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

Subject: SOI – Geophysical Field Assistance **Date:** 28 June 2007

To: Dr. Henry Lin
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Purpose:
This study is a continuation of previous work that seeks to define protocol for conducting geophysical investigations in a steeply sloping, forested watershed located in eastern United States. During this field trip, ground-penetrating radar (GPR) traverses were completed at select locations within the Shale Hill Watershed in central Pennsylvania.

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 12 and 13 June 2007.

Summary:

1. Multiple GPR traverses were conducted along nineteen traverse lines that are located on different slope components in the Shale Hill Watershed. Traverses were completed with antennas having center frequencies of 200, 400, and 900 MHz. Along each traverse line, flagged reference points were spaced a 3-m intervals. The relative elevations of these reference points were measured with an engineering level. These measurements were used to "terrain correct" the radar records for improved visualizations.

2. A major focus of this study was antenna selection. For soil/bedrock investigations within forested watershed of central Pennsylvania, the 200 MHz antenna is the preferred and recommended tool. 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 weak, discontinuous, and difficult to follow. The 200 MHz antenna is 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.

3. Radar records from this study have been mailed to Dr Lin. In subsequent months, the radar records will be further reviewed and analyzed. Results and observations will be described in a research paper.

It was my pleasure to participate in this study with you and your graduate students at Pennsylvania State University.

With kind regards,

James A. Doolittle
Research Soil Scientist
National Soil Survey Center

cc:
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Study Area:
The Shale Hills Watershed is located in northern Huntingdon County. The watershed is in the Ridge and Valley Province of central Pennsylvania. In 1961, the USDA-Forest Service established the Shale Hills Watershed Unit as a long-term forest research site. This forested watershed is relatively small (7.8 ha) and well defined. An oak-hickory cover type dominates most of the watershed. However, an oak-hemlock community exists along the lower reaches of the stream that drains the watershed. The relative topography of the watershed is shown in Figure 1. Within the watershed, elevations range from about 260 to 312 m. Slopes are gently sloping to steep. In Figure 1, the segmented line approximates the location of a small stream that drains the watershed. Within the watershed, a continuous flow of water is maintained throughout the year only along the lower reach of this stream. The watershed is underlain by the Silurian Rose Hill shale formation. The strata are thinly bedded and steeply inclined.

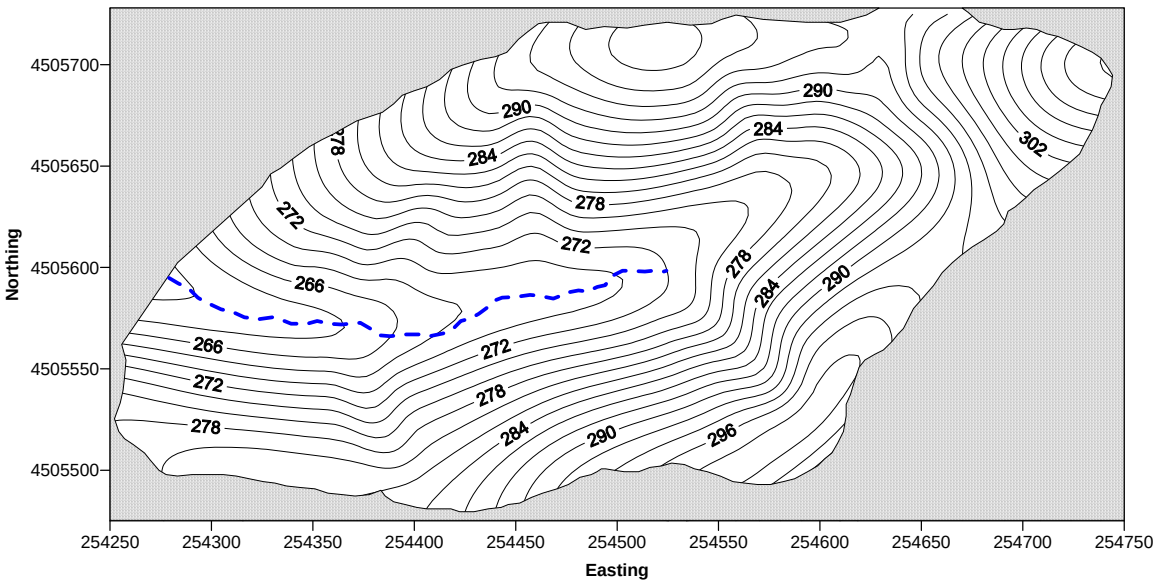

Figure 1. Relative topography of the Shale Hills Watershed.

A majority of the watershed is mapped as Berks-Weikert soils, steep, and Ernest channery silt loam, 3 to 8 percent slopes. The watershed also includes small areas of Berks-Weikert shaly silt loam, 15 to 25 percent slopes, and Berks shaly silt loam, 8 to 15 percent slopes. These soils formed in materials weathered from shale. Table 1 lists the taxonomic classification of the soils identified within 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. In addition, Berks and the very deep (> 150 cm), excessively drained Rushtown soils have formed in colluvial deposits along drainageways, indentations, or recesses (referred to as swales) of the watershed. The very deep, moderately well drained Ernest, and the moderately deep, somewhat poorly and moderately well drained Blairton soils have been identified on lower-lying, gently sloping areas along the drainageway. Ernest soil has a fragipan within depths of about 50 to 90 cm. All of these soils contain large amounts of rock fragments and are underlain at different depths by thinly bedded and highly fractured shale.

Table 1. Taxonomic classification of soils.

Series	Taxonomic Classification
Berks	loamy-skeletal, mixed, active, mesic Typic Dystrudepts
Blairton	fine-loamy, mixed, active, mesic Aquic Hapludults
Earnest	fine-loamy, mixed, superactive, mesic Aquic Fragiudults
Rushtown	loamy-skeletal over fragmental, mixed, active, mesic Typic Dystrudepts
Weikert	loamy-skeletal, mixed, active, mesic Lithic Dystrudepts

Materials and Methods:
The radar unit is the TerraSIRch Subsurface Interface Radar (SIR) System-3000 (here after referred to as the SIR System-3000), manufactured by Geophysical Survey Systems, Inc. (North 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, and surface normalization. Surface normalization corrects the radar record for changes in elevation. This processing technique greatly improved interpretations and the association of subsurface reflectors with soils and landscape components.

Survey Procedures:
Ground-penetrating radar traverses were completed along select traverse lines established across different landscape components and across different zones previously identified with electromagnetic induction (EMI). The majority of these traverses were conducted on the south-facing slopes and near the principal stream channel of the watershed. Five traverse lines were established on two prominent indentations or linear recesses that contained polygons of Rushtown and Berks soils. In Figure 2, these GPR traverse lines are identified as 1, 1A, 3A, 3B, and 3C (blue colored lines are orthogonal to the long axes and black colored lines are parallel to the center lines of the swales. Seven traverse lines were located on linear side slopes that were mapped as Weikert soil. In Figure 2, these GPR traverse lines are identified as 2, 2A, 4, 4A, 5, 6, and 15. Traverse lines 2A and 4A are orthogonal to the long axes of the slopes. Traverse lines 2, 4, 5, 6, and 15 are parallel to the long axes of the slopes. Traverse lines 7, 8, 9, 10, and 14 are orthogonal to the principal stream channel. Traverse lines 12 and 13 are located on lower foot slope areas of colluvium that parallel the principal channel.

Pulling the 400 and 200 MHz antenna along each line completed a GPR transect. Radar surveys were conducted from top to bottom for lines established along the long axes of swales or side slopes. Radar surveys were conducted from West to East for lines established orthogonal to the long axes of swales and from North to South for lines established orthogonal to the long axes of the principal channel. Survey flags were inserted in the ground at an interval of 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. The relative elevations of these positions were obtained with an engineering level and stadia rod.

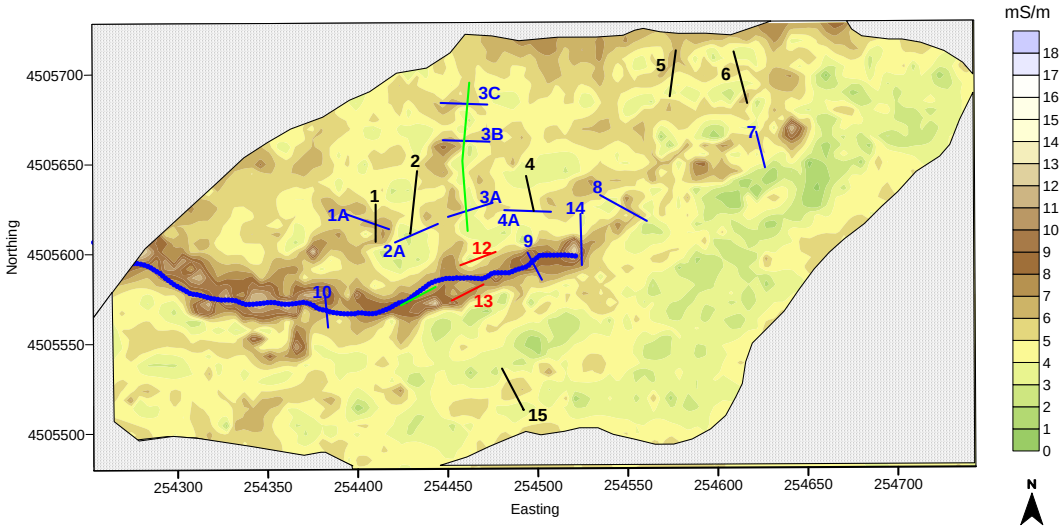

Figure 2. Locations of GPR traverse lines referenced to spatial apparent conductivity patterns that were obtained with an EM38 meter operated in the vertical dipole orientation (survey completed in February 2006).

Table 2 summarizes the traverses that were conducted during this study. For each radar record a file number is assigned. For each radar file, the identity of the traverse line and the antenna used is shown in Table 2.

Table 2 Summary of GPR traverses

Radar File #	Traverse Line	Antenna
2	1A	400 MHz
3	1	400 MHz
4	2	400 MHz
5	3A	400 MHz
6	3B	400 MHz
7	3C	400 MHz
8	4	400 MHz
9	4A	400 MHz
10	2A	400 MHz
11	12	400 MHz
12	11	400 MHz
13	13	400 MHz
14	9	400 MHz
15	14	400 MHz
16	8	400 MHz
17	7	400 MHz
18	6	400 MHz
19	5	400 MHz
20	15	400 MHz
21	10	400 MHz
24	1A	200 MHz
25	1	200 MHz
26	2A	200 MHz
27	2	200 MHz
28	3A	200 MHz
29	3B	200 MHz
30	3C	200 MHz
31	4	200 MHz
32	7	200 MHz
33	8	200 MHz
34	14	200 MHz
35	9	200 MHz
36	11	200 MHz

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 slowed by increases in soil moisture and relative permittivity.

The velocity of propagation is temporally and spatially variable. Soils were relatively dry at the time of the GPR surveys. For each antenna, based on the depth to a known, buried reflector and hyperbola-matching processing techniques (the shape of a hyperbole is dependent on the velocity), an averaged velocity of propagation was determined. In soils, the propagation velocity will vary with antenna frequency. As a consequence soils are said to be *dispersive* (Daniels, 2004). Based on the depth to a buried (53 cm) metal plate, the velocity of propagation was 0.1155 m/ns (E_r of 6.66) for the 400 MHz antenna. For the 200 MHz antenna, the velocity of propagation was 0.1207 m/ns (E_r of 6.1).

On radar records, reflections from interfaces spaced closer than one-half wavelength apart are indistinguishable due to constructive and destructive interference (Daniels, 2004). Daniels (2004) used the following equation to show the relationship between velocity of propagation (v), antenna center frequency (f), and wavelength (λ):

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

Equation [3] shows that the propagated wavelength will decrease with decreasing propagation velocity and increasing antenna frequency. For a given frequency, the propagation velocity and wavelength decrease with increasing E_r. Using equation [3] and the estimated velocity of pulse propagation results in estimated wavelengths of about 60 and 19 cm for the 200 and 400 MHz antennas, respectively. In general, interfaces spaced closer (vertically) than ½ a wavelength will be combined and can not be individually recognized on radar records. As a consequence, with the 200 and 400 MHz antennas, interfaces must be spaced greater than about 30cm (12 inches)and 14 cm (5.5 inches) respectively to be distinguished on radar records. As a consequence of this relatively coarse resolution, bedding and fracture planes in the steeply inclined shale bedrock were indistinguishable on radar records.

Results:

The 900 MHz antenna was ineffective at the Shale Hills Watershed. The depth of penetration was severely restricted (plate at 53 cm could not be detected) and high levels of unwanted background noise plagued radar records. The 200 and 400 MHz antennas provided acceptable depths of penetration and resolution of major stratigraphic features and the soil/bedrock interface.

Several examples of radar records collected with the 200 and 400 MHz antennas are provided for comparison. In each of the following figures, the depth and distance scales are expressed in meter. The white vertical marks atop each radar record represent the equally spaced, 3-m reference points. Each radar record was similarly processed. Processing included setting the initial pulse to time zero, color table and transformation selection, marker editing, distance normalization, range gain adjustments, high pass filtration, signal stacking, and surface normalization.

Figures 3 and 4 are representative portions of radar records that were collected along *Traverse Line 1* with the 200 and 400 MHz antennas, respectively. In Figures 3 and 4, the first 27 and 22 m of the radar record are shown, respectively. In Figure 3, the 200 MHz antenna provides a continuous and easily traced, high amplitude reflection from the soil/bedrock interface. In general, below this interface there are no reflectors as the shale bedrock provides a zone of no signal returns (in Figure 3, see lower part of radar record between the 0 and 10 m distance marks). Between the 12 and 27 m marks, high amplitude reflections are inferred to represent a contrasting stratum within the colluvium. Nearer the surface, reflectors appear more wavy, discontinuous, and convoluted suggesting creep and soil slumping.

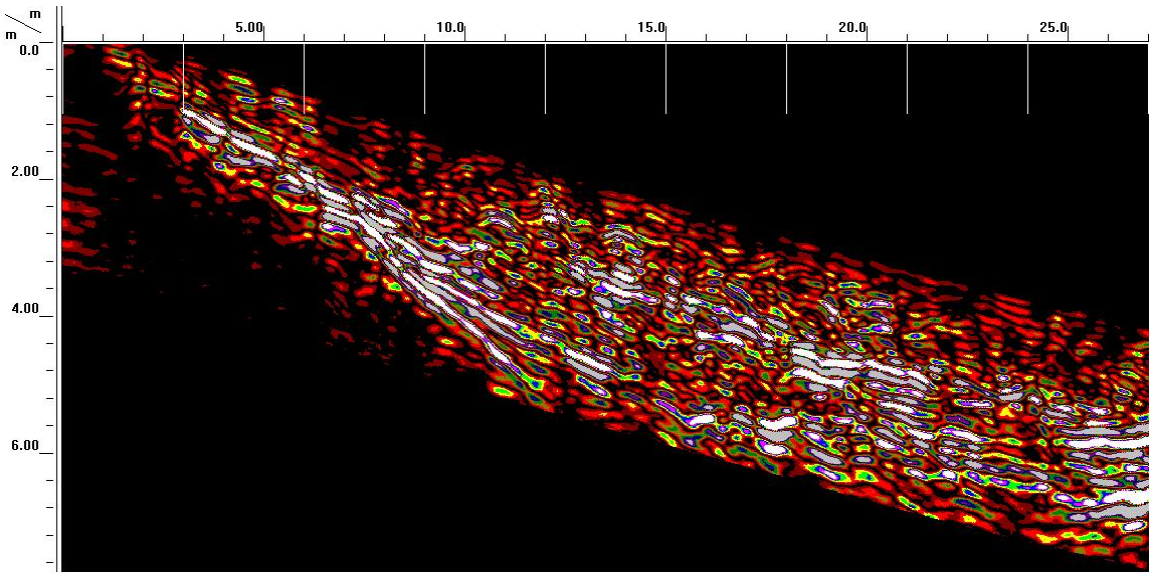

Figure 3. This radar record was collected along Traverse Line 1 with the 200 MHz antenna.

Similar, but more weakly expressed reflectors are evident in the radar record that was collected with the 400 MHz antenna along *Traverse Line 1* (see Figure 4). With the 400 MHz antenna, shallow (0 to 50 cm) soil features appear better defined than with the 200 MHz antenna. The shorter wavelength of the 400 MHz antenna provides better resolution of near surface features, but is more rapidly attenuated and weakened by the soil materials and, as a consequence, provides weaker, more difficult to identify and trace, subsurface reflections at deeper depths. The shorter wavelength of the 400 MHz does not resolve interfaces within the thinly bedded shale. The general quality of the 200 MHz antenna is preferred over the 400 MHz antenna.

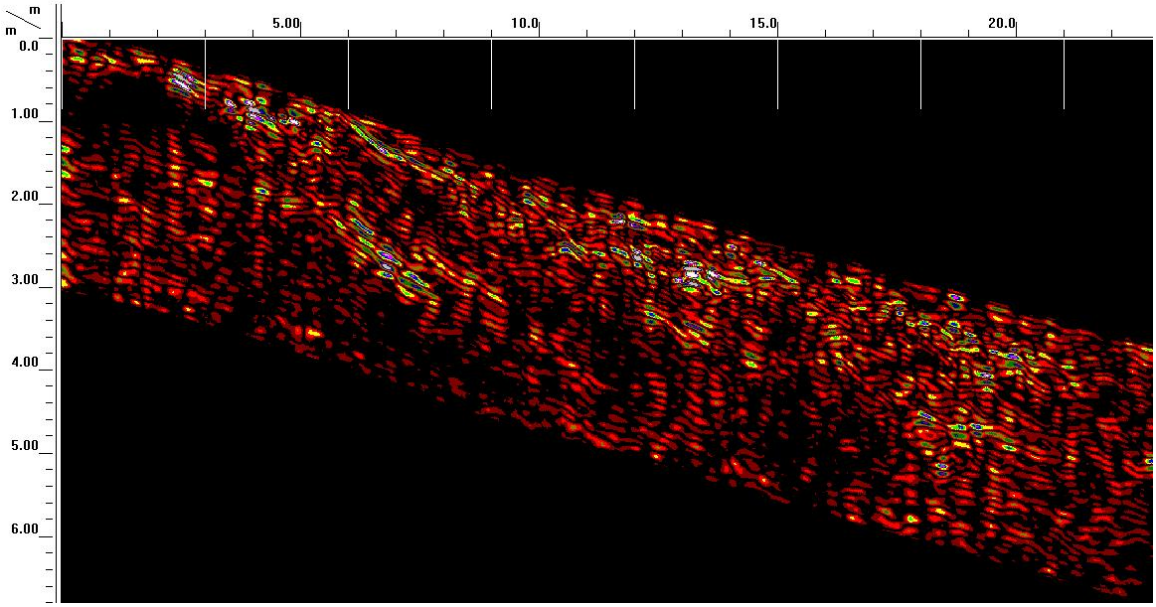

Figure 4. This radar record was collected along Traverse Line 1 with the 400 MHz antenna.

Figures 5 and 6 are representative portions of radar records that were collected along *Traverse Line 1A* with the 200 and 400 MHz antennas, respectively. This traverse line was established orthogonal to the long axis of the swale. In Figures 5

and 6, 27 and 22 m of the radar record are shown, respectively. In Figure 5, the 200 MHz antenna once again provides a continuous and easily traced, high amplitude reflections from the soil/bedrock interface and the stratum within the colluvium that fills this swale.

While the radar record collected with the 400 MHz antenna provides higher resolution, subsurface features are more weakly expressed, segmented, and difficult to trace laterally (see Figure 6). With the 400 MHz antenna, the bedrock appears to contain a large number of weakly expressed reflectors. These reflectors may represent bedding and fracture planes within the shale. However, without radar work over exposed areas of bedrock where the radar imagery can be visually correlated with features in the exposure, the features causing these reflections remains unclear and suspect. Reflectors within the shale appear to follow the contour of the ground surface and may represent reverberated signals from above. The significance of these discontinuous reflectors within the shale to hydropedological investigations is ambiguous at this point.

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 weak, discontinuous, and difficult to follow. The 200 MHz antenna is 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.

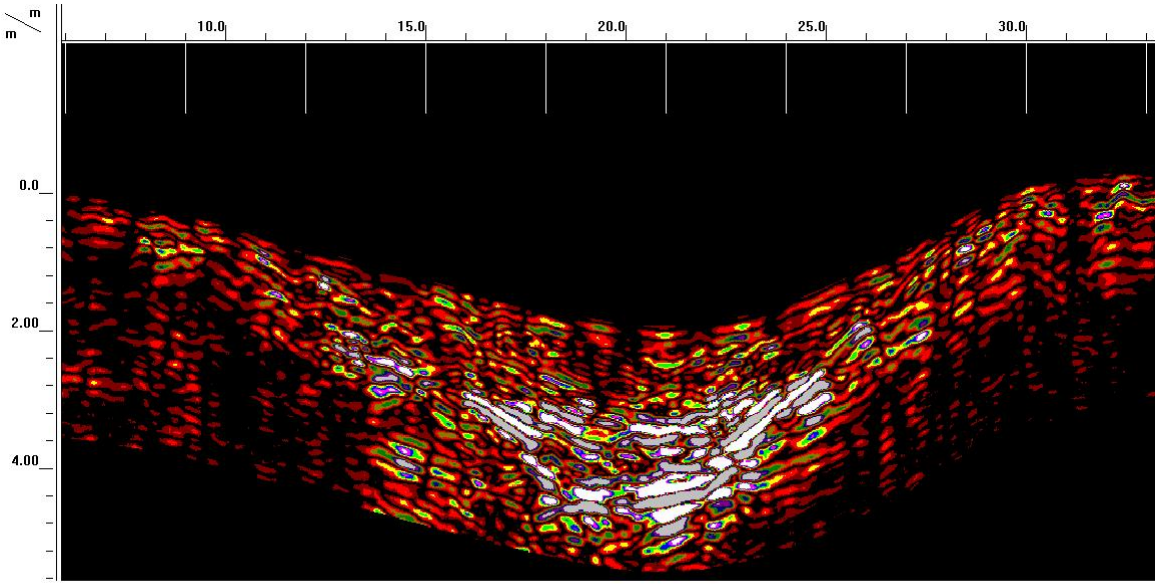

Figure 5. This radar record was collected along Traverse Line 1A with the 200 MHz antenna.

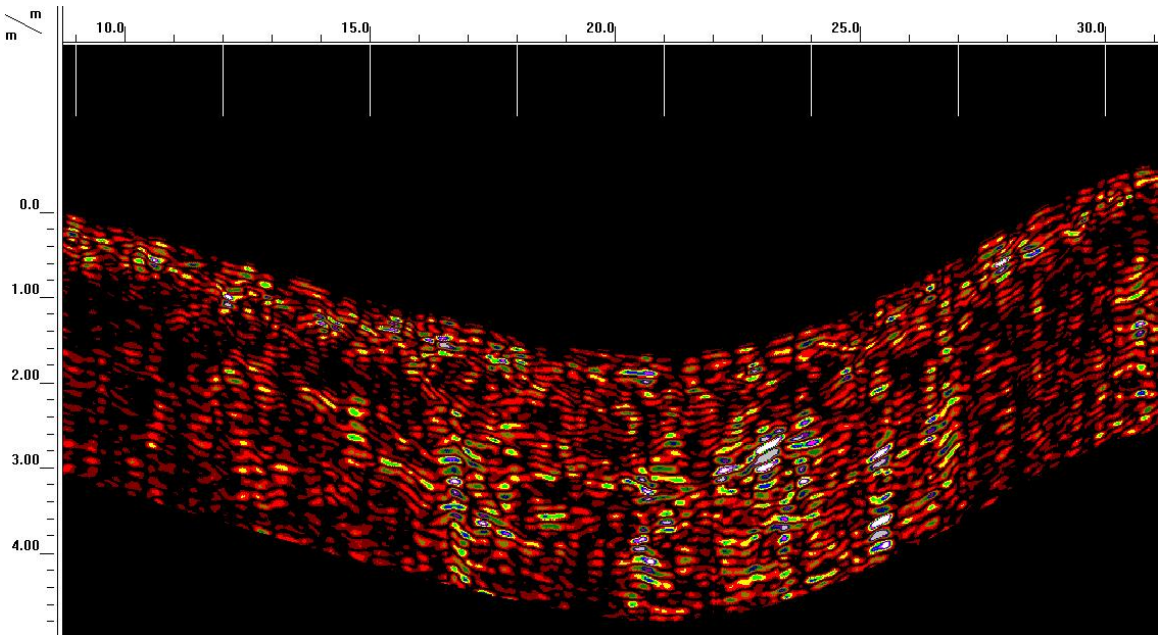

Figure 6. This radar record was collected along Traverse Line 1A with the 400 MHz antenna.

References:

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