Pore network connectivity in microbialites of the Green River Formation (Wyoming, USA): analogs for petroleum reservoir potential

By

Zack Martinez

A thesis submitted in partial fulfillment of the requirements of the degree of

Bachelor of Arts

(Geology)

At

Gustavus Adolphus College

(2016)

Pore network connectivity in microbialites of the Green River Formation (Wyoming, USA): analogs for petroleum reservoir potential

By

Zack Martinez

Under the supervision of Julie K. Bartley

ABSTRACT

The recent discovery of substantial petroleum plays in Mesozoic-aged lake deposits off the coast of Brazil has ignited interest in lacustrine carbonates as oil reservoirs. In these offshore petroleum deposits, the reservoir rock consists mainly of microbial carbonate – limestone deposited by the actions of microorganisms. Such microbialite reservoirs are relatively unusual, making it important to examine potential analogs that can inform resource exploration and development. The Green River Formation is a succession of lacustrine sedimentary rocks, exposed in Wyoming, Utah, and Colorado. During the mid-Eocene, ancient Lake Gosiute (Wyoming) accumulated an extensive, microbialite-dominated carbonate sequence that provides a potential analogue for microbialite reservoirs developed in similar settings.

In order to host extractable petroleum resources, a reservoir rock must have porosity and permeability sufficient for fluid storage and transmission. Thus, understanding the relationship between porosity and larger-scale features, such as morphology and texture, is key. Microbialites are typically described using characteristics such as morphology, texture, fabric, and stratigraphic features. However, little is known about the correlation of these variables with respect to the development and preservation of pore space. This project examines porosity development as a function of stromatolite texture and the relationship of that texture to pore interconnectivity. To assess pore space presence and connectivity, microbialites were scanned and imaged in thin slices of equal interval combined with extensive microscopic analysis. Preliminary results observed through thin section scans coupled with petrophysical observations seen through acetate peels, suggests that pore space formation and frequency is heavily dependent on its texture and fabric favoring shallow-marine lacustrine based depositional environments. Textural features derived from such environments display a high degree of variability in pore networks across a diverse array of microbialite form.

ACKNOWLEDGEMENTS

I would like to thank the Gustavus Geology Department for allowing the use of their equipment and department chair Julie Bartley for the sample collection, extensive field notes, helpful research suggestions, thesis feedback/advising, methods preparation, and software set-up. I would also like to thank Geology professors Dr. Jim Welsh and Dr. Dean Moosavi for helpful discussions and critical review of this paper. Lastly, I would like to thank the students of the geology department for their peer reviews, especially Grant Noennig, Tanner Eischen, and Lindsey Reiners for their sample collection, field notes, laboratory procedures, and thesis feedback.

TABLE OF CONTENTS

FIGURES AND TABLES

INTRODUCTION

KEY CHARACTERISTICS OF RESERVOIR ROCK:

Carbonate reservoirs contain various degrees of porosity and permeability which contain important agents in the ability to store oil and natural gasses. If successfully obtained, these reservoirs can be used for numerous energy purposes seen in figure 1. These reservoirs contain many different types of porosity and often have intricate pore size distributions ranging from 0.5-5 microns. The majority of reservoir rocks are made of coarser-grained siliclastic rocks (sandstones) that can occur anywhere and at all depths (both terrestrial and marine). Carbonate rocks, mostly forming along the sea floor in shallow marine, tropical environments, possess the necessary properties for this ability to hold oil and natural gas within its internal structure (Chilingar, 2005). Recent recognition of petroleum-bearing carbonate structures are taking the lead over the traditionally studied shale as a main source rock because of its ability in volume to generate 3 times as much oil as the same volume of shale if both contain the same amount of organic matter (Chilingar, 2005).

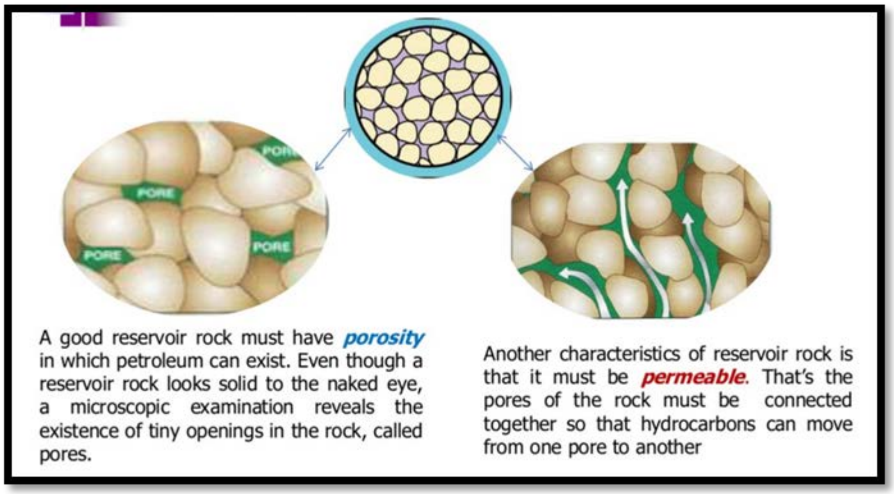


Figure 1: This figure shows where porosity and permeability exists in a reservoir rock and how fluids can travel through these spaces

Oil and natural gas are held below ground in porous rocks called reservoir rocks (porous and permeable subsurface rock that contains petroleum). Petroleum is found in large accumulations known as oil fields which can contain oil, gas, tar, and water, among other materials (Noffke, 2013). In order for a field to form, there must be a specific structure to trap and seal the petroleum to prevent leakage. A carbonate rock's potential as a reservoir depends on the presence of a suitable source rock that can deliver oil and gas to the reservoir. In addition, a reservoir rock must have adequate pore space to hold the petroleum. In order to find these features together in an area where petroleum has been generated by chemical reactions affecting organic remains, require specific timing of natural processes along with organic matter such as dead plants or animals accumulating in large quantities. Organic material can be deposited alongside carbonate sediments and later buried as more sediments accumulate on top. These sediments and organic material that later accumulate are called source rock. After burial, chemical activity in the absence of oxygen allows the organic material in the source rock to change into petroleum without the organic matter simply decaying away. A good petroleum source rock typically comes in the form of sedimentary rock such as shale, limestone or carbonates containing 1-5% organic carbon material (Noffke, 2013). Shown in figure 2, four main components are seen in sedimentary microbialites in order for significant pore space to develop. The shape and arrangement of grains: where highly angular in shape and uniformly sized grains allow for the greatest volume of pore space. Matrix: which includes clay-sized sediment that fills around the

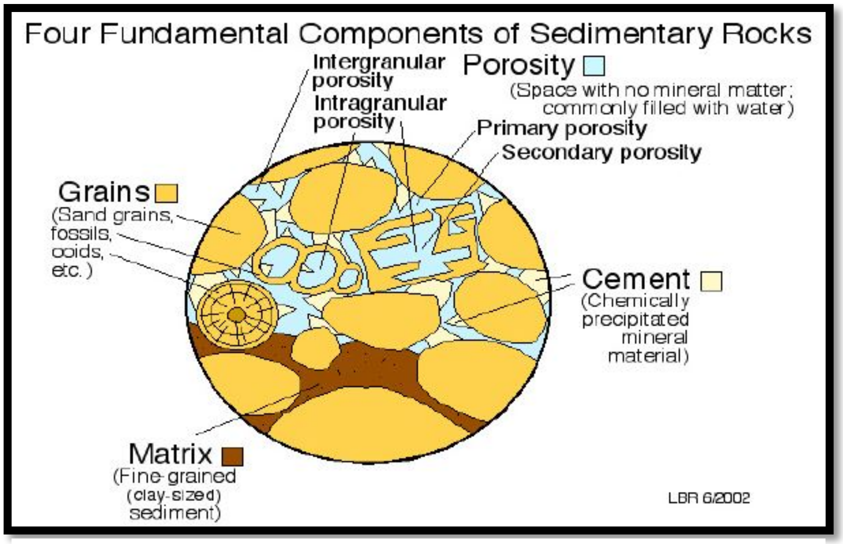


Figure 2: This figure shows the main components of sedimentary rock needed for sufficient carbonate reservoir classification

grains and act as a trap, further compacting the rock. Cement: Which preferably consists of calcium carbonate based mineral material in which is precipitated to further construct and strengthen the fabric of the rock. Porosity: The actual space in between these materials in which can hold fluids such as oil and natural gas. These rich source rocks occur in many environments such as lakes, deep areas within seas and oceans, and swamps. These rocks must be buried deep enough below the surface of the earth to heat up the organic material, but not so deep that the rocks metamorphose or that the organic material changes into graphite or other materials other than hydrocarbons. In all, each of these rock types' exhibit characteristics in composition and texture as a direct result of depositional environment and diagenetic processes further prompting the understanding of reservoir rock properties and their associated characteristics to be crucial in developing a prospect (oil potential).

Once a source rock generates and expels the petroleum, it migrates from the source rock to a rock that can store the petroleum in its pore spaces; a reservoir rock. A good reservoir rock may have pore space that exceeds 30% of the rock volume, while poor quality rocks have less than 10%. Poor quality rocks that lack pore space tend to lack permeability, a property that allows fluid to pass through the pore spaces within the rock. With very few pores, it's not likely that the pores are connected thus, making it less likely that fluid will flow through the rock as opposed to those in a rock with larger, more abundant pore spaces (Noffke, 2013). Highly porous rocks tend to have better permeability because of the greater number of pores and larger pore sizes that allow fluids to move through the reservoir more easily. With this, the property of permeability plays a critical role in the potential for oil and gas bearing materials. Furthermore, reservoir rocks must have an efficient seal to form a trap for the petroleum as well as an important aspect of timing for ample accumulation. The reservoir must have been deposited prior to the petroleum migration from the source to the reservoir rock, as well as the seal and trap having to develop prior to the petroleum accumulating in the reservoir, or else the petroleum would have migrated further (Noffke, 2013). The source rock must've also been exposed to the appropriate temperature and pressure conditions over long periods of time in order to effectively change the organic matter to petroleum. Although the necessary coincidences of these conditions are difficult to achieve simultaneously in nature, the Green River Formation is an emerging example of these processes happening in unison, and is why this project is focused within this locality.

STROMATOLITES:

Stromatolites are large accretionary structures (growing in layers) that accumulate carbonate sediment and skeletal material bound together by algae forming best within reef structures in warm, shallow equatorial waters ranging from tidal flats, to deep-water basins (Rezende et al., 2013). These benthic microorganisms form intricately organized communities called biofilms. Biofilms consist of the individual cell plus their extracellular polymeric substances (EPS). In marine and non-marine environments, benthic microbial communities interact with physical sediment and other environmental factors to bind calcium ions with bicarbonates within a system that is important for carbonate precipitation (oil/gas formation). This interaction can produce distinctive sedimentary structures called microbialites (Noffke, 2013). Microbialites have excellent reservoir facies with preserved porosity (Eberli, 2012). The ability to resist compaction of complicated pore systems in microbialites is partly caused by early microbial processes that construct and strengthen the rock. Formation of these structures include binding, biostabalization, and baffling/trapping sediment particles, along with carbonate precipitation occurring in a repetitive sequence. This mechanism creates accretionary (multi-layered) structures called stromatolites. Benthic microorganisms populate the deposited sediment surface through the assemblage of trillions of microscopic cells that form an organic layer that covers the surface like a carpet (Noffke, 2013). Under a microscope, the carpet-like structure forms an organized pattern of filaments, rods and coccoids (spherical shapes), in a slimy matrix along with the present sediment and/or mineral particles. These organism rich carpets are called microbial mats. Although there are many different types of microbes involved in mat formation, filaments are most

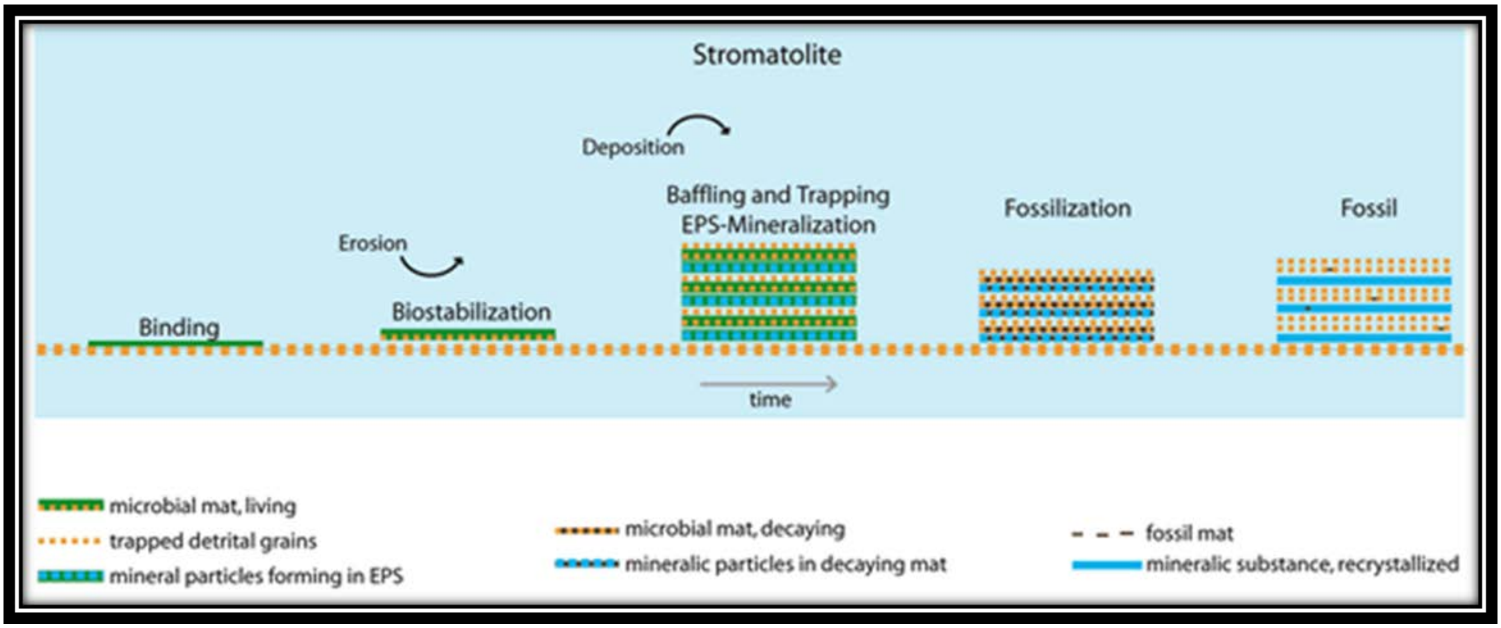


Figure 1: This figure shows the basic processes necessary for stromatolite formation (Noffke, 2013)

important in the construction that provides bridging cements that strengthen rock fabric and improve oil/gas preservation within stromatolites (Noffke, 2013). As seen in figure 3, this process of sediment trapping and binding, along with carbonate precipitation, forms layers of stacked microbial mats that can produce structures reaching meters in thickness. This layered formation of a vertical pattern often forms dome-shaped columns that have a distinct, finely-laminated appearance for which stromatolites are best recognized. Although the solidified sediment matrix cemented together to form a stromatolite may appear hard, it acts very much like a sponge. Between grains of sand, enough space often exists to trap fluids that can later be extracted in the form of oil and natural gas (among other materials). By observing stromatolites in vertical sections, understanding the morphology (structure) of these microbialites provide a better understanding of the structure's intrinsic control (the biology, or genotype and the phenotype of the micro-benthos that form the structure); and the extrinsic factors (size, nature of the sediment and the effect of hydraulic and sediment dynamics, such as waves and currents) (Noffke, 2013).

This mechanism is but one of many processes by which stromatolites are built and include others that are very important, however, this model is best fit for the Green River Formation, in which my samples were obtained. Thus, the construction mechanism of a stromatolite is the principle factor determining its potential to be a reservoir rock. The percentage of oil/gas reservoir potential yielded from these sedimentary structures are small, deeming the analysis of fundamental petrophysical characteristics within stromatolites (texture, fabric, structure size and stratigraphic features formed by depositional environments) an important topic in providing a structural framework of porosity and permeability. This approach in understanding microbialites found in carbonate reservoirs allow a better understanding into which depositional and environmental factors affect the maximum oil/gas output within pore connectivity; proving useful for the important ongoing exploration from prospecting oil companies.

CURRENT OIL BEARING CARBONATE RESERVOIR/STROMATOLITES AS RESERVOIR ROCK:

Microbialites and related lacustrine facies form significant reservoirs (Buchheim et al., 2010). However, different forms of stromatolites, resulting from different environmental/depositional processes, heavily impact properties such as pore connectivity, porosity and permeability, critical to oil recovery. With this, there is much interest in understanding the internal structure and formation of stromatolites in order to better predict their behavior as reservoir rocks (Frantz, 2015). One of the largest oil fields in the GRF is located in the Uinta Basin (Utah) and is derived from thick lacustrine microbialte bioherms that has produced nearly a million barrels of oil (Buchheim et al., 2010). The bioherms that occur in the GRF are composed of clusters approaching 0.5 km across of domical and columnar stromatolites, with some up to 3 meters in diameter. The bioherms grade laterally into adjacent fine-grained lake facies over a distance of 100 meters and into dolomitic oil shale of the Wilkins Peak Member over a distance of ~15km (Buchheim et al., 2010). Considering that these thick microbialites can be important reservoir rock,s it is key to understand the paleoenvireonmental conditions that favor the formation of bioherms over biostromes. These biostromes are found in sequences interpreted as balanced-filled lake deposits sourced from frequent transgressions and regressions over low gradient conditions (Buchheim et al., 2010). Bioherms appear to have been favored by under-filled lake-basin conditions (saline-alkaline lakes), much like the ancient Lake Gosiute, where localized fresh-water deposition was restricted to the lake margins. This importance of lacustrine microbialites as petroleum reservoirs are significant when assessing petroleum potential in lacustrine basins. Similar occurrences seen in outcrop exposures found in the Green River Basin (Wyoming), provide analogs for petroleum exploration within related lake basins.

PREVIOUS WORK/BRAZIL PRE-SALTS

Exploration in lacustrine microbialites has significantly expanded following reports on the discovery of notable quantities of hydrocarbons in reservoirs associated with microbialites observed in the pre-salt lacustrine successions off of the Brazilian coast (Awramik & Buchheim, 2013). Previous work has focused on the geological, geophysical and petrophysical interpretations within carbonate reservoir rocks that comprise main reservoir rich systems seen in the large field accumulations in the South Atlantic, particularly in the Santos Basin. These wells contain huge accumulations of oil beneath a thick layer of salt holding potential recoverable reserves from 795 million to 1.3 billion m^3 of oil equivalent. Preliminary work on the microbialites shrubs and structures similar to those within the GRF indicate that some grew on the lake bottom, forming laterally extensive biostromes under a meter thick, where others formed in cm-mm scale (seen in GRF stromatolies). Nonetheless, all models of occurrence share some common features: All occur at the basin margins during transgressions, they formed during freshening phases of the lake, and they are all associated with higher energy environments (sediments rich in grainstones) (Awramik, Buchheim, 2013). Core data suggests that these microbialtes, ranging in a mm to a cm in size, form shrub-like carbonate structures containing essential predominant elements within their respective analyzed core. Analogs, both present-day and ancient, which accommodate the necessary scale and depositional settings, closely resemble shrub structures found in the GRF under the same conditions: shallow, high-energy environments in large lake systems (Awramik & Buchheim, 2013). Geologically, this play is a product of slow tectonic and depositional processes involving continental rifting, seafloor spreading, and sedimentation. The depositional processes created source, reservoir, and seal layers necessary to successfully produce an active petroleum-rich system (Beasley et al., 2015). These microbialite reservoirs have been recognized in several other sedimentary basins worldwide including those within the GRF. Since this play is relatively new, its origins are still controversial. Current interpretations assume that these rocks may have been related to chemical precipitation of carbonates in a basin affected by numerous volcanic and hydrothermal episodes resulting in travertine deposits (white or light-colored calcareous rock deposited from mineral springs) allowing for biogenic growth. This model proves a similar analog in the formation of microbial reservoirs seen within the GRF regarding its depositional settings and petrophysical parameters (Mohriak, 2014). With the observed resemblances in extensive lake deposits that accumulated in rapidly subsiding basins, the presence of abundant carbonates, and large microbialite bioherms (among others), the GRF shares many important features with the pre-salt petroleum play of South Atlantic lacustrine basins, making it arguably the best, single known analog for carbonate reservoir rock as a petroleum bearing system (Awramik, Buchheim, 2013). From its interior basins to its deep offshore waters, carbonate reservoirs are being targeted as potential oil-bearing agents and has opened a new frontier for petroleum exploration and production (Beasley et al., 2015).

GEOLOGIC SETTING

Located within the Green River Formation (GRF), the Greater Green River Basin (GGRB) exemplifies one of the largest researched aggregation of lacustrine sedimentary rock on the planet (Chetel, 2010). Seen in figure 4, this mountainous area covers over 20,000 square miles stretching from southwestern Wyoming, northeastern Utah, and Northwestern Colorado. Tectonically, the Greater Green River Basin was formed from basement cored rock uplifts of the Laramide Orogeny (bounded by the adjacent foreland of the Sevier to the north, east and south) that formed in western North America starting in the Late Cretaceous (~70 Mya) and ending about 40 Mya (Gao, 2013). The Green River Formation (GRF) comprises several basins formed as a part of the uplifting of the Rocky Mountains during the lower Tertiary (Eocene). This formation is a heterogeneous complex of lakes that contain many different ecological and geological characteristics. The Greater Green River Basin (GGRB) is the name given to a group of five sub-basins: The Hogback Basin (northwestern portion), the Green River Basin (western portion), the Great Divide Basin (northeastern portion), the Washakie Basin (east-central portion), and the Sand Wash Basin (southeastern portion) (Self, et al., 2013). The Greater Green River Basin is one of three basins in the western US that contains oil bearing rock that has been used as a viable source of fossil fuel. The Greater Green River Basin was formed primarily through lacustrine related deposition in a sequence of continental basins. The basins found here are disjoined from each other by chains of basement-cored uplifts that collectively comprise its original orogenic formation (Smith, 2008). As a result, the basin is divided by intra-basin anticlines into four structurally and topographically distinct sub-basins. The largest and main basin is the Rock Springs uplift, which trends north-south, located in the center of the basin dividing the basin into nearly equal halves to the west and east. The Green River and Great Divide Basins are positioned in the west half, with the Washakie (Bridger) and Sand Wash Basins occupying the eastern side (Roehler, 1992). These main sub-basins are further subdivided into smaller drainage basins scattered throughout the Green River Formation.

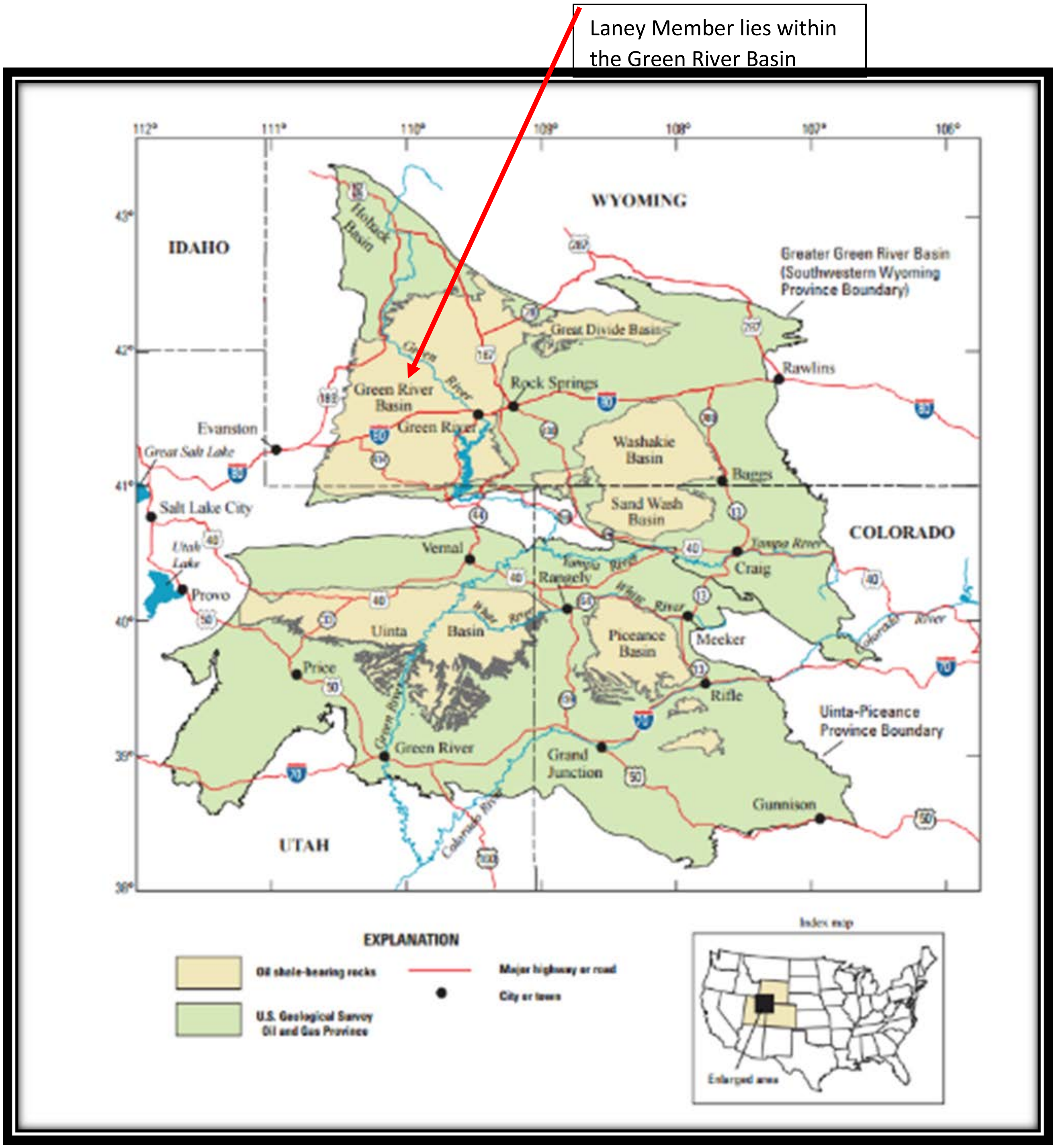


Figure 1: This figure is a broad overview of the Green Rover Formation along with its accompanying sub-basins (Oil Shale Assessment Project Fact Sheet, USGS., 2011)

The GGRB complex includes three primary lakes (Gosiute, Uinta, and Fossil) that formed as a consequence of drainage from tectonic highlands involved in the uplift of the Rocky Mountains. The GRF consists of fluvial-lacustrine rocks that were deposited in and around the ancient Lake Gosiute which covered much of southwestern Wyoming as well as northwestern

Colorado and Northeastern Utah (Surdam & Stanley, 1975). The lake was formed in a sedimentary basin during the Laramide Orogeny from the late Cretaceous to Eocene times. During its 4 million year existence, the lake changed numerous times, undergoing frequent transgression and regression events which have been characterized by three major stages, each of which corresponds to a member of the GRF's major stratigraphic units (from bottom to top): the Tipton, Wilkins Peak, and Laney Members (Surdam & Stanley, 1975).

Studies of the GRF indicate that Lake Gosiute was a part of a series of lacustrine sub-basin networks and, indeed a playa-lake complex in which the sediments of the GRF were deposited. This further suggests that the present rock products seen in the oil shale and carbonate-based sedimentary formations are a direct result of lacustrine deposition in a closed basin (Surdam & Stanley, 1975). Dynamic variables of such a basin like the area of the lake, water depth, salinity (water chemistry), seasonal inflow, and evaporation all contain evidence of excellent conditions for reservoir rock with pore space potential. During the Deposition of the GRF, Lake Gosiute underwent periods of expansion and regression (shown in figure 5), starting as a fresh-water lake, evolving to a saline-alkaline lake, and ending as a fresh water lake with subsequent fluctuations from shallow to deep water conditions. As a result, sedimentation in the lake system was strongly influenced by the relationship between evaporation and the inflow of water into the basin. In the GRF, stratification sequences, sedimentary structures, and the mineralogy of facies provide important information into the lakes evolution regarding the type of sediment that accumulated in which allow for ideal stromatolite forming conditions.

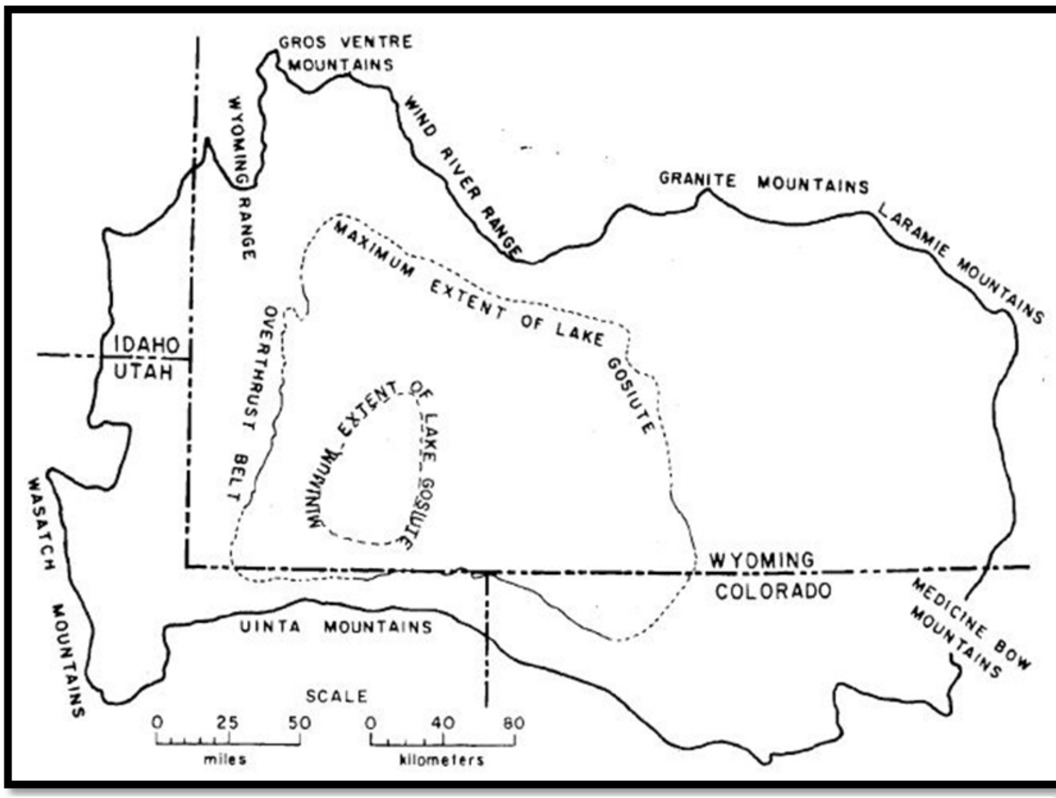


Figure 1: The maximum and minimum extent of the ancient Lake Gosuite, Green River formation, Wyoming (Surdam & Stanley, 1965)

Hydrochemistry of Lake Gosiute during the deposition of the Wilkins Peak Member was largely controlled by ground water discharge, whereas the deposition of the Laney Member was controlled largely by surface water, allowing for calcite to be precipitated into the lake as a result of calcium-rich inflow into the saline-alkaline lake waters. This variable could be of importance when attempting to reconstruct a model for ideal carbonate reservoirs which have the ability to contain oil within its pores (Surdam & Stanley, 1975). This hydrologic evolution is consistent with the necessary conditions needed for stromatolites with varying degrees of porosity to form.

Seen in Figure 6, the oldest rocks of the GRF in the GGRB are known as the Tipton Shale Member which is divided into freshwater and overlying saline beds. During Lake Gosiute's periods of expansion and regression, its waters fluctuated from deep to shallow. It was during a period of regression that the Wilkins Peak Member was deposited, followed by the Laclede Bed of the Laney member. These beds are interbedded further with higher amounts of sandstone and mudstone. Following the lake regression, the Lake expanded again, covering a much larger area of the GGRB with much deeper water depths. As seen through the rock record, this expansion marks the Laney Member, of which the samples used in this paper were taken from. This member contains the youngest of the oil-bearing strata (Self et. al, 2011). It is important to note the stratigraphic sequence of the members that were deposited during these periods of Lake Gosiute's regression and expansion when attempting to assess which depositional environments

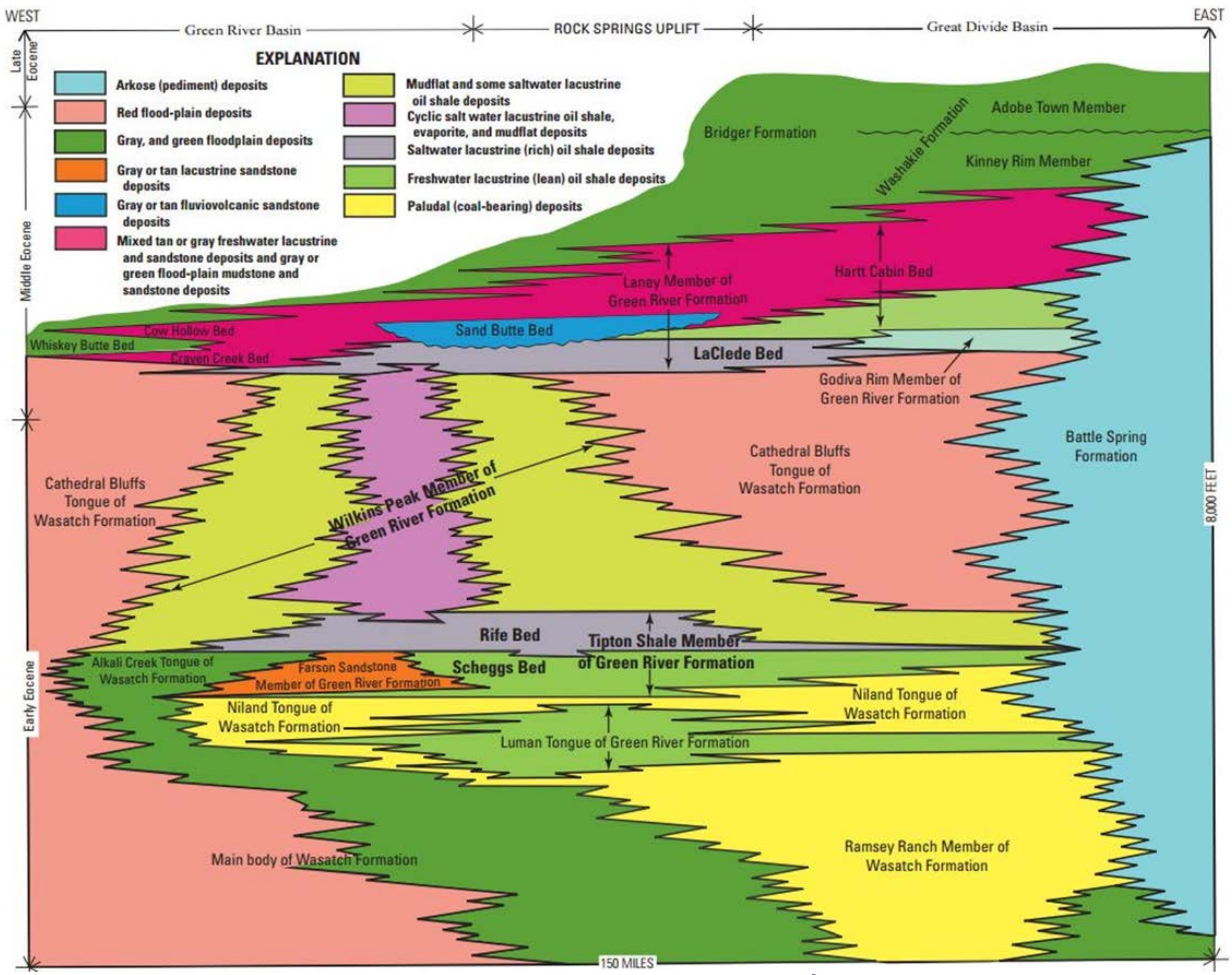


Figure 1: Stratigraphic relations of Eocene rocks within the GGRB, SW Wyoming

were present during stromatolite formation and, determining which of those environments are best fit for reservoir rocks with interconnected pore space.

This study focuses on the samples from the Laney Member, the youngest of the lacustrine rocks in the GGRB. The lowest section of the member is stratigraphically discernable from the uppermost sections of Wilkins Peak Member, recognized by a thinly layered tuff bed. This layer is followed by oil shale beds divided from an upper sandstone-mudstone portion, interbedded with gray to green mudstones, limestones, silistones, and tuff ranging in thickness from 0-630 meters. The Laney member consists of four lithofacies characterized by two major rock types: laminated carbonate, sandstone/mudstone, evaporate, and molluscan-ostracodal calcareous mudstone. These rock types were deposited during Lake Gosiute's frequent transgressions and regressions from its beach & deltaic shorelines which strongly influenced the development of nutrient-rich, algal-dominated microbes to coalesce, further allowing an environment for carbonate sedimentation to take place (Surdam & Stanley, 1975). These lithofacies and sediment types were subject to subtle changes in the physical, chemical, and/or biological features of the lake waters and reflect the evolution of organic and chemical sedimentation within the depositional basin (Surdam & Stanley, 1975). These variables are consistent with stromatolite formation necessary to hold oil/natural gas within its pores and is why this area was chosen among others for analysis. In regards to deposition, the (marginal) lacustrine origin of carbonate rocks in the Laney are recognized as representing a high stand in the history of Lake Gosiute. Repetitive depositional sequences identified by the nature of the lake depth and its surrounding environment during the formation phases of sedimentation provide more detail for the regional and temporal relationships of the rock strata within this system (Surdam & Stanley, 1965). The samples used in this paper were taken from the Sand Butte Bed and the White Mountain area, both of which lie within the Laney Member. The depositional, environmental, and stratigraphic occurrences such as the ones described in the ancient Lake Gosiute, provide an ideal analog to current petroleum-bearing carbonate reservoir rock systems such as the one observed in the pre-salt layers off the Brazilian coast. The previously mentioned mechanisms for which are ideal conditions for stromatolite formation, contain varying degrees of potential pore space network (Rezende, et al., 2013), and, is why the samples used in this paper were specifically chosen.

DEPOSITIONAL ENVIRONMENT:

Eight depositional environments are identified in Eocene rocks within the GGRB (Figure 7): Fluvial, paludal, fresh-water lacustrine, salt-water lacustrine, pond and playa-lake, salt pan, mudflat, and fluvial-volcanic (volcanic) (Roehler, 1965). Carbonate sediments accumulate in depositional environments ranging from tidal flats to deep-water basins. Most carbonate sediments originate on a shallow-water platform, or shelf, and are transported landward and basinward through varying fluctuations in water depth (Dunham, 1962). This fluctuation is seen in Lake Gosiute and provides support when connecting these environments to the samples which are studied in this paper. The lateral distribution of depositional environments reflect energy levels, topography, and organic activity in and around the environment during the time of formation. These variables have been related to variations in the characteristics observed within carbonate platforms within the GGRB. Because calcium-carbonate cementation begins directly after deposition, it is closely related to its depositional environment (Lucia, 1995). As cementation fills pore space, both pore size and porosity is affected by the amount of cement and compaction as a function of texture over time (Lucia, 1995). Ideally, stromatolites with high porosity should form under high-energy conditions in order to prevent weakened textural effects such as porosity loss and pore size reduction. Experiments and observations have shown that mud-supported sediments compact more readily than those that are grain-supported seen in Dolostone (a rock composed of dolomite) as an ideal reservoir rock. Ideal reservoir rocks containing various pore volumes analyzed through

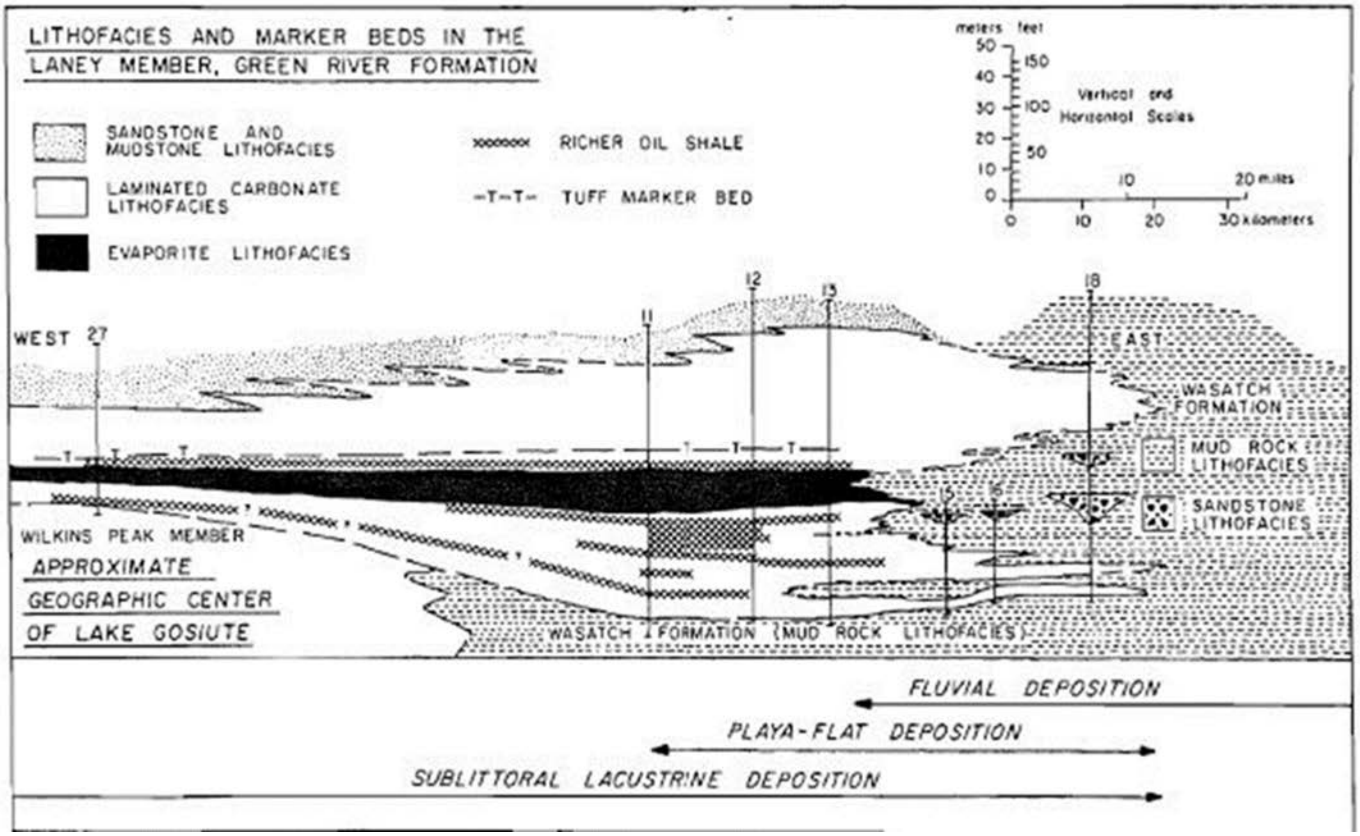


Figure7: This figure shows the lithofacies (main rock types) that have been deposited within the Laney Member. Each rock type occurs in a specific stratigraphic sequence related to its depositional environment and contains various degrees of oil-bearing potential. (Surdam & Stanley, 1975)

depositional models show a main source of magnesium that is thought to be modified through various hydrodynamic forces such as density, elevation, and temperature (Dunham, 1962). Therefore, the hydrologic system must also be understood for the distribution of carbonate reservoir rock to be predicted through time and space.

RESEARCH QUESTION

Today's world is driven by a sharply increasing demand for oil and natural gas. This demand has prompted the search for new and unconventional ways of obtaining this energy need necessary to power our daily lives. Exploration in lacustrine-related microbialite structures, targeting carbonate reservoirs as potential oil-bearing reservoir rock, has significantly expanded following reports on the recent discovery of massive quantities of petroleum-bearing hydrocarbon reservoirs under a thick salt layer off the coast of Brazil. This petroleum rich carbonate succession, associated with microbialite formation suggests that carbonate structures can and do host oil-bearing potential within its structural framework.

In the previously mentioned pre-salt play discovery, the conditions for which this system formed provides an analog for similar occurrences seen in outcrop exposures found in the Green River Basin (Wyoming, USA). Although microbialites and related lacustrine facies are understood to form potentially significant reservoirs, variations resulting from different environmental/depositional processes heavily impact properties such as pore connectivity, porosity and permeability values; critical to oil recovery. With this, there is much interest in understanding the internal structure and formation of microbial based carbonate structures, known as stromatolites. A better understanding in the structural framework and conditions in which stromatolites form can provide a better approach to predict their behavior as reservoir rocks. With observed resemblances in extensive lake deposits that accumulated in rapidly subsiding basins, the presence of abundant carbonates, and large microbialite bioherms (among others), the Green River Formation shares many important features with previously studied lacustrine based, basin models. This makes the GRF arguably the best, single known analog for studying carbonate reservoirs regarding their potential as reservoir rock.

This project will examine two different stromatolites taken from the Green River Basin within different depositional environments of the Laney Formation. Analysis of these structures will assess porosity development within microbialites as a function of stromatolite texture and the relationship of that texture to pore interconnectivity. This paper compares and contrasts, as well as indicates similarities of porosity within these carbonate systems as it relates to depositional environments. Furthermore, through the analysis of fundamental petrophysical characteristics such as texture, fabric, and structure size, integrated with stratigraphic features; a complete structural framework can provide a better understanding of pore space presence and connectivity within these pore networks. The consensus that microbialites which form under specific conditions can and do hold fluid within its pores, provide a better approach to future analysis critical in predicting worldwide analogs for petroleum potential. This paper aims to assess microbialite potential as a reservoir rock. The demonstrated methods used here attempt to connect important textural agents, critical for reservoir rock characterization and their relationship to the depositional environments in which form them.

METHODS/APPROACH

FIELDWORK:

The Green River Formation is home to a wide array of microbialite dominated carbonate rock sequences. The samples used in this paper were obtained from the Green River Basin within a sequence of sedimentary rocks deposited during the Eocene time period from a lacustrine-deposited bed, characterized as the Laney Formation. This formation contains both the Sand Butte Bed and White Mountain sequence, from which my two samples were obtained. A ten day excursion through the Green River Formation was made in June 2015 by Gustavus Adolphus Geology professor, Julie Bartley, accompanied by Gustavus students Grant Noennig, Tanner Eischen, and Lindsey Reiners.

In the field, measurements were made vertically using a Jacob's staff along with an eye level measuring technique, based on the height in line of vision. To accomplish this, measurements were taken from the height up to eye level (165cm), then directly ahead along eye line in order walk to that spot for another successive measurement. This technique allowed for a faster measurement in the scale of the outcrop, along with a measured increment that varied only slightly with the direction of sight. The beds composing each outcrop were determined and categorized based on facies changes and stratigraphic layers. Samples were taken from multiple beds at each formation. Some were found in place but most were in float, meaning they had fallen or had since been moved from their original location of deposition. Samples were gathered in float mainly due to their availability and ease of extraction while rare findings of in-place structures were taken when available. Following the conclusion of data collection in the GRF, samples from White Mountain and Sand Butte were chosen for this paper to assess their porosity development as potential analogs to similar oil-bearing microbialite carbonate reservoirs.

Properly labeling samples in the field was important in order to accurately document where each sample came from. An organized method noting important field observations were extensively noted for later referral. A cross-sectional drawing taken from the field notebook of Julie Bartley (seen in figure 8) shows an example of how the samples in each outcrop were labeled. Labels were formulated by separating the outcrop into sections termed, benches. As seen in the figure from a White Mountain outcrop, Section A is located at the base of the locality with bench 1 located between section A and section B. Section B is separated from section C by Bench 2. Section B is separated from C by bench 2, with section C and D separated by bench 3 and 4 (located at the top of the outcrop).

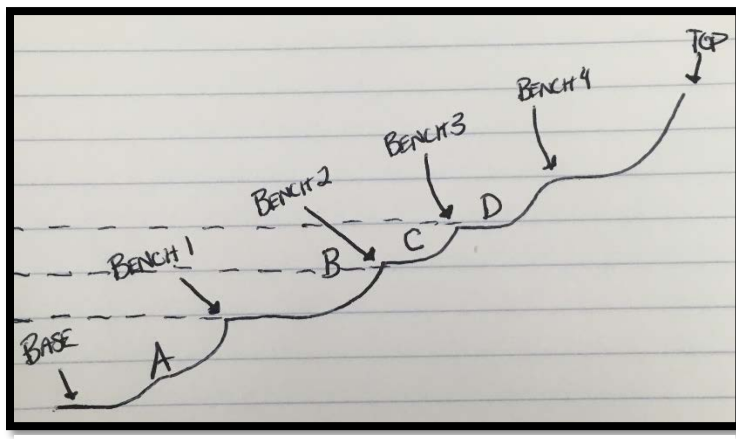


Figure 8: This is a re-created sketch taken from the field notebook of Julie Bartley. This diagram shows the outcrop of White Mountain and labeled by benches and sections from which are stratigraphically separated by strata deposited at different times

SAND BUTTE: Sample # (15SB-7B). This sample was taken from the Sand Butte Bed. This outcrop was deposited during a transgressional event of Gosiute Lake. During this time, the lake would have exhibited deep waters, with saline-alkaline to freshwater components allowing for cyanobacteria to coalesce and eventually form algal-based microbialite structures. The bed is situated near the bottom of the Laney member, just above the LaClede Bed. The rate of cementation and location of deposition within this bed offers a unique history of its structural formation and is why this sample was take from this specific locality.

WHITE MOUNTAIN: Sample # (15WM-3B). This sample was taken from White Mountain. A crude sketch seen in the figure above illustrates a cross-sectional drawing of the base of the outcrop to the top. It is here where the sample was collected and is believed to be located along the area in which the ancient Lake Gosiute's shores rested. Noting such a figure important when choosing a sample regarding where the specimen was deposited. Deposition along a shallow shore provides insight on the paleoenvironment that was present, allowing for a better understanding of how this specific environment may lead to porosity potential within its framework.

LAB WORK:

Studying the internal structure of a stromatolite can tell a lot about its potential to hold oil and natural gas within its pores. The majority of this research was conducted in the lab. The samples were labeled based on their location of origin such as the benches in which they were found, bench sequence (elevation), and were numerically categorized specifically relating to its position within the outcrop sequences.

ROCK SAW:

The samples were initially cut using the rock saw. This was done by assembling Lego pieces that extended from an adjacent wall parallel to the rock saw in order to guide the sample through the saw in a uniformed fashion. These Lego pieces could be adjusted in length to accommodate the size of each sample being cut. A small portion of each side of the sample was cut in preparation for the following grinding and scanning procedures. It is imperative that the two cut surfaces were both flat and smooth, parallel to the saw blade in order for a more accurate scan throughout the sample.

EPOXY:

After the initial cuts were made, a glass slide was mounted to the sample using an epoxy solution. This solution was mixed and stirred until the mixture was adequately blended. The glass slide was carefully placed onto one of the flat faces of the previously cut rock. It was important that the slide was properly placed to allow for an exact placement onto the scanner each time a scan was made in order for a consistent scan.

GRINDING WHEEL:

After the glass slide was mounted, the grinding of each sample could commence. This procedure used a grinding wheel at its highest power with 120 (coarse-grained) grit. Samples were ground every 0.5 mm, measured by an electric caliper and kept level with an electric leveler. A scan taken between these 0.5 mm intervals. After every 1 cm, an acetate peel was taken to characterize the petrophysical changes that the rock encountered throughout the sample. When grinding, it was important to consistently clean the grinding wheel, as the grit would build-up along the grinding wheel surface, making it difficult to effectively grind the rock. After each grind, the sample would then be rinsed off with water and thoroughly dried in preparation of its placement on the scanner.

ACETATE PEELS:

Acetate peels are an excellent method for assessing and characterizing the petrophysical characteristics of a structure such as texture, fabric, size, stratigraphic sequences and rate of cementation. A peel was taken every 1 cm throughout the sample and was further analyzed both visibly and through a petrographic microscope. The peels provide a detailed sequence within the framework of the samples for which could be characterized and compared to its depositional origins and subsequent porosity potential. This analysis further allows for a more detailed reconstruction of the paleoenvironment in which these rocks were formed and their connection of porosity development through time and space.

SCANNER:

An HP Scanjet scanner was used to scan images in 0.5 mm intervals. These images were then saved and uploaded in "Tiff" format into a google drive document for further manipulation. When scanning, it was crucial that each scan was imaged at the exact same spot on the scanner in order for a consistent arrangement needed for later use. To do this, Lego blocks were constructed at a right angle adjacent to the corner of the scanner for which the glass slide mounted on top of the samples could be slid into the same place (Figure 9). The HP Scanning software that was used allowed for the manipulation of specific criteria such as height and width dimensions, cropping devices (to allow only the sampled area to be scanned), and resolution. The samples were scanned in greyscale at 3600 resolution to provide a high quality illustration of the scans.

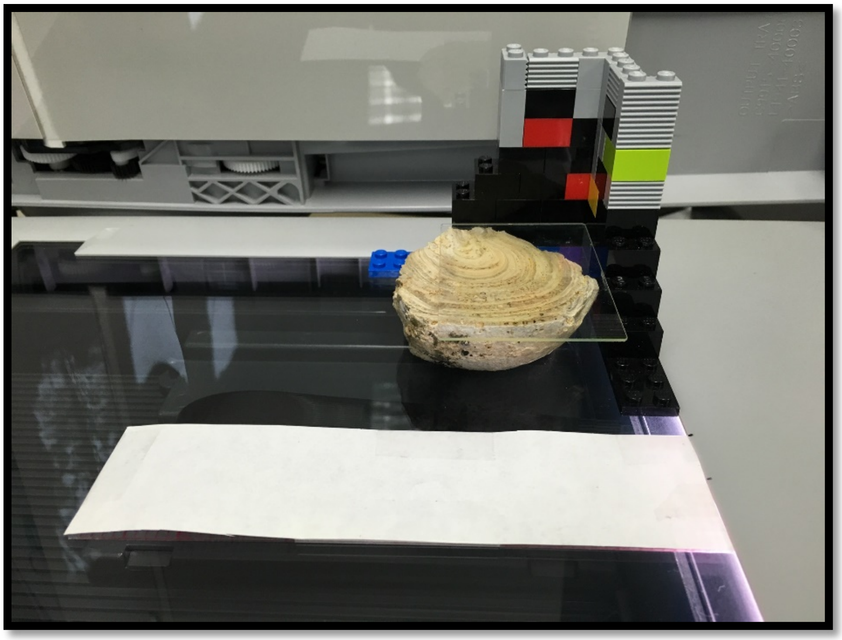


Figure 9: this image shows a sample put into place at a right angle against the Lego pieces on the scanner in order to scan each sample in the exact sample spot.

PROCEDURES

Epoxy Mounting Procedure

1.) Retrieve the epoxy solutions (part A & B) and the glass slides. You'll also need to find something to mix the solution and locate the small plastic bowl to mix in. (All located in the geology prep room)
2.) Mix up epothin solution (7 parts A to 3 parts B) for a few minutes or until the solution looks totally mixed and there are no bubbles.
3.) Clean off the glass slides before mounting with a kim wipe.
4.) Let the epothin sit for 10 minutes after mixing to let the remaining bubble dissipate. Make sure you are working on a level surface to ensure nothing will disturb the epoxy solution.
5.) Carefully spread a thin layer of the epothin over glass ensuring it covers the whole surface of the sample and leave it on for a few minutes so it can totally adhere to the sample.
6.) Let it dry for at least 24 hours

Acetate Peel Procedure

Before peeling, you must cut a flat rock face, polish the surface until smooth, and etch the sample.

1.) **For small rock saw**
    a.) Close valves and fill saw with water until both sides of saw have a steady drip
    b.) Slowly cut the rock
        i.) Porous rocks may absorb some of the water you pour in, if it starts getting hot and steaming, add more water
    c.) Remember to drain water out of saw before leaving!
2.) **For large rock saw** (only if sample is too big for the smaller saw)
    a.) Place rock in designated spot
    b.) Keep top closed at all times when running the saw
    c.) The “on” switch is found is found in front right of the saw
3.) **Trim saw and buffer** (only for small samples)
    a. Fill blue bucket/reservoir with water until the small black pump is completely submerged in water (can’t intake air- it will ruin it)
    b. Make sure hose is draining inti the top smaller tray in reservoir, and make sure the steel wool is in place (filters sediment)
    c. Turn on pump to start grinding or sawing
    d. Empty reservoir before you are done
4.) **For the grinding wheels**
    a.) Use left wheel only
    b.) Grind until surface is completely flat!
5.) **Etching**
    a.) Once you have a completely smooth rock surface you have to etch the face to exaggerate the textures for the peel to stick to.
    b.) Use 0.5M HCL, pour just enough to hold the face of your sample in the acid
        i.) Don’t just set your sample in the acid or it will cause uneven etching
        ii.) Keep the face submerged, but not touching the bottom of the dish
    c.) Keep the sample submerged for 25-40 seconds depending on how porous the sample is
        i.) More porous- less time
    d.) Rinse face off immediately after etching!
6.) **Oven**
    a.) Put your samples in the oven at or around level 6 (not the white furnace, the silver oven)
    b.) Completely dry your rock; typically takes around 4 hours
    c.) Then, you have to let your sample completely cool off or the heat will evaporate your acetone.

<u>Start the peel</u>

Now that your sample is prepared, you can begin the acetate peel

1.) Keep rock at a slight angle inside the glass pan (balance on another rock or any sturdy object)
2.) Use the squirt bottle of acetone to completely cover the face of your sample
3.) Quickly, but carefully lay the acetate sheet flat on the surface of your sample
    a.) Smooth out before the acetate starts melting
    b.) BUT, don't smear it around too much or it will alter the textures
4.) Leave the peel on for approximately 15 minutes, or until the sheet appears dry
    a.) If you take it off too early, the acetate sheet will be goopy
    b.) If you leave it on too long (especially on a porous sample), the sheet will soak into the pores and create holes in your peel
5.) Start from a corner, and slowly peel the sheet off of your sample
6.) Put it inside a heavy book or underneath something heavy to flatten it out
    a.) You may have curling on the edges, the less acetone used, the less curling of the sheet

RESULTS

PETROPHYSICAL CHARACTERISTCS

Along with scanned images of each sample every 0.5 mm, an acetate peel was taken every 1 cm and evaluated both at eye level and under a high-power microscope in order to assess the petrophysical characteristics within the rock to characterize variances in texture, fabric, size, and stratigraphic features. These features, integrated with knowledge of each samples depositional environment was analyzed in attempts to correlate these characteristics in providing a better understanding of how the origins of formation within these structures affect its porosity potential. Through this, a more complete framework can be used in predicting which depositional environment yields ideal construction of oil potential within microbialite pore space.

Sample #15SB-7B (Sand Butte) showed a wide array of porosity potential within its internal structure. The initial dimensions of this sample was 50 mm tall and 101.9 mm wide. As shown in figure 10, pictures of the sample were taken from outer (left) and inner (right) portions of the sample. Concentrated in the center of the sample, two main vugs (void spaces) are observed. The larger vug measures 1.1 cm tall and around 0.9 cm wide.

Figure 1: Picture on the left shows the initial cut of sample exhibiting separate vug porosity, while the figure on the right, upon further slicing of the rock, shows inner areas of the sample exhibiting touching vugs

The second vug is 0.9 cm tall and about 0.7 cm wide. Pore space is divided into two groups: Interparticle and vuggy, based on how the pore space is connected. The classification of pore space is an important aspect of rock fabric classification and dominate the performance of carbonate reservoirs. Through initial observation, the vugs in this sample are not visibly connected, classifying them as being connected through interparticle pore space (not touching). However, shown in the picture on the right, as the sample was further ground down, the vugs show a gradual connection, almost creating a semi-circle running from one vug to the next. Further preliminary observation shows alternating coloration from light-grey to light brown with an increase in more uniformed layering.

Seen in the pictures of figure 11, acetate peels were taken from the outer portion of the sample at 40mm (on the left) and from the center of the sample at 0mm. These peels further show void space connectivity and important porosity defining characteristics such as texture, stratigraphy and fabric. From these peels, large crystals with big void spaces are seen concentrated along the inner portion of the sample. These spaces, characterized as vuggy porosity, exhibit poor laminae with an irregular structure. As the sample moves outward, a clotted/clumped texture containing lighter-darker micrite (small carbonate grains) is seen with increasing laminated bands that run across the sample showing moderately well-developed layers. This portion does not have as pronounced open space as the center, but does appear to contain smaller, more frequent voids with low-intermediate pore space. Further outward towards the edge of the sample, laminae is finely layered with horizontally uniformed micrite running along the entire edge of the rock with no visible void spaces. As peels were taken throughout the sample, the vugs were seen gradually increasing in size and connectivity towards one another. The outward progression of open vugs, to clumped micrite, to finely laminated banding is observed throughout all peels within this sample.

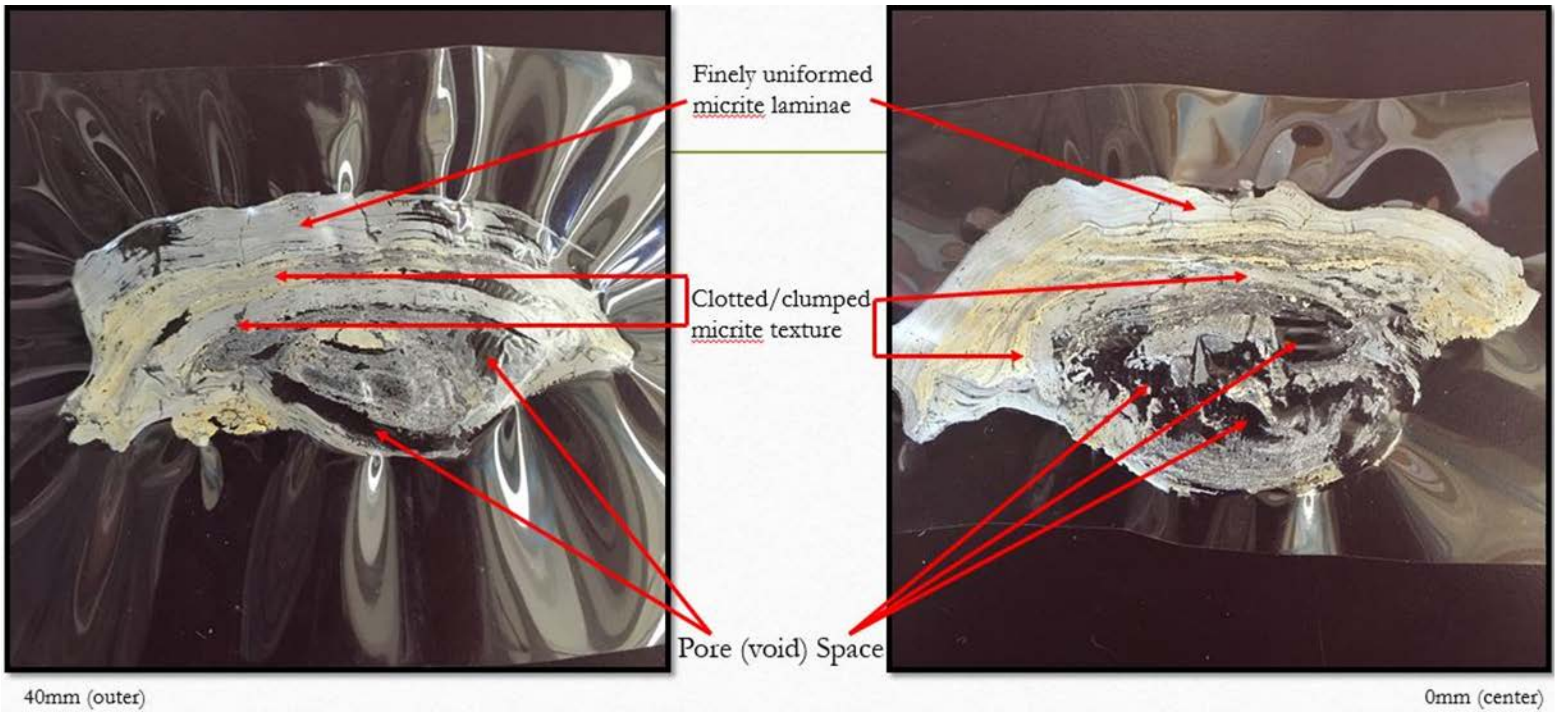


Figure 1: Peel on the left, taken from outer portion of the sample shows smaller pore space connectivity, while the peel on the right shows a high degree of vuggy porosity at the center of the sample. Both show gradual increase in micrite laminae uniformity

Sample # 15WM-3B (White Mountain) (figure 12), showed a relatively consistent pattern within stratigraphy, texture, and fabric. This sample was quite a bit smaller than that of Sand Butte with initial dimensions at 24 mm tall and 47.4 mm wide. Seen in this figure, the initial peel taken

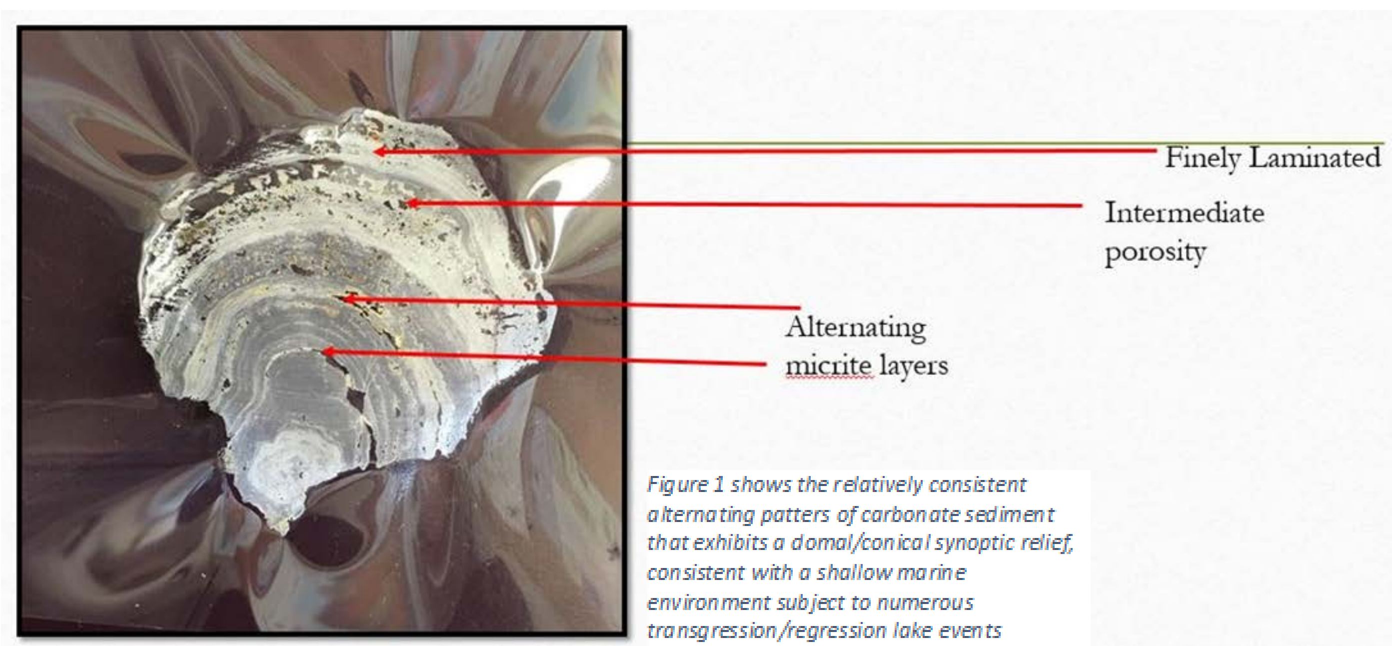
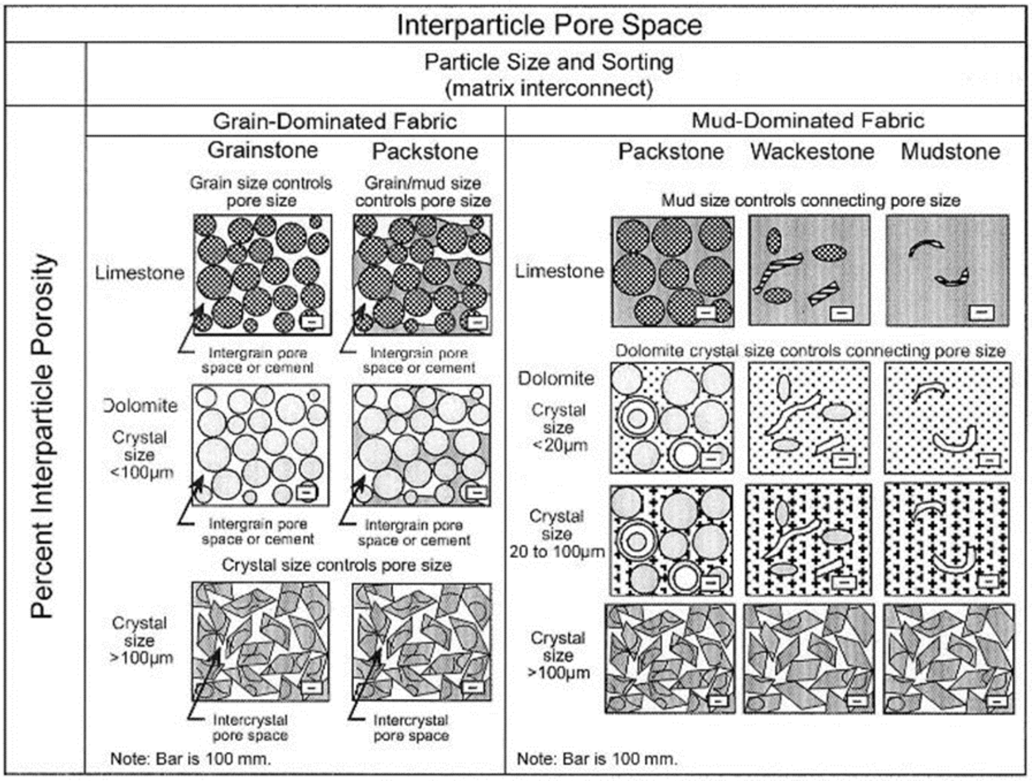


Figure 1 shows the relatively consistent alternating patters of carbonate sediment that exhibits a domal/conical synoptic relief, consistent with a shallow marine environment subject to numerous transgression/regression lake events from the outer section of the rock at 24mm is fairly homogenous in stratigraphic layering and color. The peels from the White Mountain sample show alternating bands of finely layered laminae containing clotted/clumped carbonate grains similar to that of the Sand Butte specimen. Unlike the relatively horizontal laminae seen in the Sand Butte sample, this rock is more domal and conical in its synoptic relief, providing further evidence of the paleoenvironment in which the stromatolite formed.

TEXTURAL CLASSIFICATION/COMPOSITION

The samples from both localities exhibit high variability in carbonate sediments. Knowing that the arrangement of the grains that make up these structures is highly dependent on its porosity and permeability potential, it is important to note the sediment found within them to further asses their potential as reservoir rock. Textural classification is categorized into loose and bound sediments. Loose sediment is described on the basis of mud vs. grain support and include observed grains such as grainstone which lack carbonate mud. Similarly, mud-supported textures are referred to as wackestone and mudstone. In this case, carbonate reef environments are commonly composed of large organisms such as corals and sponges with very large particles. These in-place reef materials include bafflstone and bindstone. Conversely, transported reef sediments are termed floatstone (mud-supported) and rudstone (grain-supported) (Lucia, 1999). Grainstones and boundstones found within stromatolites of the GRF are concerted in areas of highest energy, commonly at ramp & shelf margins. Sediment would have been transported from the basin, to the shelf slope, where it would have been deposited along the shoreline (shelf edge). This transport occurs primarily during high-stand and results in progradation of the shelf margin alongside the basinal deposition of calcareous sediment (among others). Surrounding sediment is also transported landward onto the shoreline, creating tidal-flat deposits usually during these periods of regression. Figure 13 shows the preference of interparticle pore space within grain vs. mud-dominated fabrics. The fabrics observed in the samples from this paper are of importance when further assessing how particle size and grain sorting affects overall porosity potential.



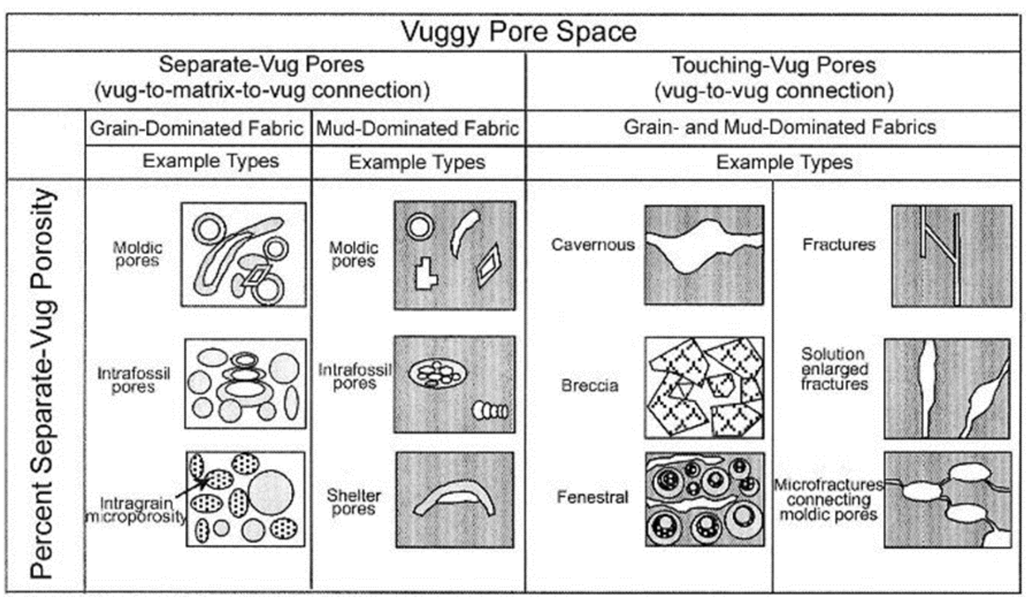


Figure 13: This diagram shows Dunham's classification of carbonate rocks in regards to depositional texture. The presence of certain grain vs. mud dominated fabrics indicate a preference of certain fabrics over others in producing porosity within carbonate rocks. (Dunham, 1962)

THIN SECTION ANALYSIS

Understanding reservoir rock properties and their associated characteristics is crucial in developing a porous reservoir rock. Seen through petrographic analysis of acetate peels, microbialite carbonate rocks display numerous features of composition and texture directly related to its depositional environment and post-depositional processes (i.e. diagenesis and cementation). Results acetate peels indicating that fabric and texture play a large role in porosity development prompt further analyses into the mechanisms that form these traits. To better understand this, images were sliced and scanned along 0.5 mm intervals using a computer scanner.

Results from the thin sections scanned from the Sand Butte Bed show a gradually increasing interconnectivity of pore space corresponding to the pattern seen from the acetate peels. Figures 14 A, B, C, and D are shown labeled in relation to the thickness at which the scans were taken. Initial observation shows a clear difference throughout each image. Image 14A was the first scan taken directly after the initial cut face of the rock at a thickness of 50 mm. This image shows an irregular structure towards the center of the sample with gradual uniformed layering running across the whole rock. The semi-curved horizontal banding is observed as gradually moving from dark brown-light brown in the middle, towards alternating coloration in light yellow to a greyish brown. Along the edge of the rock, color is mostly light grey. Image 14B was scanned at a thickness of 40 mm. This image shows a gradual opening near the center of the sample with relatively consistent horizontal banding running across the sample similar to image 14A. Coloration is a little darker near the center of the rock and may indicate the presence of lithified organic material. Image 14C, taken at a thickness of 30mm clearly shows the opening of void space along the center of the rock. The vugs here significantly larger and more connected than that of images 14A and B. Lastly, image 14D was taken near the center of the rock and shows the largest amount of void space with the two main vugs almost connecting to each other in a semi-circular shape. These samples taken at 1 cm (10mm) intervals clearly show the gradual increase in size and movement of the vugs towards one another indicating significant pore space presence.

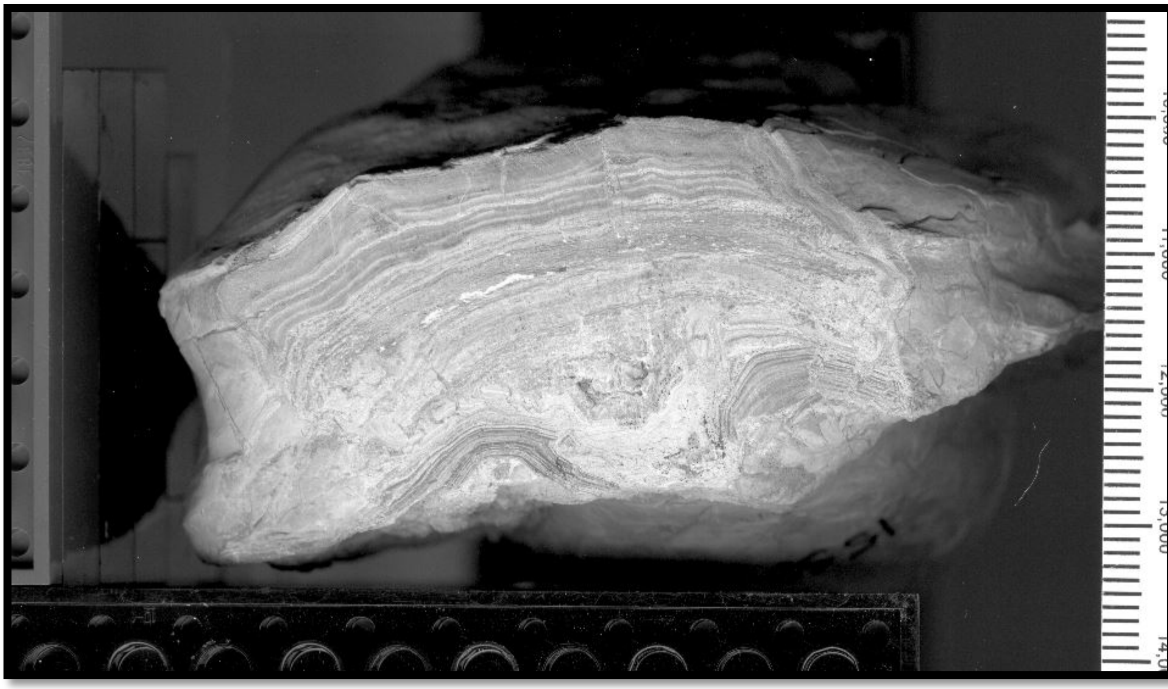


Figure 14A: This image was the first scan taken at the initial thickness of 50mm. This image shows no porosity, but a finely laminated accretionary structure

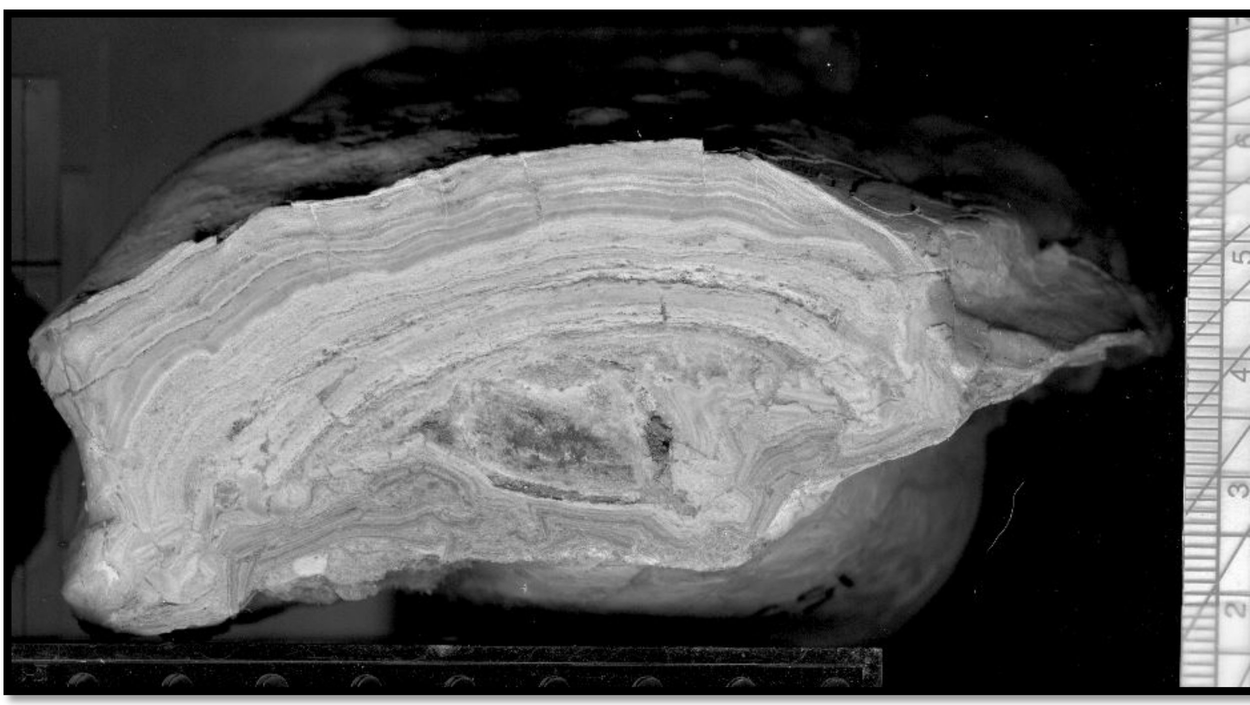


Figure 14B: This image was scanned at thickness of 30 mm and shows a small void in the center of the sample

Figure 14C: This image was scanned at a thickness of 30 mm and displays gradually increasing vug connectivity more than image 14B, but less than 14D

Figure 14D shows the scanned image taken from the center of the rock at 10 mm. The vugs in this image are clearly seen as touching vuggy porosity.

Results from the scanned images within the White Mountain samples display both similarities and differences from those seen in the Sand Butte scans. This sample, previously assessed from the acetate peels, show a relatively consistent pattern throughout. Although there is no presence of vuggy porosity, there are however more abundant intermediate void spaces higher in frequency than that of the sample from Sand Butte. In addition. A major difference between these samples is seen through the synoptic relief. The White Mountain sample shows significantly higher relief characterized as domal, or conical. Furthermore, although this sample has visibly smaller pore sizes, the presence of these pores seen at a higher frequency throughout alternating bands does not rule it out as having less pore space potential as a significant reservoir rock.

Figure 15A shows the first scan of this sample taken from its initial thickness of 25mm

Figure 15B shows the second scanned image at a thickness of 20mm.

Figure 15C shows the scan of the WM sample at a thickness of 15mm

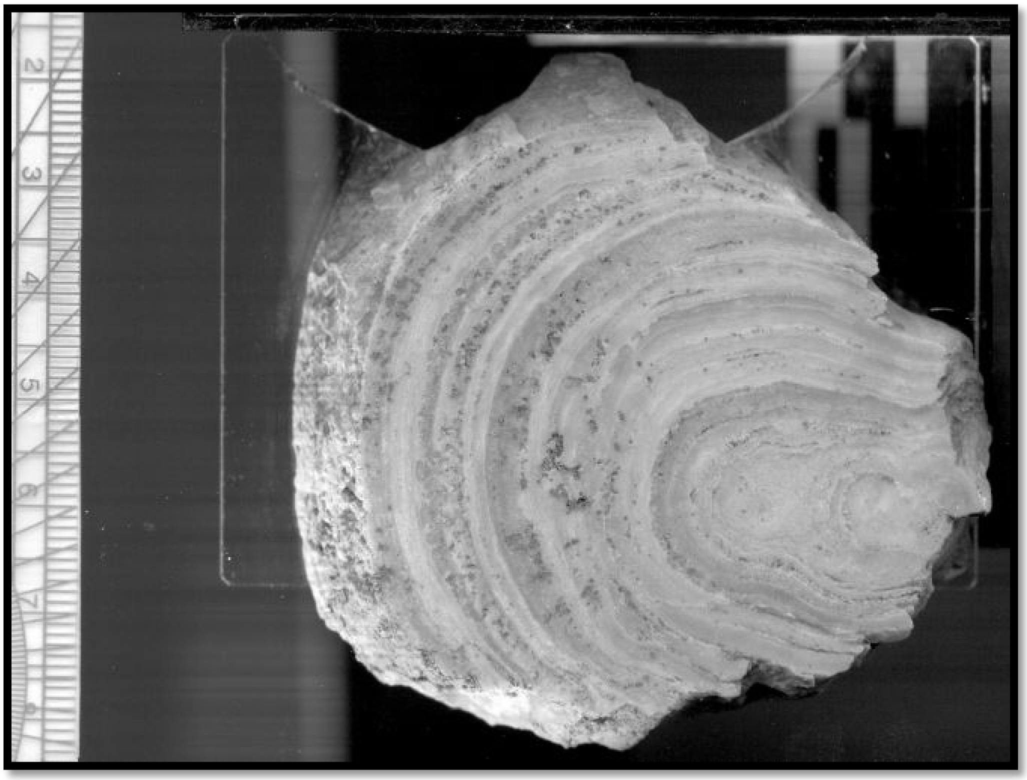


Figure 15D shows one of the last scanned images taken from a thickness of 10mm

DISCUSSION

The results of this study provides evidence that stromatolites formed in lacustrine depositional environments exhibit a high degree of variability in pore networks across a diverse array of microbialite forms. Petrophysical characteristics such as texture, fabric, size and stratigraphic sequences allow for these structures to be connected to the paleonevironmental conditions from which formed them. Further analysis taken from scanned images of these samples suggests that texture and fabric play a significant role in the development of porosity size, presence and frequency. Insight regarding which depositional successions generate specific characteristic for which fluid can be stored within its pores, provide ideal analogs targeting carbonate reservoirs for porosity potential.

The sample from the Sand Butte Bed showed promise in the ability to hold fluid within its pores. Through the observation from acetate peels specifically those taken from the innermost parts of the rock (0mm), shows the highest degree of void space, indicating significant pore space potential in which fluid could be stored. this sample exhibited touching-vuggy porosity concentrated along the center of its structure. The presence of interconnected vugs suggest a significantly connected framework allowing for potential hydrocarbon material to coalesce in the eventual form of petroleum, whereas separate vug porosity (non-touching), indicates a poorly connected framework, contributing to less permeability throughout the internal structure (Lucia, 1999). Each textural difference can be attributed to the formation within its depositional environment. Lake Gosiute’s deep-water basin contained rapidly circulating waters where carbonate sediment, along with organic and algal material, was swiftly moving at an irregular pace throughout the lake allowing for the observed open void spaces to initially form. As the sample stopped rolling, gradually uniformed micrite laminae was able to precipitate on top of the irregular structure successfully trapping the void spaces by surrounding it with latter deposited layers. This clumped texture contains intermediate pore space. As waters became more calm and shallow, more finely uniformed layers were able to accrete on top of the structure seen near the outer edge of the rock. This can further be observed through the sample's low synoptic relief and relatively horizontal layering. This relief provided evidence of its depositional origin in a shallow shelf platform where it continued to baffle and trap precipitated carbonate, eventually forming the rock as we see it today. Conversely, the sample from White Mountain exhibited no vugs or significantly large crystals. It did, however contain more frequent intermediate pore space with more uniformed laminae throughout, including significantly higher relief not seen in the Sand Butte sample; further connecting its formation to shallower water depths near the ancient shore line. This sample also showed relatively homogenous micrite layers with uniformed banding, alternating in coloration. This banding coincides with the lake's frequent transgressing/regressing water levels under a shallow shelf platform from which this sample was deposited. Both samples showed similarities in fabric and texture through the presence of clumped micrite exhibiting intermediate, more frequent pore space, and a gradual, finely-laminated uniformed sequence near the rock's edge. The variances of higher pore space in the center of the rock with gradual carbonate grains moving from irregular, to finely unformed laminae suggest that slower carbonate precipitation in rapidly circulating waters allow for the formation of void space within the Sand Butte sample. Contrastingly, faster precipitation in calm, shallower levels seen in the White Mountain stromatolites exhibit a more uniformed sequence of laminae forming tightly bound grains, disallowing the presence of large void space. Through the observational analysis of acetate peels coupled with thin section images, the properties seen in both samples suggest fabric as being the dominant factor in porosity development.

The Laney Member in which both samples were collected was indeed deposited under conditions of saline-alkaline to freshwater composition during periods of lake transgression and regression. The combination of lake environment, water chemistry, rate of cementation, and time of deposition, suggest that the necessary conditions needed to form reservoir rock with fluid-bearing pores were present during Lake Gosiute's four million year existence. Fluctuating water levels in lake-basin environments, such the Santos Basin off the Brazilian coast, exhibit similar features at a broader scale and indicate that large accumulations of hydrocarbon material, formed under deep-water, saline-alkaline and freshwater environments can and do form significant petroleum bearing plays over time.

DIAGENISIS:

Because all carbonate reservoir rocks have been subject to diagenesis, the significant physical and chemical changes that occur during the conversion of sediment to sedimentary rock; understanding the diagenetic history of carbonate sediments is of importance in regards to their depositional history and the characteristics they produce (Dunham, 1962). The window of petroleum bearing carbonates is small, and the loss of reservoir quality is common due to sediment changes after deposition. These processes that affect the resulting fabric of the rock are referred to as the diagenetic overprint. These mechanisms are grouped into their compliance within depositional patterns and include: Calcium-carbonate cementation, mechanical and chemical compaction, selective dissolution, dolomitization, evaporate mineralization, cavern collapse, and fracturing (Lucia, 1995). The second group includes dolomitzation and evaporate mineralization. These processes depend on geochemical and hydrological considerations, often made predictable due to their relation within tidal-flat and evaporate depositional environments such as the one seen in the GRF. The last group includes dissolution, fracturing, and late dolomitization, which have the lowest compliance to depositional environments, deeming them highly unpredictable and will not be further discussed. With sedimentation being a one-time event, diagenesis is continual, interacting with one another in time and space. Although complex, the sequence of diagenetic processes and the structures they produce are closely related to their depositional environments and principle in predicting depositional patterns that could produce reservoir rocks. Thus, diagenetic overprinting of depositional textures must also be understood to predict the distribution of petrophysical properties in a carbonate reservoir.

MODERN VS ANCIENT SYSTEMS

The GRF is Eocene in age, making it a relatively modern model. Although many modern carbonate sediments have ample porosity and permeability to qualify as reservoir rocks, many ancient carbonates lack the necessary porosity and permeability needed to produce economically viable hydrocarbons. In this case, the GRF's modern system proves consistent regarding the necessary criterion needed for petroleum potential within microbialite pore space. Although the acceptance of the GRF as a geologically modern system, its carbonate reservoir potential may not yet be fully developed. The alteration of organic material to oil-bearing hydrocarbons is a long process and must go through extensive processes subject to heat and pressure, diagenesis, mechanical and chemical compaction, calcium-carbonate cementation, and evaporate mineralization, to name a few. Although these processes are believed to have happened in this area, the final product that this area could generate; oil in this case, may not yet be fully complete and should be assessed as such. Contrastingly, more ancient systems such as those seen in the stromatolites of Shark Bay, Australia, have been around for billions of years. Although these structures allow scientists a greater understanding into the earliest forms of microbial life, this length of time is problematic in that any organic material that may have been converted into viably economic material, has since been decayed away.

For the sake of time, only the presence of porosity and it's interconnectivity throughout the samples were mentioned in this paper. Specific porosity values were not measured but are of importance when more thoroughly examining the exact output that these structures might yield. Specific porosity and permeability values within the same samples were, however analyzed through the work of fellow student Grant Noennig. The samples mentioned in this paper represent a minimal fraction of the vast varieties of microbialites present in this area. The analysis of just two stromatolites taken within the same formation within a similar depositional environment offer just a small interpretation of what the GRFs ultimate potential might be regarding its reservoir rock prospective. Results from acetate peels and scanned images however, do show that these rocks possess notable similarities and differences within petrophysical properties aiding the conection to their potential as useful reservoir rock.

CONCLUSION

This study revealed that microbialite pore space presence and frequency within the Green River Basin is heavily dependent on textural features, with fabric playing a principle role. Data obtained from scanned thin slice images, coupled with observations of petrophysical characteristics, allow for the conclusion that microbialite carbonate rocks that exhibit specific composition and textures are a direct result of depositional environment and post-depositional processes such as diagenesis and cementation. Furthermore, the ancient Lake Gosiute, of which deposited these rocks, possess many similar characteristics to those seen in current petroleum bearing carbonate plays observed off of the Brazilian coast. The presence of carbonate microbialite formation within lake basin systems subject to the presence of fluctuations in water depth carbonate sediments and a shallow marine environment, allow for a potential analog to be made between these modern systems. Results from data show three observed textures: vuggy porosity with interconnected void spaces and an irregular structure, clotted/clumped carbonate grains, and finely laminated carbonate layering. Each texture exhibited differences in pore space (or lack thereof) with vuggy porosity showing the highest degree of pore space size, clotted micrite texture displaying intermediate pore space with higher pore frequency, and finely laminated carbonate accretions, of which displayed no porosity. This paper shows that textural and depositional features regarding microbialite pore space connectivity are significant factors in assessing carbonate reservoir rock potential. Through research in the temporal and locational implications of these structures' ability as fluid bearing reservoir rock, microbialites may be further assessed through similar, more extensive methods in order to more accurately predict analogous oil-bearing systems around the globe.

REFERENCES

Aliakbardoust, E., Rahimpour, B. H. (2013) Integration of Rock Typing Methods for Carbonate Reservoir Characterization. Journal of Geophysics and Engineering. 10.5.

Awramik, S., M, and Buchheim, P., Microbialite "shrubs" of the Eocene Green River Formation; analogs for the Cretaceous pre-salt lacustrine systems of the South Atlantic conjugate basins (in 2013 AAPG annual convention & exhibition, Anonymous) Abstracts: Annual Meeting - American Association of Petroleum Geologists (2013) 2013

Beasley CJ, Fiduk JC, Bize E, Boyd A, Zerilli, Dribus JR, Moreira JLP and Pinto ACC: "Brazil's Presalt Play," Oilfield Review 22, no. 3 (Autumn 2010): 28–37.

Brigaud, B., Vincent, B., Durlet, C., Deconinck, J. F., Blanc, P., and Trouiller, A., 2010, Acoustic properties of ancient shallow-marine carbonates: effects of depositional environments and diagenetic processes (Middle Jurassic, Paris Basin, France), Journal of Sedimentary Research, v. 80, p. 791-807. doi: 10.2110/jsr.2010.071.

Buchheim, P., Awramik, S., Leggitt, L., 2010. Lacustrine stromatolites and microbialites as petroleum reservoirs: Department of earth and biological sciences. Department of earth science, University of California, Santa Barbra, CA. AAPG annual convention and exhibition, article #90104 (Abstract).

Burton, D., Woolf, K., Sullivan, B. (2014). Lacustrine Depositional Environments in the Green River Formation, Uinta Basin; Expression in outcrop and wireline logs. American Association of Petroleum Geologists. 98.9: 1699-1715.

Callan, B., 2012, American Geophysical Union: Stromatolites of the Green River Formation: http://agu.org/mountainbeltway/2012/12/25/stromatolites-of-the-green-river- formation/ (accessed December 2012)

Chetel, L., M, and Carroll, A., R, 2010, Terminal Infill of Eocene Lake Gosiute, Wyoming, U.S.A., Journal of Sedimentary Research, v. 80, p. 492-514. doi: 10.2110/jsr.2010.050

Chilingar, G. V., Mazzullo, S.J., Rieke, H.H., Carbonate reservoir characterization: a geologic-engineering analysis: Developments in petroleum science in Carbonate reservoir characterization, 2005, Elsevier, p. ###114

Clegg, A., Gron, H., Kloster, K., Rysst, L., 2014, The Brazilian Pre-Salt Basins: A Natural Gas Perspective, Natural Gas Technology, Tronheim, p. ###35

Dunham, R.J. 1962. Classification of Carbonate Rocks According to Depositional Texture in Classification of Carbonate Rocks—A Symposium, W.E. Ham ed.,108. AAPG Memoir No. 1. http://archives.datapages.com/data/specpubs/carbona2/data/a038/a038/0001/0100/0108.htm

Eberli, G.P., Weger, R.J., Verwer, K., Porta, G.D., 2012, “The role of microbial activity on petrophysical properties” in Microbial carbonate reservoir characterization: Houston, Texas, AAPG Hedberg Conference, p. 1-4

Ehrenberg, N., S, Nadeau, P., H, 2005, Sandstone vs. Carbonate Petroleum Reservoirs: A Global Perspective on Porosity-Depth and Porosity–Permeability Relationships, AAPG Bulletin, v. 89, no. 4, p. 435-445. doi: 10.1306/11230404071

Frantz, C.M., Petryshyn, V.A., and Corsetti, F.A., 2015, Grain trapping by filamentous cyanobacterial and algal mats: Implications for stromatolite microfabrics through time: Geobiology, doi:10.1111/gbi.12145, (in press).

Frederick, S. J., Kati, M. T., Humphrey, J. D. (2013). Lithofacies, Stable isotopic composition, and Stratigraphic Evolution of Microbial and associated Carbonates: Green River Formation (Eocene), Piceance Basin, Colorado. AAPG Bulletin. 97.11: 1937-66.

Jordan, F.C., Jr, and Wilson, J.L., 1994, Carbonate Reservoir rocks, AAPG Memoir, v. 60, p. 141-158.

Lucia, F.J. 1995. Rock-Fabric/Petrophysical Classification of Carbonate Pore Space for Reservoir Characterization. AAPG Bull. 79 (9): 1275-1300. http://aapgbull.geoscienceworld.org/content/79/9/1275.citation.

McKinley, J.M., Ruffell, A.H., Atkinson, P.M., Lloyd, A.H., Worden, R.H., 2011, How porosity and permeability vary spatially with grain size, sorting, cement volume, and mineral dissolution in fluvial Triassic sandstones: The value of geostatistics and local regression: Journal of Sedimentary Research, v. 81, p. 844-858. doi: 10.2110/jsr.2011.71/

Mohriak, W., 2014, Birth and Development of Continental Margin Basins: Analogies from the South Atlantic, North Atlantic and the Red Sea, Search and Discovery Article, AAPG, #41502 (Abstract)

Morris, T. H. (1994) Analysis of Lithofacies, Petrology/Petrography, and Porosity/Permeability of the lower Green River Formation; Willow Creek. Brigham Young University.

Noffke, N., and Awramik, S.M., 2013, Stromatolites and MISS-differences between relatives, GSA Today, v. 23. p. 4-9, doi:10.1130/GSATG187A.1.

Oil Shale Assessment Project Fact Sheet, 2011, Assessment of In-Place Oil Shale Resources of the Green River Formation, Greater Green River Basin in Wyoming, Colorado, and Utah, USGS: http://pubs.usgs.gov/fs/2011/3063/pdf/FS11-3063.pdf

Rezende, M. F., Tonietto, S. N., Pope, M. C., 2013, Three Dimensional Pore Connectivity Evaluation in a Holocene and Jurassic Microbialite build-up. AAPG Bulletin, v. 97, NO. 11, p. 2085-2101, doi: 10.1306/05141312171

Roehler, H., W. 1993. Eocene climates, depositional environments, and geography, greater green river basin, Wyoming, Utah, and Colorado in Geology of the Eocene Wasatch, green rover, and bridger (washakie) formations, greater green river basin, Wyoming, Utah, and Colorado: U.S. Geological Survey professional paper 1506-F, p. F1-F67

Roehler, H., W. 1991. Geology of the Eocene Wasatch, Green River, and Bridger (Wasahkie) formations, Greater Green River Basin, Wyoming, Utah and Colorado: Introduction to Greater Green River Basin Geology, Physiography, and History of Investigations. U.S. Geological Survey Professional Paper 1506-A, p. A1-A12

Seard, C., G. Camoin, J. M., Rouchy, Virgone. A. (2013). Composition, structure and evolution of a lacustrine carbonate margin dominated by microbialites: Case study from the Green River formation (Eocene; Wyoming, USA). Paleogeography, Paleoclimatology, Paleoecology, 381-382: 128-44.

Seard, C., G. Camoin, J. M., Rouchy. Virgone. A. Pabian-Goyheneche., C. and Poli. E. 2012. Characterization of potential lacustrine carbonate reservoirs: The microbial/algal buildups, and associated carbonate deposits from the Eocene Green River Formation. AAPG international conference and exhibition: Search and discovery article #50522

Self, J.G., Ryder, R.T., Johnson, R.C., Brownfield,and M.E., Mercier, T.J., 2011, Stratigraphic cross sections of theEocene Green River Formation in the Green River Basin, southwestern Wyoming, northwestern Colorado, and northeastern Utah, in U.S. Geological Survey Oil Shale Assessment Team, ed., Oil shale resources of the Eocene Green River Formation, Greater Green River Basin, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series DDS–69–DD, chap. 5, 7 p., 24 plates.

Smith, E. M., Carroll, A.R., Singer, B.S., 2008, Synoptic reconstruction of a major ancient lake system: Eocene Green River Formation, western United States: Geological Society of America Bulletin, v. 120, p. 54-84. doi:10.1130/B26073.1

Surdam, R. C., Wray, J.L., 1976, Lacustrine Stromatolites, Eocene Green River Formation, Wyoming, in Walter, M.R., ed., Stromatolites: Developments in Sedimentology, Volume #20: Amsterdam, Netherlands, Elsevier, 535-546 p.

Surdam, R. C., Stanley, K. O., 1975. The Stratigraphic and Sedimentologic Framework of the Green River Formation, Wyoming. Department of Geology, University of Wyoming, Laramie, WY & The Department of Geology and Mineralogy, Ohio State University, Columbus, OH. p. 205-222

Pietras, J., T., Carrol, A., R., and Rhodes, M., K., 2002, Lake Basin Response to Tectonic Drainage Diversion: Eocene Green River Formation, Wyoming, Journal of Paleontology, v. 30, p. 115-125.