United States Department of Agriculture | **Natural Resources Conservation Service** | **11 Campus Boulevard Suite 200 Newtown Square, PA 19073**

Subject: Soils – Ground-Penetrating Radar (GPR) Field Assistance **Date:** 30 January 2009

To: Paul Sweeney
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USDA-NRCS
60 Quaker Lane, Suite 46
Warwick, RI 02886-0111

Purpose:
The purpose of this visit was to conduct ground-penetrating radar (GPR) field investigations across selected soil polygons in Rhode Island.

Participants:
Jim Doolittle, Research Soil Scientist, USDA-NRCS-NSSC, Newtown Square, PA
Maggie Payne, Soil Scientist, USDA-NRCS, Warwick, RI
Jim Turenne, Assistant State Soil Scientist, USDA-NRCS, Warwick, RI

Activities:
All activities were completed during the period of 12 to 16 January 2009. Field activities were conducted on the first two days in Rhode Island; the third day was spent in the State Office reviewing, processing, and downloading files.

Summary:
Ground-penetrating radar (GPR) traverses were completed over sites located in Providence, Washington, and Newport Counties, Rhode Island. In general, soils in Rhode Island are well suited to GPR. Radar traverses provide high quality information on the depth to contrasting soil, stratigraphic, and lithologic materials. The data will be used to help determine the composition of soil map units. This information is desirable for the update of the Rhode Island soil survey and research needs of our cooperators. At Bowdish Reservoir, data were collect in shallow (< 5 m) a water environment. This data will be used to help develop an accessible database of subaqueous soils and sediments.

It was my pleasure to work in Rhode Island and to be of assistance to your staff.

With kind regards,

James A. Doolittle
Research Soil Scientist
National Soil Survey Center

cc:
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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. Jol (2009) and Daniels (2004) provide discussions on the use and operation of GPR. The 70 and 200 MHz antennas were used in this study.

The RADAN for Windows (version 6.6) software program (GSSI) 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 (see Jol (2009) and Daniels (2004) for discussions of these techniques).

Recent technical developments allow the automatic 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 for Windows (version 6.6) software 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. When this setup was used, position data were recorded at a time interval of one second along GPR traverse lines. [1]

Using the *Interactive 3D Module* of the RADAN for Windows (version 6.6) software program, depths to the base of selected contrasting soil and stratigraphic materials 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). [1] Using this module, data were compiled and exported for future plotting and visualization in GIS. Jim Turenne has noted that this data must be reduced by a factor between 1 in 200 and 1 in 500 observations for proper display in GIS. Using 1 observation in 200 yields an observation every 30 feet.

Field Methods:
Traverses were conducted with the SIR-3000 and either a 70 or 200 MHz antenna. Pulling (200 MHz) or carrying (70 MHz) an antenna by hand along a traverse line completed an individual GPR file. At Bowdish Reservoir, a Trimble AgGPS114 L-band DGPS (differential GPS) antenna was used to obtain the coordinates along GPR traverse lines. At other sites, the beginning and ending coordinates of each traverse line were recorded with a Garmin Global Positioning System Map 76 receiver (Olathe, KS). [1] At each site, ground-truth observations were made to confirm interpretations and scale the radar imagery.

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, bedrock) 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). 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.

At Bowdish Reservoir, the SIR-3000 was calibrated based on the depths to the organic/mineral interface at three observation points. With the 70 MHz antenna, the estimated average E_r though a column of snow, ice, water and organic materials was an astonishingly high 81. This is the E_r of water, which is the highest dielectric permittivity possible. However, using this Er, the differences between the measured (121.9 and 405cm) and scaled or interpreted (125.8 and 393cm) depths to the organic/mineral interface at two observation sites were only 3.9 and 12 cm. At the same site, using a 200 MHz antenna, the E_r and v were estimated to be 56.3 and 0.040, respectively. These results confirm the *dispersive* nature of these materials (attenuation and v increase with increasing frequency). At the Newport site, based on the depth to a subsurface reflector (a 30 cm diameter, metallic plate that was buried at a depth of 50 cm) and equations [1] and [2], the estimated E_r was 13.54 and the v was 0.081 m/ns. At the Bridgehampton site, v and E_r estimates were based on the measured depth (75 cm) to the contact of the aeolian sediments with the underlying outwash. Using this depth and equations [1] and [2], the estimated E_r was 19.3 and the v was 0.068 m/ns. At the Scio

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

site, v and E_r estimates were based on the measured depth (107 cm) to the contact of the aeolian sediments with the underlying till. Using this depth and equations [1] and [2], the estimated E_r was 23.7 and the v was 0.061 m/ns. All soils were either saturated or very moist at the time of these investigations.

Study Sites:
Sites were located in Providence, Newport, and Washington Counties. The Bowdish Reservoir site located (latitude 41.9235 N, longitude 71.7619 W) is located in West Glocester. Only the extreme eastern portion of this reservoir was surveyed with GPR. On soil and topographic maps, the reservoir is mapped as "water". The depth of the water was unknown prior to the GPR bathymetric survey. During winter months, the water level is purposely lowered. To the group's amazement, the reservoir is exceedingly shallow with only about 2 to 3 feet of water that covers thick deposits of organic materials. Bowdish Reservoir represents a large, inundated peatland.

The Newport site (latitude 41.5266 N, longitude 71.3682 W) is located off of Eldred Avenue in northern Conanicut Island, Newport County. Radar traverses were conducted in an open field, which is mapped as Newport silt loam, 0 to 3 percent slopes (NeB). The very deep, well drained Newport soils formed in compact till on uplands. Newport soils are moderately deep to dense basal till. The site is located along the flanks of a well expressed drumlin. The occurrence of compact till is implicit with this landform.

The Bridgehampton site (latitude 41.4790 N, longitude 71.5493 W) is located off of Ministerial Road in West Kingston. A large portion of the traversed area is wooded and mapped as Bridgehampton silt loam, 3 to 8 percent slopes (BhB). A portion of an adjoining field, which was also traversed with GPR, is mapped as Hinckley gravelly sandy loam, 0 to 3 percent slopes (HkA). The very deep, well drained and moderately well drained Bridgehampton soils formed in thick, silty deposits overlying glacial drift on outwash terraces and glaciated uplands. Solum thickness ranges from 100 to 142 cm and corresponds to the depth to contrasting glacial drift. The very deep, excessively drained Hinckley soils formed in water-sorted material on terraces and outwash plains. Included in mapping with these soils are small areas of Enfield soils. The very deep, well drained Enfield soils formed in a silty mantle (16 to 40 inches) overlying glacial outwash. Previous soil probing and excavations at this site revealed an aeolian mantle with a highly variable thickness, which overlaps the ranges of these three soil series.

The Scio site (latitude 41.4921 N, longitude 71.5197 W) is located off of Old North Road in Kingston. This site is in woodlands and mapped as Scio silt loam, 0 to 3 percent slopes (ScA). The very deep, moderately well drained Scio soils formed in eolian sediments dominated by silt and very fine sand. The eolian mantle is underlain by loamy, sandy, or gravelly material at depths greater than 40 inches. In Rhode Island, t he Scio soil is considered a glacio-lacustrine soil. The investigated site is located in an area of glacial till, which is considered atypical for Scio soil.

The Pawcatuck site (latitude 41.5100 N, longitude 71.3694 W) is located on a tidal marsh near the Newport Bridge, off of Conanicus Avenue, east-central Conanicut Island. The tidal marsh is mapped as Matunuck mucky peat (Mk). The tidal marsh is inundated by salt water twice daily. The very deep, very poorly drained Matunuck soils formed in thick sand deposits. Though mapped as Matunuck, Pawcatuck soils dominate the tidal marsh. The very deep, very poorly drained Pawcatuck soils formed in organic deposits over sandy mineral material. Thickness of the organic deposits ranges from 16 to 51 inches. The Pawcatuck soils are strongly acid to slightly alkaline. Total salt content ranges from 1,000 to 40,000 ppm. This area of Pawcatuck soils was traversed to substantiate claims that GPR is ineffective in areas of salt-affected soils.

The taxonomic classifications of the soils identified at the study sites are listed in Table 1.

Table 1. Names and taxonomic classifications of major soils traversed with GPR

Soil Series	Taxonomic Classification
Bridgehampton	Coarse-silty, mixed, active, mesic Typic Dystrudepts
Enfield	Coarse-silty over sandy or sandy-skeletal, mixed, active, mesic Typic Dystrudepts
Hinckley	Sandy-skeletal, mixed, mesic Typic Udorthents
Lippitt	Loamy-skeletal, mixed, active, mesic Typic Dystrudepts
Matunuck	Sandy, mixed, mesic Typic Sulfaquents
Newport	Coarse-loamy, mixed, active, mesic Typic Dystrudepts
Rainbow	Coarse-loamy, mixed, active, mesic Aquic Dystrudepts
Pawcatuck	Sandy or sandy-skeletal, mixed, euic, mesic Terric Sulfihemists
Scio	Coarse-silty, mixed, active, mesic Aquic Dystrudepts

Results:
<u>Bowdish Reservoir:</u>

A bathymetric survey of the eastern portion of Bowdish Reservoir was conducted to ascertain the nature (hard or soft) and depth to bottom sediments. This study was conducted to assess areas suitable for the growth of invasive plant species. A pedestrian GPR survey was conducted on ice using both the 200 and 70 MHz antennas (Figure 1). Investigators were surprised to learn that the lake consists of a relatively thin column of water underlain by thick deposits of peat. The impounded, shallow reservoir is a large, flooded peatland.

Figure 1. A radar traverse is conducted across the eastern portion of Bowdish Reservoir with the SIR System-3000 GPR, AG-114 GPS receiver, and 70 MHz antenna.

Radar records disclosed a very shallow column of ice (10 cm) and water (60 to 80 cm), which is underlain by thick organic deposits. The 200 MHz antenna provided unsatisfactory penetration depths and radar records plagued with high levels of background noise. Penetration depths were limited to depths of 3 to 4 m. Figure 2 is a highly processed radar record, which was collected with a 200 MHz antenna at Bowdish Reservoir. The ice/water and the water/organic interfaces were difficult to discern. The ice was too thin and consequently, the ice/water interface could not be resolved with either antenna.

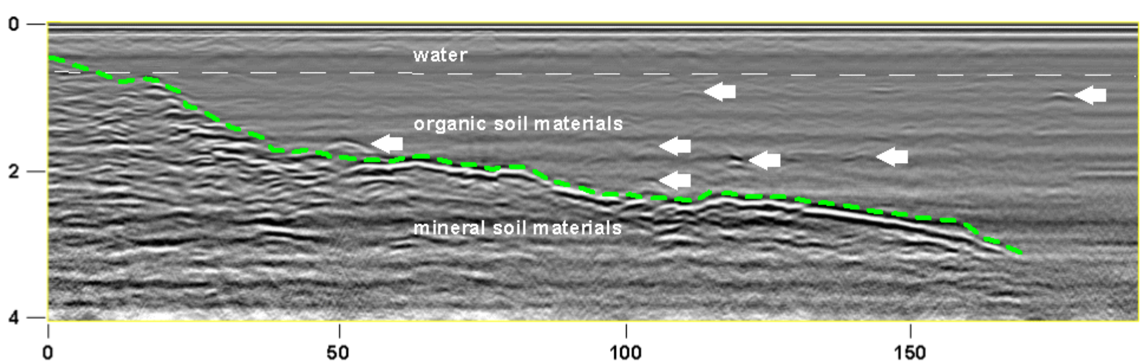

Figure 2. This radar record was collected with the 200 MHz antenna on Bowdish Reservoir. All measurements are expressed in meters.

In Figure 2, the water/organic interface provides a very weakly expressed interface at a depth of about 0.46 m (a segmented white-colored line denotes the approximate location of this interface). Variations in reflective patterns and signal intensities suggest the location of this poorly expressed interface. The interface's poor expression implies slight differences in the dielectric permittivity of the two materials (water and organics). The organic/mineral soil interface is more visible on the radar record (a segmented green-colored line denotes the approximate location of this interface). On this radar record, it varies in depth from about 75 to 305 cm. High rates of signal attenuation result in this interface's poor expression and lack of visibility below depths of about 3 m. Where visible, the organic/mineral soil interface varies in signal amplitudes. Signal amplitudes are lower in areas where the bottom is relatively soft and there is a gradual transition from organic to mineral soil materials, and where the interface is more steeply sloping. Where this interface is more steeply sloping, a greater total of the reflections are reflected away from the antenna making the interface less apparent. Higher amplitude reflections occur where there is an abrupt and contrasting boundary separating the organic from the mineral soil materials, and where the topography of this interface is relatively smooth and more gradually sloping. In Figure 2, arrows have been used to show the locations of some of the hyperbolas visible in the organic soil materials. These hyperbolas represent point reflectors assumed to be buried logs and stumps.

Figure 3 is a highly processed radar record, which was collected on Bowdish Reservoir with a 70 MHz antenna. This radar record has been stacked, migrated and gains increased to compensate for amplitude reduction with depth and through processing. The upper 80 to 90 cm of the radar record is plagued with parallel bands of background noise caused by the reverberation of reflected signals from the surface, ice/water, and water/organic soil material interfaces. Change in reflective patterns and signal amplitudes are evident at a depth of about 90 cm. This represents the water/organic interface. The organic/mineral soil interface is more easily identified on this radar record (a segmented green-colored line denotes the approximate location of this interface). This interface can be traced with a high degree of confidence to a depth of about 675 cm (the maximum depth scanned) on this radar record. Buried logs, larger roots, or stumps produce the hyperbolic reflectors that are evident within the organic materials. On this radar record, the organic materials vary in depth from about 90 to 675 cm.

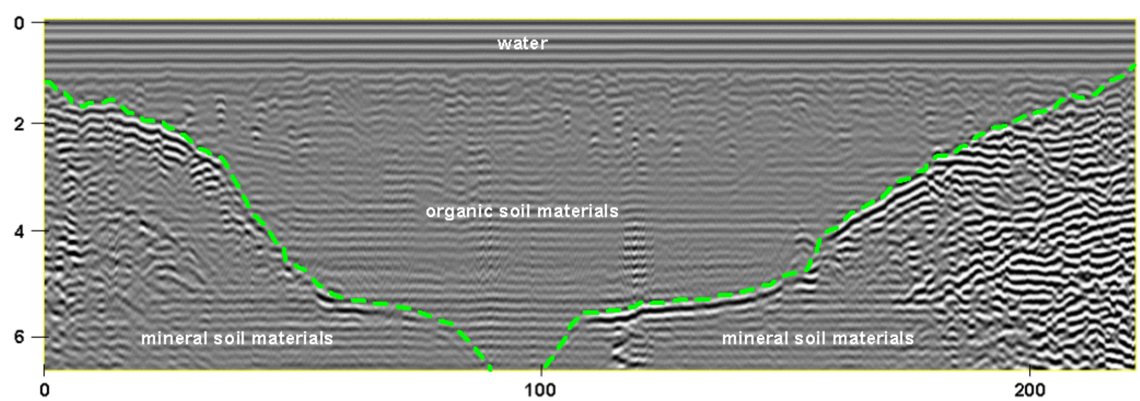

Figure 3. This radar record was collected with the 70 MHz antenna on Bowdish Reservoir.

Table 2. Some properties of organic materials within Bowdish Reservoir

Sample ID	Depth	pH (2:1 CaCl2)	Pyrophosophate color	Unrubbed fiber (%)	Rubbed Fiber (%)
Bowdish 1/14	Surface	4.88			
Bowdish wpt 183	0-30	4.73	10YR 3/2	44	18
Bowdish wpt 183	30-70	4.76	10YR 3/3	48	12
Bowdish wpt 183	70-150	4.93	10YR 4/3	56	28
Bowdish wpt 183	150-160	5.06	10YR 5/3	20	8

Table 3. Number and frequency of observations according to arbitrary depth class for the organic/mineral soil interface beneath the surveyed portion of Bowditch Reservoir

Depth Interval	Observations	Frequency
0 to 150 cm	8792	0.15
150 to 300 cm	23082	0.39
300 to 450 cm	9126	0.15
450 to 600 cm	13522	0.23

Whereas profiling depths as great as 8 to 10 m have been reported in some peatlands (Worsfold et al., 1986; Ulriksen, 1980), GPR does not provide similar results on all organic soils. In organic soils, the penetration depth and resolution of subsurface features is limited by the specific conductivity and the concentration of solutes in the pore water (Theimer et al., 1994). It has generally been assumed that GPR is more effective in acidic, low nutrient peatlands than in alkaline, high-nutrient peatlands. However, because of variations in the specific conductivity of the groundwater, wide ranges in minerotrophy exist (Bridgham et al., 2001). A distinction is made on ground-penetrating radar soil suitability maps based on the pH of the organic soil materials[2]. Organic soils with more acidic reactions (dysic) are more nutrient deficient and considered less limiting to GPR than organic soils with more neutral or alkaline soil reactions (euic). The pH of the organic materials sampled within Bowdish Reservoir was greater than 4.5 (Table 2) signifying euic conditions. More studies are need on organic soils to confirm the distinction of the dysic/euic break.

Nine radar traverses were completed across the eastern portion of Bowdish Reservoir. This resulted in 59632 georeferenced depth measurements. Table 3 summarizes the depth distribution of these measurements. Figure 4 is a *Goggle Earth* image of the surveyed area. The locations of the GPR traverse lines are shown in this image. Each traverse line is colored-coded based on the interpreted depth to the organic/mineral soil materials interface.

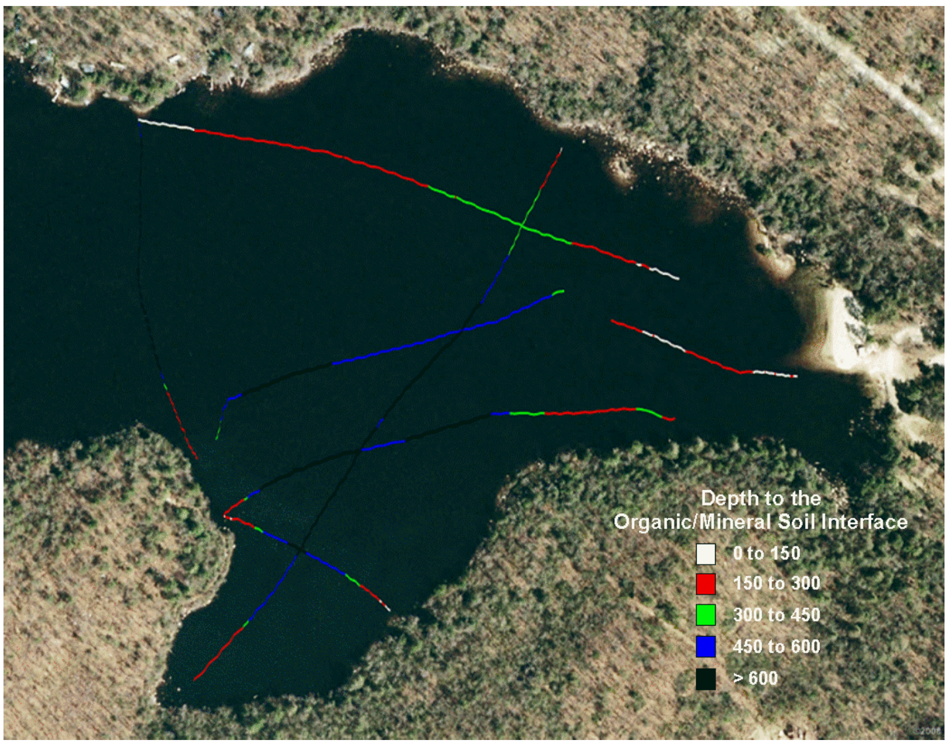

Figure 4. The depth to the organic/mineral soil interface in the eastern portion of Bowdish Reservoir. All depth classes are expressed in centimeters.

Newport Site:

Three traverses were conducted across the Newport site with a 200 MHz antenna. With a scanning time of 90 ns, the maximum depth of penetration was about 380 cm. However, interfaces were only clearly visible to depths of about 300 cm. Below this depth interfaces were less clearly expressed on radar records and interpretation were more ambiguous. The very deep Newport soil is considered to have a high potential for most GPR applications.

Figure 5 is a representative radar record from an area of Newport silt loam, 0 to 3 percent slopes. A green colored, segmented line has been used to identify a high-amplitude subsurface reflector that corresponds with the soil/bedrock interface, which was evident in several nearby soil pits. The very deep Newport soils are moderately deep to dense basal till. The interface seen on the radar record appears too jagged and irregular to represent dense basal till. The serrated appearance of this interface suggests highly fractured and folded bedrock. At this site, the underlying bedrock is the Rhode Island formation, which consists of highly folded and fractured shale intercalated with quartz seams and sandstone beds. Using the interactive module of RADAN, the depth to bedrock was quickly picked using EZ Tracker at an average distance of about 3 cm. This resulted in a total of 13,717 depth

[2] http://soils.usda.gov/survey/geography/maps/GPR/index.html

measurements. Surprisingly, the dominant interpreted soil depth classes were moderately deep and deep. The principal (20 to 60 inches) depths are outside the range of the Newport series. Tables 4 and 5 summarize the results of this survey.

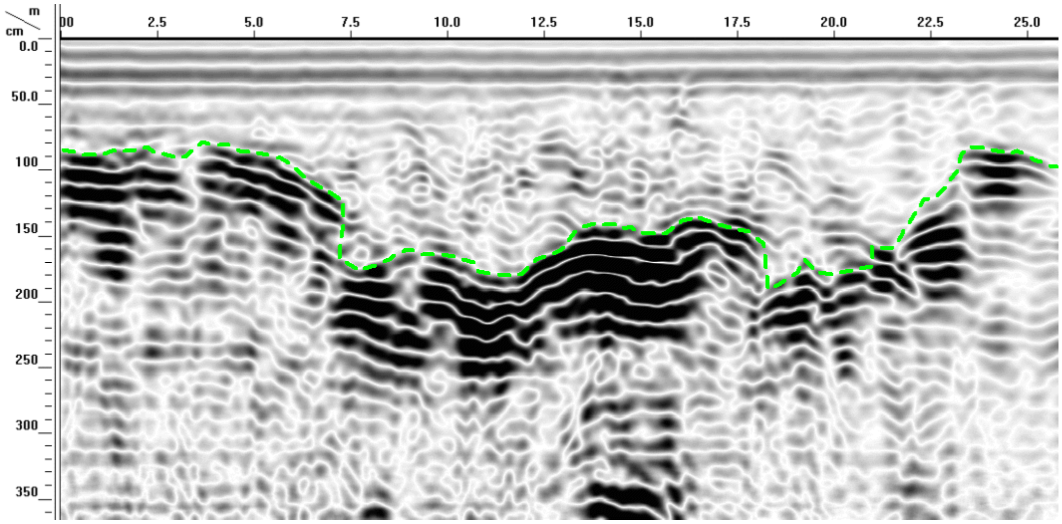

Figure 5. Representative radar record from an area mapped as Newport silt loam, 0 to 3 percent slopes. The high-amplitude planar reflector represents a soil/bedrock interface.

Table 4. These depths to bedrock statistics are for the GPR traverses completed in an area of Newport silt loam, 0 to 3 percent slopes. Observations are grouped according to soil depth classes.

	File 1	File 2	File 3
shallow	0	0	0
mod deep	2745	3457	3819
deep	974	2212	185
very deep	78	247	0

Table 5. Frequency distribution of radar interpretations of the depth to bedrock in traversed areas of Newport silt loam, 0 to 3 percent slopes. Interpretations are grouped according to soil depth classes.

	File 1	File 2	File 3
shallow	0.00	0.00	0.00
mod deep	0.72	0.59	0.95
deep	0.26	0.37	0.05
very deep	0.02	0.04	0.00

Jim Turenne had noted the occurrence of bedrock in several soil pits and multiple cores in areas mapped as Newport soils. He suggested that these areas of Newport soil be re-correlated as Lippitt soil.   The somewhat excessively drained Lippitt soils are moderately deep to weathered bedrock. Lippitt soil formed in acid till derived mainly from gneiss, schist, and granite.

<u>Bridgehampton site:</u>
Three GPR traverses were completed across the Bridgehampton site with a 200 MHz antenna. With a scanning time of 80 ns, the maximum depth of penetration was about 250 cm. Interfaces were visible throughout the entire depth column. The Bridgehampton soil is considered to have a high potential for most GPR applications. Using the interactive module of RADAN, the depth to contrasting materials (aeolian over outwash) was quickly picked using *EZ Tracker* at an average distance of about 3 cm. This resulted in a total of 18,785 depth measurements of the aeolian mantle's thickness. Tables 6 and 7 summarize the results of this survey.

Figure 6 is a representative radar record from the Bridgehampton site. Bridgehampton soils formed in thick silty deposits underlain by stratified sand and gravel or coarse-textured glacial till. In Figure 6, a green colored, segmented line has been used to identify a high-amplitude subsurface reflector produced by the aeolian mantle/outwash interface. The aeolian mantle is virtually free of high-amplitude reflectors. The outwash is characterized by linear reflectors of varying amplitudes. In Figure 6, the aeolian mantle/outwash interface is punctuated by an incised feature whose form and expression suggests an ice-wedge cast.

Table 6. Observations of the silt mantle's thickest for transects conducted in areas of Bridgehampton silt loam, 0 to 3 percent slopes are grouped into four soil depth classes.

	File 9	File 11	File 12
shallow	0	0	87
mod deep	3596	736	3609
deep	5178	4891	677
very deep	0	11	0

Table 7. Frequency distribution of data shown in Table 5.

	File 1	File 2	File 3
shallow	0.00	0.00	0.02
mod deep	0.41	0.13	0.83
deep	0.59	0.87	0.25
very deep	0.00	0.00	0.00

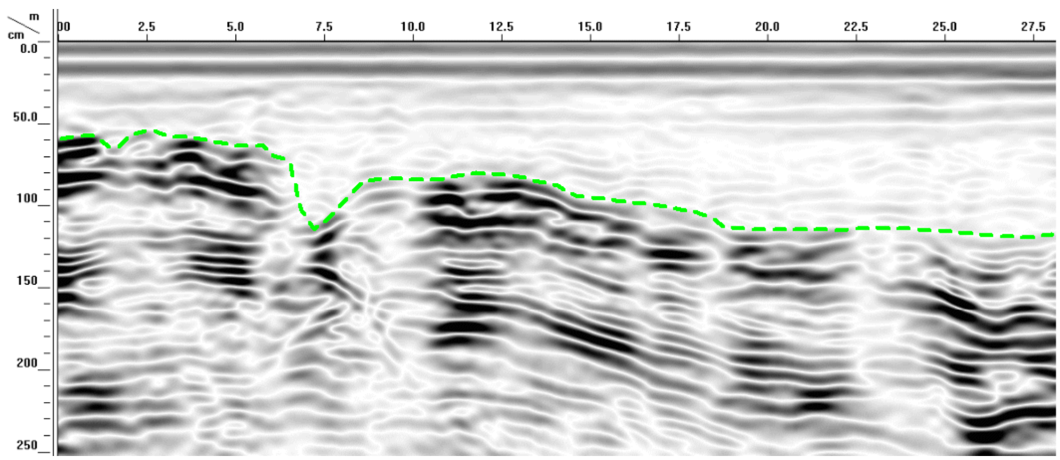

Figure 6. The contact of the aeolian mantle with the underlying glacial outwash is evident on this radar record, which was collected in an area of Bridgehampton silt loam, 0 to 3 % slopes.

Scio site:
Scio soils formed in eolian, lacustrine, or alluvial sediments dominated by silt and very fine sand. These sediments are underlain by loamy, sandy, or gravelly material at depths greater than 40 inches. In Rhode Island, Scio soils are considered lacustrine, are coarse-silty, and lack dense substrata. The investigated Scio site is located in an area of glacial till. Soils at this site are considered coarse-loamy and have a densic contact with the underlying till. These characteristics are considered atypical for Scio soils.

Figure 7 is a representative radar record from the Scio site. In Figure 7, all scales are expressed in meters. Three distinct subsurface facies were identified on this and other radar records collected at this site. Each facies has identifiable boundaries and is composed of reflectors with different signal amplitudes and patterns. The uppermost facies, the aeolian mantle, other than a few sporadic reflections from tree roots, is devoid of high-amplitude reflections. The middle facies, the till, is composed of high-amplitude point reflectors arranged in chaotic patterns. The lower facies, the bedrock, is more ill-defined and ambiguous. Here, reflectors are more linearly extensive and point reflectors are fewer and more poorly expressed. This facies occurs at depths greater than 2 m. As no ground-truth cores were extracted at this site to confirm the occurrence of the bedrock facies, this interpretations is considered vague and highly speculative.

The radar work at the Scio site helped to confirm the absence of lacustrine sediments and the presence of till underlying an aeolian mantle. As suggested by Jim Turenne, the soils in this unit will probably be re-correlated as Rainbow soils. The moderately well drained loamy Rainbow soils formed in silty mantled lodgement till. The Rainbow soils are very deep to bedrock and moderately deep to a densic contact.

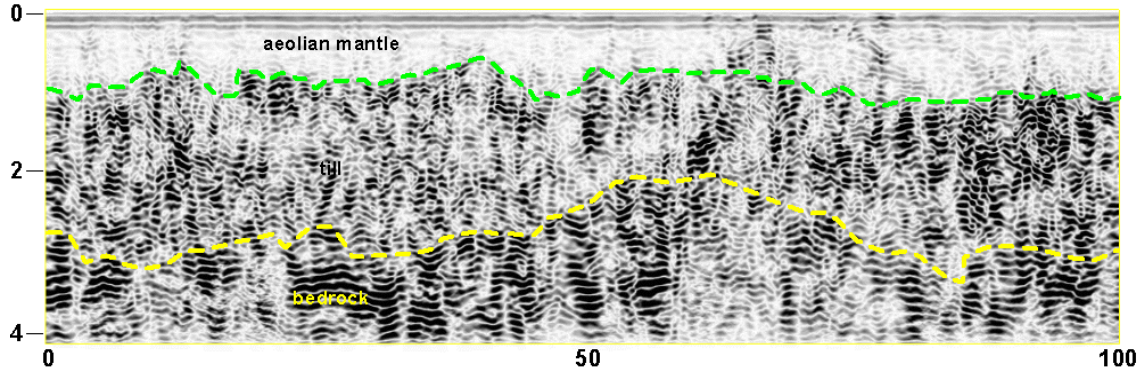

Figure 7. This representative portion of a radar record, which was collected in an area of Scio silt loam, 0 to 3 percent slope, shows three distinct subsurface facies.

<u>Pawcatuck site:</u>
Because of their high electrical conductivity, saline (saturated extract electrical conductivity ≥ 4 mmhos cm^{-1}) and sodic (sodium absorption ratio ≥ 13) soils are considered unsuited to GPR.[3] The soluble salt content of Pawcatuck soil is considered sufficiently high to reduce penetration depths and produce unacceptably high levels of unwanted background noise that impair interpretations. This study substantiates claims that GPR is ineffective in areas of saline soils.

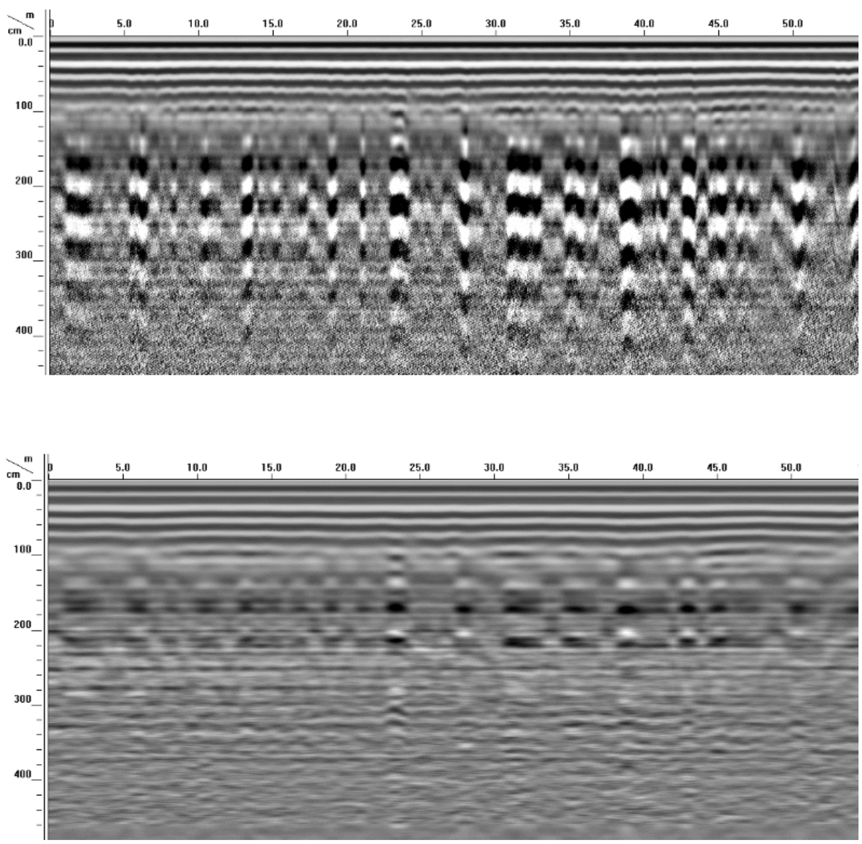

Figure 8. Both the unprocessed (upper) and processed (lower) images of the same radar record, which was collected in an area of Matunuck mucky peat, provide no meaningful subsurface information.

[3] http://soils.usda.gov/survey/geography/maps/GPR/methodology.html

A tidally influenced area of Matunuck mucky peat was traversed with a 70 MHz antenna. The vegetation consists mostly of tall reeds, sedges, and grasses. Though mapped as Matunuck soils, the area is dominated by Pawcatuck soils. Figure 8 shows *unprocessed* and more intensively *processed* images of the same portion of a radar record collected at this site. The relatively unprocessed radar record has been submitted to: header editing, setting the initial pulse to time zero, color table and transformation selection, and range gain adjustments. Parallel bands characterize the upper 100 cm of this (both) radar record. The conspicuously wide, white-colored band is believed to separate the air waves (antenna was carried above the ground with an air gap separating it from the soil surface) from the surface pulse. Other than the surface pulse, no subsurface interface can be observed in the upper part of this radar record. The high-amplitude (colored white or black) vertical reflections represent jarring of the antenna or reverberations from the operator's leg passing alongside the antenna. The lower portion of this radar record is visibly plagued with large amounts of unwanted high-frequency noise (appears as snow).

In Figure 8, the lower image has been additionally processed using deconvolution, with added range gain adjustments and signal stacking. Ringing (related to bandwidth) in a radar record negatively impacts resolution and interpretability, and therefore, must be identified and reduced or eliminated. Deconvolution is a numerical process that compresses the basic source wavelet, thereby improving temporal resolution. Through deconvolution the ringing patterns of high-amplitude reflections evident in the upper plot of Figure 8 are reduced thereby allowing a more optimal interpretation of the GPR data. Gain settings were restored following deconvolution and the data were subjected to additional signal stacking to reduce high frequency noise. In this high-loss soil, the added processing steps failed to result in any significant improvement in interpretations.

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