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) 437-5336

SUBJECT: SOI – Geophysical Assistance

December 16, 2014

TO: Dr. Henry Lin
Professor of Hydropedology/Soil Hydrology
Department of Ecosystem Science and Management
415 Agricultural Sciences and Industries Building
Pennsylvania State University
University Park, PA 16802

File Code: 330-7

Joe Kraft
State Soil Scientist
USDA-NRCS
Suite 340
One Credit Union Place
Harrisburg, PA 17110-2993

Purpose:

To strengthen ties between National Cooperative Soil Survey (NCSS) partners and to expand and improve the geophysical services that are provided by the Natural Resource Conservation Service.

Participants:

Jim Doolittle, Research Soil Scientist, USDA-NRCS-NSSC, Newtown Square, PA
Jianbin Lai, Visiting Scholar to PSU, The Chinese Academy of Sciences, Beijing, China
Henry Lin, Professor of Hydropedology/Soil Hydrology, Department of Ecosystem Science and Management, PSU, University Park, PA
Yuan Wu, PhD Student, Soil Science, Department of Ecosystem Science and Management, PSU, University Park, PA
Heil Xu, PhD Student, Department of Ecosystem Science and Management, PSU, University Park, PA
Haolinag Yu, Visiting Scholar to PSU, Ninxia University, Yuanchuan, Ninxia, China

Activities:

All activities were completed during the period of November 12 thru 14 2014.

Summary:

1. Presentations and field exercises were provided to visiting scholars and graduate students on the use of two geophysical methods: ground-penetrating radar (GPR) and electromagnetic induction (EMI). Later, guidelines on the setup, calibration, and surveying procedures for both the Profiler EMP400 (EMI) and SIR-3000 system (GPR) were reviewed at a field site located on the Klepler Research Farm. Field studies using GPR to map the depth to bedrock were carried out in an expanded

area of the Susquehanna / Shale Hills Critical Zone Observatory (CZO). Within this catchment, long-term studies are being carried out to quantitatively assess the rates of weathering, erosion, and soil formation and how these processes control soil-landscape evolution and the flow of water and energy within the Critical Zone.

2. The filing of this report was delayed by the need to have a more updated version of RADAN 7.0 (RAdar Data ANalyzer) post-processing software loaded onto Jim Doolittle's computer. The revised program (RADAN 7.4.14.117) was used to *surface normalize* the radar records collected within the Susquehanna / Shale Hills CZO. This task was completed by Michael Cornett (IT Specialist – Pennsylvania; OCIO/ITS/TSD) on 10 December 2014. In addition, guidance on advanced signal-processing was provided by Brian Jones and Roger Roberts of Geophysical Survey Systems, Inc.

3. The results of this study are interpretative. Until confirmed, geophysical interpretations are considered preliminary estimates of site conditions. The results of geophysical site investigations do not substitute for direct observations, but rather reduce their number, direct their placement, and supplement their interpretations. The lack of ground-truth observations have limited the interpretations made in this report.

4. Data collected with the 270 MHz antenna at Klepler Farm was impaired by improper signal gain settings which caused a false, artificially induced zone of higher amplitude reflections that masked the desired reflections from the soil/bedrock interface.

5. The soil/bedrock interface was difficult to identify and trace laterally along radar records collected at the Susquehanna / Shale Hills CZO. This was attributed to poor antenna coupling with the ground surface, excessive amount of clutter on radar records caused by rock fragments in the overlying soil, irregular and fractured bedrock surfaces, and varying degrees of hardness in both rock fragments and the underlying bedrock. These factors weakened the amplitude, consistency and continuity of reflections from the soil/bedrock interface; and thereby reducing the interpretability of this interface.

6. Although the data collected with the 270 and 400 MHz antennas were similar in terms of basic statistics (average bedrock depths and ranges) and frequency distributions (in terms of the most dominant soil depth class: deep), greater confidence is placed in the interpretations made from data collected with the 270 MHz antenna. Compared with the 400 MHz antenna, the lower resolution of the 270 MHz antenna has smoothed-out irregularities in the bedrock surface and reduced the clutter from smaller, less extensive, undesired subsurface features; thus improving the interpretability of the soil/bedrock interface.

7. Interpretations of the soil/bedrock interface may be further improved with the lower resolution of the 200 MHz antenna. Surface normalization can be improved by conducting shorter transects with a greater number of break points along well-defined slope components with limited relief.

JONATHAN W. HEMPEL
Director
National Soil Survey Center

Attachment (Technical Report)

cc:
Skye Wills, Soil Scientist & Liaison for SSR 6, Soil Survey Interpretation Staff, USDA-NRCS-NSSC, MS 36, Lincoln, NE
Jim Doolittle, Research Soil Scientist, USDA-NRCS-NSSC, Soil Survey Research & Laboratory Staff, Newtown Square, PA
Dave Kingsbury, Soil Survey Regional Director (SSR 6), USDA-NRCS, Morgantown, WV
Luis Hernandez, Acting Director, Soil Science Division, USDA-NRCS, Washington, DC
Wes Tuttle, Soil Scientist (Geophysical), USDA-NRCS-NSSC, Soil Survey Research & Laboratory Staff, Wilkesboro, NC
Douglas Wysocki, National Leader, Soil Survey Research & Laboratory Staff, USDA-NRCS-NSSC, MS 41, Lincoln, NE

Technical Report

James A. Doolittle

Summary:
On November 12th, a seminar on the use of geophysical methods by USDA-NRCS was provided to visiting scholars from China and graduate students. The presentation focused on the use of non-invasive, continuous profiling geophysical tools (e.g., ground-penetrating radar (GPR) and electromagnetic induction (EMI)) to reveal the complexity of soil architectures and its impact on hydrologic processes across different spatiotemporal scales. Later, guidance on the setup, calibration, and surveying procedures used with both EMI and GPR were provided at a site located on the Pennsylvania State University's Klepler Research Farm.

On November 13th, field studies using GPR to map the depth to bedrock (see Figure 1) were carried out within an expanded area of the Susquehanna / Shale Hills Critical Zone Observatory (CZO). The Susquehanna / Shale Hills CZO is a small catchment in central Pennsylvania that has been the focus of National Science Foundation supported research since the 1970s. Within this catchment, long-term studies are being carried out to quantitatively assess the rates of weathering, erosion, and soil formation and how these processes control soil-landscape evolution and the flow of water and energy within the Earth's Critical Zone.

Figure 1. Dr Henry Lin discusses ground-penetrating radar imagery with visiting Chinese scholars and graduate students within the Susquehanna / Shale Hills CZO.

On November 14th, as part of an outreach program, a workshop was conducted for students interested in careers in soil science, hydrology, and geophysics at the Holidaysburg Area High School near Altoona, Pennsylvania. Through classroom instruction and hands-on demonstrations, students were exposed to the work of a USDA-NRCS research soil scientist using GPR to carryout soil and environmental site assessments.

Equipment:

The radar unit is the TerraSIRch Subsurface Interface Radar (SIR) System-3000 (SIR-3000), which is manufactured by Geophysical Survey Systems, Inc. (GSSI; Salem, NH).[1] The SIR-3000 consists of a digital control unit (DC-3000) with keypad, Super Video Graphics Array (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 (see Figure 2). Daniels (2004) and Jol (2008) discuss the use and operation of GPR. Operating procedures for the SIR-3000 are described by Geophysical Survey Systems, Inc. (2004).The antennas used in this study have center frequency of 270 and 400 MHz.

Figure 2. At Pennsylvania State University's Klepler Research Farm, visiting Chinese scholars and graduate students were instructed on the use and operation of ground-penetrating radar and electromagnetic induction systems that are being used by USDA-NRCS in soil investigations.

The RADAN for Windows (version 7.4.14.117) software program (developed by 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, horizontal high-pass filtration, signal stacking, migration, and range gain adjustments (refer to Jol (2009) and Daniels (2004) for discussions of these techniques). For the data collected at the Susquehanna / Shale Hills CZO, because of the availability of elevation data, *surface normalization* was performed on the radar records. The *Interactive 3D Module* of RADAN was used to semi-automatically "*pick*" the depths to the interpreted soil/bedrock interface on radar records. The "*picked*" depth-to-bedrock data were exported to a worksheet for documentation and analysis.

The SIR-3000 system has a setup for the use of a GPS receiver with a serial data recorder. With this setup, each scan on radar records can be georeferenced (position/time matched). During data processing,

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

a subprogram within RADAN proportionally adjusts the position of each radar scan according to the time stamps of the two nearest positions that were recorded with the GPS receiver. A Pathfinder ProXT GPS receiver (Trimble, Sunnyvale, CA) was used to georeferenced the GPR data (see yellow backpack in Figure 2).[2] Position data were recorded at a rate of one reading per second.

The electromagnetic induction (EMI) meter used in this study is the Profiler EMP-400 sensor (here after referred to as the Profiler), which is manufactured by Geophysical Survey Systems, Inc. (Salem, NH).[2] The Profiler has a 1.22 m intercoil spacing and operates at frequencies ranging from 1 to 16 KHz. It weighs about 4.5 kg (9.9 lbs.). The Profiler is a multifrequency EMI meter that can simultaneously record data in as many as three different frequencies. For each frequency, inphase, quadrature and EC_a data are recorded. However, calibration of the Profiler is optimized for 15 KHz and, therefore, EC_a is most accurately measured at this frequency. Operating procedures for the Profiler are described by Geophysical Survey Systems, Inc. (2008).

The Profiler was held in the deeper sensing vertical dipole orientation (VDO) (Figure 2). Data were recorded at both 15000 and 5000 KHz. The sensor's electronics are controlled via Bluetooth communications with a Trimble TDS RECON-400 Personal Data Assistant (PDA). The MagMap 2000 software (developed by Geometric, Inc., San Jose, CA) was used to process the EMI survey data.[2]
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Calibration of GPR:

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., rock, 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 equation [1] (after 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 equation [2] (after Daniels, 2004):

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

In equation [2], C is the velocity of propagation in a vacuum (0.3 m/ns). Typically, velocity is expressed in meters per nanosecond (m/ns). In soils, the amount and physical state (temperature dependent) of water have the greatest effect on E_r and *v*. At the time of this study, soils were moist.

Antennas with center frequencies of 270 and 400 MHz were used in this study. The depth of exploration is governed by soil physiochemical properties and antenna center frequency. The rate of signal attenuation increases, and consequently, the depth of exploration decreases as the antenna center frequency increases. However, resolution improves as the antenna center frequency increases.

Calibration of GPR was achieved at the Susquehanna / Shale Hills CZO. Based on the measured depth and the two-way pulse travel time to a known subsurface reflector (metal plate buried at 50 cm; see Figure 3), the *v* and E_r through the upper part of the soil profile were estimated using equations [1] and [2]. For the 270 MHz antenna, the estimated *v* was 0.1095 m/ns and the estimated E_r was 7.50. For the 400 MHz antenna, the estimated *v* was 0.1161 m/ns and the estimated E_r was 6.67. These values were used to convert the time-scale into a depth-scale on the radar records that were collected within the Susquehanna / Shale Hills CZO.

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

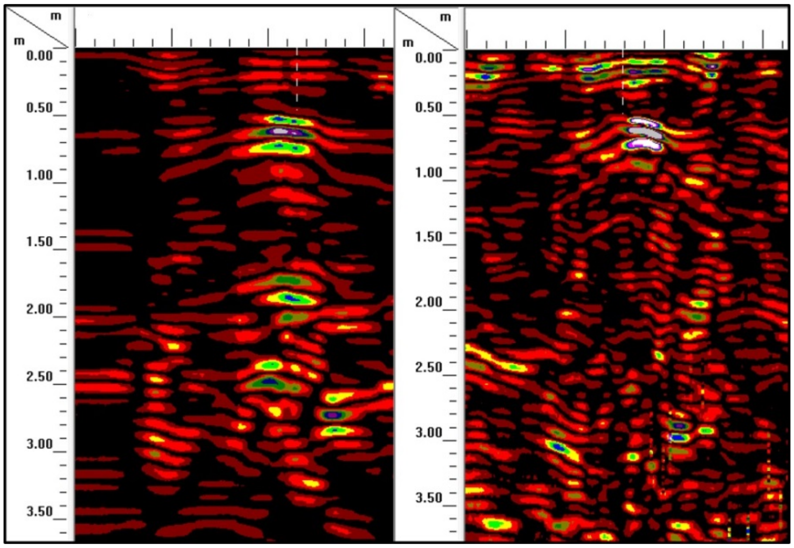

Figure 3. These radar records show reflections from a metallic plate that has been buried at a depth of 50 cm. The image on the left was obtained with a 270 MHz antenna; the image on the right was obtained with a 400 MHz antenna.

The estimated E_r values follow the general rule that the dielectric permittivity will decreases with increasing antenna frequency. The drop in E_r and the increase in *v* as the frequency is increased are the result of a net drop in polarization (caused by electrons shifting within molecules, and dipolar molecules rotating or ions changing places).

For each radar traverse conducted within the Susquehanna / Shale Hills CZO, the scanning time was 75 ns. This scanning time provided maximum depth of investigations of about 4.1 and 4.35 with the 270 and 400 MHz antennas, respectively.

Field Methods:

Multiple GPR traverses are completed by pulling the 270 MHz and 400 MHz antennas along the ground surface. A distance-calibrated survey wheel with encoder was bolted onto these antennas and provided greater controls over signal pulse transmission and data collection (see Figure 2). The survey wheel experience some slippage, which did result in some recorded line lengths (from the survey wheel) being slightly different than the actual lengths. Each radar traverse was stored as a separate file.

The GPS option was used with the SIR-3000 system. The Trimble Pathfinder ProXT GPS receiver was operated in the autonomous mode that supposedly provides a horizontal accuracy of approximately 3–9 meters. However, multipath distortion and satellite shading (caused by slope and vegetation obstructions), lessened the positional accuracy and reduced the number of radar traverses and scans that could be satisfactorily geo-referenced with GPS. Other sources of positioning error included the number of satellites in view, satellite geometry, ionospheric conditions, and of course, the quality of GPS receiver.

In order to *surface normalize* the radar records collected within the Susquehanna / Shale Hills CZO, relative elevation data were collected at major slope breaks along the traverse line with an engineering level and stadia rod.

Results:

<u>Klepler Farm:</u>

Multiple traverses were completed with the 270 MHz antenna across a portion of a research field at Klepler Farm. Here, the extensively mapped Hagerstown (fine, mixed, semiactive, mesic Typic

Hapludalfs) and Opequon (clayey, mixed, active, mesic Lithic Hapludalfs) soils have low potential for penetration with GPR because of their high clay contents and associated high rates of signal attenuation.

Unfortunately, GPS data were not recorded for a majority of the GPR traverses. For these traverses, a range of 75 ns was used. An E_r of 22.8 was used to provide a conservative estimate of the effective depth of investigation (about 2.3 m). In order to amplify deeper radar reflections, the gain curve was adjusted to linearly increase with depth. However, the raw radar data were not optimally gained on the control unit. The gain curve was established with 5 breakpoints (-20, 0, 38, 38. 43). A value of -20 was used for the first breakpoint to reduce the amplitude of the surface pulse. Unfortunately, a rather large increase in gain values occurred between the second and third breakpoints (38). It is usually considered inadvisable to increase the gain between two breakpoints by more than 20. As a result of the large increase in gain between these two breakpoints, reflections were over-gained and a false or synthetic, higher signal amplitude layer appeared on the radar records (Figure 4). Reflections from underling limestone bedrock were masked by this layer of noise and were too weak to be observed even after significant data processing (see Figure 4).

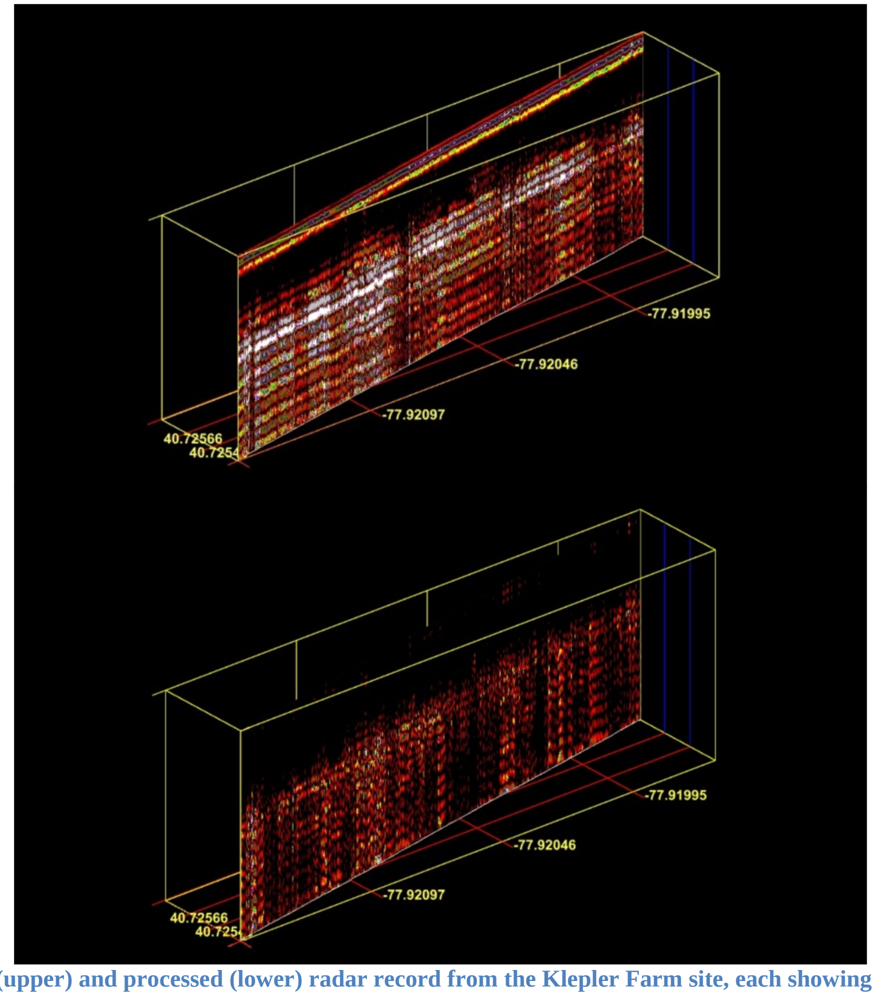

Figure 4. A raw (upper) and processed (lower) radar record from the Klepler Farm site, each showing a false subsurface layer that occurs at a constant depth and reflects the large increase in gain that was applied between two breakpoints.

<u>Susquehanna / Shale Hills Critical Zone Observatory:</u>
This CZO has been expanded to include a portion of the valley between Tussey Mountain and Leading Ridge in Huntingdon County. The valley is occupied by Garner Run, a southwest flowing stream. The

lower slopes of this valley are underlain by the Silurian Age Clinton Group, which is composed of shale from the Rose Hill Formation. The mid to upper side slopes and summit of Leading Ridge are underlain by the Silurian Age Tuscarora Formation, which consists of white sandstone and quartzite with minor beds of shale.

A traverse line was established that ascends Leading Ridge in essentially a west to east direction from near Garner Run to the summit. Along this traverse line, elevations vary from about 494 to 588 meters. The dominant soils mapped along this traverse line include: Andover, Albrights, Hazleton, and Dekalb. The very deep, poorly drained Andover and moderately well to somewhat poorly drained Albrights soils formed in colluvium derived from acid sandstone and shale on upland toe-slopes and foot-slopes positions. The moderately deep, excessively drained Dekalb and the deep and very deep, well drained Hazleton soils formed on higher-lying slope positions in residuum weathered from acid sandstone. The taxonomic classifications of these soils are listed in Table 1. These soils have moderate potential for penetration with GPR.

Table 1. Taxonomic classifications of the soils recognized along the transect line that ascended Leading Ridge in Huntingdon County.

Series	***Taxonomic Classification***
Albrights	Fine-loamy, mixed, semiactive, mesic Aquic Fragiudalfs
Andover	Fine-loamy, mixed, active, mesic Typic Fragiaquults
Dekalb	Loamy-skeletal, siliceous, active, mesic Typic Dystrudepts
Hazelton	Loamy-skeletal, siliceous, active, mesic Typic Dystrudepts

The traverse line had been cleared of debris. However, the ground surface remains highly irregular with numerous rock fragments and exposed tree roots. These obstacles often halted the movement and caused poor coupling of the antennas with the ground. In this study, flags were inserted in the ground at noticeable breaks in the topography along the traverse line. User marks were inserted on the radar records as the antenna passed by these survey flags. Later, the elevations of these points were determined using an engineering level and stadia rod. The elevation data were entered into the radar data files and used to "surface normalize" or "terrain correct" the radar records.

Surface Normalization was applied to the radar records to adjust the vertical scale to the general topographic form. Because of the large relief (about 94 m), the elevation data were reduced (by a factor of 4) prior to running the *surface normalization* procedure. In addition, the vertical scale was set to 1:4 and compressed during *surface normalization*. These steps were necessary to view the entire "surface normalized" radar record and to prevent it from "running-off" the top and the bottom of the display window.

As the radar traverses were conducted using the GPS option, these position and elevation data were recorded and available for *surface normalization*. The steeply sloping, forested terrain was extremely unfavorable for good satellite reception. Because of poor GPS reception and low positional accuracy, use of GPS elevation data resulted in a noticeably incorrect, highly "up-and-down" topography along the traverse line, which, in fact, steadily ascended the slopes. In addition, the spatial tracts of the GPS data wandered widely over a seemingly large horizontal distance orthogonal to the direction of the traverse. In such terrains, GPS data should not be imported with radar data into RADAN, as the data are incorrect and must be manually removed (a time-consuming process) prior to *surface normalization*.

The "surface normalized" plots of the radar data that were collected with the 270 MHz antenna are displayed in Figures 5 to 8. The same color table, color transformation, and gain settings were used on all of these images. Figure 5 is the radar record from the lower-lying, toe and foot slope positions nearest Garner Run. These slope components are presumably underlain by shales of the Rose Hill Formation.

Figure 6 is the radar record from the lower to mid back-slope positions. These slope components are presumably underlain by the Tuscarora Formation. Figure 7 is the radar record from the upper back-slope and summit positions, which is also underlain by the Tuscarora Formation.

In each of the surface normalized plots shown in Figures 5 to 7, a segmented, black-colored line has been used to highlight the interpreted soil/bedrock contact. This contact does not provide smooth, continuous, high-amplitude reflections that are easily charted across these radar records. The traced contact is highly irregular, segmented, and variable in reflection patterns and amplitudes. In many areas, the contact has been identified by gross changes in signal amplitude or reflection patterns. In places, seemingly planar reflectors, believed to represent cleavage or bedding planes in the underlying bedrock, approach and end near this likely contact.

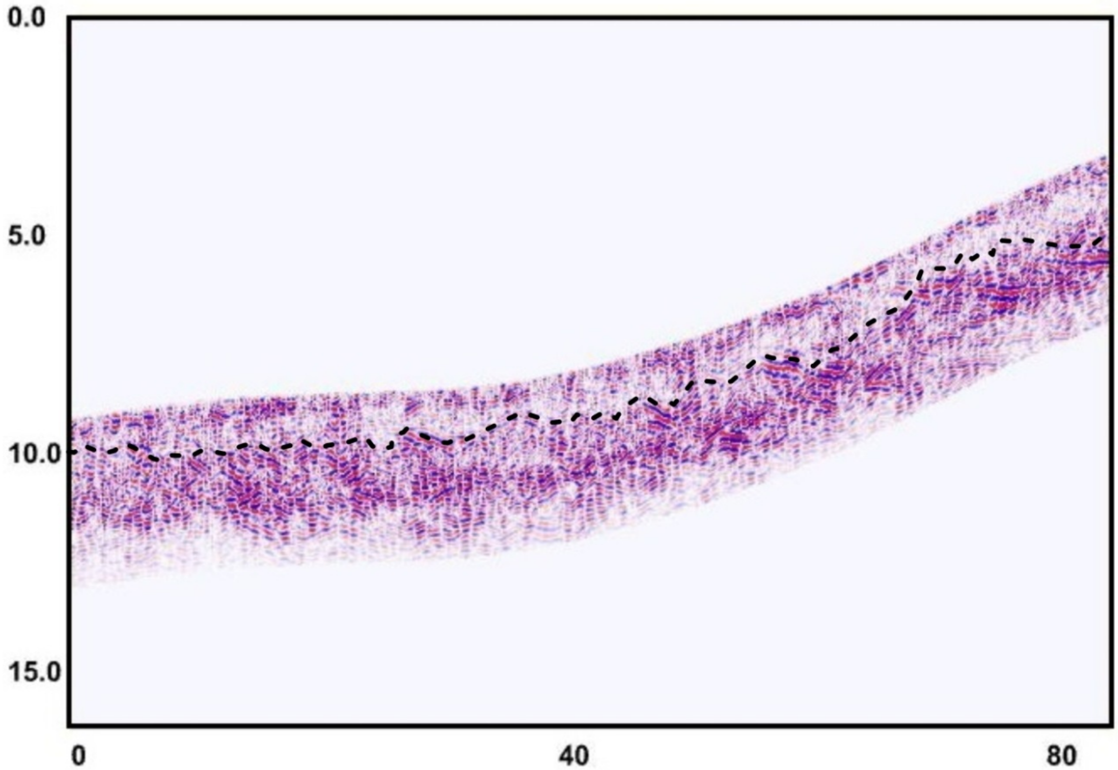

Figure 5. A surface normalized radar record that was collected along the lowest portion of the traverse line in an area of very deep Andover and Albrights soils. All scales are expressed in meters. The black, segmented line represents the interpreted soil/bedrock interface.

The lack of a continuous, easily identifiable soil/bedrock interface is attributed to unfavorable terrain conditions. Rock fragments, animal burrows, tree roots, and other inhomogeneities in the soil produced unwanted reflections or scattering of the radar waves, which adds complexity to the radar records and masked the clarity of the soil/bedrock interface. With excessive, unwanted scattering (i.e., clutter), the radar data becomes uninterpretable. On portions of the radar records, the soil/bedrock interface was unclear and difficult to accurately chart because of the large number of reflections from rock fragments in the overlying soil, the highly irregular and fractured nature of the bedrock surface, and/or the varying degree of hardness exhibited by both rock fragments and the underlying bedrock because of weathering processes. Here, the soil/bedrock contact was not evident as an abrupt and contrasting single reflector, but interpreted as a rather broad band composed of numerous segmented reflectors of varying amplitudes. Such an interpretation implies a comparatively wide, ill-defined boundary consisting of large amounts of coarse rock fragments overlying highly fractured or irregular bedrock surfaces. In addition, unwanted noise was also caused by the decoupling of the antenna to the ground surface due to rough terrain, and exposed rock fragments, roots and vegetation on the ground surface.

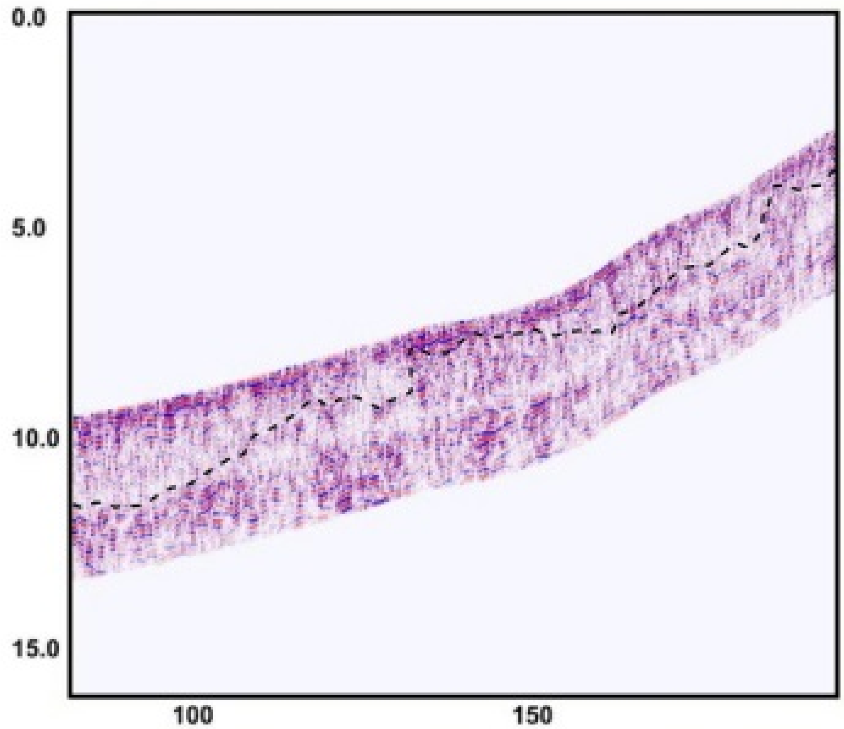

Figure 6. A surface normalized radar record that was collected along the middle section of the traverse line in an area of moderately deep Dekalb and deep and very deep Hazleton soils. All scales are expressed in meters. The black, segmented line represents the interpreted soil/bedrock interface.

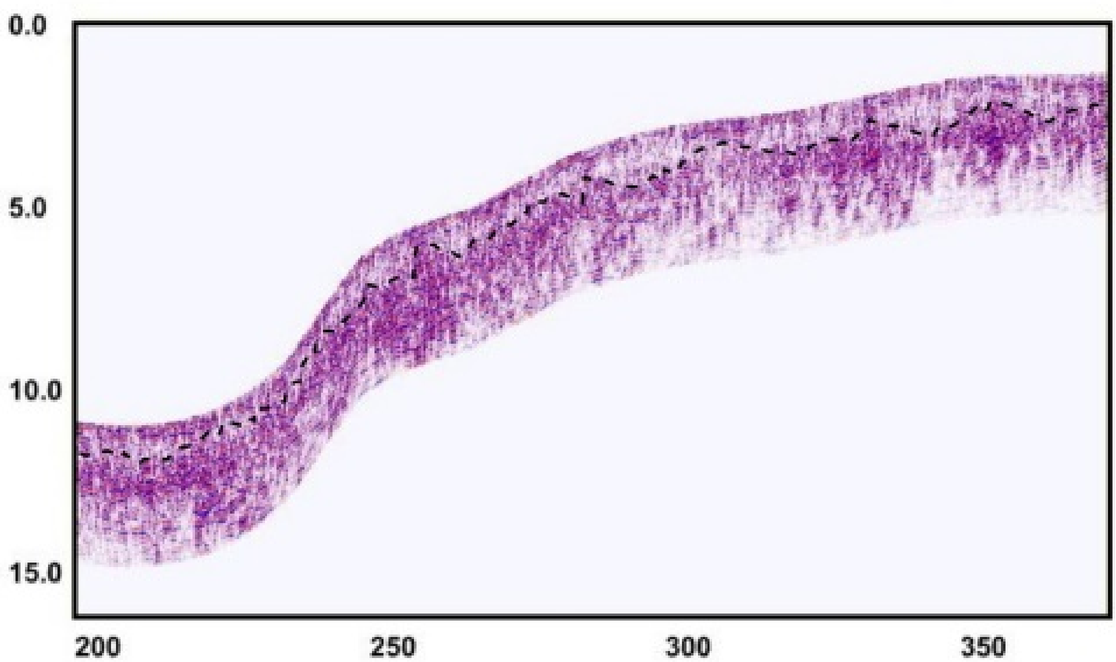

Figure 7. A surface normalized radar record that was collected along the highest-lying portion of the traverse line in an area of moderately deep Dekalb and deep and very deep Hazleton soils. All scales are expressed in meters. The black, segmented line represents the interpreted soil/bedrock interface.

Figure 8 is a composite of all three radar records that were collected with the 270 MHz antenna. These records are arranged from top to bottom, according to increasing elevation and distance along the traverse line. The vertical scales merely provide a relative measure for each radar record.

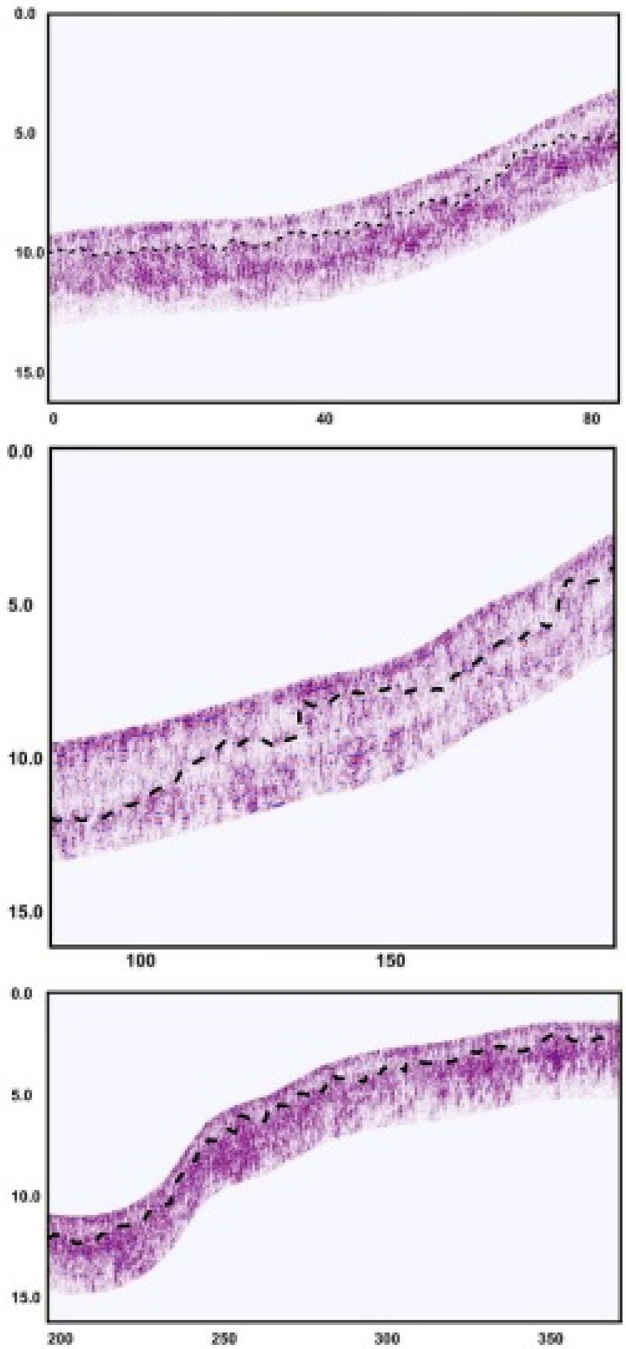

Figure 8. These three radar records were collected with the 270 MHz antenna along the traverse line. The radar records are arranged from top to bottom in order of increasing elevation and distance along the traverse lines. All scales are expressed in meters. The vertical scales provide a relative measure.

Using the interactive module of RADAN 7.0, the depth to bedrock was semi-automatically picked along the three radar records. A total of 14,901 soil-depth measurements were made. The interpreted depth to bedrock averaged 1.25 m, with a range of 0.42 to 2.69 m along this traverse line. Based on these measurements, soils are largely deep (53 %), moderately deep (24 %), and very deep (22 %) to bedrock. Table 2 provides a summary of the depth to bedrock interpretations for the three radar traverses that were made with the 270 MHz antenna. The depth classes used in this table are shallow (< 50 cm), moderately deep (50 to 100 cm), deep (100 to 150 cm) and very deep (> 150 cm).

Table 2. Frequency distribution of depth to bedrock data collected with the 270 MHz antenna along a traverse line that ascended Leading Ridge in Huntingdon County, Pennsylvania. Data are grouped into four soil depth classes.

	File 20	*File 21*	*File 22*
Shallow	0.00	0.02	0.00
Mod Deep	0.16	0.22	0.35
Deep	0.65	0.32	0.62
Very Deep	0.19	0.44	0.03

Traverses were also completed using the higher-frequency 400 MHz antenna. Figure 9 contains two surface normalized plots of the data that were collected with the 400 MHz antenna as it was pulled down Leading Ridge from the summit area to near Garner Run. In these plots, the distance scale is measured from the summit area to near Garner Run. While differences in gross reflection patterns can be used to differentiate rock from soil, on these images, the soil/bedrock interface is considered too diffuse and unclear to provide accurate soil-depth measurements. Although, resolution of subsurface features often improves as the antenna center frequency is increased, in this example, the 400 MHz antenna has detected a larger number of inhomogeneities or scattering bodies in the soil than the 270 MHz antenna. This unwanted clutter interferes with interpretations, as these reflections have obscured the soil/bedrock interface. In this study, the lower frequency 270 MHz antenna averaged reflections across a larger wave length and provided a more coherent and traceable soil/bedrock interface than with the 400 MHz antenna. Future studies should investigate the interpretability of the soil/bedrock interface on radar records collected with a lower frequency 200 MHz antenna.

Though more difficult to interpret and considered slightly less accurate, the depth to bedrock was semi-automatically picked and measured along the two radar traverses that that were completed with the 400 MHz antenna. Based on a total of 14,748 soil-depth measurements, the interpreted depth to bedrock averaged 1.37 m, with a range of 0.58 to 2.42 m, along this traverse line. This statistical data compares well with the data collected with the 270 MHz antenna (average of 1.25 m; range of 0.42 to 2.69 m). Based on the soil depth measurements made on the 400 MHz data, soils are deep (49 %), very deep (36 %), and moderately deep (15 %) to bedrock. For comparison, with the 270 MHz data, soils were interpreted as being deep (53 %), moderately deep (24 %), and very deep (22 %) to bedrock. Table 2 provides a summary of the depth to bedrock interpretations for the two radar traverses completed with the 400 MHz as it descended Leading Ridge.

Table 3. Frequency distribution of depth to bedrock data collected with the 400 MHz antenna along a traverse line that descended Leading Ridge in Huntingdon County, Pennsylvania. Data are grouped into four soil depth classes.

	File 23	*File 24*
Shallow	0.00	0.00
Mod Deep	0.26	0.04
Deep	0.51	0.48
Very Deep	0.24	0.48

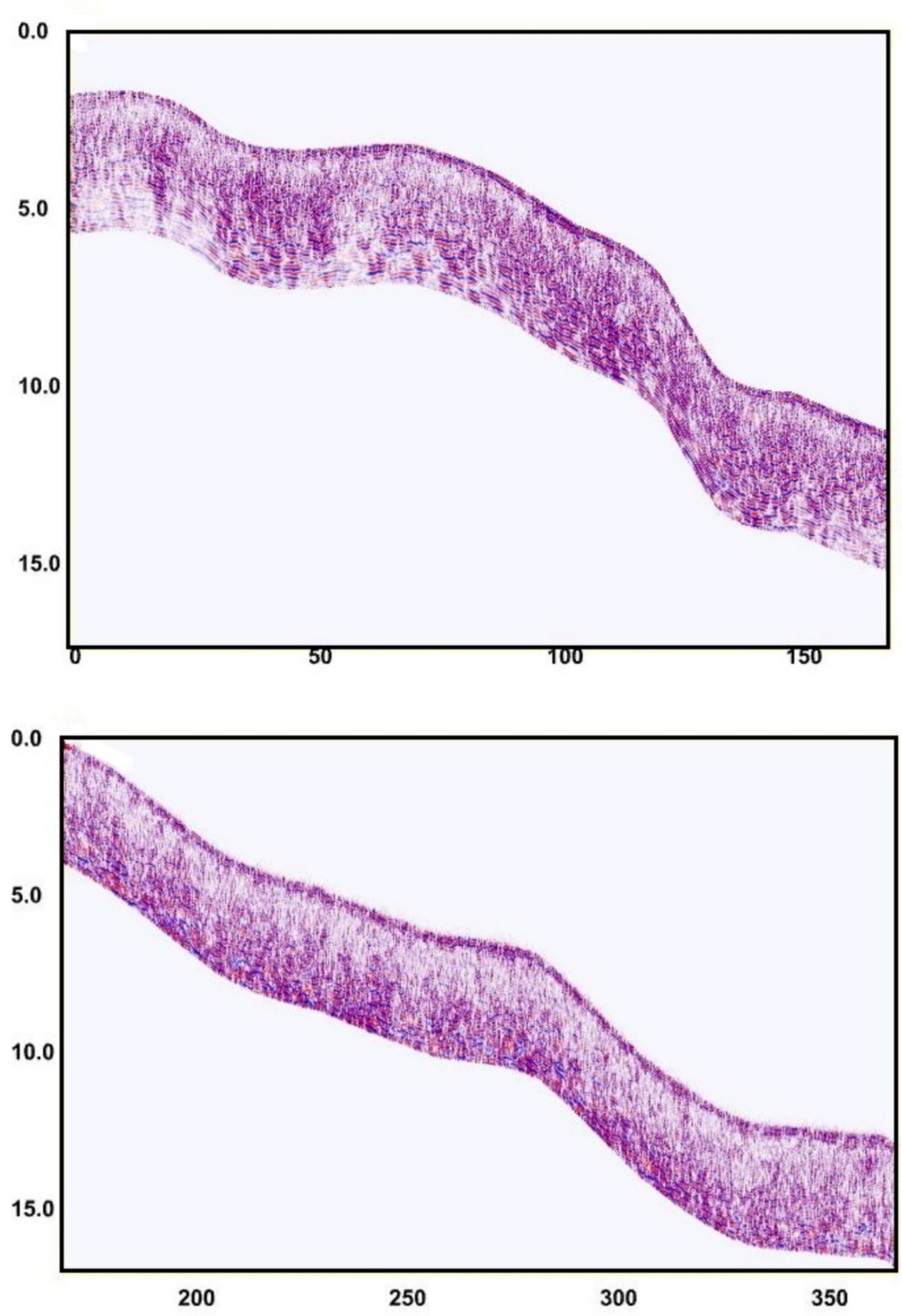

Figure 9. These two radar records were collected with a 400 MHz antenna along the traverse line. The radar records are arranged (from top to bottom) in order of decreasing elevation and increasing distance along the traverse lines that commenced near the summit of Leading Ridge. All scales are expressed in meters. The vertical scales provide only a relative measure.

References:

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

Geophysical Survey Systems, Inc., 2004. TerraSIRch SIR System-3000; User’s Manual. MN72-433 Rev D. Geophysical Survey Systems, Inc., North Salem, New Hampshire, USA.

Geophysical Survey Systems, Inc., 2008. Profiler EMP-400. User's Manual. Geophysical Survey Systems, Inc., North Salem, New Hampshire, USA.

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