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BATHYMETRIC MAPPING AND SONAR IMAGING OF TUFA AT GREEN LAKES: FAYETTEVILLE, NEW YORK

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ABSTRACT

The Fayetteville Green Lakes State Park, located in Fayetteville, New York, consists of two deep (48 m+), meromictic (non-mixing) lakes with unique limnological, bacterial, and chemical characteristics. These lakes, named Round Lake and its larger companion Green Lake, have been extensively studied for nearly 200 years because of their unique character. The lake water contains two distinct layers, the oxygen-rich mixolimnion and the anoxic monimolimnion divided by the chemocline (a chemical compositional boundary). Tufa deposits exist along the shorelines of both lakes at various depths and are a product of groundwater discharge into the lakes, as well as the lakes' unique water chemistry and microbial communities. Here, we use sonar imaging techniques to produce updated bathymetric maps of Green and Round Lake, and provide the first detailed characterization of the nearshore environment using side-scanning sonar imagery to determine the locations and morphologies of tufa deposits. We also document shoreline debris specifically large tree trunks and branches which have fallen into the lake over time and are frequently encrusted. We identified fourteen locations of tufa ranging from large formations (10s of meters long) to small tufa heads (~1 m) in Green Lake. Our updated bathymetry and documentation of tufa locations and geometry expand the extensive history of prior work, will aid future investigators by revealing lesser-known tufa localities, and will assist the Fayetteville Green Lakes State Park with monitoring and conservation efforts for this ecologically unique area.

INTRODUCTION

The Fayetteville Green Lakes State Park, located in Fayetteville, NY, contains two lakes: Green Lake and Round Lake. The unique basin geometry, water chemistry and microbial communities at Green Lake have attracted extensive study dating back to at least Vanuxem (1839). Since that time many investigations have focused on different aspects of this complex lake system's geology, formation, and limnology (e.g., Eggleton, 1931, 1956; Muller, 1967; Eggleston and Dean, 1976; Ludlam, 1984; Thompson et al., 1990; Hilfinger and Mullins, 1997; Hilfinger et al., 2001; Wilhelm and Hewson, 2012; Havig et al., 2015; Havig et al., 2018; Uveges et al., 2018; DeMott et al., 2020; Block et al., 2021). Green Lake and Round Lake are meromictic (the layers of water within them do not mix or overturn). Both lakes are located in the Lake Ontario watershed and are connected such that Green Lake receives surface water from Round Lake (Brunskill and Ludlam, 1969). Groundwater, rich in dissolved solids (such as calcium, magnesium, and sulfate) feeds the lakes (e.g., Thompson et al., 1990). These dissolved solids contribute to the permanent meromictic nature of the lakes, as well as to the distinctive blue-green color, which is created by the dissolved solids dispersing sunlight within the water (Hilfinger and Mullins, 1997). The calcium solids precipitate as calcite sometimes in spectacular whiting events (Thomson et al., 1997). Tufa (accretion of calcite by thrombolitic microbialites) form in some locations along the lakeshores of both lakes (e.g., Brunskill and Ludlam, 1969; Thompson et al., 1990) and result from accretion by cyanobacterial photosynthesis driving calcite supersaturation (Thomson et al., 1997; Wilhelm and Hewson, 2012; Uveges et al., 2018). All these characteristics make the Fayetteville Green Lakes a long-lasting curiosity and a remarkable location for research.

Here we: 1) present an updated bathymetric map of Green Lake and Round Lake using down-looking and side-scanning sonar mapping. Bathymetric maps of the Fayetteville Green Lakes exist from prior work conducted in the 1960s, but a new bathymetric survey using sonar provides a high data density survey. 2) identify the locations and morphologies of the tufa deposits using sonar imagery. The side-scanning sonar imagery provides detailed images of shoreline morphology including a new way to identify and characterize tufa formations. Comparison of the two datasets allows us to place depth constraints on the various locations of tufa formation. This work complements the rich history of study at Green and Round Lake.

BACKGROUND: FAYETTEVILLE GREEN LAKES FORMATION HISTORY AND LIMNOLOGY

The formation history of the Fayetteville Green Lakes is complex (e.g., Thompson et al., 1990 and references therein). Early on, the formation of Round and Green Lake was attributed to sinkholes but even at that time, researchers recognized differences in basin geometry from other sinkholes in karst regions (Quereau, 1897) and pondered a glacial origin (Miner, 1933; Eggleton, 1956). The development of detailed geomorphic studies regionally and locally led to the conclusion that the Fayetteville Green Lakes were most likely related to glaciation (Gilbert, 1899; Miner, 1933; Coon, 1960; Sissons, 1960; Muller, 1967). During the retreat of the Laurentide Ice Sheet (LIS) from the Syracuse area about 13,000-15,000 years ago (Hilfinger and Mullins, 1997), the orientation of valleys and regional topography caused water to flow towards the ice margin creating ice dammed lakes in lower topography areas. As the LIS continued to retreat, locations of successively lower topography were exposed, creating spillways for meltwater to flow

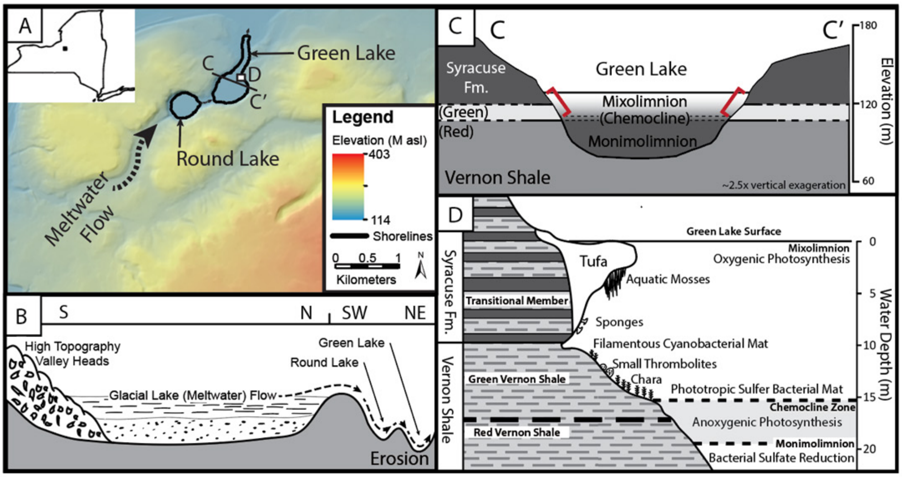

Figure 1. Location, formation history, geology, and limnology of the Fayetteville Green Lakes. (A) The Fayetteville Green Lakes are located in Fayetteville, NY. The hillshaded digital elevation model of the Fayetteville Green Lakes (U.S. Geological Survey. 1995) shows the locations of Round Lake and Green Lake (outlined in black) and the dotted arrows indicates the hypothesized meltwater spillway, associated with LIS retreat. In modern times, the lake outflow drains from south to north, from Round Lake to Green Lake and on to the Lake Ontario watershed. Transect C to C' corresponds with panel C and box D corresponds with panel D. (B) Sketch describing the relationship between ice retreat, meltwater routing and formation of the Fayetteville Green Lakes basins as part of a spillway (Wellner et al., 1996; Hilfinger et al., 2001). As ice retreated, the Fayetteville Green Lakes spillway was exposed allowing meltwater to drain. Note: the cross section shifts direction from south to north and then from southwest to northeast (along the spillway axis). (C) General geologic setting and limnology of Green Lake (Hilfinger and Mullins, 1997) brackets on each shoreline at the mixolimnion indicate tufa forming locations. (D) Profile of Deadman's Point describing the stratigraphy and limnology (Thompson et al., 1990). Note: tufa deposits are limited to the upper 15 m in the water column, above the chemocline. It is near the contact between the Syracuse Formation and the Vernon Shale (~18 m depth) and above the monimolimnion (near 20 m depth) (Havig et al., 2015; Havig et al., 2018). Below this depth, tufa depositing microbialite communities are restricted (Thompson et al., 1990).

from one valley to another (Miner, 1933). Regionally, this shifting mosaic of spillway channels is known as the Syracuse channels (Hand and Muller, 1972; Hand, 1978). The Fayetteville Green Lakes are located within one of these spillway channels. The lake basins developed as meltwater spilled over the caprock of the Middle Dolomite member of the Syracuse Formation and excavated the Lower Syracuse Formation and Vernon Shale below, forming the modern basin (Muller, 1967). The basins may have developed because of multiple episodes of cutting, infilling and re-excavation over several glacial epochs (Hand, 1978). Thus, Green Lake and Round Lake are both hypothesized to be remnants of glacial meltwater plunge pools which penetrate several geologic units (Fig. 1). The spilling meltwater would have flowed out to the southeast, entering the Mohawk Valley and Hudson River watershed. Ultimately, ice retreat would be sufficient to allow drainage in the modern direction, northwest through the Lake Ontario basin and out the St. Lawrence spillway.

The limnological conditions at Green Lakes are rare, and as such, they have been the subject of numerous paleoclimatic and limnological studies. The modern catchment area is small, only about 4.33 square kilometers. Bathymetry of the Green Lake basin was originally compiled by Eggleton (1956) and modified by Ludlam (1969). The lakes penetrate the Syracuse Formation and the green and red Vernon Shale Formations (Muller, 1967; Thompson et al., 1990). Vanuxem (1839) identified that the contact between the Syracuse Formation and Vernon Shale occurred within the lake (Fig. 1), likely contributing to the lakes' unique chemical characteristics (Thompson et al., 1990). These subsurface geologic strata bear significant amounts of gypsum (Thompson et al., 1990). As the groundwater percolates through these formations, it becomes enriched with calcium, magnesium and sulfate. Groundwater discharges into Green Lake at stratigraphic boundaries located ~10 m and ~18 m below the lakes' surfaces (Brunskill and Ludlam, 1969; Brunskill, 1969; Thompson et al., 1990). The deep and narrow basin geometry, coupled with groundwater input to the lakes, have resulted in a stratified water column where the lake waters do not vertically mix, classifying these lakes as meromictic. Mixing only occurs in the mixolimnion, the upper ~15 m of their water columns, where the lakes undergo a seasonal turnover. Below ~15 - 21 m, a sharp and persistent chemocline (chemical compositional boundary) exists and divides the oxic (oxygenated waters) and euxinic (anoxic and sulfidic waters) zones (Culver and Brunskill, 1969; Hilfinger and Mullins, 1997; Havig et al., 2015). This chemocline appears to have remained relatively unaltered for centuries, since it was documented in one of the first studies at the Fayetteville Green Lakes by Vanuxem (1839) (Thompson et al., 1990). The bottom-most layer in the water column is the monimolimnion (the lowermost, dense layer of water), which occurs at 21 – 52+ m (bottom of the lake). It is anoxic, cold, dense, concentrated in sulfide, and experiences minimal circulation especially when compared to the shallower, oxygen-rich mixolimnion (Thompson et al., 1990). Sediment cores from Green Lake show the deep quiescent waters have contributed to the deposition of laminated and varved sediments (Hilfinger et al., 2001) with intermittent massive deposits that result from slumps of sediment off the steeply sloped lake walls (Ludlam, 1974) and/or flood deposits (Hilfinger and Mullins, 1997).

Groundwater inputs have created a unique water chemistry which has defined the limnological characteristics as well as the color of the lakes. Throughout the water column, pH values are neutral or basic ~7.2-8.0 (Hilfinger and Mullins, 1997). The waters are supersaturated with respect to calcium carbonate, (Brunskill and Ludlam, 1969). The suspended calcite concentrations within Green Lake, specifically, vary throughout an annual cycle. Secchi disk readings showed that in the months of May, June and July, water clarity is minimal within the mixolimnion (Thomson et al., 1997). Secchi disk readings drop from 18 to 4.5 m over the course of these three months. July is the most turbid and water clarity increases through the fall, winter, and early spring (Thomson et al., 1997). Green Lake has a distinctive green color which results from dispersed sunlight interacting with dissolved solids (Thomson et al., 1997).

The limnological conditions have resulted in the formation of microbialite communities, some of which help to mediate tufa formation (e.g., Eggleston and Dean, 1976; Thompson et al., 1990; Hilfinger and Mullins, 1997; Thomson et al., 1997; Havig et al., 2015; Havig et al., 2018; Uveges et al., 2018; DeMott et al., 2020; Block et al., 2021). Tufa deposits exist in both Round Lake and Green Lake. It is hypothesized that they are located proximal to sites of groundwater discharge, which largely occur at various depths along the lake shorelines near geologic contacts (Thomson et al., 1997). These tufa deposits are thrombolitic microbialite structures, composed mainly of calcite accreted during cyanobacterial photosynthesis (Thompson et al., 1990; Wilhelm and Hewson, 2012; Uveges et al., 2018). The tufa deposits run from

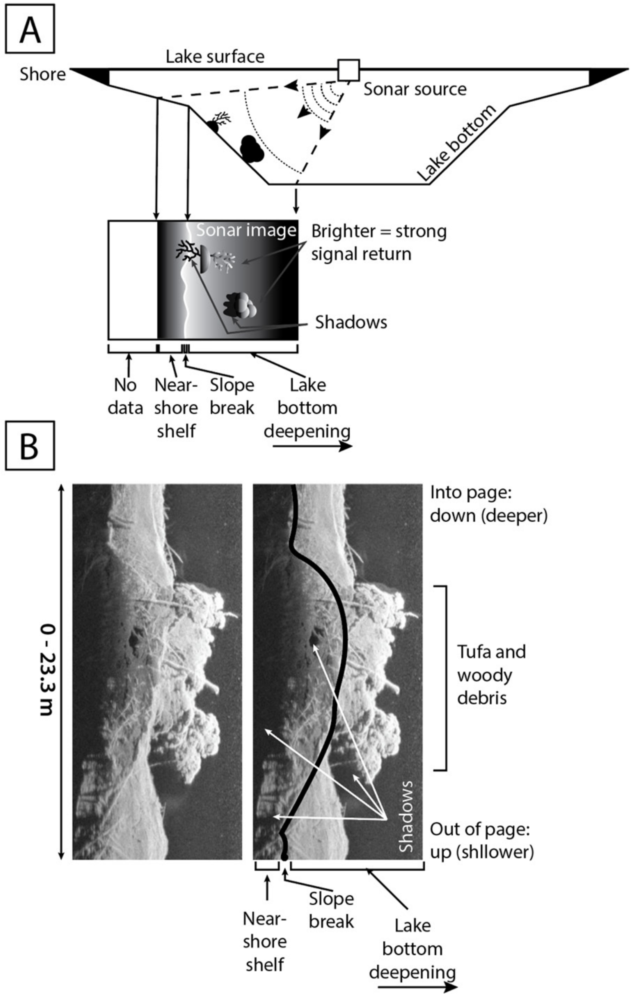

Figure. 2. Sonar geometry relative to shore and resulting imagery. (A) We used side-scan sonar to compile imagery for the nearshore environment. The sonar signal radiates outward from the sonar source and is reflected to the receiver. The strength and timing of the return is a function of the material properties of the substrate and distance. These data are compiled into an image. Hard prominent surfaces are bright (light gray to white) and softer or more distant surfaces are dark (gray to black). Since the signal originates from a single source and receiver, protruding objects can cause shadows. In the imagery there was commonly: 1) a region of no imagery because the sonar is located below the lake's surface, 2) limited imagery of the very shallow near shore environment because of the low angle of the sonar signal and shadowing effects of materials on the lake bottom, 3) a prominent image of the slope break, which is often brightly reflected, and 4) many features on the sloping lake bottom. The imagery on the sloping lake bottom is gradational in reflectance. It is brighter in the shallower water and darker with depth (a result of signal attenuation) and features (structures) on the lake bottom are discernible based on relative differences in reflectivity. In the lee of protruding objects, shadows are common. (B) Example of imagery collected from site F (see below and Fig. 3) with interpretations annotated as in (A). Tufa and woody debris are prominently protruding into the deepening water (deepening to the right). On the left, the nearshore is mostly shadowed and the slope break is brightly

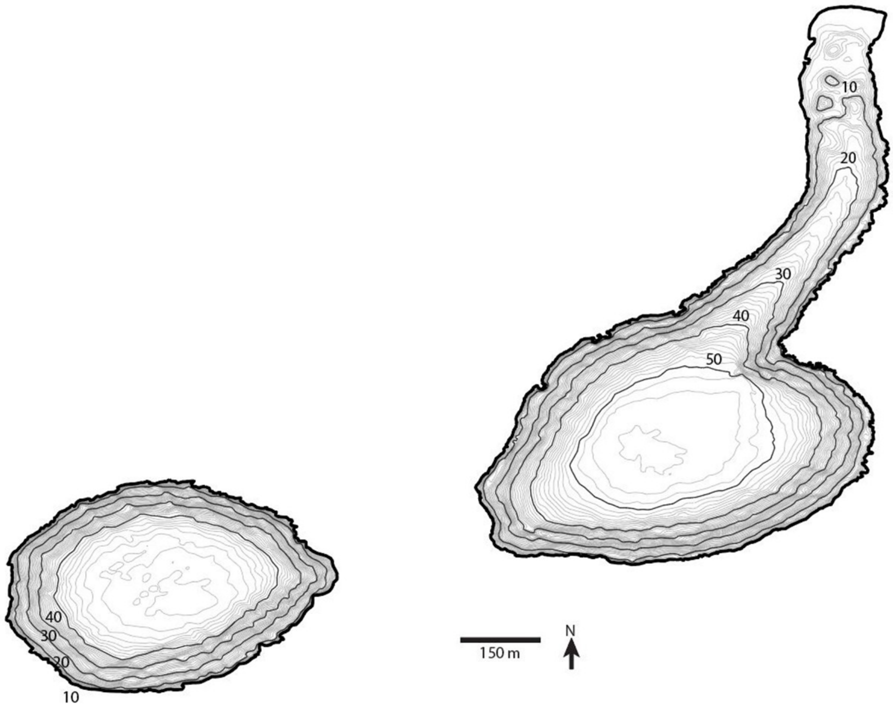

Figure 3. Bathymetry of Round Lake and Green Lake. Major (10 m) and minor (1 m) contours are indicated. Round Lake and Green Lake are ~ 48 m and ~ 53 m deep respectively.

meters to tens of meters in length. One of the largest sites is "Dead Man's Point" (Fig. 1). Thompson et al., 1990 suggested that the south-west facing aspect of this site received significant sunlight compared to other locations on the shoreline and therefore, that photoautotrophic organisms played a significant role in tufa formation. Visual observations of the Dead Man's Point tufa location indicate the formation is ~10 m thick and protrudes into the lake, forming a ledge (Thompson et al., 1990). Underneath the ledge, aquatic mosses and freshwater sponges thrive in alcoves. The contact between the Syracuse Formation and Vernon Shale (Fig. 1) occurs about 9-10 m depth at the base of the tufa. These observations inform the hypothesis that groundwater injects into the lake at this contact. Smaller microbialite formations were also discovered at deeper depths with less sunlight exposure. These deposits tend to form on harder substrates such as tree branches and rocks around 14-15 m in depth (Thompson et al., 1990), and all of these complex communities were documented above the chemocline. We have built on these prior investigations by creating higher-resolution bathymetric maps of both Round and Green Lakes using sonar technology. Known tufa sites have been located and mapped in the two lakes, and several more have been discovered. Maps such as this are critical not only for the study presented here but will assist with other paleolimnological studies of the lakes. Furthermore, updated maps and data will help Green Lakes State Park in maintaining this unique and protected natural area.

METHODS

Data Collection

Sonar data was collected during the summer and fall of 2019 and 2020 using a Humminbird SOLIX 12 CHIRP MEGA SI + G2 with frequencies of 5/83/200/455/800 kHz & 1.2 MHz. During each data collection period, the transducer was placed beneath the water behind the boat at a set depth of 0.43 meters and was leveled in all directions to ensure accuracy between data collection periods. Daily water level fluctuations between collection periods were accounted for by measuring the lake water level relative to a fixed benchmark (an outflow drain located on the northern tip of Green Lake). A fixed benchmark was not required within Round Lake as data collection was completed in a day's time. During data collection, rocking of the boat was minimized by limiting movement within the boat, and a consistent speed over water of about 2.4 km/h was maintained in order to help minimize signal distortions. The waters of both lakes are generally calm, and wave action was minimal at the time of data collection. The data collection track was planned to provide comprehensive coverage of the lake. Track patterns consisted of: 1) a grid pattern of tracks along the long and short axis of the lakes, which provided a dense and evenly distributed data coverage. 2) Several tracks around the perimeter of each lake in alternating clockwise and counterclockwise directions, which ensured sonar coverage along the shorelines and reduced shadow effects. This was important for the identification and documentation of the tufa deposits. 3) Tracks in an inward spiral were collected to help tie the bathymetric data together, provide sonar imagery at a range of angles and depths, and help gather additional data in locations of rapid bathymetric change. Together, our data collection strategy allowed for capture of enough depth measurements to map locations of rapid change and reduce imagery and contouring edge effects from tracks that ran perpendicular to shore. The data collection scheme was applied to both lakes.

Data Processing

Sonar data was processed and analyzed using Reefmaster software. This software also allowed for correction of lake surface elevation changes and returns, which was necessary to determine accurate depth measurements of the lakes. Small inconsistencies within the sonar data are common because of many determinants. Anytime the sonar signal interacts with an object with substantial density greater than that of water (i.e., plants, woody debris, tufa, rocks and fish), the signal is reflected back to the sonar transducer (Fig. 2). The system then calculates the precise location where the signal was echoed back by measuring the 2-way travel time for the signal to travel out and back to the transducer-microphone. The software calculates depth by choosing reflectors at or near the perceived sediment water interface. In some cases, "false" depths are selected because of differences in sediment density or where there is a significant amount of vegetation or woody debris. "False" depths were manually corrected in the first step of data processing by checking the software interpreted depth choices against our own interpretations and placing them within the context of their immediate surrounding depths. Using the corrected data, bathymetric maps of each lake were generated. The data were interpolated using a triangulated irregular network (TIN) and default smoothing. The Reefmaster Bottom Composition Module was also used to calculate the relative hardness and roughness of the lake bottom. The software examines various depth positions from returned pings and echoes to provide information about bottom hardness and roughness. The strength of the peak (first) sonar return indicates the lake bottom (Peak SV, highly correlated with bottom hardness). Subsequent returns (E1) immediately following the peak return provide an indication of bottom roughness and are also correlated with bottom hardness. The second echo return is also used as an indicator of bottom hardness. The software generates individual maps and a composite map indicative of relative bottom hardness.

The side-scan sonar data was processed using Sonar TRX. Speed, angle and noise corrections were applied to remove geometric distortions from changes in the sonar angle, boat speed and signal artifacts. The resulting noise-reduced shoreline imagery was transformed into mosaic images that were imported into Google Earth and ArcGIS for visual interpretation. After processing the sonar imagery, a known tufa location (i.e., Deadman's Point) was used as a training set to visually search the shoreline imagery for objects with similar tufa morphologies (see below). In some instances, it was possible to verify tufa localities visually in the field and using remote imagery (see below).

RESULTS

Bathymetry and Bottom Hardness

Sonar data was compiled to create bathymetric maps of Round Lake and Green Lake (Fig. 3). Round Lake is ~ 350 m in diameter, has a surface area of ~ 0.13 km^2, and the maximum water depth detected was 48.63 m. The lake is flanked on its north and south shores by hillslopes which taper into the lake, and limit the drainage basin area. The lake basin is bowl shaped with evenly spaced contours and a relatively flat bottom. While the lake is called Round Lake, it is more accurately slightly ovular, with the long axis oriented near East-West aligned with the long axis of Green Lake. Outflow from Round Lake consists of a small channel, which flows about 450 m from the southeastern shore of Round Lake to the southwestern shore of Green Lake (Fig. 1).

The geometry of Green Lake is more complex than Round Lake. Green Lake has a small primary basin as well as a long narrow arm. The primary basin is ~450 m wide and ~500 m long, roughly ~0.19 km^2 in area (Fig. 3). The long and narrow arm is ~650 m long and ~100 m wide. The long axis of the lake is 1.14 km and the total lake surface area is 0.26 km^2. The maximum water depth is located near the center of the primary basin and is about 53.33 m. Around much of the lake's shoreline, the slope of the surrounding hillsides extends at a similar angle below the water excluding the northern side of the basin where there is a narrowing of the lake (~110 m) which corresponds with a gradual shallowing from the main basin to shore over about 630 m. Green Lake's outflow is located at the northern most end of the lake. Water travels through a culvert and into Pools Brook.

Bottom hardness mapping for both lakes indicates relatively hard shorelines and softer lake floors (Fig. 4). Comparison of the bathymetry and hardness data, show locations where trough and ridge patterns are present on the sloping lake walls, which correspond to soft and hard surfaces (Fig. 4).

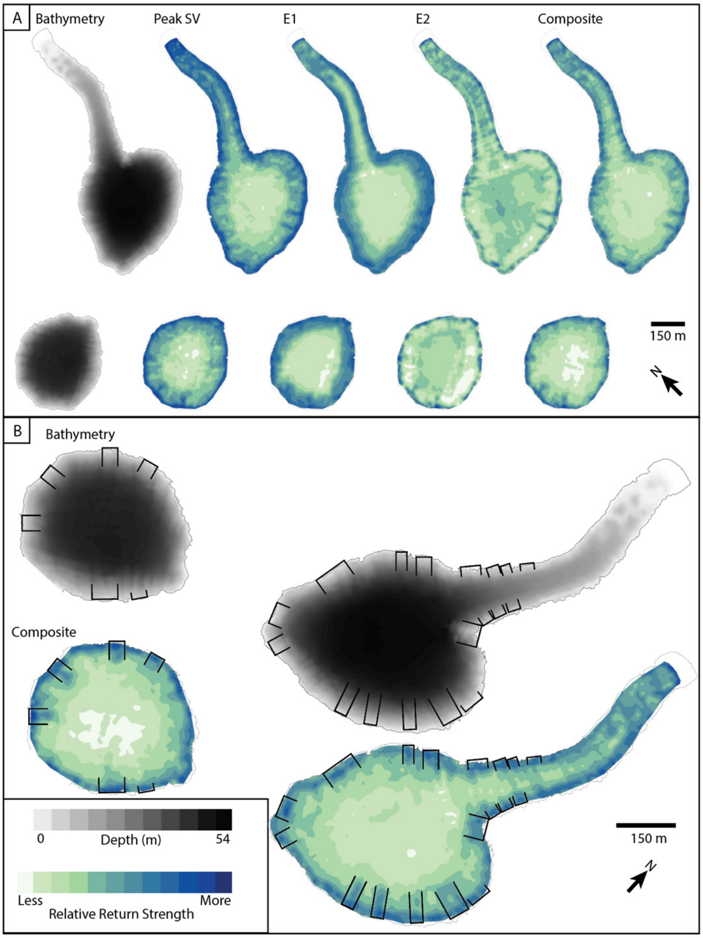

Figure 4. Bathymetry and bottom characteristics of Green Lake and Round Lake. (A) Bathymetry shows a shaded isobath map contoured and shaded at 1 m intervals (light shades indicate shallower locations and dark shades indicate deeper locations). Peak SV first return indicates bottom hardness, E1s second return indicates bottom hardness and roughness, E2 second echo indicates bottom hardness, and the Composite integrates bottom data from each return dataset. Color shading indicated the relative strength of each return. A stronger return (blue) indicates harder surfaces (stratigraphy or shorelines), and a weaker return (green) indicates a softer surface (e.g., sediment-rich bottom). (B) Bathymetry and composit maps (same as panel A) with brackets marking locations of ridges which correspond to higher (shallower lake depths) and harder surfaces. There is a correspondence between the undulating lake surface transitioning from ridges to troughs (alternating light and darker bathometric colors) and locations of harder and softer lake bottom. The ridges are harder than the troughs, likely because of sediment focusing effects.

Sonar Mapping of Shorelines and Tufa

Sonar mapping of the shoreline revealed multiple tufa locations, woody debris, and steep slopes (Fig. 2, Fig. 5 and Table 1). Tufa formations were readily identified based on their morphology, as the sonar provided detailed images of tufa geometries, as well as numerous locations of encrusted woody debris.

In Round Lake, four locations of tufa deposition were identified, and were concentrated on the eastern and southern shores (Fig. 5). Two of the tufa locations (Fig. 5 sites R and S) were spread over a range greater than 10 meters along the southern shoreline and consisted of ~ 10 distinct tufa "heads". It is unclear whether these two localities are continuous or discrete. However, the imagery clearly shows submerged structures with tufa like morphologies (Fig. 5). Two other locations along the northeastern shore (Fig. 5 sites P and Q) are less definitive but also have tufa like morphologies. These are smaller and less prominent than the first two sites.

In Green Lake, fourteen locations of tufa deposition, some with multiple tufa heads, were observed (Fig. 5). Five of these sites were previously identified and documented (e.g., Ludlam, 1969; Thompson et al., 1990), and were large (>10 meters long) with multiple masses (Fig. 5 sites O, L, F, A, and D). Nine sites were smaller and less prominent consisting of one or two distinct tufa heads, up to several meters in size (Fig. 5 sites R and S). Tufa were also visible in UAV (unmanned aerial vehicle) imagery, providing an opportunity for identification, validation, and as a strong visual for the formations' morphologies (Fig. 6). Tufa deposits in Green Lake are concentrated on the eastern and western shores. The observed deposits were limited in depth to the upper ~15 m of the water column (Fig. 7), similar to the lower limit of tufa formation identified at Deadman's Point, and to the location of the chemocline (Thompson et al., 1990).

DISCUSSION

This investigation provides updated bathymetric maps of Green Lake and Round Lake, as well as bottom hardness data and near shore sonar imagery of each lake. The combined dataset together with prior work has improved our understanding of sedimentation processes in the lake, and the locations of tufa, another step in understanding the unique conditions needed for their formation.

Bathymetry and Bottom Hardness

The bathymetry (Fig. 3 and 4) of Round Lake and Green Lake determined from the sonar mapping is consistent with prior work, and the shape of the basins and their orientations support the spillway and plunge pool hypothesis (Fig. 1, 3, 4, and 7). The collection of high-resolution bathymetric data has confirmed that there are no additional undocumented sub-basins, and that the lakes' bottoms have low relief. No doubt, the relatively flat lying geology and sediment focusing has contributed to the flat bottom of the lake. One improvement to prior bathymetric mapping is along the steeply sloping shorelines, where the sonar has provided much higher data density resulting in higher-resolution mapping. The updated bathymetry with additional focus on the lake margins has proven helpful for understanding the depth range over which the tufa deposits form and for capturing small scale trough and ridge patterns.

Bottom hardness mapping confirmed that the lake shores and upper slopes are commonly hard (Fig. 4). Conversely, the softer lake bottoms are maintained by sediments settling to the lake floor. Turbidity

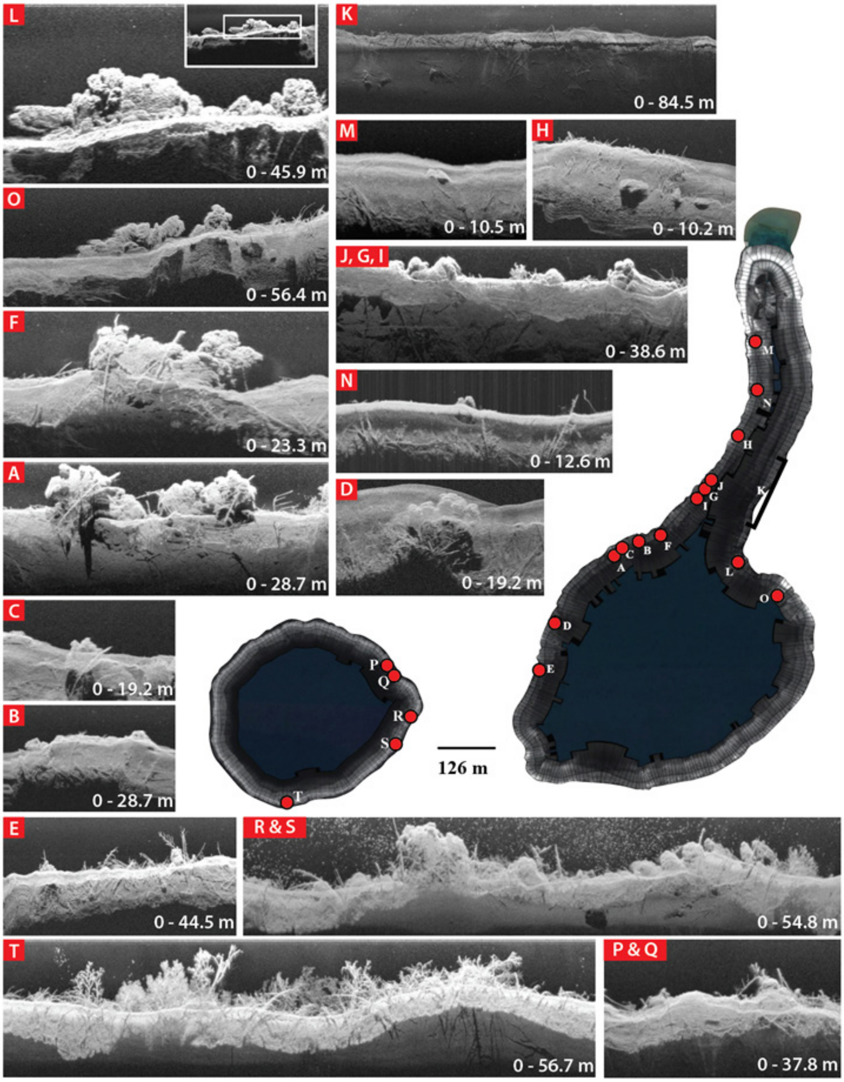

Figure 5. Sonar mosaic of Round and Green Lake with a selection of side-scan sonar images focused on identified tufa localities. Locations and corresponding imagery are as marked. The length of the ground track (width of the image) is indicated in the bottom right corner of each image. Sites A, F and L (Deadman's Point) are the most prominent tufa deposits, and their morphologies are clear. Other sites show similar morphologies. Encrusted woody debris is also common (e.g., sites E, and R&S show encrustation and tufa like morphologies). Site T is an example of extensive woody debris in the lake (submerged fallen trees). Note: both Round and Green Lake are in the same scale and orientation. However, the position and distance between the lakes has been abridged for figure formatting purposes.

Note: sonar imagery is collected parallel to shore from above at an oblique downward looking angle (Fig. 2). In the images above, the bottom of the image corresponds with the shore, the upper portion of the image is the water column and the light-colored structures (e.g., lake bottom, rocks, woody material, and tufa) towards the center of the image are materials reflected back as imagery of the sloping lake bottom near shore. Since the sonar energy is radiating outward from a single source, large or protruding objects can cause shadows (e.g., bottom right side of (T) there are black shadows of the woody material present, in the center of (H) and (R&S) protruding material causes shadows near the centers of the images, shadows are present behind the protruding tufa in (D) and similarly in (A)).

GREEN LAKE		
Site	Lat.	Long.
M	43.055845	-75.964028
N	43.055067	-75.964081
H	43.054507	-75.964176
J	43.053543	-75.965008
G	43.053458	-75.965043
I	43.053161	-75.965468
F	43.052472	-75.966258
B	43.052373	-75.966637
C	43.052145	-75.967477
A	43.052051	-75.967664
D	43.050292	-75.969123
E	43.049947	-75.969368
O	43.051448	-75.963585
L	43.051914	-75.964496
ROUND LAKE		
Site	Lat.	Long.
P	43.048851	-75.973036
Q	43.048562	-75.972884
R	43.047700	-75.972620
S	43.047556	-75.972730
T	43.046089	-75.975149

Table 1. Locations of sites as indicated on Figure 5.

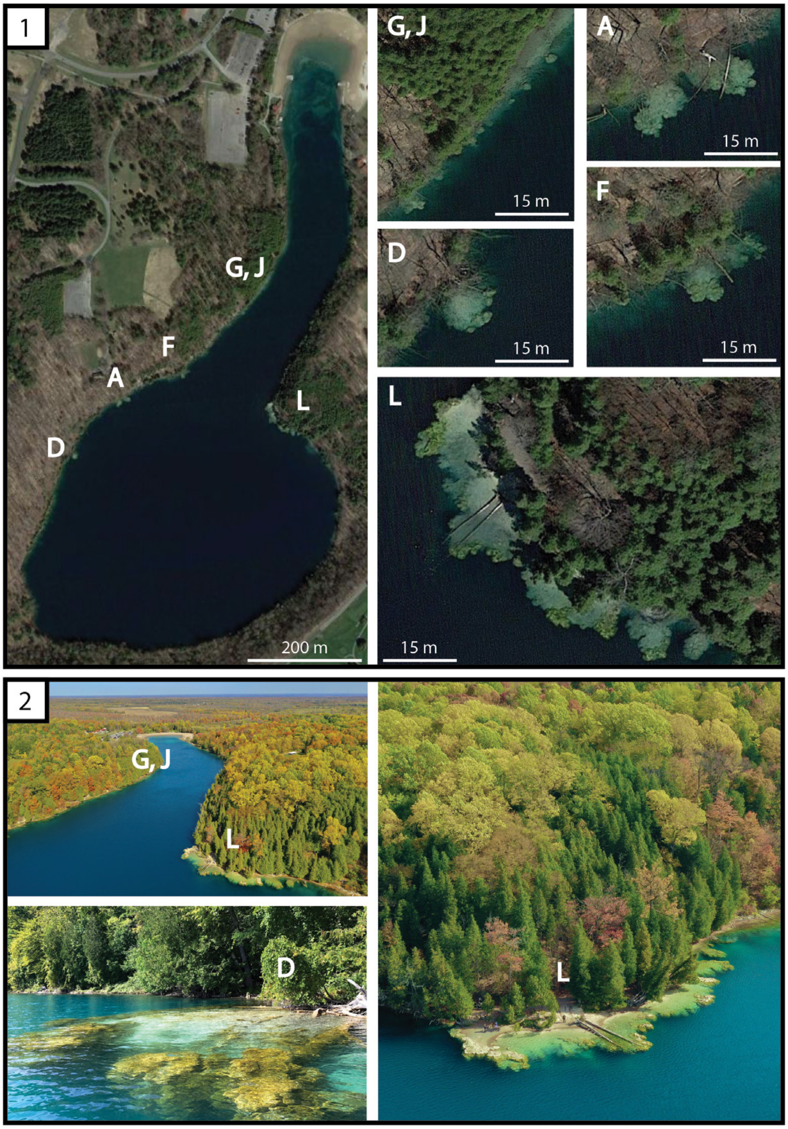

Figure 6. Imagery of some prominent tufa sites in Green Lake. (1) Upper panels, overhead imagery were acquired from Google Earth (imagery dated 4/13/2017). Left, images of Green Lake with tufa sites marked (site letters correspond with Fig. 5). (2) Lower panels, UAV images of tufa seen through the water, collected during this study. Upper left, view north, down the long axis of Green Lake. Right, Deadman's Point (L) and bottom left, site D.

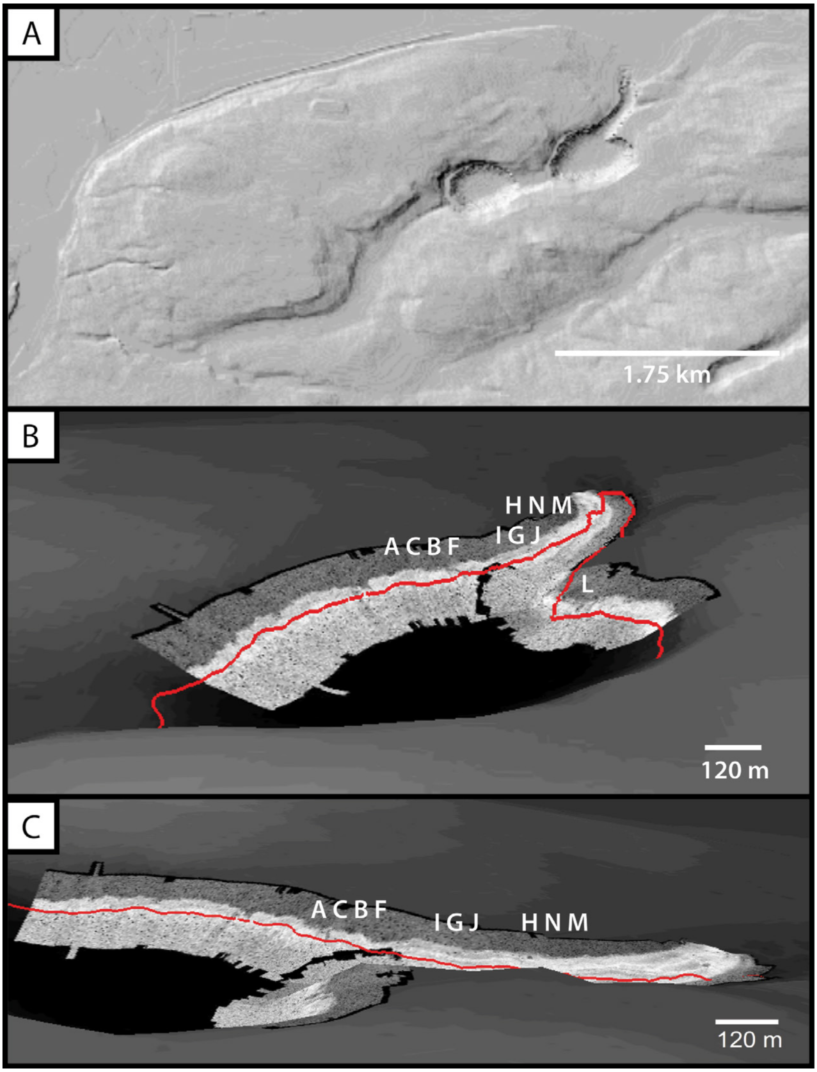

Figure 7. Synthesis of topographic and bathymetric datasets and evaluation of tufa positions. A) Combined digital elevation model (DEM) and hillshade of topography and bathymetry (lake surface removed to show the landscape surface) shows the geometry of the meltwater outlet channel (trough). The deep plunge pools, now Round Lake and Green Lake, are clearly visible as are the steep flanking slopes. B) Sonar mosaic draped over the DEM (view approximately obliquely north) with a contour line marked at 15 m depth below the lake surface shows that tufa deposits (approximate locations indicated) are located above this depth. This is likely a result of a combination of factors discussed in the main text. Note: the data are obliquely projected, thus the foreshortening of the image and appearance of the contour line on the right (east) side of the lake. C) Sonar mosaic draped over the DEM (view approximately obliquely west, approximate locations indicated).

currents (sediment flows) have been documented in Green Lake and the associated lobate turbidite deposits extend from the lake margins toward the lake center (Ludlam, 1974). While these events are not regularly timed and do not occur uniformly across the basin, individual deposits over the course of a year can be mm to cm thick (Ludlam, 1974). These thin and broad deposits are likely too small to be detected in the bathymetric survey. However, when combining the bathymetry and hardness data there are some locations where trough and ridge patterns are present that are consistent with turbidite processes (Fig. 4). Here, we observe relatively harder surfaces on topographic highs and softer surfaces in the trough locations. We attribute this pattern to the effects of sediment focusing in lower trough areas. Perhaps, these sediment accumulations are the initiation points for turbidites which are known to occur in the lake. Topographic and hardness heterogeneities may incite the initiation of turbidite processes due to preexisting troughs and ridges, or alternatively the troughs and ridges may result from the deposition of turbidites. Towards the center of the basins, the lake bottom is relatively soft and there is little topography. This is consistent with the laminated and varved sediments that have been documented on the lake floor (Ludlam, 1969, 1984; Hilfinger et al., 2001). The bathymetry and bottom hardness observations presented here are consistent with prior sedimentological studies of the lakes.

Tufa Identification, Location, and Geologic Context

At Green Lake, comparison of sonar mapping and bathymetry of Deadman's Point with the description and cross section of Thompson et al., (1990) shows remarkable consistency (Figs. 1, 5L, and 6). This site provides an obvious location to compare tufa sonar imagery with a well-studied site where tufa morphologies are clear and well documented. Furthermore, we were able to clearly identify this site and others using satellite and UAV imagery for comparison and validation of the sonar imagery (Fig. 6). The sonar imagery shows the morphology of the tufa formations, and encrusted woody debris clearly indicates tufa growth. The tufa morphology in the sonar imagery is clear and combining the site locations and bathymetry demonstrates that tufa localities are restricted to the upper ~15 m of the water column in Green Lake (Fig. 7). Thus, water stratification, sun exposure, and underlying geology all play a role in restricting the depth range of the tufa. The tufa are dominantly along the east and west sides of Green Lake along the long axis shorelines, at locations below taller and steeper topography. Perhaps, preferred locations of tufa formation result from steep uphill gradients that promote groundwater flow along geologic contacts (i.e., the contact between the Syracuse Formation, and the Vernon Shale) and bedrock fractures. Since bottom hardness mapping indicates that hard surfaces (good initial substrates for tufa formation) are abundant, it is our view that a limiting factor influencing the presence of tufa formations is the location of groundwater springs with sufficient flow to foster tufa growth. Together, lake stratification, sunlight availability, and groundwater flow contribute to limiting the depth range and position of the tufa deposits. A notable observation is the consistency of the maximum depth-range of tufa formation in Green Lake to above ~15 m (Fig. 7). This is likely because of the lakes stratification and geologic controls (Fig. 1, Thompson et al., 1990).

The controls on the locations of tufa formation appear to be varied and complex. Bottom hardness mapping in this study was not predictive of tufa locations. The shorelines are generally harder than the mid-level slopes and lake bottoms. Since hard shorelines are abundant, this does not seem to be the limiting factor in controlling tufa formation. Prior work suggests that tufa result from a mix of groundwater discharge and biological processes that do best with good sun exposure (Thompson et al., 1990). The tufa locations in Round Lake are not entirely consistent with these parameters, in particular, the locations of potential groundwater flow and tufa location. Based on observations from Green Lake, tufa should form on the southern, western, and northern shores of Round Lake. At these locations, the bedrock should be nearer the surface and should have sufficient head to drive groundwater discharge at the contact of the Syracuse Formation and Vernon Shale, like the conditions in Green Lake. However, the locations identified as sites with probable tufa are towards the outflow end of the lake. Whereas sonar imagery is consistent with tufa morphology, perhaps these sites are rather a result of encrustation of debris and are different from the prominent tufa deposits in Green Lake, or these sites are influenced by fracture systems. Interestingly, no tufa deposits were observed on the western end of Green Lake, the downstream direction of surface and subsurface flow from Round Lake. This suggests that conditions were not favorable for tufa formation due to diminished groundwater flow coming from a direct bedrock source into the area and water chemistry changes likely modified by mixing with lake water. It is likely that Round Lake groundwater entering the southwest end of Green Lake is traveling through the shallow subsurface from Round Lake and is not from deeper groundwater sources that would foster tufa growth.

CONCLUSIONS

The Fayetteville Green Lakes are a unique location. The site was sculpted by glaciation leading to the excavation of two deep lakes associated with a glacial meltwater trough. These lakes penetrate the Syracuse and the Vernon Shale Formations, and the lakes are fed by emerging groundwater. The deep and narrow basin geometry has led to a stable meromictic water column. The lake bathymetry data shows that each lake has a main flat-bottomed basin with steep slopes. Bottom hardness indicates relatively hard nearshore environments which trend into softer layered sediments toward the bottom of the lake. In the near surface waters along the shore of Green Lake, we were able to identify multiple locations of tufa using sonar and we were able to validate these with field observations and UAV and satellite imagery. In Green Lake, tufa are present in the upper 15 m in the oxic zone at locations where groundwater discharge is likely. We argue that the tufa deposits form at these locations because of the available hard surfaces that can be encrusted and exposure of a geologic contact that allows for groundwater discharge. This flow exits geologic contacts and fractures at specific depths above the chemocline where the mineral rich waters can be biologically mediated to form tufa. In Green Lake, tufa are primarily located on the east and west sides of the lake. We believe they are concentrated in these locations because of steep surrounding topography which promotes groundwater flow into the lake. Tufa were not observed on the southwest end of the lake likely due to the effects of mixed groundwater and lake water outflow from Round Lake. In Round Lake, the probable tufa sites were located on the east side of the lake. Our work underscores the unique and specific conditions needed for tufa formation and highlights the complex morphologies of the tufa. Sonar imaging of the nearshore environment has proven to be an exceptional tool for identifying and surveying the complex tufa structures and viewing woody debris in the lakes. It shows the usefulness of sonar imaging as a surveying tool to identify unique environments and repeated surveys may be applied for ongoing monitoring.

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CITATIONS

Block, K. R., O'Brien, J. M., Edwards, W. J., and Marnocha, C. L., 2021, Vertical structure of the bacterial diversity in meromictic Fayetteville Green Lake: *MicrobiologyOpen, v. 10, no. 4,* p. e1228.

Brunskill, G., and Ludlam, S., 1969, Fayetteville Green Lake, New York. I. *Physical and Chemical Limnology 1: Limnology and Oceanography, v. 14, no. 6*, p. 817-829.

Brunskill, G. J., 1969, Fayetteville Green Lake, New York. II. Precipitation and Sedimentation of Calcite in a Meromictic Lake with Laminated Sediments 1: *Limnology and Oceanography, v. 14, no. 6*, p. 830-847.

Coon, R., 1960, *Surficial geology of the Syracuse East and Manlius*: New York, v. 7, no. 1, p. 2.

Culver, D., and Brunskill, G., 1969, Fayetteville Green Lake, New York. V. Studies of Primary Production and Zooplankton in a Meromictic Marl Lake 1: *Limnology and Oceanography, v. 14, no. 6*, p. 862-873.

DeMott, L. M., Napieralski, S. A., Junium, C. K., Teece, M., and Scholz, C. A., 2020, Microbially influenced lacustrine carbonates: A comparison of Late Quaternary Lahontan tufa and modern thrombolite from Fayetteville Green Lake, NY: *Geobiology, v. 18, no. 1*, p. 93-112.

Eggleston, J. R., and Dean, W. E., 1976, Freshwater stromatolitic bioherms in Green lake, New York, *Developments in sedimentology, Volume 20*, Elsevier, p. 479-488.

Eggleton, F. E., 1931, A limnological study of the profundal bottom fauna of certain fresh-water lakes: *Ecological Monographs, v. 1, no. 3*, p. 232-331.

-, 1956, Limnology of a meromictic, interglacial, plunge-basin lake: *Transactions of the American Microscopical Society, v. 75, no. 3*, p. 334-378.

Gilbert, G. K., 1899, Glacial sculpture in western New York: *Bulletin of the Geological Society of America*, v. *10, no. 1*, p. 121-130.

Hand, B. M., 1978, *Syracuse meltwater channels*.

Hand, B. M., and Muller, E. H., Syracuse channels: evidence of a catastrophic flood, in *Proceedings New York State Geological Association Guidebook*, pp. I-1-J-12. 44th Annual Meeting, Hamilton, New York1972.

Havig, J. R., Hamilton, T. L., McCormick, M., McClure, B., Sowers, T., Wegter, B., and Kump, L. R., 2018, Water column and sediment stable carbon isotope biogeochemistry of permanently redox-stratified Fayetteville Green Lake, New York, USA: *Limnology and Oceanography, v. 63, no. 2*, p. 570-587.

Havig, J. R., McCormick, M. L., Hamilton, T. L., and Kump, L. R., 2015, The behavior of biologically important trace elements across the oxic/euxinic transition of meromictic Fayetteville Green Lake, New York, USA: *Geochimica et Cosmochimica Acta, v. 165*, p. 389-406.

Hilfinger, I. M. F., and Mullins, H. T., 1997, Geology, limnology, and paleoclimatology of Green Lakes State Park, New York: *69th Annual New York State Geological Association Field Trip Guide*: Clinton, NY, Hamilton College, p. 127-159.

Hilfinger, I. M. F., Mullins, H. T., Burnett, A., and Kirby, M. E., 2001, A 2500 year sediment record from Fayetteville Green Lake, New York: evidence for anthropogenic impacts and historic isotope shift: *Journal of Paleolimnology, v. 26, no. 3*, p. 293-305.

Ludlam, S. D., 1969, Fayetteville Green Lake, New York. III. The Laminated Sediments 1: *Limnology and Oceanography, v. 14, no. 6*, p. 848-857.

-, 1974, Fayetteville Green Lake, New York. 6. The role of turbidity currents in lake sedimentation 1: *Limnology and Oceanography, v. 19, no. 4*, p. 656-664.

-, 1984, Fayetteville Green Lake, New York, USA: VII. *Varve chronology and sediment focusing: Chemical geology, v. 44, no. 1-3*, p. 85-100.

Miner, N., 1933, The origin and history of Green and Round Lakes in Green Lake State Park at Fayetteville: New York [MS thesis]: Syracuse, NY, Syracuse Univ.

Muller, E., 1967, Geologic setting of Green and Round Lakes near Fayetteville, New York: Some aspects of meromixis.

Quereau, E. C., 1897, Topography and history of Jamesville lake, New York: B*ulletin of the Geological Society of America, v. 9, no. 1*, p. 173-182.

Sissons, J., 1960, Subglacial, marginal, and other glacial drainage in the Syracuse-Oneida area, New York: *Geological Society of America Bulletin, v. 71, no. 11*, p. 1575-1588.

Survey, U. S. G., 1995, Digital Elevation Models (DEM), S27 - Moravia: Cornell University Geospatial Information Repository.

Thompson, J. B., Ferris, F. G., and Smith, D. A., 1990, Geomicrobiology and Sedimentology of the Mixolimnion and Chemocline in Fayetteville Green Lake, New York: *PALAIOS, v. 5, no. 1*, p. 52-75.

Thomson, J. B., Schultze-Lam, S., Beveridge, T. J., and Des Marais, D. J., 1997, Whiting events: biogenic origin due to the photosynthetic activity of cyanobacterial picoplankton: *Limnology and oceanography, v. 42, no. 1*, p. 133-141.

Uveges, B. T., Teece, M. A., Fulton, J. M., and Junium, C. K., 2018, Environmental controls on pigment distributions in the freshwater microbialites of Fayetteville Green Lake: *Organic Geochemistry, v. 125*, p. 165-176.

Vanuxem, L., 1839, *Third annual report of the geological survey of the Third District: Documents of the Assembly of the State of New York: Sixty-second Session, v. 5*, p. 241-285.

Wellner, R. W., Anderson Jr, W. T., and Dwyer, T. R., 1996, Seismic stratigraphy of the Finger Lakes: a continental record of Heinrich event H-1 and Laurentide ice sheet instability: *Subsurface geologic investigations of New York Finger Lakes: Implications for Late Quaternary deglaciation and environmental change, v. 311*, p. 1.

Wilhelm, M. B., and Hewson, I., 2012, Characterization of thrombolitic bioherm cyanobacterial assemblages in a meromictic marl lake (Fayetteville Green Lake, New York): *Geomicrobiology Journal, v. 29*, no. 8, p. 727-732.