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SPATIAL DISTRIBUTION AND CHARACTERISTICS OF MICROBIALITES THROUGH THE USE OF SONAR TECHNIQUES-GEOACOUSTIC INVESTIGATIONS AT PAVILION LAKE (CANADA)

Abstract - A.C. Trembanis, G.R. Gutsche, S*patial distribution and characteristics of microbialites through the use of sonar techniques- geoacoustic investigations at Pavilion Lake (Canada).*

Previously collected diver and submersible derived video survey data have documented a diverse community of living microbialites on the lakebed of Pavilion Lake, BC. Research conducted prior to 2005 involved discrete sampling locations rather than an examination on a synoptic scale. Through a series of lake-wide sonar survey measurements (including swath bathymetric and side-scan systems) utilizing a variety of surface vessel and autonomous underwater vehicle (AUV) mounted sonars, acoustic backscatter derived bottom-type maps were created. These bottom classification maps allowed for the analytical study of the microbialite habitat with respect to the collected bathymetry of the lake. The sonar data (bathymetry and backscatter) was compiled to create a base map of the lakebed at a very high resolution of 25 cm. The bathymetry data allowed analysis of bedforms within Pavilion Lake, as well as any erosional episodes that may affect the growth of microbialites. By analyzing the dense phase measuring bathymetric coverage of the lake bottom, with respect to rugosity (i.e., localized slope) and depth, it was possible to examine trends in changing benthic conditions in regions with microbialites present. Acoustic backscatter data was used to differentiate between soft sediment erosional deposits and hard bottom microbialite morphologies to evaluate changing conditions. The distribution and growth pattern characteristics were then analyzed and allowed for inferences to be made concerning preferential habitat characteristics. These maps allowed for a better understanding of the habitat characteristics of the microbialite landscape level patterns found in these lakes. Furthermore, these data products aid in the interpretation of patterns in the paleolimnogical record, in addition to the interpretation of the growth conditions and biological origins of these structures.

Key Words - microbialites, geoacoustic investigations, sonar, Pavilion Lake, Canada

Riassunto - A.C. Trembanis, G.R. Gutsche, *Distribuzione spaziale e caratteristiche di microbialiti tramite tecniche sonar e indagini geoacustiche nel Lago Pavilion (Canada).*

Dati ottenuti in precedenza da video ripresi da subacquei o da sommergibili avevano documentato una ricca comunità di microbialiti viventi sul fondale del Lago Pavilion, British Columbia. Le ricerche condotte prima del 2005 avevano interessato aree di campionamento separate anziché rilevamenti a scala sinottica. Tramite una serie di misurazioni dei rilievi sonar sull'intero lago (compresi sistemi batimetrici multi-beam e a scansione laterale) eseguiti con sonar installati su diversi tipi di imbarcazioni di superficie e veicoli subacquei autonomi, sono state create mappe del tipo di fondale derivate da retro diffusione acustica. Queste mappe di classificazione del fondale hanno consentito di studiare in modo analitico l'habitat delle microbialiti in funzione della batimetria del lago. I dati sonar (batimetria e retrodiffusione) sono stati assemblati per creare una mappa di base del fondale lacustre alla risoluzione di 25 cm. I dati batimetrici hanno consentito di analizzare le forme di fondale del Lago Pavilion e i fenomeni erosivi che possono influire sulla crescita delle microbialiti. Tramite analisi della copertura batimetrica del fondale relativa alla fase densa rispetto alla rugosità (cioè pendenza locale) e profondità, è stato possibile esaminare le tendenze delle condizioni bentoniche variabili nelle regioni in cui erano presenti microbialiti. I dati di retro diffusione acustica sono stati usati per differenziare i depositi erosivi di sedimento molle dalle morfologie microbialitiche di fondo duro e valutare le condizioni di variabilità. Sono state quindi analizzate la distribuzione e le caratteristiche dei modelli di crescita, che hanno permesso di dedurre le caratteristiche degli habitat preferenziali. Queste mappe hanno consentito una migliore comprensione delle caratteristiche dell'habitat dei complessi di microbialiti a livello di paesaggio trovata in questi laghi. Inoltre, i dati prodotti aiutano a interpretare i modelli nella documentazione paleolimnologica, oltre alle condizioni di crescita e alle origini biologiche di queste strutture.

Parole chiave - microbialiti, indagini geoacustiche, sonar, Pavilion Lake, Canada

Introduction

Stromatolitic fossils date to 3500 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 stromatolite morphologies are abundant in strata deposited during the last billion years of the Proterozoic (Awramik, 1984). Through advances in lake bottom mapping it has been observed that modern microbialites thrive in freshwater lake environments, much like ancient stromatolites, which are believed to have thrived in similar environments. Previously collected data shows that a diverse community of living stromatolites are present within Pavilion Lake, BC, Canada (Laval *et al.*, 2000; Lim *et al.*, 2009). This work utilizes high-resolution geoacoustic data (collected in 2009 and 2010) in order to perform detailed morphological analysis of microbialite patterns in modern settings as evidenced from Pavilion Lake.

Due to advances in acoustic mapping and automated classification, it is possible to create high-resolution

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mapping products of lake bottom features that can be used to characterize bedform morphologies with high accuracy (Subramaniam, 1993; Preston 2009). 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 comprehensive assessment of the lake bottom. Using multiple software packages (e.g., MATLAB®, Fledermaus, ArcGIS, SonarWIZ) the sonar data was analyzed and the slope and rugosity were calculated and classified in a similar method used for coral reefs in the ocean (Williams *et al.*, 2010; Forrest *et al.*, 2012; Trembanis *et al.*, 2017). Similar to multibeam sonar systems which have been utilized to collect large amounts of information about seabed characteristics (Preston *et al.*, 2001), the sonar data collected for this study can be queried with respect to a self-similar classification structure or catalogue (Raineault *et al.*, 2012; Trembanis *et al.*, 2012) in addition to visualizing lakebed characteristics.

It has been speculated that physical factors such as depth and slope are important to the development of microbialite morphologies; however, this relationship remains largely uncharacterized (Andres and Reid 2006; Lim *et al.*, 2009). 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 improve the efficiency of subsequent manned exploration efforts. Pavilion Lake is an ideal location for just such a study due to the morphological diversity and richness that is unique in its level of documentation among modern microbialite systems (e.g., Lim *et al.*, 2009; Brady *et al.*, 2010).

This study utilized backscatter derived classification maps to reveal specific microbialite habitat conditions that reveal strong signs of microbialite biological activity. A GAVIA autonomous underwater vehicle was used to develop a map of Pavilion Lake using various sonar data products. This information was then analyzed to create a site-specific geoacoustic classification map. In conjunction with previously collected imagery, this classification map was queried with respect to the collected bathymetry data and a voluminous archive of HD video and still camera images in order to ground truth the acoustically derived bottom types. The local bathymetric environment (primarily depth and slope) of the various classes was described and results indicate that the microbialite features grow within specific slope (5-25°) and depth (20-30 m) thresholds.

Study area

Pavilion Lake is approximately 420 km northeast of Vancouver, in southern-central British Columbia, Canada. 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 along a northwest to southeast axis and is ~6 km in length. Pavilion Lake is a slightly basic (pH 8.4), freshwater lake. The maximum-recorded depth during this survey was 55 m, which differs slightly from previously reported value of approximately 60 m (Mullins *et al.*, 2007). The microbialites found within the lake range from centimeters to meters in height depending on the associated depth in the lake. In addition, morphologies of the microbialites vary widely in the lake (Laval *et al.*, 2000) and this diversity is the source of ongoing investigations (Lim *et al.*, 2009). Previous investigations including surface-based sonar and drop camera work (Mullins *et al.*, 2007) and submersible-based research has confirmed the extensive presence of microbialites at varying depth ranges, throughout Pavilion Lake (Forrest *et al.*, 2009; Lim *et al.*, 2010). 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.

Previous work

Research work at Pavilion Lake using DeepWorker submersibles and GAVIA Autonomous Underwater Vehicle (AUV) exploration platforms have provided a

Table 1. Autonomous Underwater Vehicle (AUV) mapping configuration sensor properties.

Sensor	Frequency (kHz)	Phenomenon
Side-scan Sonar	900/1500	Backscatter
Geoswath+	500	Bathymetry and Backscatter
Camera		Images
Inertial Navigation System (INS)		Position and Altitude

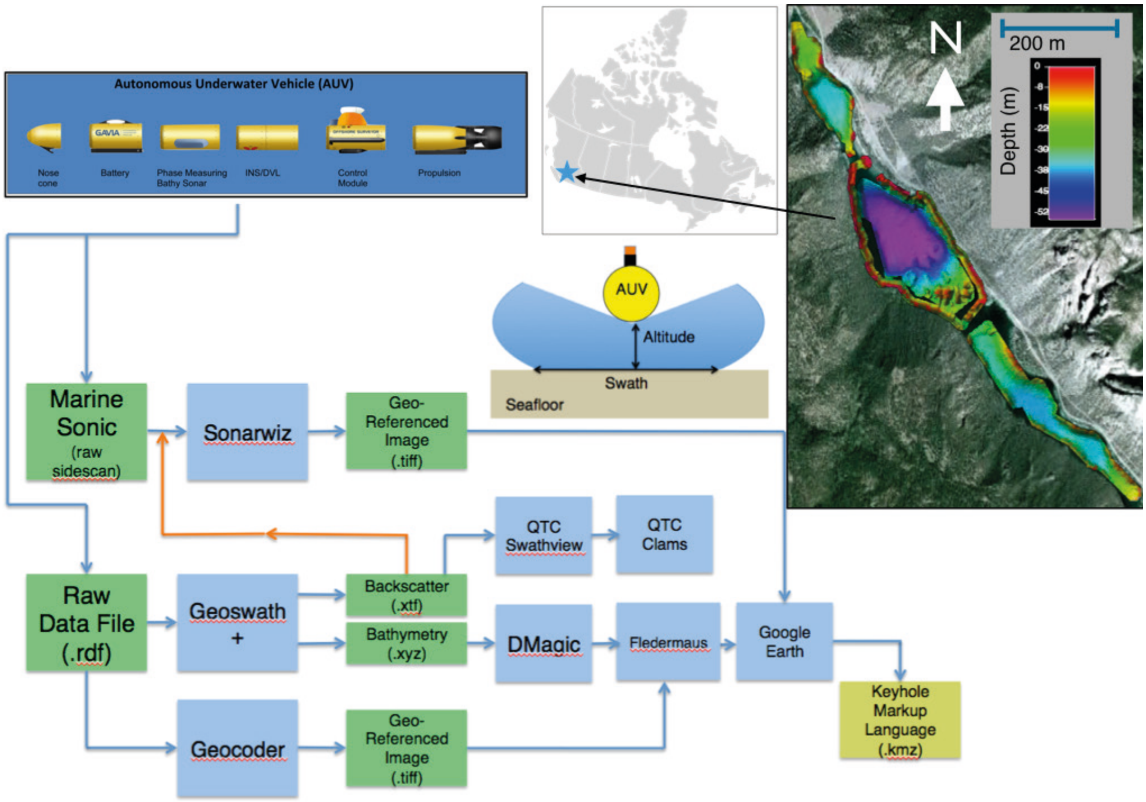

Figure 1. Site Map of Pavilion Lake (upper right) located in British Columbia Canada. Gavia AUV as configured for lake mapping (upper left) and workflow of geoacoustic data processing.

coordinate synoptic view of the lake bottom (Lim *et al.*, 2010). These results 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 the basis for this work, it was 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.

Preliminary sonar investigations at Pavilion Lake began in October 1998 and August 1999 with field work consisting of both boat mounted swath bathymetry sonar and towfish mounted sidescan sonar measurements. Although full coverage of the lake was not completed during these early measurements, microbialite features were visually identified in the acoustic backscatter data with accompanying confirmation through the use of drop cameras and scuba investigation. As sonar techniques were thus demonstrated to be a useful tool in the mapping of the lake and directing mission planning in for other sampling techniques, three additional sonar field measurements were undertaken in June and September of 2005 and September of 2006 (boat mounted swath bathymetry). Measurements taken in June 2005 yielded the discovery of microbialites at depths greater than 35m in the central basin of Pavilion Lake, however acoustic refraction from thermal stratification of the water column led to a geometry that was not conducive to mapping the whole lake. Sonar measurements taken in September 2005, 2006 were used to create preliminary backscatter maps to assist in the planning of subsequent Remotely Operated Vehicle, DeepWorker and AUV missions (Lim *et al.*, 2011; Mullins *et al.*, 2007).

Methods

The mapping efforts conducted within Pavilion Lake utilized a Geoswath sonar mounted on a Gavia autonomous underwater vehicle (Figure 1). The Gavia Autonomous Underwater Vehicle (AUV) is a modular person portable survey platform configured with geoacoustic sensors, a positioning system, and a color digital camera for seafloor or lakebed mapping (Tab. 1).

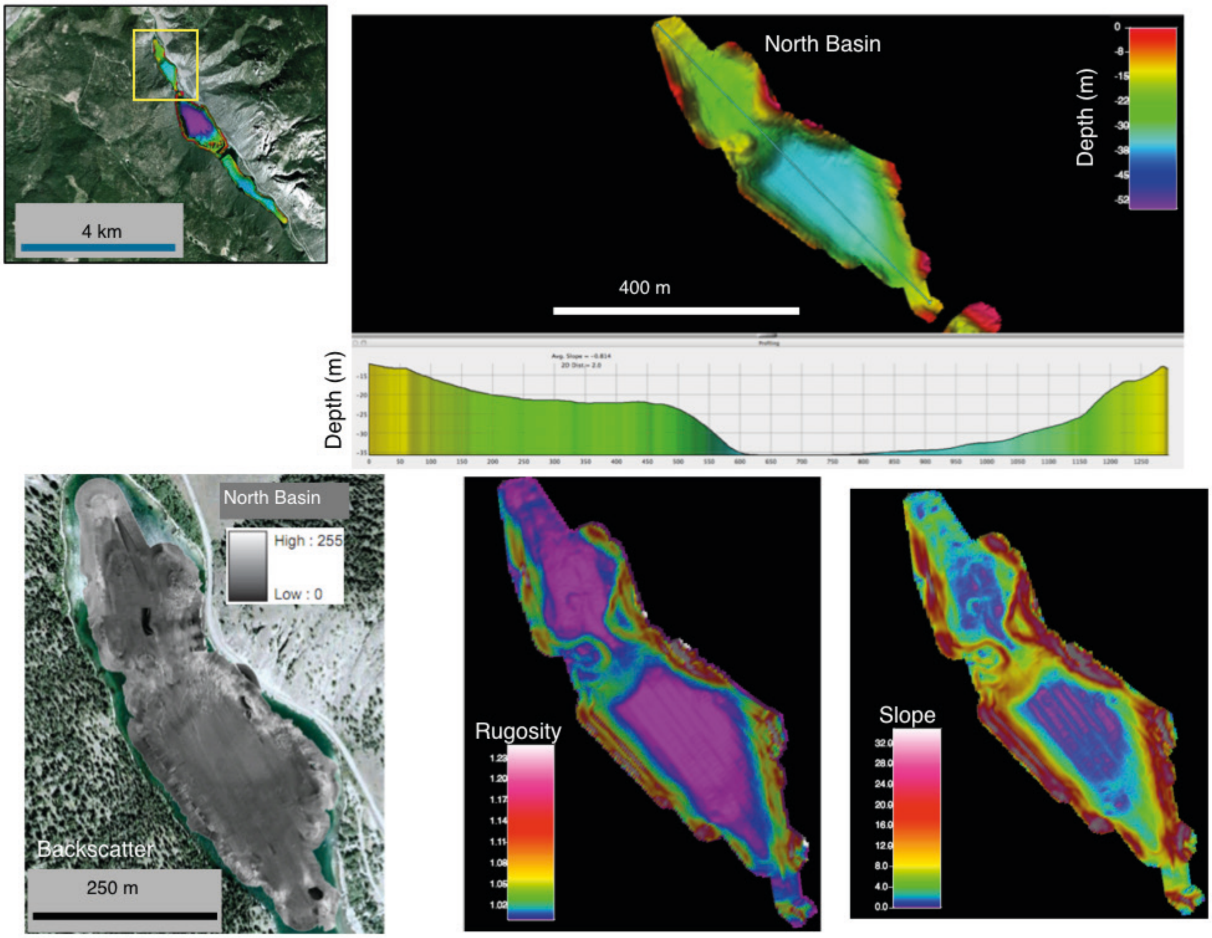

Figure 2. Geoacoustic mapping products compiled for the North Basin including: 5 m/pixel gridded bathyme-try (upper right), slope (lower right), rugosity (lower center), and 0.18 m/pixel scaled backscatter (lower left).

Data Collection

The Gavia AUV was capable of running missions by either following a set depth or keeping a constant altitude (i.e., height above bottom) above the lake-bed. Preliminary missions were run at a set depth to ensure vehicle safety. The data gathered during those missions was subsequently used to establish safe working altitudes for the vehicle to follow the lake bathymetry. The Gavia AUV allows for variable velocities to be selected during mission setup by directly controlling the propeller revolutionary rate. Experience based on trial and error produced optimal results for GeoSwath data gathering in Pavilion Lake of 600 rpm, which is equivalent to 1.5 m/s speed over ground. The three distinct basins of the lake made it possible to build design missions specific to each of basins and areas of the lake.

Data Analysis

DMagic™ was used to grid the bathymetric files (.xyz) that were processed using Geoswath Plus™ software. The ungridded .xyz files were loaded into a new project file created within DMagic™. Since 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 were loaded, the trackline of the survey was analyzed. By comparing the trackline to the set list of ungridded .xyz files it was 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

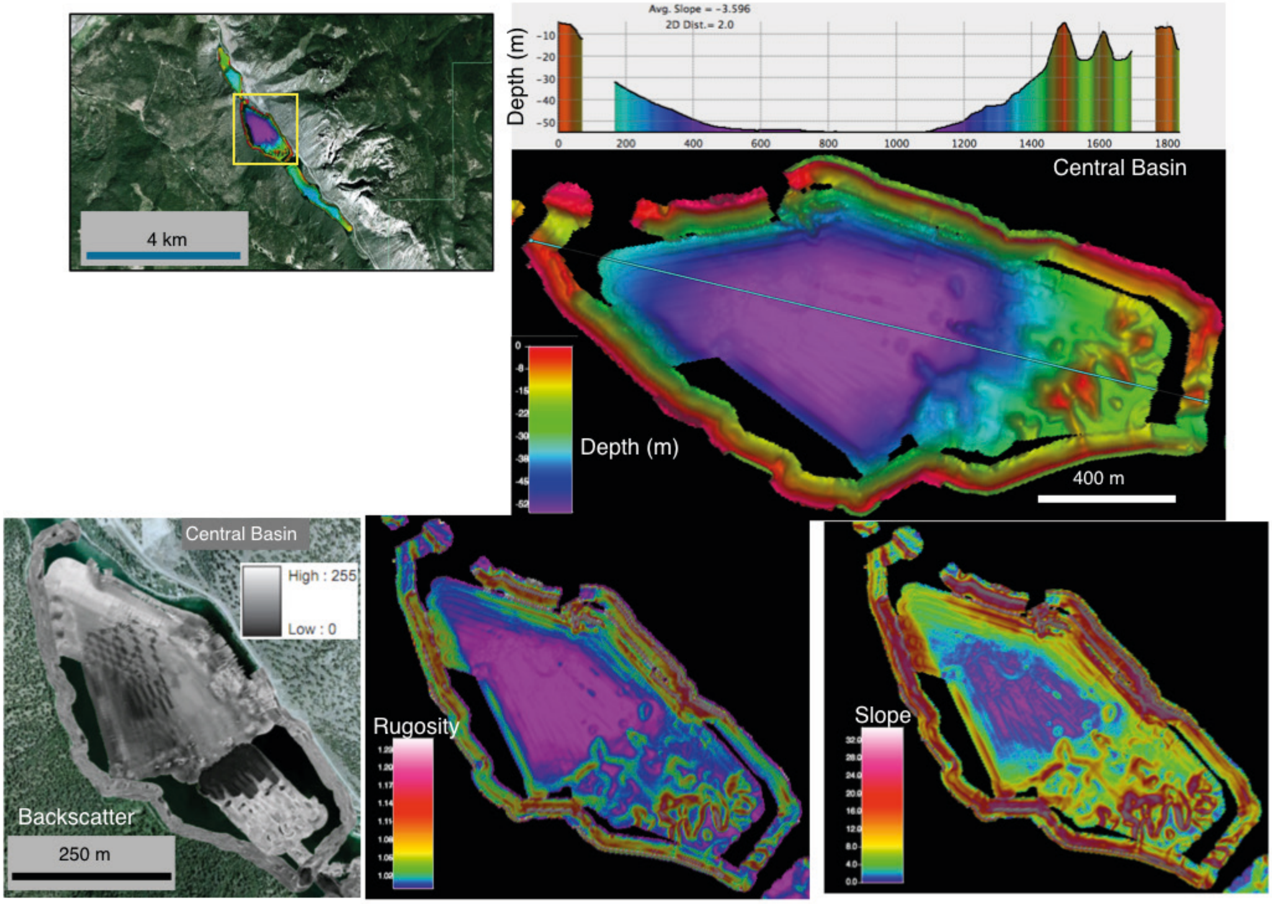

Figure 3. Geoacoustic mapping products compiled for the Central Basin including: 5 m/pixel gridded bathymetry (upper right), slope (lower right), rugosity (lower center), and 0.18 m/pixel scaled backscatter (lower left).

resolution. A combined 5 m grid size was chosen for the Pavilion Lake survey data in order to provide an overall map with reduced gaps. This resolution was determined to be fine enough to show the large-scale microbialite features. The highest resolution bathymetry and backscatter products of ~20 cm/pixel were retained and used for detailed analysis.

After the gridded data was compiled and had been viewed, analytical calculations were conducted on the data. First the slope characteristics of the entire lake were calculated; this calculation was completed after opening the gridded file in DMagic^{TM}. The slope calculation was completed and added as an additional to the scene, and was opened in Fledermaus^{TM}. DMagic^{TM} was used to calculate the slope using the "fitted plane" slope process. This 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 range the small-scale variations in slope could be better visualized and understood. In addition to the slope, the rugosity of the lake bottom was also calculated. Rugosity is calculated based on the work of Jenness (2004) and represents the ratio between the surface area surrounding a bathymetric cell and the planar area of each cell. The rugosity of the lake bottom quantifies vertical roughness of the submerged terrain. 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. More recently, Friedman *et al.*, 2012 have extended the approach and calculation of rugosity to very fine scale measurements utilizing stereo image reconstruction of the seafloor and a similar geometric approach as developed in Jenness (2004) with the added inclusion of aspect and the ability to project the rugosity estimates onto the aspect direction. Regardless of the approach the resulting measure of rugosity is a two-dimensional ration of the actual surface area to the projected surface and provides a unitless index of relative roughness of the terrain model. The resulting backscatter, depth, rugosity and slope data are displayed for the North Basin in Figure 2, the Central Basin in Figure 3, and the South Basin in Figure 4.

The acoustic backscatter data, originally processed using Geoswath Plus^{TM}, was then utilized by Quester Tangent Corporation (QTC) Swathview^{TM} and QTC Clams^{TM} to build a categorical map of the Pavilion Lake research area. QTC Swathview treats and analyzes the collected and processed backscatter information with similar methods to remote sensing data as shown in Figure 5.

QTC Swathview^{TM} 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^{TM} deduces an extensive matrix of backscatter data to a set classification map (Preston 2001). QTC Swathview^{TM} analyzes the backscatter image, correcting for angle bias, to create a classification map.

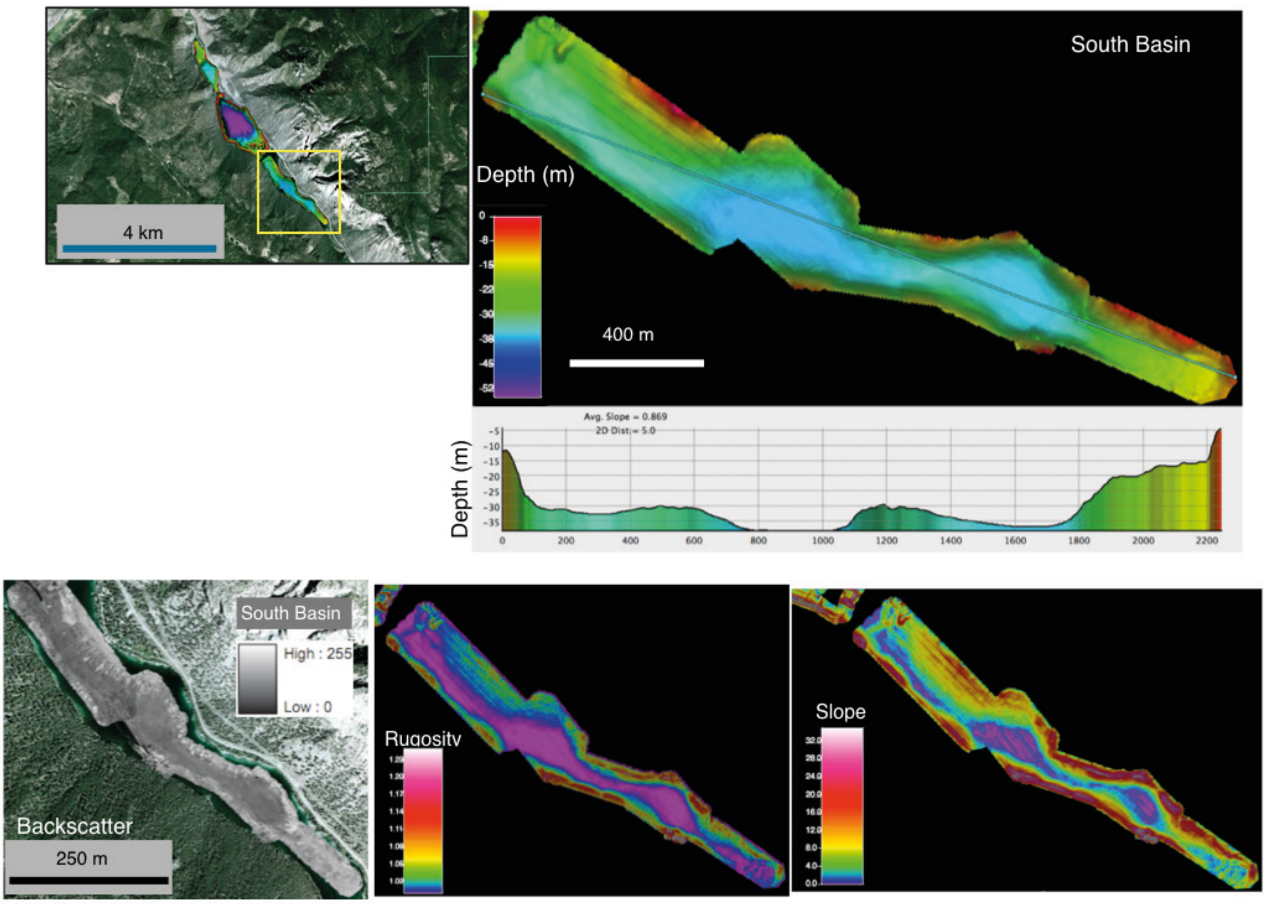

Figure 4. Geoacoustic mapping products compiled for the South Basin including: 5 m/pixel gridded bathymetry (upper right), slope (lower right), rugosity (lower center), and 0.18 m/pixel scaled backscatter (lower left).

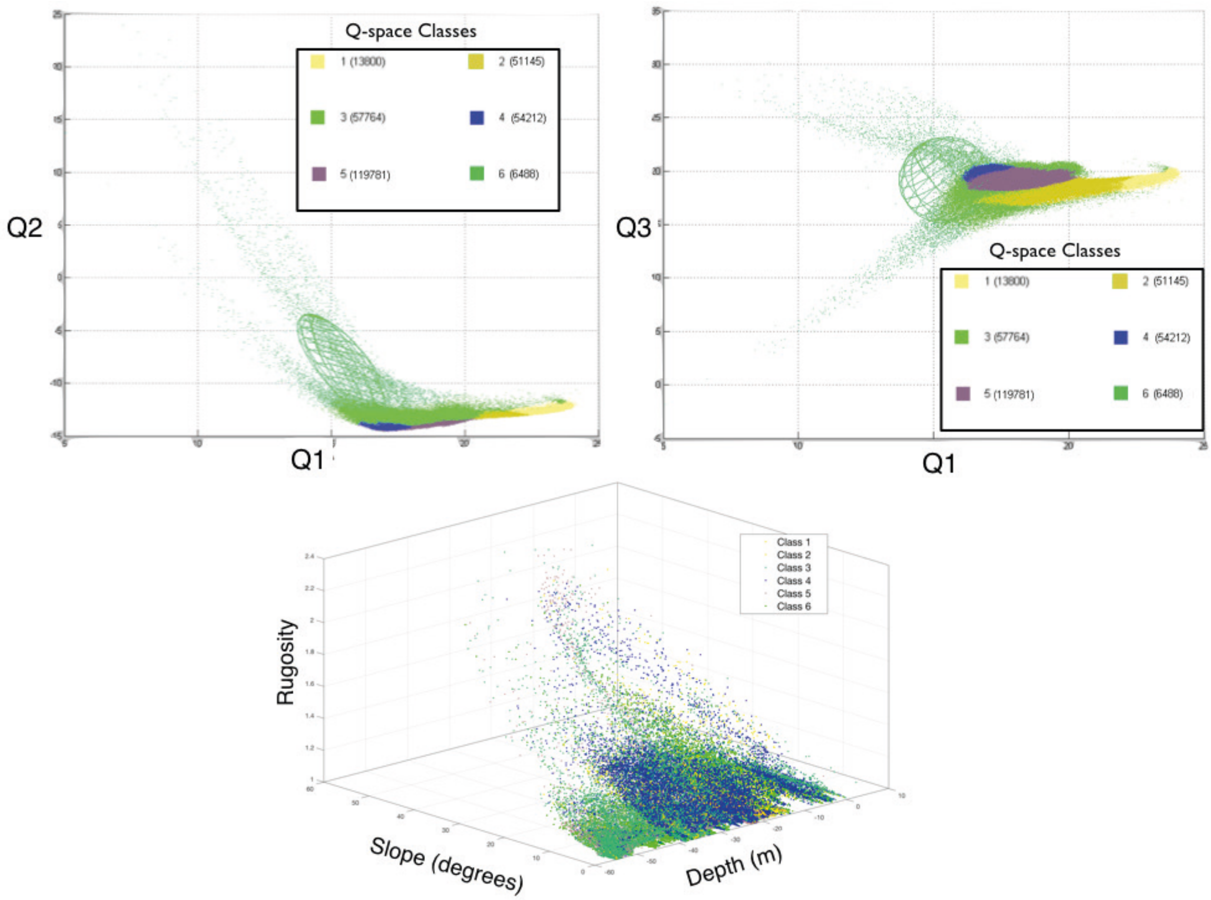

Figure 5. Principal component Q-Space view of multidimensional geoacoustic data analysis displaying components Q1 and Q2 (upper left) and components Q1 and Q3 (upper right). Distribution of each of the 6 class types in relation to depth, slope, and rugosity (lower panel).

Results

The shallow water slope characteristics of the lake highlight the steep walls of the lake's coastal features. Figures 2, 3 and 4 demonstrate the general slope trends of Pavilion Lake: a decrease in slope with depth (lower right subfigure in Figures 2, 3, and 4). This decrease in slope is characteristic of the bowl-like shape of the three lake basins.

Automated classification-QTC Swathview, QTC Clams

QTC Swathview™ and QTC Clams™ were used to produce the principal component vector classes (Figure 5 upper panel) and to then spatially portray these categorical classes as maps illustrated in Figure 6. To better highlight regions of the lake, the classification map was divided into the three primary lake basins (North, Central and South Basins). QTC Swathview™ and QTC Clams™ were utilized to produce a map that included six classifications of the collected backscatter. QTC Swathview uses the backscatter information to build a set of classes of the bottom types by grouping together similar acoustic backscatter image data using principal component analysis (Figure 5 upper panel). The number of classes can either be prescribed by the user based on *a priori* knowledge of the bottom type or determined by an an automated clustering process using a Simulated Annealing K-Means algorithm (Preston 2001). The 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 of classes (Preston, 2001). QTC Clams takes the categorical output of Swathview and interprets the points to a raster grid. The combination of Swathview (principal components and cluster analysis) and Clams (categorical gridding) allows for the backscatter image, correcting for angle bias, to produce a final categorical classification map (Figure 6). This automated ground discrimination and classification approach has been used successfully in a variety of other environmental settings from Delaware Bay (Raineault *et al.*, 2012) to coral reefs of Bonaire (Trembanis *et al.*, 2017) The resulting classification map displays variations in seafloor material and bottom-type. The color-scheme used for the classification was set to "scaled similarity" which selected similar colors to represent similar backscatter characteristics. Q-space vectors are based on the proprietary factors extracted from the sonar imagery withing QTC Swathview and are not directly relatable to physical properties such as depth, slope, and rugosity. A plot of Q-space derived classes relative to morphologic parameters or depth, slope, and rugosity did not reveal any clear discernable patterns (Figure 5 lower panel). Further analysis and sampling of the lake bed classes could be conducted to determine what physical parameters are responsible for the similarity and dissimilarity between classes such as organic matter content or chemical composition. Next, MATLAB® was used to visualize the distribution of the principal component vector classes throughout the lake (Figure 5).

Figure 6 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 available for the Bright Green, Class 6 as this represented acoustic noise in the water column (Figure 6). 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, and no DeepWorker missions surveyed this area.

Geoacoustic classification images

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.

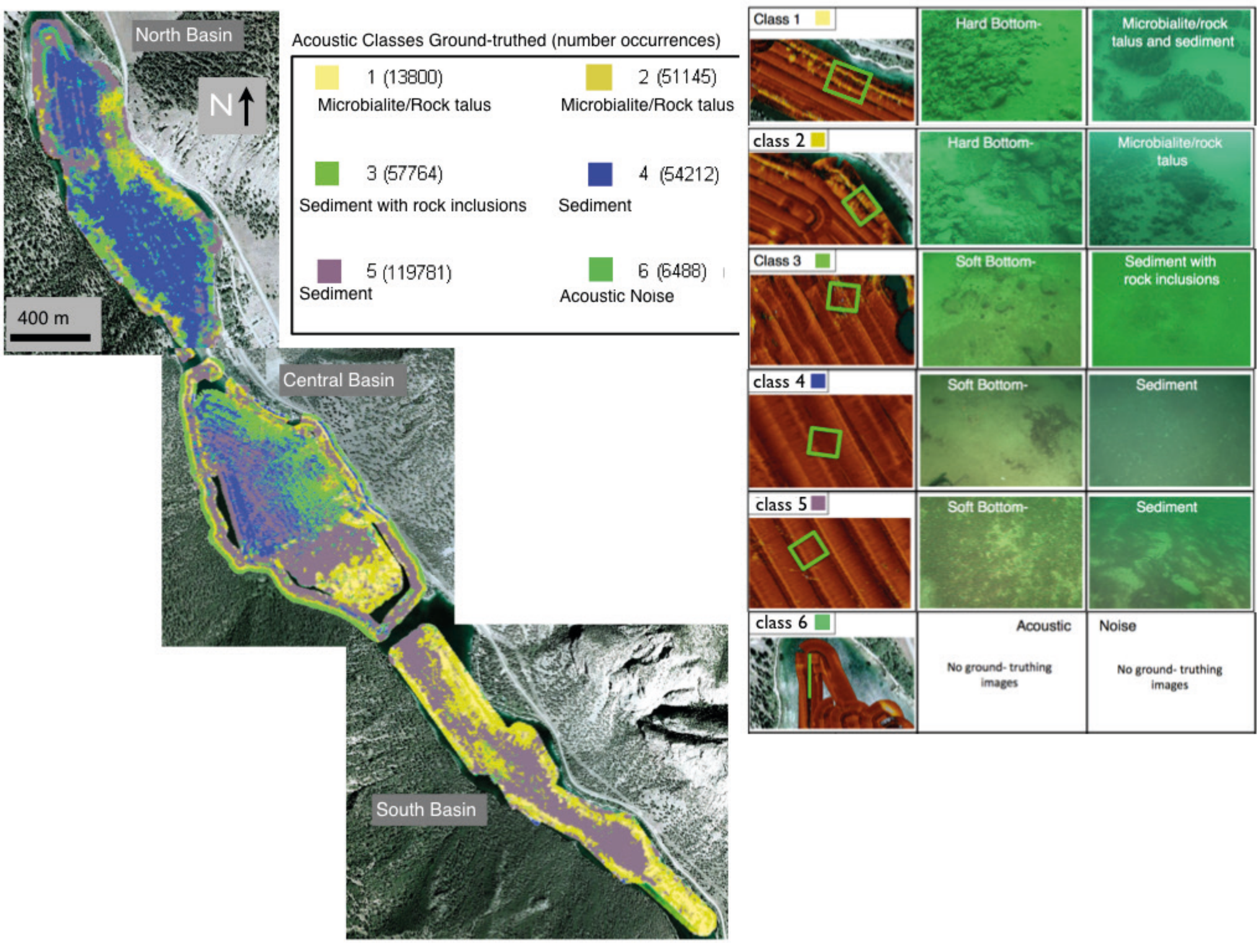

Figure 6. QTC automated backscatter classification map of Pavilion Lake (left panel). A side-scan sonar image of each classification, along with the color. Ground-truthing images collected with the DeepWorker submersible (right panel).

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 two (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 two 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 two.

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 60 m, are where classification three is most prevalent.

Classification Four (Blue, Soft Bottom-Sediment)

Classification four (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 four 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 four continued to decrease with depth. In the range of 10 m to 20 m depth classification four 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 five (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 five rose slightly. Classes Four and Five both represent soft bottom sediment cover and are virtually indistinguishable based on the DeepWorker camera images but were registered as acoustically unique based on the principal component cluster analysis (Figure 5). Further investigation into the lake sediments should aim to determine if there is a compositional perhaps gas or organic matter inclusions that set these two classes apart acoustically.

Classification Six (Bright Green, Noise Pings)

The location of the majority of classification six 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 six.

Geoacoustic signatures

The biosignatures observed within nodules collected from the surface of Pavilion Lake microbialites display a photosynthetic influence (Brady et. al. 2010). 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 computer and are displayed in Figure 7. 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 th e microbialite structures present in Pavilion Lake formed utilizing photosynthetic means. 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 shallower areas of the lake, generally less than 10 m. 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, reducing the available light for microbialite productivity.

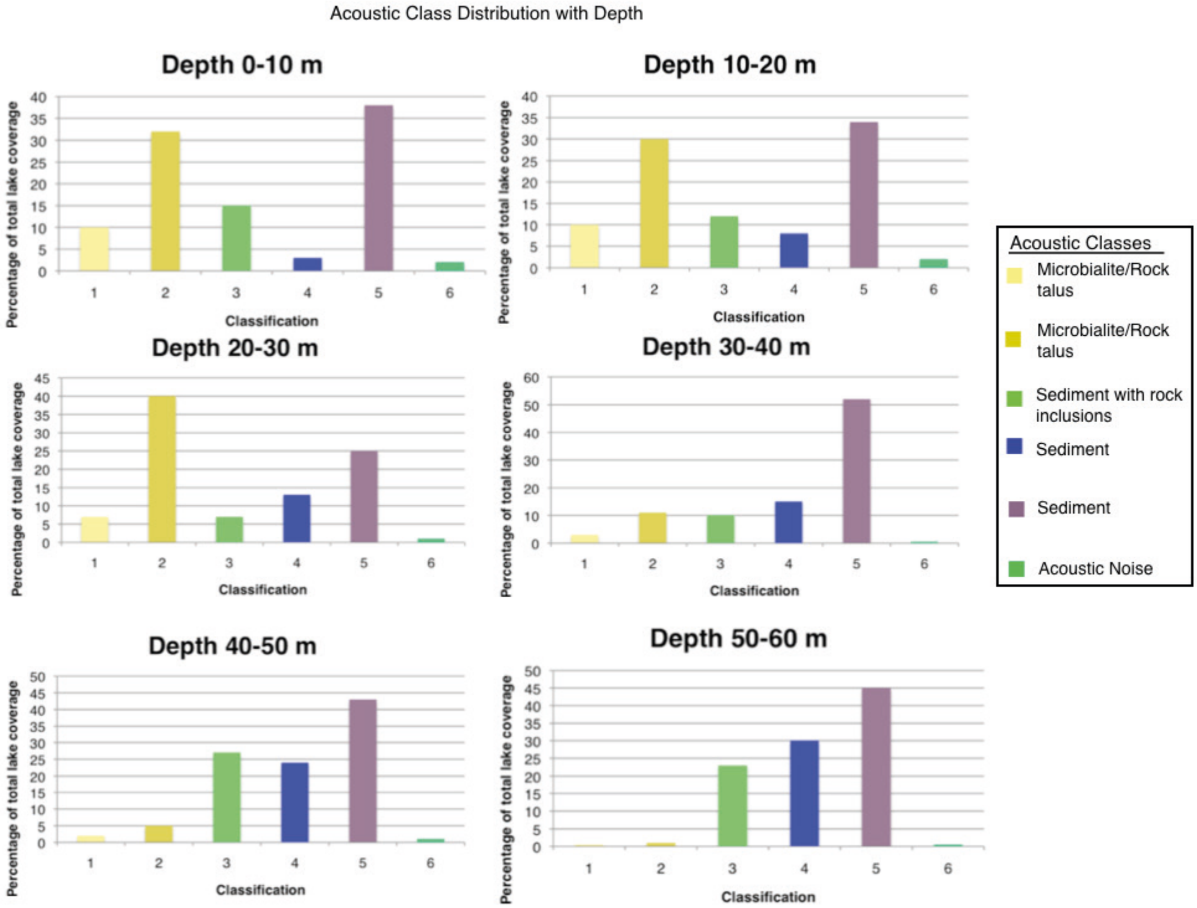

Figure 7. Distribution plots showing the percentage cover of the lake bed for each of the acoustically derived (ground truth confirmed) class types within 10 m depth intervals from the surface (upper left) to the maximum depth of the lake (lower right).

The preferential growth environment for microbialites within Pavilion Lake strengthens the hypothesis of Lim *et al.* (2009) that the microbialites are of biological origin. 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, reinforce the hypothesis that the microbialite structures are of 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 Figure 8 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, and increase the change of an erosional episode. The slope preference discovered may be due to both physiological characteristics of the microbialites and the structural characteristics of the lake.

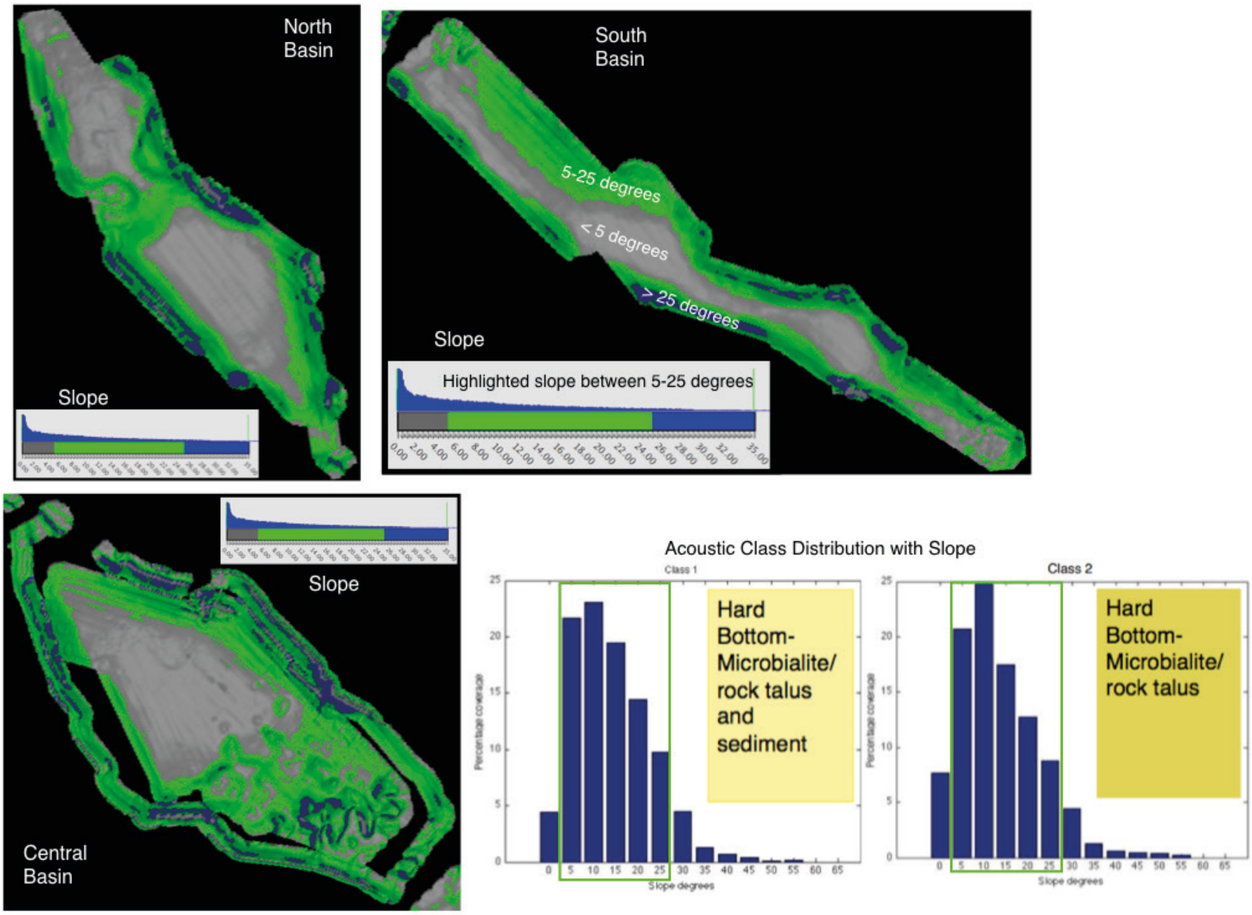

Figure 8. North Basin, Central Basin, and South Basin slope 5-25° highlighted green. The blue area is slope greater than 25°, and the gray area is slope less than 5°.

The plot of slope (Figure 8, lower right) for classes one and two are very similar. Both of the classess 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. Tab. 2 shows 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. 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 2. Classification prevalence between 5-25° slope.

Classification	Bottom Type	Percentage Present (Slope 5-25°)
1	Hard Bottom-Microbialite/ rock talus and sediment	**88.40%**
2	Hard Bottom-Microbialite/ Rock talus	**84.70%**
3	Soft Bottom-Sediment with rock inclusions	67.50%
4	Soft Bottom-Sediment	47.70%
5	Soft Bottom-Sediment	64.90%
6	Acoustic Noise	77.80%

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 two (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 6, 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. The high-resolution photos collected by the DeepWorker allow for the classified areas to be differentiated. 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.

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. Using Autonomous Underwater Vehicles (AUVs) as exploration platforms to conduct surveys of the lake bottom, very high-resolution sonar data was and analyzed. This success is also partly due to the extensive backlog of mission photographs collected by the DeepWorker submersible for a means of ground-truthing. By analyzing the dense phase measuring bathymetric sonar of the lake bottom, with respect to slope and rugosity, it was possible to map the morphological trends of the stromatolites. The bathymetric data was compiled to create a base map of the floor of Pavilion Lake. This data is gridded at a very high resolution, 25cm. The bathymetry data allowed analysis of bed forms within Pavilion Lake, as well as any erosional episodes that may affect the growth of microbialites. Backscatter data was also collected and processed. The backscatter data shows the strength of the sonar return, and in turn the density of the base material. The backscatter data allows the researcher to differentiate between soft sediment erosional deposits and hard bottom microbialite morphologies. The combination of backscatter and bathymetry allows for a further understanding of bedforms and microbialite growth patterns. A key finding from this investigation is that the majority of the areas within Pavilion Lake, which are rich in microbialite growth, are found within a slope ranging between 5 and 25° and range in depth from 0-30 m.

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