SPATIAL VARIABILITY AND CONTROL ON THE DISTRIBUTION OF MICROBIALITES: CASE STUDY FROM PAVILION LAKE, BRITISH COLUMBIA, CANADA

by

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A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science in Geology

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DEDICATION

This manuscript is dedicated to my parents who, throughout my life, have offered helpful guidance during my life’s many adventures. As well, I would like to dedicate this to my lifelong adventure companion, my sister Alison.
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ABSTRACT

Stromatolitic fossils date to 3500 million years ago (Ma) (Awramik et al., 1983; Lowe, 1980; Walter et al., 1980), and comprise the most abundant fossil group from 2500 to 570 Ma ago. A variety of fossil stromatolite morphologies are abundant in strata deposited during the last billion years of the Proterozoic (Awramik, 1984). With advances in lake bottom mapping it has been observed that modern microbialites, which are much like the ancient stromatolites, can thrive in freshwater lake environments. Previously collected data show that a diverse community of living stromatolites are present within Pavilion Lake in British Columbia, Canada (Laval et al., 2000, Lim et al., 2009). This project builds on recently collected high-resolution geoacoustic data to perform detailed morphological analysis of microbialite patterns in modern settings as evidenced from Pavilion Lake.

Using Autonomous Underwater Vehicles (AUVs) as exploration platforms to conduct surveys of the lake bottom, very high-resolution sonar data has been collected. By analyzing this bathymetric and backscatter sonar of the lake bottom, with respect to slope and rugosity, it is possible to map the morphological trends of the microbialites present in Pavilion Lake. DeepWorker (DW) submersibles and SCUBA divers were used to ground truth the sonar images to ensure the sonar data offered a true representation of the
microbialites on the lake bottom. The sonar data collected offers nearly complete coverage of the lake bottom.

The growth pattern morphology characteristics have been compiled into a full-scale map of the lake bottom. This map allows for a better understanding of the morphological characteristics of the microbialite macro-patterns found in Pavilion Lake and will aid in the interpretation of patterns in both other modern lakes and in the ancient rock record.

Using multiple software packages the sonar data has been analyzed and the slope and rugosity calculated and a multivariate principal components analysis classification was applied to the sonar backscatter to generate acoustic seabed types using a commercial automated classification system. The aim of this thesis was to create a quantified classification of the large-scale morphological characteristics (1-100 m) of the microbialites of Pavilion Lake. Results indicate that the microbialite features grow within specific slope and rugosity thresholds.
Chapter 1

INTRODUCTION

Due to recent advances in acoustic mapping and automated classification, it is possible to create high-resolution mapping products of lake bottom characteristics that can be used to characterize bedform morphologies with high accuracy (Preston, 2009; Subramaniam, 1993). The use of an autonomous underwater vehicle (AUV) can further these efforts because the sensor arrays of the AUV can collect multiple data products that, when combined, give a representative image of the lake bottom. The seabed images collected using multibeam sonar systems are able to convey large amounts of information about the seabed (Preston, 2001). As well as visualizing the seabed characteristics, the sonar data can be queried with respect to an established classification structure.

It has been speculated that physical factors are important to the development of stromatolite/microbialite morphology; however, this relationship remains largely uncharacterized (Andres and Reid, 2006). Modern environments allow for directly observable and testable linkages between microbialite morphology, environmental factors, and microbial communities. Utilizing a systematic morphometrics-based classification system for microbialites in a modern setting and relating morphological trends to physical
influences has the potential to be immensely revealing. Pavilion Lake in British Columbia, Canada has provided an ideal location for just such a study due to the morphological diversity and richness that is uniquely documented among modern microbialite systems.

The goals of this study were to map and classify the large-scale (>1m) morphologies of microbialite growth in Pavilion Lake. The specific hypotheses tested were:

1. Microbialite morphologies reflect type specific affinities for slope and depth settings. Specifically, slope and depth tolerances will vary between morphotypes.

2. Microbialite morphotype variability is greater in a vertical distribution than a horizontal distribution. Specifically, the vertical diversity of microbialite macro-morphology in the lake will exceed the lateral diversity.

To test these hypotheses a GAVIA autonomous underwater vehicle will be used to develop a map of Pavilion Lake using various sonar data products. This map will then be analyzed and used to create a site-specific classification map. In conjunction with previously collected imagery, this classification map will be queried with respect to the collected bathymetry data.
Chapter 2

BACKGROUND

Study Area

Pavilion Lake is approximately 420 km northeast of Vancouver, in southern-central British Columbia, (Figures 1 & 2). Figure 2 contains the bathymetry map collected during the 2010 survey campaign. The colormap represents shallow depths with warm colors, and deeper areas with cooler colors. The lake is comprised of three distinct basins and is positioned within the confines of a limestone walled canyon at an altitude of approximately 825 m above sea level (Brady et al., 2010). The relief within the canyon walls is approximately 900 m. The lake is oriented in a northwest to southeast position and measures approximately 6 km in length. Pavilion Lake is a circumneutral (pH 8.4), freshwater lake. The maximum-recorded depth during this survey was 55 m. The microbialites found within the lake range from centimeters to meters in height and the morphologies of the microbialites vary throughout the lake (Laval et al., 2000; Lim et al., 2009). Previous submersible-based research has confirmed the extensive presence of microbialites at varying depth ranges, throughout Pavilion Lake. Pavilion Lake is particularly notable for its variety of microbialite macro-morphologies. Submersible data have also shown that the macro-morphologies in Pavilion Lake are diverse and range
from nodular to terete macro- and meso- forms, and vary in discernible size from 0.25 m to > 1 m in diameter (Marinova et al., in prep).

Figure 1. Location of Pavilion Lake, British Columbia, Canada
Figure 2. Study area of Pavilion Lake
**Previous Work**

Divers as well as locals to the Pavilion Lake area were the first to observe the microbialites found in Pavilion Lake. Although they had been observed, the first scientific documentation of the microbialites in Pavilion Lake was published in 2000 in the journal *Nature* (Laval et al., 2000). The microbialite groupings are primarily distributed along the walls of the lake basin (Laval et al., 2000).

The Pavilion Lake Research Project was developed to explore and analyze the microbialite growth. The Pavilion Lake Research Project (PLRP) has also been utilized by NASA and the Canadian Space Agency as an analog for continued human planetary exploration (Lim et al., 2010). Because the PLRP is an underwater field project it is a learning opportunity for astronauts because it provides an environment for discovery in an extreme setting (Lim et al., 2010). The Pavilion Lake Research Project has also been a vital analog because of its use of multiple research platforms.

In addition to the GAVIA AUV the Pavilion Lake Research Project has utilized DeepWorker submersibles and SCUBA divers. The DeepWorker research missions gave the astronauts the opportunity to work alongside the research team in gathering data (Lim et al., 2010). The DeepWorker submersibles allowed for the collection of data and microbialite samples at depths greater than 30m. The Pavilion Lake Research Project, in addition to
collecting data to better understand the microbialite population, has been used as an analog for further space exploration because of the extreme setting and the logistics of a research program using a dynamic set of research tools (Lim et al., 2010).

Research work at Pavilion Lake using DeepWorker submersibles and GAVIA Autonomous Underwater Vehicle (AUV) exploration platforms have yielded results which, in coordination, suggest associations and trends between the macro and meso-microbialite morphological variation and physical lake properties such as depth and slope. However, these observations had yet to be tested or confirmed. As such, we proposed to characterize the influence of physical lake properties on microbialite morphological variation.

Data including water chemistry (Lim et al., 2009), sedimentation rates, microbialite samples and microbialite photos have been collected. By analyzing the microbialite samples, it was determined that the biosignatures of the microbialites show signs of photosynthetic preference (Brady et al., 2010). The study of photosynthetic preference consisted of 27 different microbialite nodules. It has also been discovered that Kelly Lake (British Columbia, Canada) not only contains small thrombolites as reported by Ferris et al. (1997), but also larger microbialites that share some of the gross morphological features as those found in Pavilion Lake.
Chapter 3

METHODS

The mapping efforts conducted within Pavilion Lake utilized a Geoswath sonar mounted on a Gavia autonomous underwater vehicle.

Gavia Autonomous Underwater Vehicle

The Gavia Autonomous Underwater Vehicle (AUV) is a modular person portable survey platform. Figure 3 highlights the modular nature of the AUV, as well as the modules used for the survey of Pavilion Lake.

![Autonomous Underwater Vehicle (AUV)](image)

Figure 3. GAVIA AUV displaying the individual modules.
Table 1. Displays the sensor payload of the GAVIA AUV.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Frequency</th>
<th>Phenomenon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side-scan Sonar</td>
<td>900/1500 kHz</td>
<td>Backscatter</td>
</tr>
<tr>
<td>Geoswath</td>
<td>500 kHz</td>
<td>Bathymetry and Backscatter</td>
</tr>
<tr>
<td>Camera</td>
<td>4 Hz</td>
<td>Images</td>
</tr>
<tr>
<td>Inertial Navigation System (INS)</td>
<td></td>
<td>Position and Attitude</td>
</tr>
</tbody>
</table>

The nose cone of the AUV contains a downward facing color camera with an adjustable focal length and adjustable frame rate. As well as the camera, the nose contains a forward-facing obstacle avoidance sonar which will instruct the vehicle to immediately stop if an obstacle is in the proposed path of the AUV. The battery module contains six lithium-ion battery cores, and is the power source for the AUV. The battery module powers the vehicle using 33 volts, and when fully charged contains approximately 1200 watt/hours. A fully charged battery allows for a survey mission of approximately 4 hours.

Following the battery, in a normal configuration, is the Geoswath module. This module contains a phase measuring bathymetric sonar (pmbs). The sonar is used to collect seafloor data within a user-defined swath. The swath is the total width, combining port and starboard, from which the sonar
beams collect data (Figure 4). Usable swath generally equals ten times the AUV altitude.

![Figure 4](image-url)

Figure 4. Simplified image depicting a sonar swath interacting with a smooth seafloor. The AUV orientation is facing into the page.

The Geoswath module consists of one transmit and four receive staves on both port and starboard of the vehicle. The sonar operates by transmitting a single stave and comparing the phase difference between pairs of receive transducers to measure the angle of the received signal as it bounces off the seafloor. With each ping comes a time-series of phase, and hence angle, measurements to the strongest return at that instant, usually the sea floor. The time is the two-way travel time to the seafloor and with knowledge of the
speed of sound in seawater these travel times can be converted to range measurements. Also in the signal is an amplitude, backscatter or side-scan, measurement.

The Geoswath operates the port and starboard transducers separately as though they were separate systems, alternating between them on successive pings. Within the Geoswath raw data file (rdf) data record, for each ping, there is an "RAA" record containing a time series of Range, Angle and Amplitude values. These are converted to geographic coordinates, first relative to the AUV's position, and then relative to geographic coordinates by post-processing software.

Aft of the Geoswath module is the Inertial Navigation System (INS)/Doppler Velocity Log (DVL) module. The Inertial Navigation System (INS) is coupled to a Doppler Velocity Log (DVL). The two modules make up the primary subsurface navigation of the AUV. The INS system utilizes an internal gyroscope to note sub-angle changes in the heading of the vehicle once it is below the surface, and has lost Global Positioning System (GPS) signal. The DVL system uses a downward-facing sonar to obtain a Doppler reading from the seafloor which is used to calculate the velocity of the AUV over the seafloor. By analyzing the precise heading and velocity of the vehicle a sub-meter location value is obtained.
The Control Module of the AUV contains the system firmware and hard drives for the AUV missions and control. As well, the Control Module is the module where the AUV communication systems are based. The Gavia AUV contains three different communication systems. The first system is LAN connectivity. The LAN system on the AUV can be utilized either in wireless form or with wired connectivity. Both the wired and wireless systems have a limited distance in which they are capable of transmitting.

The Control Module also contains an iridium satellite phone, which gives the user extended connectivity. Both the LAN and the iridium connectivity are limited to when the vehicle is positioned on the surface. When the AUV is conducting a mission an acoustic communication channel is established using an acoustic modem a hydrophone positioned on the base of the Control Module, and a second hydrophone located near the researcher, connected to the mobile computer running Control Center. Acoustic communications allow for periodic updates on mission progress. In addition to the communication capabilities of the AUV, the Control Module also contains the GPS receiver used by the AUV while on the surface. The Control Module also contains a variable frequency Marine Sonic side-scan sonar. This sonar system is utilized to build backscatter acoustics images of the seafloor.
The entirety of the propulsion system for the Gavia AUV is contained within the Propulsion Module. The AUV is propelled by a four-blade propeller and navigated with four independent servo-controlled fins.

**Data Collection**

The Gavia AUV is capable of running missions by either following a set depth or keeping a constant altitude above the bottom features. Preliminary missions were run at a set depth to ensure vehicle safety. The data gathered during those missions was used to later set a safe altitude for the Gavia to follow the lake bathymetry. The Gavia AUV allows for variable velocities to be selected during mission setup. The velocity for the AUV is set using the revolutionary rate of the propeller. Experience tells us that 600 rpm is optimal for GeoSwath data gathering in Pavilion Lake and is equivalent to 1.5 m/s., or 3 knots.

During the 2010 Pavilion Lake Research Project campaign, 125 km of survey trackline was collected using the Gavia AUV as the survey platform. The missions were planned using Control Center, which is the primary planning software for the Gavia AUV. The primary survey technique used for the mapping of Pavilion Lake is known as a “lawnmower” pattern. This pattern consists of a number of parallel lines that are connected by alternating turns. This technique allows for the Gavia to safely follow its trackline while also conducting survey that has consistent overlap of the swath. The overlap allows
for the data to be processed without having any gaps. Survey missions were conducted on Pavilion Lake on nine separate days. Table 2 shows the dates of the survey, along with the length of mission track collected on that day.

Table 2. Mission survey lengths of the Pavilion Lake survey campaign. The mission area was computed using a swath width of 60 m.

<table>
<thead>
<tr>
<th>Date</th>
<th>Mission Length (km)</th>
<th>Mission Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 28 2010</td>
<td>3.5</td>
<td>0.21</td>
</tr>
<tr>
<td>June 29 2010</td>
<td>25</td>
<td>1.5</td>
</tr>
<tr>
<td>June 30 2010</td>
<td>12</td>
<td>0.72</td>
</tr>
<tr>
<td>July 1 2010</td>
<td>13</td>
<td>0.78</td>
</tr>
<tr>
<td>July 2 2010</td>
<td>20</td>
<td>1.2</td>
</tr>
<tr>
<td>July 3 2010</td>
<td>22</td>
<td>1.32</td>
</tr>
<tr>
<td>July 4 2010</td>
<td>15</td>
<td>0.9</td>
</tr>
<tr>
<td>July 6 2010</td>
<td>9</td>
<td>0.54</td>
</tr>
<tr>
<td>July 7 2010</td>
<td>6</td>
<td>0.35</td>
</tr>
</tbody>
</table>

The first day of survey, June 28, was set aside as a testing and engineering day. This was to ensure that during transit to the research location, the vehicle did not sustain any damage.

The three distinct basins of the lake made it possible to build missions specific to basins and areas of the lake. After the engineering missions of June 28, the missions conducted on June 29 and June 30 covered the majority of the central basin. The Gavia AUV was capable of mapping the northern basin
completely, on July 1. Only 13 km of trackline were needed to map the north basin with the same resolution as the central basin.

Data Processing

The specific steps taken to process the collected sonar data are described in Appendix D.

Data Analysis

DMagic was used to grid the bathymetric files (.xyz) that were processed using Geoswath software (see Appendix D for details). The ungridded .xyz files were loaded into a new project file created within DMagic. Because the depths of the lake basins vary, all of the Pavilion Lake survey was loaded into one project. This consistency allowed for the data to share one consistent depth scale. Once the ungridded data files are loaded the trackline of the survey is analyzed. By comparing the trackline to the set list of ungridded .xyz files it is possible to remove any files that may negatively affect the precision of the final bathymetry map.

During the survey the AUV may have collected data at a time when the obstacle avoidance sonar had moved it off of its course, and the data collected would not benefit the survey. After the trackline plot of the .xyz files correctly reflects the survey pattern the grid size was determined. The grid size reflects
the lateral resolution. A 5 m grid size was chosen for the Pavilion Lake survey data. This resolution was determined to be fine enough to show the large-scale microbialite features.

Figure 5 shows one 5m grid and the individual ping soundings contained within each cell. Figure 6 shows the ping density of gridding within a 1 m grid. Because the GAVIA AUV is not constantly pinging there are small gaps in the data. The size of these gaps depends on a combination of the vehicle speed and the ping-rate of the data collection. The line spacing in both Figure 5 and Figure 6 is approximately 25 cm. This gap in the data represents smallest gridding size possible for the data. If a grid of .25 m was used, only one line of pings could be included in the grid, and the data would be sparse. With a gap size of approximately .25 m, the smallest appropriate grid would be a .5 m grid size according to Nyquist theory.

The gridding process within DMagic takes into consideration the trackline overlap of the survey pattern. This allowed for the adjoining swaths to be averaged at the edges. The gridded data was saved as an .sd file, which was viewed and analyzed in Fledermaus.
Figure 5. One 5 m grid showing the number of pings contained in each gridded cell. Approximate sounding density n=1875.

Figure 6. Four 1 m grids showing the density of the pings within each cell. Approximate point density of n=75.
After the data was processed and gridded in DMagic it was initially viewed in Fledermaus software. Fledermaus allowed for a true three-dimensional viewing of the data sets. The file-type primarily used within the Fledermaus suite is the .sd file. By including all survey missions in one large Fledermaus scene the depth-based color-map was consistent throughout the entire lake. Figures 13, 18, 24 display the processed bathymetry of Pavilion Lake using a purple-red, percentage color-map.

After the gridded data are compiled and has been viewed, analytical calculations can be conducted on the data. First the slope characteristics of the entire lake were calculated; this calculation was completed after opening the gridded .sd file in DMagic. The slope calculation is completed and added as an additional .sd to the scene, and can be opened in Fledermaus. DMagic was used to calculate the slope using the “fitted plane” slope process. This

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
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<tr>
<td>D</td>
<td>E</td>
<td>F</td>
</tr>
<tr>
<td>G</td>
<td>H</td>
<td>I</td>
</tr>
</tbody>
</table>

Figure 7. Example of a 3x3 window of cells
\[
\text{percentRise} = \sqrt{\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2}
\]  
(Eq. 1)

Rate of change in the x direction:
\[
\frac{dz}{dx} = \left(\left((c + 2f + i) - (a + 2d + g)\right)\right)\left(8 \cdot \text{cell\_size}\right)
\]  
(Eq. 1a)

Rate of change in the y direction:
\[
\frac{dz}{dy} = \left(\left((g + 2h + i) - (a + 2b + c)\right)\right)\left(8 \cdot \text{cell\_size}\right)
\]  
(Eq. 1b)

\[
\text{Angle} = \tan^{-1}(\text{percentRise})
\]  
(Eq. 1c)

Equation 1. Equation to calculate slope angle of cell E.

Slope calculation consists of creating multiple small planes over a 3x3 window of cells (Burough et al., 1998). The nine elevation points within each of the 3x3 grids are used to derive the slope of the area.

To allow for a better analysis of the slope calculation the color-map for the slope was set to range from a value of 0° to 35°. By limiting the slope the small-scale slope variations could be better seen and understood. In addition to the slope the rugosity of the lake bottom was calculated.

The rugosity of the lake bottom quantifies fine scale bathymetric changes. Rugosity is the ratio of the true surface area of a region to the planimetric area of the same region (Jenness, 2004). Rugosity is calculated by
using the elevation information of a set area. The area is designated into a grid of cells with an equal length and width. The elevation of the center-point of each grid is measured. The surface length of the space between the center-point of a cell to each of the center-points of the surrounding eight cells is found using the Pythagorean theorem (Jenness, 2004). The lines of the surface distance create a network of triangles representing the surface, taking into account variations in elevation. The area of the triangles is computed and combined. The final rugosity is calculated by dividing the true surface area, calculated by combined the areas of the triangles created by connecting the cell center-points, by the planimetric area of the given survey.

Figure 8. Planimetric area of the surface created using the Pythagorean theorem across the nine cell grid (Jenness, 2004)
semiperimeter \( s = \frac{a + b + c}{2} \)  \(\text{(Eq. 2)}\)

(a, b, c = length of triangle sides)

\[ \text{Area} = \sqrt{s(s-a)(s-b)(s-c)} \]  \(\text{(Eq. 2a)}\)

Heron’s formula for finding the area of a triangle, given the lengths of three sides (Weisstein, n. d.).

To allow for a better analysis of the slope calculation the color-map for the slope was set to range from a value of 0° to 35°. By limiting the slope the small-scale slope variations could be better seen and understood. In addition to the slope the rugosity of the lake bottom was calculated.

Similar to the visualization of the slope calculation, the rugosity color-map was set to a defined range of 1 to 1.15. This small range allowed for the measured rugosity to highlight the areas of enhanced roughness (e.g. microbialite and rock talus).

The acoustic backscatter data, originally processed using Geoswath+, was then utilized by Quester Tangent Corporation (QTC) Swathview and QTC Clams to build a categorical map of the Pavilion Lake research area. QTC treats and analyzes the collected and processed backscatter information with similar methods to remote sensing data.

QTC uses the backscatter information to build a user-defined number of
classifications of the bottom types by grouping together similar acoustic backscatter image data. Image-based seabed classification consists of the segmentation of the seabed into separate discrete classes (Preston, 2001). QTC Swathview deduces an extensive matrix of backscatter data to a set classification map (Preston, 2001). QTC analyzes the backscatter image, correcting for angle bias, to create a classification map. The classification map displays variations in seafloor material and bottom-type (Figure 10).

Figure 9. The acoustic variations of different bottom types. (QTC)
Both QTC Swathview and QTC Clams use distinct steps to analytically classify seabed changes in substrate. These specific steps are described in Appendix E.

The classification file is interpolated within QTC Clams to create the exportable classification map.
Chapter 4

RESULTS

The three basins of Pavilion Lake were sampled. Bathymetry data along with side-scan sonar data were collected using the Gavia AUV.

Bathymetry

Using the bathymetry combined with the computed slope and rugosity, plots were created in Matlab to display the characteristics of the lake.

Figure 11. A plot of the slope characteristics at an increasing depth within Pavilion Lake. N=77,621
The shallow water slope characteristics of the lake highlight the steep walls of the lake’s coastal features. Figure 11 shows the general slope trends of Pavilion Lake: a decrease in slope with depth. This decrease in slope is characteristic of the bowl-like shape of the three lake basins.

Figure 12. A plot of the rugosity characteristics at an increasing depth within Pavilion Lake. N=72,958

The rugosity of Pavilion Lake generally decreased with depth. Despite
two spikes in rugosity, Figure 12 shows a distinct trend of a decreasing rugosity. The spikes occurred at depths of approximately 10 m and 30 m.

**North Basin**

The North basin of Pavilion Lake was measured to be the smallest basin. This basin is positioned in a northwest to southeastern orientation and is approximately 1350 m long. The widest area in the North basin was measured to be approximately 370 m. Figure 13 shows the collected bathymetry of the north basin.
Figure 13. North to South profile of the north basin
Figure 14. Profile taken from southwest to northeast of the north basin.

Figure 15. Profile taken from southwest to northeast of the deepest section of the north basin.
As can be seen in the profile of the centerline of the North basin in Figure 13, the deepest portion of the basin is 36 m. The profile of the basin also shows that a terrace feature with a depth of approximately 13 m bounds the northern extent of the lake. This terrace slopes at approximately -2.5° to a second terrace feature. A slope of approximately -6.5° was measured from the second terrace to the deepest portion of the North basin. The depth gradually decreased, with an average slope of approximately -2.6°, from the deepest portion of the basin to the southernmost point in the North basin.

The profiles of the eastern and western walls of the lake within the North basin are similar. Figure 15 shows a profile taken from southwest to northeast of the north basin; the western slope is approximately 16.5° while the eastern slope is approximately 15.5°. This profile also displays the deepest portion of the North Basin.

The slope and rugosity were calculated for the North basin using the collected bathymetry data. The slopes of the North basin range from the flat center of the basin area, with a slope of 0.0°, to the steep walls of the lake on the eastern and western side, with a slope of more than 30.0°. Figure 16 shows the slope of the North basin using a logarithmic inverse colormap ranging from 0.0° to 35.0°. Figure 17 shows the rugosity, previously described as “roughness,” of the North basin.
Figure 16. Computed slope of the North Basin, displaying 0-35°
Figure 17. Computed rugosity of the North Basin, displaying 0-1.25
The areas of highest rugosity were found along the walls of the lake and not in the generally flat portions of the North basin center.

**Central Basin**

The Central basin is also oriented in a northwest to southeast orientation and contains the deepest areas of the lake, reaching a depth of 55 m. The widest area of the basin measures 850 m and passes through the deepest portion of Pavilion Lake. This basin is approximately 2000 m in length, Figure 18, and contains a very diverse bathymetric terrain. The northern portion of the Central basin consists of rather steep walls with slopes of approximately 16.7° on the western wall and 16.5° on the eastern wall. The southern portion of the Central basin is distinctly different than that of the northern portion. A depth difference of nearly 10 m was measured between the northern portion and the southern portion, with a slope of approximately 6.2°. The gap in the data from the Central Basin is a result of missions focusing on the center of the basin, and an additional survey focusing on the shallow areas within the basin.

The southern portion of the Central basin contains bathymetry far more complex than the northern portion of the basin. Figure 29 shows a cross section of the southern portion of the basin. Within this area, there is a maximum approximate depth change of 29 m. The area also contains slopes that are measured to be at a maximum of approximately 23.2°.
Figure 18. Bathymetry map of the Central Basin
Figure 19. Southwest to northeast profile of the Herms feature within the Central basin.
Figure 20. North to south profile of the Central Basin, including the deepest portion of the lake
Figure 21. West to east profile of the Central Basin, including the deepest portion of the lake

The computed slope for the Central basin is shown in Figure 24. The general slope characteristics of the Central basin are more greatly varied than those of the North or South basin. The north-central portion of the basin center has very little slope, with the walls of the lake having a high slope (>30°), much like the North basin. The southern portion of the Central basin contains a feature known as the Herms. This area dynamically changes the general slope characteristics of the Central basin. The profile in Figure 22 shows the slopes computed at the Herms. The eastern coast of the southern portion of
the Central basin contains slopes that are less than the walls of the lake in the northern portion of the Central basin. Slopes along this portion of the lake edge only reach approximately 13.0° on the eastern edge, whereas on the western edge the slope reaches over 30.0°. In addition to the Herms feature, the southern portion of the Central basin contains banded areas in which the slope was measured to reach approximately 22.0°.

Much like the slope, the calculated rugosity of the northern portion of the Central basin is very similar to that of the North basin. The center basin of the northern portion contained no areas of high rugosity (Figure 23). The rugosity of the eastern and western walls of the lake were computed to be very similar, much like the North basin of Pavilion Lake. The eastern and western walls of the
Figure 22. Calculated slope of the Central Basin, displaying 0-35°

Figure 23. Calculated rugosity of the Central Basin, displaying 0-1.25
northern portion of the Central basin were the only areas in which a high rugosity was measured.

**South Basin**

The South basin, like the other basins within the lake, is positioned in a northwest to southeastern orientation. This basin is approximately 2300 m long and has a width of approximately 500 m at the widest area (Figure 24). The South basin has the shallowest average depth of the three basins: approximately 30 m. Erosional deposition is common within Pavilion Lake due to the lake’s position within a steep walled canyon. The deepest portion of the South basin lies south of an erosional fan. The depth in this area reaches approximately 39.0 m.

The computed slope, Figure 25, shows that a channel of very low slope runs the length of the South basin. The steepest areas within the basin are located on the eastern and western lake edge of the southern half of the South basin. The computed rugosity of the south basin, Figure 26 shows that the South basin has a computed rugosity very similar to that of the north basin. The areas of high rugosity in the south basin are located along the eastern and western walls of the southern areas of the basin.
Image 24. Bathymetry of the South basin, with a North to south profile of the South Basin
Figure 25. Calculated slope of the South Basin, displaying 0-35°
Figure 26. Calculated rugosity of the South Basin, displaying 0-1.25
**Backscatter**

**North Basin**

The backscatter images collected by the Geoswath+ module are shown in Figure 27. Like the backscatter collected using the Marine Sonic module, the light colored areas represent a strong return and a hard bottom-type. The figure shows, similarly to the Marine Sonic, the central area of the North basin is a soft bottom-type. Figure 28, collected with Marine Sonic, also shows the hard bottom-types found on the lake walls.

Backscatter images collected using the Marine Sonic side-scan sonar module are shown in Figure 28. The amber colormap was chosen because of the available color options it best highlighted the variations in bottom-type. The light amber areas show a hard-bottom type. The central area of the basin appears to be relatively uniform soft sediment. The walls of the basin are shown to contain light areas in the backscatter image. These light colored areas represent a carbonate, hard bottom-type.
Figure 27. Backscatter collected by the Geoswath module, processed using GeoCoder, of the North Basin. Light colors represent high acoustic return (0.18 m/pixel).
Central Basin

Like the North Basin, both Geoswath and Marine Sonic data was collected. Figure 29 shows the Marine Sonic backscatter. Figure 29 highlights an area of high return, specifically microbriate carbonate structures. Additionally, Because of the nature of the Herms feature and the GAVIA mission behavior, limited data was collected directly over the Herms. The
Herms feature, as displayed in the profile in Figure 19, nearly reach lake surface. This severe change in water depth limited the ability to survey this feature. Despite the limited data, Figures 29 and 30 display consistent high return areas on the peaks of the Herms structures.

The backscatter data collected by the Geoswath module is shown in Figure 29. The missions of the Central Basin included trackline overlap, which strengthened the precision of the bathymetry resolution, but created the dark areas on the Geoswath backscatter images.

Figure 29. Backscatter collected by the Geoswath module, processed using GeoCoder, of the Central Basin. Light colors represent high acoustic return (0.18 m/pixel).
Figure 30. Backscatter collected by the Marine Sonic sonar, processed using Sonarwiz, of the Central Basin. Light colors represent high acoustic return (0.18 m/pixel).

**South Basin**

The backscatter data collected using the Geoswath+ shows an area of high return, hard bottom-type, on nearly the entire visible lake coast. The southern portion of the basin is displayed in a lighter color, potentially displaying a harder bottom-type. The eastern wall of the lake, in the northern section of the South Basin shows an area of high returns in a fan shape reaching into the center of that basin area. This feature is known to be a fan-
shaped erosional feature. The Geoswath backscatter, Figure 31, highlights the area.

The Marine Sonic (Figure 32) collected backscatter displays the high return features best in the southern portion of the basin. The erosional feature is less visible because of the overlapping lines. This backscatter image does highlight an area of high return along the eastern wall of the lake, at the midpoint of the basin.

![Image of backscatter](image_url)

Figure 31. Backscatter collected by the Geoswath module, processed using GeoCoder, of the South Basin. Light colors represent high acoustic return (0.18 m/pixel).
Figure 32. Backscatter collected by the Marine Sonic sonar, processed using Sonarwiz, of the South Basin. Light colors are hard bottom represent high acoustic return (0.18 m/pixel).

**Automated Classification-QTC Swathview, QTC Clams**

Using the methodology described above QTC Swathview and QTC Clams were used to produce the classification maps shown below. To better highlight regions of the lake, the classification map was divided into the three primary lake basins. QTC produced a map that included six classifications of the collected backscatter.
Figure 33. Graph of the number of classes by the score received after running the AutoCluster (ACE) function within Swathview
Figure 34. Classification colors, number of records of each color

- **1 (13800)** Hard Bottom-Microbialite/rock talus and sediment
- **2 (51145)** Hard Bottom-Microbialite/rock talus
- **3 (57764)** Soft Bottom-Sediment with rock inclusions
- **4 (54212)** Soft Bottom-Sediment
- **5 (119781)** Soft Bottom-Sediment
- **6 (6488)** Acoustic Noise

Figure 35. QTC automated backscatter classification map of the North Basin.
Figure 36. QTC automated backscatter classification map of the Central Basin.

Figure 37. QTC automated backscatter classification map of the South Basin.
The color-scheme used for the classification was set to “scaled similarity” which selected similar colors to represent similar backscatter characteristics.

Matlab was used to visualize the distribution of the class distribution throughout the lake. The lake depths were separated into depth segments of 10 meters. The percentage of each of the depth segments occupied by a specific backscatter class was then graphed.

![Graph](image)

**Figure 38.** Percentage of Pavilion Lake (Depth 1-10m) occupied by each of the 6 classes

![Graph](image)

**Figure 39.** Percentage of Pavilion Lake (Depth 10-20m) occupied by each of the 6 classes
Figure 40. Percentage of Pavilion Lake (Depth 20-30m) occupied by each of the 6 classes

Figure 41. Percentage of Pavilion Lake (Depth 30-40m) occupied by each of the 6 classes
Figure 42. Percentage of Pavilion Lake (Depth 40-50m) occupied by each of the 6 classes

Figure 43. Percentage of Pavilion Lake (Depth 50-60m) occupied by each of the 6 classes
Figure 44. Plot of slope, depth and rugosity of the 6 classifications. Class 1-blue, Class 2-magenta, Class 3-red, Class 4-yellow, Class 5-cyan Class 6-green.

Figure 44 displays the six QTC classifications with respect to both slope and rugosity. The figure displays the entirety of the slope and rugosity data.

The following figures offer a visual analysis of the six classification systems. A side-scan sonar image was placed next to two of the ground-truthing images collected by the DeepWorker, where available. No ground-truthing images were collected for the Bright Green, classification six. The lack of images is due to the fact that the Bright Green represents noise in the
acoustic backscatter. This line of noise, shown in the northern edge of the North Basin represents such a small area of the lake bottom, no DeepWorker missions surveyed this area.
Figure 45. A side-scan sonar image of each classification, along with the color. Ground-truthing images collected with the DeepWorker submersible, when available.
Figure 46. A side-scan sonar image of each classification, along with the color. Ground-truthing images collected with the DeepWorker submersible, when available.
Classification One (Cream, Hard Bottom-Microbialite/rock talus and sediment)

From depths ranging from 0-20 m classification one (Hard Bottom-Microbialite/rock talus and sediment) steadily represented 10% of the lake-bottom area. This level declined severely in the depth range 20-40 m, from approximately 7% to approximately 2% respectively. In the deepest portions of the lake, depth ranges of 40-60 m, classification one was minimally present, making up only approximately 1% of the deep lake-bottom surface area.

Classification two (Dark Yellow, Hard Bottom-Microbialite/Rock talus)

Classification four (Hard Bottom-Microbialite/Rock talus) was found to cover much more of the shallower lake areas than the deeper portions. The percentage of coverage dropped slightly, from approximately 16% to 14%, in the shallower 0 m to 20 m areas of the lake. Classification four covered the largest percentage, 40%, of the lake from the depths 20 m to 30 m. The percentage severely dropped off after a depth of 30 m. From a range of depths 30 m to 40 m classification four covered approximately 12% of the lake-bottom surface area. The percentage of coverage continued to drop with depth; approximately 7% coverage at 40 m to 50 m. The deepest portion of the lake, 50 m to 60 m, consisted of only approximately 2% surface area coverage by
Classification Three (Dark Green, Soft Bottom-Sediment with rock inclusions)

Classification three (Dark Green, Soft Bottom-Sediment with rock inclusions) varied significantly from the shallow depth segments to the deeper depth segments. Within the shallower depths of the lake classification the percentage of surface area covered by classification three was nearly 15%. The middle depth sections of the lake, 20 m to 40 m, saw a drop on the prevalence of classification three. Within the depth segment ranging from 20 m to 30 m the percentage of classification three falls to approximately 7% of the total surface area. The deepest segments of the lake, 40 m to 60m, are where classification three is most prevalent.

Classification Four (Blue, Soft Bottom-Sediment)

Classification five (Soft Bottom-Sediment) was found to be most prevalent in the deeper portions of the lake. From the depths of 50 m to 60 m classification five covered nearly 30% of the lake bottom surface area. The middle depth portions of the lake, 20 m to 40 m, consisted of a surface area coverage percentage ranging from approximately 13% to 18%. The prevalence of classification five continued to decrease with depth. In the range
of 10 m to 20 m depth classification five covered approximately 8% of the lake-bottom surface area. The shallowest portions of the lake, 0 m to 10 m, exhibited the least percent coverage, 2%.

**Classification Five (Lavender, Soft Bottom- Sediment)**

Classification six (Soft Bottom- Sediment) covers the majority of the lake-bottom surface area in all depth ranges, other than that between 20 m and 30 m. After the percent coverage dipped slightly, 27%, between 20 m and 30 m, the percentage was measured to be the highest, 54%, between 30 m and 40 m. In the deeper portions of the lake, 30 m to 60 m, the percentage of surface area covered by classification six rose slightly.

**Classification Six (Bright Green, Noise Pings)**

The location of the majority of classification two was located in the northern edge of the North Basin. This area was not surveyed using the DeepWorker submersible. Because of the lack of survey, there are no images of the area designated as classification two.
Chapter 5

DISCUSSION

The results qualitatively suggest a correlation between microbialite habitat and depth, slope, and rugosity. Classification One (Hard Bottom-microbialite/rock talus and sediment) and Classification Four (Hard Bottom-microbialite/rock talus) represent the areas of the lake where the majority of the microbialite growth was found. Although the areas highlighted by these classifications are not strictly microbialite formations, it can be understood that these regions highlight the present location of microbialite growth as well as potential areas of future microbialite growth. The high-resolution photos collected by the DeepWorker allow for the classified areas to be differentiated. As can be seen in the images collected by the DeepWorker submersible, Figure 45 and Figure 46, erosional deposits of cobble sized rock material appear similar to microbialite growth. The collected sonar data was not capable of differentiating between areas of rock talus and microbialite growth. These similarities make QTC Swathview incapable of identifying microbialite growth and rock deposits as separate classifications. Without the high resolution photographs taken by the Deep Worker submersibles, determining the difference between rock and microbialite cannot be completed using sonar data alone. This inability to distinguish microbialites from rocks in the sonar
data removes the possibility of estimating lake-bottom surface area coverage by microbialite by sonar data alone.
Figure 47. Percentage of total lake coverage of Classification 1, with respect to rugosity

Figure 48. Percentage of total lake coverage of Classification 2, with respect to rugosity
Figure 49. Percentage coverage of Classification 1, with respect to slope

Figure 50. Percentage coverage of Classification 2, with respect to slope
Histograms of lake coverage by rugosity (Figures 47 and 48) are very similar between the two classifications. As seen in the images collected by the DeepWorker submersible (Figure 44 and Figure 45) the texture of the areas classified as hard bottom were visibly rougher and more textured. This rough texture is due to the material that is found on the lake-bottom in the regions within classifications one and two. The submersible images show that the lake-bottom in these areas is covered by cobble to boulder-sized rocks, many covered in microbialite growth, or individual nodules of microbialite growth.

The rugosity characteristics of the two classifications containing the microbialite communities were also similar, but may not have determined where the microbialite communities were found. As the microbialite structures grew they would inherently influence the rugosity of the area that they occupy. The increase in microbialite presence would increase the measure of rugosity. This influence on the rugosity may explain why the areas of microbialite prevalence contain elevated rugosity levels. The prevalence of microbialite growth within areas of higher rugosity may not show a preference for areas of higher rugosity, it may show that the extensive microbialite growth in these areas is directly influencing the rugosity within the areas.

Much like the calculated rugosity, the plot of slope (Figure 49 and 50) for classifications one and four are very similar. Both of the classifications
show a peak in percentage of lake-bottom surface area coverage at a slope of 10°. This increase in coverage at a set slope shows that the microbialite communities, as well as potential growth environments, are found at the same slope characteristics. This slope range, 5-25°, represents a preferential growth range for the microbialite assemblages within Pavilion Lake. The total measured slope range for Pavilion lake was 0°-60°. Approximately 88% of classification one (Hard Bottom-Microbialite/rock talus and sediment) occurs within this designated slope range 5-25°, as well as nearly 85% of classification two (Hard Bottom-Microbialite/rock talus). The slope measured in Pavilion Lake appears to have influenced the spatial coverage of the microbialite communities. Table 3 displays that only 67.50% of classification 3 (Soft Bottom-Sediment with rock inclusions is found within the desired slope range. This lower percentage may be due to the characteristics of classification 3. The sediment material may be less able to be deposited within areas of the lake with elevated slope (Figure 50). The same assumptions made about the sediment characteristics hold true for the two Soft Bottom classifications. The percentages of the two Soft Bottom classifications found within the desired slope ranges were found to be 47.70% and 64.90%, respectively.
Table 3. Classification prevalence between 5-25° slope

<table>
<thead>
<tr>
<th>Classification</th>
<th>Bottom Type</th>
<th>Percentage Present (Slope 5-25°)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Hard Bottom-Microbialite/rock talus and sediment</td>
<td>88.40%</td>
</tr>
<tr>
<td>2</td>
<td>Hard Bottom-Microbialite/Rock talus</td>
<td>84.70%</td>
</tr>
<tr>
<td>3</td>
<td>Soft Bottom-Sediment with rock inclusions</td>
<td>67.50%</td>
</tr>
<tr>
<td>4</td>
<td>Soft Bottom-Sediment</td>
<td>47.70%</td>
</tr>
<tr>
<td>5</td>
<td>Soft Bottom-Sediment</td>
<td>64.90%</td>
</tr>
<tr>
<td>6</td>
<td>Acoustic Noise</td>
<td>77.80%</td>
</tr>
</tbody>
</table>
Figure 51. North Basin, slope 5-25° highlighted green. The blue area is slope greater than 25°, and the gray is slope less than 5°.
Figure 52. Central Basin, slope 5-25° highlighted green. The blue area is slope greater than 25°, and the gray is slope less than 5°.
Figure 53. South Basin, slope 5-25° highlighted green. The blue area is slope greater than 25°, and the gray is slope less than 5°.

The biosignatures observed within nodules collected from the surface of Pavilion Lake microbialites display a photosynthetic influence (Brady et. al. 2010). Figures 38, 39, and 40 display the backscatter classifications with respect to depth (0-30 m). The classification of “Hard Bottom-Microbialite/rock talus and sediment” and “Hard Bottom-Microbialite/rock talus” qualitatively suggests a correlation between microbialite habitat and depth. The depth and slope preferences of the microbialite communities reinforces the understanding that the microbialite structures present in Pavilion Lake formed utilizing photosynthetic means. The microbialite growth in the Central and
South Basins consists of marl reef structures that reach to within approximately 5 m of the lake surface (Lim et. al., 2009). This growth limitation may be due to the chara plant coverage found within the more shallow areas of the lake. Because it has been shown that the microbialite structures rely on photosynthetic processes, the lack of microbialite formations in the shallow depths may be due to the chara growth covering potential microbialite habitat. In these areas the chara populations utilize the present solar energy.

The preferential growth environment for microbialites within Pavilion Lake strengthens the previously published hypothesis that the microbialites are a result of biological origin (Lim et al., 2009). Although not included in this survey, direct measurements of photosynthetically active radiation (PAR) were collected from Pavilion Lake (Laval et al., 2000). The light levels were found to drop off by approximately one order of magnitude with each 10 m increase in depth (Laval et al., 2000). These measurements of photosynthetically active radiation, along with the preferred microbialite habitat being found between 5-30 m depth, also reinforce the hypothesis that the microbialite structures have a biological origin.

The complete slope range measured within Pavilion Lake was approximately 0°-60°. The preferred microbialite habitat slope range of 5°-25° may be due to physiological limitations of the microbialite structures. The abyssal regions of the lake are primarily soft-bottom which may be the reason
for the lack of microbialite growth in these areas. The areas of the lake that were primarily rock talus material may provide the microbialites a requisite hard-bottom habitat. As can be seen in Figures 51, 52, and 53, much of the lake wall area is included within the slope range of 5°-25°, although not all. The areas that are steeper than 25° may not allow for the microbialite structures to affix to the lake wall. As well as physical slope limitations, steeper slopes may also create an environment in which shallower structures are blocking photosynthetically active radiation from deeper microbialite structures. The lake structure may also be responsible for the preferred slope characteristics. As the slope of the lake wall increases the wall may become less stable. The slope preference discovered may be due to both physiological characteristics of the microbialites and the structural characteristics of the lake.

The hypotheses of this project were:

1. Microbialite morphologies reflect type specific affinities for slope and depth settings. Specifically, slope and depth tolerances will vary between morphotypes.

2. Microbialite morphotype variability is greater in a vertical distribution than a horizontal distribution. Specifically, the vertical diversity of microbialite macro-morphology in the lake will exceed the lateral diversity.
The two hypotheses for this project were selected and thought to be viable because specific assumptions were made concerning the expected resolution of the sonar data. When planning the data collection and analysis methods it was assumed that the sonar data would be gridded at a sub-meter scale. The latency that was observed in the collected data forced the grid size to be larger. By increasing the grid size to 5 m, the small scale (<1 m) morphological variations could not be measured. Because of this change, it was no longer possible to differentiate specific microbialite morphologies by analyzing the sonar data. Without the latency in the sonar data it may have been possible to differentiate variations between specific morphologies. However, the analysis of the DeepWorker imagery displayed the morphological similarities between rock talus material and microbialite growth, and even with sub-meter gridded bathymetric data differentiation of microbialite morphology may not be possible. Because of the morphological similarities, the differentiation between rock talus and microbialite growth may not have been possible, even with sub-meter gridded bathymetric data.

Appropriate data collection methodology is integral to building a morphological classification system based on acoustics data. Because all of the acoustic data was collected within a nine-day window it can be assumed that the conditions within Pavilion Lake remained constant and no large-scale changes occurred on the lake bottom. Because of the similarities between
many of the microbialite morphologies and erosionally deposited rocks, the timeline of the survey ensured that the data represented a consistent classification of the lake-bottom surface.

The photographic images collected by the DeepWorker submersibles enhanced the accuracy of the morphotype classification developed for Pavilion Lake. The resolution of the imagery collected by DeepWorker far exceeded the image resolution of the GAVIA camera. The camera mounted on the DeepWorker submersible was of a higher resolution than that of the camera mounted on the GAVIA AUV. In addition, during a data collection mission the GAVIA is never stationary, even when collecting photographs. This movement coupled with limited light conditions within areas of Pavilion Lake produced images that did not allow for much analysis. As well, the GAVIA camera system is best suited for image capture approximately 2m above the bed. The dynamic nature of the lake bottom, and the limited swath width resulting from a low fly altitude, did not allow for missions to be flown at this altitude. With the addition of the georeferenced DeepWorker image dataset, it was possible to properly interrogate the classification system developed in QTC Swathview. Reviewing previously collected geo-referenced DeepWorker images completed this interrogation. The images had been compiled into a database viewable within Google Earth. It was then possible to review images collected within the areas designated as different bottom-types. The ground-truthing
allowed for specific areas of the classification to be highlighted using photographs of the lake bottom. This allowed for the understanding of what specific characteristics made up each of the six classifications. Without this dataset of images it would not have been possible to confidently trust the morphotype classification system.
Chapter 6

CONCLUSION

The results of this investigation indicate that the acoustic data collected using a GAVIA AUV survey platform has a high capacity for building bottom-type classification structures. This success is also partly due to the extensive backlog of mission photographs collected by the DeepWorker submersible for a means of ground-truthing. A summary of major points in support of this conclusion follow:

1. The majority of the areas within Pavilion Lake, which are rich in microbialite growth, are found within a slope ranging between 5 and 25°.

2. The majority of the areas within Pavilion Lake, which are rich in microbialite growth, are found within a depth ranging between 0m and 30 m.

The use of QTC Swathview and Clams displayed the weaknesses in attempting to highlight small-scale morphotype classification. Specifically for Pavilion Lake, the individual microbialite morphologies are subject to very small-scale (<1 m) changes. The acoustic data that was collected was unable to analyze morphotype changes of this scale. The collected backscatter, once
classified, created a very descriptive map of lake bottom-types. It was then possible, with the use of classified photographs, to determine that specific QTC classifications were microbialite material. Despite the fact that QTC, using the acoustic backscatter, was unable to differentiate between specific morphtypes, the program produced a map of potentially viable microbialite growth areas. The backscatter was unable to differentiate between specific microbialite morphotypes because the resolution of the collected data was not fine enough to display the individual variations in microbialite growth. The backscatter data was gridded at a sub-meter resolution (0.18 m/pixel), but was larger than that of the small-scale morphological changes. The hard carbonate microbialite structures created similar backscatter signatures to that of the rock talus material surrounding many microbialite sites. The differences between rock talus and microbialite structure were not observed by the QTC software packages. The uniformity of the swath width coverage utilized within each missions helped to create a set of data-products that were very consistent for the entire survey.

**Future Work**

The GAVIA survey platform could serve as an excellent survey tool for future microbialite surveys. The classification structure created for Pavilion Lake could be used within QTC Clams to create a classification map for future research efforts. The portability and ease of deployment of the GAVIA AUV
would allow for a preliminary survey to be conducted with limited infrastructure in place.

It is known that other lakes within the region are suspected to contain microbialite growth. Kelly Lake, which is located approximately 13 km northwest of Pavilion Lake, is known to contain microbialites, but the study of the lake has been very limited. During the 2010 field season a reconnaissance survey was conducted within Kelly Lake. Although the bathymetry of the lake was unknown the mission parameters of the GAVIA allowed for a preliminary survey to be conducted. After the data was analyzed, another survey mission was conducted using the same terrain following settings used for Pavilion Lake. The collected, then processed, acoustic data was then analyzed using QTC Clams to create a preliminary classification structure. The analysis of the acoustic backscatter data was completed within QTC Clams, using the classification structure created for Pavilion Lake. The classification structure created for Kelly Lake will allow for the DeepWorker submarine flights planned for the upcoming field season to focus the survey efforts of areas believed to be high value microbialite rich areas. The acoustic data collected within Pavilion Lake allowed for the creation of a classification structure that can be used to build preliminary classification structures for future exploratory studies.
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"http://mathworld.wolfram.com/NyquistFrequency.html


Appendix A-Histograms of lake-bottom surface area coverage of each classification with respect to rugosity

Figure 54. Plot of total lake percent coverage with respect to rugosity of Class 3

Figure 55. Plot of total lake percent coverage with respect to rugosity of Class 4
Figure 56. Plot of total lake percent coverage with respect to rugosity of Class 5

Figure 57. Plot of total lake percent coverage with respect to rugosity of Class 6
Appendix B Plots of lake-bottom surface area coverage of each classification with respect to slope

Figure 58. Plot of total lake percent coverage with respect to slope of Class 3

Figure 59. Plot of total lake percent coverage with respect to slope of Class 4
Figure 60. Plot of total lake percent coverage with respect to slope of Class 5

Figure 61. Plot of total lake percent coverage with respect to slope of Class 6
Appendix C-Navigation plots produced after each mission.

The following plots were produced using Matlab from Navigator information collected by the AUV during each of the missions. Each plot shows the path that the GAVIA AUV traveled for the survey. The general behavior of the vehicle is plotted to gather information concerning the mission.
Figure 62. Navigator plot for the survey completed on June 28, 2010
Figure 63. Navigator plot for the survey completed on June 29, 2010
Figure 64. Navigator plot for the survey completed on June 30, 2010
Figure 65. Navigator plot for the survey completed on July 1, 2010.
Figure 66. Navigator plot for the survey completed on July 2, 2010
Figure 67. Navigator plot for the survey completed on July 3, 2010
Figure 68. Navigator plot for the survey completed on July 4, 2010
Figure 69. Navigator plot for the survey completed on July 6, 2010
Figure 70. Navigator plot for the survey completed on July 7, 2010
Appendix D

Data Processing

Data processing of the collected GeoSwath data uses a variety of software packages. Figure 71 shows a simple workflow diagram of the steps taken to produce the final data products.

Figure 71. Uniform coloring of the data processing workflow diagrams.

Geoswath+, is the proprietary software used for initial processing of swath bathymetry and side-scan sonar data generated by the GeoSwath+
Figure 72. Workflow diagram showing the production of final data products
bathymetric sonar module for the AUV. Geoswath+ performs data processing and generation of digital terrain models, as well as side-scan mosaics. Post-processing filters can be applied within the software to provide a higher-level of data quality by removing outliers caused by errant pings within the water column and by limiting the extremities of the ping distributions. Files can be exported in various formats to provide better visualization and for other processing algorithms to be applied. This flexibility in file format allows for the sonar data to be analyzed and viewed in multiple software packages. Figure 73, shows the specific steps take within Geoswath+ to process the bathymetry and backscatter data. Individual Geoswath+ projects were created for each day of survey in Pavilion Lake. By creating individual project files, it was possible to process each survey a vessel settings file was created to ensure that the transducer position was accounted for in post-processing. This file contains the location of the sensor payload of within the vessel. These measurements were used in conjunction with navigation data to ensure precision within the sonar data. The vessel file contains the dimensions of the vessel in the form of a 3D graphical representation and along with the absolute positions (relative to center of vessel) of the GPS antenna and the transducer assembly. The frequency settings within Geoswath+ were overridden and set to the Geoswath frequency of 500 kHz. Because the data was collected in a
non-tidally influenced water body the Geoswath+ was set to use vehicle navigation height.

Geoswath+ allows for the utilization of multiple filters to remove unwanted noisy data from the survey.
Figure 73. Geoswath+ workflow diagram.
The following image shows the four windows used during the processing of data. The Depth window (A) shows the position of the AUV, red circle, and the green dotted line is an individual ping locating the lake bottom. The Waterfall window (C) shows a color-coordinated map of the survey area being processed. The slope of the lake bottom shown in the Depth window is visualized in an along-track view in the Waterfall window. The Side-scan analog window (B) displays the strength of the backscatter return of a single ping. Like the Waterfall window the Side-scan window (D) builds a backscatter image of the side-scan pings in an along-track view.

Figure 74. Geoswath+ processing windows during survey data processing. The processing completed within each window is described above.

Sonarwiz was the software package used to process the side-scan sonar collected by the Marine Sonic system housed in the Control Module. Figure 75
shows the work flow used to process the raw side-scan files.
Figure 75. Workflow diagram for processing side-scan backscatter using Sonarwiz
GeoCoder is a software package, developed by Yuri Rzhanoy from the Center for Coastal and Ocean Mapping at the University of New Hampshire. Geocoder was used to process the backscatter data, and build mosaics of the data for analysis. The same raw data files (.rdf) used for Geoswath+ were loaded into Geocoder for processing. To ensure that the proper georeferencing information was used the program parameters were set to gather information from the heading of the sampling vehicle, which was the Gavia AUV. Geocoder was used to build a backscatter mosaic by connecting the survey tracks of each mission day. After the tracks were analyzed the backscatter information was compiled and built into a mosaic. The mosaic information was exported as a geo-referenced image, which could be draped over the bathymetric maps of Pavilion Lake.
Appendix E- Description of the process of creating a classification map using QTC.

Load Raw Data

The data are batch loaded into QTC Swathview. The data are then archived by QTC, into a set folder configuration.

Image Compensation

The backscatter images are a result of the acoustic information received by the sonar. This information is influenced by the sediment type, but also the angle and range of the ping. To standardize the backscatter images the angle and range affect on the backscatter image must be nullified.

Rectangle Placement

Swathview uses rectangles of a set size distributed to determine the amplitude levels of the backscatter image. For the Pavilion Lake survey a rectangle size of 65 by 17 was used. The rectangle consisted of 65 across track samples by 17 pings. By accounting for the ping rate and the speed of the AUV, the rectangle size was generated.

Statistical features are generated using the rectangle (65 by 17) acoustics backscatter amplitudes from each of the rectangle patches. The methods for seabed discrimination and the feature algorithms are based on previously published methods (Preston, 2001). Principal component analysis (PCA) was then used to best select the component characteristics that most
appropriately describe the data set. Prior to PCA, the major components that were generated from the acoustic backscatter information were merged to create three key principal components, Q1, Q2, and Q3.

Principal component analysis (PCA) is used extensively throughout modern data analysis (Shlens, 2009). PCA is used within QTC Swathview because of its ability to analyze complex, seemingly random, datasets and deduce the underlying data structures.

Figure 76. Rectangle settings within QTC Swathview

**Clustering**

Clustering is a required step within QTC Swathview if an unsupervised segmentation is being performed (Preston, 2004). This unsupervised segmentation first assigned all of the records to one class, before being
clustered within QTC Swathview (Preston, 2004). Using \( k \)-means clustering algorithm to analyze the original data from the 65 by 17 rectangles the backscatter records are then assigned to the closest class center, within Q-Space. Q-Space is the three-dimensional plot of the three principal components, Q1, Q2, Q3.

Figure 77. Q-Space, displaying components Q1 and Q2.
Figure 78. Q-Space, displaying components Q2 and Q3

Figure 79. Q-Space, displaying components Q1 and Q3
Within the context of QTC Swathview, the $k$-means clustering algorithm is used with the three-dimensional Q-Space to build a user-set number of clusters by identifying data points in a similar area. The middle of each of the clusters, the cluster center, is positioned as to minimize the mean-squared distance between the cluster center and the data points (Kanungo, 2002). Q-Space begins with a three dimensional cloud of data points. The $k$-means algorithm is used to group the data points into a user defined number of clusters by grouping the data in a way that minimizes the distance from the data point to its respective cluster center. By completing this clustering, QTC Swathview has grouped the data points that contain similar acoustics backscatter information.

**Create A Catalog/Classification**

A catalog file is created within QTC Swathview, which is used to classify the seabed, using the aforementioned clusters. Using the catalog file a classification file is created (.seabed). During the classification of the seabed a confidence value is computed for each of the clustered points. This value shows a confidence (0-100%) that the data point has been assigned to the proper classification.
Figure 80. Confidence map of the classification produced using QTC Swathview.