United States Department of Agriculture

NRCS

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SUBJECT: MGT – Trip Report – Geophysical Assistance

May 8, 2013

TO: Denise Coleman
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File Code: 330-7

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Purpose:
Geophysical investigations were conducted at the Shale Hills *Critical Zone Observatory* (CZO) in Huntington County, and at Pennsylvania State University's *Living Filter Field* in Centre County, Pennsylvania. The principal goal of the interdisciplinary research that is being conducted at the Shale Hills CZO is to quantitatively predict the formation, evolution, and structure of regolith as a function of the biologic, geochemical, geomorphologic, hydrologic and pedologic processes operating in a temperate, forested landscape. The Shale Hills CZO serves as an experimental catchment for the study of spatial and temporal variations in hydrological responses. The focus of the present research is to characterize the depth to rock, stratigraphic layers and soil horizons that influence the flow of water thru different soil-landscape components within the catchment.

Since 1982, the Living Filter Research Project has studied the continuous application of effluent on farmlands and woodlands. Permitted to spray effluent at a rate of two inches per week, researchers are studying the effect of soil properties on the extraction and filtration of nutrients contained in the waste water. The focus of the geophysical research is to characterize the variability of soil and rock structure and their impact on water filtration.

Participants:
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Activities:
Field activities were completed during the period March 4-7, 2013.

Summary:

1. Ground-penetrating radar was used to determine the depth and characterize the inherent structural variability of the underlying fractured rock in the Shale Hills CZO and the Pennsylvania State University's *Living Filter Field*. At both locations, the depth to rock corresponded with map unit concepts and soil-landscape models. Within the Shale Hills CZO, soils are dominantly shallow (Weikert series) and moderately deep (Berks series) to rock with shallower soils dominating higher-lying soil-landscape components and moderately deep and deeper soils dominating lower-lying soil-landscape components. Within the Living Filter Field, soils are dominantly deep and very deep, which conforms to the concepts of the mapped Hagerstown consociations. At both sites, as revealed by GPR, the expression and structure of the underlying rock is highly variable. This variability will affect the flow of water resulting in different flow patterns over differently structured rock.

2. Electromagnetic induction was used to survey portions of the *Living Filter Field*. The results are unsatisfactory for several reasons. The *Living Filter Field* should be resurveyed with greater control and more intensive data collection.

DAVID R. HOOVER
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Attachment (Technical Report)

cc:
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Technical Report on Geophysical Investigations conducted at the Shale Hills *Critical Zone Observatory* (CZO) in Huntington County and at Pennsylvania State University's Living Filter Field in Centre County on March 4-7, 2013.

James A. Doolittle

GPR

Equipment:

The radar unit is the TerraSIRch Subsurface Interface Radar (SIR) System-3000 (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 typically requires two people to operate. Daniels (2004) and Jol (2008) discuss the use and operation of GPR. The 400 and 200 MHz antennas were used in this investigation. A survey wheel was used with each antenna.

The RADAN for Windows (version 6.6) software program (developed by GSSI) was used to process the radar records.[1] Processing included: header editing, setting the initial pulse to time zero, color table and transformation selection, signal stacking, horizontal high-pass filtration, migration, and range gain adjustments (refer to Jol (2009) and Daniels (2004) for discussions of these techniques). The *Interactive 3D Module* of RADAN was used to semi-automatically "*pick*" the depths to the interpreted rock surface on radar records. The picked data were exported to a worksheet (in an X, Y, and Z format; including longitude, latitude, and depth to rock) for documentation.

The SIR-3000 system contains a setup for the use of a GPS receiver with a serial data recorder (SDR). With this setup, each scan of the radar can be geo-referenced (position/time matched). Following data collection, a subprogram within the RADAN for Windows software program 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 AG114 L-band DGPS (differential GPS) antenna (Trimble, Sunnyvale, CA) was used to collect position data.[1] Position data are recorded at a rate of one reading per second. The scanning rate of the GPR is 64 scan/sec.

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):

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

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

Where C is the velocity of propagation in a vacuum (0.3 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. At the time of these studies, soils are moist.

Based on the measured depth and the two-way pulse travel time to a known subsurface reflector (metal plate buried at 50 cm), the velocity of propagation and the relative dielectric permittivity through the upper part of soil profiles were estimated using equations [1] and [2]. The calibration site is located in an area of Rushtown soils. For the 200 MHz antenna, an estimated v of 0.0918 m/ns resulted in an E_r of 10.7. For the 400 MHz antenna, an estimated v of 0.0862 m/ns resulted in an E_r of 12.1. It must be noted that using one E_r value for transforming travel times into depth scales generally lead to slightly distorted values due to assumption of uniform layers with constant E_r, and not accounting for spatial and depth variations in the soil architecture and moisture contents. The v and E_r determined at Shale Hills CZO were also used in the interpretations for the *Living Filter Field*.

Field Methods:
Multiple GPR traverses are completed by pulling the 400 MHz antenna along the ground surface. A distance-calibrated survey wheel with encoder was bolted onto the antenna and provided greater controls over signal pulse transmission and data collection. The survey wheel experienced some slippage resulting in the fractional line length from the survey wheel being slightly off from the actual length. Each radar traverse was stored as a separate file. The GPS option was used with the SIR-3000 system, and a majority of the radar scans were geo-referenced. Satellite shading, caused by slope and vegetation obstructions, reduced the number of radar traverses and scans that could be geo-referenced with GPS.

Results:
Twenty-eight radar traverses are completed across the Shale Hills CZO with a 400 MHz antenna and survey wheel. However, because of poor satellite reception, ten traverses could not be geo-referenced and used. For the eighteen traverses that were used a total of 125,527 geo-referenced radar measurements of the depth to rock were obtained. Along the traverse lines, the average depth to rock is 42 cm with a range of 0 to 161 cm. Table 1 summarizes the data collected along these traverses according to soil depth classes. Beneath the traverse areas, the depth to rock is largely shallow (75 %; < 50 cm) with inclusions of moderately deep (22 %; 50 to 100 cm) and deep (3 %; 100 to 150 cm) soils.

Table 1. Distribution of GPR depth to rock measurements according to number and relative frequency into recognized soil-depth classes.

Depth Class (cm)	Number	Frequency
< 50	94775	0.75
50 to 100	27132	0.22
100 to 150	3428	0.03
> 150	192	0.00

Figure 1 is a Google Earth image showing the Shale Hills CZO and the location of the aforementioned eighteen GPR traverses. Colors have been used to identify the different soil depth classes (white - shallow; red - moderately deep; yellow – deep; and green – very deep (> 150 cm)). As evident in Figure 1, soils are dominantly shallow along the trail that encircles the watershed and delineates its perimeter and summit area. Along these radar traverse lines, the average depth to rock is 31 cm with a range of 0 to 79 cm. Soils are 96 % shallow and 4 % moderately deep along these summit traverse lines. Soils are deeper on lower slope components within the interior of the watershed. Along these radar traverses, the average depth to rock is 59 cm with a range of 10 to 161 cm. Soils are 43 % shallow, 50 % moderately deep and 7 % deep along these lower-lying, more interior, side slope traverse lines.

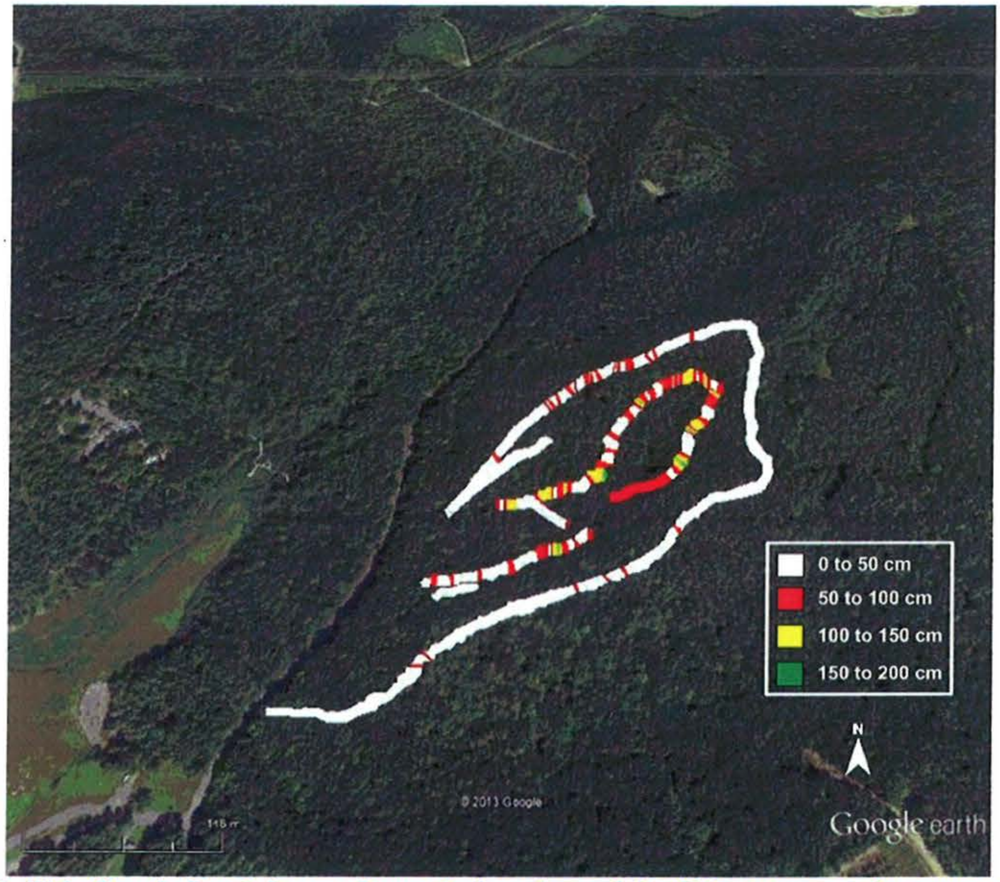


Figure 1. This Google Earth image shows the locations of the GPR traverses that were recently completed within the Shale Hills Critical Zone Observatory. Major depth classes are indicated by color-codes used along each of the traverse lines. (Image courtesy of Brian Jones, GSSI).

Rough Grids:

Four survey grids were arranged on linear, upper back slope components of Weikert (loamy-skeletal, mixed, active, mesic Lithic Dystrudepts) soils. Two sets of grids were located on both south-facing and north-facing slopes. Multiple, one-directional radar traverses were conducted across each grid site using the 400 MHz antenna with an attached survey wheel. The origin of the south-facing and north-facing grids was located in the southwest and northeast corner of the grid, respectively. Traverse lines were spaced 50 cm apart. The dimensions of the grids were 7 by 5 meters for traverses conducted parallel with the slope contours and 5 by 5 m for traverses conducted perpendicular with the slope contours. Radar records from these grids provided detailed images of the soil and rock architectures and the soil/rock interface.

Figure 2 contains four, 2D radar records that were collected in two different directions (parallel and perpendicular with contours) across the two south- and north-facing grid sites. On each of these radar records, the soil/rock interface, though evident, does not present a smooth, continuous, easily charted single reflection. The multiple, high-amplitude (in Figure 2, reflectors that are white and grey colored) reflections that occur at a depth of about 50 cm help to identify the soil/rock interface. At this scale, the soil/rock interface is poorly defined, as it is composed of numerous, segmented reflectors of various shapes and inclinations. The apparent inclinations of these reflectors suggest bedding or cleavage planes and fractures in the underlying shale. These inclined interfaces appear to be slightly better expressed on the radar records that were collected perpendicular to the slope contours. The overlying soil contains low amplitude (colored red) reflectors that are assumed to represent rock fragments, roots, and other inhomogeneities. The irregular topography and the segmented appearance of the soil/rock interface suggest that the underlying rock is highly fractured and provides numerous potential avenues for preferential flow rather than forming a continuous impenetrable barrier to water movement.

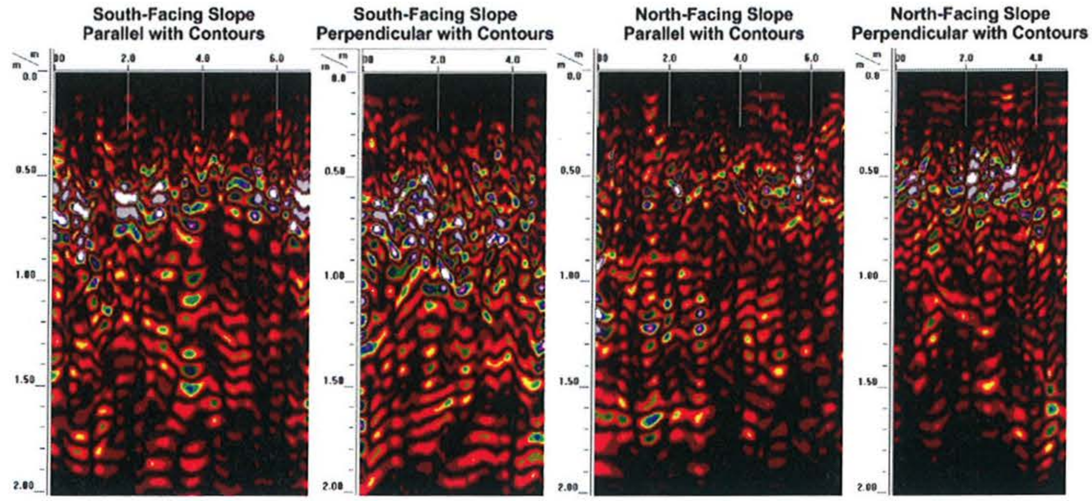


Figure 2. These 2D radar records were collected in areas of Weikert soil on linear, upper side slopes. Radar traverses were conducted across two different slope aspects, and for each aspect, in directions parallel and perpendicular with contour lines.

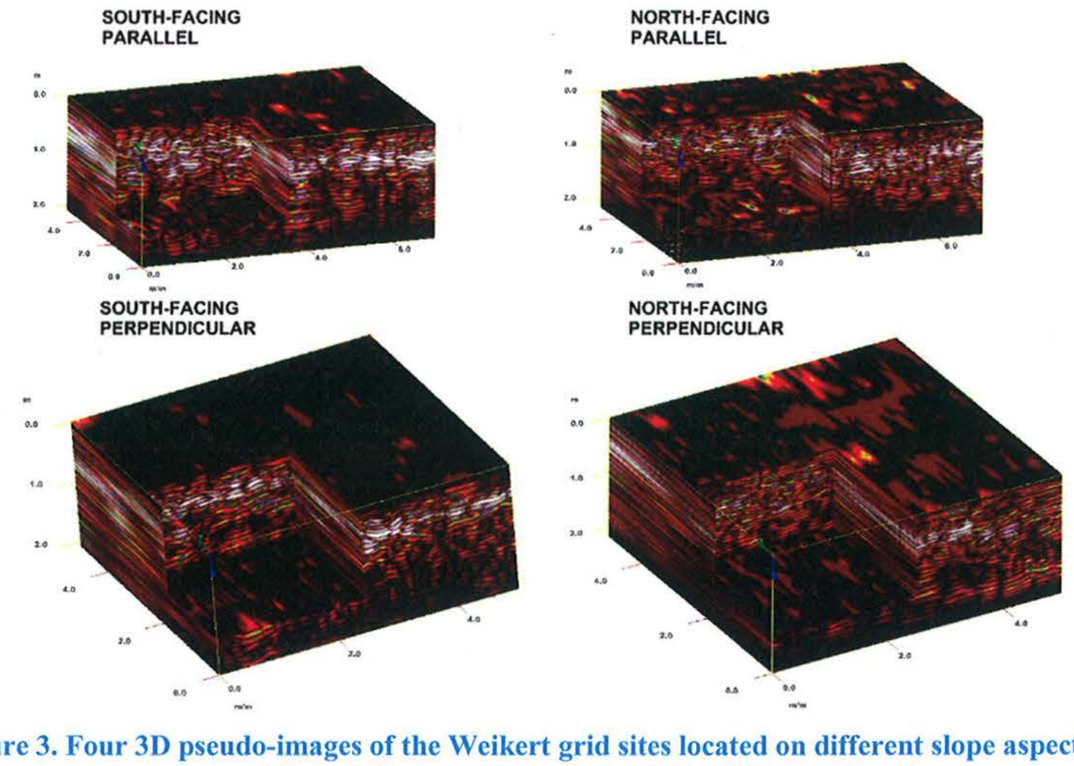


Figure 3. Four 3D pseudo-images of the Weikert grid sites located on different slope aspects and constructed from radar traverses conducted in different directions.

Figure 3 contains 3D-GPR pseudo images of the four grid sites. These pseudo-images were prepared from data collected with a 400 MHz antenna. A small inset cube has been graphically removed from each pseudo-image to improve the viewing of the soil and rock structure. In each pseudo-image, the soil/rock interface is identified by the band of high-amplitude reflections that appears between depths of about 40 to 70 cm. This band of high-amplitude reflections is believed to represent a zone of more weathered and highly fractured rock. The very appearance of this zone suggests a rather open and permeable medium consisting of many avenues for water infiltration.

EMI & GPR

Living Filter Field:

Ground-penetrating radar and electromagnetic induction surveys were completed at Pennsylvania State University's *Living Filter Field*. The Living Filter Research Project sprays sewage effluent onto wood land and agricultural plots as part of a wastewater renovation cycle in which the biologically active soil profile serves as the final treatment step in sewage effluent remediation. The *Living Filter Field* has been in continuous operation since 1982 and receives as much as two inches of sprayed effluent per week.

Figure 4 - This soil map shows the areas that are surveyed (enclosed by segmented lines) at the Living Filter Field.

Figure 4 is a soil map of the surveyed portion of the *Living Filter Field*.[2] Electromagnetic induction surveys were confined to the southern, cultivated portion of the *Living Filter Field* (see Field B in Figure 4).

[2] Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at http://websoilsurvey.nrcs.usda.gov/ accessed [04/14/2013].

This area has been mapped as Hagerstown silt loam, on 3 to 8 percent slopes (HaB) and 8 to 15 percent slopes (HaC). The deep and very deep, well drained Hagerstown soils formed in residuum weathered from limestone. Hagerstown is a member of the fine, mixed, semiactive, mesic Typic Hapludalfs taxonomic family. Ground-penetrating radar surveys were completed across the northern portion of the Living Filter Field (see Field A in Figure 4). The same map units occur in this portion of the *Living Filter Field.*

EMI Meters:
The EM38-MK2 meter (Geonics Limited; Mississauga, Ontario) was used in this.[1] Operating procedures for the EM38-MK2 meter are described by Geonics Limited (2009). The EM38-MK2 meter operates at a frequency of 14.5 kHz and weighs about 5.4 kg (11.9 lbs.). The meter has one transmitter coil and two receiver coils, which are separated from the transmitter coil at distances of 1.0 and 0.5 m. This configuration provides two nominal exploration depths of 1.5 and 0.75 m when the meter is held in the vertical dipole orientation (VDO), and 0.75 and 0.40 m when the meter is held in the horizontal dipole orientation (HDO).

The Geonics DAS70 Data Acquisition System was used with the EM38-MK2 meter to record and store both EC_a and GPS data. The acquisition system consists of the EMI meter, an Allegro CX field computer (Juniper Systems, Logan, Utah), and a Trimble Ag114 L-band DGPS (differential GPS) antenna (Trimble, Sunnyvale, CA).[1] With the acquisition system, the meter is keypad operated and measurements are automatically triggered. The RTmap38MK2 software program developed by Geomar Software Inc. (Mississauga, Ontario) was used with the EM38-MK2 meter and the Allegro CX field computer to record, store, and process EC_a and GPS data.[1]

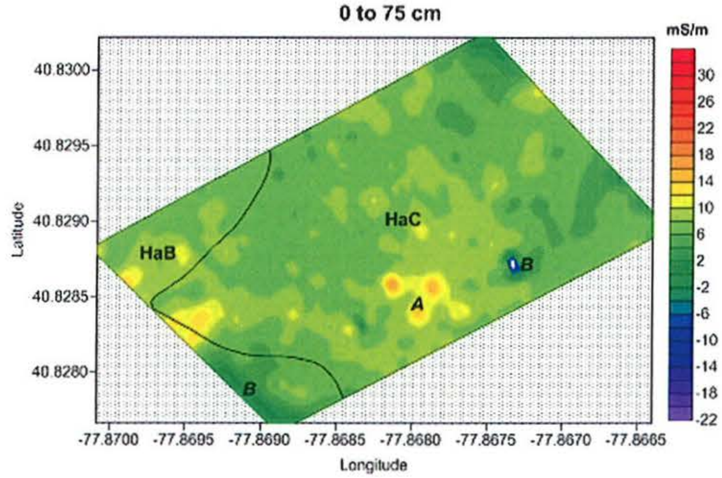
To help summarize the results of the EMI survey, SURFER for Windows (version 10.0), developed by Golden Software, Inc. (Golden, CO), was used to construct the simulations shown in this report.[1] Grids of EC_a data were created using kriging methods with an octant search.

Field Procedures:
The EM38-MK2 meter was operated in the VDO and in the continuous recording mode. The meter was towed in a sled behind a 4WD all-terrain-vehicle. Measurements were recorded at a rate two measurement per sec. The EC_a data were not corrected to a standard temperature of 75° F. Areas with noticeably aberrant EC_a values were recorded in the survey that was conducted across the northern portion of the *Living Filter Field* (portion closest to offices). As this portion of the field lies beneath the approach to the Penn State Airport, which is located less than 2.0 km to the northeast, these strange values could be due to electromagnetic interference. The EMI data from this portion of the *Living Filter Field* are considered unusable and not described in this report.

Results:
<u>EMI:</u>
Basic statistics for the EMI survey that was conducted in area B (see Figure 4) are listed in Table 2. Results obtained with the 100 cm intercoil spacing appear correct, but those of the 50 cm intercoil spacing do not. It is possible that the settings for the 50 cm intercoil spacing were improperly calibrated or drifted during operation. For the data collected with the 100 cm intercoil spacing (exploration depth of 150-cm), EC_a averaged 17 mS/m and ranged from about 3 to 39 mS/m. However, one-half of the measurements recorded with the 100 cm intercoil spacing were between only 16 and 18 mS/m. This narrow range may be the result of the amount and distribution of water in the soil profiles. Greater variations in EC_a were expected and attributed to variations in clay content, depth to limestone and the presence of buried drainage lines.

Table 2. Basic statistics for EMI survey that was conducted on a portion of the *Living Filter Field* with an EM38-MK2 meter. Other than the number of observations, all EC_a values are expressed in mS/m; all IP values are expressed in ppt.

	100 EC_a	*100 IP*	*50 EC_a*	*50 IP*
Number	1901	1901	1901	1901
Minimum	2.7	-36.9	-69.9	-203.7
25%-tile	15.9	5.9	6.5	-69.3
75%-tile	18.4	27.5	8.4	-38.7
Maximum	38.8	118.4	21.2	51.0
Average	17.2	16.9	7.3	-56.0
St. Dev.	2.8	16.5	2.8	27.1



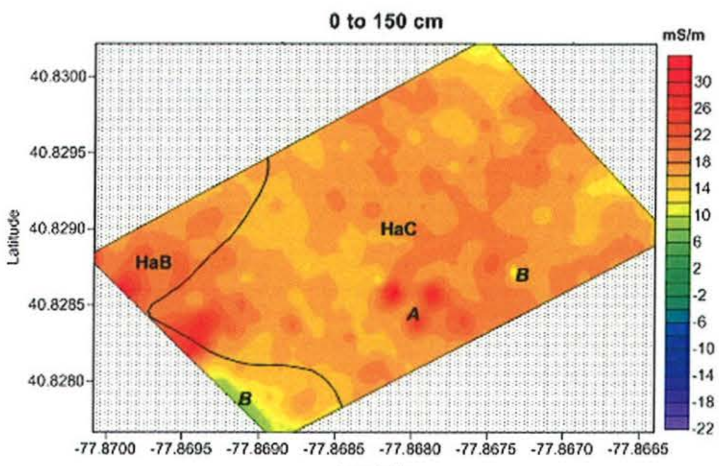


Figure 5. An EM38-MK2 meter was used to obtain these spatial apparent conductivity patterns across the southern, cultivated portion of the *Living Filter Field*.

Figure 5 contains plots of EC_a collected for the shallower sensing, 50-cm (upper plot) and deeper sensing, 100-cm (lower plot) intercoil spacing within Field B. In these plots, the soil boundary lines have been digitized from Web Soil Survey data[3]. In both plots, higher EC_a is recorded adjacent to a buried drainage line (see *A* in Figure 5) that is located in the south-central portion of this field. Other areas with seemingly anomalous EC_a are suspected to represent scattered metallic debris (see *B* in Figure 5). Comparing these two plots, it is obvious that EC_a increases with increasing soil depth. This relationship is assumed to be a function of higher moisture and clay contents at lower soil depths. However, measurements made with the shallower-sensing 50-cm intercoil spacing seem to be unusually low and are suspected of error.

Table 3. Basic statistics for EMI surveys that were conducted on similar portions of the Living Filter Field with an EM38-MK2 meter in June 2012 and March 2013. Other than the number of observations, all EC_a values are expressed in mS/m; all IP values are expressed in ppt.

	MAR 2013	*MAR 2013*	*JUN 2012*	*JUN 2012*
	100 EC_a	50 EC_a	100 EC_a	50 EC_a
Number	1901	1901	2469	2469
Minimum	2.7	-69.9	-3.8	-75.4
25%-tile	15.9	6.5	25.1	21.4
75%-tile	18.4	8.4	28.8	24.6
Maximum	38.8	21.2	45.9	36.3
Average	17.2	7.3	27.1	23.1
St. Dev.	2.8	2.8	3.0	3.5

Table 3 and Figure 6 provide a comparison of EC_a data and spatial patterns that were derived from surveys conducted with the EM38-MK2 meter in June 2012 and March 2013. In these plots, the soil boundary lines have been digitized from Web Soil Survey data.[3] Though not identical, the survey area is essentially the extreme southern portion of the cultivated *Living Filter Field*. Unfortunately, the data were collected at different intensities and were not temperature corrected. In June 2012, a smaller portion of the field was surveyed at a greater intensity. As a consequence, a buried drainage pipe and some spatial EC_a patterns can be seen in greater detail on the June 2012 plots.

Typically, cultivated field in Pennsylvania are wetter in the spring (March 2013) than in the summer (June 2012). The higher moisture contents in the spring correspond to higher EC_a. This season trend is not evident in the plots shown in Figure 6. Apparent conductivity averaged 27.1 and 23.1 mS/m for the 100 and 50 cm intercoil measurements in June 2012 and 17.2 and 7.3 mS/m for the 100 and 50 cm intercoil measurements in March 2013. Factors responsible for these apparent inconsistencies include: irrigation schedule and quantity of effluent applied, lack of temperature corrected data, incorrect instrument calibration and possibly operator errors.

[3] Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at http://websoilsurvey.nrcs.usda.gov/ accessed [04/14/2013].

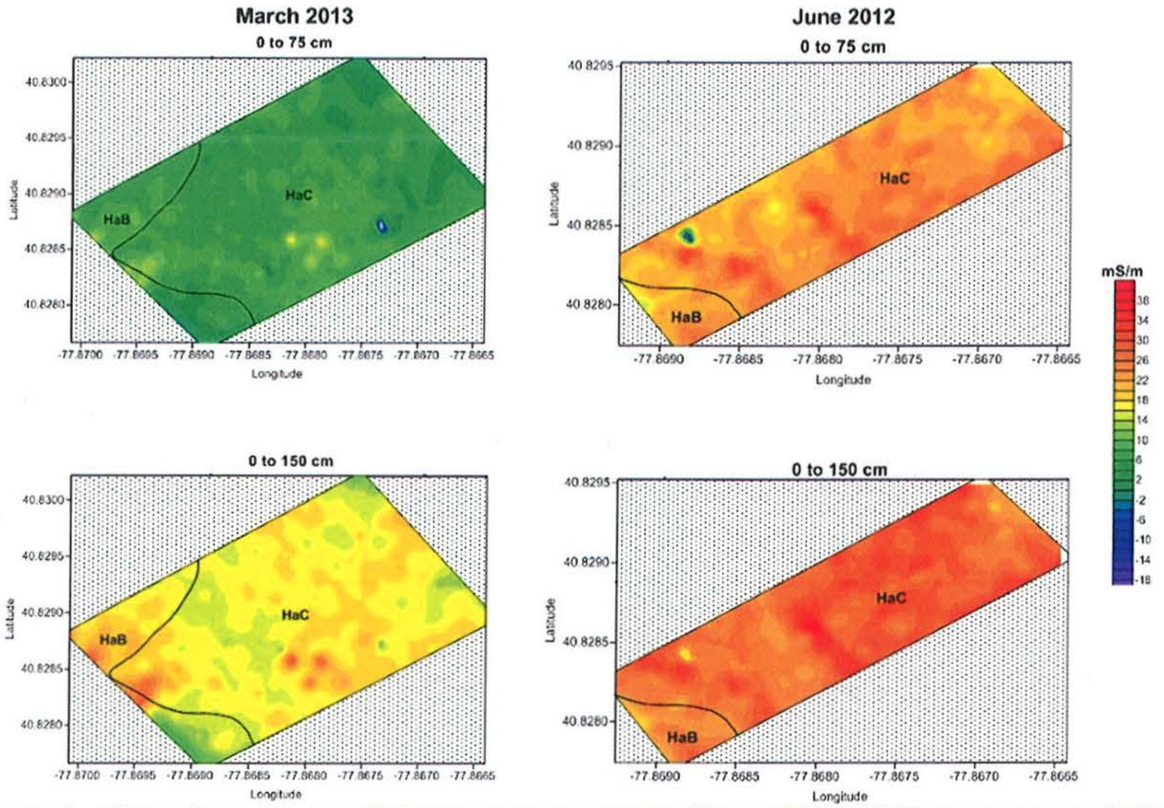


Figure 6. These plots compare EC_a data were recorded with an EM38-MK2 meter across similar portions of the *Living Filter Field* in June 2012 and March 2013.

GPR:

A total of eight radar traverses were completed across the northern portion of *Living Filter Field* with the 200 MHz antenna. This resulted in 111,817 geo-referenced radar measurements. Based on these measurements, the average depth to rock within the traversed areas is 1.38 m with a range of 0.13 to 3.77 m. One-half of the measurements are between 1.0 and 1.63 m. The data conform to the conception that the site consists of nearly level to rolling Hagerstown soils underlain by limestone at principally deep and very deep depths, but pitted by deeper solution cavities and punctuated by shallower limestone pinnacles and ledges. Table 4 summarizes the data collected along these traverses according to soil depth classes. Beneath the traverse areas, the depth to rock is largely deep (41 %) with substantial inclusions of very deep (32 %) and moderately deep (25 %) soils.

Table 4. Basic Statistic for GPR Traverses conducted in the northern portion of *Living Filter Field*.

	Number	Frequency
Shallow	1121	0.01
Mod-Deep	28310	0.25
Deep	46233	0.41
Very Deep	36153	0.32

Figure 7 is a *Google Earth* image showing the distribution of soils by depth classes along the radar traverse lines that were completed across cultivated areas of the *Living Filter Field*. Colors have been used to identify the different soil depth classes. This image testifies to the variability in the depth to rock that exists within these fields.

Figure 7. The depth to rock within the northern portion of the *Living Filter Field* as interpreted from radar data is shown on this Google Earth image (courtesy of Brian Jones of GSSI).

As evident in Figure 7, the depth to rock is variable across the *Living Filter Field*. The depth to rock ranges from about 0.1 to 3.8 m in the areas traversed with GPR. The radar data indicate that not only the depth, but the expression of the soil/rock interface is variable. Figure 8 contains three radar records from the study site. Although all records were identically processed and displayed, the expression and underlying structure of the limestone are noticeably different on each radar record. On these radar records, areas of lower amplitude reflected signals suggest more intense weathering and/or more saturated conditions (water often dilutes the dielectric gradient across interfaces). The underlying rock structures, while appearing fragmented by bedding planes, fractures and solution features, are inherently spatially variable.

In the upper radar record (A) shown in Figure 8, signal amplitudes are low and the structure is highly segmented suggesting more intense weathering. The soil/rock interface appears less weathered, but pitted with cavities of lower signal amplitudes separating steeply inclined bedding planes in the middle radar record (B). The bedding planes appear more continuous in the lower plot (C) and are assumed to provide a more restrictive barrier to the flow of water than on the radar records (A) and (B).

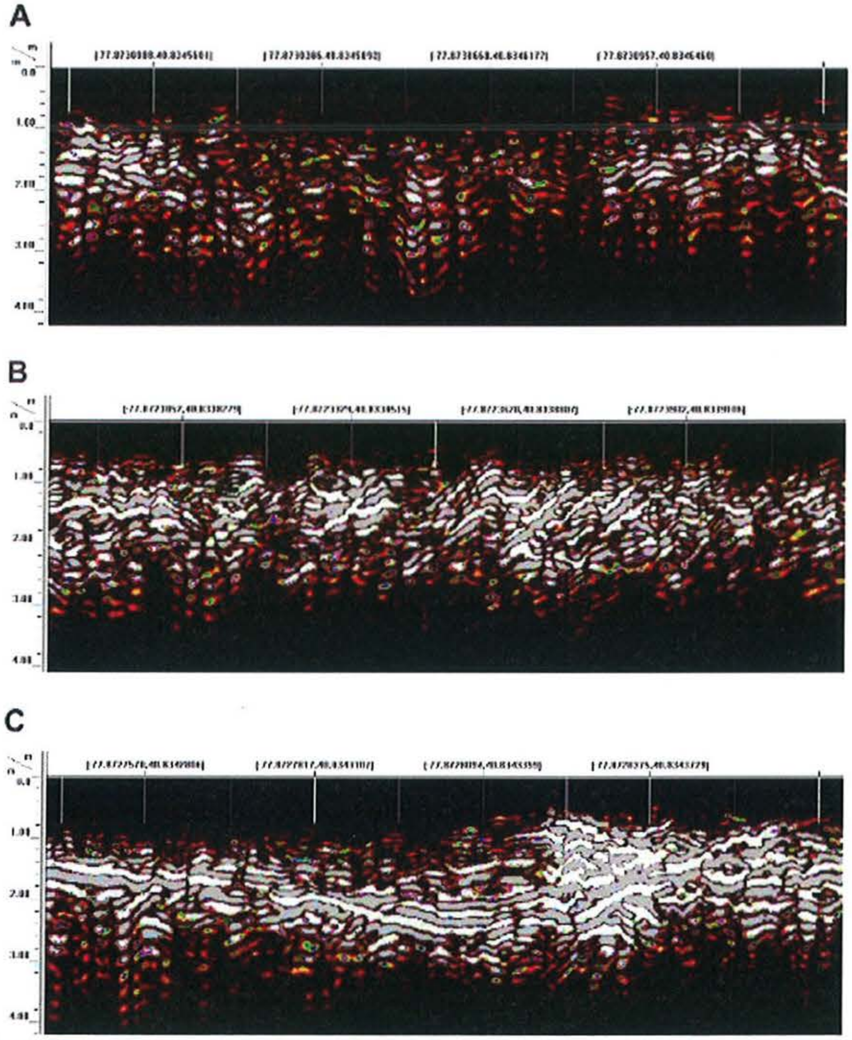


Figure 8. These 2D radar records from the Living Filter Field illustrate the variability in the structure of the underlying limestone.

References:

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

Geonics Limited, 2009. EM38-MK2-2 ground conductivity meter operating manual. Geonics Ltd., Mississauga, Ontario.

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