United States Department of Agriculture

NRCS

Natural Resources Conservation Service
National Soil Survey Center
Federal Building, Room 152
100 Centennial Mall North
Lincoln, NE 68508-3866

Phone: (402) 437-5499
FAX: (402) 437-5321

SUBJECT: SOI – Geophysical Assistance

March 22, 2010

TO: Karen Woodrich
Acting State Conservationist
NRCS, Colchester, Vermont

File Code: 330-7

Purpose:
The objective of this study was to expand our knowledge of freshwater subaqueous soils. To attain this objective, ground-penetrating radar (GPR) was used to determine water depths, identify underwater landforms, and characterize subaqueous soils in Missisquoi Bay, Vermont.

Participants:
Roger Dekett, Soil Scientist, USDA-NRCS, St. Johnsbury, VT
Jim Doolittle, Research Soil Scientist, USDA-NRCS-NSSC, Newtown Square, PA
Andrea Lini, Associate Professor, Geology Department, University of Vermont, Burlington, VT
Kellie Merrell, Vermont Department of Environmental Conservation, Waterbury, VT
Thomas Villars, Resource Soil Scientist, USDA-NRCS, White River Jct, VT

Activities:
Multiple GPR traverses were conducted on ice over the Goose Bay portion of Missisquoi Bay on February 17-18, 2010.

Summary:

1. Ground-penetrating radar provided information on water depths, bottom topographies, and subaqueous soils and sediment types within the Goose Bay portion of Missisquoi Bay in northwestern Vermont.

2. Thirty-one radar traverses were completed across Goose Bay. This resulted in 367,936 georeferenced water-depth measurements that were picked from the radar records. Based on these picks, in the traversed areas, at the time of this survey, the average water depth was 1.69 m with a range of 0 to 3.89 m. One-half of the picks had water depths between 1.1 and 2.2 m.

3. Areas of mineral (Wassents) and organic (Wassists) subaqueous soils were identified and mapped with GPR.

4. Interpretations of radar records lead to the identification of six unique subaqueous *radar facies* beneath the traversed portions of Goose Bay. A *radar facies* is a mappable three-dimensional unit composed of GPR reflections whose internal reflection patterns and characteristics differ from adjoining units. Each of the six subaqueous radar facies defines different combinations of subaqueous soil types, parent materials and bottom topographies. The number of facies is considered large for the area investigation and portends to the complexity of the subaqueous

environment within Missisquoi Bay. Facies may help to define, characterize and map subaqueous units.

It was the pleasure of Jim Doolittle and the National Soil Survey Center to be of assistance to your staff in this study.

JONATHAN W. HEMPEL
Director
National Soil Survey Center

cc:
James A. Doolittle, Research Soil Scientist, Soil Survey Research & Laboratory, NSSC, MS 41, NRCS, Lincoln, NE
Micheal L. Golden, Director, Soils Survey Division, NRCS, Washington, DC
Stephen H. Gourley, State Soil Scientist, NRCS, Colchester, VT
David Hvizdak, State Soil Scientist/MO Leader, NRCS, Amherst, MA
John W. Tuttle, Soil Scientist, Soil Survey Research & Laboratory, NSSC, MS 41, NRCS, Lincoln, NE
Thomas R. Villars, Resource Soil Scientist, NRCS, White River Jct., VT
Larry T. West, National Leader, Soil Survey Research & Laboratory, NSSC, MS 41, NRCS, Lincoln, NE
Michael A. Wilson, Research Soil Scientist, Soil Survey Research & Laboratory, NSSC, MS 41, NRCS, Lincoln, NE

Technical Report on Ground-Penetrating Radar Investigations conducted on ice over Missisquoi Bay, Vermont, on 17 and 18 February 2010.

Jim Doolittle

Background:

> "The concept that sediments in shallow water environments undergo soil forming processes, are capable of supporting rooted plants, and meet the definition of soil according to the criteria defined in Soil Taxonomy has been moving soil scientists into a new frontier of soil survey – mapping subaqueous soils." (Jim Turenne; http://nesoil.com/sas/sasinfo.htm).

Subaqueous soils occur under both fresh and salt waters. These soils have the ability to support rooted plants in natural environments. The depth limit for subaqueous soils is presently proposed at an arbitrary, maximum water depth of 2.5 meters. This depth limit is assumed to represent the "*normal*" maximum depth below which most emergent vegetation will not grow. However, in some areas, emergent vegetation is known to grow at deeper depths.

In order to document, map, and classify subaqueous soils, it is important to have knowledge of water depths, bottom topography, sediment types and thickness, and subaqueous processes. Over open water, acoustical fathometers and acoustic sub-bottom profilers (SBP) and radio-frequency ground-penetrating radar (GPR) have proven to be effective in providing information on water depths, bottom topography, sediment types and thickness (Feurer et al., 2008). However, these open-water "*remote sensing*" methods, because of drift, often suffer from imprecise positioning of verification and sampling core sites (Moorman and Michael, 1997). Ground-penetrating radar, however, can also be used on ice-covered water bodies, which provide stable platforms for the more accurate positioning of core sites and transect (Hunter et al., 2003).

Ground-penetrating radar has been used extensively for bathymetric surveys of fresh water lakes (Fischer et al., 2007; O'Driscoll et al., 2006; Buynevich and Fitzgerald, 2003; Hunter et al., 2003; Moorman, 2001; Moorman and Michel, 1997; Mellett, 1995; Sellmann et al., 1992; Izbicki and Parker, 1991; Truman et al., 1991; Haeni et al., 1987) and rivers (Sambuelli et al., 2009; Feurer et al., 2008; Spicer et al., 1997; Kovacs, 1991; Annan and Davis, 1977). In these studies, GPR provided continuous, highly detailed, two-dimensional records of subbottom sediment type, thickness, and topography. These studies illustrate how GPR can provide more comprehensive observations of bottom and subbottom conditions than possible from core data alone. Traditional coring methods are labor intensive, and have very high cost/area ratios (Feurer et al., 2008). As a consequence of the costs, the number of cores is often limited. Limited measurements and observations can result in an oversimplification of relatively complex subaqueous environments (Stevens et al, 2009). Ground-penetrating radar can provide complete and continuous records of bottom sediments, which document spatial changes in subaqueous soils. Accurate radar interpretation, however, requires a lesser, but still adequate number of available core data to confirm interpretations.

In reported studies conducted in low-conductivity waters, GPR has been used to identify the water / bottom sediment interface to depths as great as 22 to 25 m, and provide accurate and detailed bathymetric cross-sections and contour maps (Moorman and Michel, 1997; Delaney et al. 1992; Sellmann et al., 1992). Moorman and Michel (1997) reported GPR measurements of fresh-water lake bottoms to depths as great as 19 m with an accuracy of ± 3%. However, in conductive waters, GPR is more depth restrict. The use of GPR in brackish or salt waters is impractical because of their high electrical conductivity and attenuation rates, which severely restricts penetration.

The purpose of this investigation was to obtain data with GPR on water depths, bottom topographies, and sediment types within the Goose Bay portion of Missisquoi Bay, Vermont.

Equipment:

The radar unit is the TerraSIRch Subsurface Interface Radar (SIR) System-3000 (here after referred to as the SIR-3000), manufactured by Geophysical Survey Systems, Inc. (GSSI; Salem, NH).[1] The SIR-3000 consists of a digital control unit (DC-3000) with keypad, SVGA video screen, and connector panel. A 10.8-volt lithium-ion rechargeable battery powers the system. The SIR-3000 weighs about 9 lbs (4.1 kg) and is backpack portable. With an antenna, the SIR-3000 requires two people to operate (Fig. 1). Jol (2009) and Daniels (2004) discuss the use and operation of GPR. The 70 and 200 MHz antennas were used in this study.

Figure 1. A GPR traverse being conducted with a 200 MHz antenna across an ice-covered portion of Missisquoi Bay.

The RADAN for Windows (version 6.6) software program (GSSI; here after referred to as RADAN) was used to process the radar records shown in this report.[1] Processing included: header editing, setting the initial pulse to time zero, color table and transformation selection, range gain adjustments, signal stacking, migration, and high-pass filtration (refer to Jol (2009) and Daniels (2004) for discussions of these techniques).

[1] Trade names are used for specific references and do not constitute endorsement.

Recent technical developments allow the integration of GPR and GPS data. The SIR-3000 system provides a setup for the use of a GPS receiver with a serial data recorder (SDR). With this setup, each scan on radar records can be georeferenced (position/time matched). Following data collection, a subprogram within the RADAN is used to proportionally adjust the position of each radar scan according to the time stamp of the two nearest positions recorded with the GPS receiver. A Trimble AgGPS114 L-band DGPS (differential GPS) antenna (Trimble, Sunnyvale, CA) was used to collect position data.[2] Position data were recorded at a time interval of one second along GPR traverse lines.

Using the *Interactive 3D Module* of the RADAN, depths to the water/ subaqueous soil interface were automatically and reasonably accurately picked, and outputted to a worksheet (X, Y, Z format; including latitude, longitude, depths to interface or layer, and other useful data).

Field Methods:
Traverses were conducted using the SIR-3000 with either a 70 or 200 MHz antenna (Fig. 1). Transects were completed by either carrying the 70 MHz antenna by hand or towing the 200 MHz antenna along a traverse line.

Calibration:
Ground-penetrating radar is a time scaled system. The system measures the time that it takes electromagnetic energy to travel from an antenna to an interface (e.g., soil horizon, stratigraphic layer, lake bottom) and back. To convert the travel time into a depth scale, either the velocity of pulse propagation or the depth to the reflector must be known. The relationships among depth (D), two-way pulse travel time (T), and velocity of propagation (v) are described in the following equation (Daniels, 2004):

$$v = 2D/T \qquad [1]$$

The velocity of propagation is principally affected by the relative dielectric permittivity (E_r) of the profiled material(s) according to the equation:

$$E_r = (C/v)^2 \qquad [2]$$

where C is the velocity of propagation in a vacuum (0.298 m/ns). Typically, velocity is expressed in meters per nanosecond (ns). In soils, the amount and physical state (temperature dependent) of water have the greatest effect on the E_r and v.

As different antennas were used each day, separate calibrations were performed with each antenna. Both antennas were calibrated based on the measured depths to the water/subaqueous soil interface at several calibration points (core sites). Calibrations were performed at seven and six calibration points for the 70 and 200 MHz antennas, respectively. At these points, ice thickness varied from 29 to 64 cm, and depths to the water/subaqueous soil interface varied from 0.55 to 3.5 m.

The 70 MHz antenna was used to survey deeper portions of Goose Bay. With the 70 MHz antenna, the average E_r though columns of snow, ice, and water was 68.2, but ranged from about 57 to 83. The observed range in E_r reflects the relative influence (thickness) of the ice and water columns, antenna frequency, and errors in core measurements and radar picks. Using the estimated E_r, the average difference between measured (101 to 350 cm) and interpreted (111 and 374 cm) depths to the water/subaqueous soil interface at seven calibration sites was only 11 cm, with a range of 2 to 24 cm.

---

[2] Trade names are used for specific references and do not constitute endorsement.

The 200 MHz antenna was used to survey shallower portions of Goose Bay. With the 200 MHz antenna, the average E_r though columns of snow, ice, and shallow water was 32.9, but ranged from about 57 to 83. At some core sites, there was essentially no water column and the probe went from ice directly into subaqueous soil materials. Using the estimated E_r, the average difference between measured (55 to 130 cm) and interpreted (53 and 137 cm) depths to the water/subaqueous soil interface at six calibration sites was only 8 cm, with a range of 1 to 20 cm.

Study Sites:
The focus of this study was Goose Bay, the southeastern-most extension of Missisquoi Bay in Franklin County, Vermont (Fig. 2). Extensive areas of Carlisle Muck (Ce), Limerick silt loam (Le) and Marsh (Ma) occupy the littoral portions of Goose Bay. The very deep, very poorly drained Carlisle soils (euic, mesic Typic Haplosaprists) formed in woody and herbaceous organic materials in depressions within lake plains. The very deep, poorly drained Limerick soils (coarse-silty, mixed, active, nonacid, mesic Fluvaquentic Endoaquepts) formed in loamy alluvium on flood plains. As can be seen on the soil map of Goose Bay (Fig. 2), the shoreline is highly irregular and composed of both mineral and organic soils. The southwestern portion of the Bay appears very shallow and was suspected to contain submerged organic soil materials.

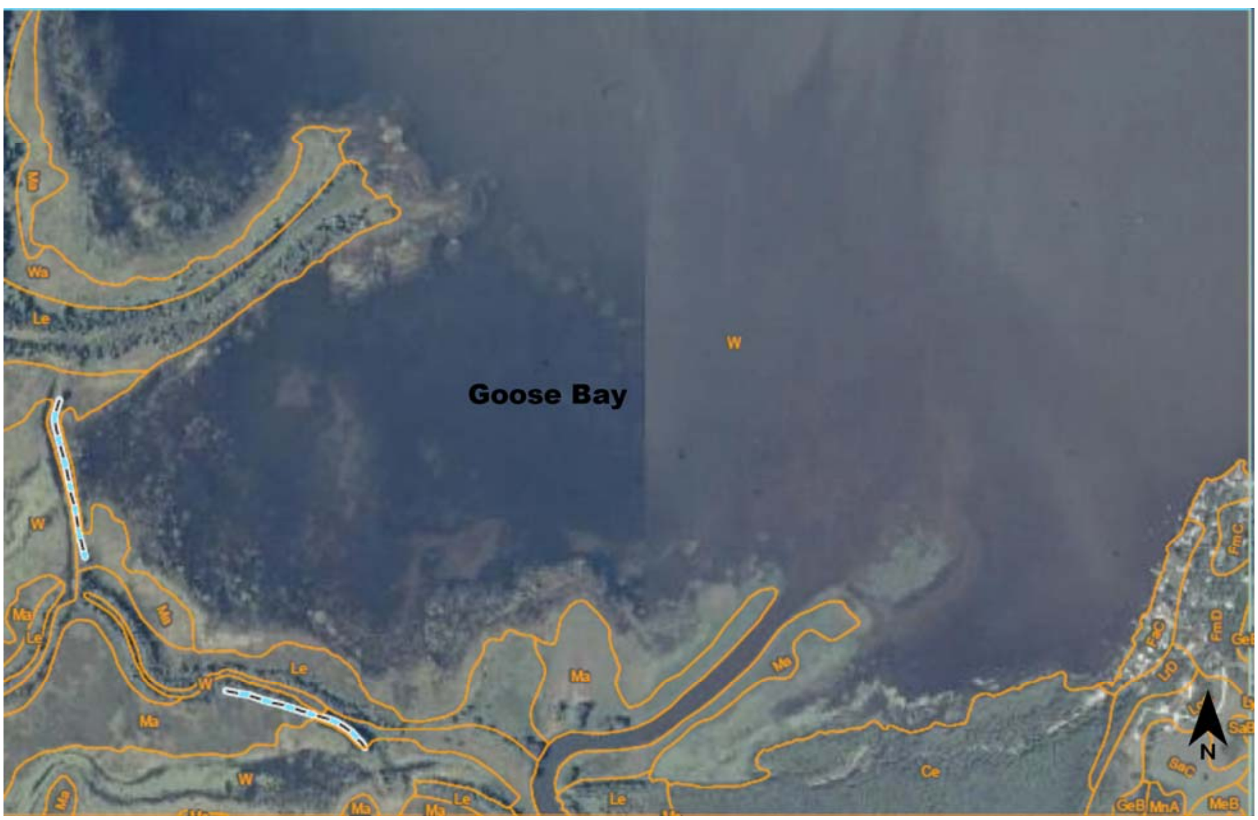
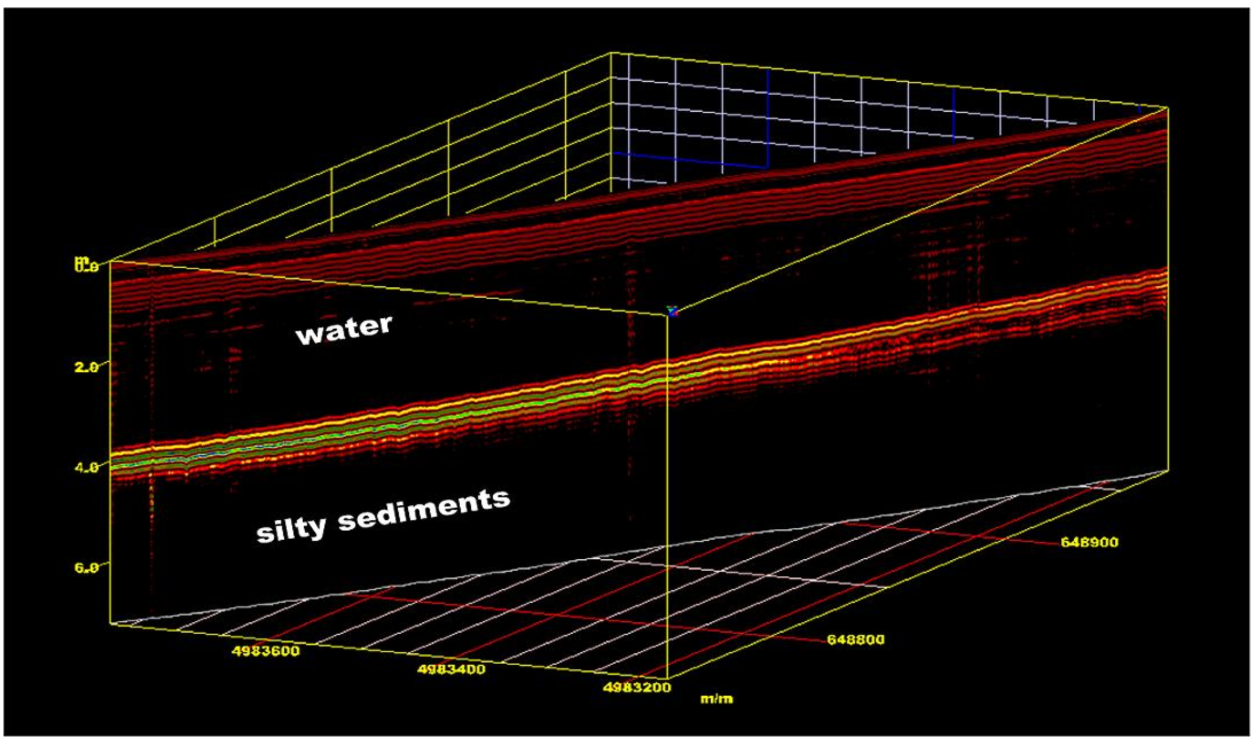


Figure 2. This soil map of the littoral areas that border Goose Bay was taken from the Web Soil Survey.

Results:
<u>Interpretations:</u>
All radar records shown in this report are imaged as three-dimensional (3D) block diagrams with all scales expressed in meters. For display purposes, the vertical scales have been exaggerated. The X and Y

axes are UTM coordinates. The Z axis is depth. High-amplitude reflections are shown in shades of white, pink, and blue; intermediate-amplitude reflections are shown in shades of yellow and green; and low-amplitude reflections are shown in shades of red and black.

Ground-penetrating radar traverses were conducted with the 70 MHz antenna over the deeper, northern portion of Goose Bay. Figure 3 is a representative 3D block diagram of a georeferenced radar record from this portion of the bay. On this image, a clear and continuous interface exists between the water and bottom sediments. This interface maintains a uniform depth of about 3.9 m. Other than reverberations from this interface, no additional subbottom information is available. The radar energy has been strongly attenuated and penetration depths restricted by the properties of the subbottom materials. Here, the subbottom materials form a blanket deposit that has higher silt and clay contents. Though described as silty, the deposits have sufficient clay contents and exchange properties to attenuate the radar energy. For deeper, level portions of Missisquoi Bay, this is the identifying radar *facies*. A *radar facies* is a mappable 3D unit composed of GPR reflections whose parameters (internal reflection patterns and characteristics) differ from adjoining units (Jol, 2009).



Figurer 3. This radar record was collected with the 70 MHz antenna on the deeper, northern portion of Goose Bay.

In Fig. 3, the water/subaqueous soil material interface grades laterally from intermediate (yellow- and green-colored) to low (shades of red) amplitude reflections. This gradation indicates changes in the abruptness and contrast of dielectric properties across this interface. As a rule, the greater and more abrupt the contrast in the E_r of two adjoining materials, the greater the amount of energy that will be reflected back to the antenna, and the greater the amplitude of the reflected signal appearing on radar records. Interfaces that have similar E_r are poor reflectors of electromagnetic energy and produce low-amplitude reflections that can be difficult to identify on radar records. The *reflection coefficient*, *R*, is a measure of the strength (high to low amplitudes) of reflections across an interface and is expressed as (after Neal, 2004):

$$R = \frac{\sqrt{E_r 2} - \sqrt{E_r 1}}{\sqrt{E_r 2} + \sqrt{E_r 1}} \qquad [3]$$

where E_r1 and E_r2 are the relative permittivity of adjoining materials 1 and 2. As evident in equation [3], *R* is dependent on the difference in the E_r that exists between two adjoining materials.

Water has the highest E_r (80 to 81); air has the lowest E_r (1). The E_r of most dry and wet mineral materials ranges from about 3 to 8 and 10 to 30, respectively. The E_r of soil materials is strongly dependent upon moisture content. As a consequence, the *reflection coefficient* is greatly influenced by the abruptness and difference in moisture contents that exist between adjoining materials. As water has relatively uniform E_r, lateral variations in R along the water/bottom interface (as evident in Fig 3) are presumed to reflect lateral variations in the bottom materials. It is assumed that the bottom materials evident in Fig 3, though relatively uniform, become more transitional (caused by slight variations in texture, presence of admixed organic materials, greater moisture content, lower soil density) in areas that have lower amplitude signals.

Figure 4 is a 3D block diagram of a georeferenced radar record that was collected with the 200 MHz antenna over a shallower and more sheltered portion of Goose Bay. This radar record captures a subaqueous soil area with greater variations in water depths, subaqueous soil materials, and topographic expressions. Compared with the radar record obtained over the deeper portion of the bay (Fig. 3), penetration depths are greater through the subbottom materials shown in Fig. 4. As signal attenuation is less, the bottom sediments are presumed to be coarser-textured and contain fewer fines.

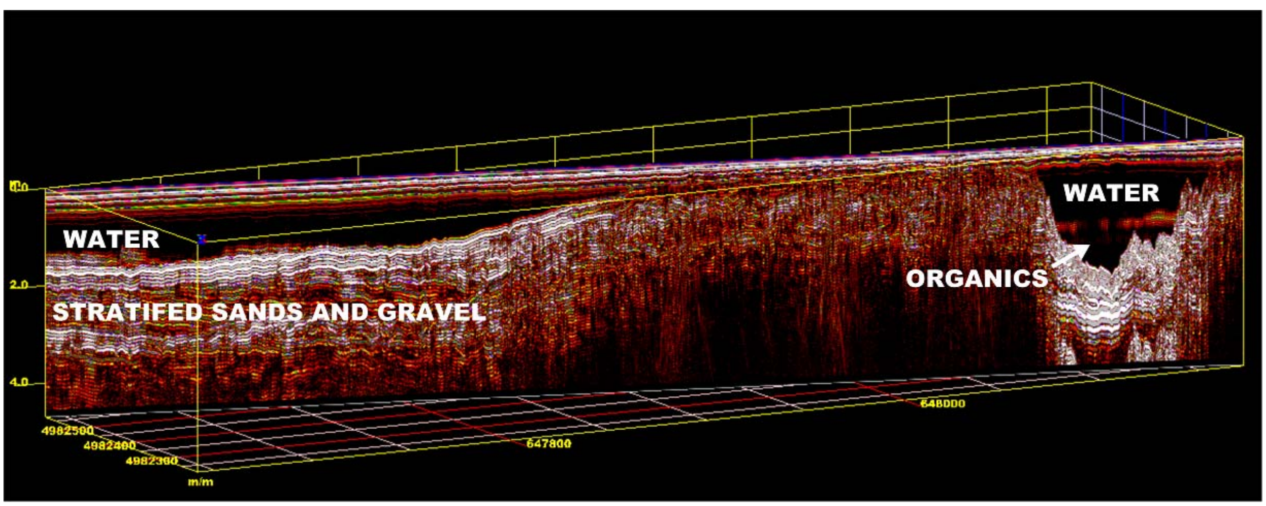


Figure 4. This radar record was collected with the 200 MHz antenna on a shallower portion of Goose Bay. Large variations in water depth, topographic and subaqueous soil types are evident on this 3D image

There are three distinct radar facies evident on the 3D block diagram shown in Fig. 4. In the extreme right-hand portion of the radar record, a submerged stream channel is evident. Within this channel, the low-amplitude, segmented, planar reflections from the water/bottom sediment interface (at depth of about

150 cm) identify the presence of submerged organic soil materials. In this submerged channel, the organic soil materials are thick enough for the subaqueous soil to be classified as a submerged Histosols (Wassists). Submerged organic materials are often distinguishable by the low-amplitude reflections along their interface with water and the absence of high amplitude reflections within the organic materials themselves. Within this submerged stream channel, the deeper interface separating organic and mineral soil materials is distinguished by its continuous, high-amplitude reflections, which indicates large differences in the moisture contents between these materials. These underlying mineral soil materials have an irregular topography and are stratified. Because of their high-amplitudes, these mineral soil materials are presumed to consist of alternating beds with strongly contrasting grain size distributions. This *channel facies* has an irregular topography with high subaqueous relief.

In Figure 4, areas to the left of the submerged stream channel consist of mineral bottom materials (Wassents), which are distinguished by high- and intermediate-amplitude reflections and the presence of internal reflections patterns. Within this area of subaqueous, mineral soils materials, the left- and right-hand portions are strikingly dissimilar. The extreme left-hand portion of these subaqueous, mineral soil materials are overlain by a relatively deeper column of water and consists of multiple, intermediate- and high-amplitude planar reflectors. These planar reflectors suggest stratified sand and gravel deposits (a radar facies indicative of a shallow subaqueous environment underlain by stratified sands and gravel). The center and right-hand portions of these subaqueous, mineral soil materials are higher-lying, have very shallow water depths (may be partially or entirely emergent at times), and display more chaotic, internal reflection patterns, which suggest till rather than stratified sediments (a radar facies indicative of a shallow subaqueous environment underlain by tills) Multiple, steeply inclined, hyperbolic reflectors present in this section represents cracks and fissures in the overlying ice and their reverberated signals.

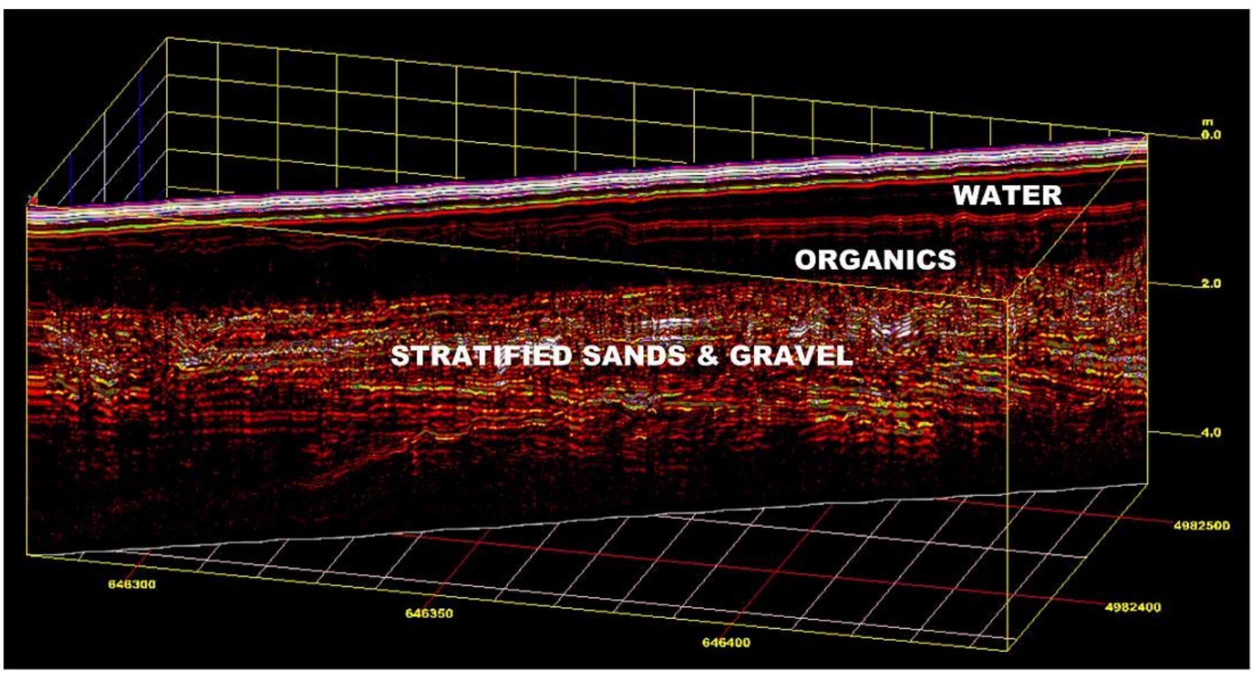


Figure 5. This radar record was collected with the 200 MHz antenna over a shallower portion of Goose Bay. A relatively homogeneous, submerged blanket deposit of organic soil materials overlies stratified sands and gravels. The water column deepens towards the right.

The 3D image in Fig. 5 shows a near-shore portion of Goose Bay that is underlain by submerged organic deposits. All subaqueous soils on this radar record would be classified as Wassists. The water/organic material interface is nearly level and continuous across this radar record, but slopes and deepens towards the right. The thickness of the submerged organic materials also thins from left to right with the deepening of the water column. Beneath the submerged organic deposits, the underlying mineral soil materials are stratified; consisting of multiple planar reflectors, which can be themselves separated into two distinct zones or facies that are distinguished by the continuity, amplitude, and inclinations of their planar reflectors. The image shown in Fig. 5 represents an additional radar facies: a shallow, relatively level, subaqueous soil environment with submerged organic materials underlain by stratified sand and gravel deposits.

The 3D image in Fig. 6 shows a yet another subaqueous soil environment in Goose Bay. Here, in contrast to the environment shown in Fig. 5, there is no submerged organic deposits and the subaqueous soils are mineral (Wassents) consisting of stratified deposits (with noticeable angular nonconformities) of sand and gravel. Unlike the radar facies shown in Figure 4, the radar facies shown in Fig. 6 has a more level topography with less relief (similar to the facies shown in the extreme left-hand portion of Fig. 4), but the layers of stratified sands and gravel are separated into facies with different reflection densities, amplitudes, and inclinations.

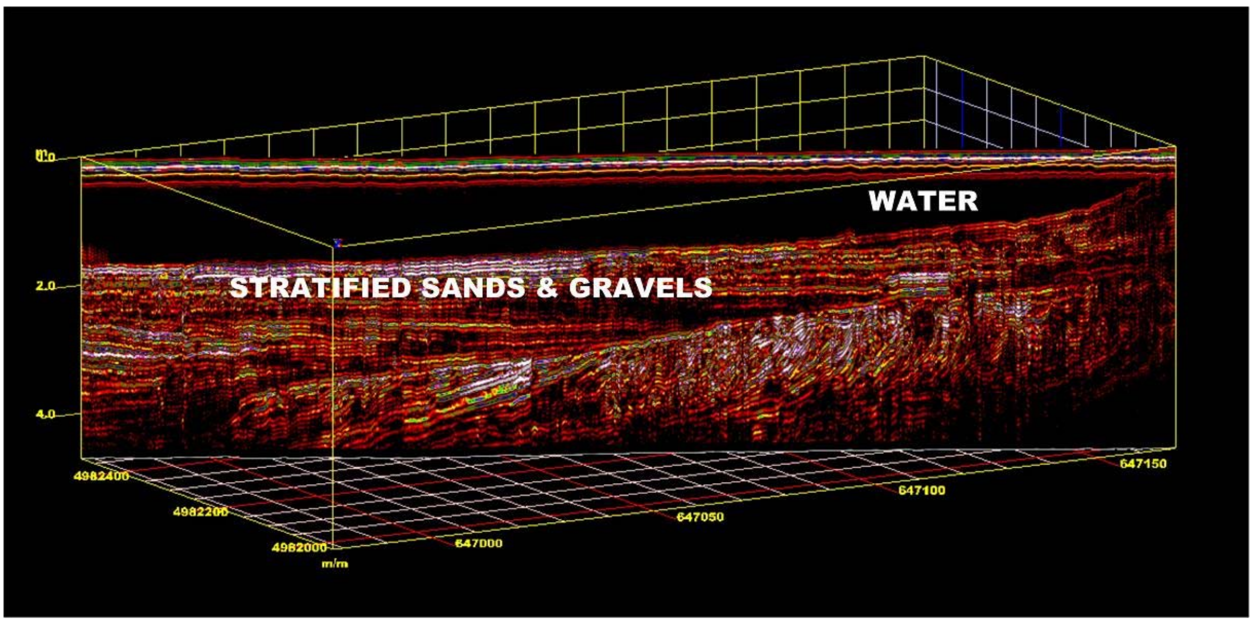


Figure 6. This radar record was collected with the 200 MHz antenna over a shallower portion of Goose Bay. Variations in the number, inclination, and amplitudes of reflected signals within the underlying mineral soil materials can be used to identify different periods of deposition.

Thirty-one radar traverses were completed across the Goose Bay, fourteen with the 70 MHz and seventeen with the 200 MHz antenna. This resulted in 367,936 georeferenced depth measurements picked from the radar records. Based on these picks, in the traversed areas, at the time of this survey, the average water depth was 1.69 m with a range of 0 to 3.89 m. One-half of the picks had water depths between 1.1 and 2.2 m.

Figure 7 contains two *Goggle Earth* images of Goose Bay. The locations of the GPR traverse lines are shown in upper image. Each traverse line is colored-coded based on the interpreted depth to the water/subaqueous soil interface. Along some radar traverses, the bottom sediments consisted of organic soil materials. Where organic materials were both present and attained sufficient thickness, the subaqueous soils can be classified as Wassists. In the lower Google Earth image shown in Fig. 7, the locations of thicker organic deposits and Wassists are shown where they occur along the traverse lines.

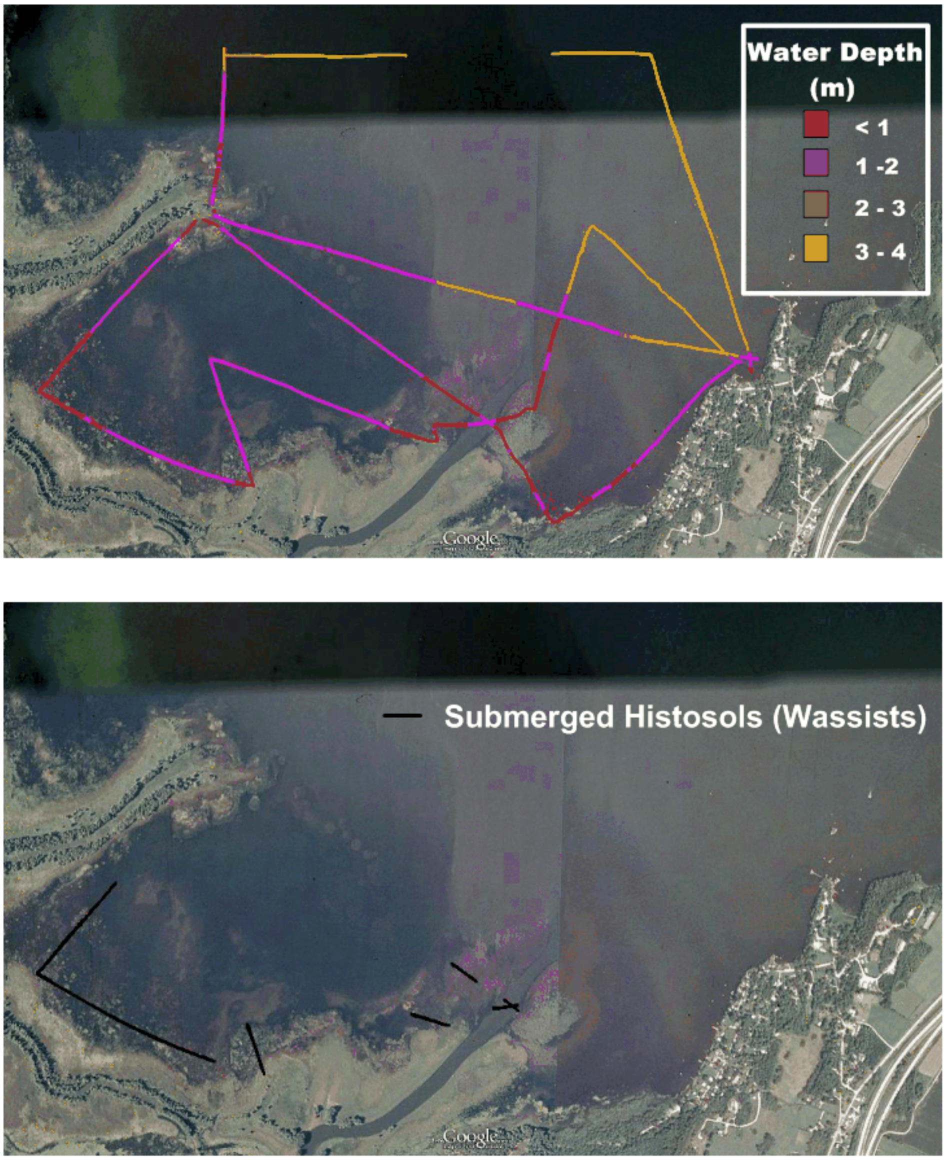


Figure 7. The upper Google Earth image shows the locations of GPR traverses and the interpreted water depths in Goose Bay. The lower Google Earth image shows the locations of Wassists along these GPR traverse lines.

Reference:

Annan, A.P., and J.L. Davis, 1977. Impulse radar applied to ice thickness measurements and freshwater bathymetry. 63-65 pp. *In*: Report of Activities, Part B, Paper 77-1B. Geological Survey of Canada, Ottawa, Canada.

Buynevich, I.V., and D.M. Fitzgerald, 2003. High-resolution subsurface (GPR) imaging and sedimentology of coastal ponds, Maine, U.S.A.: Implications for Holocene back-barrier evolution. *Journal of Sedimentary Research* 73 (4) 559-571.

Daniels, D. J. 2004. Ground Penetrating Radar; 2nd Edition. The Institute of Electrical Engineers, London, United Kingdom.

Delaney, A.J., P.V. Sellmann, and S.A. Arcone, 1992. Sub-bottom profiling: a comparison of short-pulse radar and acoustic data. 149-157 pp. *In*: Hanninen, P., and S. Autio (ed.) Fourth International Conference on Ground-Penetrating Radar. 7 to 12 June 1992. Rovaniemi, Finland. Geological Survey of Finland, Special Paper 16.

Fischer, T.G., W.L. Loope, W. Pierce, and H.M. Jol, 2007. Big lake records preserved in a little lake's sediment: an example from Silver Lake, Michigan, USA. *Journal of Paleolimnology* 37: 365-382.

Feurer D., J.-S. Bailly, C. Puech, Y.L. Coarer, and A.A. Viau, 2008. Very-high-resolution mapping of river-immersed topography by remote sensing. *Progress in Physical Geography* 32(4): 403-419.

Haeni, F.P., D.K. McKeegan, and D.R. Capron, 1987. Ground-penetrating radar study of the thickness and extent of sediments beneath Silver Lake, Berlin and Meriden, Connecticut. US Geological Survey Water-Resources Investigation Report 85-4108. Hartford, Connecticut.

Hunter, L.E., M.G. Ferrick, and C.M. Collins, 2003. Monitoring sediment infilling at the Ship Creek Reservoir, Fort Richardson, Alaska, using GPR. 199-206 pp. *In*: Bristow, C.S., and H.M. Jol (eds.) *Ground Penetrating Radar in Sediments*. Special Publication 211, Geological Society of London, London, United Kingdom.

Izbicki, J.A., and G.W. Parker, 1991. Water depth and thickness of sediment in Reservoirs 1 and 2, Framingham and Ashland, Massachusetts. US Geological Survey Open-File Report 91-508. 18 p.

Jol, H., 2009. Ground Penetrating Radar: Theory and Applications. Elsevier Science, Amsterdam, The Netherlands.

Kovacs, A., 1991. Impulse radar bathymetric profiling in weed-infested fresh water. CRREL Report 91-10. U. S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover New Hampshire.

Mellett, J.S., 1995. Profiling of ponds and bogs using ground-penetrating radar. *Journal of Paleolimnology* 14:233-240.

Moorman, B.J. 2001. Ground-penetrating radar applications in paleolimnology. 1-25 pp. *In*: Last, W.M. and J.P. Smol (eds.). Tracking Environmental Change using Lake Sediments: Physical and Chemical Techniques. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Moorman, B.J., and F.A. Michel, 1997. Bathymetric mapping and sub-bottom profiling through lake ice with ground-penetrating radar. *Journal of Paleolimnology* 18:61-73.

Morey, R.M., 1974. Continuous subsurface profiling by impulse radar. pp. 212-232. *In*: Proceedings, ASCE Engineering Foundation Conference on Subsurface Exploration for Underground Excavations and Heavy Construction, Aug. 11-16, 1974, Henniker, New Hampshire.

Neal, A., 2004. Ground-penetrating radar and its use in sedimentology: principles, problems and progress: *Earth-Science Reviews* 66: 261-330.

O'Driscoll, M.A., S.R. Riggs, D.V. Ames, M.M Brinson, D.R. Corbett, and D.J. Mallinson, 2006. Geomorphic, ecologic, and hydrologic dynamics of Merchant Millpond, North Carolina. Hydrology and Management of Forested Wetlands, Proceeding of International Conference, 8-12 April 2006, New Bern, North Carolina.

Sambuelli, L., C. Calzoni, and M. Pesenti, 2009. Waterborne GPR survey for estimating bottom-sediment variability: A survey of the Po River, Turin, Italy. Geophysics 74(4): B95-B101.

Sellmann, P.V., A.J. Delaney, and S.A. Arcone. 1992. Sub-bottom surveying in lakes with ground-penetrating radar. CRREL Report 92-8. U. S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Spicer, K.R., J.E. Costa, and G. Placzek, 1997. Measuring flood discharge in unstable stream channels using ground-penetrating radar. *Geology* 25(5): 423-426.

Stevens, C.W., B.J. Moorman, S.M. Solomon, and C.H. Hugenholtz, 2009. Mapping subsurface conditions within near-shore zones of an Arctic delta using ground penetrating radar. *Cold Regions Science and Technology* 56: 30-38.

Truman, C.C., L.E. Asmussen, and H.D. Allison, 1991. Ground-penetrating radar: A tool for mapping reservoirs and lakes. *Journal of Soil and Water Conservation*. 46(5):370-373.

Warner, B.G., D.C. Nobes, B.D. Theimer. 1990. An application of ground-penetrating radar to peat stratigraphy of Ellice Swamp, southwestern Ontario. *Canadian Journal of Soil Science* 27: 932-938.