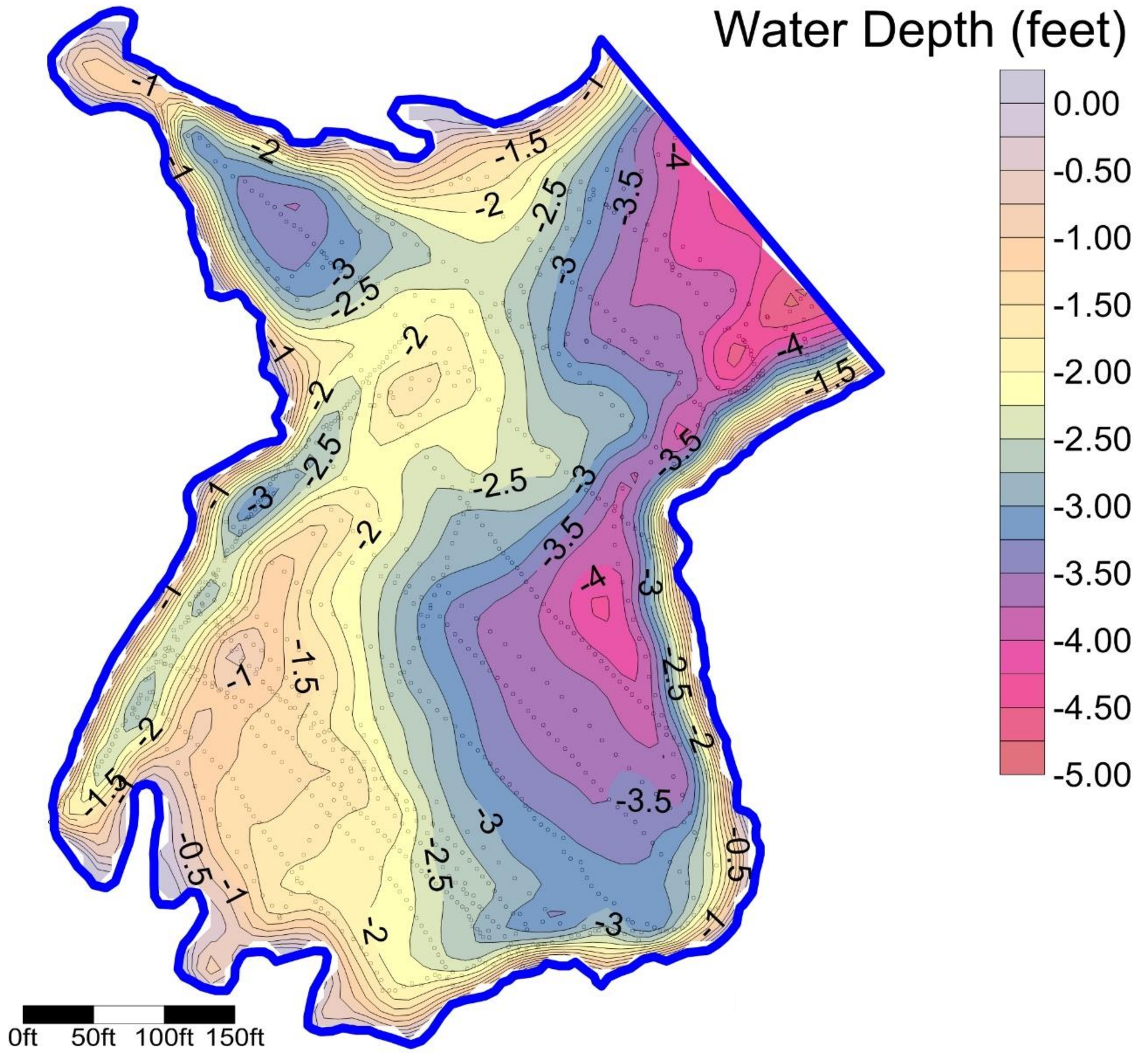
Probing, Coring, and Radar Analyses of Soft Sediment In The South Bay of Andover Lake



Drew Hyatt, Environmental Earth Science Department,

Eastern Connecticut State University

Abstract

Sediments within the south bay of Andover Lake were examined to estimate their volume, internal stratigraphy, bulk sediment geochemistry, and age. This research received $1500 support from ALMA-ALPOA to pay for ^{210}Pb dating analyses. Field assistance from several present and former Environmental Earth Science students at Eastern Connecticut State University was most helpful. As summarized at the end of the report, this study reports several key findings related to (1) drainage basin size and volume of water in the bay, (2) soft sediment probing, (3) analysis of sediment cores, (4) bulk sediment geochemistry, (5) ground penetrating radar imaging, and (6) ^{210}Pb chronologies of sedimentation in the bay. The report closes with a discussion of the implications of this research to potential dredging activities.

The south bay of Andover Lake is very small in relation to the size of the drainage basin delivering sediment and water. This, together with the constricted juncture between the bay and the lake are the primary reasons why sediments accumulate in the bay. Sediment probing, described in a previous interim report, indicates a sizable volume of soft sediment (≈412,800 ft^3) underlies the bay, although coring and ^{210}Pb dates imply that nearly 40% of these deposits were present before the lake was formed in 1927. Soft sediment beneath the bay varies in thickness with location from slightly more than 5 ft. at a few locations to less than 0.5 feet. Sediment cores reveal a stratigraphy that includes, from the top-down, lake sediments overlying pre-lake soils that have formed within silty sediments on top of coarse-grained sands, gravels and cobbles that have a glacial legacy. The lake sediments and top of the underlying soils look very similar and would likely be difficult to distinguish were dredging undertaken. Bulk sediment geochemical analyses indicate that uppermost sediments, which would most easily be disturbed during dredging, have the highest elemental concentrations. Ground penetrating radar (GPR) visualizations identify the underlying geologic stratigraphy beneath the bay. As well, water depths were extracted from GPR records and used to construct a detailed bathymetric map for the bay (featured on the front cover). This map and comparisons of soft sediment depth and the thickness of lake sediment at coring sites enable construction of a map depicting water depths in the bay shortly after Andover Lake was formed (around 1930 or so). Based on these maps, average water depth in the south bay in *ca*. 1930 was ≈1.1 ft. deeper on average than in 2014, although specific water depths for both time periods vary with location in the bay. In general, the deepest waters are located in an East Basin, while a sandy ridge running parallel to inflow from Cheney Brook creates shallows in the middle of the bay. ^{210}Pb dating is consistent with interpretations of lake sediments overlying pre-existing pre-lake soils. Mass sedimentation rates and sediment accumulation rates derived from ^{210}Pb data indicate maximal deposition in the lake around 1975, most likely following land-clearing for nearby high tension power lines. ^{210}Pb data also indicate slight increases in sedimentation rates since ≈2000 for which visible changes in the surrounding watershed are not evident. The cause of this increase is not known, but may reflect increased contributions from sediments produced within the lake by natural biogeochemical processes.

Dredging remains a costly and potentially problematic approach to addressing sedimentation in the bay. In addition to knowing the cost, the membership should be informed that a significant amount of soft sediment in the bay pre-dates the formation of Andover Lake. If dredging is considered further additional chemical analyses should be undertaken by an agency familiar with dredging protocols in freshwater lakes.

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Introduction

This final report describes findings arising from field and laboratory work that examined the volume and character of sediments that have accumulated in the south bay of Andover Lake. Field work and subsequent analyses began in the summer of 2014 and continue to the present making use of samples and measurements at sites identified in Figure 1.

The following introduces the study site, considers controls on sedimentation, and presents findings on sediment probing, analysis of sediment cores, ground penetrating radar imaging, and age determinations for sediments in the bay. The report closes with a summary of key findings and discussion of the implications of this work to dredging.

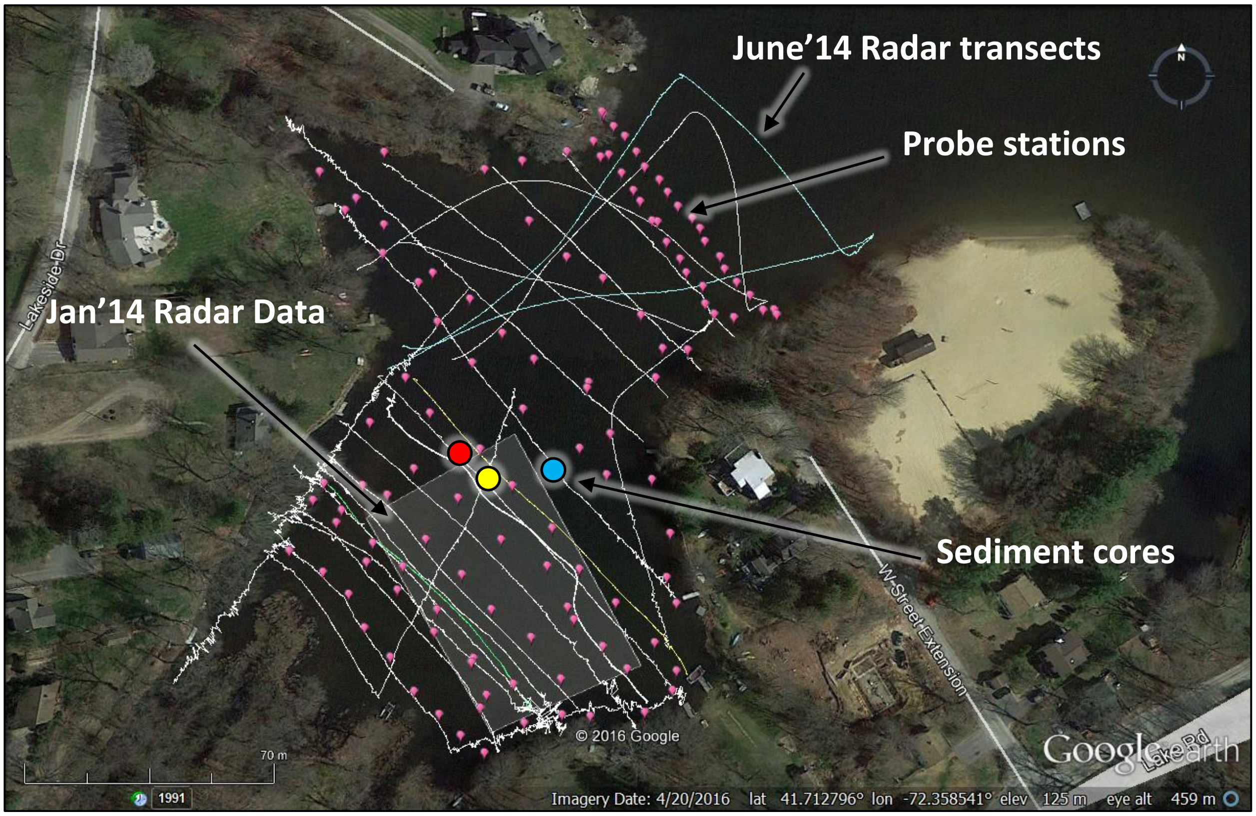


Figure 1. Google Earth imagery of the south bay and adjacent beach at Andover lake with annotations identifying sampling locations for this study. All location data were measured with either Garmin or Trimble GPS instruments accurate to ≈ ±3m. Thin white lines identify 200 MHz GPR transects, the grey box indicates the location of 100 MHz radar data. Pink markers are center positions for soft sediment probe measurements. In many cases additional probe measurements were made at set distances away from these markers. The three large colored dots identify sediment core locations for And2014-01 (red), And2014-02 (yellow), and AND2015-02 (blue).

The body of this report examines several related areas of research. This includes the following:

1) The size of the area contributing water and sediment to the bay is described and general controls on sedimentation in the bay are reviewed including the geologic setting for the site.

2) Soft sediment probe data are analyzed to prepare maps and estimate the volume of sediment in the bay. Findings presented in a January 2015 interim report are updated, noting some adjustments to the original sediment thickness map and volume estimates.

3) Sediment cores recovered from the bay in June 2014 and January 2015 are described. Sedimentary packages (units) are identified and related to the depth of probing so as to better understand how sediment volume estimates relate to the sedimentary record.

4) Bulk sediment geochemical trends for the 2014 cores are summarized and comparisons are made between sedimentary units and between soft sediment and underlying materials.

5) Ground Penetrating Radar (GPR) data collected in January 2014 and June 2014 are reviewed. Three dimensional visualizations of 100 MHz data to ≈10 m (Jan., 2014) reveals the general geologic framework beneath the south bay. Higher-resolution 200 MHz data (Jun., 2014) collected along 21 transects are used to: *(a)* prepare a detailed bathymetric map of the south bay, *(b)* estimate water volume in the bay, *(c)* to consider likely circulation patterns within the bay, and *(d)* estimate water depth for the bay *ca.* 1930 (*i.e.* soon after the lake was formed).

6) ^{210}Pb analyses for the 2015 core are presented and trends in the age of sediments and changing rates of sedimentation through time are discussed. Results from these analyses provide important temporal context for all of the data sets.

Timing of Final Report:

This report has been unavoidably delayed for reasons I wish to clarify. Complications arose in obtaining ^{210}Pb dating results. The initial ^{210}Pb piston core collected in the summer of 2014 was too short to justify the expense of dating ($1500). Accordingly, longer cores were collected through lake ice in January of 2015. Sub-samples were submitted to MyCore Scientific for ^{210}Pb analyses in August of 2015. In October of 2015, chief MyCore scientist Dr. Jack Cornett indicated that background ^{210}Pb values for the submitted samples were high. Since background ^{210}Pb is critical to proper age determinations, Dr. Cornett recommended measuring this activity independently (at no additional cost). This involved two lengthy analyses that were necessary to ensure the validity of background ^{210}Pb values. As a result, final ^{210}Pb results were not received until late February, 2016. Other class and research commitments at that time delayed analysis of the ^{210}Pb results until very recently.

1) Study Site and Factors Influencing Sedimentation in South Bay

The south bay of Andover Lake is a shallow ≈2.18-hectare inlet that receives runoff from Cheney Brook and tributaries (Figure 2). The bay and the southern ≈20% of the lake is generally shallow, with water depths increasing northward towards the dam. The deepest waters in Andover Lake occur along a submerged stream channel at the north end of the lake that was flooded in 1927 following construction of Andover Lake Dam. In northern sections of the lake shorelines are mostly wave-washed, sandy, and often contain boulders left behind by retreating glaciers at least ≈18, 000 years ago. In contrast, in the south bay sandy glacial deposits have been blanketed by silty-to-sandy soft sediments. As expanded on in this report, these soft sediments have accumulated because of ongoing natural processes that are a consequence of the significant flow from Cheney Brook and tributaries into a relatively small bay that has a constricted juncture with the rest of the lake.

All lakes, whether natural or dammed, are depositional basins in which sediments accumulate through time. The majority of sediments deposited in lakes are derived from the drainage basin that surrounds the lake. A drainage basin is a topographic depression that captures precipitation and directs water down-hill over the land and into streams which eventually drain into the lake. Sediments are picked up (eroded) by water *en route* to the lake, such that streams discharge both water and sediments to lakes. It should be noted, however, that lakes also produce their own sediments within the waterbody by normal biogeochemical processes within the lake. Thus, both allochthonous (derived outside-the-lake) and authochthonous (derived inside-the-lake) sediments mix, settle, and eventually accumulate on the lake bed.

The locations and manner in which sediments accumulate is strongly influenced by environmental conditions at the site of deposition. For example, virtually every standing waterbody of any size will accumulate coarser sandier sediments in places where higher-energy sediment-laden flows enter standing water. As the flow slows it becomes less competent to carry larger (and heavier) sediment particles. As a result, larger sediment grains (*e.g. sands*) tends to be deposited while finer sediments (clay) are carried further out into the lake. Wave action on shorelines also stirs up sediments promoting the transport of finer sediments to deeper parts of the lake. These trends are clearly evident at Andover lake, where well developed deltas (deposits of sand and gravel where streams enter the

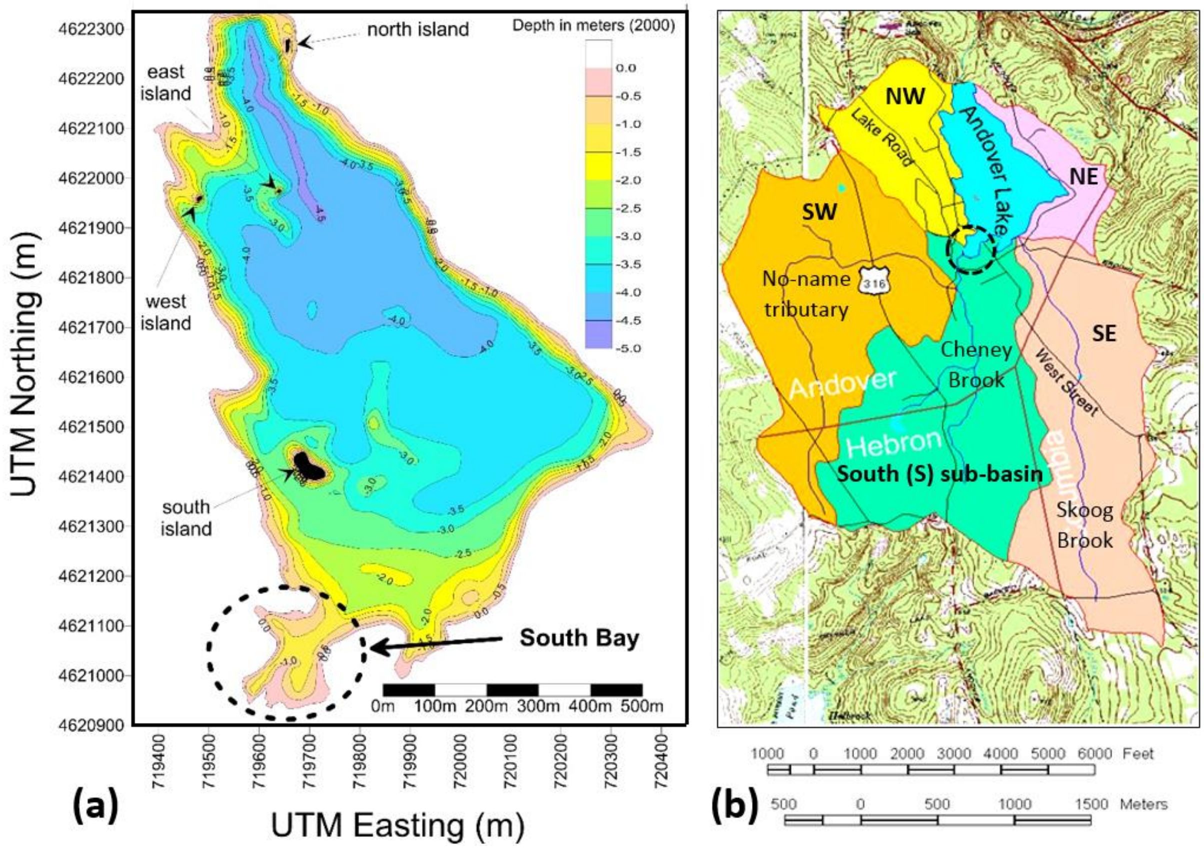


Figure 2. (a) Bathymetric map of Andover Lake (in meters) constructed from echo sounding data collected in 2000. Dashed circle identifies the study area. ***(b)*** Topographic map with overlay of drainage sub-basins contributing runoff to Andover lake. Note: (1) Cheney Brook and its no-name tributary contribute waters to the south bay derived from the southwest (SW) and the south (S) sub-basins. (2) A small portion of the upper part of the S basin in this figure does not contribute water to the bay. Figure modified from Tokraz (2003).

lake) occur off shore from Eridoni creek and in association with discharge from Cheney Brook in the south bay.

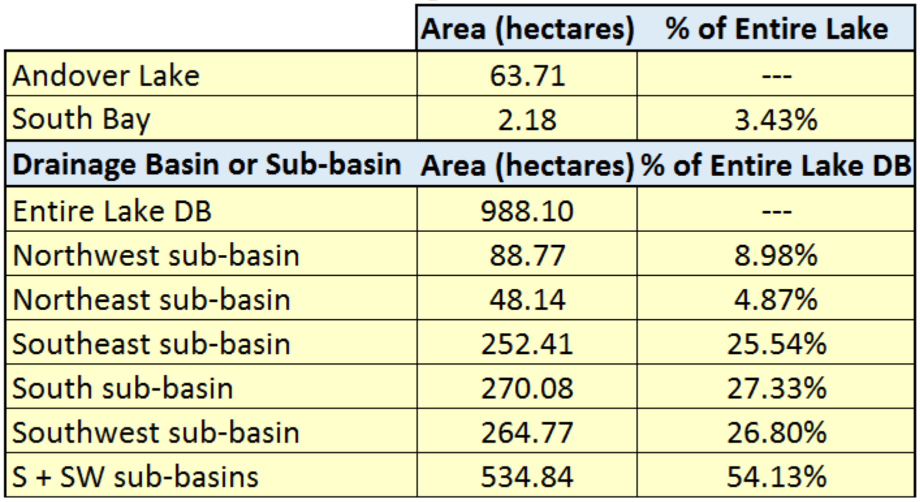
In addition to deltaic deposition near inflowing streams, the distribution of sediments in lakes is also influenced by other factors including the configuration of lake basins, thermal structure, and circulation within the lake. Moreover, because lakes support diverse ecosystems factors such as water depth, the penetration of light in the water column, and the murkiness (turbidity) of water also influence and are influenced by sedimentation. Suffice it to say, lakes are complex natural systems with many interacting controls. Unlike a swimming pool, there are rarely simple answers to addressing changing environmental conditions that often are recognized by changes in aquatic life and/or water quality.

Drainage Basin and Geologic Setting for the South Bay

With the preceding discussion in mind, it is useful to consider the size and location of the south bay in relation to the entire lake's drainage basin and for tributary sub-basins (Figure 2*b*, Table 1). The south bay is only ≈3.4% of the size of the entire lake, yet, the bay receives runoff from both Cheney Brook and an unnamed tributary stream to the southwest. Collectively these streams provide the greatest volume of water and sediment entering Andover Lake. More importantly, the southwest (SW) and south (S) sub-basins, which direct waters into the bay (Figure 2*b*), represent 54% of the entire drainage basin for Andover Lake (Table 1). That is to say 3.4% of Andover lake receives direct runoff from more than half of the entire lake's drainage basin.

The geologic setting for Andover Lake also influences the sedimentation in the south bay. The underlying mid-to-early Paleozoic (350-500-million-year-old) bedrock, consisting of various schist and gneissic rocks, exerts considerable control on the shape of bay, the lake, and the surrounding landscape. In particular, numerous northwest-to-southeast trending bedrock ridges occur around and

Table 1. Lake area and Drainage basin or Sub-basin Areas



	Area (hectares)	**% of Entire Lake**
Andover Lake	63.71	---
South Bay	2.18	3.43%
Drainage Basin or Sub-basin	**Area (hectares)**	**% of Entire Lake DB**
Entire Lake DB	988.10	---
Northwest sub-basin	88.77	8.98%
Northeast sub-basin	48.14	4.87%
Southeast sub-basin	252.41	25.54%
South sub-basin	270.08	27.33%
Southwest sub-basin	264.77	26.80%
S + SW sub-basins	534.84	54.13%

Data derived from Tokraz (2003) and Hyatt (2003).

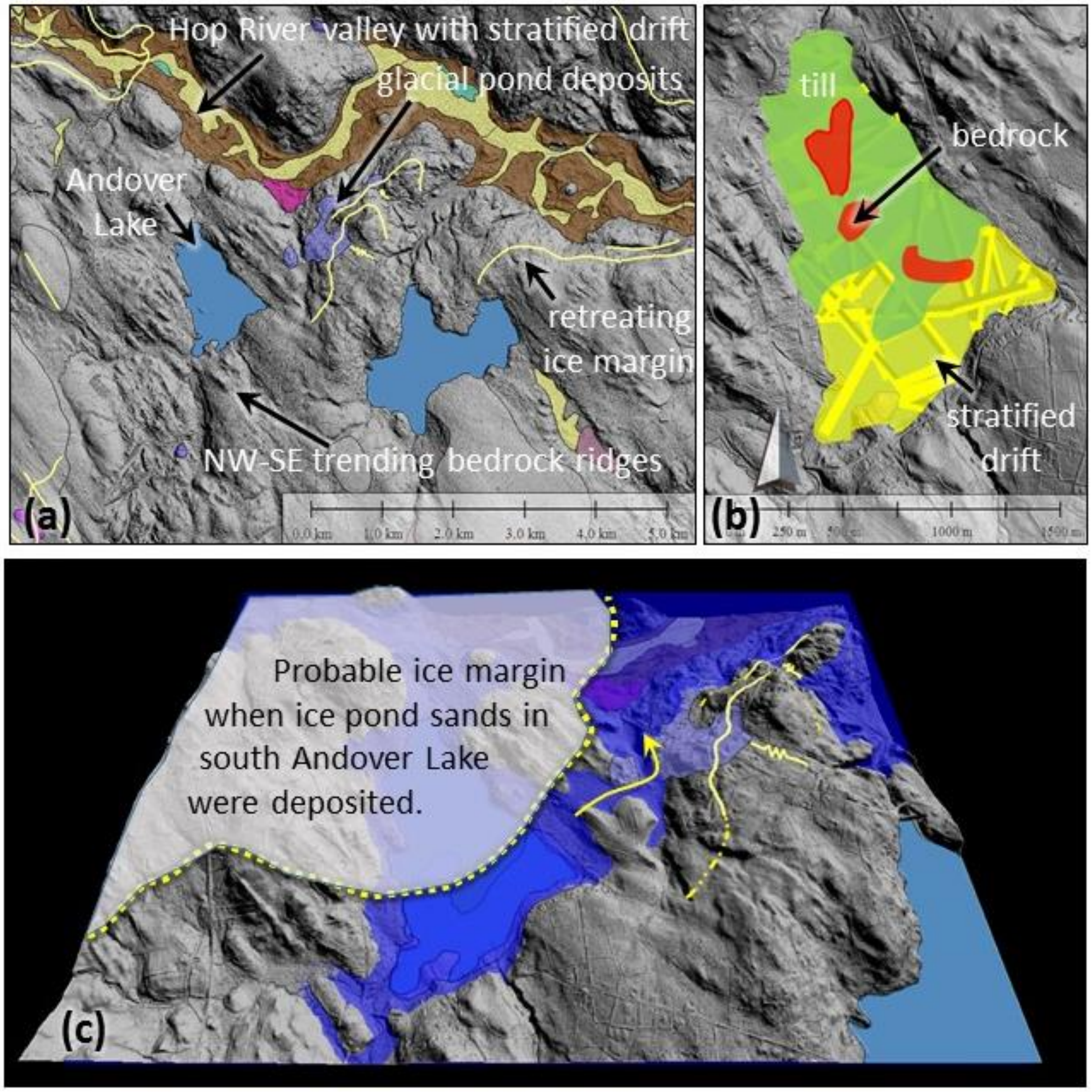


Figure 3. (a) Light distance and ranging (LIDAR) bare earth model (grey area) depicting elevations around Andover and Columbia lake. These models are based on elevation measurements collected every 3 feet across the landscape. Data processing is able to strip away tree cover to reveal the shape of the underlying "bare earth." Stratified drift glacial deposits in the Hop River valley and near Andover lake (colored regions) as well as retreating ice margin positions (yellow lines) are shown as mapped by the United States Geological Survey. ***(b)*** Lake bottom conditions for Andover Lake based on previously collected radar data. This includes glacial till (green), bedrock (red) and stratified drift occurring beneath Andover Lake. The south bay is underlain by sandy glacial pond deposits that Hyatt *et al.* (2015) link to nearby purple glacial pond deposits identified in (a). ***(c)*** The transition from till to stratified drift across Andover lake and the deltaic character of sub-lake and sub-beach sands (not presented here) suggest a still-stand position for retreating ice with drainage temporarily to the northeast (yellow curved arrow). Regardless of its origin, sandy stratified drift underlies most of the southern third of Andover Lake.

under Andover Lake (Figure 3*a*). In fact, it is likely that a buried bedrock ridge underlies West Street extension at depth, contributing to the constricted nature of the mouth of south bay. As well, without dwelling on the details, bedrock in the study area is typically overlain by two types of glacial deposits. This includes glacial till laid down directly by glacial ice, and associated meltwater deposits collectively referred to as stratified drift (Stone, 2013). Previous radar work at the lake (Cedrone, 2012; McCarry, 2012; Hyatt *et al.*, 2015) revealed that till underlies the norther two-thirds of Andover lake while sandy stratified drift underlies the southern third of the lake (Figure 3*b*). Typically stratified drift deposits are found in valley bottoms because those are the locations where meltwater formed sizable rivers draining away from retreating ice. For example, significant accumulations of stratified drift occur along the Hop River (Figure 3*a*). It is also common that stratified drift accumulated in meltwater ponds that form in front of retreating ice sheets. This is believed to have been the case for the southern third of Andover Lake (Figure 3*c*) where stratified sandy sediments occur at depth beneath the beach and all of the south bay.

2) Revised Estimates of Soft Sediment in the South Bay

As described in Interim report, sediments in the south bay were probed with an aluminum push rod to determine the thickness of soft sediment. As illustrated in Figure 4 the thickness of soft sediment is simply the difference between water depth and the depth of refusal for the probe. Data in Figure 4 illustrates variations in thickness along a transect across the mouth of the south bay. A more useful approach is to build a thickness map for the entire bay.

To prepare such a map individual point measurements from all stations were assembled into a data set. This includes 262 measurements of water depth and depth to refusal in the lake and 417 points along the shoreline where water depth and probing were set to zero. Each data point then includes Easting and Northing values in feet (using Connecticut State Plane, NAD 83 coordinates), and measures of water depth and SS thickness. All derived maps and volume estimates were trimmed to only consider regions inside the shoreline of the bay.

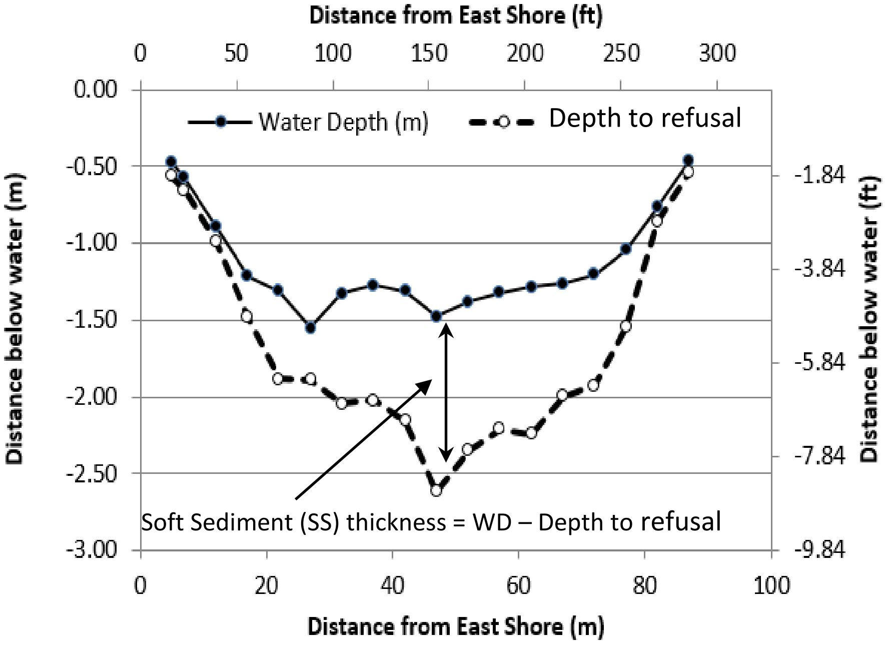


Figure 4. Variations in water depth and the depth to refusal, or the distance from the water surface to the bottom of soft sediment, across the mouth of the south bay (Figure 1). The thickness of soft sediment (SS) is calculated as the difference between water depth and the depth of refusal.

Maps and volumes of soft sediment were presented in the 2015 Interim report. However, in preparing this final report an error in data entry was detected. Specifically, east-to-west water depth and depth to refusal measurements were reversed during data entry along two transects. This has been corrected and a direct comparison between the original interim map and the new map is presented in Figure 5.

Corrected thickness data reveal more spatially consistent distributions of soft sediment than was presented in the interim report (compare Figure 5*a* and 5*b*). In particular, areas underlain by 2 to 3 ft. of soft sediment (green areas in the map) cover more of the bay-bottom, especially in central-eastern portion of the bay. There is little change in the distribution of thin SS zones on the west side of the bay, although areas with thin soft sediments (red and salmon colors) are more closely confined to the east shore than in the original map.

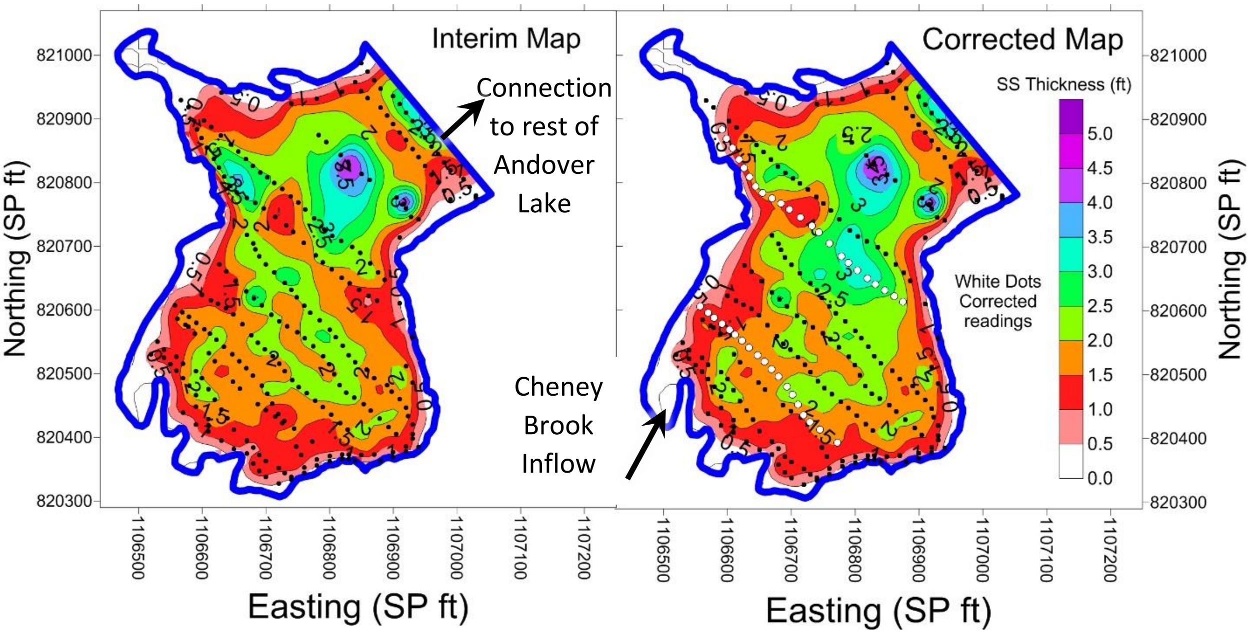
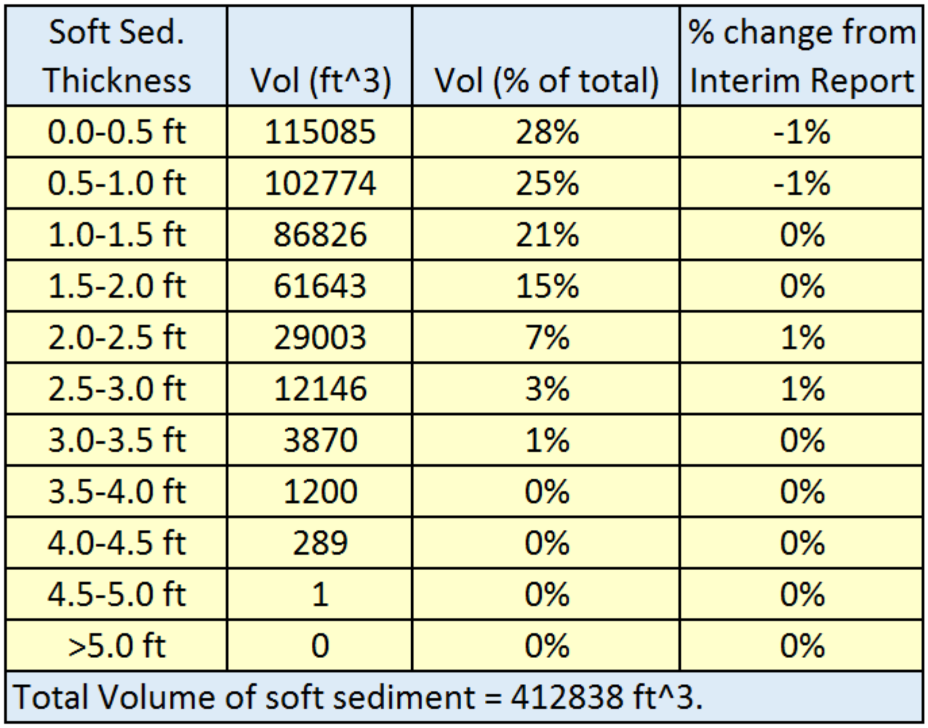


Figure 5. Comparison of soft sediment thickness maps presented ***(a)*** in the original preliminary report and ***(b)*** using corrected depth data. As noted above, depth data for probe locations shown in white were originally reversed. The ***(b)*** corrected map reveals a more spatially coherent distribution of soft sediment and a slight increase in the area underlain by 2-3 ft. of soft sediment.

The total volume of soft sediment in the bay based on the corrected data set increases slightly to 412,838 ft^3 (Table 2). This is an increase of ≈9,100 ft^3 or ≈2.2% over the value given in the interim report. Despite the slightly higher estimates of soft sediment, key findings from the interim report are unchanged. There remains a sizable quantity of soft sediment in the bay. The thickness of soft sediments is not the same everyone, and soft sediment clearly is thicker in the central part of the bay than it is near the shoreline (Figure 5b). The larger volume of sediment would likely translate to approximately a 2% increase in the estimated cost of dredging presented in the interim report.

Table 2. Soft Sediment Volume Estimates by Depth



Soft Sed. Thickness	Vol (ft^3)	Vol (% of total)	% change from Interim Report
0.0-0.5 ft	115085	28%	-1%
0.5-1.0 ft	102774	25%	-1%
1.0-1.5 ft	86826	21%	0%
1.5-2.0 ft	61643	15%	0%
2.0-2.5 ft	29003	7%	1%
2.5-3.0 ft	12146	3%	1%
3.0-3.5 ft	3870	1%	0%
3.5-4.0 ft	1200	0%	0%
4.0-4.5 ft	289	0%	0%
4.5-5.0 ft	1	0%	0%
>5.0 ft	0	0%	0%
Total Volume of soft sediment = 412838 ft^3.			

3) Sediment Cores

Three sediment cores were collected from the south bay at locations identified in Figure 1 using a vibracoring technique (Figure 6). Cores And14-01 and And14-02 were recovered from a water-based coring platform in June of 2014 while Core And15-02 was extracted through the ice in January of 2015. These cores were examined to note changes in sediments, soil color, organic debris, as well as subsampling to determine changes in moisture content, organic and inorganic carbon, bulk density, and a variety of whole-sediment chemical concentrations. The following provides a brief description of these cores, with particular emphasis on the presence of a buried soil profile within the sediment column.

Figure 6. (left) Eastern students Samantha Walter and Trent Stevens assist Drew Hyatt with vibracoring in the summer of 2014, while (right) John Corl, former Eastern student Amberlee Nicoulin and UCONN graduate student Megan McCaster collect a core in January of 2015.

All of the cores displayed very similar changes in character with depth below the pond bottom. A photo log for all cores is given in Figure 7 while changing physical properties for core And14-02 is

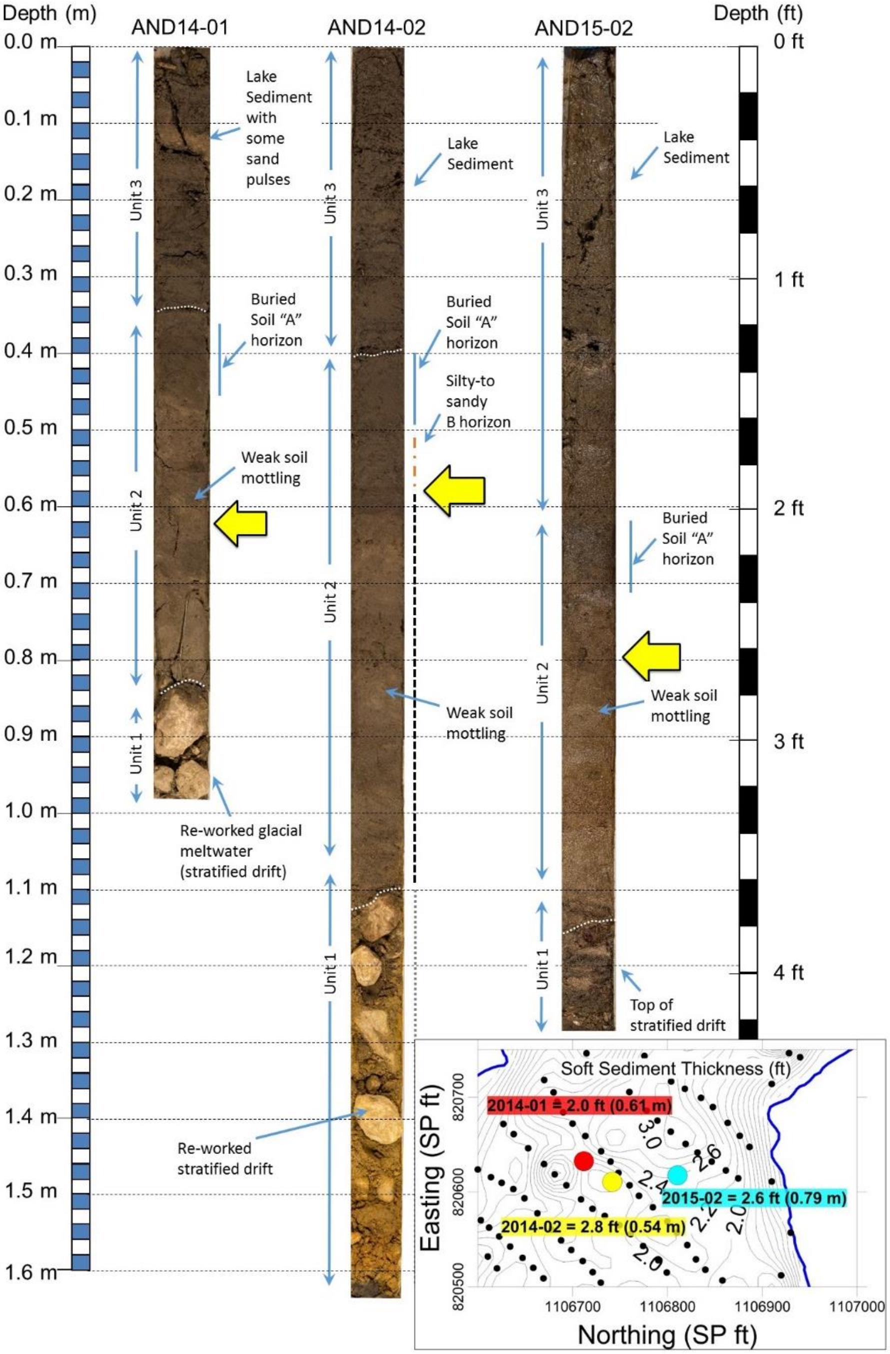


Figure 7. Photo core logs for cores collected from the south bay. All three cores display consistent sedimentary characteristics including a buried soil profile (Unit II) which could only have formed before Andover Lake was dammed. Yellow arrows identify approximate depths of penetration for the soft sediment probes at the locations of the cores. Inset map shows the location of each core in relation to the thickness of soft sediment.

summarized in Figure 8.

Three sedimentary units are present in all cores. These units are described from the top-down, although geologic convention is to number units from the bottom-up. Uppermost sedimentary unit III, consists of organic-rich lake muds commonly referred to as gyttja. Unit III has elevated organic carbon, high moisture contents, and the lowest bulk density values of any unit (Figure 8). This lake gyttja overlies a silty-loam textured deposit (Unit II) that contain features indicative of a period of soil formation in a subaerial (*i.e.* not underwater) setting. Soils develop very slowly and very little if at all beneath lakes. As such, Unit II soils must have formed before the damming of Andover Lake. The top of Unit II has elevated organic carbon and moisture concentrations but those measures decrease with depth. Bulk density shows a corresponding inverse trend, increasing with depth as the soils become sandier downwards. The soils of Unit II formed within pre-existing deposits that transition from fine silty-sand in Unit II to coarse sands, gravel, and large rounded cobbles within Unit I. These Unit I coarse sands to cobbles are most likely glacial meltwater deposits that were reworked by streams draining the valley after glaciers retreated but before Andover Lake was formed. Key characteristics for these sedimentary units are summarized in Table 3, while Figure 9 illustrates soil features recognized in the core along with a view of the transition to basal stratified drift.

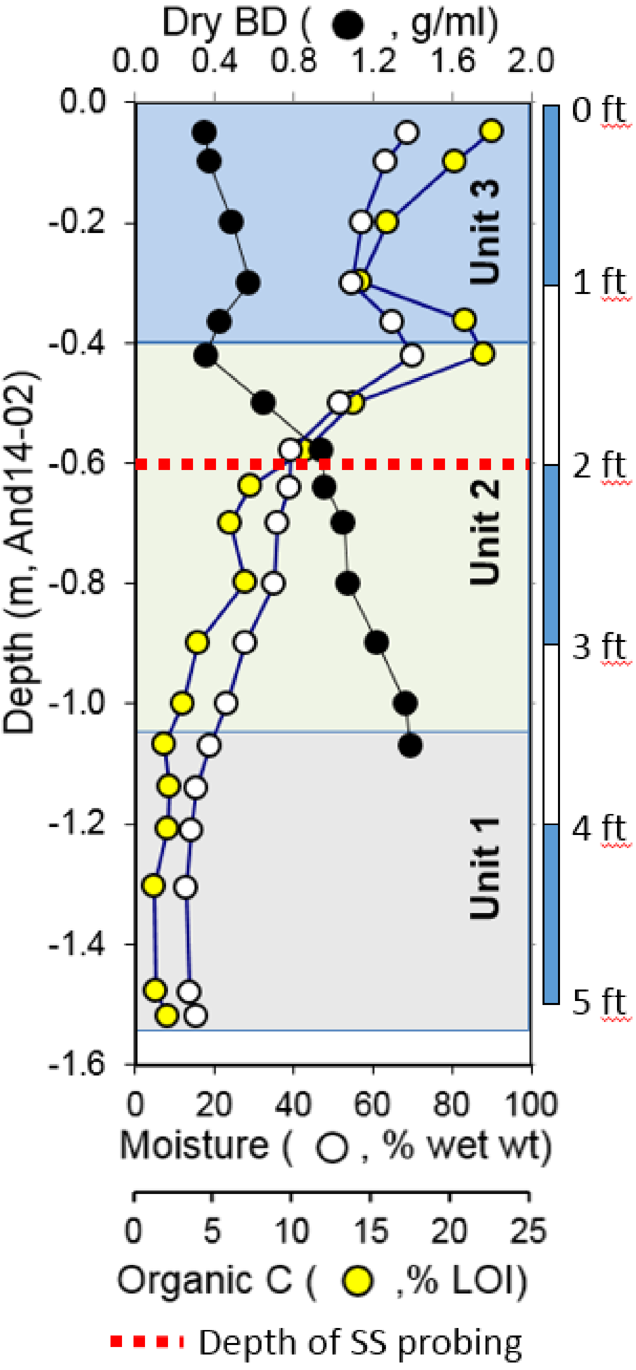


Figure 8. Physical properties for core And14-02 with depth. Sedimentary units, described above, are identified by colored shading (blue, green, grey) while the depth of soft sediment probing is indicated by a bold dashed red line at 0.61 m depth in the core. Interestingly, the soft sediment depth of refusal occurs just below the organic-rich A-horizon in Unit 2. This also corresponds to the depth at which bulk density of the sediments increases, likely explains why probes penetrated no deeper.

Table 3. Summary characteristics for Sedimentary Units observed in cores.

Unit and Thickness		Interpretation and Key Characteristics
III	And14-01: 35 cm And14-02: 40 cm And15-01: 61 cm	***Lake Sediments*** Dark brown to black (Munsell color: 10YR 2/1), loose consistency, low density, rich in organics including abundant leaf and twig fragments, decayed, odiferous, silty-sand pulses in some core.
II	And14-01: 48 cm And14-02: 70 cm And15-01: 40 cm	***Buried Land-based soil profile*** Dark brown (10YR 2/2) to dark-yellowish brown (10YR 4/4), organic rich, firm silty-clay upper "A" horizon with transitional base. Becomes denser downward, with increasing slit and sand. Lower portions of the profile have weakly defined discolorations believed to be preserved soil mottling.
I	And14-01: >15 cm And14-02: >52 cm And15-01: >14 cm	***Reworked coarse-grained sands, gravels, and rounded cobbles*** Yellowish-brown (10Y 3/4) buff colored sand and gravel. Very little to no organic material, clasts are rounded indicating water transport. Much denser and more sandy material than above.

The interpretation of Unit II as a buried soil is very important to understanding the sedimentary record of infilling in the south bay. As such, Figure 9 presents some of the subtler but important characteristics that indicate the presence of a paleosol (past soil). First, soil formation within the silty-sand loams of Unit II are suggested by the presence of discoloration blotches (called mottles) at depth. Mottles commonly form in soils by alternating periods of wetting and drying which drives reversible oxidation-reduction reactions in the soil. Indeed, many Eastern Connecticut soils in valley bottom positons (*e.g.* Saco series soils) develop dark grey mottles in silty loams that are similar to those visible in Figure 9*a*. However, the strongest evidence for a buried soil origin for Unit II is the presence of a very dark to black organic-rich silty loam at the top of Unit II (Figure 9*b*). This layer is believed to be buried top soil (a former soil "A-horizon"). Elevated carbon concentrations (Figure 8) and notably higher silt, a stiffer consistency, and the absence of organic debris present in lake sediments all support a buried A-horizon interpretation. In fact, the transition to overlying black organic rich lake sediments (*i.e.* Unit III in Figure 9*c*) is subtle and is more easily recognized in core because of the much looser and watery appearance of the overlying gyttja and the presence of partially decomposed organic detritus (*e.g.* leaves and twigs).

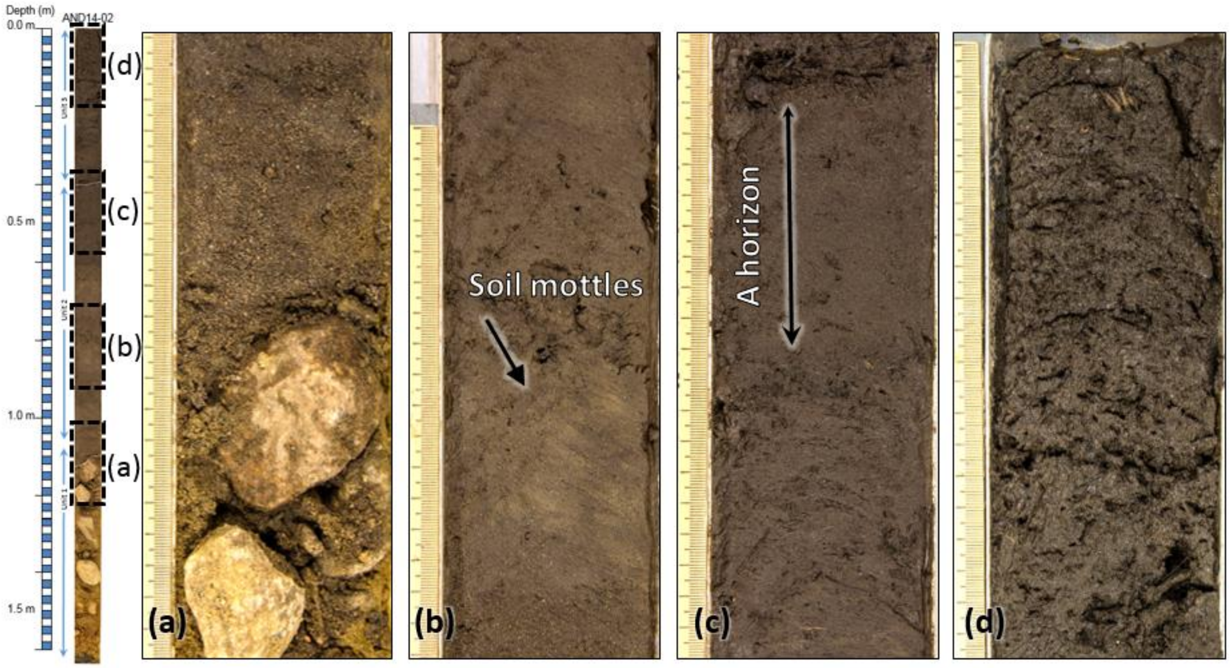


Figure 9. Close views of selected portions of core And14-02 illustrating ***(a)*** reworked stratified drift in Unit I, ***(b)*** soil mottles, and ***(c)*** a buried topsoil or A-horizon in unit II, with ***(d)*** covering organic rich lake gyttja that contains abundant partially decomposed organic fragments. Note: all images have been significantly lightened so that details are visible. The cores are much darker than shown above.

4) Bulk Sediment Chemistry for 2014 Cores

In addition to estimating the thickness of soft sediment, there is interest in evaluating the chemical character of sediments in the bay to better understand whether dredging might introduce unwanted constituents to the lake. This is in fact a complex undertaking because many factors influence chemical exchange between lake waters and sediments. For example, the sediment-water interface is subject to changing oxidation-reduction (redox) conditions which can strongly influence the mobility of elements between sediments and the water column. As well, the manner with which elements are bound to sediment and organic particles is complex and subject to change.

The following adopts a simple descriptive approach in characterizing bulk sediment geochemistry. A total of 32 dried sub-samples from cores And14-01 and And14-02 were submitted to ALS Chemex Geochemistry laboratories for digestion and multi-element scans using inductively coupled plasma-atomic emissions spectrometry. Digestions were performed by Chemex using a mix of nitric and hydrochloric acid (*i.e.* aqua regia dissolution) that dissolves most soluble materials but does not break down silicate crystal structures within minerals. As such, whole sediment chemistry values reported below are likely somewhat higher than the bioavailable fraction but are less than what would be expected from a total digestion method.

For this study, elemental scans are used purely as a descriptive means to indicate the relative abundance of elements within different parts of the sediment column. Putting it more simply, the chemical results below may be best thought of a measure of the chemical richness of the sediments. Results presented here do not follow protocols used to evaluate dredging waste. If dredging were considered further it would be essential to obtain appropriate chemical data from a certified lab with experience assessing the geochemistry of dredge spoil in fresh water lakes.

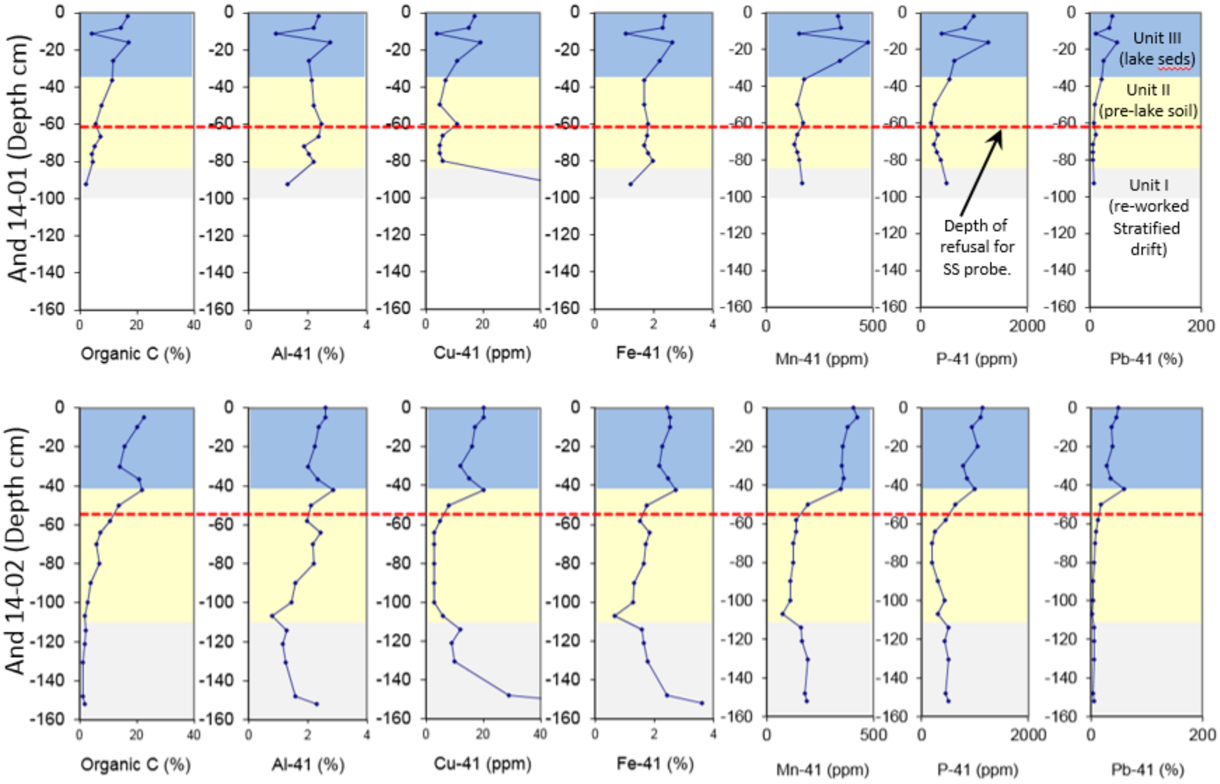


Figure 10. Plots depicting variations down core in the concentration of Organic Carbon, aluminum (Al), copper (Cu), Iron (Fe), Manganese (Mn), Phosphorous (P), and lead (Pb) for (top) And14-01 and (bottom) And 14-02. See text for discussion.

With these caveats in place, it is useful to examine concentration profiles for several of the 41 scanned elements (Figure 10). The left-most graph for each core presents changes in organic carbon with depth based on mass loss on ignition at high temperature. These are the same carbon values as presented in Figure 8, and are included because organic debris often binds elements and therefore elemental trends may track variations in organic carbon. The remaining elements in Figure 10 were chosen because their concentrations were above detection limits throughout the cores, and in some cases they may have environmental significance. For example, aluminum (Al) and Manganese (Mn) are common in earth materials and may reflect erosive input to the bay, copper (Cu) and iron (Fe) can be mobilized by changing redox conditions, and lead (Pb) and phosphorous (P) can be important to ecosystem functioning through exchange with plants.

Each plot in Figure 10 depicts changing concentration with depth illustrating how elementally abundance varies in lake sediments (Unit III), pre-lake soils (Unit II), and basal re-worked stratified drift (Unit 1). Trends are mixed. For example, Organic C, Mn, P, and Pb generally are highest in Unit III and decrease with depth in the sediment column. Al does not display persistent changes in concentration with depth, while Cu, and Fe have highest concentrations near the bottoms of cores in Unit I (at least for And14-01).

More definitive comparisons of mean concentrations for each element is given in Table 4. These tests compare the mean concentrations in the uppermost lake sediments (Unit III) and for the whole thickness of soft sediment with concentrations in underlying sediments. Significant differences are indicated by yellow shading. Viewing the entire table several patterns are apparent: First, And14-01 results are more ambiguous than are results from And14-02, suggesting that geochemical trends, like the thickness of soft sediment, may vary with location. Secondly, on balance most elements have higher concentrations in Unit III and in the soft sediments than in deeper sediments. These findings suggest that any mixing of sediments by dredging activities would likely introduce the chemically richest sediments to the water column.

Table 4. Statistical comparisons of elemental abundance for samples grouped by sedimentary unit

	And14-01		**And14-02**	
	Ho: [Unit III] >[lower seds]	**Ho: [Soft Seds] >[lower seds]**	**Ho: [Unit III] >[lower seds]**	**Ho: [Soft Seds] >[lower seds]**
Organic C	SD, p=0.023	SD, p<0.004	SD, p<0.000	SD, p<0.000
Al	ND, p=0.480	ND, p=0.261	SD, p=0.003	SD, p=0.001
Cu	ND, p=0.387	ND, p=0.385	ND, p=0.159	ND, p=0.350
Fe	ND, p=0.102	SD, p=0.040	SD, p=0.005	SD, p=0.040
Mn	SD, p=0.014	SD, p=0.014	SD, p<0.000	SD, p<0.000
P	SD, p=0.014	SD, p=0.034	SD, p<0.000	SD, p<0.000
Pb	SD, p=0.010	SD, p=0.007	SD, p<0.000	SD, p<0.000

5) Ground Penetrating Radar Mapping

GPR data collected in the south bay serve three purposes. First, January 2014 data enables development of a 3D visualization of materials beneath a 50 m x 80 m area in the bay (see Figure 1 for locations). This visualization identifies major subsurface reflectors that define the sub-lake geologic framework. Secondly, June 2014 transect data, also identified in Figure 1, provide higher resolution visualizations of reflectors beneath the entire bay. This will support future efforts to evaluate the spatial distribution of sub-lake GPR reflectors, something that goes beyond the scope of this report. Thirdly, the June 2014 radar data are well suited to extracting detailed water depth in support of building a detailed bathymetric map for the south bay. This map is helpful in estimating the volume of water in the bay, to infer likely pathways for circulation as water enters the bay moves out to the lake, and to estimate original water depths in the bay *ca.* 1930 (*i.e.* shortly after the lake would have been fully formed).

January 2014 Radar Data

Fifty 100 MHz GPR transects, each 80 m in length, were collected in January 2014 at a 1 m spacing using a Sensors and Software Pulse Ekko Pro GPR on a smart cart that was pushed across the ice (Figure 11). Transect data were assembled into 3-dimensional visualization of subsurface reflectors using Ekko software (Figure 12). The geologic framework beneath the bay includes packages of sediments that overly bedrock. Numerous internal reflectors are present indicating transitions between bedrock, overlying glacial deposits, and capping lake sediments. It is noteworthy that the basal bedrock reflector in Figure 12 shallows as one moves toward the southwest shoreline. This is to be expected as there are many locations around the lake where bedrock becomes exposed at the surface. Although lake bed reflectors are clearly evident, the transition from soft sediment to deeper silty/sandy sediments is faint and poorly controlled in this volume. Indeed, these subtle reflectors are much more apparent in the 200 MHz data set described next.

Figure 11. View to the SSE of the Pulse Ekko Pro GPR and smart cart at the time of data collection. Wheel lines visible in the snow indicate the direction of travel while collecting GPR data.

June 2014 Radar Data

The 200 MHz data set provides higher resolution sub-lake reflectors within ≈5 m of the lake bed. A single transect is illustrated in Figure 13 using a velocity that is appropriate for water. As such, the yellow dashed line, which identifies the bottom of the bay is scaled correctly on the left-hand axis, and these depths may be extracted to prepare a bathymetric map of the bay (Figure 14). In addition to the lake bed, several internal reflectors are present including: *(a)* a transition from soft sediments to harder sandier deposits at depth; *(b)* numerous internal reflectors indicative of bedding in sandy sediments interpreted as glacial stratified drift; and *(c)* hard reflectors at depth that most likely mark either a transition to glacial till or bedrock.

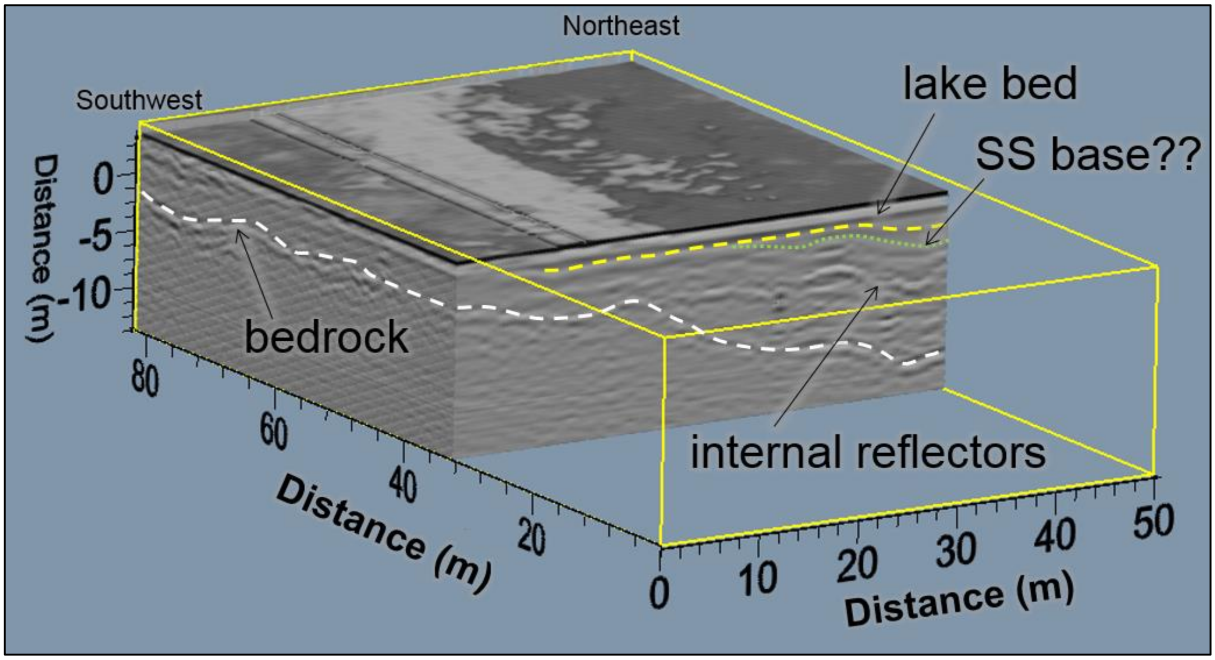


Figure 12. Three-dimensional block diagram of 100 MHz radar data collected within the shaded region of the south bay identified in Figure 1. At least 3 reflectors are evident in this diagram which, from bottom-to-top, are interpreted as bedrock (white dashed line), the base of soft sediment (green dots), and the lake bed yellow dashed line).

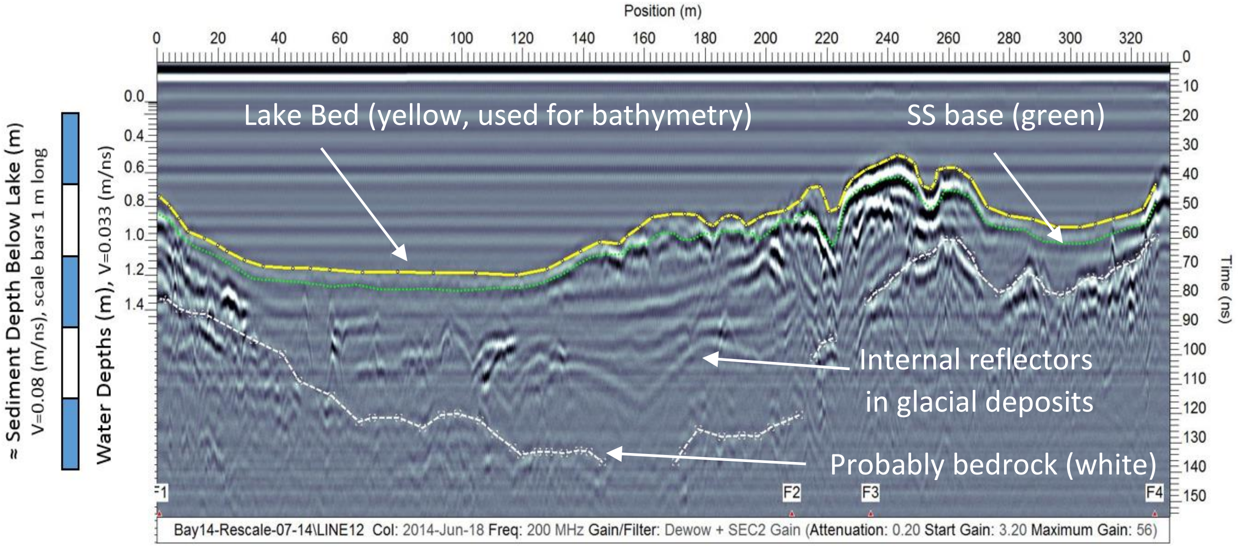


Figure 13. GPR transect 12 depicting subsurface reflectors including the lake bed (yellow dashed line) which was extracted from all radar transects to prepare a bathymetric map.

Detailed analyses of these subsurface reflectors is complicated by significant differences in the velocity of radar waves as they pass through lake water, which has a relatively slow 0.033 m/nanosecond velocity, to underlying sediments that have velocities closer to 0.08 m/nanosecond. As such, the primary depth scale on the left-hand axis of Figure 13 identifies water depth, while a second colored scale bar based on V= 0.08 m/ns should be used to consider depths beneath the lake bed. Resolving true depths for deeper radar reflectors will be pursued in the future separate from this study. The remainder of this section focusses on findings associated with the lake-bed reflector which is known from all June 2014 transects.

Radar-Derived Bathymetric Map of South Bay

All radar lines from June 2014 GPR data set were digitized to identify the lake bed and prepare a detailed bathymetric map of the south bay. Depth measurements were extracted at 5 m intervals along each line and imported into Surfer software to build a digital elevation model of the lake bottom in the bay (Figure 14).

Several topographic features are evident from the new bathymetric map (Figure 14). Two deeper basins are present including a larger elongate East Basin that extends along the east shore of the bay out to the center of the bay and northwest toward the rest of the lake. As well, a smaller and somewhat shallower West Basin occurs in the northwest inlet. Finally, a ridge-like shallow zone (yellow colors in the map) separates these basins running parallel to a deeper pathway that conveys much of the incoming water from Cheney brook.

As water flows into the lake variations in depth will influence the pathways by which water circulates through the bay. Bold arrows in Figure 15 identify probable locations where water is funneled by shallow areas toward the deeper basins. In general, flow introduced by Cheney Brook likely splits near the northern end of the shallow sandy ridge. Some continues northward joining flow from the northwest inlet, while some flow moves eastward into the main basin. In fact, during extensive draw down of the lake it is possible to observe these pathways. Flow patterns identified in Figure 15 are undoubtedly subtle and are subject to change as the topography of the lake bottom changes. Perhaps the most significant point to be made is that water entering the bay would appear to circulate throughout much of the bay as it moves to the rest of the lake. That is, there is a strong connection between water in the bay and the rest of Andover Lake.

Digital elevation model data used to build these maps also supports calculation of water volume in the bay. For normal summer water levels ≈ 16,940 m^3 of water is present in the bay. This is equivalent to ≈4.48 million gallons or 13.7 acre-feet. It is useful to compare this volume to that of the entire lake, based on the digital elevation model data used to construct the map in Figure 2*a*. The total volume of the lake is ≈1,879,10m^3 (≈1523 acre-feet). As such, the south bay represents ≈0.9% of the lake's volume.

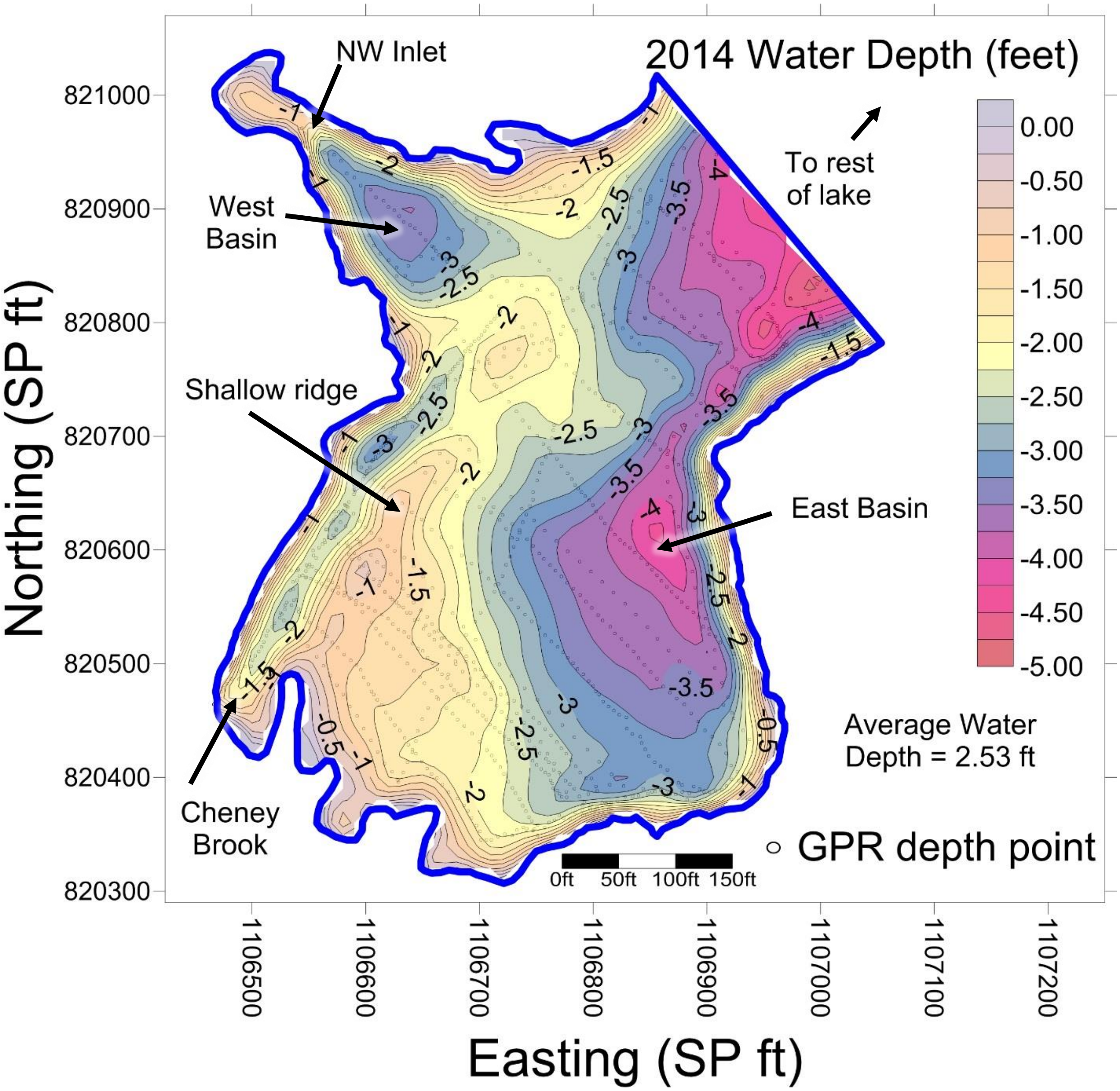


Figure 14. Bathymetric map for the south bay for typical summer water levels. This map is based on depth soundings derived from GPR records at locations identified by faint grey circles. Discussion in the text refers to two depositional basins, a sandy ridge, and the northwest inlet identified with labels above.

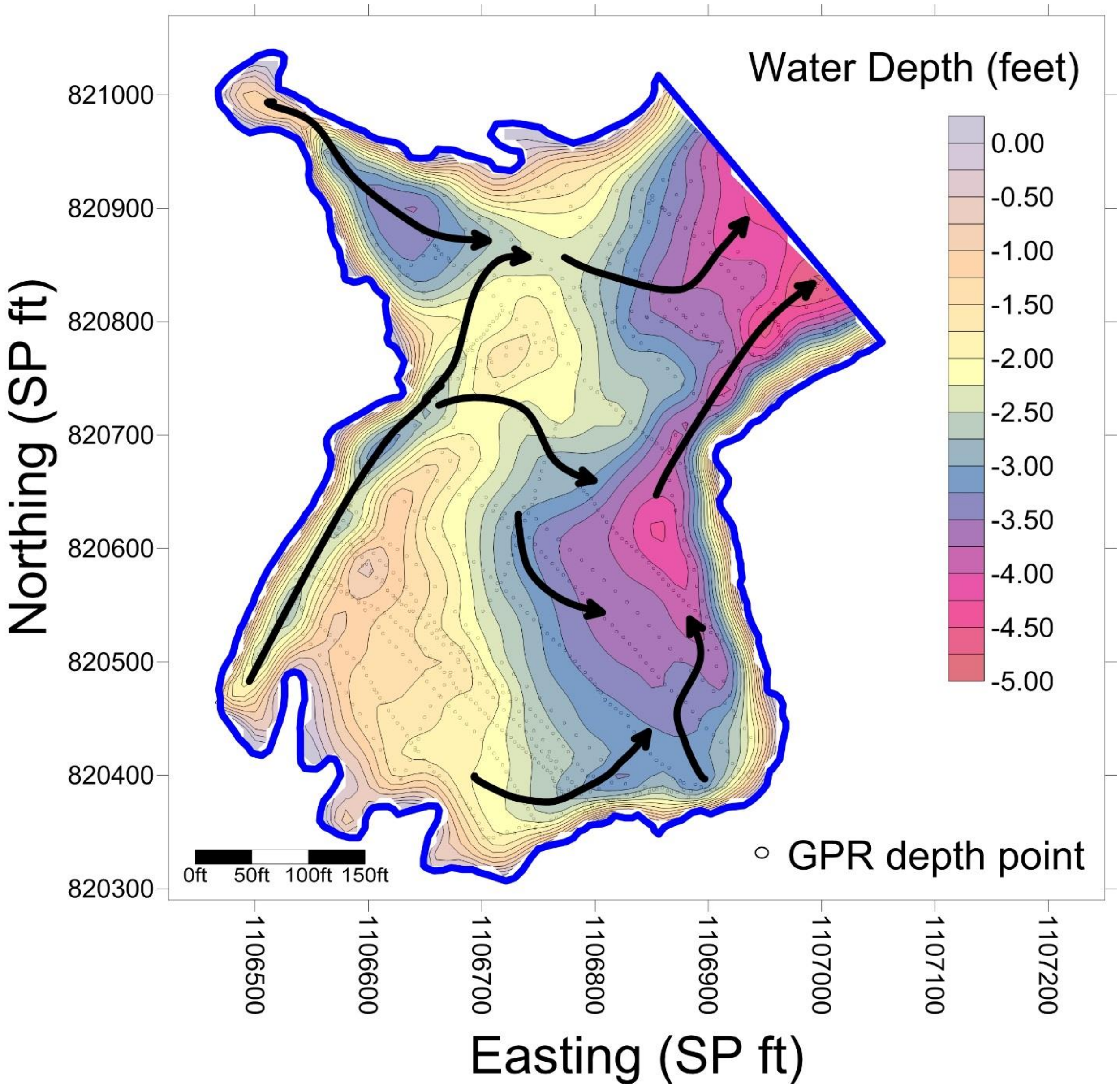


Figure 15. Bathymetric map for the south bay with arrows indicating likely pattern of circulation in the bay. Primary input to the bay is directed flow from Cheney Brook, although small amounts of runoff are also derived from intermittent flow coming in to the NE inlet. Secondary circulation likely also occurs over the submerged sandy ridge adjacent to inflow from Cheney Brook.

An important point arises from the preceding comparison of water volume in the bay and the rest of the lake. That is, given that 54% of the lake's drainage basin delivers runoff into the bay, and the volume of the bay is tiny (0.9%) when compared to the rest of the lake, it is clear that waters entering and circulating in the bay must continue into the rest of the lake. As such, although waters entering the bay will inevitably slow promoting deposition of coarser sediments (sand and silt) in the bay, it is also clear that most of the incoming water and associated sediments will be transported further out to the lake. This means that while the bay is indeed an area where sands and silts accumulate, the vast majority of water and sediment entering the bay is carried out further into the lake. As such, the bay is very much connected to the rest of the lake, and were dredging considered further it would be important to receive advice on how conditions in the bay might impact water quality and aquatic life in the rest of the lake.

Previous Water Depths in the South Bay

Anecdotal accounts by long-term residents of Andover suggest the bay was previously much deeper than at present; some have even suggested (at the most recent semi-annual meeting) that the bay used to be the deepest part of the lake. These anecdotal reflections may be compared to estimates of past water depths derived from data developed in this report.

A map depicting probable water depths shortly after Andover Lake was formed (say ≈ 1930) is presented in Figure 16. This map assumes that the water surface in summer, once the lake was fully formed, was the same as the water surface elevation as mapped in 2014. The depth of the original bay, however, would have been deeper because none of Unit III lake sediments would have as yet been deposited. As such, probably depths for the *ca.* 1930 bay would be roughly equivalent to the depth to the bottom of Unit III as mapped in 2014. The thickness of Unit III at probing locations (Figures 7, 8) on average is 68% of the depth of sediment probing at these coring sites.

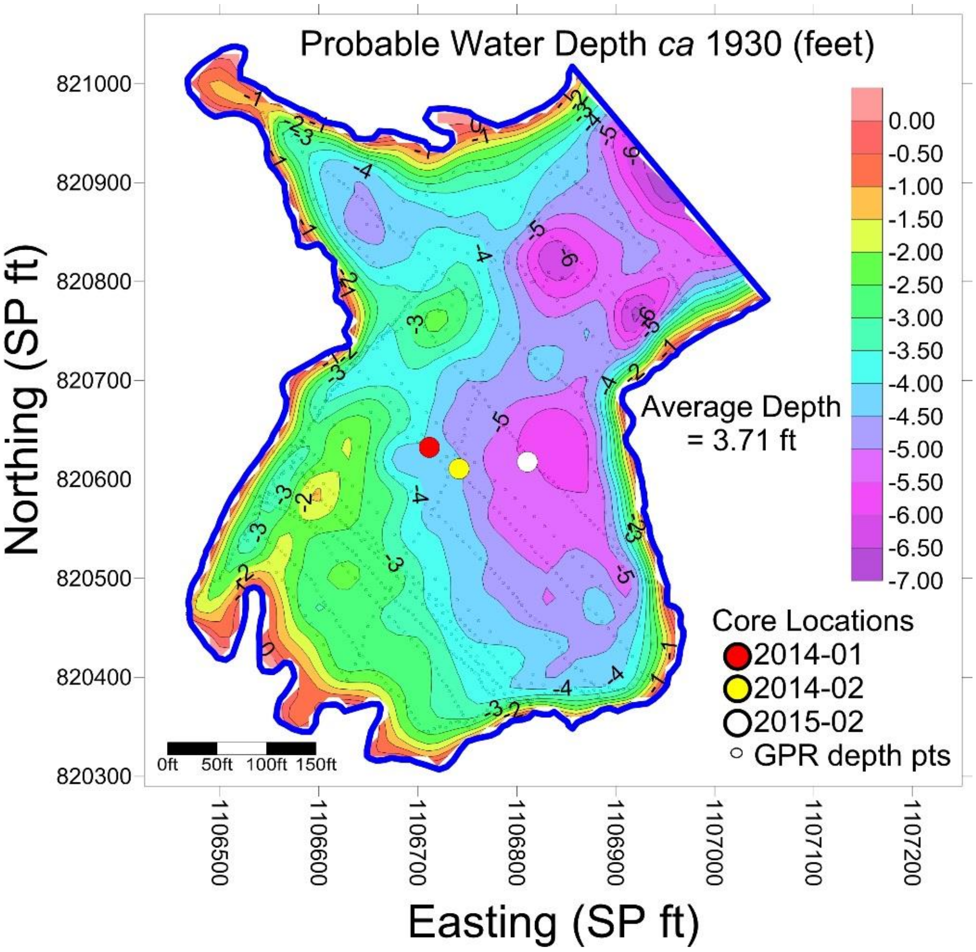


Figure 16. Bathymetric map for the south bay in ≈1930. These hypothetical depths are derived by subtracting estimates of the thicknesses lake sediments (Unit III) deposited in the bay since Andover Dam was built in 1927 from the 2014 bathymetry of the bay. These depths are an approximation, and rely on several assumptions extracted from measurements made at the locations of Cores And2014-01, And2014-02 and And15-02.

Thus, as a first approximation, the *ca.* 1930 depth may be calculated for the entire bay as:

$$\text{Depth}_{1930} = \text{Depth}_{2014} - \text{Thickness Unit III}_{2014} \qquad \textbf{[1]}$$

where all variables in equation [1] are in matrix form and consist of:

Depth_{2014}: Depth matrix derived from GPR data and used to build Figure 14

$\text{Thickness Unit III}_{2014}$: is the thickness of sedimentary unit III. Based on the three core locations, Unit III is on average 68% the thickness of the soft sediment. Thus the thickness of Unit III is calculated as 0.68 x the matric of soft sediment thickness values.

Original water depths (*ca.* 1930) in the south bay as presented in Figure 16 bear some resemblance to present-day conditions. For example, the East Basin is present both 2014 bathymetric (Figure 10) and in *ca.*1930 maps. However, the East Bay was ≈2 feet deeper and somewhat larger early in the lake's history. As well, the flow path from Cheney Brook is more clearly defined in *ca.* 1930 map. It is interesting to compare average water depths for both maps. In *ca.* 1930 the average water depth of the south bay is estimated to have been 3.71 feet which is ≈1.1 feet deeper than the average water depth in 2014 (2.53 ft.). Thus, while the deeper basins have infilled more than some other locations in the bay, average water depth has only decreased by a little more than 1 foot. Also, Figure 16 suggests that south bay was never deep throughout. Indeed, even at its deepest locations in *ca.* 1930 the south bay was still only ≈45% of the maximum depth of Andover Lake (*i.e.* 14.8 ft. near the dam; see Figure 2a).

6) ^{210}Pb Dating of Core And15-01

^{210}Pb is a common but complicated dating technique that is used to determine the age and mass sedimentation rate for lake sediments extending back ≈150-200 years (Appleby, 2001). This technique relies on measurements of ^{210}Pb activity and sediment mass throughout the full length of a core. ^{210}Pb arrives at the lake both by atmospheric deposition (referred to as unsupported ^{210}Pb) and by decay from radium within minerals in the sediments (referred to as the supported ^{210}Pb or "background"). As such, ^{210}Pb dating must first determine the "excess ^{210}Pb" which is the unsupported ^{210}Pb less background. An inventory of excess ^{210}Pb in the core is then calculated and mass sedimentation is modeled to determine ages. More detailed explanation of this technique and associated limitations may be easily found by searching "explain 210-Pb dating" on-line.

^{210}Pb results for And2015-02 are presented in Figure17. This is a complex figure that requires some explanation. First, variations in moisture content and bulk density with depth are depicted in Figure 17*a*. Similar to And2014-02 (Figure 8) uppermost lake sediments (blue) have higher moisture and lower bulk density than is present in underlying pre-lake soils (Unit II, yellow) and basal stratified drift (Unit I, grey). ^{210}Pb are presented in Figure 17*b*. The solid line with red and white dots indicates changing mass sediment accumulation in the lake, while labels identify dates with error bars for sediment at ^{210}Pb sample depths.

Although ^{210}Pb activity was measured for samples to the bottom of Units II (yellow region in Figure 17*b*) the oldest ^{210}Pb date (1907 at 52 cm depth) occurs near the bottom of Unit III (lake sediments) which is just the top of Unit II soils. Again, deeper sediments in Unit II soils were measured for ^{210}Pb,

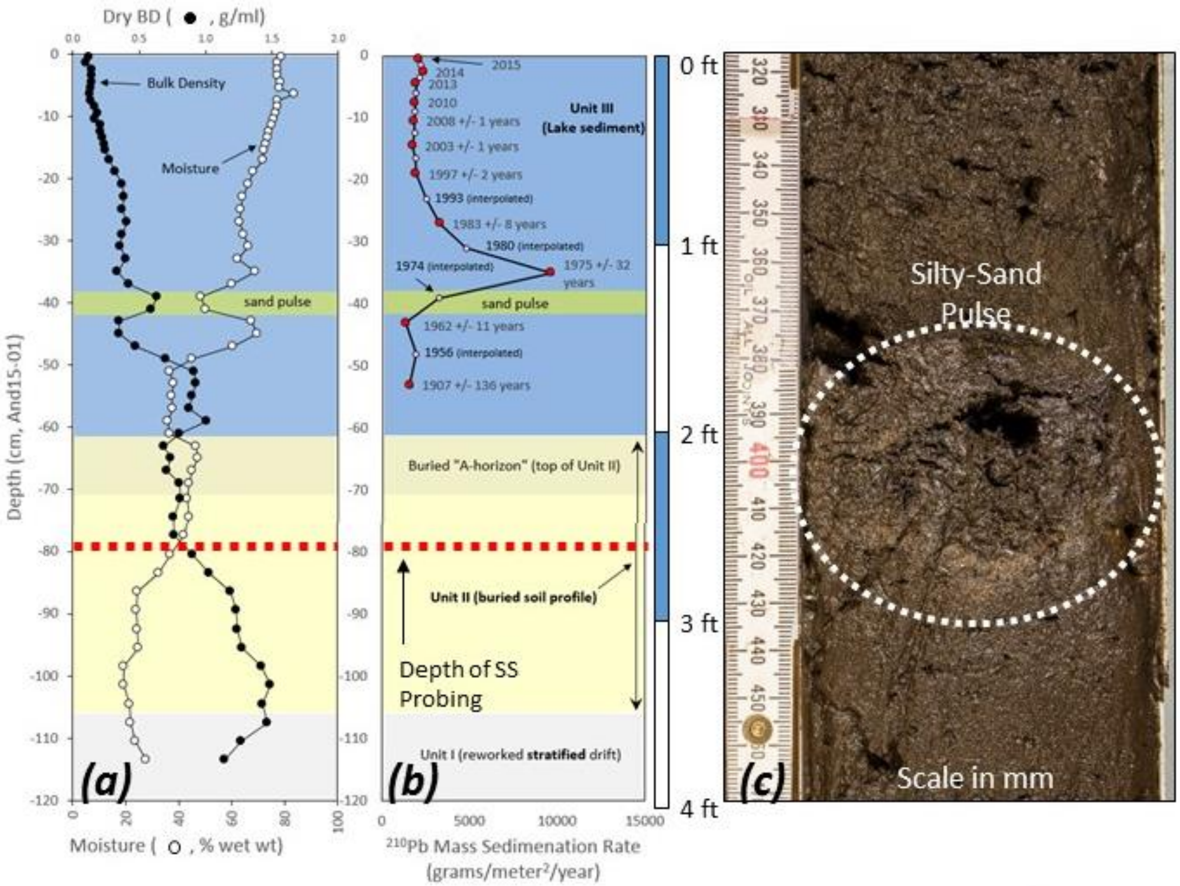


Figure 17. Summary graphic for Core And15-02 including ***(a)*** Variations in dry bulk density (black dots) and moisture content (white dots) with depth, ***(b)*** 210Pb results that depict changes in mass sedimentation with depth (red dots are measured values, pink dots are interpolated values), and ***(c)*** a close view of a silty-sand pulse present from ≈38- cm depth. Note colors reflect sedimentary units (blue = unit III, yellow = unit II, and grey = unit 1). Also the thick dashed red line identifies the depth to which sediment probing penetrated in the vicinity of this core. See text for discussion.

but those samples were too old to yield a finite date. Recall, that the Unit II soils existed before Andover Lake was formed by damming in 1927. Soils take a very long time to form, so it is entirely reasonable that Unit II would be older than the datable range for ^{210}Pb. Nonetheless, the 1907 date (10 years before the dam was built) is clearly within lake sediments (Unit III) which should be no older than 1927. This is initially perplexing. However, the bottom-most ^{210}Pb date (1907) has very large error bars. This is typical for the basal ^{210}Pb dates because very little excess ^{210}Pb remains. That is to say, the activity in the oldest ^{210}Pb dated sample is very near the background ^{210}Pb signal. As a result, the 1907 date is indistinguishable from a 1927 date of damming. Consequently, the basal ^{210}Pb date is consistent with the interpretation of Unit III as lake sediments sitting atop pre-existing older soils (Unit II).

Clearly the most notable aspect of the mass sedimentation curve (Figure 17*b*) is the distinct peak in sedimentation around 1975. This increase in mass sedimentation occurs just above (and likely is associated with) a silty-sand layer in the core (Figure 17*c*). Typically, discrete sand layers like this are indicative of a pulse of sediment entering the lake. Although the specific cause of this layer is not

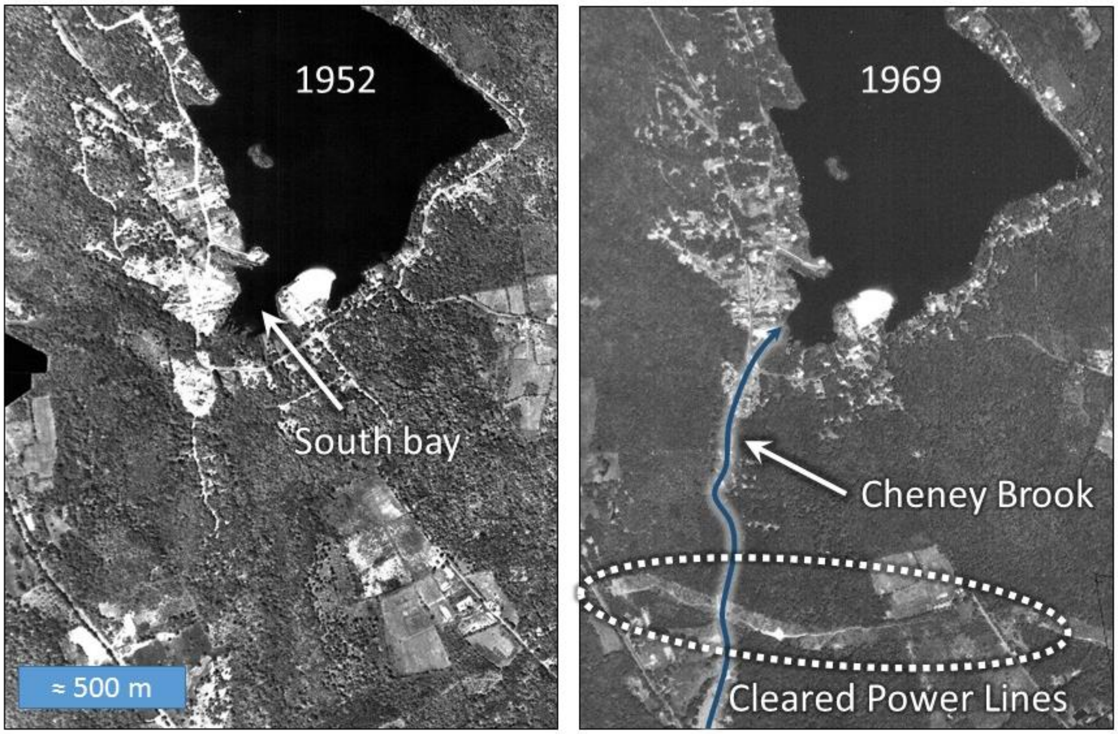


Figure 18. Historical aerial photographs of the southern end of Andover Lake and nearby drainage basin. These images show conditions before (left) and after (right) land clearing for power lines south of the lake. Eroded sediments from this clearing may have entered Cheney Brook contributing to elevated mass sedimentation in the south bay which peaked in 1975.

known, it is possible that a large storm event flushed sediment into the lake. For example extratropical storm Doria tracked through Connecticut in 1971 (www.weather.gov/mhx/Doria). Alternatively, the influx of sediment may have been caused by land clearing near the lake which would enhance erosion. An examination of historical aerial photography reveals that a strip of land was cleared in the 1960's for high-tension power lines that crossed Cheney Brook less than 1 km from the south bay. Figure 18 presents bracketing aerial image this area before (1952) and after (1969) the power lines are visible. Cheney Brook may have entrained more sediment following land-clearing thereby contributing to higher mass sedimentation rates in the south bay.

^{210}Pb dates may also be used to examine sediment accumulation rates (Figure 19). For example, ≈32 cm of sediment accumulated at the coring site since 1975, nearly 20 cm of which was laid down since 2000. Rates of change of sediment thickness based on ^{210}Pb samples are presented in Figure 19*b*. Some 3 cm of sediment was introduced in association with the 1975 event described above. Perhaps the most interesting aspect of this plot is that the thickness of accumulated sediment in the bay has increased slightly since about 2000. This suggests ongoing sedimentation in the bay at a time of normal flow conditions and no land disturbance in historical air photographs. Although speculative, this may suggest increased sediment production through biogeochemical processes within the lake (i.e. autochthonous sources alluded to in section 1, p. 6).

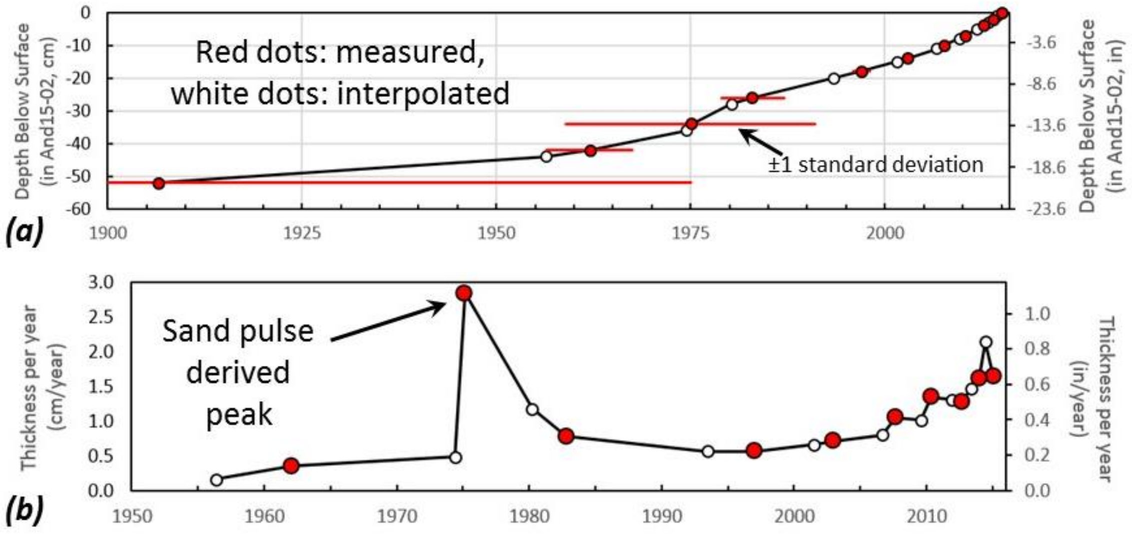


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Figure 19. (a) Plot of sediment ages with depth in And15-01. Standard deviation error bars are given as horizontal red lines. The plot may be used to estimate the amount of accumulated sediment at different points in time. ***(b)*** Accumulation rates for sediments based ^{210}Pb data. Note the slight increase in sedimentation rate since 1997 in the south bay.

Summary of Key Findings

Key findings arising from research on sediments in the south bay include the following.

Drainage Basin Size and Volume of Water in the Bay

1) The south bay is small with an area 3.4% that of the entire lake, yet the bay receives water and sediments derived from 54% of the entire lake's drainage basin. Thus, a large supply of water and contained sediment is introduced to a constricted small bay. This makes the south bay a natural trap for coarse grained sediments.
2) The bay has a small volume of water which is less than 1% of the volume of the whole lake. Since the bay receives a large volume of flow from Cheney Brook and tributary, water will move into and through the bay and onward to the lake. This indicates a strong connection between water in the bay and the rest of the lake. What happens in the bay does not stay in the bay!

Sediment Probe Data and Soft Sediment Volume

1) Total soft sediment volumes for the bay (≈412,800 ft^3) is 2.2 % higher than indicated in the interim report. Sediment thickness varies with location, it is thickest beneath an East and West Basin (Figure 14), and thinnest along a shallow sandy ridge that parallels the inflow channel from Cheney Brook.
2) Costs for dredging would be likely be high (>$500,000). Dredging spoil would require a sizable area to drain, and there would be significant transport issues to remove dredged sediments from the site.

Sediment core analysis

1) All core reveal three sedimentary units: upper most lake sediments (Unit III), underlying pre-lake soils (Unit II), and basal reworked stratified drift (Unit I). Only unit III has accumulated in the lake.
2) On average cores indicate that the lake sediments (Unit III) account for the uppermost ≈68% of soft sediment beneath the bay. As such, approximately ≈32% of soft sediment in the bay existed before Andover Lake was formed.
3) The appearance of the bottom of lake sediments (Unit III) and the top of the underlying soil (Unit II) is very similar. Both are dark, both are soft, and both are organic-rich. If dredging were undertaken, it likely would be difficult to recognize the transition from Unit III to Unit II. As a result, dredging would almost certainly remove some sediments that existed at the site prior to the flooding of Andover Lake.

Bulk Sediment Geochemistry

1) Plots and statistical tests of selected elemental concentrations in the sediment column indicate that the uppermost sediments in the bay have the richest chemical compositions. This is the portion of the sediment column that is most likely to be disturbed during dredging. Since bay water circulates with the rest of the lake, dredging could risk introducing unwanted chemical constituents and nutrients to the rest of the lake unless significant efforts were made to limit circulation from the bay to the lake.
2) If dredging is considered further it would be important to collect new samples from the bay to determine if they contain hazardous materials. Analyses of these samples should be performed by an agency familiar with dredging assessment protocols.

Ground Penetrating Radar

1) Both 100 MHz and 200 MHz data reveal subsurface reflectors that are related to bedrock, overlying glacial deposits, and capping lake sediments beneath the bay.
2) In this report, GPR data are mainly used to construct a detailed bathymetric map of the bay. This map reveals clearly the presence of two deeper basins, and a sandy ridge adjacent to inflow from Cheney Brook.
3) Likely circulation patterns for water within the bay inferred from the bathymetry map implies some direct flow out of the bay in line with Cheney Brook, but also mixing in the deeper east basin.
4) A hypothetical bathymetric map for the bay shortly after the lake was formed (*ca.* 1930) is developed from GPR and coring data. The bay likely was on average of 1.1 feet deeper in 1930 than in 2014. East and west basins were slightly larger and deeper, although maximum water depths likely did not exceed 6.5 ft.
5) The average depth for the south bay in ≈1930, as derived from the present bathymetry less the thickness of accumulated lake sediment, is estimated to have been ≈3.7 ft.

^{210}Pb Dating

1) ^{210}Pb dating indicates that only uppermost Unit III sediments are of an age that they could have been deposited in the lake. This is consistent with interpretations that Unit II soils pre-date the lake.
2) Mass sedimentation rates for the lake peaked in 1975 shortly after a sandy pulses of sediment in Unit III of the core. The most likely cause for this period of increased mass sedimentation was clearing of land for high tension power lines that Cheney brook crossed ≈800 m (≈0.5 mi) from the bay.
3) Mass sedimentation rates in the bay decreased from ≈1975 to ≈2008 but have increased slightly (by a factor of 1.1) since.
4) Plots of sediment accumulation (thickness) rates also peak rate in association with the 1975 sedimentation event, and increased thereafter.
5) No visible change in aerial imagery of the surrounding drainage basin explains this recent increase in mass sedimentation or accumulation rates.

Implications for Dredging

Dredging has been raised as a possible means for remediating sediment accumulation in the south bay. As noted in the interim report, and refined here, a large volume of soft sediment does exist in the south bay, some of which was inherited from conditions at the site that existed before the lake was formed. Be that as it may, several questions arise when considering dredging.

First, as has previously been made clear, dredging would be very expensive, likely costing between $500,000 and $900,000. If membership-derived funds were used to pay for dredging it would be important to inform the membership that >30% of the soft sediment in the bay existed before Andover Lake was formed.

Secondly, there are several challenges that would arise if dredging were undertaken. If the goal were only to remove sediments that have accumulated since the lake was formed (*i.e.* only Unit III sediments), it may be difficult for dredgers to know when that depth has been reached. The subtle transition from dark, organic rich lake sediments (Unit III) to dark organic-rich upper soils (upper part of Unit II) is not easily recognized in core, and may similarly be difficult to distinguish in the field. Moreover, chemical data presented in this report, while admittedly purely descriptive, indicate that the uppermost sediments (both Unit III and the probed soft sediments) on average have higher elemental concentrations than do underlying sediments. Thus, dredging would likely disturb sediments with high chemical concentrations. As such, it would be essential for dredgers to explain how such sediment would be prevented from mixing with the rest of the lake. This could be complicated by the large volume of water that is flushed into, through and out of the south bay from Cheney Brook. It would also be essential to analyze new samples from the bay prior to dredging to understand what, if any, hazardous materials might be present. These analyses should be performed by an agency familiar with dredging protocols in freshwater lakes. Similarly, the potential impact of effluent draining from dredge spoil into the bay or lake during dewatering would need to be assessed.

Finally, the geographic location and geologic setting for the south bay is what makes this inlet a natural sand/silt trap. As noted in this report, 54% of Andover Lake's drainage basin drains into the south bay, which represents only 3.4% of the area of the bay. Furthermore, the juncture with the lake is constricted. These factors are the root cause of sedimentation in the bay, and they are not going to change regardless of remediation efforts. That said, it is completely understandable that residents around the bay have concern for sediment infilling and associated expansion of aquatic plants which take advantage of the naturally warmer and shallower water. Moreover, ^{210}Pb data presented here do indicate a slight increase in mass sedimentation rates in the bay since ≈2008 and an increase in sediment accumulation rates since ≈2000. There are no visible changes in the surrounding drainage basin that explain this trend. This may indicate a greater influx of organic matter, trends that are consistent with organic carbon concentrations in some cores.

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