A preliminary investigation of the Madison aquifer for a drinking water supply in Bozeman, Montana
by Karin Bohacek Kirk

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University

Abstract:
The purpose of this study was to perform a preliminary assessment of the potential of the Madison aquifer in Sourdough Canyon for use as a supplement to the municipal water supply of Bozeman, Montana. The Paleozoic rock units in the upper Sourdough Creek drainage basin were mapped and a geologic cross section was constructed. The Mississippian Madison Group is comprised of the lower Lodgepole Limestone and the upper Mission Canyon Formation, and is 430 meters (1420 feet) in total thickness. Karst features and fractures were common in the Mission Canyon Formation and enhance the permeability of the formation. Recharge to the aquifer was estimated by measuring stream losses where streams flowed across the Madison Group rocks. Each of the streams in the Sourdough Creek watershed was found to be losing water and the estimated stream loss is 3,200,000 m^3/year (2,600 acre-feet/year). One spring was found that was discharging from the Lodgepole Limestone. The spring stage was measured by a data logger within a stilling well from October 2000 to October 2001. During this period, the annual spring discharge was 1,100,000 m^3/year (900 acre-feet/year). Correlation of a peak in the spring discharge with an isolated precipitation event revealed a response time of 5 days, suggesting a rapid connection between the surface water and the spring discharge. The water temperature, ion chemistry and tritium concentration all indicate the spring has a shallow circulation pattern , and a short residence time. Hence the spring is not representative of a deep, regional aquifer system within the Madison aquifer, and the depth to the regional saturated zone is unknown. The City should not drill a production well without further investigation of the depth to the saturated zone. By drilling a test well, the depth to saturation, well yield and subsurface geology could be determined. This is recommended if the City chooses to pursue the development of groundwater resources in the Sourdough Creek drainage. Other options for water development include the prevention of stream losses in order to provide a net gain to Sourdough Creek, and an assessment of the Madison aquifer in the Hyalite Creek drainage.

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Karin Bohacek Kirk

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

ABSTRACT

The purpose of this study was to perform a preliminary assessment of the potential of the Madison aquifer in Sourdough Canyon for use as a supplement to the municipal water supply of Bozeman, Montana. The Paleozoic rock units in the upper Sourdough Creek drainage basin were mapped and a geologic cross section was constructed. The Mississippian Madison Group is comprised of the lower Lodgepole Limestone and the upper Mission Canyon Formation, and is 430 meters (1420 feet) in total thickness. Karst features and fractures were common in the Mission Canyon Formation and enhance the permeability of the formation. Recharge to the aquifer was estimated by measuring stream losses where streams flowed across the Madison Group rocks. Each of the streams in the Sourdough Creek watershed was found to be losing water and the estimated stream loss is 3,200,000 m^3/year (2,600 acre-feet/year). One spring was found that was discharging from the Lodgepole Limestone. The spring stage was measured by a data logger within a stilling well from October 2000 to October 2001. During this period, the annual spring discharge was 1,100,000 m^3/year (900 acre-feet/year). Correlation of a peak in the spring discharge with an isolated precipitation event revealed a response time of 5 days, suggesting a rapid connection between the surface water and the spring discharge. The water temperature, ion chemistry and tritium concentration all indicate the spring has a shallow circulation pattern and a short residence time. Hence the spring is not representative of a deep, regional aquifer system within the Madison aquifer, and the depth to the regional saturated zone is unknown. The City should not drill a production well without further investigation of the depth to the saturated zone. By drilling a test well, the depth to saturation, well yield and subsurface geology could be determined. This is recommended if the City chooses to pursue the development of groundwater resources in the Sourdough Creek drainage. Other options for water development include the prevention of stream losses in order to provide a net gain to Sourdough Creek, and an assessment of the Madison aquifer in the Hyalite Creek drainage.

INTRODUCTION

Problem

The City of Bozeman, Montana is seeking an additional source of municipal drinking water to meet the needs of its growing population. Water supply wells in the Madison aquifer in the northern Gallatin Range near Sourdough Creek may provide a viable groundwater source of drinking water for the City, but the aquifer potential has not yet been studied.

Bozeman receives its drinking water from three sources: Sourdough Creek, Hyalite Creek and Lyman Creek. Until the early 1980s water from Sourdough Creek had been stored behind the Mystic Lake Dam (Fig. 1-1). In 1984 – 1985 the Mystic Lake Dam was intentionally breached due to concerns over the dam's integrity. With the loss of the Mystic Lake Dam, the City lost the ability to store approximately 7,400,000 cubic meters (6,000 acre-feet) of water (URS Greiner Woodward Clyde, 1999).

The estimated safe yield of the City's current water supplies is 13,3000,000 cubic meters per year (10,795 acre-feet per year), not including Mystic Lake (URS Greiner Woodward Clyde, 1999). Based on an estimated water use of 200 gallons per day per capita, Bozeman's current water supply can meet the needs of 48,000 people (URS Greiner Woodward Clyde, 1999). Depending on the rate of population growth in Bozeman, it is predicted that the City will need to expand its water supply in as little as 20 years.

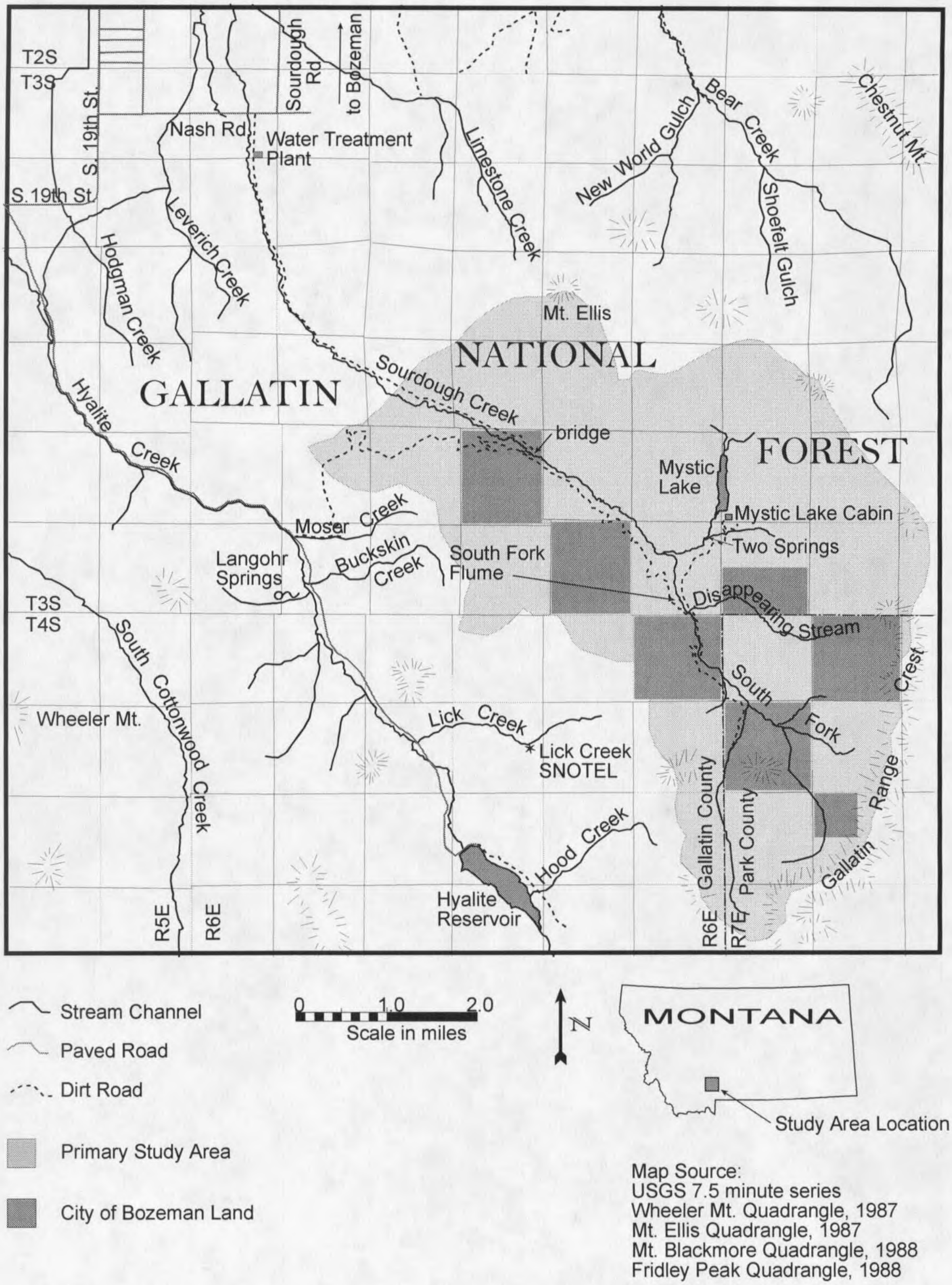

Figure 1. The study area.

Although it may be 20 years before Bozeman needs an additional source of water, it is prudent that a thorough search for the best alternative begin well in advance of the need. Most water development projects take 20 years or more from conception to completion. By allowing ample time for planning, there will be time to investigate all of the available options, make a well-informed decision, acquire land and water rights, and construct the infrastructure necessary for an expansion of the public water supply. This proactive planning should save money for the city and will avoid the need for crisis management should the problem be left unanswered. This research on the Madison aquifer potential is a preliminary step in the important process of assessing Bozeman's water supply options.

Background

In June 1999 the Bozeman Broad Spectrum Task Force issued recommendations to the Bozeman City Commission regarding Bozeman's future water needs. The task force recommended that the potential use of groundwater as a water supply "warrants immediate investigation and action" (Bozeman Broad Spectrum Task Force, 1999). Specifically, the Task Force recommended the following specific goals regarding the Madison aquifer.

- Determine water yield potential of the Madison aquifer.
- Determine water storage potential of the Madison aquifer (Bozeman Broad Spectrum Task Force, 1999).

A report submitted to the City by URS Greiner Woodward Clyde in January 1999 investigated the feasibility of building another dam in Sourdough Canyon. However, there are several concerns associated with the construction of a new dam. According to the URS

Greiner Woodward Clyde report, there are seven threatened or endangered animal species that may be present in the area. These species are the bald eagle, American peregrine falcon, grizzly bear, gray wolf, lynx, fluvial Montana arctic grayling, and the western toad (URS Greiner Woodward Clyde, 1999). There are also 35 species that may occur in the area that are listed as Montana threatened, endangered or of special concern (URS Greiner Woodward Clyde, 1999). Another concern regarding the construction of a reservoir is the loss of recreational areas for hiking, horseback riding, fishing, biking, ski touring and hunting. Due to these environmental and recreational concerns, other options for a water supply should be investigated before plans for a new dam are pursued.

URS Greiner Woodward Clyde (1999) found that the development of the Madison aquifer as a water supply "merits future evaluation due to its use in other areas as a groundwater resource and [its] proximity to the Sourdough Creek drainage" (URS Greiner Woodward Clyde, 1999). Several recommendations for further investigation were put forth in the report, including, "detailed geologic field characterization and mapping of outcrops of the Madison Formation should be performed in the Mystic Lake area to provide further information on structural, stratigraphic, and secondary porosity characteristics of the formation" (URS Greiner Woodward Clyde, 1999).

This study assesses the groundwater potential of the Madison aquifer in the Sourdough Creek watershed (Figure 1-1). This drainage area was selected because it contains large exposures of the Madison Group which may serve as recharge areas for the aquifer, because Bozeman's water treatment facility is at the base of Sourdough Canyon, and because the ideal water source would be located proximal to and uphill from the water treatment plant to minimize conveyance losses and to avoid the need to pump the water uphill to the city.

Goals and Objectives

This research addresses several questions that are listed below.

1. Is the karst porosity and permeability that has been documented in the Mission Canyon Formation near Livingston present in the Sourdough Creek watershed?
2. Is there dolomite porosity and permeability in the Madison Group rocks in the Sourdough Creek watershed?
3. Do streams recharge the Madison aquifer in the study area? If so, at what rate? Are the springs ephemeral or perennial?
4. Does the Madison aquifer discharge into springs and streams in Sourdough Canyon? If so, at what rate?
5. Do fold-axis fractures or faults affect recharge potential, direct or control the groundwater flow, or control the locations of springs?
6. Is the water quality from the Madison aquifer suitable as a raw drinking water source?
7. Can suitable locations for drilling a test well be determined?
8. Are there known water rights issues pertaining to large-scale use of Madison aquifer water in Montana?

Anticipated Outcomes

There are several anticipated outcomes that arise from the questions above.

1. Karst features are present and do allow rapid transmission and storage of groundwater.
2. Dolomite porosity is present in the Mission Canyon Formation of the Madison Group and represents storage capacity.
3. Streams recharge the Madison aquifer.
4. Springs discharge the Madison aquifer, especially along faults and at the contact between the Madison Group rocks and underlying formations.
5. Additional recharge and discharge areas exist along fracture zones at the crest of anticlines.
6. Water from springs discharging the Madison aquifer may be high in hardness and sulfate, but the water quality will be acceptable for a raw water source for a public drinking water supply.
7. There are suitable locations for drilling a test well in the Madison aquifer in Sourdough Canyon.
8. Water rights issues have been encountered for other large-scale users of Madison aquifer water, and water rights must be considered before Bozeman pursues groundwater development in Sourdough Canyon.

Previous Work

Regional Stratigraphy of the Madison Group

The Mississippian Madison Group rocks are cyclically deposited, fine to medium grained limestones and dolomites with evaporite units. The Madison Group is made up of three formations, the basal Lodgepole Limestone, the Mission Canyon Formation, and the Charles Formation. The Lodgepole Limestone is further subdivided into the Paine Shale and the Woodhurst Limestone. The Mission Canyon Formation has been divided into an upper and lower member. The Charles Formation consists largely of evaporite rocks and is often not present at the surface, presumably due to dissolution of the evaporites. The Charles Formation is present in the subsurface of the Williston Basin (Aram, 1981).

The thickness of the Madison Group rocks ranges from 210 meters (700 feet) in the Bighorn Mountains, to 610 meters (2000 feet) in the Williston Basin (Miller, 1976). The depth of the formation ranges from surface outcrops in mountainous regions, to 3000 meters (10,000 feet) along the Montana – Wyoming border (Miller, 1976). Madison Group rocks lie conformably over the upper Devonian to lower Mississippian Sappington Formation. The uppermost unit of the Sappington Formation is the Bakken shale, which is an organically rich, black shale and is a confining layer below the Madison aquifer. The Bakken Shale also is the source of much of the petroleum and natural gas found within the Madison aquifer (Downey, 1984). Within the study area, the Sappington Formation was not recognized by Roberts (1964) and the Madison Group directly overlies the Three Forks Formation, which is comprised of shale and fine-grained limestone and also acts as a confining layer. The rocks of the Madison Group are overlain uncomformably by the upper Mississippian Big Snowy Group or the lower Pennsylvanian Amsden Formation, both of which are confining layers. Where present, the uppermost member of the Madison Group, the Charles Formation, can act as a confining layer as well.

Local Stratigraphy of the Madison Group

The rocks in the Madison Group near Livingston, Montana were studied by Roberts (1966). The unit was measured to be 346 meters (1,136 feet) thick and is divided into two formations, the Lodgepole Limestone and the Mission Canyon Limestone (Figure 1-2; Roberts, 1966). The Lodgepole Limestone consists of the Paine Shale Member and the Woodhurst Limestone Member. The Paine Shale is 102 meters (334 feet) thick and is generally limestone and dolomite but contains some silty units. The Woodhurst Limestone is 45 meters (146 feet) thick and is comprised of thin-bedded limestone and dolomite (Roberts, 1966). The Mission Canyon Limestone is further subdivided into a lower and upper member. The lower member is 100 meters (330 feet) thick and consists of massive, medium to fine grained limestone and dolomite. The upper member of the Mission Canyon Limestone is 99 meters (326 feet) thick and is comprised of finely crystalline limestone and dolomite interbedded with dolomitic solution-breccia (Roberts, 1966). The Charles Formation is comprised primarily of evaporite deposits and is typically absent at the surface. In some localities, a solution breccia is present in the same stratigraphic position as the Charles Formation.

The limestone units of the Madison Group were described as massive or thickly bedded with some fossils and fossil debris. Oolites and pelletal material are minor constituents and a small percentage of the rock is comprised of clastic material. The dolomite units are either fine-grained or medium-grained and are a product of recrystallization of limestone. Roberts (1966) observed that the limestone units are resistant

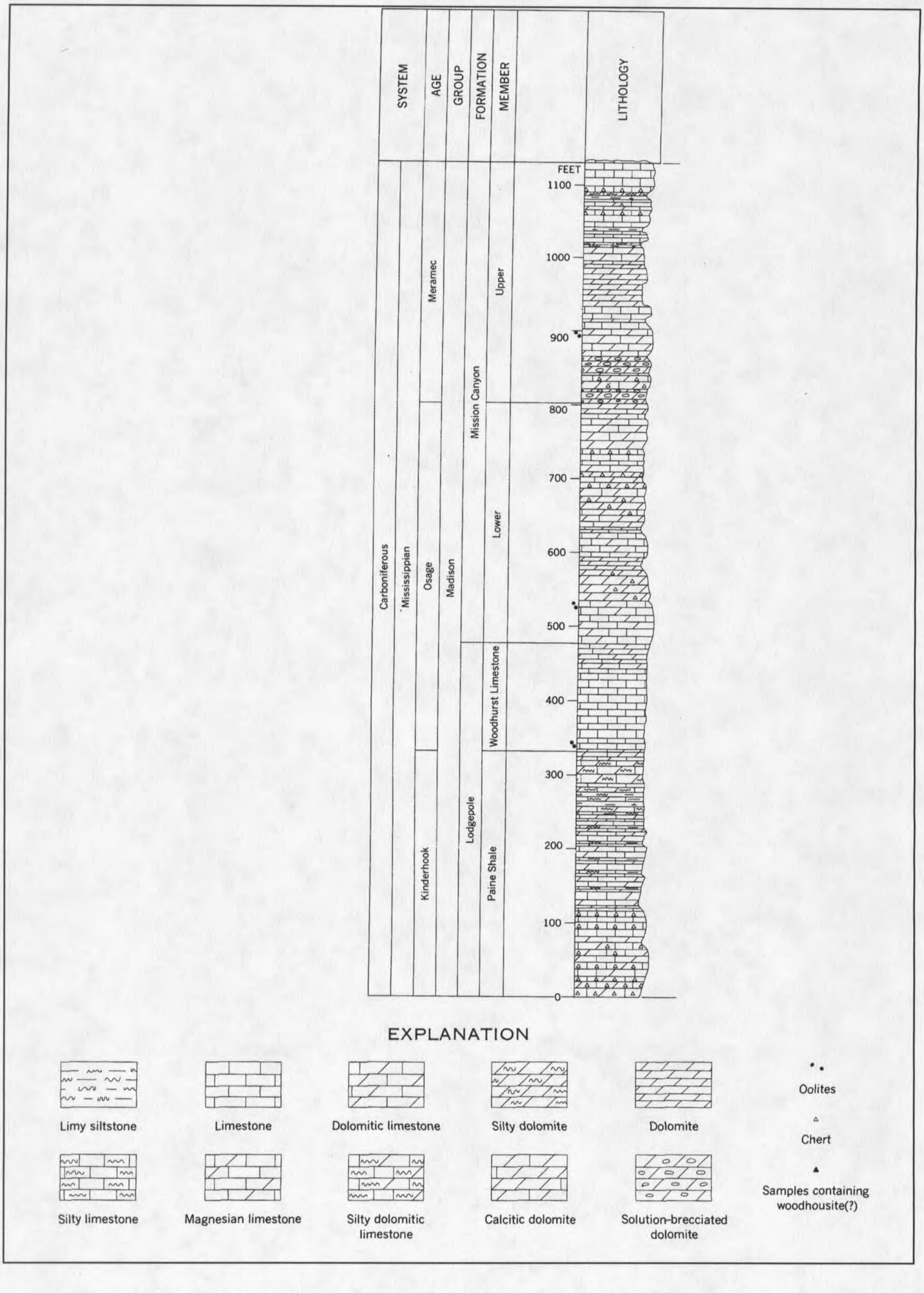

Figure 1-2. Stratigraphic column of the Madison Group, from Roberts (1966).

to erosion and form cliffs and ridges while the dolomites weather more rapidly and create indentations in the profile of the outcrop.

Tectonic Setting for the Deposition of the Madison Group

During the Antler Orogeny in late Devonian and early Mississippian time, a volcanic arc was converging with western North America (Reid and Dorobek, 1989). This created a foreland basin east of the orogenic zone. The foredeep was located in east-central Idaho, and an extension of the foredeep extended into western and central Montana. On the eastern margin of the foredeep, a broad shallow platform developed. The North American continent was positioned so the paleoequator was 5 to 10 degrees south of Montana, thus the area experienced a warm climate. This combination of shallow water and warm climate set the stage for carbonate deposition of the Madison Group rocks (Reid and Dorobek, 1989).

Depositional History

The rocks within the Madison Group were deposited in the Madison Sea during the late Mississippian period (Reid and Dorobek, 1989). Cyclical beds of limestone, dolomite and evaporites represent alternating environments of deep marine and shallow marine, restricted circulation environments. The Antler foreland basin filled with thick deposits of siliciclastic sediments eroding from the Antler highlands, but the western part of the basin was dominated by carbonate deposition. The Lodgepole Limestone was deposited in a subtidal environment on the carbonate ramp (Reid and Dorobek, 1989). This produced thin-bedded, fine to coarse grained, fossiliferous limestones with occasional silty horizons.

The Mission Canyon Formation was deposited conformably above the Lodgepole Limestone in a shallow subtidal to peritidal environment. This setting allowed for subaerial exposure and the precipitation of evaporite minerals (Reid and Dorobek, 1989). Many of the parasequences show a shallowing-upward trend and there is evidence for subaerial exposure during deposition, such as desiccation features, pseudomorphs after evaporite minerals, vadose diagenetic fabrics and crytpalgal laminae. The subaerial exposure was caused by aggradation of the platform deposits and relative drops in sea level (Reid and Dorobek, 1989). These parasequences are regionally correlated. The top of the Mission Canyon Formation represents a regional unconformity that spanned 9 to 14 million years of subaerial exposure (Reid and Dorobek, 1989).

The depositional setting of the Mission Canyon Formation was a gradual inundation of the Wyoming shelf to create a broad and shallow sea (Vice and Utgaard, 1989). Individual microfacies in the Mission Canyon Formation were examined in the northern Bighorn Basin region of Montana and Wyoming, and evidence of subaerial exposure was recognized. Evidence of desiccation and a hypersaline environment include sparse biota with low diversity, bird's eye limestone structures, pseudomorphs after evaporite minerals and cryptalgal laminae. These features were characteristic of supratidal and upper intertidal zones. The hypersaline environment in the supratidal zones on the edge of the platform allowed for precipitation of evaporite facies such as gypsum and anhydrite. These units may become dissolved, leaving large secondary pore spaces. If the voids are large enough, collapse breccias may form (Vice and Utgaard, 1989).

Development of Solution Breccias and Karst Features

The Madison Group is often characterized by the presence of solution breccias and karst features (Sando, 1988). The majority of these features are near the top of the Mission Canyon Formation and its stratigraphic equivalents. The development of these secondary pore spaces has created large voids within the rock, and has increased the permeability of the formation in some cases. There have been at least two episodes of karst development in the Mission Canyon Formation (Sando, 1988). The depositional and post-depositional history of the Mission Canyon Formation has contributed to the formation of karst features and solution breccias and will be discussed below.

Paleokarst. Deposition of Madison sediments ceased during early Meramecian time in the mid-Mississippian (about 345 m.y. BP). The craton was uplifted and sea level fell (Gutschick et al., 1980). The Madison shelf became exposed and was subject to subaerial weathering and the development of karst (Sando, 1988, Roberts, 1966). Many of these caves subsequently collapsed or filled with sediments as the overlying formations were being deposited. Beginning in late Meramecian time the Amsden-Big Snowy transgression began and the Darwin Sandstone member of the Amsden Formation was deposited from west to east in Wyoming. In southwestern Montana the Kibbey Formation of the Big Snowy Group was deposited instead of the Darwin Sandstone. The Kibbey Formation consists of red shale, siltstone, fine sand and small amounts of evaporites. The transgression proceeded from west to east, thus the western portions of the Madison shelf were exposed for a shorter length of time than the areas to the east. It has been estimated that the Madison shelf was exposed for between 9 and 34 million years (Reid and Dorobeck, 1989, Sando, 1988). Sando