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

Subject: SOI – Geophysical Field Assistance **Date:** 5 September 2007

To: Ed White
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Purpose:
The potential of using ground-penetrating radar (GPR) and electromagnetic induction (EMI) to characterize soils and soil properties in Erie County and MLRA 139 (*Lake Erie Glaciated Plateau*) were explored.

Participants:
Alex Dado, Soil Scientist, USDA-NRCS, New Castle, PA
Jim Doolittle, Research Soil Scientist, USDA-NRCS-NSSC, Newtown Square, PA

Activities:
All field activities were completed on 28 & 29 August 2007.

Summary:

1. Electromagnetic induction (EMI) shows potential for identifying differences in soils and soil properties and inclusions in some soil map units.

2. Ground-penetrating radar (GPR) can be used as a quality control tool to support soil surveys in MLRA 139. GPR is appropriate for use on coarse and moderately-coarse textured soils that have abrupt and contrasting soil horizons and stratigraphic layers. GPR can be most effectively used to estimate the depth to diagnostic horizons and soil features and the composition of soil map units based on soil depth criteria.

3. With an appropriate antenna and under suitable soil conditions, GPR can be used to study fragipans. Differences in the brittleness and/or hardness of fragipans are detectable with GPR. GPR can be used in some soils to trace the lateral extent and expressions of fragipans. The absence of a Bt horizon overlying a Btx horizon enabled the resolution of the fragipan in areas of Erie soil. Further GPR investigations of soils with fragipans are encouraged in this MLRA.

It was my pleasure to work with Alex and to participate in this study. I wish to thank Alex for providing additional information that was needed to complete this report.

With kind regards,

James A. Doolittle
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cc:
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Study Sites:

The study sites are located in Erie County. These sites are in the *Lake Erie Glaciated Plateau* Major Land Resource Area (MLRA 139) of western Pennsylvania. Most of this MLRA is characterized by gently rolling to strongly rolling, dissected glaciated plateau (USDA-NRCS, 2006). Surfaces are mantled with till, outwash and glaciolacustrine sediments. Two sites (Teller Road and Township Road sites) were selected for intensive EMI surveys. Traverses were completed with GPR across additional sites.

<u>Teller Road:</u>

This site is located in a hay field off of Teller Road (41° 58' 35" N. Lat., 80° 21' 55" W. Long.). The site is located behind a beach ridge of a glacial predecessor to Lake Erie. The topography and vegetation across this nearly level field (slopes less than 2 %) provided no indication of the soils and the soil patterns that were identified on the soil map of this site (see Figure 1). Polygons of Birdsall (BdA), Platea (PbA), and Rimer (RaA) soils are recognized on the soil map. The taxonomic classifications of the soils that were mapped at the EMI study sites are listed in Table 1. The very deep, very poorly drained Birdsall soils formed in water laid deposits of silt and very fine sands. The very deep, somewhat poorly drained Platea soils formed in till. Platea soils are shallow or moderately deep to a fragipan. The very deep, somewhat poorly drained Rimer soils are deep or moderately deep to dense till. Rimer soils formed in sandy glaciolacustrine deposits overlying till. Differences in particle-size classes, parent materials, and soils portend the complexity of soils at this site. Subsurface drainage tiles drained the field.

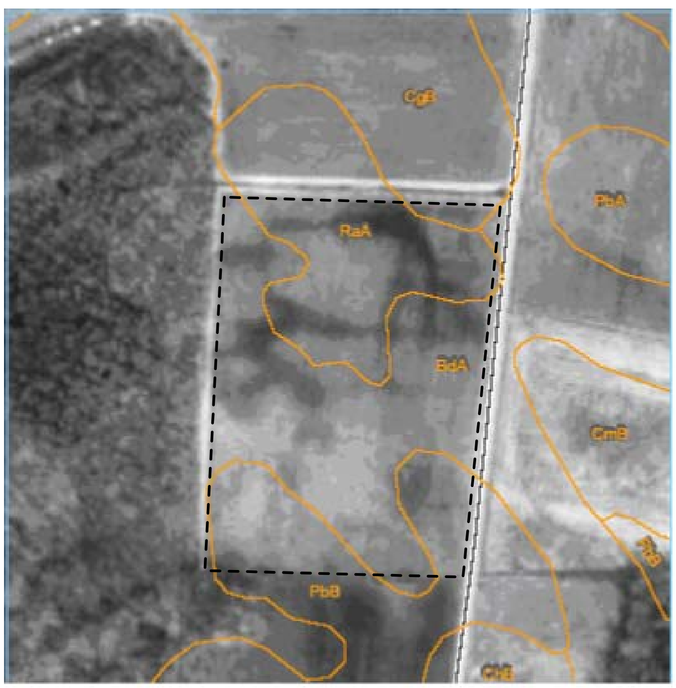

Figure 1. The location of the Teller Road Study Site is outlined on this soil map.

Table 1.
Taxonomic classification of soils recognized at EMI study sites.

Series	*Taxonomic Classification*
Berrien	Inactive series
Birdsall	Coarse-silty, mixed, active, nonacid, mesic Typic Humaquepts
Platea	Fine-silty, mixed, active, mesic Aeric Fragiaqualfs
Rimer	Loamy, mixed, active, mesic Aquic Arenic Hapludalfs
Wallington	Coarse-silty, mixed, active, mesic Aeric Fragiaquepts

Townline Road:
This site is located in a hay field off of Townline Road (42° 00' 11" N. Lat., 80° 23' 12" W. Long.). Polygons of Rimer (RaA) and Wallington (WaC) soils dominate the site. The very deep, somewhat poorly drained Wallington soils formed in silty lacustrine deposits. The taxonomic classifications of the soils mapped at this site are listed in Table 1. A noticeable beach ridge crossed this site, but was not recognized in mapping.

Figure 2. The location of the Townline Road Study Site is outlined on this soil map.

Materials and Methods:
The radar unit is the TerraSIRch Subsurface Interface Radar (SIR) System-3000, manufactured by Geophysical Survey Systems, Inc. (Salem, New Hampshire).[1] The SIR System-3000 consists of a digital control unit (DC-3000) with keypad, SVGA video screen, and connector panel. The SIR System-3000 weighs about 4.1 kg (9 lbs) and is backpack portable. With an antenna, this system requires two people to operate. The 200 and 400 MHz antennas were used in this study.

The RADAN for Windows (version 5.0) software program developed by Geophysical Survey Systems, Inc, was used to process the radar records. [1] Processing included setting the initial pulse to time zero, color table and transformation selection, marker editing, distance normalization, range gain adjustments, signal stacking, and migration.

The EM38 meter (see Figure 1) is manufactured by Geonics Limited (Mississauga, Ontario). [1] This meter weighs about 1.4 kg (3.1 lbs) and needs only one person to operate. No ground contact is required with this instrument. The EM38 meter has a 1-m intercoil spacing and operates at a frequency of 14,600 Hz. When placed on the soil surface, it has effective penetration depths of about 0.75 m and 1.5 m in the horizontal and vertical dipole orientation, respectively (Geonics Limited, 1998).

Geonics DAS70 Data Acquisition System was used with the EM38 meter to record and store both apparent conductivity (EC_a) and position data.[1] The acquisition system consists of the EM38 meter, an Allegro CX field computer (Juniper Systems, North Logan, UT), and a Garmin Global Positioning System (GPS) Map 76 receiver (with CSI Radio Beacon receiver, antenna, and accessories that are fitted into a backpack)(Olathe, KS). [1] When attached to the acquisition system,

[1] Manufacturer's names are provided for specific information; use does not constitute endorsement.

the EM38 meter is keypad operated and measurements can be automatically triggered. The NAV38 and Trackmaker38 software programs developed by Geomar Software Inc. (Mississauga, Ontario) were used to record, store, and process EC_a and GPS data.

To help summarize the results of the EMI surveys, SURFER for Windows, version 8.0 (Golden Software, Inc., Golden, CO), was used to construct two-dimensional simulations of EC_a data.[1] A two-dimensional plot of the Teller Road site was also prepared using the ESAP Software Suite for Windows (Version 2.35R) that was developed by the USDA-ARS, Salinity Laboratory (Riverside, CA).

Figure 3. Alex Dado completes an EMI survey at Townline Road Site in Erie County.

Survey Procedures:
The EM38 meter was operated in the deeper-sensing (0 to 1.5 m) vertical dipole orientation. Only conductivity data were collected. Data are expressed as values of apparent conductivity (EC_a) in milliSiemens/meter (mS/m). The EM38 meter was operated in the continuous (measurements recorded at 1-sec intervals) mode with the DAS70 system. Using the NAV38 program, both GPS and EC_a data were simultaneously recorded on an Allegro CX field computer. While surveying, the EM38 meter was held about 5 cm (about 2 inch) above the ground surface and orientated with its long axis parallel to the direction of traverse (see Figure 3). EMI Surveys were completed by walking at a uniform pace, in a random or back and forth pattern across each site.

At each of the GPR survey sites, the 200 and 400 MHz antennas were pulled along short traverse lines. Survey flags were inserted in the ground at intervals ranging from 1- to 3-m along each line and served as reference points. Along each line, as an antenna was towed passed a reference point, a vertical mark was impressed on the radar record. These marks referenced known positions.

Calibration of GPR:
Ground-penetrating radar is a time scaled system. This system measures the time that it takes electromagnetic energy to travel from an antenna to an interface (e.g., soil horizon, stratigraphic layer) and back. To convert the travel time into a

depth scale, either the velocity of pulse propagation or the depth to a 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 permittivity (E_r) of the profiled material(s) according to the equation (Daniels, 2004):

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

where "C" is the velocity of propagation in a vacuum (0.2998 m/nanosecond). Velocity is expressed in meters per nanosecond (ns). The velocity of propagation is inversely related to E_r, which increases with increasing soil moisture content.

The velocity of propagation is temporally and spatially variable. Soils were relatively moist at the time of this investigation. For the 200 and 400 MHz antennas, based on the depths to known buried reflectors and/or hyperbola-matching techniques (the shape of a hyperbola is dependent on the propagation velocity), an averaged velocity of propagation was determined for each antenna at each site.

Results:

<u>EMI:</u>

Teller Road Site:

Apparent conductivity was relatively low across the Teller Road Site. Based on 1233 measurements, EC_a averaged 11.6 mS/m and ranged from 3.98 to 33.88 mS/m across this site. One-half of the EC_a measurements were between 9.0 and 13.8 mS/m. Maps of EC_a data display intricate spatial patterns (see Figures 4 and 5). These patterns are believed to principally reflect differences in clay contents associated with a relatively dynamic depositional environment and the transition from glaciolacustrine to till deposits.

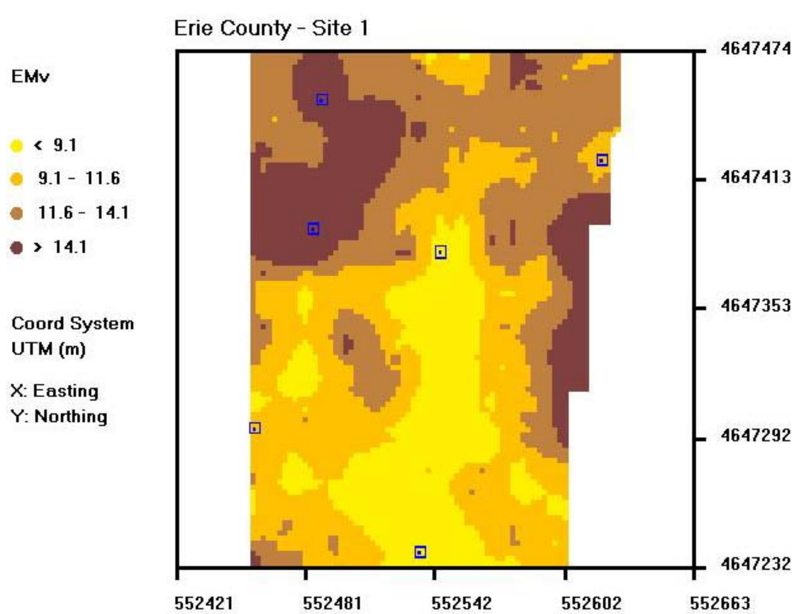

Figure 4. This plot of spatial EC_a patterns within the Teller Road Site was prepared using ESAP Software Suite. Based on a response surface sampling design, six optimal sampling sites (blue squares) were generated.

Plots of spatial EC_a patterns within the Teller Road Site are shown in Figures 4 and 5. The plots shown in Figures 4 and 5 were prepared using the ESAP Software Suite and SURFER for Windows programs, respectively. In each plot, different colors and color intervals are used. However, both show similar, broad spatial EC_a patterns. In general EC_a increases towards the north and Lake Erie. This trend suggests soils with increasing clay and/or moisture contents.

One of the statistical programs available in ESAP Software Suite is the *Response Surface Sampling Design* (RSSD). This program quickly generates an optimal sampling design based on the EC_a data. Sampling designs are based on 6, 12, or 20 sampling points. Because of limited resources, the sampling design shown in Figure 4 is based on 6 sampling points. The optimal sampling design provides the best possible information for generating predictive models of soils and soil properties based on spatial EC_a patterns. The locations of the optimal sampling sites are shown in Figure 4 as blue-colored squares.

The seemingly complex spatial EC_a patterns shown in Figures 4 and 5 are believed to principally represent differences in clay contents. These patterns are more complex and do not correspond with the boundaries of soil polygons mapped at this site (see Figure 1). The spatial patterns seen in Figures 4 and 5 reflect dissimilar soil properties and soil inclusions that are difficult to consistently and accurately delineate at the scale of an order-two soil survey.

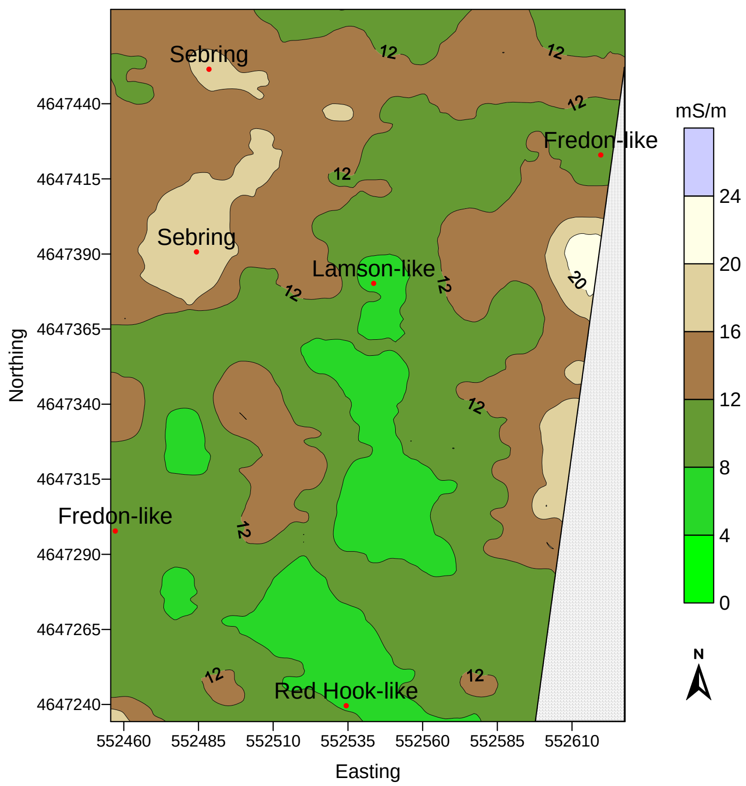

Figure 5. This EC_a map of Site #1 was prepared with data collected with the EM38 meter in the vertical dipole orientation. The locations of the 6 sampling points and the names of the soil identified are shown in this plot.

Ground-truth soil auger observations confirmed the general relationship of increasing EC_a with increasing clay content. The taxonomic classifications of the nearest soil to the soils identified in the six auger holes are listed in Table 2. The names and the locations of the observed soil pedons are shown in Figure 5. The Fredon-like pedons were fine-loamy over sandy, sandy-skeletal and have finer-textured layers than are permitted by the Fredon series description. The Lamson-like pedon had a silt loam layer within depths of 76 cm. The texture of this layer is outside the range of the Lamson series. The Red Hook-like pedon has a loamy fine sand BC horizon, which is outside the range of the Red Hook series. Soils identified as Sebring are more poorly drained than typical for map unit in this survey area.

In general, soils with the lower clay contents have lower EC_a; soils with higher clay contents have higher EC_a. Water filled the auger holes in areas of Fredon-like, Lamson-like, and Red Hook-like soils. However the thick silt mantle of Sebring soil acted as an aquitard to the upward flow of ground water and water was not observed to depths of 1.5 m.

Table 2.
Taxonomic classification of soils series that most closely fit the soils described at the six observation points within the Teller Road Site.

Soil Series	*Taxonomic Classification*
Fredon	Coarse loamy over sandy or sandy skeletal, mixed, active, nonacid, mesic Aeric Endoaquepts
Lamson	Coarse loamy, mixed, active, nonacid, mesic Aeric Endoaquepts
Red Hook	Coarse loamy, mixed, superactive, nonacid, mesic Aeric Endoaquepts
Sebring	Fine silty, mixed, superactive, mesic Typic Endoaqualfs

Townline Road Site:
Apparent conductivity was relatively low across Townline Road Site. Based on 1254 measurements, EC_a averaged 8.8 mS/m and ranged from -3.13 to 18.5 mS/m. One-half of the EC_a measurements were between 6.9 and 10.5 mS/m. Negative values are attributed to metallic artifact and cultural features, which influenced the EMI response. Areas of lower EC_a are associated with soils that have lower moisture and clay contents and deeper depth to carbonates.

Figure 6 is a plot of the EC_a data collected with the EM38 meter at the Townline Road Site. In general, EC_a was noticeably lower as we crossed a slightly higher-lying beach ridge that cut across the field from west-southwest to east-northeast. The beach ridge was subdued and poorly expressed in some areas of the field. In the plot of EC_a data (Figure 6), alternating, linear patterns of low EC_a (< 8 mS/m) indicate the approximate locations of two weakly-expressed beach ridges.

The ESAP Software Suite' *Response Surface Sampling Design* (RSSD) was not used as no ground-truth auger observations were attempted at this site.

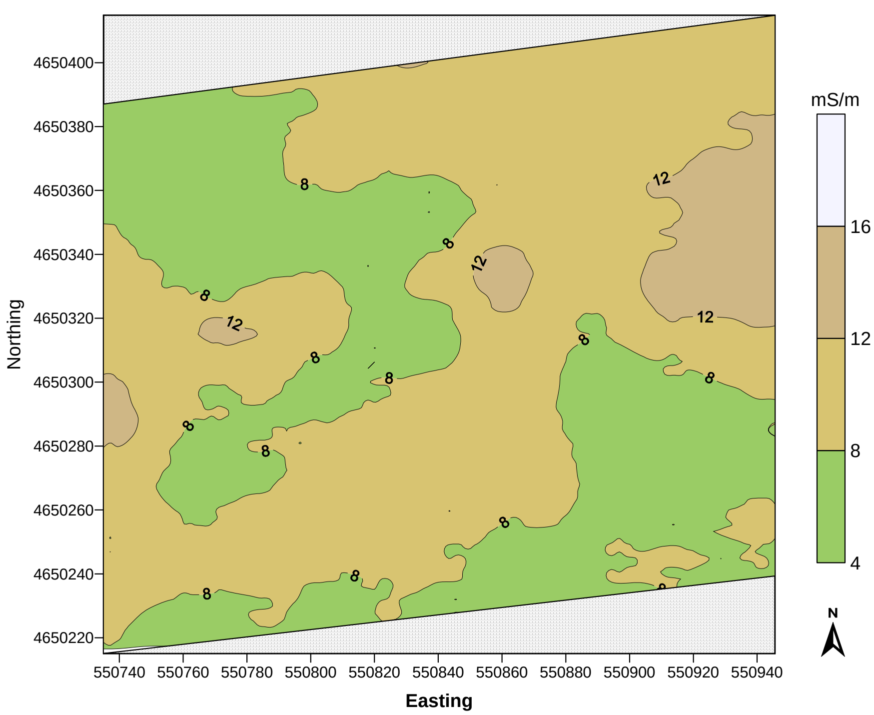

Figure 6. This EC_a map of the Townline Road Site was prepared with data collected with the EM38 meter in the vertical dipole orientation.

At both of the sites, EMI provided detailed maps of EC_a and provided an additional layer of soil information, which may help soil mapping decisions and interpretations.

GPR:

Area of Tyner Soil:

A radar traverse was conducted across an area of Tyner soil in a cultivated field (41.98152 N. Lat., 80.36408 W. Long.). The very deep, excessively drained Tyner soils formed in sandy outwash. Tyner is a member of the mixed, mesic Typic Udipsamments family.

The control section of Tyner soil contains only 0 to 10 percent rock fragments. This soil is well suited to GPR.

Based on the depth to a buried metallic reflector, the radar records collected with the 200 MHz antenna were depth scaled using equations [1] and [2]. This resulted in an estimated E_r of 5.61 and an estimated *V* of 0.1258 m/ns.

Figure 7 is a 14-m portion of a radar record that was collected with the 200 MHz antenna at the *Tyner Soil Site*. On this radar record, all scales are expressed in meters. Differences in reflected signal amplitudes are attributed to differences in grain size distributions and the abruptness of boundaries. The higher the signal amplitude (higher amplitudes are signified by white, pink, blue and green colors), the more abrupt and/or greater the contrast in grain-size distributions. This radar record provides highly resolved images of the alternating beds of sand, coarse sand, fine sand; or loamy sand, which characterize the outwash materials and affect hydropedological processes. The depth of consistent signal penetration in this area of Tyner soil is about 3 m.

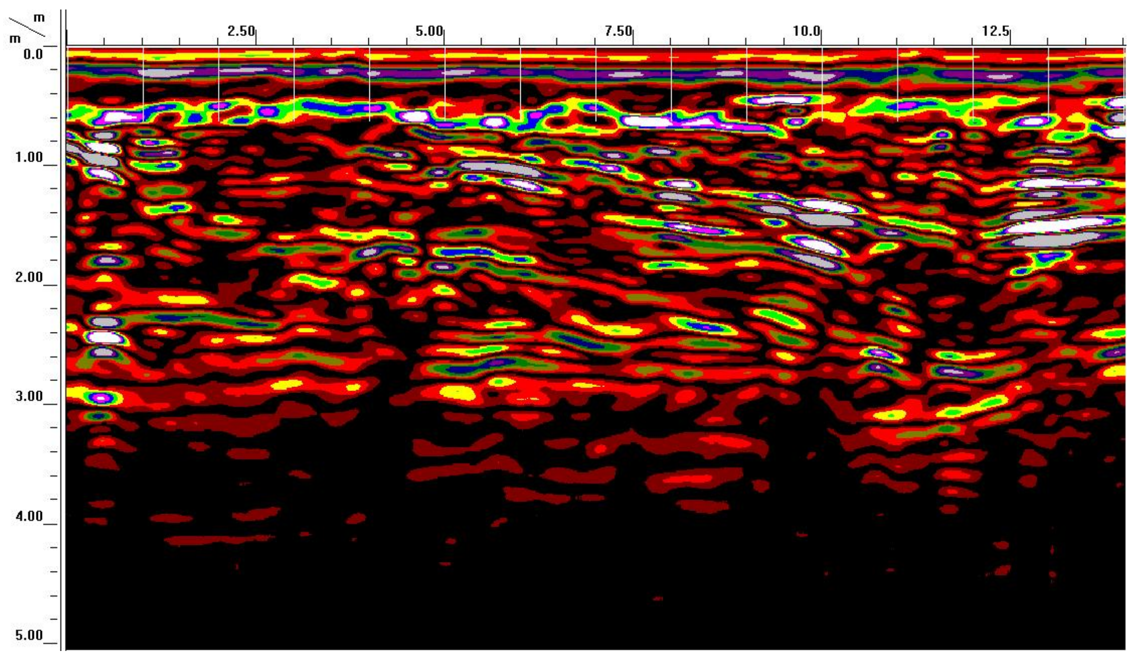

Figure 7. Strata of different grain size distribution provide high amplitude reflectors in this area of Tyner soil.

On radar records, interfaces that are too closely-spaced will overlap and cannot be resolved. Vertical resolution is based primarily on the propagated wavelength. The following equation shows the relationship among velocity of propagation (v), antenna center frequency (f), and wavelength (λ)(Daniels, 2004):

$$\lambda = v/f \qquad [3]$$

According to Equation [3], the propagated wavelength will decrease with increasing antenna frequency. For a given frequency, the propagation velocity and wavelength will decrease with increasing E_r and water content. At the Tyner Soil Site, using equation [3] and the estimated propagation velocity for the 200 MHz antenna, the projected wavelength is 63 cm (25 inches). In general, interfaces spaced closer (vertically) than ½ a wavelength will be indistinguishable on radar records (Daniels, 2004). As a consequence, in areas of Tyner soil, interfaces must be spaced at vertical distances greater than 31 cm (12 inches) to be distinguished with the 200 MHz antenna. Interfaces spaced closer than this distance will be indistinguishable. On the radar record of Tyner soil shown in Figure 7, multiple features (surface and plow layers, Bw horizon, wetting front) occur within the upper 60 cm of the soil profile. These features are too closely spaced to be distinguishable with the 200 MHz antenna.

Area of Otisville Soil:
A radar traverse was conducted across an area of Otisville soil, which is located in a cultivated field (42.02052 N. Lat., 80.37807 W. Long.). The very deep, excessively drained Otisville soils formed in outwash. In the substratum, rock fragments range from 30 to 70 percent, and include up to 15 percent cobbles and stones. Otisville is a member of the sandy-skeletal, mixed, mesic Typic Udorthents family.

The Otisville soil is considered closely similar to the Tyner soil in electromagnetic properties. As a consequence, the same E_r (5.61) and *V* (0.1258 m/ns) that were used for the Tyner soil were used to depth scale the radar records collected with the 200 MHz antenna in this area of Otisville soils.

Figure 8 is a 14-m portion of a radar record that was collected with the 200 MHz antenna at the *Otisville Soil Site*. On this radar record, all scales are expressed in meters. Once again, differences in reflected signal amplitudes are attributed to differences in grain size distributions and the abruptness of boundaries. While depths as great as 4 m were achieved in this area of Otisville soil, reliable penetration depth of only 3 m should be expected. Compared with the radar record from the *Tyner Soil Site*, the number of subsurface interfaces is similar, but the interfaces are more steeply inclined in this area of Otisville soils. Once again, features within the upper 60 cm of the soil profile are too closely spaced to be resolved with the 200 MHz antenna.

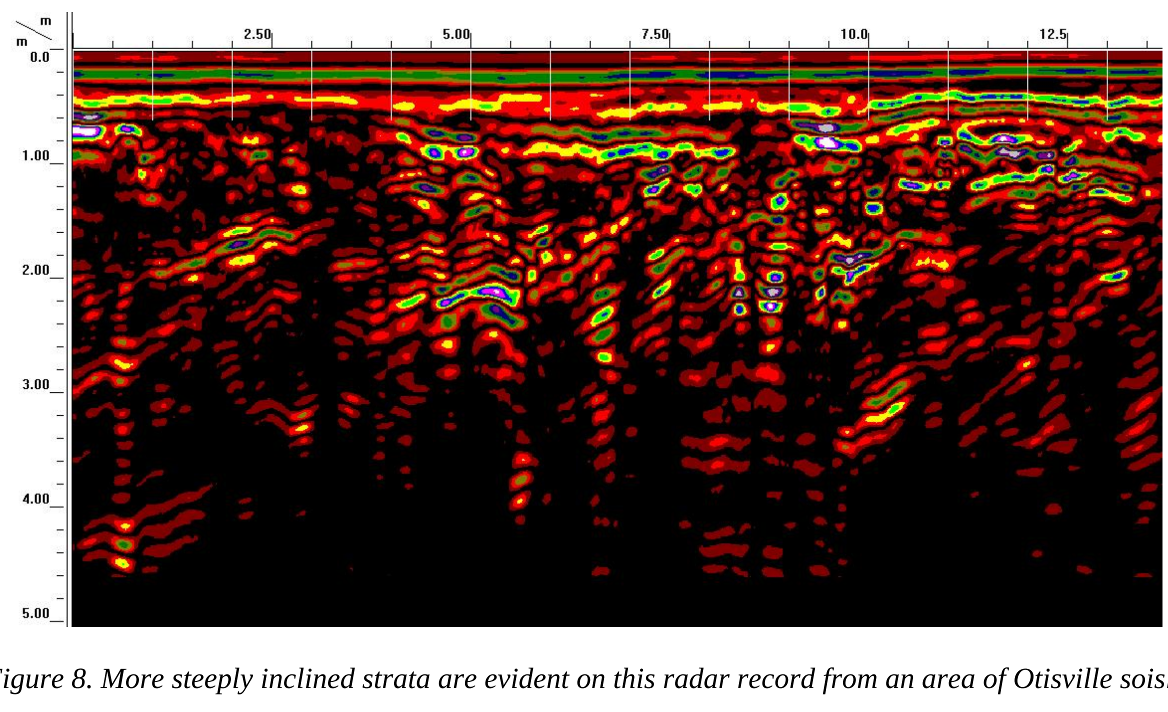

Figure 8. More steeply inclined strata are evident on this radar record from an area of Otisville soisl.

Area of Harbor Soil:

A radar traverse was conducted across an area of Harbor soils that is located in a wooded area (41.9787 N. Lat., 80.46350 W. Long.). The very deep, moderately well drained Harbor soils formed in sandy glaciolacustrine sediments that overlie till. The depth to the underlying till ranges from 50 to 100 cm. The coarse-textured glaciolacustrine sediments are relatively transparent to GPR and the contact of the sandy glaciolacustrine sediments with the underlying loamy till often will provide a highly contrasting interface, which is easily recognized on radar records. A thin stone line typically occurs at the contact of the glaciolacustrine sediments and the till. Depth to carbonates ranges from 30 to greater than 200 cm. Harbor is a member of the coarse-loamy, mixed, active, mesic Aquic Hapludalfs family.

In this area of Harbor soils, based on the depth to contrasting materials (contact of glaciolacustrine sediments with underlying till), radar records collected with the 200 MHz antenna were depth scaled using equations [1] and [2]. The estimated E_r was 7.34 and the estimated V was 0.1100 m/ns.

Figure 9 is a 9-m portion of a radar record that was collected with the 200 MHz antenna at the *Harbor Soil Site*. On this radar record, all scales are expressed in meters. The contact of the glaciolacustrine sediments with the underlying till is clearly expressed and ranges in depth from 90 to 143 cm. The Harbor series description allows the depth to till to range from 50 to 100 cm. Radar energy is rapidly attenuated in the medium textured, calcareous till. In this area of Harbor soil, the effective penetration depth is restricted to the upper part of the till or about 2 m. In similar areas of Harbor soils, GPR can be used to determine the depth to till and to differentiate soils based on soil-depth criteria.

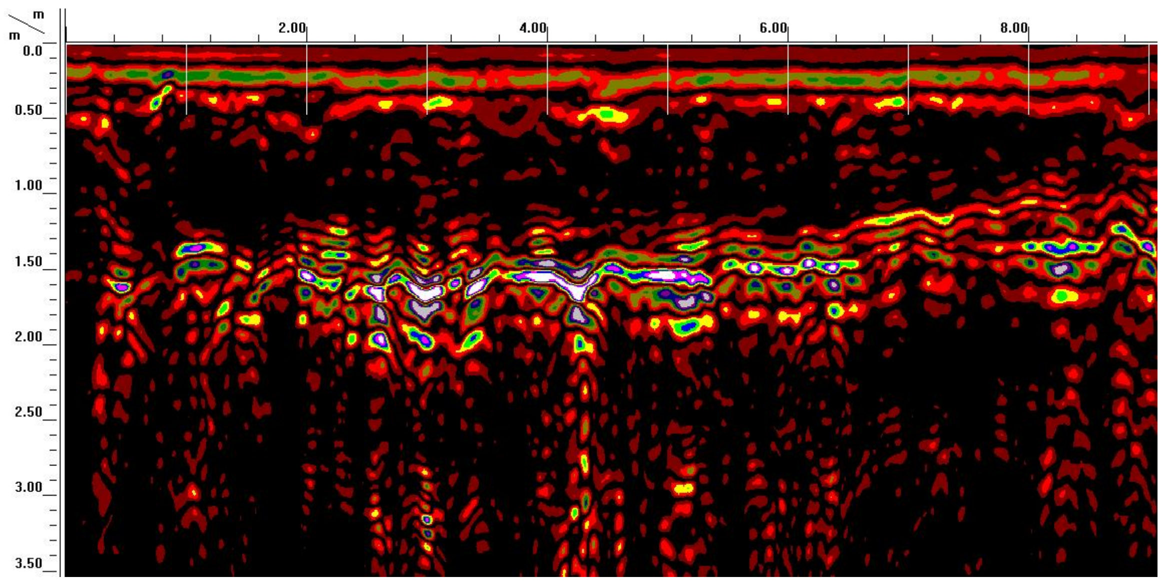

Figure 9. The contact of sandy glaciolacustrine deposits with medium textured till provides a distinct subsurface reflector in an area of Harbor soil.

Area of Erie Soil:

This site is in an area of Erie silt loam, 3 to 8 percent slopes, moderately eroded, which is located in a hay field on Pennsylvania State Game Preserve land (42.09578 N. Lat, 79.80742 W. Long). The very deep, somewhat poorly drained Erie soils formed in loamy till derived from siltstone, sandstone, shale, and some limestone. Erie soils have a fragipan at depths of 25 to 53 cm below the soil surface. The Erie series is a member of the fine-loamy, mixed, active, mesic Aeric Fragiaquepts family. Erie soils lack argillic horizons. Included in mapping are areas of Fremont soils. The deep and very deep, somewhat poorly drained Fremont soils lack fragipans. Depth to bedrock is greater than 40 inches. The Fremont series is a member of the fine-loamy, mixed, semiactive, acid, mesic Aeric Endoaquepts family.

Based on the depth to a known, buried metallic reflector, the radar records collected with the 200 MHz antenna were depth scaled using equations [1] and [2]. This resulted in an estimated E_r of 9.5 and an estimated V of 0.0966 m/ns.

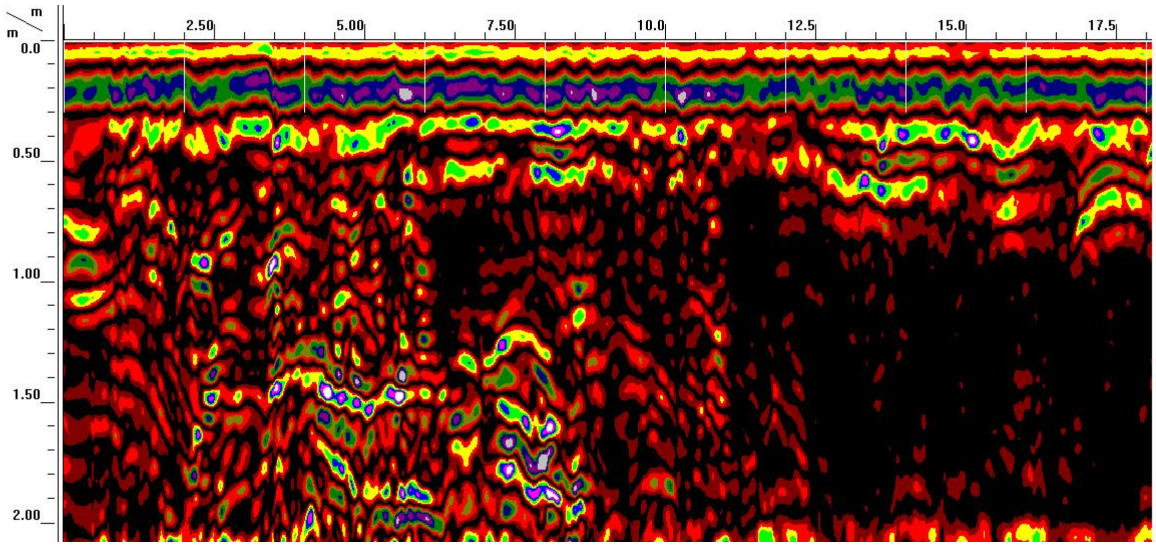

Figure 10 Reflections from the fragipan are difficult to detect in this radar record that was collected with the 200 MHz antenna in an area of Erie silt loam, 2 to 8 percent slopes, moderately eroded.

Figure 10 is an 18-m portion of a radar record that was collected with the 200 MHz antenna at the *Erie Soil Site*. On this radar record, all scales are expressed in meters. Though difficult to detect, a shallow to moderately deep fragipan is intermittently expressed across this radar record. The occurrence of multiple interfaces within the upper 60 cm of this soil and the relatively broad wavelength (48 cm) of the 200 MHz antenna makes the identification of the fragipan difficult.

To improve interpretations, traverses were conducted with a higher frequency 400 MHz antenna. Based on the depth to a known, buried metallic reflector, the radar records collected with the 400 MHz antenna were depth scaled using equations [1] and [2]. This resulted in an estimated E_r of 10.0 and an estimated V of 0.0942 m/ns. The propagated wavelength was estimated to be about 23.5 cm in this area of Erie soil. Vertical resolution is about ½ λ, or about 12 cm.

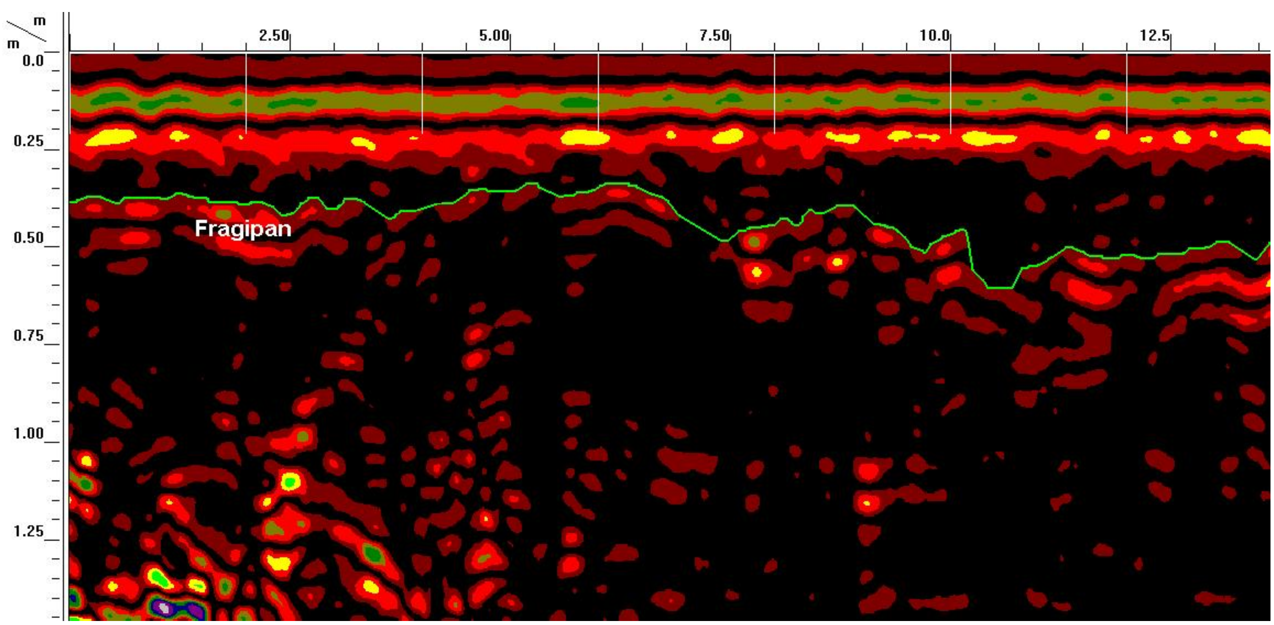

Figure 11. A continuous subsurface interface with intermittent fragic properties is suggested on this radar record that was collected with the 400 MHz antenna in an area of Erie silt loam, 2 to 8 percent slopes,

moderately eroded.

Figure 11 is a 14-m radar traverse that was collected with the 400 MHz antenna in this area of Erie soil. In Figure 11, a green-colored line has been used to identify a continuous interface that grades from well to very poorly expressed across this radar record. Ground truth observations confirmed that where this interface consists of higher amplitudes (colored yellow, brownish-yellow, or bright red), a fragipan exists (see where the label is located) and the soil is considered Erie. Where this interface consists of low amplitude reflections (colored black and dull red), the soil may contain some fragic properties, but not a fragipan and the soil is considered Fremont. Though this traverse was collected in a consociation of Erie soils, interpretations made along the GPR traverse lines suggest the dominance of Fremont soils.

As the soils were recently wetted, the moisture content and distribution may have been favorable for the display of the fragipan in this area of Erie soils. The absence of a Bt horizon overlying a Btx horizon enabled the resolution of the fragipan. Further GPR investigations of soils with fragipans are encouraged in this MLRA.

Area of Fredon-like Soil:
A short traverse was conducted with the 200 MHz antenna in the extreme northeast corner of the Teller Road Site (41^{o} 58' 35" N. Lat., 80^{o} 21' 55" W. Long.). This traverse was conducted in an area of Fredon-like soils. The surface layers were moist, heavy silt loam. This layer rapidly attenuated the radar signal and limited the penetration depths and the recognition of subsurface interfaces.

Based on hyperbola matching techniques, the radar record collected with the 200 MHz antenna was depth scaled using equations [1] and [2]. This resulted in an estimated E_r of 9.5 and an estimated *V* of 0.0967 m/ns.

Figure 12 is a 14-m portion of the radar traverse that was collected in this area of Fredon-like soil. Migration, horizontal high-pass filtration, and signal stacking programs were used to improve the display and interpretative qualities of this radar record. The low-amplitude point reflectors seen in the upper part of this radar record may represent larger rock fragments or larger clay balls in the overlying glaciolacustrine sediments. Below a depth of about 1 m, planar reflectors are evident on the radar record. Though weakly and intermittently expressed, an interface is discernible in the lower part of the radar record at depths ranging from about 75 to 125 cm. Though not verified with ground-truth observations, this weakly expressed interface may represent the contact of the glaciolacustrine sediments with the underlying till.

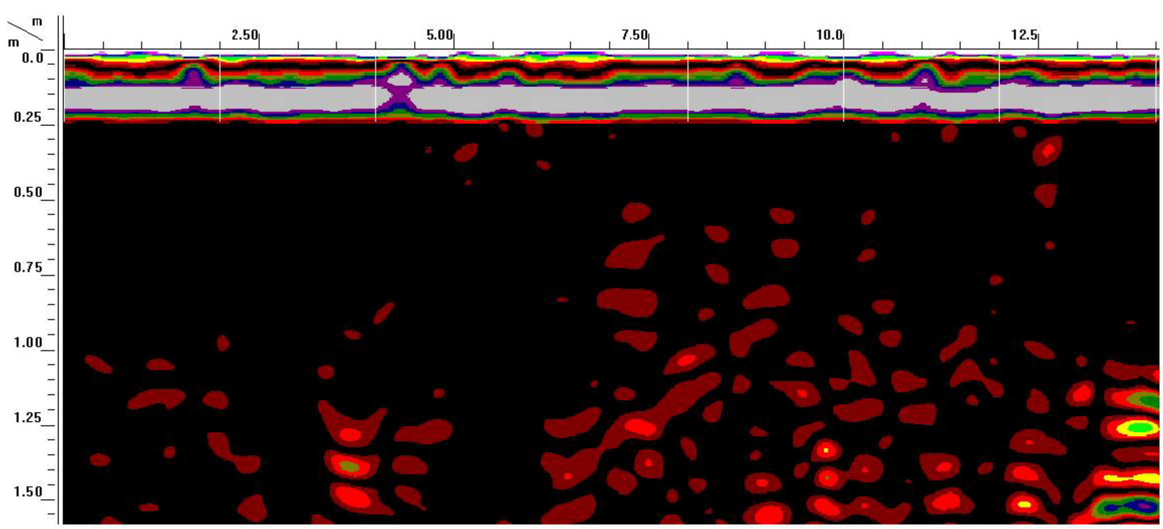

Figure 12. This highly processed radar record was collected in an area of Fredon-like soil at the Teller Road site.

In general, the effectiveness of GPR is considered poor in areas of Sebring and Fredon-like (fine-loamy variant) soils because of their relatively high clay contents.

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