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

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Purpose:
This study is a continuation of work that seeks to define protocol for conducting geophysical investigations in steeply sloping, forested watersheds located in the eastern United States. During previous field work in the Shale Hill Watershed, the response of ground-penetrating radar (GPR) to the underlying shale was unclear. In this study, bedrock exposures were examined and surveyed with GPR. Exposures were used to compare lateral and vertical changes in GPR-reflection patterns with outcrop features and to confirm interpretations.

Participants:
Danielle Andrew, PhD Student, Department of Crop & Soil Sciences, PSU, University Park, PA
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Activities:
All field activities were completed on 16 August 2007.

Summary:

1. Shale of the Rose Hill formation restricts GPR signal penetration and limits the choice of antennas. Internal features (fracture and cleavage planes) of the shale were indistinguishable with GPR.

2. The 900 MHz antenna is unacceptable for imaging the soil/bedrock interface and for hydropedological investigations within the Shale Hill Watershed. The 400 MHz antenna provides higher resolution than the 200 MHz antenna, but subsurface reflections are often weak, discontinuous, and difficult to follow. The 200 MHz antenna is physically larger and more difficult to maneuver than the 400 MHz antenna across a steeply sloping, forested terrain, but provides the best balance of depth of penetration and resolution of subsurface features. For soil/bedrock investigations within forested watershed of central Pennsylvania, the 200 MHz antenna is the preferred and recommended tool.

3. Based on the results from two bedrock exposure sites, GPR appears to provide greater subsurface information when the shale bedrock is mantled with soil rather than being exposed at the surface. When exposed at the

surface, high levels of background noise plagued the radar records. When buried beneath relatively thin (40 to 200 cm) mantles of soil, the soil/bedrock interface and some bedrock features were identifiable on radar records.

4. As an experiment, 12 gallons of water were poured on the surface across a portion of a traverse line. The addition of water increased the contrast between some interfaces, which resulted in high-amplitude reflection beneath the wetted area. Along the exposed road cut, water was observed to flow laterally across the duff/ mineral soil contact and to selectively seep from portions of the exposed bedrock. Under wetted conditions, several additional, closely-spaced interfaces were noticeable on the radar records. GPR appears suitable for mapping some preferential flow paths in areas of Berks and Weikert soils.

It was my pleasure to participate in this study.

With kind regards,

James A. Doolittle
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cc:
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Study Area:
Shale Hills Watershed is located in northern Huntingdon County. The watershed is in the *Northern Appalachian Ridges and Valleys* Major Land Resource Area (MLRA 147) of central Pennsylvania. This MLRA is characterized by folded and faulted areas of parallel ridges and valleys that are carved out of anticlines, synclines, and thrust blocks (USDA-NRCS, 2006).

In 1961, the USDA-Forest Service established the *Shale Hills Watershed Unit* as a long-term forest research site. This relatively small (7.8 ha), well defined watershed is underlain by the Middle Silurian Rose Hill formation. During Alleghanian deformation, flow and dissolution occurred resulting in the compression of this formation and the development of slaty cleavages. The Rose Hill formation consists principally of olive-colored clay shale that is intercalated with thin layers of gray siltstone and red hematitic sandstone (Folk, 1960). Thin sections collected from this formation show the presence of small amounts of coarse-grained magnetite and hematite (French and Van derVoo, 1979). The clay shale has a high illite content (French and Van derVoo, 1979). Typically beds are thin and steeply dipping to overturned.

The Rose Hill formation consists of marine or brackish-water deposited materials (Folk, 1960). Marine or brackish-water deposited materials often have chemical and mineralogical components that foster high rates of signal attenuation. The presence of magnetite and hematite in this formation should increase the magnetic susceptibility of the shale, which would also increase the rate of signal attenuation. The ostensibly unfavorable chemical and mineralogical composition of the Rose Hill formation makes deep penetration with GPR unlikely. The formation is highly compressed, with extremely narrow and closely-spaced cleavage and fracture planes. These structural characteristic makes their detection unlikely with GPR.

Berks and Weikert soils dominate the watershed. The well drained, shallow (25 to 50 cm) Weikert and moderately deep (50-100 cm) Berks soils are mapped on higher-lying, more sloping areas of the watershed. These soils contain large amounts of rock fragments and are underlain by "*thinly-bedded and highly fractured shale*". The clay content of the subsoil ranges from 5 to 32 % and from 10 to 25 % for Berks and Weikert soils, respectively. Taxonomically, Berks and Weikert soils are members of the loamy-skeletal, mixed, active, mesic Typic Dystrudepts; and the loamy-skeletal, mixed, active, mesic Lithic Dystrudepts families, respectively. These soils are considered moderately suited to GPR.

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, 400, and 900 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, high pass filtration, migration, and surface normalization. Surface normalization corrects the radar record for changes in elevation.

Survey Procedures:
Survey sites were located in northern Huntingdon County. At each site, the 400, 200, and/or 900 MHz antenna were pulled along short traverse lines. Survey flags were inserted in the ground at intervals of 1-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. At the two bedrock exposure sites, the relative elevations of the reference points were obtained with an engineering level and stadia rod. For each radar record a file number is assigned. Table 1 summarizes the locations of the traverse line, and the antennas and time windows used.

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

Site preparation included: clearing the antenna path of obstructions, flagging reference points, and collecting relative elevation measurements. The removal of debris from the antenna path enhanced the coupling of the antenna with the ground and eliminated spurious reflections caused by these features on the radar records.

Table 1. Summary of GPR traverses

Radar File #	Location	Antenna	Time window
1	Transect 4A	900 MHz	20 ns
2	Transect 4A	900 MHz	15 ns
3	Transect 4A	900 MHz	15 ns
4	Transect 4A	900 MHz	15 ns
5	Exposure 1	400 MHz	70 ns
6	Exposure 1	200 MHz	50 ns
7	Rock floor (dry)	400 MHz	25 ns
8	Rock floor (dry)	400 MHz	25 ns
9	Rock floor (wet)	400 MHz	25 ns
10	Rock floor (wet)	200 MHz	50 ns
11	Exposure 2 (dry)	200 MHz	50 ns
12	Exposure 2 (dry)	400 MHz	25 ns
13	Exposure 2 (wet)	400 MHz	25 ns
14	Exposure 2 (wet)	200 MHz	50 ns
15	Exposure 2 (wet)	900 MHz	25 ns

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., bedrock, 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 contents.

The velocity of propagation is temporally and spatially variable. Soils were relatively dry at the time of this investigation. For the 200 and 400 MHz antennas, based on hyperbola-matching techniques (the shape of a hyperbola is dependent on the propagation velocity), an averaged velocity of propagation was determined for each antenna. Based hyperbola-matching, the velocity of propagation was 0.1126 m/ns (E_r of 7.0) for the 400 MHz antenna. For the 200 MHz antenna, the velocity of propagation was 0.1096 m/ns (E_r of 7.4). As no satisfactory hyperbola was evident on radar records collected with the 900 MHz antenna, this technique could not be applied. An arbitrary velocity of 0.1146 m/ns (E_r of 6.76) was used for the data collected with the 900 MHz antenna.

Resolution and GPR antennas:

In order to detect a subsurface interface and extract its geometrical attributes (size, shape, thickness, etc.), the feature must be resolvable. Resolution is a measure of the smallest separation that can be distinguished, and is dependent on the frequency of the GPR antenna. Higher frequency antennas have smaller wavelengths and provide better resolution of subsurface features. Resolution is composed of two components: vertical (or depth) and lateral (or horizontal) resolution.

Vertical resolution is based primarily on the propagated wavelength. Daniels (2004) used the following equation to show the relationship among velocity of propagation (v), antenna center frequency (f), and wavelength (λ):

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

Equation [3] shows that the propagated wavelength decreases with increasing antenna frequency. For a given frequency, the propagation velocity and wavelength will decrease with increasing E_r and water contents. Using equation [3] and the propagation velocities estimated in this study, the projected wavelengths of the 200 and 400 MHz antennas through the soils are 56 and 27 cm, respectively. In general, interfaces spaced closer (vertically) than ½ a wavelength are indistinguishable on radar records (Daniels, 2004). As a consequence, interfaces within the shale must be spaced at vertical distances greater than about 28 cm (11 inches) and 13.5 cm (5.3 inches) to be distinguished with the 200 and 400 MHz antennas, respectively. Because internal structural features (cleavage and fracture planes) within the Rose Hill formation occur at scales smaller than these projected wavelengths, they will be largely indistinguishable on radar records.

Horizontal resolution is affected by antenna design (monostatic or bistatic), the spacing between receiver and transmitter, and the sampling rate. Lateral averaging of reflected energy is dependent on antenna wavelength and the depth to the feature. Energy is radiated downwards into the subsurface as a wave front which forms a conceptual conical pattern. The *footprint* area that is scanned by an antenna increases with the depth of penetration. The horizontal resolution of an antenna is approximated by the following equation, which shows the relationship among the radius of the footprint area (R), the depth (z), and wavelength (λ): (Daniels, 2004):

$$R = \sqrt{z} * \lambda \qquad [4]$$

Based on equation [4] and the propagation velocities estimated in this study, the horizontal resolution of the 200 MHz antenna is 0.75 m and 1.3 m at depths of 1 and 3m, respectively. The horizontal resolution of the 400 MHz antenna is 0.52 m and 0.90 m at depths of 1 and 3m, respectively.

Results:

900 MHz antenna:

The modest clay and water contents of Berks and Weikert soils result in exceptionally high rates of signal attenuation for energy radiated from the 900 MHz antenna. Figure 1 is a radar record collected with the 900 MHz antenna over an area of Weikert soil. On the radar record shown in Figure 1, the penetration depth of the 900 MHz antenna is severely restricted. Meaningful reflections from subsurface features appear to be restricted to depths of less than 25 cm. Below a depth of 25 cm, high levels of unwanted system noise plagued the radar record.

The parallel bands evident between depths of 25 and 50 cm represent low-frequency system noise. The parallel bands evident in the lower portion of the radar record (Figure 1) are believed to represent *ringing* and *multiples*. Ringing and multiples are inherent in GPR systems and are especially noticeable in high loss environments. Ringing appears as nearly horizontal and periodic events, which can often be removed through effective signal processing. Ringing is caused by the resonance of the antennas. Multiples are multiple reflections (i.e. echoes) from a single reflection interface. Multiples occur when the radar signal bounces back and forth between the antenna and an interface (soil surface, bedrock). This system noise is identifiable because it appears at the same depth or time interval across the entire record. With each subsequent "bounce," however, the signal dissipates in energy so that subsequent echoes become increasingly faint in the resulting GPR data.

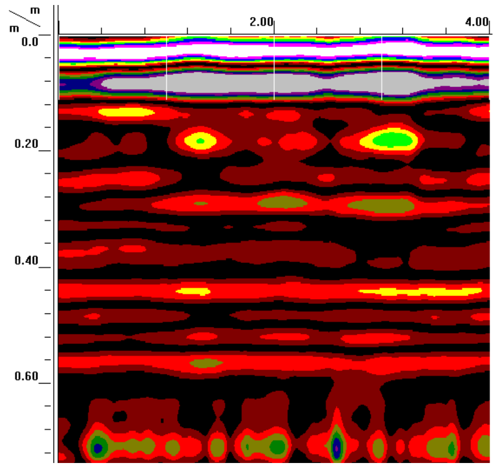

Figure 1. The 900 MHz antenna is exceedingly depth restricted in the Weikert soils of the Shale Hill Watershed.

<u>Bedrock Exposure Site #1:</u>

This site is located along Township Road 540 in northern Huntingdon County (40.66940 ° N. Lat., 77.88083° W. Long.). At this site, a 6-m traverse line was established across an outcropping of shale bedrock. Along the traverse line, shale bedrock was exposed or was buried beneath a very thin (< 5 cm) soil mantle. Along the traverse line, relief was 104 cm. Survey flags were inserted in the ground at 1-m intervals along the traverse line and served as reference points. Figure 2 is a picture of this site. Cleavage planes in the shale are evident in this picture. Figure 3 provides a close up view of the shale. The shale is relatively hard and breaks up into rectangular fragments. What are believed to be closely-spaced, cleavage and fracture planes are evident in this picture of the shale.

Figure 4 contains terrain-corrected radar records that were collected at Exposure Site #1 with the 400 (upper record) and 200 (lower record) MHz antennas, respectively. While both radar records were migrated, the data obtained with the 400 MHz antenna has been filtered using a horizontal high pass filter to remove bands of noise that plagued the radar record and masked subsurface features. Because of its very shallow depth (mostly at the surface), the soil/bedrock interface is indistinguishable with both antennas.

Figure 2. A photograph of the Exposure 1 site showing the exposure, the relative topography of the site, and the location of the GPR traverse line.

Figure 3. This photograph shows what are presumed to be cleavage and fracture planes in the Rose Hill formation. The tape scale is in cm.

Small-scale subsurface heterogeneities often generate scattering losses, which weaken the propagated signal. Scattering attenuation is frequency dependent and increases rapidly with antenna frequency (Annan, 2003). Scattering losses caused by small-scale features can be reduced by selecting a lower frequency antenna with a larger wavelength. In the highly processed radar record that was collected with the 400 MHz antenna (Figure 4, upper), subsurface heterogeneities within the shale appear to have produced a large number of point reflectors. These incoherent point reflectors may also be an artifact of processing. Regardless of their nature or origin, the data contained in this radar record (Figure 4, upper) is unintelligible.

Prominent bands that parallel the soil surface characterize the radar record that was collected with the 200 MHz antenna at Bedrock Exposure Site #1 (Figure 4, lower). These bands do not correspond with observed structural patterns in the shale bedrock and are believed to represent noise. These bands of noise parallel the surface and are presumed to represent the effects of *ringing*. In soils, the low frequency spectral components are less attenuated than the high frequency spectral components of the radar pulse. This results in propagation dispersion, which accounts for the fairly wide widths of the bands shown on this radar record.

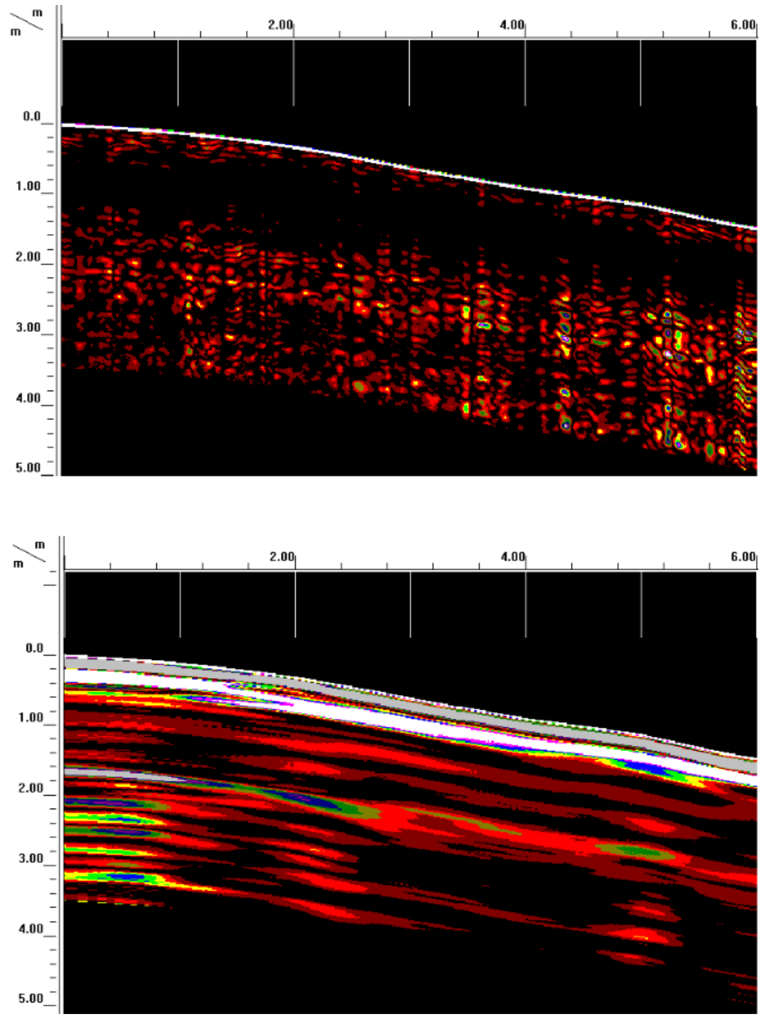

Figure 4. These terrain-corrected radar records were collected at Bedrock Exposure Site #1 with the 400 (upper record) and 200 (lower record) MHz antennas.

<u>Bedrock Exposure Site #2:</u>
This site was located along a road cut on Township Road 537 in northern Huntingdon County (40.66767^{o} N. Lat., 77.88593^{o} W. Long.). A 5-m traverse line was established 1-m behind the exposed face of the road cut (see Figure 5). Survey flags were inserted in the ground at 1-m intervals along the traverse line and served as reference points. Along the traverse line, the observed depth to shale in the road cut ranged from 43 to 61 cm. Relief was 58 cm.

Figure 5 is a picture of this site. Closely-spaced, cleavage and fracture planes characterize the shale bedrock. Figure 6 provides a close up view of the shale. The shale is relatively hard and breaks up into rectangular fragments.

The soil/bedrock interface was clearly expressed on radar records obtained with the 200 and 400 MHz antennas at this site (see Figure 7). Green-colored lines have been used in these images to highlight the interpreted soil/bedrock interface. Differences in the location and geometry of these lines can be attributed to the different paths and resolution of these antennas. Some indication of layering within the upper portion of the shale is evident in these radar records (though especially with the 400 MHz antenna). After evaluating the results from the two bedrock exposure sites, it appears that GPR can provide greater subsurface information when the bedrock is mantled with soil rather than being exposed at the surface. When exposed at the surface, high levels of background noise often plagues the radar records. When buried beneath relatively thin (40 to 200 cm) mantles of soil, the soil/bedrock interface can be traced laterally across the radar record.

Figure 5. A portion of the GPR traverse line with shale exposed in a road cut at Bedrock Exposure Site #2.

Figure 6. A close-up of the shale at Bedrock Exposure Site #2.

As an experiment at Bedrock Exposure Site #2, 12 gallons of water were poured on the surface between the 2- and 3-m distance marks. After waiting 30 minutes, additional radar traverses were completed with the 200 and 400 MHz antennas along the traverse line. The results of these surveys are shown in Figure 8. The addition of water created greater contrasts between some interfaces, which resulted in high-amplitude reflection (white, blue and green colors) beneath the wetted area. Along the road cut, water was observed to flow laterally across the duff/ mineral soil contact and to selectively seep from portions of the exposed bedrock. Under wetted conditions, several additional, closely-spaced interfaces are apparent on each radar record (Figure 8). Because of this additional layering, with the 200 MHz antenna, the actual soil/bedrock interface is more ambiguous and interpretative under wetted than under dry conditions (compare Figures 7 and 8). Once again, differences in these records are attributed to the different paths and resolution of the antennas and spatial variations in the velocity of propagation due to wetting.

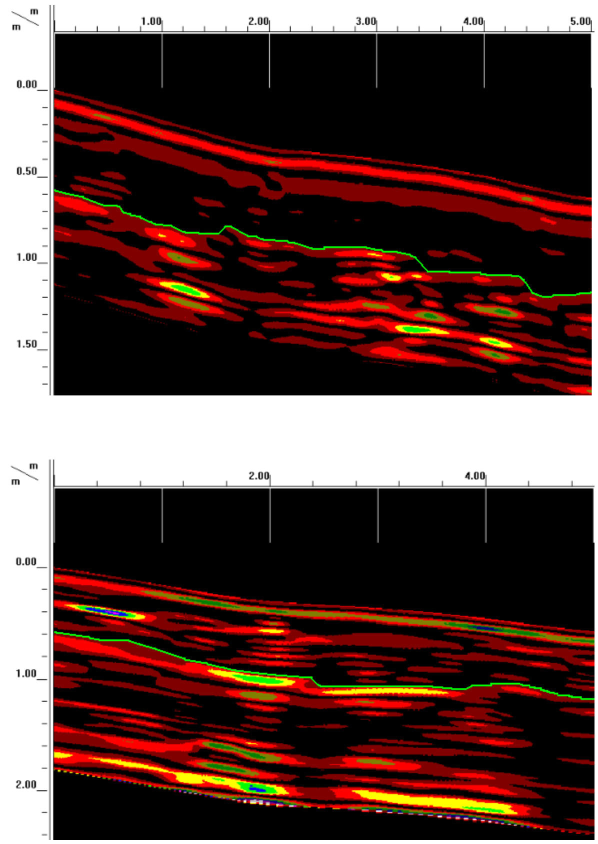

Figure 7. These terrain-corrected radar records were collected at Bedrock Exposure Site #2 with the 400 (upper record) and 200 (lower record) MHz antennas. These records were obtained over relatively dry soil profiles.

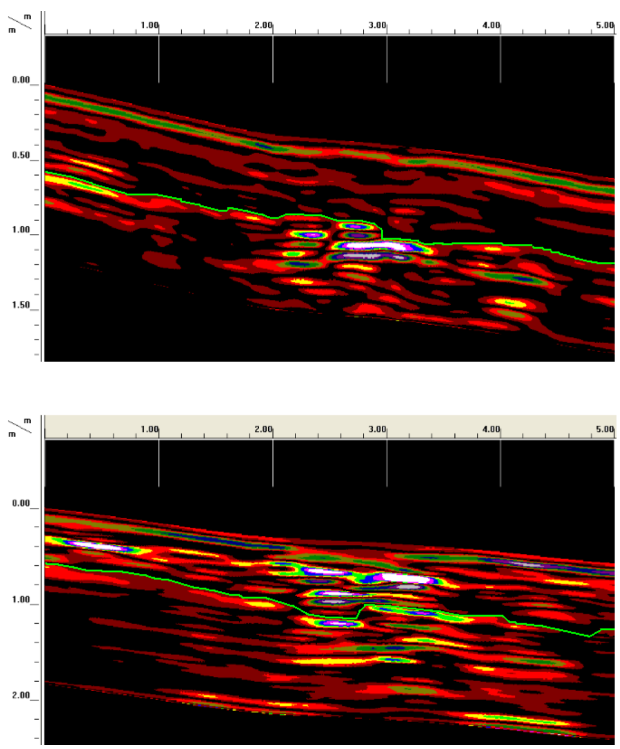

Figure 8. These radar records were collected at Bedrock Exposure Site #2 with the 400 (upper record) and 200 (lower record) MHz antennas. Twelve gallons of water had been spilled on the soil surface between the 2 and 3 m

distance marks.

References:

Annan, A. P., 2003. Ground Penetrating Workshop Notes. Sensors & Software Inc., Mississauga, Ontario, Canada.

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

Folk, R. L., 1960. Petrography and origin of the Tuscarora, Rose Hill, and Keefer formations, Lower and Middle Silurian of eastern West Virginia. *Journal of Sedimentary Research*; 30 (1): 1-58.

French, A. N., and R. Van derVoo, 1979. The magnetization of the Rose Hill formation at the classical site of Graham's fold test. Journal of Geophysical Research, 84 (B13): 7688-7696.

USDA-NRCS, 2006. Land Resource Regions and Major Land Resource Areas of the United States, the Caribbean, and the Pacific Basin. USDA Handbook 296, US Government Printing Office, Washington, District of Columbia.