
The Yellowstone outcrop is located near the town of Cook City, to the north from the US212, on the southern slope of the Mineral Mountain and opposite the Abiathar Peak, along the east-west Cook City fault zone, in the Yellowstone River valley (Figure 2.10). The Three Forks outcrop is 24 m thick and is overlain by the Madison Formation, and underlain by the Birdbear Formation. GPS coordinates are N45°0’52”, W110°1’37”.

In the Absaroka Range there is an outcrop to the west of the town of Cody, in the Shoshone Canyon, on the northern side of the US20 Road. The Three Forks Formation is 11 m thick at this locality. GPS coordinates are N44°30’42”, W109°9’5” (Figure 2.12).

![Figure 2.10](image.png)

Figure 2.10. Geologic map of the southern Beartooth Mountains, with location of the Yellowstone outcrop (black dot), north is up. Legend is on the Fig. 2.11 (Foose, 1961).

2.2.2 Big Horn Mountains

The Big Horn Mountains are located in Wyoming with the northernmost part of the range extending into southern Montana. It is a compound elongated anticline with steep sides, especially the eastern one, an almost flat top, and a gentle western side. In the basement there are horst-like features on the top of which sediments passively form ‘flats’ and monoclines. The Big Horn Mountains were uplifted during the Laramide orogeny with considerable faulting and folding along its edges (Burcher, 1933). One
Figure 2.11. Legend for the Figures 2.9 and 2.10 (Foose, 1961).

Figure 2.12 Geologic map of the northern Absaroka Range with location of outcrop in Clarks Fork Canyon (black dot). Legend is on the Figure 2.13 (Love and Christiansen, 1985).
outcrop, containing 12 m of section is located on the western side of the mountains, near Lovell, north from the road US14, in the canyon formed by Cottonwood Creek. GPS coordinates are N44°51′56″, W108°3′5″. A second outcrop with 20 m of the Three Forks Formation occurs on the eastern side, along the road US14 in Wyoming (Figure 2.13). GPS coordinates are N44°48′17.75″, W105°19′23″.

2.2.3 Big Snowy Mountains

The Big Snowy Mountains, in central Montana, is an asymmetric anticline with a steep southern (40–60° dips) limb and a gentle northern (3-10° dips) limb. Its axis has a northwest – southeast direction (Figure 2.14). An initial structure was formed during Proterozoic rifting and is underlain by a northeast dipping basement fault. It was reactivated during the Laramide orogeny (Nelson, 1992). Four meters of the Three Forks Formation is exposed in the Big Snowys, and is overlain by the Jefferson Formation. Its lower contact is generally covered. It is located on the road from Lewistown, on the way to the Crystal Lake. GPS coordinates are N46°48′49″, W109°29′47″.

Figure 2.13. Geologic map of the northern Big Horn Mountains with locations of two outcrops (black dot) (Love and Christiansen, 1985).
2.2.4 Black Hills Uplift

The Black Hills are a dome-shaped uplift with length of about 125 miles and a width of 60 miles, located in South Dakota, near Wyoming border (Feldman and Heimlich, 1980 in Naus et al., 2001). The core is composed of Precambrian metamorphic and igneous rocks. Overlying Paleozoic and Mesozoic sediments were deposited almost horizontally and were uplifted during Laramide orogeny. This orogeny also caused erosion of sediments in the central Black Hills and exposure of the Precambrian core there. Sediments are exposed in rings around the core (Figure 2.15, 2.16). During the Laramide time, fracturing, folding, and intrusions occurred (Naus et al., 2001). Two outcrops were described in the area. One is located in the north of the Black Hills, in Whitewood Creek Canyon, along the road US14 in between the towns of Deadwood and Sturgis. GPS coordinates are N44°23'26'', W103°42'16''. A second outcrop occurs to the west of Rapid City, along the Nemo road/166, near the Bogus Jim Creek. GPS coordinates are N44°7'803'', W103°24'819''.

Figure 2.14. Top: geologic map of the Big Snowy Mountains (Porter, 1996) showing outcrop location (black dot); bottom: cross-section through the Big Snowy Mountains (Reeves, 1931); right: general stratigraphic column. Modified by Angster, 2010.
Figure 2.15. Geologic map of the Black Hills with outcrop locations. Modified from Strobel et al., 1999 in Naus, 2001.
Figure 2.16. Geologic cross-section through the Black hills Uplift. Location is shown on the Fig. 2.15. Modified from Strobel et al., 1999 in Naus, 2001.
CHAPTER 3
METHODOLOGY

This research represents the description and integration of nine outcrops from Montana, Wyoming and South Dakota, and a core from Wyoming. Lithofacies description is interpreted within a sequence stratigraphic framework, and this study includes the diagenetic history and fracture distribution of the Three Forks Formation. Surface sections and a core were logged, and 80 thin-sections were described using standard petrographic description. Five thin-sections were point counted with a grid of 1.5 x 1 mm. (vert. x horizontal) for grain types and porosity (an average of 150 pores were counted in each sample). For classification of porosity in carbonate rocks a scheme proposed by Choquette and Pray (1970) was used (Figure 3.1).

Figure 3.1 Classification of porosity in carbonates (modified after Choquette and Pray, 1979; in Moore, 2001).
Outcrop description includes sedimentary textures and structures, grain size, lithology, thickness of individual beds, interpreted facies associations, and description of shallowing upwards depositional cycles (Figure 3.2, Appendix A and B) Standard petrographic description in this work includes fabric, crystal size, composition, textures, sorting and grain shapes for dolomite textures, clastic grains, fossils, and porosity. Characterization of all thin-sections is in Appendix B. They are placed according to their location in the measured sections. Cathodoluminescence was performed on 5 thin sections. These data helped to properly correlate rock units, interpret depositional environments, and to predict porosity and permeability changes within the formation. Lateral and vertical variations in the Three Forks Formation were documented based on both outcrops and a core.

The predominant majority of rocks are dolomites. For classification of dolomite fabric and nomenclature the Randazzo and Zachos (1983) scheme was used, based on textures defined by Friedman (1965) (Fig. 3.3). Friedman (1965), Randazzo and Zachos (1984) and Wright (1992) used the crystal size scale with three divisions: dolomicrostone (crystal size < 0.004 mm), dolomicrosparstone (crystal size 0.004 – 0.01 mm) and dolosparstone (crystal size > 0.01 mm), and summarized in Flugel (2004).

The fracture study includes:

- an average of 100 fractures (dips and strikes) measured in each outcrop location using a standard Brunton compass,
- plotting these measurements on rose diagrams and stereo nets,
- comparison of local structural trends with trends within the outcrops,
- comparison of regional trends to a tectonic model,
- documentation of fracture density and mechanical stratigraphy for the different lithofacies units.
Figure 3.2. Example of sedimentary log from the Clarks Forks Canyon outcrop.
Figure 3.3. Classification of dolomite fabrics (Randazzo and Zachos (1983), based on terminology defined by Friedman (1965), from Flugel, 2004).
CHAPTER 4
FACIES AND FACIES ASSOCIATIONS

Six facies associations and ten facies were interpreted based on the outcrop description and thin-section analyses.

4.1 Facies Association 1 (FA 1)

1. Lithofacies A: Lag with conodonts

Lithofacies A is a transgressive lag on the top of the Gallatin Forest section in the Beartooth Mountains. It is 4 cm thick. This lag contains abundant conodonts, and brown cellular plant debris, that are rounded and elongated in shape, and up to 1 mm in size. Sub-rounded silt-size quartz grains are scattered throughout the lag. It has a wavy, irregular, erosional lower contact with FA 3, and 3% intergranular porosity (Figure 4.1).

Figure 4.1 Transgressive lag with conodonts, plant debris and sub-rounded quartz, lithofacies A, sample GF 7, Gallatin Forest outcrop, upper most part, Three Forks Fm.
4.2 Facies Association 2.1 (FA 2.1)

This FA is represented by *lithofacies B – yellow, massive dolostone with horizontal burrows* (Figure 4.2). It is an equigranular mosaic dolosparstone with sieve fabric of loosely packed euhedral crystals of coarse silt to very fine sand size dolomite. Rocks are light yellow in color, moderately bedded, with beds 25 cm thick. The bottom of each bed shows horizontal and vertical burrows formed by *Thalassinoides isp.* Individual beds are structureless, heavily dolomitized so the original fabric and fossils are difficult to distinguish. Only echinoderm spines and foraminifera are identified. Dolomites contain 5% of scattered well-rounded medium quartz grains, rare authigenic muscovite and glauconite. Porosity ranges from 4% to 8%

FA 2.1 has sharp lower and upper contacts, and is bounded at the bottom by FA 2.2 and at the top by the Madison Fm.

Figure 4.2 Lithofacies B, Three Forks Formation. A: Dolostone with *Thalassinoides isp.* burrows (displayed on lower bed boundaries); B*: dolosparstone showing intercrystalline porosity (blue), sample CC 8, Cottonwood Canyon.

4.3 Facies Association 2.2 (FA 2.2)

FA 2.2 consists of three lithofacies:

1. *Lithofacies C: Massive dolosparstone with calcite nodules* (Figure 4.3).

This lithofacies consists of equigranular peloidal dolosparstone with loosely packed euhedral crystals of medium silt to very fine sand size dolomite. Dolomite is light yellow to pink in color.
Figure 4.3 Lithofacies C, Three Forks Formation. A: calcite filled nodules (blue arrows), ‘Fallen City’ outcrop; B: photomicrograph, peloidal dolosparstone showing intercrystalline and interparticle porosity, sample FC 13, ‘Fallen City’.

Lithofacies C has a massive structure, is thickly bedded with 50 cm thick beds. At the lower part of the beds there are horizontal lamination of different shades of purple. In the core (well 25-M LBB), vertical burrows were observed filled with anhydrite. Round calcite nodules are common in this lithofacies. Under the microscope, calcite in these nodules has ‘flow’ texture. Brachiopods and occasional crinoids are present. In the South Black Hills location there are bryozoans and crinoids restricted to one 20 cm thick layer. Dead oil occasionally fills pore spaces. In the core this lithofacies was heavily oil stained. There are rare quartz grains (about 2-3%), rare chalcedony, chert and calcite. Porosity is estimated to be 10-13%.

2. Lithofacies D: Laminated, clayey dolomicrostone (Figure 4.4).

Lithofacies D is represented by thinly laminated, fissile, clayey, dolomicrostone. It contains thin layers of dolomicrosparstone. Dolomite crystals are inequigranular, porphyrotopic, and have a contact rhomb texture. There is no visible porosity. It erodes in a fissile manner, usually forms thin layers from 1 cm to 5 cm thick. Color ranges from yellowish to grey. This lithofacies is very common in all locations.

3. Lithofacies E: Dolosparstone with sand lenses, and lag deposits (Figure 4.5).

It consists of yellow, green, purple colored equigranular dolosparstone. It has mosaic, sutured texture with sand lenses containing medium and coarse sand size quartz.
Figure 4.4 Laminated clayey dolomicrostone, lithofacies D, Three Forks Formation. **A:** ‘Fallen City’ outcrop; **B:** photomicrograph, dolomicrostone with layers of dolomicrosparstone, sample 13A, well 25-M LBB.

Figure 4.5 Sand lenses in lithofacies E, Cottonwood Canyon, Three Forks Fm.

The quartz sand lenses display inclined stratification. Quartz grains are well-rounded, and poorly sorted. There is average 40% of quartz in these rocks. This lithofacies has no visible porosity.

Overall FA 2.2 has sharp upper and lower contacts. It is bounded at the bottom by FA 3 or FA 4 or Madison Fm. at the top. The upper boundary is regionally erosional with low angle truncation below and low angle downlap above. The lower boundary is very
sharp and is seen in all outcrops. It is a boundary between more shaly laminated rocks below and thick bedded to massive beds above.

4.4 Facies Association 3 (FA 3)

FA 3 is made of lithofacies D, E, F and G:

1. **Lithofacies F: Laminated dolostone (Figure 4.6).**

   This lithofacies is made up of inequi- to equigranular, mosaic dolosparstone. It is yellow to brown in color, has planar lamination, and is frequently fractured.

![Figure 4.6 Fractured dolosparstone, lithofacies F (yellow resistant beds) laminated with dolomicrostone, lithofacies D (grey thin beds weather in a shaly manner), Gallatin Forest outcrop, Three Forks Fm.](image)

2. **Lithofacies G: Dolostone with stromatolites**

   Lithofacies G is comprised of dolosparstone displaying an equigranular, mosaic, and sutured texture, with coarse silt size crystals that form laterally linked stromatolites (Figure 4.7). Stromatolite growth lines are demarcated by lamina of fine sand size dolomite rhombs. There is 5% of calcite, and about 5% porosity. Thickness varies from 40 to 50 cm. This facies is developed in the upper part of the outcrop in the Beartooth Mountains, and lower part of the outcrop in the Shoshone Canyon locality near Cody, Wyoming.
4.5 Facies Association 4 (FA 4)

FA 4 is represented with lithofacies D, E and F, H and I:

1. Lithofacies H: *Cryptalgalaminated dolostone with rip-up clasts and desiccation cracks*.

Lithofacies H is a buff to brown dolostone. Crystal size can vary from dolomicrosparstone to dolosparsstone (coarse silt). Crystals are inequ- to equigranular, and occur in a mosaic, fogged to sutured texture. This lithofacies is commonly laminated and laminations are flat to crinkly.

Beds in lithofacies H vary from planar laminated, dolosparsstone containing rip-up clasts to dolosparsstone with algal mat rip-up clasts (Figure 4.8 A). Algal mats have a clotted structure. Cryptalgalamination can fill horizontal veins and vertical desiccation cracks.

The abundance of calcite generally does not exceed 10%. It generally fills fractures or fenestral pores in the cryptalgalamine (Figure 4.8 B). Dead oil was observed in some intervals. Porosity varies from 3% to 14%.
Figure 4.8 Lithofacies H, Three Forks Formation. A: dolostone with rip-up clasts and desiccation cracks, Cottonwood Canyon; B: cryptalgalaminate with clotted structure and calcite filling fenestral pores, sample FC 14, ‘Fallen City’; C: tidal channel, ‘Fallen City’; D: fenestral porosity, Shoshone Canyon; E: tepee structure, Shoshone Canyon.
In the eastern Big Horn outcrop a small tidal channel was observed. It is 0.5 meters deep and about 3 meters wide (Figure 4.8 C). It is difficult to measure width precisely, because only one bank of the channel is seen. In the Shoshone Canyon, there is fenestral porosity that is open or filled with calcite (Figure 4.8 D). Tepee structures are present in the upper part of the section (Figure 4.8 E).

2. Lithofacies I: Purple colored lag with symmetrical ripples (Figure 4.9).

In the Clarks Fork Canyon outcrop, in the lower part of the section, purple colored cross-laminated lags are observed. Their thickness does not exceed 2 cm. They contain symmetrical ripples. In petrographic thin sections, this lithofacies is a peloidal dolosparstone, that is comprised of a mosaic of inequigranular crystals that have a fine sand crystal size. Lithofacies I contains about 10% of organic matter along layers, and approximately 2% porosity.

FA 4 has sharp to gradational contacts, and is commonly bounded by FA 5, FA 3 or FA 2.2.

4.6 Facies Association 5 (FA 5)

This FA is not widely present in the study area. It is rarely present in the outcrop and mostly found in the core (well 25-M LBB). It is represented by lithofacies E and J –
dolomicrostone with anhydrite nodules (Figure 4.10). Lithofacies J is an aphanotopic dolomicrostone with anhydrite nodules. In the Beartooth Mountains outcrop a dissolution breccia was found. It has disorganized wavy lamination and loading structures. No significant porosity was observed in thin sections. Contacts range from sharp to gradational, and this FA is generally bounded by FA 3 and FA 4.

![Image](image_url)

Figure 4.10 Lithofacies J, Three Forks Formation. A: dolomicrostone with anhydrite nodules (white), well 25-M LBB; B: photomicrograph, dolomicrosparstone with anhydrite (bright grain), sample 10A, well 25-M LBB.

Table 1 summarizes the lithofacies descriptions and their relation to the facies associations. FA 2.1, 3, 4 and 5 are similar to the ones interpreted in the Williston basin by Gantyno, 2010: FA 5 – open marine (Sanish member), FA 4 – lower intertidal, FA 3 – upper intertidal and FA 2 – lower supratidal sabkha. Gantyno’s FA 1, upper supratidal sabkha, was not interpreted in this study.

### 4.7 Interpretation

FA 1 (lag with conodonts) is located in the upper part of the Gallatin Forest section and consists of only one lag. The lag with conodonts and plant debris is a clearly transgressive one, with the Bakken Fm. above it showing landward shift of the shoreline. This lag is interpreted as a subtidal transgressive lag.

FA 2.1 was interpreted only in the western Big Horn outcrop. Horizontal burrows formed by *Thalassinoïdes isp* signify open marine environments of deposition. Uniform dolomite rhomb size (coarse silt to fine sand) within this FA, its massive character,
Table 1 Lithofacies and lithofacies associations present in the Three Forks Fm.

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Name</th>
<th>Description</th>
<th>Facies Association</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>lag with conodonts and plant debris</td>
<td>transgressive lag with conodonts, plant debris, sub-rounded scattered silt size quartz, 3% porosity.</td>
<td>FA 1</td>
</tr>
<tr>
<td>B</td>
<td>yellow massive dolosparstone with horizontal burrows</td>
<td>yellow dolosparstone with coarse silt to v. fine sand size crystals, massive, moderately bedded (25cm thick), Thalassinoides isp. burrows, heavily dolomitized, 5% Q.</td>
<td>FA 2.1</td>
</tr>
<tr>
<td>C</td>
<td>massive dolosparstone with calcite nodules</td>
<td>light yellow to pink, peloidal dolosparstone with medium silt to very fine sand size crystals, massive, vertical burrows, anhydrite nodules, brachiopods, crinoids, dead oil, 3% Q.</td>
<td>FA 2.2</td>
</tr>
<tr>
<td>D</td>
<td>laminated dolomicrostone</td>
<td>dolomicrostone, thinly laminated, fissile, forms thin (1 cm-5 cm) layers.</td>
<td>FA 2.2, 3, 4</td>
</tr>
<tr>
<td>E</td>
<td>dolosparstone with sand lenses, lag deposits</td>
<td>yellow, green, purple dolosparstone, sand lenses of medium and coarse sand size quartz, in one location conodonts and plant debris, sand could be in clinoforms.</td>
<td>FA 2.2, 3, 4, 5</td>
</tr>
<tr>
<td>F</td>
<td>laminated dolosparstone</td>
<td>yellow, brown, dolosparstone. It has planar laminated frequently with lithofacies C, no tidal features.</td>
<td>FA 3</td>
</tr>
<tr>
<td>G</td>
<td>dolosparstone with stromatolites</td>
<td>dolosparstone, coarse silt size crystals, laterally linked stromatolites, 50 cm thick.</td>
<td>FA 3</td>
</tr>
<tr>
<td>H</td>
<td>algal dolostone with rip-up clasts and desiccation cracks</td>
<td>buff to brown dolostone, algal mats, rip-up clasts, desiccation cracks, loading structures, ti-ri structures, tidal channels, dead oil.</td>
<td>FA 4</td>
</tr>
<tr>
<td>I</td>
<td>purple lag with symmetrical ripples</td>
<td>lag, purple, cross-laminated, peloidal dolosparstone, symmetrical ripples, 10% OM.</td>
<td>FA 4</td>
</tr>
<tr>
<td>J</td>
<td>dolomicrostone with anhydrite nodules</td>
<td>dolomicrostone with anhydrite nodules, disorganized wavy lamination, algal rip-up clasts, loading structures</td>
<td>FA 5</td>
</tr>
</tbody>
</table>
limited lateral distribution, and its association with FA 2.2 lagoon deposits suggests FA 2.1 was deposited as a high energy, subtidal to shoaling deposit. This FA is referred to as equivalent to the Sanish Member of the Three Forks Formation in the Williston basin.

FA 2.2 is a peloidal dolosparstone with scattered calcite nodules and vertical burrows filled with anhydrite. Calcite nodules have round shape, are hollow inside and have ‘flow’ texture. This is typical for the secondary calcite that replaces anhydrite. In thin sections, dolomite rhombs have ‘dusty’ center that indicates original dolomitization from mud. So FA 2.2 is interpreted to be deposited in a back-barrier lagoon environment.

FA 3 through FA 4 show signs of tidal influence (Table 2). FA 3 is planar and wavy laminated dolomicrostone with occasional stromatolites. This FA does not show any significant tidal signs, but in context with FA 4 it could be interpreted as lower intertidal deposits. In FA 4 very distinctive features were seen like rip up clasts, desiccation cracks, rhythmic lamination, suggesting periodic subaerial exposure that occurred in the upper intertidal zone. There are algal mats with clotted structure and rip up clasts, and fenestral pores generated by gas escape during decay of the mats.

FA 5 is composed of carbonate mud showing low energy environments of deposition and disturbed lamination with scattered anhydrite nodules. Low energy restricted environments identify supratidal zone. Occasional lags in FA 5 and FA 4 signify transgressive events bringing thin layers of coarser deposits.
Table 2 Facies associations in the Three Forks Formation. Colors are the same as in the depositional model.

<table>
<thead>
<tr>
<th>Facies Associations</th>
<th>Description</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FA 1</td>
<td>Transgressive lag with multiple conodonts, plant debris, sub-rounded scattered silt size quartz. Lower boundary is erosional.</td>
<td>Subtidal</td>
</tr>
<tr>
<td>FA 2.1</td>
<td>Dolosparstone with dolomite rhombs of coarse silt to very-fine sand size, light yellow, massive, <em>Thalassinoides isp.</em>, bioturbation, moderately bedded (25 cm), structureless within individual beds, contains 5% of quartz, rare authigenic muscovite and glauconite, average porosity is 8% from dolomite dissolution. Rocks are hardly dolomitized, so the original fabric is not seen. Overall showing transgressive phase deposition. Bounded at the bottom by facies succession FA 4.1 with sharp contact.</td>
<td>Open Marine</td>
</tr>
<tr>
<td>FA 2.2</td>
<td>Dolopackstone, peloidal, with dolomite rhombs of coarse silt to fine-grained sand size, light yellow to pink in color, massive, thickly bedded (50 cm) to thinly bedded (5 cm), horizontal lamination of slightly different colors, vertical bioturbation, secondary calcite nodules after anhydrite, contains rare quartz grains (2-3%), porosity from dolomite dissolution is about 8%. In the Black Hills area fossils were found: bryozoans, crinoids, brachiopods, molluscs. Overall has deepening upward cycles with lower contacts. Bounded by FA 4.1, FA 2 and FA 1.</td>
<td>Back Barrier</td>
</tr>
<tr>
<td>FA 3</td>
<td>Dolosparstone, yellow, parallel and wavy lamination, with rare planar or close laterally linked stromatolites, with shallowing upward successions, sharp upper and lower contacts. Bounded by FA 4.1, FA 2 and FA 1.</td>
<td>Lower Intertidal</td>
</tr>
<tr>
<td>FA 4</td>
<td>Dolomicrostone to dolosparstone, buff colored, laminated (5 cm), contains desiccation mudcracks, algal mat, fenestral porosity, rip up clasts, ripples, wavy lamination, has lags with cross-laminated material and lenses of coarse quartz, has sharp to gradational contacts, has shallowing upward cycles. This FA association is commonly bounded by FA 1, FA 3 or FA 4.1.</td>
<td>Upper Intertidal</td>
</tr>
<tr>
<td>FA 5</td>
<td>Dolomicrostone pink to brown with anhydrite nodules, dissolution breccia, disorganized wavy lamination, rarely present in the outcrop and mostly found in the core. Overall has shallowing upward stacking pattern. Contacts are from sharp to gradational. Bounded with FA 2.</td>
<td>Supratidal</td>
</tr>
</tbody>
</table>
5.1 Paleogeographic Setting

The Three Forks Formation was deposited in a restricted epeiric sea. Epeiric seas are characterized by gentle dips of the sea floor, and shallow water depths. They occupy large territories of low topography, and covered vast areas of the North America craton in the late Devonian time (Tucker and Wright, 1996). Tides, especially in the channels, and storms influenced sedimentation. Water depths were shallow, perhaps less than 10 m, and environments ranged from shallow subtidal, with occasional lagoons, to intertidal and supratidal sabkha environments. Tidal flats were developing around slightly elevated areas. Deeper and shallower places probably reflected pre-existing topography (Irwin, 1965).

Gantyno (2010) and Berwick (2008) describe similar depositional environments in their work, with the exception of the lagoonal environments identified in this study. Also, in the Williston basin there are more anhydritic supratidal rocks than in Wyoming and Montana. The Williston basin was a topographically low area at that time with larger accommodation that allowed accumulation of thicker Three Forks Formation. In the beginning of Three Forks time, when bedded anhydrite accumulated in the Williston basin, there may have been low-energy, stagnant environments in Montana and Wyoming with extremely low accumulation rates, or even areas of non-deposition or hiatus.

Figure 5.1 shows a palogeographic reconstruction of late Devonian time in the study area. There were paleo-highs and paleo-lows. Deeper areas include the Antler foreland basin, Central Montana Trough, Powder River Basin and Williston Basin. Shallow regions are the Central Montana Uplift, the paleo-Absaroka high, and the Big Horn and Black Hills uplifts. The Central Montana Uplift is present in the western and central parts of Montana. Sandberg (1962) described a section in Montana, near the town of Logan that later became a type section for the Three Forks Formation and is located within the Central Montana Trough. He measured 73 m of the Three Forks Formation there, suggesting the presence of a paleo-low. No data proving connection of the Williston Basin and the Central Montana Trough were found. In the western part of
Montana, a carbonate bank developed. It separated the Central Montana Trough from the Antler foreland basin, and may have been one of the factors that formed restricted environments in Montana (Peterson, 1981). The Transcontinental Arch was a source of sediments, in addition to the continental landmass to the NE. The cross-section A-A’ from east to west (Figure 5.1) that connects the outcrops of this study shows different paleo-relief that influenced sediment accumulation and outcrop thicknesses (Figure 5.2).

Figure 5.1 Paleogeographic reconstruction of the late Devonian time (modified after Sonnenfeld, 1996).

5.2 Correlation

For correlation of outcrops and the one core, the character of the lower and upper contacts as well as of other possible significant surfaces within the Three Forks Formation become particularly important. The lower boundary of the Three Forks
Formation with the late Devonian Birdbear Formation (Nisku Formation, western Canada Deep Basin) in most of the outcrop locations is unconformable. In the Black Hills outcrops, Ordovician rocks underlie the Three Forks Formation. In these locations, the lower boundary is unconformable due to widespread but gentle erosion, resulting in the regional truncation between Upper Devonian and Ordovician rocks (Peterson, 1981). The lower boundary follows the paleo-relief of the late Devonian time, including onlap onto paleo-uplifts in the Black Hills, Big Horn and paleo-Absaroka mountain areas (Figure 5.2). The Three Forks appears to fill in the paleo-relief at the late Devonian time, and facies associations do not change rapidly along the profile. The stratigraphic profile from west to east in Figure 5.2 also shows the upper boundary of the Three Forks with approximately 20 m of erosion.

In the lower part of the Three Forks Formation mostly upper, and minor lower intertidal and supratidal facies are interpreted, and these consist of dolomite, evaporite and clastic sediments. The Birdbear Formation, underlying the Three Forks Formation in most of the locations, comprises a number of facies including stromatoporoid and coral bearing dolomite, fossiliferous limestone, evaporite, and shaly limestone (Peterson, 1981). In other places such as the Black Hills, the underlying Ordovician rocks are marine shales, limestones and fossiliferous dolomites with no clastic admixture (Peterson, 1987). This abrupt and sharp change in facies is interpreted to represent a sea level fall and subaerial exposure, and the lower contact of the Three Forks Formation is interpreted to be a Type 1 sequence boundary. This boundary type is characterized by intense erosion, abrupt basinward shift of facies and coastal onlap. It happens when the rate of eustatic fall exceeds basin subsidence, producing relative sea level fall (Emery and Myers, 1996). The stratigraphic profile shows erosion that may be greater then 20 m (Figure 5.2).

The upper boundary with the Madison Formation displays regional erosion. In the eastern Big Horn outcrop a low angle downlap is interpreted to occur above the top Three Forks, and top truncation below the boundary (Figure 5.3). The Gallatin Forest outcrop displays a transgressive lag deposit of early Mississippian age that occurs on the top Three Forks and correlates to the base of the upper Bakken shale, indicating a late Devonian-earliest Mississippian hiatus. These observations suggest that the upper contact
Figure 5.2 Correlation of outcrops and a well from west to east in a sequence stratigraphic framework. Location of the cross section is on the map in red. For more detailed sections see Appendix A and B.
Figure 5.3 ‘Fallen City’ outcrop, interpreted in a sequence stratigraphy framework, eastern Big Horn Mountains.
is a Type 1 sequence boundary. These sequence boundaries were considered as a datum for the cross-section, but because of the paleotopography and erosion on both of them, they were not appropriate for this purpose.

Within the sequence there is a sharp surface at the base of the FA 2.2 in all locations (Figure 5.2). It marks an abrupt change from laminated tidal flat facies to massive lagoon or laminated lower intertidal facies (most prominently shown in the Gallatin Forest outcrop), suggesting a regional deepening. This surface is interpreted as a Transgressive Surface (TS) and was chosen as a datum for the cross-section. It corresponds to the time when relative sea level rose across the area. The cross-section was constructed (Figure 5.2) from west to east, from the Big Snowy Mountains, through the Beartooth Mountains, the Absaroka Range, the Big Horn Mountains and the Black Hills Uplift.

5.2.1 Lowstand Systems Tract

Thickness of the Three Forks Formation varies from 5 m in the Clarks Fork Canyon outcrop to 28 m in the Gallatin Forest outcrop. Strata below the TS fill the paleo-lows, and are interpreted to onlap the paleo-highs. Strata above this surface are deposited almost horizontally, parallel to the TS. Strata below the TS were deposited in the upper and lower intertidal, supratidal and lagoon environments. This interval is interpreted to represent a Lowstand Systems Tract (LST). In the LST, six shallowing upward cycles or parasequences (PS) are interpreted. Van Wagonner (1990) describes a parasequence as a relatively conformable succession of genetically related beds and bedsets bounded by marine flooding surfaces. Marine flooding surface is a surface separating younger from older strata across which there is evidence of an upward increase in water depth (Emery and Myers, 2008).

The PS have different appearance and correlation criteria in the western part and the eastern part of the study area. In the western part of the study area three shallowing upward cycles were correlated. They are represented by thickening and coarsening upward dolomite layers and thinning upward clayey dolomite layers. At the end of every cycle there is a flooding event represented with an abrupt change in the stacking pattern and in the grain size to clayey dolomite (Figure 5.4).
In the eastern part of the study area the shallowing upward pattern is less distinctive. PS were correlated based on the top of the chaotic dolomite facies and transgressive quartz lags. The three lower cycles consist of mainly upper intertidal facies, with lower intertidal and lagoon facies in the eastern part of the profile in the Shoshone Canyon, well 25-M LBB, and in the Cottonwood Canyon.

The upper four cycles in Cottonwood Canyon, and all cycles in the Northern Black Hills outcrop are not shown. They have a uniform clayey composition. PS boundaries were pushed through them at the same level as they are in the nearest outcrops.

Cycles aggrade and thin upward. The western most part of the profile is the thickest. In the late Devonian time, the Beartooth shelf, proximal to the Central Montana trough, and northern Black Hills area, close to the Williston basin, were paleo-lows and had greater accommodation.

Figure 5.4 Part of the correlation profile in the LST bounded by the TS, with upper three shallowing upward PS. Further explanation is in the text.
5.2.2 Transgressive Systems Tract

The more subtidal rocks above the TS are interpreted to be a Transgressive System Tract (TST) according to the facies associations present there and previous works. No Highstand Systems Tract is present above the TST, and suggests erosional removal (Figure 5.2 and 5.3). The LST sediments appear to fill paleo-lows while the TST were deposited almost parallel to the Transgressive Surface. Six shallowing upward cycles were interpreted.

PS were distinguished based on shallowing upward pattern, when on the top of every cycle there is an abrupt change in the grain size, from a very fine grained to clay size, and lithology, from dolomite to clayey dolomite below showing a flooding event. To the east from the well 25-M LBB eastward, this pattern is not that distinctive. In Cottonwood Canyon, cycle boundaries in the tidal bar facies are represented by the bottoms of clayey dolomite layers within the fine dolomite. Flooding events bring deeper, finer sediments on the top of the coarser tidal bar, preserving burrows. Burrows in the outcrops were seen only on the bottom parts of the beds, on the boundary with finer dolomite rocks. Coarse, clay free sediments within the bar tend not to preserve burrows. Eastward from the ‘Fallen City’ outcrop PS boundaries are placed at the same level as in the western outcrops.

Figure 5.5 shows decrease of the flooding intensity from west to east, from the well 25-M LBB to the ‘Fallen City’ section. The well 25-M LBB has five distinctive PS. The ‘Fallen City’ outcrop on this figure shows the lowest cycle in the TST from the Figure 5.3. It reflects only several distinctive PS. In the Black Hills outcrops cycles are not seen. PS boundaries were placed at the same level as in the nearest outcrops to the west.

According to this correlation, flooding events had different intensity throughout the profile and are reflected differently. Flooding and tidal signs are strongest in the western localities, near the Antler Foreland basin. As we move eastward, further away from it and closer to the Williston basin, cycles become less pronounced.

Gantyno (2010) interpreted sequence boundaries at the top and base of the Three Forks Formation, and LST and TST with TS in between them. He recognized three cycles in the LST and three cycles in the TST. Sections in the Williston basin are much thicker
Figure 5.5 Part of the correlation profile in the TST, with four shallowing upward PS. Cycles become less pronounced from left to right.

than in the studied area, so cycles in a current work and cycles from Gantyno (2010) work are in different scales and their correlation appears to be difficult.

Berwick (2008) interpreted SB at the top of the Three Forks Formation, a bounding disconformity at the base of the Sanish member and a flooding surface within it in some cores. In the current study, the Sanish member was interpreted in one location (Cottonwood Canyon). Below the Sanish member in Cottonwood Canyon is a flooding surface, no disconformity was observed.

5.3 Depositional Model

Upper Devonian time is the time of the Antler orogeny when the Antler foreland basin was forming. To the east of the foreland basin, in the western part of Montana, a
carbonate bank developed at that time (Peterson, 1981) (Figure 5.1). It is known that carbonates tend to grow on highs, so this carbonate bank may have grown on the forebulge and the rest of the platform eastward was a shallow back-bulge basin. In this shallow restricted basin there were tidal flats and lagoons. In order to show these various environments a depositional model by Reinson (1984) has been modified (Figure 5.6). This model is not to scale.

During the Three Forks lowstand mostly upper intertidal (FA 4) and supratidal (FA 5) FA accumulated. These facies were forming broad tidal flats with tidal creeks. There were occasional small lagoons (FA 2.2), surrounded by lower intertidal facies (FA 3). Later, during the transgression, lagoon deposits with seaward situated coarser grained and well sorted shoals were deposited (FA 2.1). Lagoons occupy the major part of the studied area with lower intertidal facies deposited in the northern Beartooth Mountains and in the Big Snowy Mountains, located on the Central Montana Uplift. The large carbonate bank in the western part of Montana and localized tidal bars and paleo-highs provided restriction in the studied area for lagoonal deposition.
Figure 5.6. Depositional model with tectonic framework, modified after Reinson 1984.
6.1 Data Overview

The Three Forks Formation consists of 90% dolomite. Crystal size and texture varies greatly. Dolomite in the open marine (FA 2.1) and lagoonal facies (FA 2.2) is mostly equigranular dolosparstone with a sutured and sieve fabric, and crystals of silt to very fine sand size (Figure 6.1 A). Crystals with ‘dusty’ centers and clear rims are common (Figure 6.1 B). In the Black Hills outcrops, rocks from the lagoonal facies are represented with inequigranular dolomicrospartone (Figure 6.1 C). In the intertidal facies (FA 3, 4) inequigranular dolomicrosparstones with contact–rhomb and floating rhomb textures are common (Figure 6.1 D). Aphanotopic dolomite is present in the supratidal facies within cryptagalaminites.

Figure 6.1. Types of dolomite present in the Three Forks Formation. A: equigranular dolosparstone, sutured texture, sample CC 8, FA 2.1, Cottonwood Canyon; B:
equigranular dolosparstone, sieve texture, sample FC 13, FA 2.2, ‘Fallen City’; C: inequigranular dolomicrosparstone, contact-rhomb texture, sample NBH 5, FA 2.2, North Black Hills; D: inequigranular dolomicrosparstones, contact–rhomb texture, sample CF 4, FA 4, Clarks Fork Canyon. Porosity is in blue.

6.2 Dolomitization

There are different views regarding the dolomite problem. Strakhov (1953, in Chilingar, 1956) believed that during the Precambrian and the Paleozoic, due to the high concentration of $\text{CO}_2$ in the atmosphere, high concentrations of $\text{Ca}^{2+}$ and $\text{Mg}^{2+}$ occurred in sea water, and dolomite precipitated directly from the sea water. Direct precipitation of dolomite is happening even now in the eastern part of the Lake Balkhash in Kazakhstan.

Most geoscientists today consider dolomites to be diagenetic in origin rather than being a result of direct precipitation from the sea water. The reaction proceeds according to:

$$2\text{CaCO}_3 + \text{Mg}^{2+} = \text{CaMg(CO}_3)_2 + \text{Ca}^{2+}$$

If the replacement of $\text{Ca}^{2+}$ by $\text{Mg}^{2+}$ is mole to mole and $\text{Ca}^{2+}$ ions are removed, porosity increase takes place. In most cases, volume to volume replacement happens and $\text{Ca}^{2+}$ ions are not removed. This could lead even to porosity reduction (Chilingar, 1956). According to Moore (2001) dissolution by meteoric waters is still the main process enhancing reservoir quality.

Mountjoy and Marquez (1997) studied the dolomitization process and porosity evolution in the Upper Devonian Leduc buildup, in the Deep Alberta Basin. When modified, their study could be used in the current work (Figure 6.2 and 6.3). After sedimentation of wackestones or lime mudstones, gypsum precipitates from pore fluids removing $\text{Ca}^{2+}$ from the system, and increasing the molar $\text{Mg}^{2+}/\text{Ca}^{2+}$ of the fluid. It is favorable for the formation of dolomite, so nucleation and early dolomite growth starts (Patterson and Kinsman, 1977; McKenzie, 1981, in Moore, 2001). For this process to be effective lime mud should have primary permeability and porosity. Further dolomite patches form in the matrix around these nucleation sites. Dissolution of possible skeletal grains, dolomite rhombs, anhydrite and fracturing could start at the later stage of the dolomitization process (Figure 6.2). It is a very simplified model. Many more stages of dolomitization and dissolution can take place. The resulting dolomite fabric depends on original grain size and salinity. The larger the grain size is and/or the higher the salinity,
the coarser the dolomite rhombs are (Moore, 2001; Humphrey J.D., personal oral communication).

![Diagram showing dolomitization process]

Dolomite rhombs within a certain FA generally have similar sizes. They have ‘dusty’ centers and clear rims suggesting an original muddy substrate and a later stage of dolomite growth (Figure 6.1).
All the above, in context with lagoon–tidal-flat depositional model suggests that the reflux dolomitization model may be appropriate for the Three Forks dolomitization. Intensive evaporation lowers the water level and increases specific gravity of the remaining brine. Light marine waters inflow to the lagoon, where dense evaporated marine waters percolate downwards creating a pycnocline, and dolomitizing underlying rocks. King (1947) called seaward escape of dense brines a reflux action (Adams, 1960).

Moore (2001) listed six major criteria for recognition of ancient reflux dolomites. He listed them in decreasing order of reliability: (1) close relation of dolomite to an evaporite sequence that is subaqueous in origin; (2) geologic settings should be appropriate for the development of a barred basin or lagoon; (3) dolomites should be porous enough and have hydrologic continuity at the time of dolomitization; (4) reflux dolomites should show dolomitization gradient; (5) reflux dolomites have coarser crystal size than dolomite formed in the sabkha; (6) increasing Sr and Na trace elements, and increasing \(^{18}O/^{16}O\) ratio suggests an evaporative brine source.

All criteria above are right for the Three Forks Formation, with the exception of (4) and (6). Dolomitization gradient is not seen due to several episodes of dolomitization and its complex nature. Trace element and stable isotope analyses were not conducted.

The reflux dolomitization model developed by Kendall (1988) was modified and applied to the Three Forks Fm (Figure 6.3).

Figure 6.3 Reflux dolomitization model in lagoon, modified after Kendall (1988).

Cathodoluminescent microscope zoning in dolomite and calcite was observed, and suggests that the Three Forks Formation underwent multiple dolomitization episodes.
From cathodoluminescence analyses, three types of dolomite could be identified (Figure 6.4):

1. bright outer zones and sometimes cores – low Fe $^{2+}$
2. dark red crystal interiors – high Fe $^{2+}$
3. black micrite - high Fe $^{2+}$

These three different types of dolomites were interpreted to represent three episodes of dolomitization.

Firstly, Fe $^{2+}$ poor, red dolomite formed. It can form as a micrite, if there are many nucleation sights, or sparite, if there are few of them. This is interpreted to be an early episode of dolomitization. This episode can be seen in the brighter crystal cores and outer zones on Figure 6.4 A-A’ and in the bright red nucleation sites within the micrite mass on Figure 6.4 B-B’. The second phase happened during shallow burial, when dark red dolomite, slightly higher in Fe $^{2+}$ concentration replaced the earlier bright red crystals. This dolomite replaces crystal interiors. Crystal interiors may have abundant inclusions and irregular structure that provides fluid flow pathways and makes them more susceptible to the dissolution than the outer parts. On Figures 6.5 A-A’ and C-C’ dolomite rhombs have bright outer ring and a core, but the middle part is dark red, showing the second dolomitization episode. The third dolomitization stage, during the deep burial, occurs when Fe $^{2+}$ poor dolomite that is red is altered to Fe $^{2+}$ rich dolomite (Figure 6.4 B-B’).

Berwick (2008) distinguished two types of secondary dolomite in his thesis. They are an early (shallow dolomitization) dolomite with very fine size crystal and a late dolomite (deep burial) with larger, fine to medium size crystals.

### 6.3 Porosity

At the end of Three Forks time, regional exposure and erosion took place, when dolostones were dissolved by meteoric waters forming secondary porosity. Point counting for porosity showed that the Sanish member or barrier facies have only intercrystalline porosity formed due to dolomitization, while lagoon and tidal-flat facies have additional moldic, vuggy and fracture porosity that resulted from dissolution (Figure 6.5). Intracrystalline porosity was observed mainly in the lagoon facies. Figure 6.1 B
Figure 6.4 Cathodoluminescent microscope photomicrographs on the left and corresponding standard microscope photomicrographs on the right. **A, A’**: zoned calcite and dolomite due to different dolomitization episodes, sample FC 15, FA 2.2, ‘Fallen City’, eastern Big Horn Mountains; **B, B’**: multiple bright orange calcite nucleation cites and later dull luminescent Fe$^{2+}$ rich dolomite cement with larger zoned rhombs, sample 3A, FA 2.2, well 25-M LBB; **C, C’**: zoned dolomite with brighter core and outer part and with darker middle part, sample FC 15, FA 2.2, ‘Fallen City’.
shows pore space within the crystals. This type of porosity occurs due to solution of larger crystals by meteoric waters.

Samples from FA 2.1 showed 8% porosity consisting of intra-/ intercrystalline porosity. In the FA 2.2 two samples were point counted for porosity. The first one showed 13% total porosity consisting of 67% intra-/intercrystal, 15% vuggy, 11% moldic and 1% fracture porosity. The second sample has 10% of total porosity consisting of 51% intra-/intercrystal, 33% vuggy and 16% fracture porosity. FA 3 has 15% porosity including 20% intra-/intercrystal porosity. FA 4 has 14% porosity consisting of 73% intercrystal, 20% vuggy and 7% fracture porosity (Figure 6.6). FA 5 did not show any porosity under microscope.

![Pore type graph](image)

**Figure 6.5.** Porosity types in different FA using point counting technique.

6.4 Diagenetic History

The diagenetic history of Three Forks has been interpreted from petrographic thin-sections (Figure 6.7). All facies associations are heavily dolomitized. Original fabric and fossils in many thin-sections are not seen even when using the ‘white card’ technique. This simple method requires putting a white paper underneath a thin-section and viewing it under transmitted plane-polarized light. It enhances recognition of the original fabric (Dravis, 1990). Other processes imprint the dolomite fabric. Anhydrite precipitation
Figure 6.6 Types of porosity. A: Pore types present: intercrystalline (BC), moldic (MO), and microvug (VUG), 13% total porosity, sample 17A, FA 2.2, well 25-m LBB; B: Pore types present: intercrystalline, and microvug, 10% total porosity, sample 17A, FA 2.2, well 25-m LBB; C: Pore type present: intercrystalline, 8% total porosity, sample CC 7, FA 2.1, Cottonwood Canyon, western Big Horn Mountains; D: Pore type present: intercrystalline, 15% total porosity, sample FC 1, FA 3, ‘Fallen City’, eastern Big Horn Mountains; E: Pore types present: intercrystalline, microvug, and fracture (not seen on the figure), 14% total porosity, sample FC 9, FA 4, ‘Fallen City’, eastern Big Horn Mountains.
occurred during and after dolomitization. Thin-sections show how anhydrite is ‘growing’ into dolomite, and filling available pore space (Figure 6.7A). Anhydrite has a poikilotopic texture suggesting that cementation occurred very early in the geologic history. Compaction takes place during the whole history of the rock starting from its deposition. At the end of Three Forks time regional exposure and erosion took place. At that time meteoric waters dissolved anhydrite and dolomite creating secondary porosity. Some pore space remains (Figure 6.8 B), and characteristic rectangular pores after anhydrite are observed. Figure 6.8 C shows a ‘flow’ texture of calcite inherited after anhydrite. Fracturing and stylolitization (Figure 6.8 E.) have occurred as a result of multiple orogenic events, including the Antler orogeny. Both vertical and horizontal stylolites were observed in the well from the western part of the Big Horn basin caused by the Laramide orogeny. Most of the samples were collected from the outcrops so they show changes common for surface processes such as calcite replacement of anhydrite, and dedolomitization (Figure 6.8 D) that are not widely seen in the subsurface.

<table>
<thead>
<tr>
<th>DIAGENESIS</th>
<th>TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolomitization, pore formation</td>
<td>early</td>
</tr>
<tr>
<td>Anhydrite precipitation</td>
<td></td>
</tr>
<tr>
<td>Compaction</td>
<td></td>
</tr>
<tr>
<td>Exposure</td>
<td></td>
</tr>
<tr>
<td>Calcite replacement of anhydrite</td>
<td></td>
</tr>
<tr>
<td>Dedolomitization</td>
<td></td>
</tr>
<tr>
<td>Fracturing</td>
<td></td>
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<tr>
<td>Stylolitization</td>
<td></td>
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<td>late</td>
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Figure 6.7. Diagenetic history of the Three Forks Formation interpreted from the thin-sections.

Work conducted by Gantyno (2010) on Williston basin cores shows some differences with this study. He recognized cementation by illite, chlorite and pyrite. This could be connected with his study’s more proximal location to the sedimentary source, which is the continental interior to the northeast, and also to surface processes in the outcrops.
Figure 6.8 A: anhydrite precipitation, sample 16A, FA 5, well 25-M LBB; B: anhydrite dissolution, sample 5A, FA 2.2, well 25-M LBB; C: ‘flow’ texture in calcite, calcite replacement of anhydrite, sample SC 13, FA 2.2, Absaroka Range, Shoshone Canyon; D: dedolomitization, sample SC 12, FA 2.2, Absaroka Range, Shoshone Canyon; E: horizontal stylolite with dead oil along it, sample 5A, FA 2.2, well 25-M LBB.
CHAPTER 7
FRACTURE ANALYSES

7.1 Data Overview

Regional fracture data was collected from outcrops and from the literature. Angster (2010) collected fracture measurements from Bakken and Lodgepole Formation outcrops in the Big Snowy and Little Rocky Mountains, Montana, and from Clarks Fork Canyon in the Beartooth Mountains. Literature from the Williston basin, in the North Dakota by Narr and Burrus (1987), Strum and Gomez (2009) describes fractures in two cores – Anhel Grassy Butte No. 12-31 H3 and Rauch Shapiro Fee 13-3. They all show three predominant directions in the Williston basin (Figure 7.1). These are NW, NE and S-N (Sonnenberg, 2011, in press). In Montana, Wyoming and South Dakota the same fracture trends were observed. In the Big Snowy, Clarks Fork and ‘Fallen City outcrops a strong NE trend was documented. In the Gallatin Forest, Shoshone Canyon and Cottonwood Canyon outcrops a strong NW trend occurs. In the Shoshone Canyon, ‘Fallen City’ and Black Hills outcrops, a N – S trend is observed.

Most of the fractures are close to vertical. Stereonets display dips of fractures using Fisher concentrations in Figure 7.2. They show where poles normal to the fault planes cross the lower half-sphere. The warmer the color on the stereonet, the higher the pole density is, and the higher the fracture concentration in the selected area. Poles plotted in the middle of the stereonet circle signify horizontal fracture planes. Poles plotted near the edges of the circle annotate almost vertical fracture planes. Data from this study show a dominant vertical and near vertical orientation for Three Forks fractures. Angle between fracture planes is usually from 70 to 90 degrees. General spacing between major fractures of similar direction is 20 cm and less.

7.2 Mechanical Stratigraphy

There are confined and unconfined fractures in the Three Forks Formation. Confined fractures occur within several beds. Unconfined ones pass through the whole Three Forks Formation and go upwards, to the Madison Formation and downwards, to the Birdbear Formation.
Figure 7.1 Regional map of Wyoming, Montana, South Dakota and North Dakota with fracture trends in the studied outcrops and in the Williston basin. White rose diagrams are from literature. Black rose diagrams show results of Angster (2010) and this outcrop study.

Laminated siltstone layers and massive dolostone layers of the back-barrier facies show the most number of fractures (Fig. 7.3). The lower intertidal facies association is intensively fractured in the Gallatin Forest (Fig. 7.4) and Big Snowy outcrops, where there are better exposures of these facies. This facies association is thinly bedded (1-2 cm thick), enhancing fracturing and horizontal and lateral conductivity between beds. Barrier facies association (FA 2.1) show many fractures in the Cottonwood Canyon outcrop.

The upper intertidal facies association (FA3) is fractured in the Cottonwood Canyon and ‘Fallen City’ outcrops. The barrier facies association (FA1.1) shows less fracture density. More laminated rocks tend to have higher fracture density than massive rocks. The lagoon, tidal bar and thinly bedded (2-5 cm thick) intertidal facies associations demonstrated the most number of fractures. In the tidal bar facies there are approximately
Figure 7.2 Stereonets showing fracture orientations and dips using Fisher concentrations in the studied outcrops.
Figure 7.2 Continued.
four fractures per meter. Spacing varies from 10 cm to 1 m. In the lagoon facies there are about six fractures per meter with average spacing of 15 cm. In the lower intertidal facies there are about six fractures per meter with 15 cm spacing. In the upper intertidal facies there are about ten fractures per meter with 10 cm spacing.

### 7.3 Regional Fractures

Regional fractures are dominant in unfolded areas and are normal to the bedding plane (Lorenz et al, 1991). In tectonically deformed places regional fractures are overprinted by localized ones. Regional fractures generally follow fault trends in the area. Figure 7.5 show regional fault trends. Dominant trends are NE and NW. In Montana and
Figure 7.3 Mechanical stratigraphy of the Three Forks Formation from outcrops, displaying quantity of fractures per given lithology. Colors show different facies associations and are similar to those in the depositional model: orange – FA 1.1, barrier, yellow – FA 1.2, lagoon, green – FA 2, lower intertidal, pink – FA 3, upper intertidal. Red color stands for unconfined fractured.
Wyoming, the NW direction is more pronounced compared to the Williston basin. This could be related to their location in different tectonic blocks. The Williston basin overlies the Trans-Hudson Orogenic belt. Wyoming and Montana overlie the Wyoming craton. Previous local and regional studies emphasize the importance of the wrench tectonics in formation of regional faults, lineaments and fractures. The existing fault pattern of the NE and NW direction is largely a result of strike-slip movements connected with regional strike slip deformation of the whole North America and is basement controlled.
Figure 7.5 Major faults and lineaments in the studied area during Paleozoic (Brown et al, 1982).

Zolnai (1991) in his work suggests that the rhomb-pattern was formed during late Paleozoic by a right-lateral, NW-SE oriented transcontinental megashear that remobilized parts of an earlier structure (mid to late Proterozoic). During the Laramide orogeny faults were reactivated by a conjugate, compressive wrench system of the NW-SE left-lateral and NE-SW right-lateral direction, reverse to those in late Paleozoic. Zolnai (1991) interpreted strike-slip movements in the late Paleozoic as a ‘simple shear’ couple and in the Tertiary as an E-W oriented ‘pure shear’ couple. During this study no shear fractures were documented in the field. The origin of regional fracture trends is still debatable.

7.4 Local Fractures

Local fractures are structure-related fractures. They can be observed throughout a vast area, but only where the similar local structural features are present. Stearns (1964, 1967) found five fracture patterns associated with folds. Only two of them have the most number of fractures and are significant to understanding fold formation (Figure 7.6).
Pattern 1 or hinge perpendicular fracture set includes two conjugate shear fractures and an extension fracture. The principal stress axis (σ₂) is normal to the bedding and the greatest principal stress (σ₁) and the least principal stress (σ₃) are parallel to the bedding plane. σ₁ is along the dip direction. There is a shortening in the dip direction and elongation in the strike direction.

Pattern 2 or the hinge parallel fracture set also consists of two shear fractures and one extensional fracture. The principal stress axis (σ₂) is still normal to the bedding, but σ₁ follows the strike direction and σ₃ – the dip direction. In the Pattern 2, there is elongation in the dip direction and shortening in the strike direction. Theses patterns have relation with the bedding, but not with the fold axis (Stearns and Friedman, 1972).

Fractures from the patterns 1 and 2 have different morphologies. Pattern 1 generally includes large fractures with a single orientation, both laterally and vertically continuous. Pattern 2 never reaches large scale of the pattern 1. It consists of small, connected fractures of all three orientations, generally forming a dense net. This pattern is more effective for fluid conductivity and forms more open systems. But these fractures do not develop until folding progresses in a substantial way.

Figure 7.7 shows rose diagrams with interpreted fracture patterns 1 and 2. In the study area, local structures have NW orientation and local fracture trends overprint regional fracture trends. Pattern 1 has the same orientation as NE regional fractures. Pattern 2 is oriented to the NW. In this case it is difficult to distinguish between local and regional fracture sets. In the Shoshone Canyon and the ‘Fallen City’ outcrops the N-S regional trend is pronounced. In Cottonwood Canyon the NW regional fracture orientation is observed. In most of the outcrops in Montana and Wyoming, with the exception of the Big Snowy and ‘Fallen City’ outcrops, hinge parallel fracture sets include the dominant number of fractures. It could be a result of a slow dip change on the structure limbs. Black Hills Uplift is an elongated dome. Outcrops here have almost circular fracture pattern that is characteristic for domes.
Figure 7.6 The most abandoned fracture patterns associated with the fold. 

A: pattern 1 or hinge perpendicular fracture set; B: pattern 2 or hinge parallel fracture set. These patterns are related to the bedding, not to the fold axis (modified by Angster, 2010 from Stearns and Friedman, 1972).
Figure 7.7 Summary fracture map with locations of outcrops and a well. Pink on rose diagrams shows hinge perpendicular fractures sets, blue – hinge parallel sets.
CHAPTER 8
SUMMARY AND DISCUSSION

The late Devonian Three Forks Formation accumulated in restricted environments of a shallow epeiric sea, at the time of the Antler orogeny, when the Antler Allochthon was thrusting to the east, forming an Antler Foreland basin.

The formation comprises a sequence with a sequence boundary (SB) at the top and at the base. The lower SB follows the relief in the late Devonian time. The upper SB is regionally erosional with more than 20 m of removed strata. In the beginning of the Three Forks time a predominant upper intertidal facies filled paleo-lows and onlapped paleo-highs during a lowstand in sea level. It has five shallowing upward parasequences in it. Later, regional transgression occurred, causing an abrupt change in lithofacies from intertidal dolomicrostone to lagoon dolosparstone. This surface is a Transgressive Surface (TS). After transgression, sediments did not fill paleo-lows anymore but were deposited regionally over a relatively flat topography forming a Transgressive System Tract. The TST is dominated by lagoon and lower intertidal facies. There are occasional tidal bars, parts of the Sanish member, in Cottonwood Canyon, and in the Williston basin. In the late Devonian time the area was uplifted, and formation of a regional unconformity occurred. This top Three Forks SB was followed by a regional transgression and accumulation of the Bakken shale.

The Three Formation is an important reservoir in the Williston basin and is becoming one in Montana. New resources have been discovered in the areas that were paleo-lows in the late Devonian time, like the Antler Foreland basin (Glacial County), where the Bakken source rock is present. Others remain yet undiscovered, like in the Central Montana Trough. Porosity varies from 0% to 15% in different facies. The lagoon, tidal bar, lower and upper intertidal facies associations have the most porosity. Porosity is associated with dolomitization, and subaerial exposure during late Devonian and early Mississippian time. Fracturing has enhanced permeability.

The subaerial exposure of the Three Forks was regional, and meteoric waters could have influenced the formation hundreds of meters below the unconformity. Generally, in the subsurface, only the upper 20 m of the Three Forks Formation is porous and oil
stained. It is reasonable to suspect that meteoric waters influenced this interval, forming secondary porosity. In some areas, like the Poplar Dome in northern Montana the whole Three Forks interval is porous and contains oil. Fractures formed after the Antler orogeny could be pathways for meteoric waters helping to dissolve the formation at deeper burial depths, and forming more porosity and permeability. So reservoirs with better characteristics could be related to structures that were active during the Antler time. But there were no data available to support this hypothesis.

Fracturing is the main mechanism to enhance permeability in the formation. There are three main regional trends in the area: NE, NW and N-S. NE and N-S are paleo-trends, responding to paleo-stresses in the same directions. The NW trend is a late Laramide, and a present day trend, reflecting present day NW regional stress. Local trends have almost the same directions. It is triggered with the NE orientation of structures in Wyoming and Montana. Regional trends were caused by wrench faulting changing its direction from NE to NW, and back again at different periods of the geologic history. These are probably related to global processes affecting the North American continent.

The lagoon, tidal bar and thinly bedded (2-5 cm thick) intertidal facies demonstrated the most number of fractures. In the tidal bar facies there are approximately four fractures per meter. Spacing varies from 10 cm to 1 m. In the lagoon facies there are about six fractures per meter with average spacing of 15 cm. In the lower intertidal facies there are about six fractures per meter with 15 cm spacing. In the upper intertidal facies there are about ten fractures per meter with 10 cm spacing.

To extend and build on this study, future work could include: (1) correlation of the well data in the Williston basin to the outcrops in Montana; (2) outcrops from the Central Montana Trough and from the Foreland basin could be described and correlated to the Williston basin; and (3) this work could be tied to the late Devonian strata in Canada.
CHAPTER 9
CONCLUSIONS

1. The Three Forks Formation comprises a single sequence in the outcrop. The basal sequence boundary reflects paleo-topography below the Three Forks. There is an erosional sequence boundary at the top and at the base, with more than 20 m of erosion of the late Devonian strata. The Three Forks sequence is composed of a lower lowstand systems tract and an upper transgressive systems tract separated by a prominent transgressive surface. The highstand systems tract appears to have been eroded at the upper unconformity.

2. There are mostly upper intertidal facies in the lower and middle parts of the formation and back-barrier, lagoon deposits - in the upper part.

3. Diagenetic changes include three dolomitization episodes, anhydrite precipitation, compaction, dissolution, calcite replacement of anhydrite, dedolomitization, and stylolitization.

4. All facies showed porosity formed during dolomitization. Lagoonal and tidal facies also show porosity formed after subaerial exposure and dissolution in the latest Devonian and early Mississippian time.

5. Porosity ranges from 3% to 15%. Pores should be connected because of the lamination and fracturing.

6. There are three major regional fracture trends: NE, NW and N-S. Local trends have the same orientation because of the NW orientation of structures in Montana and Wyoming. Lagoon, barrier and intertidal facies have the highest density of fractures.

7. The best reservoirs could be expected near structures active during the Antler orogeny.
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Revisited; 38th Annual Field Conference Guidebook, p. 17 – 25


### APPENDIX A
### OUTCROP LOCATIONS

<table>
<thead>
<tr>
<th>N</th>
<th>Outcrop</th>
<th>Location</th>
<th>GPS coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Clarks Fork Canyon</td>
<td>Southern Beartooth Mountains, along Canyon Road, west of US120 road.</td>
<td>N44° 51'9'', W109° 18'13''</td>
</tr>
<tr>
<td>2</td>
<td>Gallatin Forest</td>
<td>Northern Beartooth Mountains, Baker Mountain, west from the Main Boulder road.</td>
<td>N45° 31'58'', W110° 12'58''</td>
</tr>
<tr>
<td>3</td>
<td>Yellowstone NP</td>
<td>Southern Beartooth Mountains, southern slope of the Mineral Mountain, west of Cooke City, northern side of the US212 road.</td>
<td>N45° 0'52'', W110° 1'38''</td>
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<tr>
<td>4</td>
<td>Shoshone Canyon</td>
<td>Northern Absaroka Range, west of Cody, northern side of the US20 road.</td>
<td>N44°30'42'', W109°9'5''</td>
</tr>
<tr>
<td>5</td>
<td>Cottonwood Canyon</td>
<td>Western Big Horn Mountains, east of Lovell, north from the US14 road.</td>
<td>N44°51'56'', W108°3'5''</td>
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<td>6</td>
<td>‘Fallen City’</td>
<td>Eastern Big Horn Mountains, west of Dayton, along the road US14.</td>
<td>N44°48'18'', W105°19'23''</td>
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<tr>
<td>7</td>
<td>Big Snowys</td>
<td>Big Snowy Mountains, along the road from Lewistown to the Crystal Lake.</td>
<td>N46°48'49'', W109°29'47''</td>
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<td>8</td>
<td>Northern Black Hills</td>
<td>Northern Black Hills Uplift, along the road US14, between towns of Deadwood and Sturgis, Whitewood Creek Canyon.</td>
<td>N44°23'26'', W103°42'16''</td>
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<td>9</td>
<td>Southern Black Hills</td>
<td>Southern Black Hills Uplift, west of Rapid City, along the Nemo/166 road, near the Bogus Lim Creek.</td>
<td>N44°7'803'', W103°24'819''</td>
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APPENDIX B
OUTCROP DESCRIPTIONS

Legend

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<tr>
<th>Lithology</th>
<th>Facies Associations (FA)</th>
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<tr>
<td>- clayey dolomite</td>
<td>- FA 2.1, barrier, open marine</td>
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<tr>
<td>- dolomite</td>
<td>- FA 2.2, lagoon</td>
</tr>
<tr>
<td>- calcareous dolomite</td>
<td>- FA 3, upper intertidal</td>
</tr>
<tr>
<td>- chaotic dolomite</td>
<td>- FA 4, lower intertidal</td>
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<tr>
<td>- sandstone</td>
<td>- FA 5, supratidal</td>
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<tr>
<td>- shale</td>
<td></td>
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<tr>
<td>- anhydrite</td>
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Sedimentary Features

- calcite nodules
- burrows
- loading structures
- ripples
- desiccation cracks
- tepee structures
- stromatolites
- purple lag with symmetrical ripples
- oil staining

Sedimentary Structures

- parallel lamination
- sand lences
- wavy lamination
- disturbed lamination
- chaotic structure
### Texture, Sedimentary Structures

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>CF2: Dolomicrosparstone, inequigranular, mosaic, fogged texture, fine crystal size, 2% calcite, 4% dead oil.</td>
</tr>
<tr>
<td>4 m</td>
<td>CF3: Chaotic in appearance, Dolomicrosparstone, inequigranular, mosaic, fogged texture, fine crystal size, fractures some filled with calcite, 4% dead oil.</td>
</tr>
<tr>
<td>2 m</td>
<td>CF5: Purple cross-laminated transgressive lag, Peloid dolomicrosparstone, inequigranular, mosaic, fogged texture, fine crystal size, 10% OM along layers, 2% porosity.</td>
</tr>
<tr>
<td>1 m</td>
<td>CF6: Dolomicrosparstone, inequigranular, porphyrotopic, contact rhombs and floating rhombs texture.</td>
</tr>
<tr>
<td>0</td>
<td>CF4: Yellow-brown, massive</td>
</tr>
</tbody>
</table>

**Location:** Clarks Fork Canyon, Beartooth Mountains

**GPS:** N44°51'9", W109°18'13"

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Yellowish-grey dolomitic limestone, massive, sucrosic texture, irregular sharp upper contact.
### Sedimentary Structures

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<th>Depth (m)</th>
<th>Texture, Sedimentary Structures</th>
<th>Lithology</th>
<th>Stacking pattern</th>
<th>Thin sections</th>
<th>Formation</th>
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**Comments**

- Bakken
  - CF1: Peloidal equigranular mosaic sieve dolosparstone, coarse silt crystal size, 3% quartz, 8% calcite, 6% porosity, 2% dead oil.
- Three Forks
  - Orange massive, heavily fractured dolostone.
<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Texture, Sedimentary Structures</th>
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<th>Stacking pattern</th>
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<td>17 m</td>
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<td></td>
<td>GF3</td>
<td>Yellowish-brown, very laminated dolomparstone and dolomicrosparstone. From 14 m to 15.75 m there are 5 shallowing upward cycles. GF3: V. fine sand composed of v. fine size quartz.</td>
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<td>13.8 m of covered slope</td>
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<td>1 m</td>
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<td></td>
<td>GF1</td>
<td>Yellowish-brown brecciated dolomite, laminated, with disrupted bedding, iron nodules, rare lithoclasts up to 10 cm in diameter, clasts are disoriented, fabric - grain to matrix supported. GF1: Dolomicrosparstone inequigranular, mosaic, fogged texture, discontinuous lamination lined with OM, irregular clasts of dolomicrosparstone, no porosity.</td>
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<td>GF2</td>
<td>Yellowish-brown brecciated dolomite, laminated, with disrupted bedding, iron nodules, rare lithoclasts up to 10 cm in diameter, clasts are disoriented, fabric - grain to matrix supported. GF2: Dolomicrosparstone inequigranular, mosaic, fogged texture, with clasts of dolomparstone with dead oil filling their pore space, no porosity.</td>
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Location: Gallatin Forest, Beartooth Mountains
GPS: N45°31′58", W110°12′58"

Birdbear
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GF7: Lag deposits - Many conodonts, brown cellular plant fragments, dark-brown in cross-polars, round and elongated in shape, up to 1 mm in size mixed with fine sand size quartz. Vertical laminated stromatolites, up to 24 cm high, 4 cm thick, branching.

GF6: Laterally linked stromatolites. Dolostone equigranular, mosaic, sutured, coarse silt crystal size. Stromatolite growth lines are aligned with fine sand size dolomite rhombs, vugs and calcite (5%), 5% vuggy, fracture, intercrystal porosity.

GF5: Dolostone equigranular, mosaic, sutured texture, crystal size of medium silt, peloidal, 20% scattered sub-angular quartz of coarse-silt size.
<table>
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<td></td>
<td></td>
<td>Three Forks</td>
<td></td>
</tr>
<tr>
<td>4 m</td>
<td></td>
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<td></td>
<td></td>
<td>Grey massive dolomite with calcite nodules, forms steep cliffs, sharp upper and lower contacts.</td>
<td></td>
</tr>
<tr>
<td>3 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Grey thinly bedded dolomite and clayey dolomite, cliff forming.</td>
<td></td>
</tr>
<tr>
<td>1 m</td>
<td>Thinly laminated clayey dolomite with green and purple stripes, irregular upper and lower contacts.</td>
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<tr>
<td>9 m covered</td>
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<td></td>
<td>Birdbearp</td>
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Location: Southern Beartooth Mountains, Yellowstone NP, near Cooke City
GPS: N45°0'52", W110°1'38"

<table>
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<th>Depth (m)</th>
<th>Texture, Ich-Fossils, Sedimentary Structures</th>
<th>Lithology</th>
<th>Stranding pattern</th>
<th>Thin sections</th>
<th>Formation</th>
<th>Comments</th>
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<tbody>
<tr>
<td>8 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Madison</td>
<td></td>
</tr>
<tr>
<td>7 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Three Forks</td>
<td></td>
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<tr>
<td>6 m</td>
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<tr>
<td>5 m</td>
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<td>4 m</td>
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<td>3 m</td>
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<td>2 m</td>
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<tr>
<td>1 m</td>
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</tbody>
</table>

Grey thinly bedded dolomite and clayey dolomite clif forming steep cliffs with sharp upper and lower contacts.
### Sedimentary Structures

- **Texture, Ich-Fossils:**
  - **Sedimentary Structures:**
  - **Texture:**
  - **Ich-Fossils:**
- **Lithology:**
  - **Stacking pattern:**
  - **Thin sections:**
- **Formation:**
- **Comments:**

#### 0 m

SC1: **Dolomicrosparstone equigranular, peloidal to mud, porphyrotopic, vuggy porosity.**

#### 1 m

SC2: **Dolostone equigranular, peloidal crystal size of a very fine sand, 15% calcite within dolomite rhombs, 5% OM, 6% fracture, inter-, intracrystal porosity.**

#### 2 m

SC3-1: **Dolostone equigranular, peloidal, mud to fine sand, vuggy porosity.**

SC3-2: **Dolostone equigranular, peloidal, intercrystal porosity.**

#### 3 m

SC4: **Dolomicrosparstone equigranular, peloidal texture, low angle cross-bedding, 5% calcite, 15% vuggy, inter-, intracrystal porosity, scour surface in the lower part.**

#### 4 m

SC5: **Lag deposits, Dolomicrosparstone equigranular, mosaic, sutured texture, 10% calcite, net of fractures lined with OM, 3% fracture porosity, irregular appearance.**

#### 5 m

SC6: **Dolomicrosparstone equigranular, mosaic, sutured texture, 2% glauconite, 2% nodular calcite, fracture porosity.**

#### 7.5 m

SC7: **Dolomicrosparstone equigranular, peloidal texture, wavy disturbed lamina with dessication cracks filled with calcite, loading structures, calcite (10%) veins and nodules, clotted structure, 7% fracture, intercrystal, vuggy porosity.**

#### 10 m

SC8: **Dolomicrosparstone equigranular, peloidal with irregular calcite patches forming multiple loading structures, clotted structure, rip-up clasts, clasts of dark-brown laminated algal mat, 40% calcite, 4% intercrystal, vuggy porosity.**
<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Texture, Ich-Fossils, Sedimentary Structures</th>
<th>Lithology</th>
<th>Stacking pattern</th>
<th>Thin sections</th>
<th>Formation</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 m</td>
<td>crs, med, fn, silt, cl</td>
<td></td>
<td>SC13</td>
<td></td>
<td></td>
<td>SC13: Dolostone equigranular, mosaic, sutured texture, 30% calcite with ‘flow’ structure, 5% glauconite, many crinoids, 3% OM, 2% intercrystal porosity.</td>
</tr>
<tr>
<td>8 m</td>
<td></td>
<td></td>
<td>SC12</td>
<td></td>
<td></td>
<td>SC12: Lower part: sparite with coarse silt size crystals, 20% dolomite, 80% calcite. In the upper part there is destructed algal mat with round calcite nodules in it with ‘flow’ texture, plant debris with cellular structure, 3% fracture porosity.</td>
</tr>
<tr>
<td>7 m</td>
<td></td>
<td></td>
<td>SC11</td>
<td></td>
<td></td>
<td>SC11: Sparite inequigranular, porphyrotopic, 70% calcite, 30% dolomite, layers of algal mat also filling desiccation cracks below, oval calcite patches with horizontal and vertical alignment, 3% fracture porosity.</td>
</tr>
<tr>
<td>6 m</td>
<td></td>
<td></td>
<td>SC10</td>
<td></td>
<td></td>
<td>SC10: Dolostone equigranular, mosaic, sutured texture, coarse silt dolomite rhomb size, horizontal veins and vertical desiccation cracks forming net filled with algal mat, 5% calcite in round patches and filling fractures.</td>
</tr>
<tr>
<td>4.5 m</td>
<td></td>
<td></td>
<td>SC9</td>
<td></td>
<td></td>
<td>SC9: Dolostone equigranular, peloidal texture, coarse silt size crystals with 20% calcite filling fractures, forming nodules and filling pore space, at the very top there is a 1mm thick layer with fibrous calcite, rare brachiopods, 5% intercrystal porosity, vertical stylolites lined with OM.</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>Texture, Ich-Fossils, Sedimentary Structures</td>
<td>Lithology</td>
<td>Stacking pattern</td>
<td>Thin sections</td>
<td>Formation</td>
<td>Comments</td>
</tr>
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<td>13 m</td>
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<td>12 m</td>
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<td>11 m</td>
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<td>10 m</td>
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<tr>
<td>9 m</td>
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</tbody>
</table>

**Location:** Shoshone Canyon, near Cody

**GPS:** N44°30'42", W109°9'5"

**Comments:**
- Yellow, laminated dolomite.
<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>CC4: Lag deposits. Well rounded quartz of a medium sand size and subangular quartz of a very fine sand size floating in dolomicrostone, angular clasts of dolomicrostone without quartz, rare glauconite.</td>
</tr>
<tr>
<td>25</td>
<td>CC2: Dolomicrospar stone equigranular, mosaic, sutured texture, calcite crystals of a very fine sand size, discontinuous and continuous laminae lined with OM, finer dolomite crystals, OM 10%, brachiopods, crinoids.</td>
</tr>
<tr>
<td>75</td>
<td>CC1: Lag deposits, breccia. Well rounded coarse sand size quartz and subangular v. fine sand size quartz (straight and slightly undulose extinction) floating in dolomicrostone matrix, big brachiopods, rare glauconite, 3% calcite, 1% vuggy porosity.</td>
</tr>
<tr>
<td>50</td>
<td>Yellow dolomite with sand lenses, heavily fractured.</td>
</tr>
<tr>
<td>25</td>
<td>Light brown laminated, blocky calcareous dolomite.</td>
</tr>
<tr>
<td>75</td>
<td>CC0: Dolomicrosparstone mosaic, sieve texture, dolomite crystals are of fine sand, space between them is filled with calcite, 20% calcite, 2% OM, no porosity.</td>
</tr>
<tr>
<td>50</td>
<td>Greyish - dark brown siltstone, structureless, small calcite nodules, sharp upper contact.</td>
</tr>
</tbody>
</table>

**Location:** Cottonwood Canyon, Big Horn Mountains  
**GPS:** N44°51'56", W108°3'5"
<table>
<thead>
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<th>Depth (m)</th>
<th>Texture, Sedimentary Structures</th>
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<th>Thin sections</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>4.5 m</td>
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</tbody>
</table>

**Comments**

**CC8:** Dolostone equigranular, mosaic, sutured texture, laminated - layers with v. fine sand crystal sizes and with medium silt sizes, 10% quartz, 2% OM, rare glauconite, almost no porosity.

**CC7:** Dolostone equigranular, mosaic, sieve texture, crystal size of a coarse silt, ostracods, brachiopods, 5% quartz, rare muscovite and glauconite, 8% intercrystal and intracrystal porosity.

Light yellow massive dolomite with horizontal burrows by Thalassinoides isp at the base of beds.

**CC6:** Dolostone equigranular, mosaic, sutured texture, crystal size of a very fine sand, 5% calcite, possible trilobites, 5% vuggy, intercrystal and fracture porosity, not even, mostly in the upper part of the thin-section, 20% calcite, 5% OM, 5% quartz in a burrow.

**CC5:** Dolostone equigranular, mosaic, sieve structure, crystal size of a very fine sand, 4% calcite between dolomite rhombs, 4% OM in pore space, 8% intercrystal porosity, heavily dolomitized ostracods, brachiopods, crinoids.

Grey slope forming shaly silstone.
Location: 'Fallen City', Eastern Big Horn Mountains
GPS: N44°48'18", W105°19'23"

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Texture, Ich-Fossils, Sedimentary Structures</th>
<th>Lithofacies</th>
<th>Stacking pattern</th>
<th>Thin sections</th>
<th>Formation</th>
<th>Comments</th>
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<td>med</td>
<td>fn</td>
<td>vf</td>
<td>silt</td>
<td>cl</td>
</tr>
<tr>
<td>4 m</td>
<td>crs</td>
<td>med</td>
<td>fn</td>
<td>vf</td>
<td>silt</td>
<td>cl</td>
</tr>
<tr>
<td>3 m</td>
<td>crs</td>
<td>med</td>
<td>fn</td>
<td>vf</td>
<td>silt</td>
<td>cl</td>
</tr>
<tr>
<td>2 m</td>
<td>crs</td>
<td>med</td>
<td>fn</td>
<td>vf</td>
<td>silt</td>
<td>cl</td>
</tr>
<tr>
<td>1 m</td>
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<td>med</td>
<td>fn</td>
<td>vf</td>
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<td>fn</td>
<td>vf</td>
<td>silt</td>
<td>cl</td>
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Brownish-grey limestone, slight lamination at the bottom, wavy irregular upper contact.
<table>
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<th>Depth (m)</th>
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<th>Lithology</th>
<th>Stacking pattern</th>
<th>Thin sections</th>
<th>Formation</th>
<th>Comments</th>
</tr>
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<tbody>
<tr>
<td>9 m</td>
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<tr>
<td>7 m</td>
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<tr>
<td>6 m</td>
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<tr>
<td>5 m</td>
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<tr>
<td>4.5 m</td>
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</tbody>
</table>

Red, purple, brownish massive dolomite with rare sand lenses in selected layers.

Very sharp upper contact.

FC10: Dolomicrosparstone, algal mat, horizontal lamination, fluid escape and loading structures, lamina of dolosparsparstone with coarse silt size quartz and 1 cm thick layers of quartz sand at the top, 3% intercrystal porosity in coarse layers.

FC9: Dolomicrosparstone, algal mat with round features filled or empty, rip-up clasts, 19% intercrystal, vuggy and fracture porosity, 10% calcite.

FC8: Dolomicrosparstone inequigranular, porphyrotopic, clotted texture, microbial, horizontal lamina of dolosparsparstone, veins filled with calcite, 3% intercrystal porosity in the upper part.
<table>
<thead>
<tr>
<th>Depth</th>
<th>Texture, Ich-Fossils, Sedimentary Structures</th>
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<th>Stacking pattern</th>
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<th>Formation</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 m</td>
<td>Fine sand size crystals</td>
<td>LC</td>
<td></td>
<td></td>
<td>FC13</td>
<td>FC13: Dolostone equigranular, mosaic, sieve, fine sand size crystals, 12% vuggy, inter, intracrystal porosity, vein filled with calcite.</td>
</tr>
<tr>
<td>10 m</td>
<td></td>
<td>LC</td>
<td></td>
<td></td>
<td>Three Forks</td>
<td></td>
</tr>
<tr>
<td>11 m</td>
<td></td>
<td>LC</td>
<td></td>
<td></td>
<td>Three Forks</td>
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</tr>
<tr>
<td>12 m</td>
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<td>LC</td>
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<td></td>
<td>Three Forks</td>
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<tr>
<td>13 m</td>
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<td>Three Forks</td>
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<td>50 m</td>
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<td>LC</td>
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<td>Three Forks</td>
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<tr>
<td>Depth (m)</td>
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<td>Lithology</td>
<td>Lithofacies</td>
<td>Stacking pattern</td>
<td>Thin sections</td>
<td>Formation</td>
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<td>18 m</td>
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<tr>
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<tr>
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<tr>
<td>14 m</td>
<td>karst</td>
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<tr>
<td>13.5 m</td>
<td></td>
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</tbody>
</table>

**Comments**: Pink, massive dolomite with calcite nodules.

**FC14**: Dolomicrostone equigranular, algal mat, clotted structure, rip-up clasts with dolosparite in between (up to v. fine sand crystal size), 8% vuggy, fracture, intercrystal porosity.
Pink, massive dolomite with calcite nodules.
### Location: Big Snowy Mountains

GPS: N46°48'49", W109°29'47"

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Texture, Sedimentary Structures</th>
<th>Lithology</th>
<th>Stacking pattern</th>
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<th>Comments</th>
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</thead>
<tbody>
<tr>
<td>50</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>BS1: Equigranular mosaic sutured microsparstone, no porosity observed.</td>
</tr>
<tr>
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<td></td>
<td>BS2: In the lower part 2 cm thick layer of very fine sand (40% quartz) with doloparstone cement, and in the upper part dolomicrosparstone with scattered silt size quartz, 2% fracture porosity.</td>
</tr>
<tr>
<td>4 m</td>
<td></td>
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<td></td>
<td>BS3: Dolosparstone inequigranular, mosaic, spotted, with dolomicrite and clayey angular, elongated clasts, fracture filled with pyrite, 3% fracture porosity.</td>
</tr>
<tr>
<td>3 m</td>
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<td></td>
<td>BS4: Dolomicrosparstone inequigranular, porphyrotopic, contact rhomb texture, 3% quartz: a layer of coarse silt and fine silt scattered in the sample, no porosity.</td>
</tr>
<tr>
<td>2 m</td>
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<td></td>
<td>Brownish-grey dolostone, fissile.</td>
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<tr>
<td>1 m</td>
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<td>0</td>
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<td></td>
<td></td>
<td>Lower contact wasn’t identified. Slope covered - 3m, 45° angle.</td>
</tr>
</tbody>
</table>
### Location: Northern Black Hills, near the Deadwood

GPS: N44°23'28", W103°42'16"

<table>
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<td>Madison</td>
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<td>9.25 m</td>
<td>9 m shaly slope</td>
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**Depth (m)**
- **25 m**: Yellow massive calcareous dolomite. NBH5: Dolostone equigranular, mosaic, sutured, 2% OM, 4% calcite.
- **17 m**: Yellowish-brown dolostone, parallel lamination, sharp contacts, has net of fractures, getting more massive upward.
  - NBH4: Dolostone equigranular, mosaic, sutured, 10% OM, at the top uniform calcite layer with lot's of OM, 1% quartz.
  - Swamp-green chert, nodule structure, wavy contacts, irregular thickness from absence to 4 cm (tense).
  - NBH3: Chert, chaledony, polycrystalline quartz, nodular structure, dolostone along some nodules, 3% calcite, replaced brachiopod shell.
- **12 m**: NBH2: Dolomicrosparstone equigranular, mosaic, sutured, 2% strained quartz with inclined extinction.
- **11 m**: NBH1: Dolomicrosparstone inequigranular, porphyrotopic, crystal size up to coarse silt, 2% OM, 2% quartz, rare elongated Q needles.
  - Purple dolostone, fissile, forms gentle cliffs and slope.
- **9.25 m**: Yellow massive limestone, sucrosic texture, cliff forming, sharp upper contact.
- **9 m shaly slope**: Yellow massive limestone, sucrosic texture, cliff forming, sharp upper contact.
- **Birdbear (Whitewood)**: Yellow massive limestone, sucrosic texture, cliff forming, sharp upper contact.
<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Texture, Sedimentary Structures</th>
<th>Lithology</th>
<th>Lithofacies</th>
<th>Stacking pattern</th>
<th>Thin sections</th>
<th>Formation</th>
<th>Comments</th>
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</table>

SBH2: Dolosparstone equigranular, mosaic, sutured texture, weak wavy lamination, medium silt size crystals, peloidal, very many crinoids, less echinoderms, bryozoans and moluscs, 30% calcite, 2% OM, 2% porosity.

SBH1: Dolosparstone equigranular, mosaic, sutured texture, heavily dolomitized, horizontal lamination or coarser and finer crystals, peloidal. Crystals are of maximum coarse silt size, 4% quartz, 5% OM, 2% calcite, rare brachiopods, 4% intercrystal porosity in coarser layers.

Purple dolostone, massive, getting blocky upwards, beds are continuous.
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<td>9 m</td>
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<td>SBH4</td>
<td>Orange massive calcareous dolomite, getting lighter upwards. SBH4: Dolostone equigranular, mosaic, sutured texture, peloidal, rare brachiopods and crinoids, 3%</td>
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<td>SBH1</td>
<td>Three Forks (Englewood)</td>
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<td>SBH9</td>
<td>Purple dolostone, massive, getting blocky upwards. Beds are continuous.</td>
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<td>SBH4</td>
<td>SBH3: Dolostone equigranular, mosaic, sutured texture, coarse silt - v. fine sand crystal size, peloidal, brachiopods, crinoids, 2% chert, 1% quartz, 3% OM, 3% calcite, 3% intergranular pores.</td>
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