Analysis of Stromatolite Reservoir Potential using Computed Tomography

By:

Grant Noennig

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

Bachelor of Arts
(Geology)

At

Gustavus Adolphus College

2016

Volumetric Analysis of Stromatolite Reservoir Potential using Computed Tomography

By:
Grant Noennig
Under the supervision of Dr. Julie Bartley

ABSTRACT

Stromatolites are lithified microbial mats formed when microbes bind and trap carbonate grains or induce precipitation of carbonate material (Ahr et al., 2011). If sufficient porosity occurs within these microbialites, they have potential to contain and transmit fluids, such as petroleum. Carbonate rock accounts for more than half of the world's oil reservoirs and 40% of the world's natural gas reservoirs, but due to the complexity of fractures and matrix composing these beds, their reservoir potentials are difficult to estimate (EIA, 2013). Stromatolites from the Laney Member of the hydrocarbon-rich Green River Formation in the central United States offer an opportunity to study reservoir potential in a well-exposed succession. Most research on carbonate reservoir potential is sedimentary, stratigraphic, or petrophysical, but more complex reservoirs like stromatolites require specific techniques to determine their potential (Rezende et al., 2013). In order to determine the porosity, permeability, and pore-connectivity of this facies, samples from this location were cut into rectangular blocks and scanned using x-ray computed tomography (XRCT) at the University of Minnesota. XRCT analysis allows for the quantification of porosity and permeability values to evaluate the reservoir potential at a small scale, in three dimensions. Preliminary results indicate that Green River stromatolites are highly variable in their porosity characteristics, but some have sufficient porosity and permeability to be effective reservoir rock. This approach allows a quantitative and qualitative description of porosity characteristics in a microbial carbonate and will yield useful data for upscaling to reservoir-scale properties, relating these properties to depositional factors, and outlining the diagenetic and cementation history of these microbial carbonates.

ACKNOWLEDGEMENTS

I would like to thank Dr. Julie Bartley, my advisor and professor, for introducing me to her stromatolite research and aiding in all the aspects of completing this thesis. I am grateful to University of Minnesota Professor, Dr. Brian Bagley, for allowing me to scan the stromatolite samples and helping me utilize the three dimensional software AVIZO. The data gathered during this experiment's field excursion could not have been obtained or categorized without the aid of Gustavus students Lindsey Reiners and Tanner Eischen. Gustavus Professors Jim Welsh and Dean Moosavi both reviewed and made corrections to this thesis throughout the entire process. I would like to thank Gustavus Adolphus College for allowing me to use their campus vehicles to get to the University of Minnesota during the analysis of this data. The Petroleum Research Fund supported the fieldwork and sampling costs of this thesis, both of which could not be completed without these funds. I would finally like to thank the Sigma Xi organization for the grant I received to complete the CT scans of my samples.

TABLE OF CONTENTS

FIGURES AND TABLES

Introduction

Oil and natural gas have become the world's predominant fuel sources, causing easily accessible and tapped reservoirs to begin to run dry. This dependency on these fossil fuels has forced scientists across the globe to explore new extraction and exploration methods in order to locate and obtain more of this crucial resource from our planet. These resources occur only in specific geological systems, requiring multiple structural components, a source of hydrocarbons, adequate porosity and permeability, and specific temperature and pressure factors. The constricting aspects allow formation of oil and natural gas in a few specific depositional environments, including clastic and carbonate beds (Figure 1).

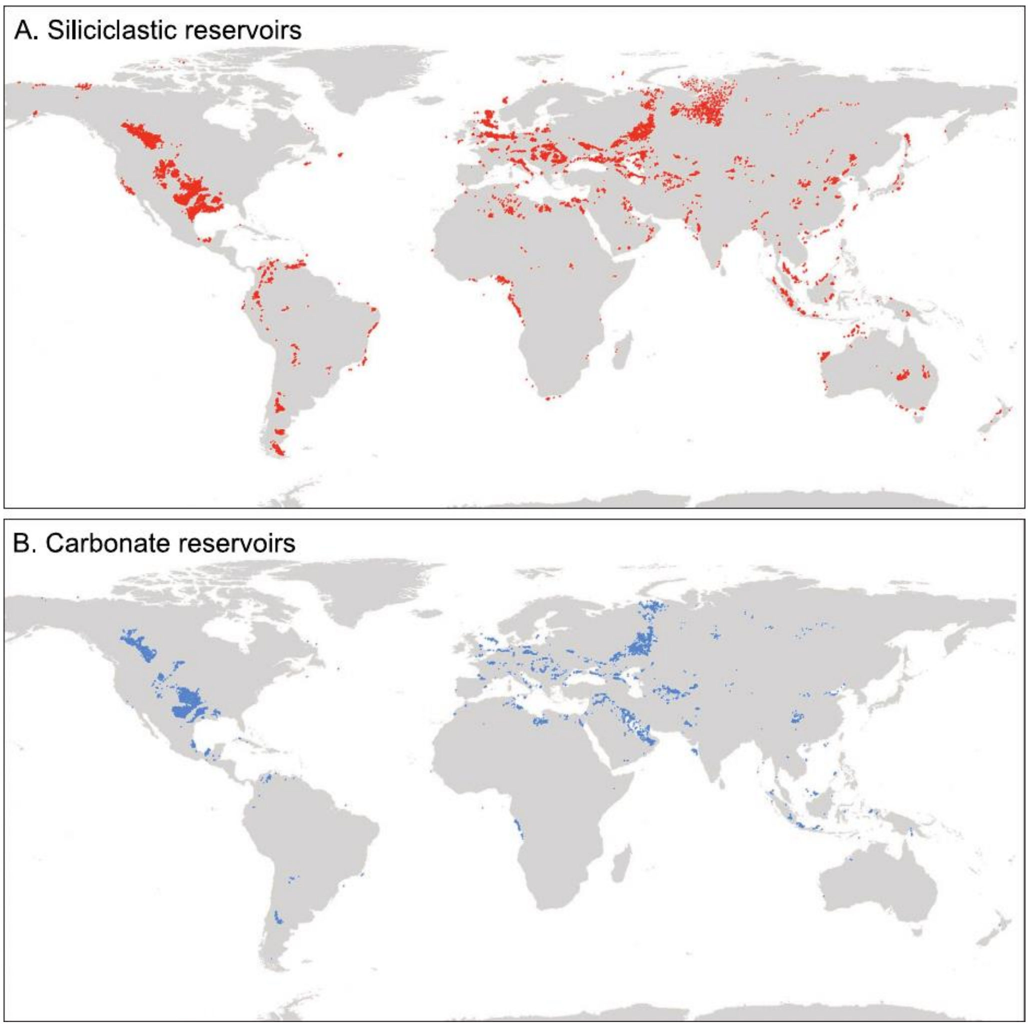

Figure 1. Geographic distribution of petroleum reservoirs based on their compositional type, either sandstone or carbonate (Ehrenberg and Nadeau, 2005).

It is estimated that over half of the world's remaining oil and gas reservoirs are located within carbonate beds. However, due to the complex mixture of fractures and matrix that make up these beddings, their reservoir potentials are difficult to estimate as compared to simpler clastic reservoir rocks. Most sandstone reservoirs are single porosity systems of homogenous nature, but carbonate reservoirs are typically multiple porosity systems of heterogeneous nature (Mazzullo, 2004). Other factors that cause the complexity of carbonate beds include: a wide range of pore sizes and distribution, the heterogeneous nature of limestones, the unexpected behavior of diagenesis and secondary porosity development, and the determination of non-effective porosity (Abdel et al., 1997). Another contributing aspect to the difficulty of assessing these potential reservoirs is the dominance of microporosity, and its difference in behavior from macro- and mesopores. Micropores are defined by a pore diameter less than 10μm, mesopores have a diameter of 10-1000μm, and macropores are any void spaces with a diameter larger than 1000μm. Generally carbonate reservoirs are considered inefficient in their production rates and poor in overall oil recovery, because of this difference in pore size and structure, which causes large volumes of oil and gas to be overlooked or seem difficult to extract (Abdel et al., 1997). A specific technique to predict the porosity and permeability within these highly spatially variable systems is necessary for a complete analysis of carbonate reservoir potential.

Currently, extensive research is being done by petroleum companies to better understand the reservoir potential of these complex carbonate layers. However, traditional techniques for assessing simple reservoirs, clastic sandstone beds, are less effective or sometimes even counterproductive when applied to carbonate reservoirs (Abdel et al., 1997). Isolated sampling techniques for determining reservoir potential, such as borehole logging and seismic surveys, offer measurements of porosity and permeability on a large scale, but have become outdated and replaced by techniques that determine the lateral extent of reservoir microporosity, overall effective porosity, and illuminate disguised pore network systems through volumetric analysis (Abdel et al., 1997).

A recent influx of interest in microbial carbonates as potential reservoirs for oil and natural gas has stemmed from the discovery of oil in the lacustrine Cretaceous pre-salts of Angola and Brazil (Awramik and Buchheim, 2014). Although this is a major discovery and new possible resource, analyses of similar ancient and recent microbial carbonates are necessary to aid in determining models and facilitation methods for exploration. The Green River Formation, an Eocene lacustrine unit, is thought to be an ideal analog for modeling this pre-salt potential reservoir, prompting this research to investigate an analog for reservoir potential, at a small scale, of the White Mountain stromatolites (Awramik and Buchheim, 2014). The well exposed microbialites here can help uncover relationships between large-scale stratigraphic architecture, outcrop-scale microbialite forms and textures, and small-scale degrees and distributions of porosity through the analysis of this analogue. The goal of this research is to determine the relationship between microbialite form and porosity of the structure.

Stromatolites are layered lithified microbial mats (microbial carbonates) formed when microbes bind and trap carbonate grains or induce precipitation of carbonate, causing these structures to have different porosity and permeability values than their surrounding matrix (Ahr et al., 2011). Microbial carbonates are not typically viewed as reservoir rocks, but this research will strive to determine the usefulness of these specific stromatolites as analogs for similar potential reservoir rocks. Stromatolites from different depositional environments, with different modes of construction, or with different diagenetic histories may differ dramatically in porosity and permeability, controlling their ability to become potential reservoirs, and requiring more research into their reservoir potential. These relationships, though, are not well understood.

The Eocene-aged Green River Basin shares close similarities with newly discovered carbonate-hosted oil and natural gas deposits in the "pre-salt" successions of Brazil and Angola, making it an extremely useful analog to other systems. Establishing a relationship between the porosity of microbial carbonate beds and their potential to form reservoirs will aid in forming an invaluable tool in locating, estimating, and determining potential reservoirs. This study uses XRCT to create a 3-dimensional reconstruction of the pore structure of a set of stromatolites, to evaluate porosity and small-scale reservoir potential. Qualitative analysis of these samples was also concluded to highlight the distribution of pores, textural variation, and morphological differences.

Geologic Setting

The Green River Formation covers areas in Wyoming, Colorado, and Utah, having been deposited over a six million year period, during the Eocene (Figure 2, Seard et al., 2013). The Formation is a lacustrine system covering over 77,000km^2 and determined to be 2000m thick in certain portions (Awramik and Buchheim, 2014). A combination of lithostratigraphy, biostratigraphy, and sediment analysis depicts this area to have been deposited during the warmest portion of the Cenozoic, roughly 53-49 million years ago (Seard et al., 2013). These Eocene weather patterns and climate changes played a major role in determining the depositional environment and overall geography of the Green River Basin as well as the entire Formation, specifically affecting different aspects with rainfall and temperature changes (Roehler, 1993).

These climatic variations played a major role in determining lake size and chemistry, controlling the main conditions for stromatolite growth along the shorelines of the basin. Other contributing factors to the deposition of this area included the altitude, latitude, tectonic and orogenic activity, and planetary volcanism (Roehler, 1993).

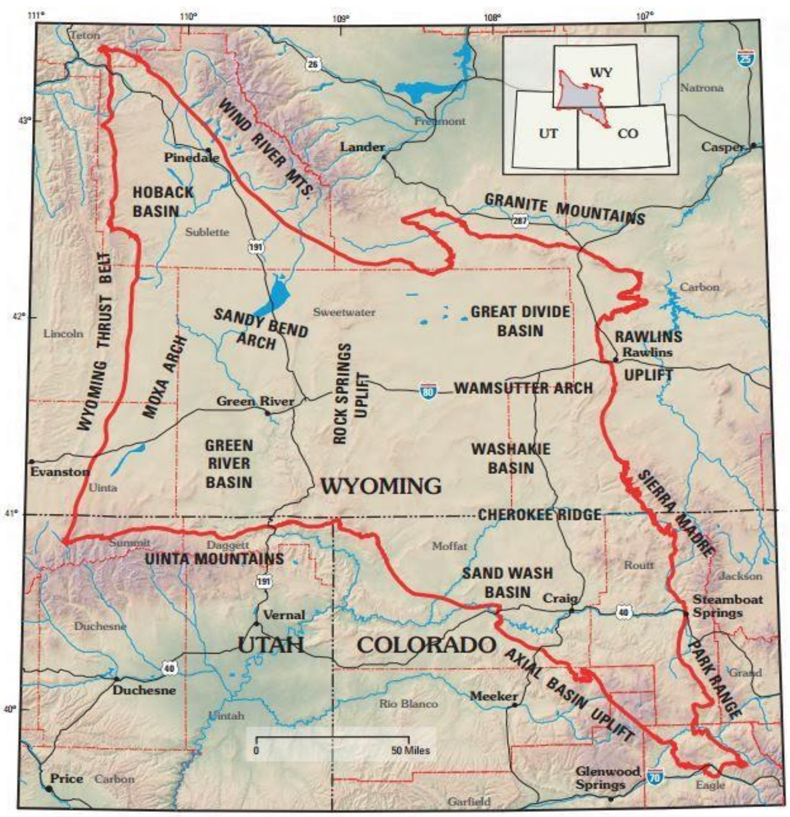

Figure 2. The Green River Formation is outlined in red, encompassing the main basins and tectonic formations labelled (Roberts, 2005).

The Green River Basin is classified as a small retro-arc basin, formed entirely on the continental crust, caused by the breakup of block faulting within the subduction zone (Hutchison, 1983). The entire reservoir was formed during orogenic activity of the Rocky Mountains and is composed of limestone, claystone, and vast amounts of oil shale reserves (Seard et al., 2013). The reoccurring deposition of sand sediment encased the Green River Formation with shales and mudstones. The large structural and sedimentary basins composing the Green River Formation were deposited within their lacustrine environment coinciding with the late portion of the Laramide Uplift (Seard et al., 2013). The Gosiute, Uinta, and Fossil Lakes composed the entire lacustrine system of this depositional environment, although they were infrequently connected, causing the formation of the smaller sub-basins composing each major basin (Figure 2, Awramik and Buchheim, 2014). The Formation is divided in four uplift separated basins: Green River, Washakie, Uinta, and the Pisceance Creek (Figure 2). Specifically Lake Gosiute was the overlying depositional environment for the Green River Basin, this research's location of interest. The Gosiute Lake lacustrine system covered 40,150km^2 at the apex of its extent (Bradley and Eugster, 1969). This lake varied in its extent due to its response to climactic and tectonic events, causing growth variations within the outlying microbialite as they adapted to the current water levels and climactic conditions (Seard et al., 2013).

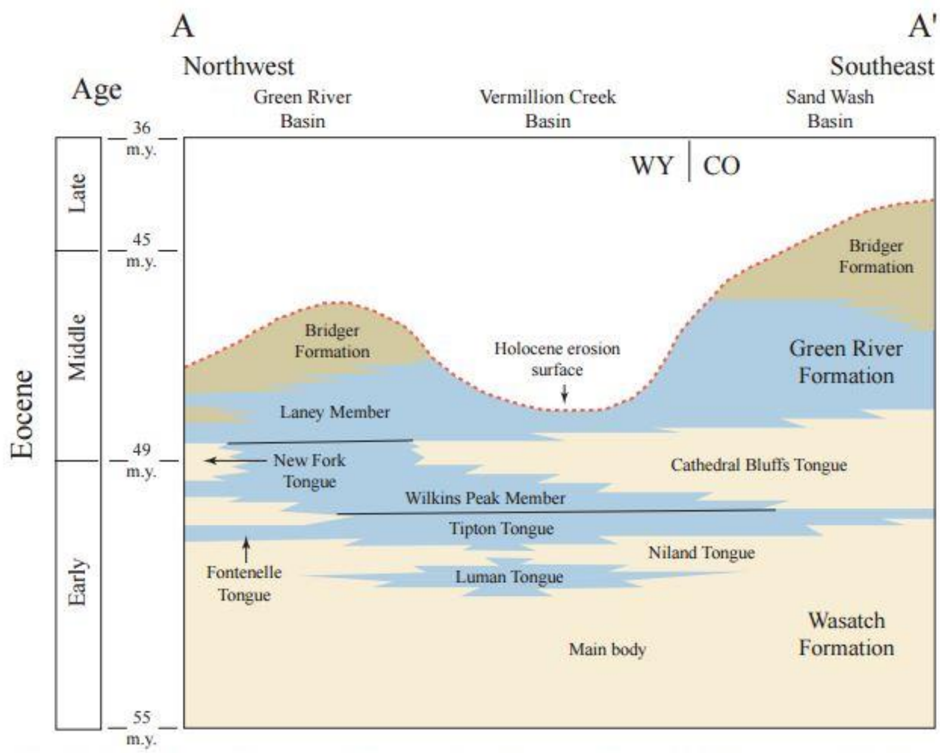

Figure 3. This cross section of the Green River, Vermillion Creek, and Sand Wash Basins shows the stratigraphic context below each area as well as their time of deposition (Roberts, 2005).

The sedimentary succession of the Green River Basin is described, from oldest to youngest, as the Tipton Shale, Wilkins Peak, and Laney Members (Seard et al., 2013). These stratigraphic layers have been studied heavily due to their stromatolite inclusions, within the Laney Member, but mainly their inclusion of the world's largest oil shale deposit and its potential analog to similar systems (Figure 4). Each of these stratigraphic layers was deposited during different environmental conditions, offering a depiction of the chemical and spatial evolution of the entire lacustrine system, focusing on Gosiute Lake (Seard et al., 2013).

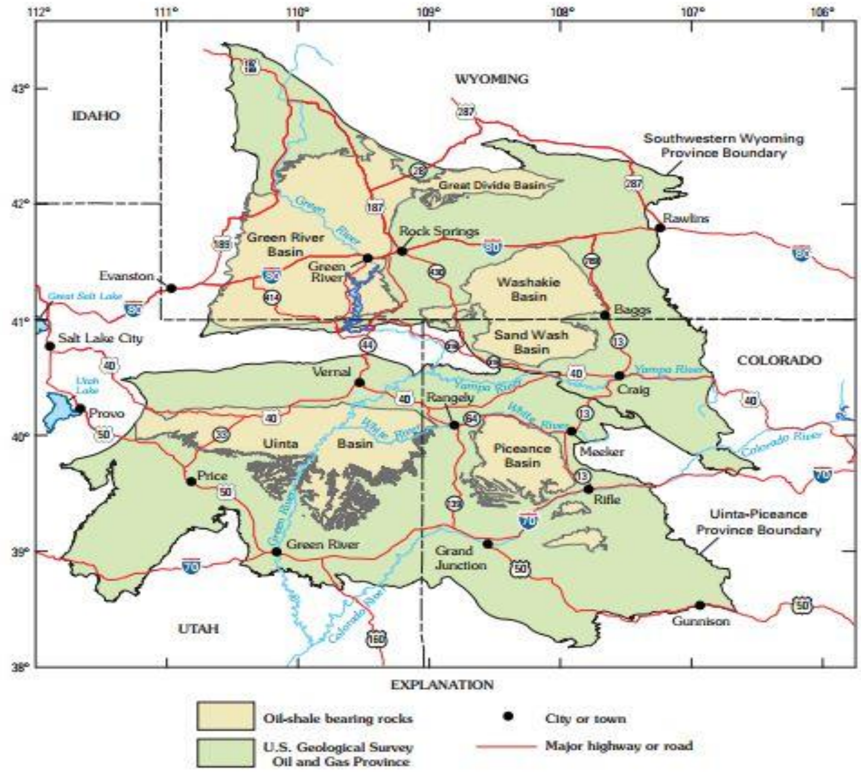

Figure 4. A map of the Green River Formation's oil reservoirs shows the regions of high and low concentration. This map also shows the spread of the carbonate bedding throughout three states, giving scale to its immense size (Johnson et al., 2010).

The Tipton Shale was deposited during a period of saline development within Lake Gosiute, while the Wilkins Peak member was deposited during a time when the lake was under-filled and hypersaline because it was cut off from outside freshwater sources. The oil shale deposits of the greater Green River basin were deposited in a desert environment with much hotter and drier conditions compared to those of the thriving microbialites (Roehler, 1993). The oil shale beds of the overall Green River Formation illustrate varving, deposition in low energy lakes with varying rates of sedimentation and little to no wave action (Roehler, 1993). These varved beds alternated in amount of organic matter (kerogen) and thickness, due to fluctuations of algal blooms and seasonal changes. The organic material composing these oil shales is derived from the blue-green algae that thrived within the past lake environment. The formation of these shale beds varied from 2,000 – 8,200 years of deposition and diagenetic processes, depending on the richness of the oil unit (Bradley and Eugster, 1969). The Laney member was deposited when Gosiute Lake was balanced and saline initially, but concluded deposition during the overfilled freshwater time of Gosiute Lake due to spring and river influx (Seard et al., 2013).

The hypersaline conditions coupled with the hydrologic input of calcium carbonate from streams during the Wilkins Peak Member deposition allowed for microbialites to thrive without natural predators or niche competition, creating stromatolite bioherm structures seen at the White Mountain outcrop. Lake environments with pH levels greater than 9 are enriched with Na, Mg, and Si, making them hypersaline-alkaline conditions and favorable to stromatolite growth (Awramik and Buchheim, 2014). The combination of freshwater spring calcium-rich water entering the ambient state of the lake caused carbonate to precipitate rapidly, as indicated by the large size and structure of these bioherms seen at the White Mountain location (Awramik and Buchheim, 2014). These microbes precipitate silica as cement to replace the carbonates. The Green River Formation shows aragonite precipitated as whitings during the mixing of these water types, unique to this Formation and Searles Lake only (Buchheim and Surdam, 1981, Smith, 2009).

Stromatolites

Stromatolites are defined as organo-sedimentary structures, because of the interaction between sediment and the photosynthetic cyanobacteria to form the laminated microbial structures. These "microbial mats" form through two distinct accumulative processes: binding and trapping or precipitation of carbonate. Trapped and bound stromatolites form through the trapping and binding of grains onto cyanobacteria filaments and biofilms (Figure 5). Trapped-and-bound microbialites have variations in their thickness of layers, a clastic texture, and less synoptic relief in their horizontal layering. Precipitated structures form when microbial mats induce precipitation of calcite to form more clotted, micritic, and crystalline structures. This microbialite type is characterized by more uniform thickness of layers, variation in synoptic relief, and over-steepened layers. The White Mountain stromatolites show evidence of both trapped-and-bound and precipitated growth styles.

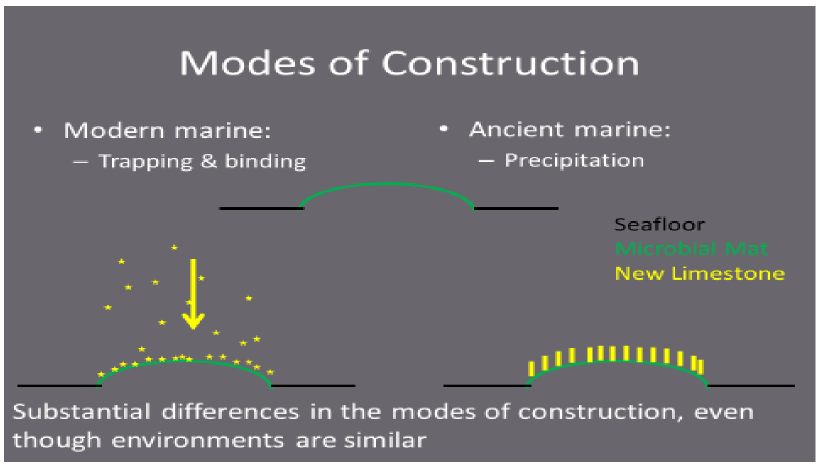

Figure 5. The difference in the formation of modern stromatolites trapping and binding sediment and ancient stromatolites precipitating limestone depicted (Reiners, unpublished).

Stromatolites generally form where cyanobacterial mats grow in environments that favor rapid carbonate precipitation or lithification. If waves are present, such as in higher energy areas, the stromatolite structure will become more domal or columnar in shape due to the disruption of the laminae (Hoffman, 1994). The shape of all stromatolites depends on three factors: synoptic relief, inheritance, and rate of sedimentation/supply.

How high these stromatolites rise above the surface they form on is described as their synoptic relief. Synoptic relief is essentially the measurement of layer height based on the rate of structural accretion, the higher the accretion rate the higher the synoptic relief. Low relief structures allow sediment to interfere with accretionary processes, causing branching of stromatolites, while high relief produces columnar or cone shaped stromatolites (Hoffman, 1994).

Another key aspect of stromatolite formation is inheritance. A high inheritance stromatolite will appear as a column structure, as the layers stack directly on top of one another as they are deposited. Low-inheritance stromatolites look irregular in their laminations, with each successive generation occurring at a different location than the previous one. High inheritance indicates continuity of environment through time and in some cases a distinct difference in a colonized substrate versus the uncolonized areas. Low inheritance stromatolites most likely grew in environments that were periodically disrupted, forcing the microbial layers to start over occasionally. The final determining factor contributing to the formation of stromatolites includes the sediment supply and its effect on the morphological features of the stromatolite structure. A larger sediment supply will allow for more accumulative structural growth of the microbialites, whereas a small sediment supply yields less growth (Hoffman, 1994).

Previous Work

Previous work has been concluded in defining the differences between carbonate and sandstone reservoirs. Sandstone and carbonate reservoirs differ in many aspects of their structure and formation, but these aspects are caused by two main differences: the area of sediment production and greater reactivity of the chemically derived carbonate reservoirs (Choquette and Pray, 1970). The differences in porosity and permeability values of sandstone and carbonate reservoirs are characterized by variations in early diagenesis, textures and composition, depth, and temperature outline in the table below (Ehrenberg and Nadeau, 2005). As depth increases, the dissolution of materials is found to be less of an impacting force than the cementing and diagenetic factors affecting these reservoirs. The tendency of fractures to form within carbonate reservoirs facilitates economic extraction for these less porous rocks. This research strengthens the need for specific techniques to determine carbonate reservoir potential, compared to simpler clastic bedded deposits.

Differences	Sandstone	Carbonate
Site of sediment production	Allochthonous	Autochthonous
Chemical reactivity	Low	High
Proportion of low porosity values	Lower at all depths	Higher at all depths
Proportion of high permeabilities at low porosities	Lower	Higher
Dominant porosity feature	Intergranular	Vugs

Table 1. This table outlines some of the interesting differences between carbonate and clastic reservoirs, based on Ehrenberg and Nadeau's research (Ehrenberg and Nadeau, 2005).

Research to determine the 3-dimensional pore connectivity of microbialite buildups has yielded results indicating microbial reservoir characteristics similar to those displayed by the stromatolites of this Formation (Rezende et al., 2013). This research offers promising data that concluded reservoir potential in the studied microbialites using techniques of the same variety and with less specificity.

The study of microbialites has become more valuable due to the biomineralization information given through their structure and evolution of porosity, as well as their potential to serve as hydrocarbon reservoirs (Bahnuik et al., 2014). The Lower Cretaceous Codo Formation in Brazil was deposited in a similar environment to the Green River Formation of the United States, a closed lacustrine system with alternations in expansion and contraction which developed microbialite structures (Bahnuik et al., 2014). A reconstruction of the paleoenvironmental evolution of these potential carbonate reservoirs can be determined based on the systematic microbialite structural formation displayed by these stromatolites. Chemical conditions, rather than physical ones, have been determined to be the dominant control on the morphology of stromatolites as well as their type in shallow environments like these. Other factors such as evaporation could affect the microbialite metabolism and overall growth of the structure, illustrated by cyclical growth due to water level variation.

Research Methods

During the summer of 2015, Professor Julie Bartley along with myself and two other students ventured on a 10-day expedition to the Green River Basin in Wyoming, Colorado, and Utah. This field research was necessary to observe and gather data on the Green River Formation's stratigraphy and microbialite structures within. The Sand Butte, White Mountain, and Radio Tower locals were each observed, documented, and measured to obtain the relevant data necessary for this thesis. All of these areas were marked with a GPS locator to specifically locate each area afterwards, as seen below (Table 2).

Sample #	Locality	Latitude	Longitude	Unit
15WM3	White Mountain	41.894	109.265	Laney Member
15WM3A1	White Mountain	41.894	109.265	Laney Member
15WM3G	White Mountain	41.894	109.265	Laney Member
15WM3Q	White Mountain	41.894	109.265	Laney Member
15WM4N	White Mountain	41.894	109.265	Laney Member

Table 2: This table gives the sample number along with the locality, latitude and longitude, and the unit the samples were taken from within the Green River Basin.

Measurements were made vertically using a Jacob's staff combined with an eye level measuring technique, based on the height of my line of vision. To accomplish this we measured the height up to my eye level (165cm), then I would gaze directly ahead along my eye line and walk to that spot for another successive measurement. This simple technique allowed for a faster measurement of the scale of the outcrop, along with a measured increment that varied only slightly with the direction of my sight. The beds composing each outcrop were determined and categorized as well, based on facies changes and stratigraphic layers (Figure 9). Samples were taken from multiple beds at each formation, some 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, ease of extraction, and rare findings of in-place structures, except the overlying bioherm. Following the conclusion of gathering data on the Green River Formation, White Mountain was chosen to display its porosity and permeability values as a potential analog to oil filled microbialite carbonate reservoirs.

Figure 6. These images show the chosen sample stromatolites cut in half in order to determine the best area to sectionalize further and scan using XRCT. (Top Left: 15WM3, Middle Left: 15WM3A1, Top Right: 15WM4N, Middle Right: 15WM4G, Bottom: 15WM3Q)

The stromatolite samples from White Mountain were chosen based on their visible porosity, textural differences, and morphological features to provide a wide variety of results. These samples were then photographed with a scale and given sample numbers to characterize them further. The stromatolites were then cut with the Gustavus Adolphus department rock saw into rectangular samples roughly the dimensions of a thin section (Figure 7). This cut was made out of the center of the stromatolite structure to best display average values for the whole specimen (Figure 6). The reason these specimen had to be cut was to ensure the samples would fit into the CT scanner at the University of Minnesota. After the cuts were finished, the samples were again photographed and documented (Figure 7).

Figure 7. This picture shows the cuts made using a rock saw to trim the specimens into the proper sized samples, roughly 3cm by 5-7cm. (15SB11B was included to show diversity of stromatolites at various locations.)

Now that the samples were the correct dimensions, they were brought to the computerized tomography (CT) scanner at the University of Minnesota to determine their porosity, permeability, textural differences, and diagenetic impacts. Dr. Brian Bagley, the XRCT Lab Manager, aided in the scanning process and the three-dimensional reconstruction using the AVIZO program. Each sample was placed in a small plastic tube and held there by Styrofoam both above and below the stromatolite. After proper placement, the tube was latched to a pole within the CT scanner to keep the scanned material centered and provide a proper three-dimensional depiction (Figure 8). An initial scan of each sample was necessary to ensure it was centered and accurately placed within the CT scanner, before the complete scan took place. Each scan took close to an hour to complete, varying with density of the sample and the amount of time the machine had already been running. According to Professor Bagley, the temperature change within the CT scanner (sometimes close to 4'C) could affect the outcome of the scan, so time was taken between each sample. After each sample was scanned completely, the data was transferred onto a 2 terabyte drive in order to utilize and transport the gathered information.

Figure 8. The left image shows the entire CT scanner along with the controlling computer system. The right image shows the inside of the machine as the calibration process is taking place before scanning begins.

The University of Minnesota only had one updated copy of the AVIZO program onsite, this necessity of a specific computer combined with the degree of difficulty needed to fully utilize all the components of this program forced further analysis of the samples using Blob3D reconstruction software. The three-dimensional structures were fully illustrated using the AVIZO program which allows for presentative aspects and overall volume depiction, even though the desired values of porosity and permeability were unobtainable. The BLOB3D program provided accompanying useful extracted data measurements due to its availability and simpler procedural methods.

The BLOB3D program is designed to determine highly efficient and accurate measurements of thousands of features (pore sizes, clasts, mineral grains, etc.) within a sample. The program defines a “blob” as a contiguous set of voxels or 3D pixels that meet a desired criteria to determine specific data sets. This program offers complete control over the 2D and 3D representations created, allowing for precise measurements and interpretations.

The three steps involved in this data processing program are Segmenting, Separating, and finally Extracting. Segmenting prompts the user to enter a set of criteria in order to define the voxels of interest. Following this Segmenting process, contiguous sets of attached voxels are distinguished to either divide these groups of interconnected or touching objects as unique individual objects called Separating. The final step of Extracting performs measurements on the desired objects such as size, shape, and connectivity relationships.

Due to the large amount of data required to be processed for each sample (4000+ slides), the stromatolite samples were processed in increments of 500 slides for each analysis. Although this program offered some useful information and images, the measurements of pore space and connectivity were again unobtainable due to the dimensions of the samples, their dense composition, and lack of experience utilizing this program. These shortcomings of functionality in both reconstruction programs forced qualitative analysis of the pore space compared to texture, location and formation of pores, and overall distribution throughout the samples.

RESULTS

This experiment was successful in producing lamina-scale resolution of stromatolites in samples with both high and low porosity using XRCT. This is the one of the first ancient stromatolites to be scanned and depicted using this method, offering new information and useful data for future measurements. The White Mountain outcrop was measured, observed, and described in the field to create a stratigraphic column of the featured benches (Figure 9).

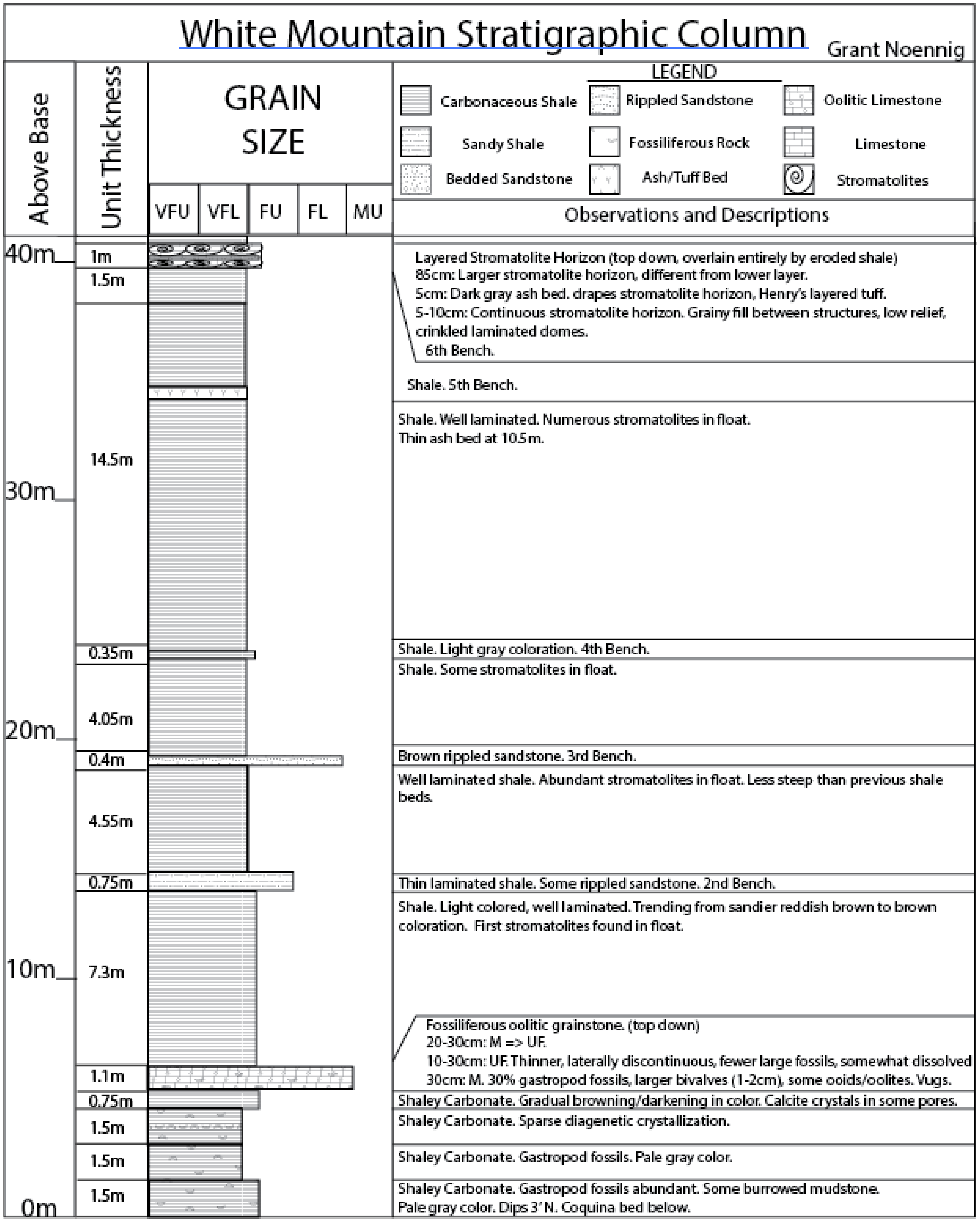

Figure 9. This stratigraphic column depicts the measurements made in-field using a Jacob's staff along with gathered observational data including grain size, layer characteristics, and bench classifications. (Grain Size: VFU=Very fine upper, VFL=Very fine lower, FU=Fine upper, FL=Fine lower, MU=Medium upper)

The stromatolites were depicted in three-dimensions to assess their visible pore space, textural variations, overall structure, and determine their evolution of porosity. Each sample is described and illustrated below:

15WM3A1

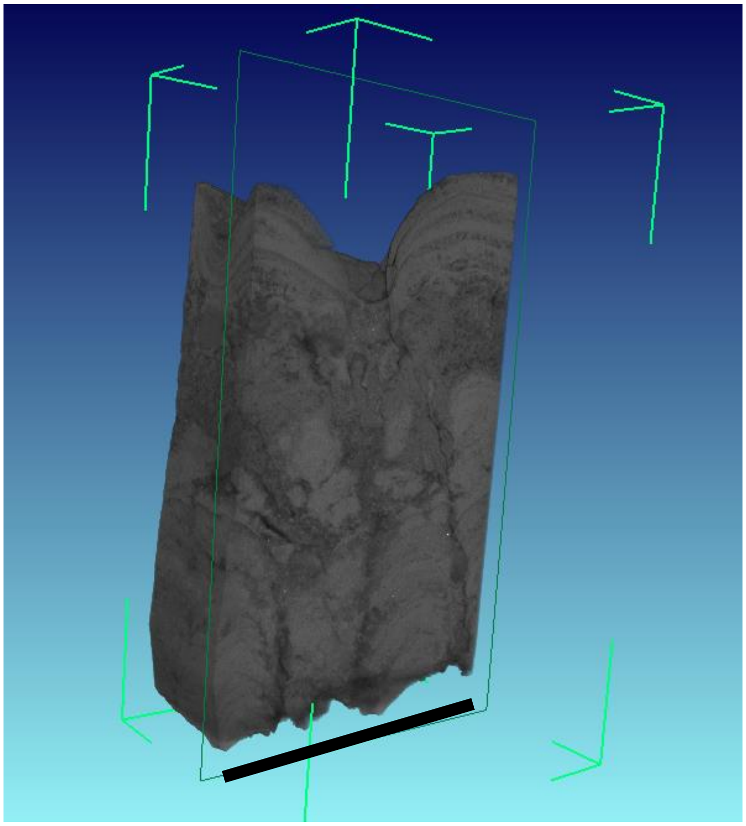

Figure 10. Three-dimensional depiction of sample 15WM3A1, showing microbialite form and structure, outlined within rectangular axes. (Scale bar = 3cm)

The lower 2.5cm of this stromatolite sample show finely laminated columnar structures, with few visible pores. This is not uncommon, however, pores rarely occur along laminae because they would have to be formed during the original deposition of the laminae layer, indicating primary porosity. The upper region of this sample illustrates a trapped and bound texture, different from the accretionary growth seen at the base. This change in method of formation is indicated by larger and irregular grains, no uniform laminae, and greater distribution of pore space. Using this three-dimensional representation, the overall structural differences were observed, along with their diagenetic variations, and differences in pore structures.

15WM3G

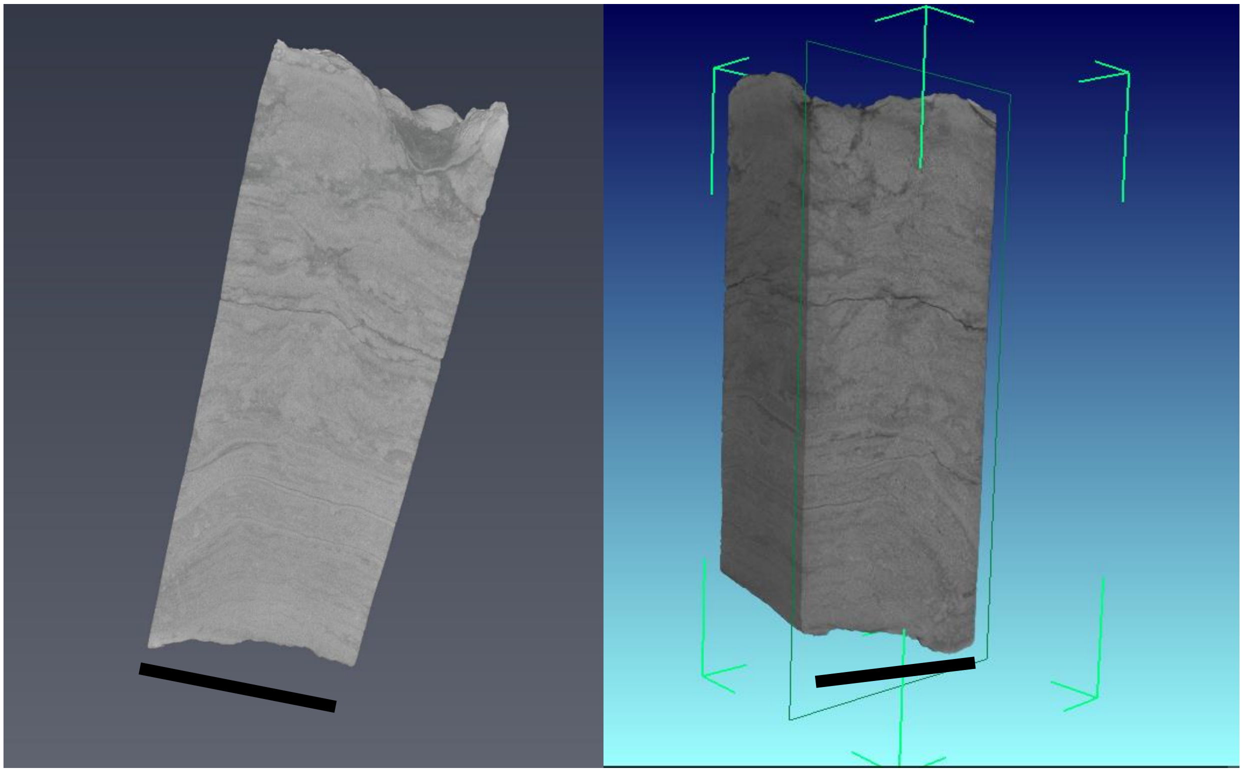

Figure 11. Both of these images show this sample in three-dimensionality to illustrate fabrics, pores, and overall structure. (Scale bar = 3cm)

This sample varied in structural composition, when compared to the previous specimen, having well laminated features throughout. The variations in thickness of these horizontal layers are emphasized by these depictions, along with the color variations and composing elements. There is clotted areas within this sample, as seen in the upper portion of the specimen as well. The completely laminated layers at the base of this sample seem to accumulate growth vertically, until they begin to form individual columns near the top, which creates the irregular shapes on top of the sample. This sample has relatively no visible pore space and little distribution of those minute pores. A fracture is seen within this sample, a common feature of carbonate rock, but this occurred after the rock was cut and scanned.

15WM3

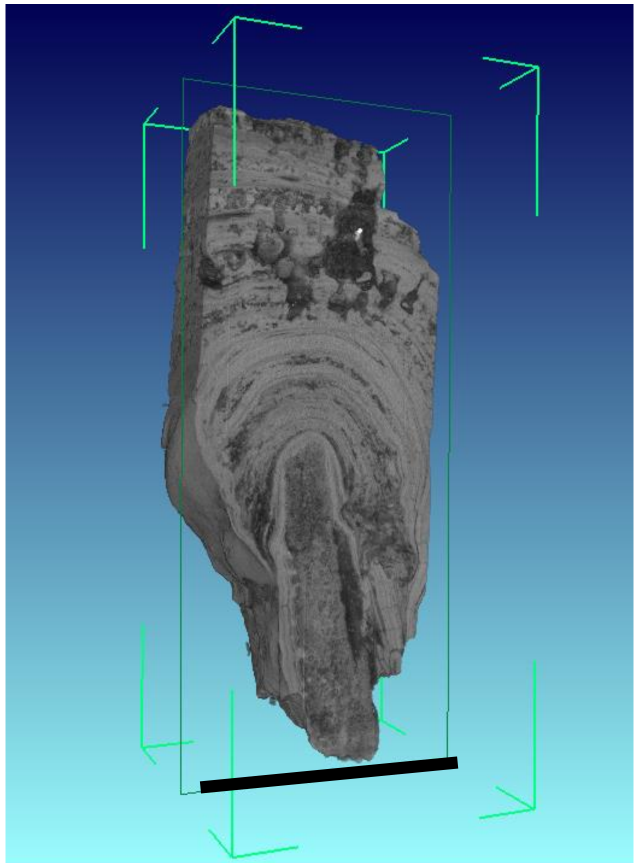

Figure 12. This image shows the three-dimensional reconstruction of sample 15WM3. (Scale bar = 3cm)

This sample was different from the others described so far for multiple reasons, including overall structure, angle of layers, and this was the only sample that had an Epoxy applied. This sample was chosen to determine if an Epoxy would affect the slices created by the CT scanner, whether enhancing the data or skewing it. This sample is unique in its morphological shape, showing layers accumulating around a section of clasts, rather than horizontally on top of one another. The stromatolite also shows layers of varied thickness and coloration, stemming from the origin of the inner clast structure. This sample also showed the highest amounts of visible pore space within any of the samples scanned. Some of the pores in this sample show origins of primary porosity, seen within the laminar layers. The majority of the pore space in this image is seen cutting across accretionary layers, illustrating the effects of dissolution on secondary porosity development within these stromatolites.

15WM4N

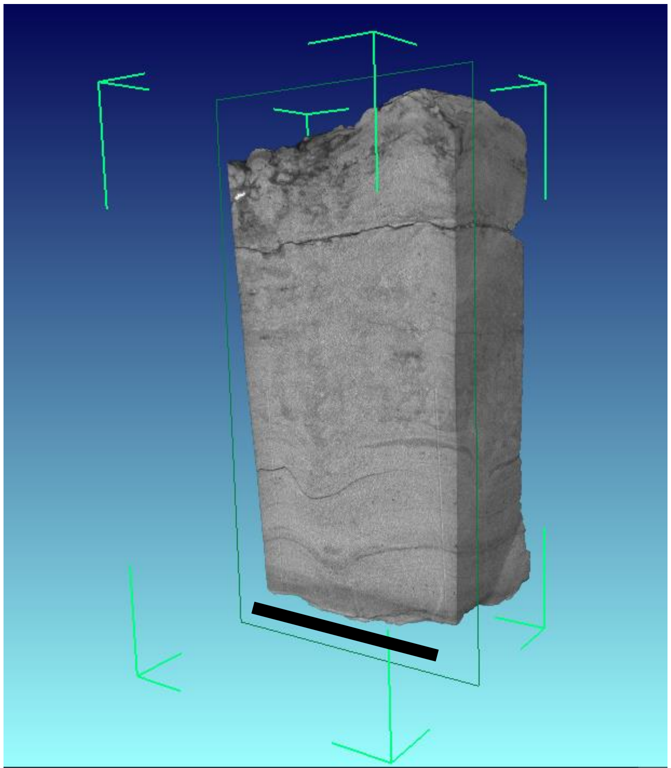

Figure 13. This image shows the reconstruction of sample 15WM4N in three dimensions. (Scale bar = 3cm)

The structure of this stromatolite sample also shows the variations in growth type, from accretionary methods to trapping and binding as the sample grew. The bottom 1cm of this sample displays finely laminated layers of horizontal growth. The portion above this organized section is more erratic in layering, encases larger grains, and displays more porous rock. This sample also illustrates some areas with filled pore spaces due to mineralization, further describing diagenetic impacts on the reservoir potential of microbial carbonates. The large fracture seen within this specimen occurred post deposition, caused by human impact.

15WM3Q

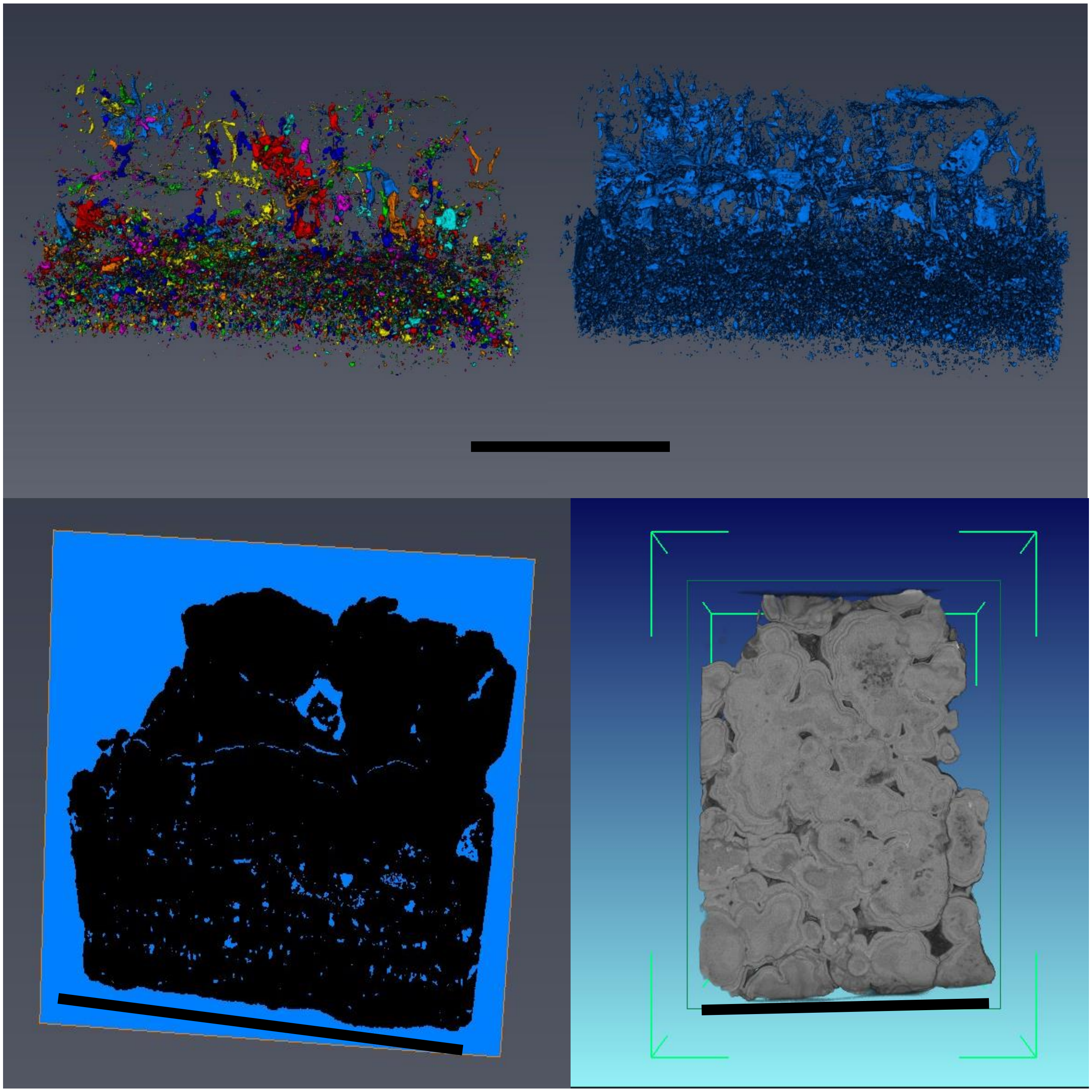

Figure 14. Top Images: These two images are depictions of the pore spaces within sample 15WM3Q, as displayed by AVIZO. The bottom left picture shows an orthogonal slice of this sample, highlighting the pore space seen within an individual slice. The bottom right image is the three-dimensional reconstruction derived from the BLOB3D program. (Scale bar = 3cm)

This sample was different from the others because of the available data gathered initially using the AVIZO program at the University of Minnesota. This sample displayed high levels of porosity in both the outer and inner depictions of the specimen. The top images show the pore network of this sample, first exposing different pre sizes and shapes in color on the left and then the overall network on the right in blue. The bottom portion of this sample is composed of finely laminated with included pore spaces. The change in synoptic relief is evident as the stromatolite continues to grow into less horizontal laminae. Above this ordered structure, the microbialite changes its growth orientation from horizontal layering to forming multiple individual globular stromatolites. Although these layers are more permeable than the bottom, there is less visible pore space seen in this region. The distribution of pores is clearly highlighted within the orthogonal slice of the sample, more distribution along the layered bottom than the larger fracture seen above.

The three-dimensional depictions of these stromatolites offer a key medium to convey this research to the public and industrial world, through a visually stimulating representation. Not only do these reconstructions illustrate the pore space and distribution across fabrics within this Formation, but they also are a key factor in determining the depositional environment and its effects on the stromatolites. Other factors determined by this analysis included the relationship of the age of the stromatolite compared to pore space values and the illustration of diagenetic impacts affecting potential reservoir possibilities.

Discussion

Three-dimensional XRCT imaging allows the visible pore space and distribution to be determined within these complex microbialite structures. It is possible to see both diagenetic and growth-related porosity development. Importantly, change in porosity size, proportion, and distribution occurs in nearly all of the samples, calling for interpretation of growth technique and the reason for changing. The predominant pattern within all of the stromatolite samples is a trending porosity that follows the stromatolite construction, specifically within their laminae or trapped-and-bound textures.

The determination of porosity within these stromatolites encompasses multiple factors for proper identification of these values, including: depth, matrix composition, diagenesis, and other contributing processes. In general, higher porosity values correlate with shallower depths and lower porosity values correlate with deeper regions, based on research from the Khuff and Arab reservoirs in the Middle East (Ehrenberg et al., 2007). The loss of porosity at greater depths is caused by compacting forces as well as cementation processes, negatively affecting the permeability of potential reservoir areas as well. The decreasing values of porosity and permeability as depth increases, reflects the diagenetic porosity loss in response to the increase in thermal exposure (Ehrenberg and Nadeau, 2005). Carbonate reservoirs have varying values of porosity and permeability both locally and across the entire region of the reservoir, now aided in determination by these analyzed samples.

The pore types of these carbonate rocks can be classified by their timing of porosity evolution, whether primary or secondary in their structure. Primary porosity is classified as the porosity at the time of deposition, while secondary porosity occurs after deposition. Because of the relatively high amounts of diagenetic processes and cementation undergone by these chemically reactive carbonate beds, development of secondary porosity is thought to be the major source of porosity (Mazzullo, 2004). There are multiple recognized mechanisms that can potentially affect the generation of secondary porosity within these stromatolites. For example, as organic matter matures into hydrocarbon material, gases and organic acids are produced and migrate both vertically and horizontally through stratigraphic layers. This migration of acids and gases can potentially dissolve carbonate material just ahead of the trailing hydrocarbon migration as it follows these dissolving forces (Mazzullo, 2004).

The chemical reactivity of carbonate beds is key to the effects of this diagenetic process that impacts the lithification of these types of reservoirs and modifies their pore network through dissolution. Although these differences are widely recognized within the geologic field, little to no quantitative documentation has been published. Dissolution has affected the porosity of these sampled stromatolites, as seen in 15WM3, as pores have formed across previously deposited and lithified layers. Primary porosity is seen within some of the samples as well, developed along laminations or within bound and trapped structures. This dissolution process combined with cementation sequencing throughout time produces the highly complex networks and structures within potential carbonate reservoirs.

The effects of dissolution and cementation cannot usually be reversed, except through specific and ideal circumstances, however these processes can be deterred. The idea that early oil charge in both carbonates and sandstones inhibits later cementation processes has been debated heavily by scientists, but has not been proven. Although the presence of petroleum and other possible diagenetic inhibiting mechanisms does not prevent the trend of decreasing porosity with depth, carbonate reservoirs show higher levels of porosity when they are composed of these petroleum filled strata (Ehrenberg and Nadeau, 2005). This minor aspect of fluid pressure plays a key role in the evolution of secondary porosity within carbonate reservoirs, and requires further research.

The evolution of porosity within these microbialite buildups is a direct result of the successive growth of the structures during favorable conditions, followed by periodical breaks in accretionary growth due to lake fluctuation. This growth variation is evidenced by the samples illustrating a change in growth technique to best adapt to their current conditions. Most stromatolites can be categorized as ancient or modern based on their method of growth, but this growth change increases the complexity of determining potential microbialite reservoirs and comparing stromatolites from different time periods.

The main factor that determines the porosity values of these stromatolite samples is their structure and formation, allowing pores to form along laminar layering within precipitated structures or within the irregular trapped-and-bound growth type.

Conclusions

This research is useful as a contextual analog for comparing and discussing individual reservoirs, as well as determining possible trends that may indicate general primary controlling processes of reservoir formation. The unique White Mountain outcrop allows for a direct interpretation of the controls on lacustrine evaporate depositional events, based on the cycles displayed within the exposed strata (Pietras and Carroll, 2006). The lack of research in specific microbialite carbonate reservoirs, calls for the addition of contributions to this topic in order to better understand similar potential reservoirs containing oil or natural gas.

The origin of the White Mountain pores can be determined based on their characteristics of size, dispersion, stratigraphic locations, and composing materials which allows for a generalization of pore structure formation based on depositional environment. Developing a clear interpretation of the depositional and environmental conditions that affect microbialite facies provides information and data which can then be used to better evaluate the porosity, permeability, and overall reservoir potential of possible carbonate reservoirs (Bahnuik et al., 2014). The culmination of this research has yielded data that supports the relationship between this immature microbial carbonate reservoir and mature oil filled reservoirs. Establishing this relationship is key to determining the potential of this reservoir to serve as a prime analog when studying the reservoir potential of similar structural systems with economic value. The Green River stromatolites are scientifically comparable to more mature systems with structural and compositional similarities, and should be utilized as guides for mapping reservoirs with economic potential.

Future research could be done to further analyze the scanned samples and quantify the pore space, connectivity, permeability, and reservoir potential.

References Cited

Abdel Latif, A., D. Sunger, I. Stockden, and C. Cao Minh. 1997, Borehole Nuclear Magnetic Resonance: Experience and Reservoir Applications in West Kuwait Carbonate Reservoirs, Society of Petroleum Engineers.

Ahr, W., Mancini, E., and Parcell, W., 2011, Pore Characteristics in Microbial Carbonate Reservoirs: AAPG Bulletin, Article #30167.

Awramik, S., Buchheim, P. 2014. Giant Microbialites from the Green River Formation, Laney Member, Sand Wash Basin, Colorado. Search and Discovery Article #50984.

Bahnuik, A.M., Anjos, S., Franca, A.B., Matsuda, N., Eiler, J., Mckenzie, J.A., and Vasconcelos, C., 2014. Development of microbial carbonates in Lower Cretaceous Codo Formation (north-east Brazil): Implications for interpretation of microbialite facies associations and paleoenvironmental conditions. Journal of International Association of Sedimentologists. V.62, p.155-181

Bradley, W. H. and Eugster, H. P., 1969. Geochemistry and paleolimnology of the trona deposits and associated authigenic minerals of the Green River Formation of Wyoming: U.S. Geol. Survey Prof. Paper 496-B, p. 71.

Buchheim, H.P. and Surdam, R. C., 1981. Paleoenvironments and fossil fishes of the Laney Member, Green River Formation, Wyoming. In: Gray, J., A. J. Boucot, and W. B. N. Berry (eds.), Communities of the Past. Hutchinson Ross, Stroudsburg, PA, p. 415-452.

Choquette, P. W., and L. C. Pray, 1970, Geological nomenclature and classification of porosity in sedimentary carbonates: AAPG Bulletin, v. 54, p. 207– 250.

Ehrenberg, S.N., and 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

Ehrenberg, S.N., Nadeau, P.H., and Aqrawi, A.A.M., 2007. A comparison of Khuff and Arab reservoir potential throughout the Middle East. AAPG Bulletin, V. 91, NO. 3, p.275-286

Hoffman, H.J. 1994. Quantitative Stromatolitology. Paleontological Society. Journal of Paleontology, Vol. 68, No. 4. P. 704-709.

Hutchison, C.S., 1983. Economic Deposits & Their Tectonic Setting.

Johnson, R.C., Mercier, T.J., Brownfield, M.E., Pantea, M.P., Self, J.G. 2010. An Assessment of In-Place Oil Shale Resources in the Green River Formation, Piceance Basin, Colorado. Oil Shale and Nahcolite Resources of the Piceance Basin, Colorado. Ch.1, Figure 2.

Mazzullo, S.J., 2004. Overview of Porosity in Carbonate Reservoirs. Kansas Geological Society Bulletin, V. 79, Nos. 1 and 2.

Pietras, J.T., and Carroll, A.R., 2006. High-Resolution Stratigraphy of an Underfilled Lake Basin: Wilkins Peak Member, Eocene Green River Formation, Wyoming, U.S.A. Journal of Sedimentary Research, V.76, p.1197-1214

Rezende, M. F., Tonietto, S. N., Pope, M. C. (2013). Three-dimensional Pore Connectivity Evaluation in a Holocene and Jurassic Microbialite Buildup. The American Association of Petroleum Geologists, 97.11: 2085-101.

Roberts, S.B. 2005. Geologic Assessment of Undiscovered Petroleum Resources in the Wasatch– Green River Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. Petroleum Systems and Geologic Assessment of Oil and Gas in the Southwestern Wyoming Province, Wyoming, Colorado, and Utah. Ch.12.

Roehler, H., 1993. Eocene Climates, Depositional Environments, and Geography, Greater Green River Basin, Wyoming, Utah, and Colorado. U.S. Geological Survey Professional Paper 1506-F, p. 1-72

Seard, C., Camoin, G., Rouchy, J.M., 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). Palaeogeography, Palaeoclimatology, Palaeoecology. Elsevier.

Smith, G.I., 2009. Late Cenozoic geology and lacustrine history of Searles Valley, Inyo and San Bernardino Counties, California. U.S. Geol. Surv. Prof. Paper 1727, p. 115.

U.S. Energy Information Administration (EIA), 2013, Technically Recoverable Shale Oil and Shale Gas Resources: An Assessment of 137 Shale Formations in 41 Countries outside the United States: Independent Statistics & Analysis.