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

Subject: Soils – Geophysical Assistance

Date: 21 April 2009

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Purpose:
The purpose of this assignment was to provide geophysical field assistance and assess the potential of using ground-penetrating radar (GPR) and electromagnetic induction (EMI) in several of the major land resource areas (MLRA) that are located in Arkansas. The performance of these tools was evaluated on select soils within the Ozark Highland (116A), Ouachita Mountains (119), and Cretaceous Western Coastal Plain (135B) MLRAs. In Izard County, results of an EMI survey were used to assess hazards imposed by a recently opened sinkhole.

Participants:
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Activities:
All activities were completed during the period of 6 to 9 April 2009.

Summary:

1. At the *sinkhole site* in Izard County, two areas of interest were identified with EMI. One was interpreted as a potential sinkhole (which was distant to and did not threaten existing farm structures). Though a potential sinkhole can not be ruled out, because of the high apparent conductivity (EC_a), the other feature was interpreted as a former contaminant plume emanating northwards from the northern-most poultry barn. In order to confirm these interpretations, these two areas of interests should be cored. In addition, lineations of anomalously high EC_a appear along and near the northern site boundary. These lineations are associated with *cultural noise* from fence and utility lines.

2. The color display for the RTmap38 program (see Figure 1) allows soil scientists to immediately track, observe, and interpret the results of EMI surveys. Following an EMI survey, soil scientists can move directly to sampling locations based on the color-scaled, pseudo-grid image displayed on the screen of the Allegro field computer. With this software, soil scientists can visually correlate EMI data with soil and landscape patterns, and move directly and accurately to soils with different EC_a for sampling and verifications of the factors influencing the EC_a. The availability of this software should foster a greater use of EMI by field soil scientists in Arkansas.

3. On the investigated medium and fine-textured soils located in Ozark Highland (116A), Ouachita Mountains (119), and Cretaceous Western Coastal Plain (135B) major land resource areas, EC_a was remarkably low. The low EMI response is attributed to the dominance of low activity clays and the low base status of these soils.

4. At all sites, the range in EC_a was low. As a consequence, the effects of operator and equipment errors (generally about 2 mS/m) will be more noticeable and will affect results to a greater degree than on soils with higher EC_a (>20 to 30 mS/m). In addition, the contrast among soils with contrasting clay and moisture contents will be more difficult to discern in these areas than in other areas of Arkansas (such as the Southern Mississippi River Alluvium (131A), Arkansas River Alluvium (131B), and Southern Mississippi Terraces (131D)).

5. Because of greater dominance of low activity clays, many of the soils of the Ouachita Mountains MLRA (119) have moderate to high potential for GPR. The use of GPR as a quality control tool for depth to bedrock determination and improved map unit design and interpretations is recommended in this MLRA.

It was my pleasure to work in Arkansas and to be of assistance to your fine staff.

With kind regards,

James A. Doolittle
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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 requires two people to operate. Daniels (2004) and Jol (2008) discuss the use and operation of GPR. A 200 MHz antenna was used in this study.

The RADAN for Windows (version 6.6) software program (GSSI) was used to process the radar records.[1] Basic processing steps, which were applied to all radar records, included: header editing, setting the initial pulse to time zero, color table and transformation selection, display range gain adjustments. Many radar records were subjected to additional, more sophisticated processing to improve visualizations and interpretations. The added processing included: signal stacking, horizontal high-pass filtration, migration, and range gain adjustments (see Daniels (2004) and Jol (2008) for discussions of these processing techniques).

Recent technical developments allow the automatic integration of GPR and global positioning system (GPS) data. This integration effectively geo-references each scan appearing on a radar record. Using the *Interactive 3D Module* of the RADAN for Windows (version 6.6) software program, depths to subsurface interfaces were interpreted and depth estimates were automatically picked and outputted to files (X, Y, Z format; containing latitude, longitude, and depth). Using this module, data can be quickly compiled and exported for future plotting and visualization in *Goggle Earth* and/or GIS.

A Trimble AgGPS 114 L-band DGPS (differential GPS) antenna (Trimble, Sunnyvale, CA) was used to georeferenced both GPR and EMI data.[1] An Allegro CX field computer (Juniper Systems, North Logan, UT) was used to record and store both EMI and position data.[1] Using the recently marketed RTmap38 program developed by Geomar Software, Inc. (Mississauga, Ontario), both GPS and apparent conductivity (EC_a) data were simultaneously recorded and displayed on the Allegro CX field computer.[1] The color display for the RTmap38 program (see Figure 1) allows soil scientists to immediately track, observe, and interpret the results of EMI surveys. With this software program, soil scientists can visually correlate EMI data with soil and landscape patterns, and move directly to sites of different EC_a for sampling and verifications of the factors influencing the EC_a. In Figure 1, the left-hand plot shows the display as data are being recorded; the right-hand plot shows the screen when data collection is paused and the *hidden menu* appears.

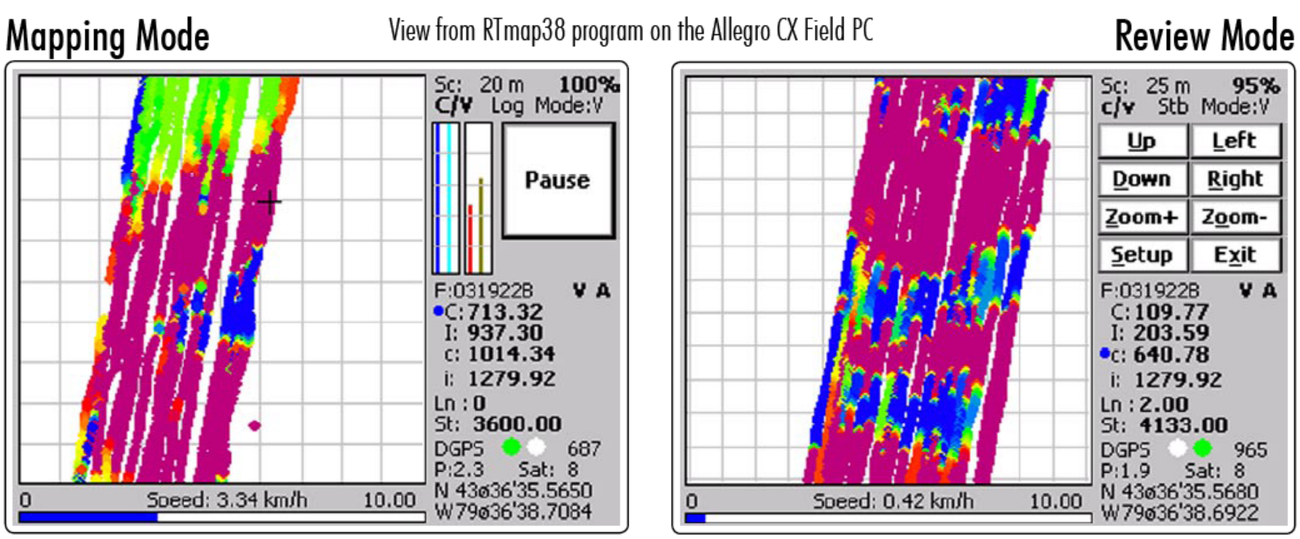


Figure 1. The RTmap38 program provides an instaneous track of each traverse and EC_a measurements displayed as a colored image on the Allegro field computer (courtesy of Geomar Software, Inc.).

The EM38 and EM31 meters (Geonics Limited, Mississauga, Ontario) were used in this investigation.[1] These meters require no ground contact and only one person to operate. These meters measured the EC_a of soils, which is expressed in

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

milliSiemens/meter (mS/m). The EM38 meter weighs about 3 kg (6.6 lbs), has a 1-m intercoil spacing and operates at a frequency of 14,600 Hz. When placed on the soil surface, it has effective penetration depths of about 0.75 m and 1.5 m in the horizontal and vertical dipole orientation, respectively (Geonics Limited, 1998).

The EM31 meter weighs about 9 kg (19.9 lbs), has a 3.66 m (12 ft) intercoil spacing and operates at a frequency of 9,810 Hz. When placed on the soil surface, the EM31 meter provides effective penetration depths of about 6 and 3 m in the vertical and horizontal dipole orientations, respectively (McNeill, 1980). McNeill (1980) has described the principles of operation for the EM31 meter.

To help summarize the results of the EMI surveys, SURFER for Windows, version 8.0 (Golden Software, Inc., Golden, CO), was used to construct simulations of EC_a data.[2] Grids of EC_a data shown in this report were created using kriging methods with an octant search.

Field Methods:

EMI:

At the Izard County site, an EMI survey was conducted with the EM31 meter operated in the deeper-sensing vertical dipole orientation (VDO). The EM31 was operated in the continuous mode (measurements recorded at 1-sec intervals). Using the RTmap31 dating logging and mapping program, both GPS and EC_a data were simultaneously recorded and displayed on an Allegro field computer. The meter was held at hip height (abut 1 meter above the soil surface) and orientated with its long axis parallel to the direction of traverse. In this setup, the nominal depth of penetration was about 5 m. Surveys were completed by walking at a uniform pace, in a random pattern across the site.

For the EMI surveys that were completed in Montgomery and Nevada Counties, an EM38 meter was operated in the deeper-sensing VDO. For these high-intensity EMI surveys the EM38 meter was operated in the continuous (measurements recorded at a rate of 1/sec) mode. Using the RTmap38 dating logging and mapping program, both GPS and EC_a data were simultaneously recorded and displayed on an Allegro field computer. While surveying, the EM38 meter was held about 5 cm (about 2 inch) above the ground surface and was orientated with its long axes parallel to the direction of traverse. Surveys were completed by walking at a fairly uniform pace, in a back and forth pattern across each field. The EC_a data discussed in this report were not temperature corrected.

GPR:

At each site, a small metallic reflector was buried in the soil at depths ranging from about 43 to 50 cm. A short traverse line was extended across the position of the buried reflector. The 200 MHz was pulled along the traverse line to calibrate the GPR and depth scale the radar records. Additional GPR traverses were completed at each site to characterize the soils.

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., soil horizon, stratigraphic layer, bedrock) 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):

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

Where C is the velocity of propagation in a vacuum (0.298 m/ns). 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.

Based on the measured depth and the two-way pulse travel time to a known subsurface reflector (a 25-cm diameter, metal plate), the velocity of propagation and the relative dielectric permittivity through the upper part of soil profiles were

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

estimated using equations [1] and [2]. In Izard County, in an area of Portia soils, based on the plate being buried at a depth of 47 cm, the estimated E_r was 11.2 and the estimated v was 0.0890 m/ns. In Garland and Montgomery Counties, in areas of Littlefir and Bismarck soils, based on the plate being buried at depths of 38 and 43 cm, the estimated E_r was 4.2 and the estimated v was 0.1453 m/ns. In Nevada County, in an area of Darden soils, based on the plate being buried at a depth of 50 cm, the estimated E_r was 4.03 and the estimated v was 0.1484 m/ns.

Study Sites:

Izard County:

The site is located in a pasture (latitude 36.05997^{o} N, longitude 91.831889^{o} W) near Melbourne. The site includes polygons of Boden gravelly sandy loam, 3 to 8 % slopes (7); Portia sandy loam, 3 to 8 % slopes, eroded (26); and Portia sandy loam, 8 to 12 % slopes, eroded (27). The well drained, deep Boden and very deep Portia soils formed in residuum weathered from sandstone and shale on upland of the Ozark Highlands. The taxonomic classifications of these soils are listed in Table 1. Depth to bedrock ranges from 40 to 60 for Boden soils and greater than 80 inches for Portia soils. Because of their clay contents and mineralogy, Borden and Portia soils are assumed to have moderate and low potential for GPR, respectively (http://soils.usda.gov/survey/geography/maps/GPR/methodology.html).

The Melbourne site contains a recently opened sinkhole. Chris King (King, 2008) reported that:

> "The sinkhole is circular in shape, about 30 feet in diameter, about 10 feet deep, with vertical sides that appear to be sloughing off. No competent bedrock was exposed in the feature, as there were large (approximately 4 feet across) sandstone boulders lying at steep angles in the sides at the bottom of the sinkhole. The relatively flat bottom was covered with sandy soil that had recently washed in. It was unclear as to how much deeper the top of dolostone might lie beneath the bottom of the sinkhole."

Garland County

The site (latitude 34.53061^{o} N, longitude 93.35258^{o} W) is located in a wooded area off of Hickorynut Mountain Road about 1.1 miles northwest of Crystal Springs. The site is located in an area of Bismarck-Carnasaw complex, 3 to 8 percent slopes (8). The shallow, somewhat excessively drained Bismarck and the deep, well drained Carnasaw soils formed in residuum weathered from tilted and folded shale bedrock on uplands of the Ouachita Mountains. The taxonomic classifications of these soils are listed in Table 1. Based principally on soil depth and clay contents, Bismarck and Carnasaw soils are considered to have high and low potential for GPR, respectively.

Table 1. Taxonomic Classification of Soils recognized at the Garland, Izard, Montgomery, and Nevada County sites.

Soil Series	Taxonomic Classification
Bismarck	Loamy-skeletal, mixed, semiactive, thermic, shallow Typic Dystrudepts
Boden	Fine, mixed, semiactive, mesic Typic Hapludults
Bonnerdale	Coarse-loamy, siliceous, active, thermic Aquic Hapludults
Carnasaw	Fine, mixed, semiactive, thermic Typic Hapludults
Darden	Thermic, coated Typic Quartzipsamments
Honobia	Clayey-skeletal, mixed, semiactive, thermic Typic Hapludults
Littlefir	Fine, mixed, semiactive, thermic Oxyaquic Hapludults
Pirum	Fine-loamy, siliceous, semiactive, thermic Typic Hapludults
Portia	Fine-loamy, siliceous, semiactive, mesic Typic Paleudalfs
Sherless	Fine-loamy, mixed, semiactive, thermic Typic Hapludults

Montgomery County

Site 1 (latitude 34.36933^{o} N, longitude 93.432866^{o} W) is located in an open pasture about 2.5 miles north-northwest of Welsh. The site includes polygons of Pirum-Sherless complex, 1 to 8 % slopes (42C); and Sherless-Littlefir complex, 1 to 8 % slopes (45C) (See Figure 2). These soils formed in loamy residuum weathered from tilted, fractured and folded sandstone bedrock on uplands in the Ouachita Mountains. The well drained Pirum and Sherless soils are moderately deep to deep, and moderately deep to bedrock, respectively. The moderately well drained Littlefir soils are moderately deep to deep to bedrock. Included in mapping are areas of Bonnerdale soils. The deep, somewhat poorly drained Bonnerdale soils formed in loamy sediments over weakly cemented, tilted shale. Depth to tilted shale ranges from 40 to more than 72 inches. The taxonomic classifications of these soils are listed in Table 1. Based principally on clay contents, Bonnerdale, Pirum and Sherless soils are considered to have moderate potential for GPR. The fine-textured Littlefir soils are considered to have low potential for GPR.

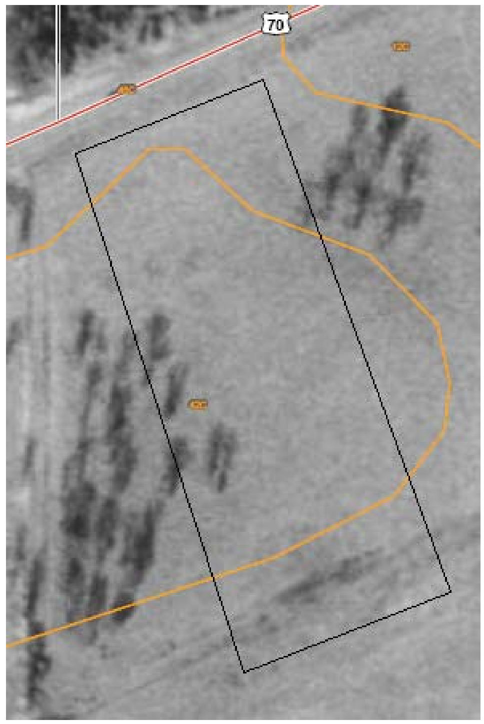


Figure 2. Soil map of Site 1 in Montgomery County from the Web Soil Survey.

Site 2 (latitude 34.46888 ° N, longitude 93.69671 ° W) is located in an open pasture about 1 mile northwest of Norman. The site is located in an area of Bismarck-Honobia complex, 8 to 15 % slopes (9D). The moderately deep, well drained Honobia soils formed in residuum weathered from tilted and folded shale bedrock with thin strata of interbedded sandstone, chert, and novaculite on uplands of the Ouachita Mountains. The fine-textured Honobia soils are considered to have low potential for GPR.

Nevada County:
The site (latitude 33.67956 ° N, longitude 93.16532 ° W) is located in an open area near a cemetery about 3 miles southwest of Bluff City. The site is in an area of Darden loamy fine sands, 1 to 8 % slopes (DaC). The very deep, excessively drained Darden soils formed in sandy, unconsolidated Coastal Plain sediments on uplands. The sandy Darden soils are considered well suited to GPR.

Results of EMI Surveys:
Izard County site:
A total of 4,424 georeferenced EC_a measurements were collected in a field bordering the northern and western sides of two poultry barns. Across most of this site, EC_a was comparatively low and invariable (standard deviation of 1.96). Within the site, EC_a averaged 6.2 mS/m and ranged from about -3.1 to 20.2 mS/m. One-half of the EC_a measurements were between about 5.2 and 6.8 mS/m.

Figure 3 is a plot of the EC_a data that were collected with an EM31 meter (operated in the VDO) at the Izard County site. The plot shows the spatial distribution of EC_a within the upper 5 meters of the earthen materials. In this plot, an orange colored circle represents the location of the open sinkhole. A road, fence line and overhanging power lines borders the northern boundary of this site (upper border of plot). These cultural features, as well as possible buried utility lines, are believed to cause some "*cultural interference*", which resulted in the noticeably higher EC_a recorded along the eastern half of this survey's northern boundary. A short, anomalously high, north-south trending lineation is apparent between the northeast corner of the northernmost poultry barn and the road. This feature is believed to represent a buried utility line.

Two areas of interest are labeled (see *A* and *B*) in Figure 3. A circular feature of with higher EC_a is evident at *A*. This feature borders the north side of an ill-defined drainageway that crosses the site from near the southeast corner of the survey area to near the sinkhole. As increases in clay content will result in an increase in EC_a, the feature may represent either an area of higher clay content or deeper depths to bedrock. If the latter, the feature at *A* could define a sediment filled sinkhole or depression in the underlying bedrock surface.

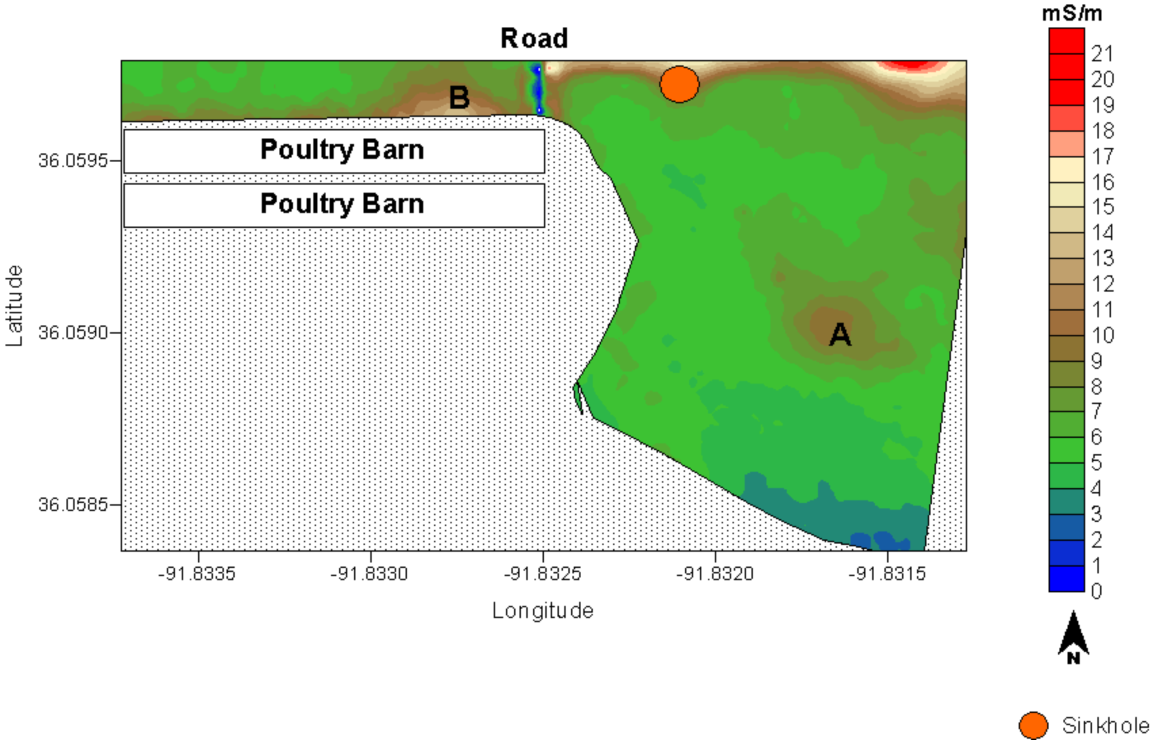


Figure 3. In this plot of EC_a *recorded at a farm site near Melbourne, Arkansas, the locations of an open sinkhole(orange circle) and two areas of concern (see A and B) have been identified.*

The feature identified by *B* in Figure 3 appears to extend outwards from the poultry barns. Compared to the feature at *A*, this feature (*B*) displays anomalously higher EC_a. As it extends outwards from the poultry barns and EC_a decreases in a downslope direction away from these structures, a former contaminant plume is inferred from these spatial patterns.

The area of low EC_a (colored blue) in the southeast corner of the site (lower-right) is associated with outcroppings of exposed bedrock. The dolostone bedrock is more electrically resistive than the overlying soil materials and therefore displays a very low EC_a. The interpretation presented in this report should be confirmed with ground-truth observations.

<u>Montgomery County site:</u>
Table 2 provides basic statistics for the EMI surveys that were completed with an EM38 meter at two sites within Montgomery County. Within Site 1 (Littlefir, Pirum, and Sherless soils), EC_a ranged from about -2.0 to 13.0 mS/m. At Site 1, measurements obtained with the EM38 meter averaged only 1.74 mS/m, with one-half of the measurements between about 0.2 and 3.1 mS/m. Measurements were slightly higher and more variable at Site 2 (area of Bismarck and Honobia soils). Here, EC_a averaged 2.4 mS/m, and ranged from about -17.0 to 9.9 mS/m. At Site 2, one-half of the measurements were between about 0.6 and 4.2 mS/m. At both sites, the measured EC_a is considered exceptionally low for medium and fine-textured soils. The low EMI responses are attributed to the dominance of low activity clays and the low base status of these

soils. The low ranges of EC_a experienced at these sites will affect the scales used to display the data and the accuracy of interpretations (observation and equipment errors can alone amount to 2 mS/m).

Table 2. Basic statistics for the EMI surveys that were conducted at sites in Montgomery County with the EM38 meter operated in the vertical dipole orientation

Site	Number	Minimum	25%-tile	75%-tile	Maximum	Mean	St. Dev.
1	3241	-2.0	0.25	3.13	13.0	1.74	1.97
2	1271	-17.5	0.63	4.25	9.88	2.40	2.44

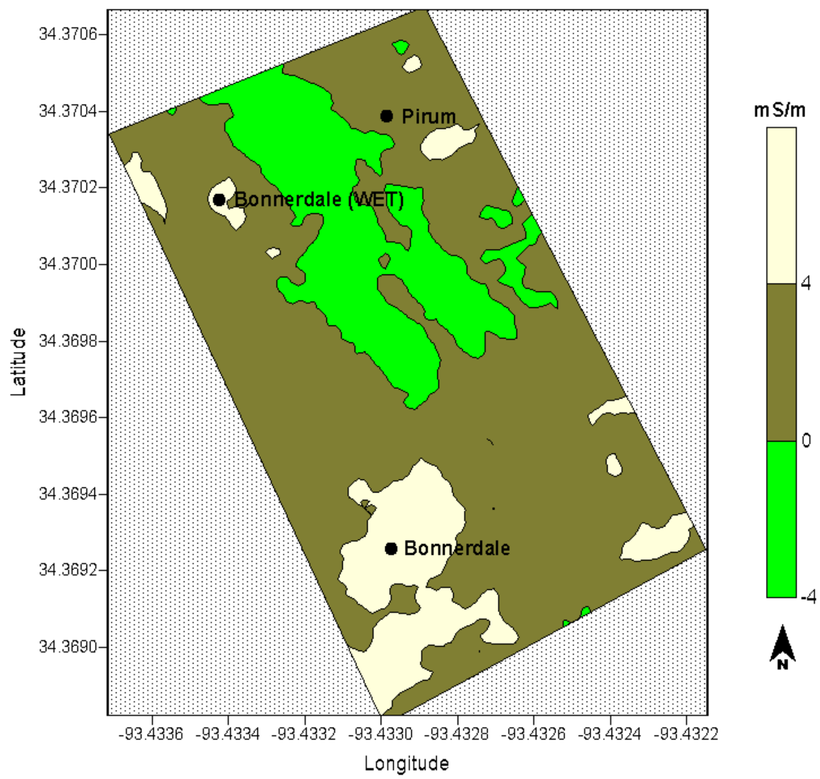


Figure 4. This plot of EC_a is from an area of Pirum, Littlefir, and Sherless soils (Site 1) in Montgomery County. The locations and identities of three cored soil profiles are shown.

Figure 4 contains a plot of the EC_a data collected with EM38 meter at Site 1. Following the EMI survey, soil scientists used the color-scaled pseudo-grid image displayed on the screen of the Allegro field computer to guide them to three sampling sites based on EMI responses. The names and locations of the soils identified at these three core sites are shown in Figure 4. The core extracted in areas of low EC_a (2.5 mS/m in VDO), was identified as the medium-textured Pirum soil. A core extracted from a lower-lying position near the southwest corner of the survey area was identified as the coarser-textured Bonnerdale soil. This soil displayed a relatively higher EC_a (8.0 mS/m in VDO). A third core was extracted from a higher lying slope component. Although a perched water table was observed within 50 cm of the soil surface, the soil had an EC_a of only 4.5 mS/m and was identified as a wet phase of Bonnerdale soils. While spatial EC_a patterns helped to identify three distinct soil types, the soil properties causing these patterns remain unclear. Generally EC_a will increase with increases in clay, moisture, and/or soluble salt contents. The lack of a stronger association with clay and moisture contents suggests the possible greater influence of clay mineralogy in these soils.

Figure 5 contains a plot of the EC_a data collected at site 2 in Montgomery County. The location and identity of the soils observed at two cores sites are shown in this plot. One core was extracted in a lower-lying area that had relatively higher EC_a (6.5 mS/m in VDO). The soil identified in this core was the fine-textured Littlefir. The EC_a recorded at the Littlefir core site is considered exceptionally low for a moderately deep (71 cm to bedrock), fine-textured soil. A core extracted from a higher-lying knoll in the northern portion of the survey area was identified as Bismarck soil. At this core site, the Bismarck soil has a very low EC_a (- 1.2 mS/m in VDO), and is shallow to bedrock (38 cm). [The negative response may reflect the effects of calibration errors or magnetic susceptibility. Because we are concern with relative responses and spatial EC_a patterns, a negative value is not disturbing]. Because of distinct combinations of physical and chemical properties, each soil will display a unique range in EC_a. Values of EC_a can be used to help identify and determine the composition and distribution of these soils within some soil delineations.

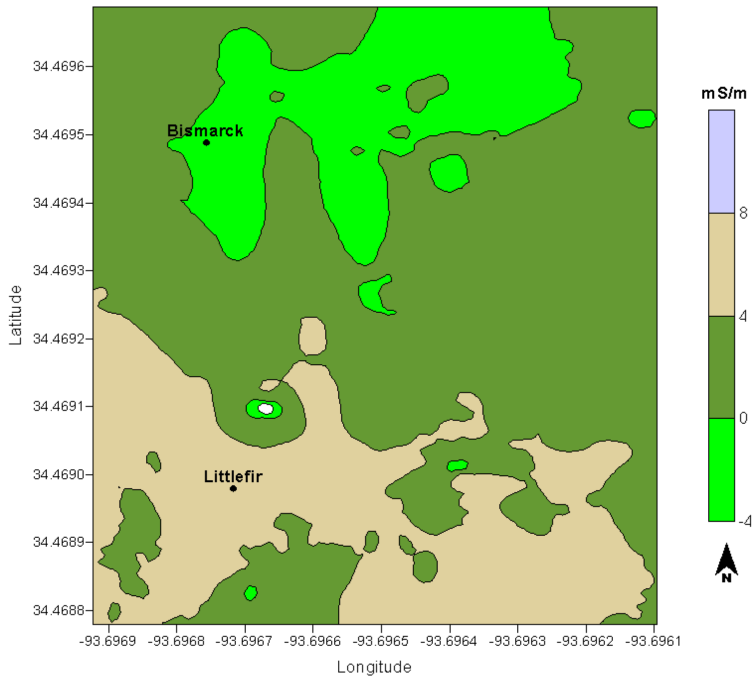


Figure 5. This plot of EC_a is from an area of Bismarck and Honobia soils (Site2) in Montgomery County. The locations and identities of two observed soil profiles are shown.

<u>Nevada County site:</u>
Measurements obtained with the EM38 meter operated in the deeper-sensing VDO averaged 2.08 mS/m, with a range of -23.5 to 138.8 mS/m. However, across most of this site, EC_a was very low and invariable with one-half of the observations between about 1.1 and 2.6 mS/m. At this site, the relatively large range in EC_a is attributed to scattered and buried artifacts. The site borders a road and cemetery and is heavily used. The low and relatively invariable EC_a may make EMI an unacceptable tool for the discrimination of soil properties in this and similar areas of Darden soils.

In general, the EC_a at this site were as low and invariable as those measured at the Montgomery County sites. This was initially surprising, as the soils at the Nevada County sites are sandy, while the soils at the Montgomery County sites are moderately-fine and fine textured. Ordinarily, EC_a will increase with increasing clay content. In the highly weathered soils of the Ouachita Mountains, clay mineralogy appears to have a more pronounced effect on EC_a than clay content. With further research, EMI may prove useful in discriminating soils based on CEC and classifying soils with kandic horizons.

Figure 6 is a plot of the EC_a data collected with the EM38 meter at the Darden site in Nevada County. The site is sandwiched between a cemetery (left-hand border) and a county road (right-hand border). Areas colored red and blue identify the probable locations of buried artifacts. Other than the responses from these presumed artifacts, EC_a is relatively invariable across the site. This uniformity reflects the consistency of the physical and chemical soil properties at this site

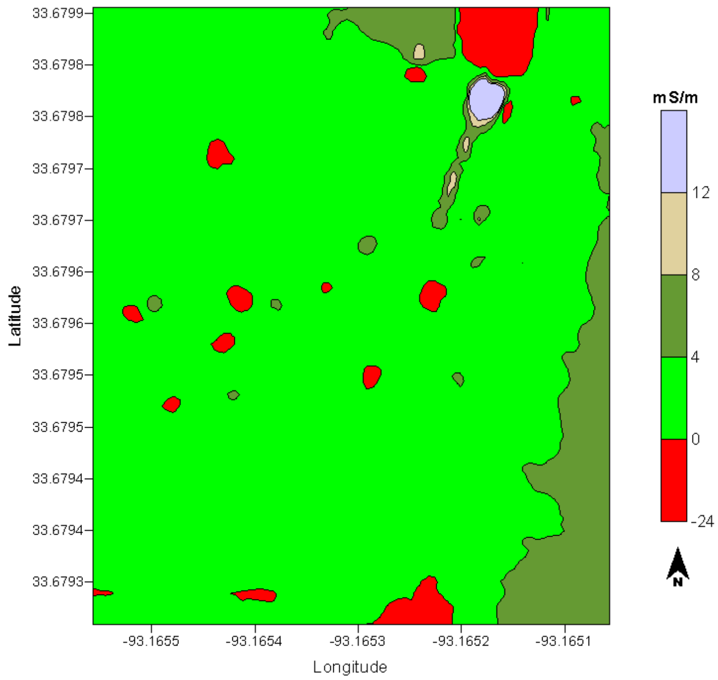


Figure 6. Plot of spatial EC_a patterns recorded with the EM38 meter at Darden soil site in Nevada County.

GPR Results:

Izard County:

Because of their moderate to high clay contents, the depth of penetration and the resolution of subsurface features were anticipated to be restricted in areas of Boden and Portia soils. Boden and Portia soils are classified as having moderate and low potential for GPR, respectively (http://soils.usda.gov/survey/geography/maps/GPR/methodology.html). In these soils, the proper analysis and interpretation of radar records should require the use of advanced processing procedures. As an example, Figure 7 contains two renderings of the same radar record. On both radar records, the vertical and horizontal scales are expressed in centimeters and meters, respectively. The upper record has been subjected to only the basic processing steps of header editing, setting the initial pulse to time zero, color table and transformation selection, distance normalization, and display range gain adjustments. Additional processing procedures were applied to the lower radar record. These processing procedures included: signal stacking, horizontal high-pass filtration and range gain adjustments. Signal stacking is used to remove unwanted high frequency background noise (appears as “snow-like” noise on the upper radar record). A horizontal high-pass (background removal) filter is used to remove bands of low-frequency ringing noise (mostly reverberations from the strong surface pulse and noise evident from high gain settings). Range gain adjustments were used to compensate for amplitude reduction caused by increasing signal attenuation with depth and by the application of added signal processing procedures.

In the lower record shown in Figure 7, a green-colored line has been used to indicate the interpreted depth to a subsurface interface, which is believed to represent the surface of the underlying dolostone bedrock. On this radar record, the interpreted depth to bedrock ranges from about 34 to 237 cm. For Boden and Portia soils, the depth to bedrock ranges from 100 to 182 cm and from 150 to greater than 200 cm, respectively. Even with processing, the soil-bedrock interface is unclear and difficult to trace laterally in some sections of the radar record. With processing, the soil-bedrock interface may be interpreted to depths of 2 to 3 meters in this area of deep and very deep, medium- and fine-textured soils. However, the soil-bedrock interface is unclear and can not be interpreted with confidence in other portions of the radar records. In general, interpretations can be made to slightly deeper depths in areas of shallow and moderately deep soils.

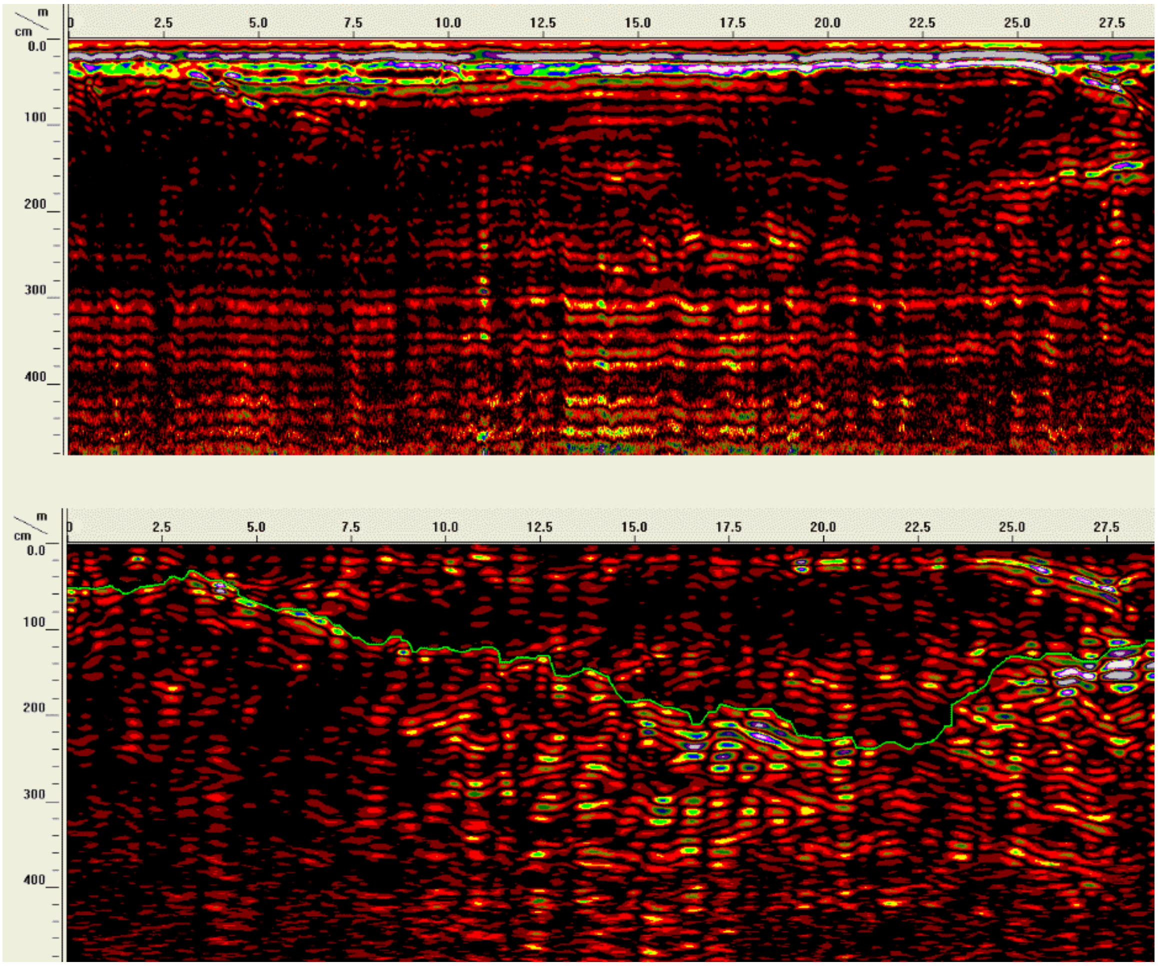


Figure 7. A relatively unprocessed (upper) and processed (lower) radar record from an area of Boden soils.

Montgomery County Site:

Figure 8 contains a relatively unprocessed (upper) and a more fully processed radar record from an area of Bismarck soils. On both radar records, the vertical and horizontal scales are expressed in centimeters and meters, respectively. Both radar records were subjected to the same basic processing steps of header editing, setting the initial pulse to time zero, color table and transformation selection, distance normalization, and display range gain adjustments. The lower radar record has been subjected to additional signal stacking, horizontal high-pass filtration and range gain adjustments.

Because of shallow depths to electrically resistive bedrock, Bismarck soils are considered well suited to GPR and advanced signal processing is generally not essential for visualizations and interpretations. In Figure 8, both radar records provided exceptional resolution of the tilted bedding planes in the underlying shale bedrock to depths 2 to 4 m. The soil-bedrock interface is interpreted on these radar records by following the inclined strata to their closest approach to the soil interface. Where these strata end, the moderately-fine textured soil materials begin.

In bedrock, variations in dielectric properties are principally associated with changes in water content (Davis and Annan, 1989). Abrupt changes in water content produce strong radar reflections. Saturated fractures and bedding planes will produce higher-amplitude reflections than air-filled or unsaturated fractures (Lane et al., 2000). Differences in the geometry, separation, and contents of fractures and bedding planes will affect their detection with GPR. Because of scattering losses, attenuation, wave-length scale heterogeneities, and geometric constraints, the number of fractures interpreted on radar records is an order of magnitude less than the number observed in outcrops (Lane et al., 2000). Closely spaced bedding and fracture planes will produce reverberations that can masked other reflections. Lane et al. (2000) observed that fractures spaced closer than ¼ of the transmitted wave length were obscured by constructive interference. Larger dip-angles and/or more irregular or rough surfaces will also result in greater scattering of the reflected wave front away from the antenna.

Vertical interfaces reflect very little energy towards the antenna. Fractures and bedding planes with dip-angles greater than about 45 degrees are affected by spatial aliasing distortion and are not be accurately imaged (Buursink and Lane 1999).

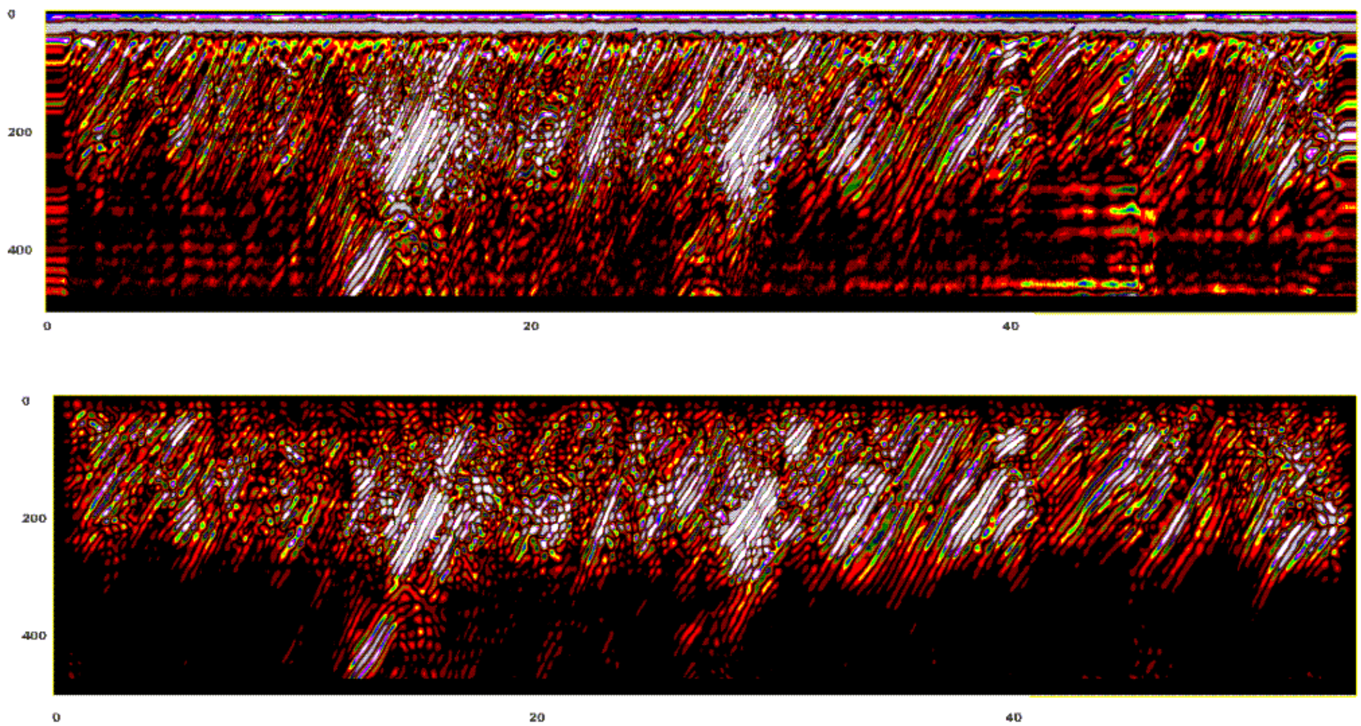


Figure 8. A relatively unprocessed (upper) and processed (lower) radar record from an area of Bismarck soils.

Figure 9 contains a relatively unprocessed (upper) and a more highly processed radar record from an area of Honobia soils (Bismarck-Honobia complex, 8 to 15 % slopes) at Site 2. The moderately deep, fine-textured Honobia soils are considered to have low potential for GPR. On both of these renderings of the same radar record, the vertical and horizontal scales are expressed in centimeters and meters, respectively. Once again, both radar records shown in Figure 9 were subjected to the same basic processing steps of header editing, setting the initial pulse to time zero, color table and transformation selection, distance normalization, and display range gain adjustments. The lower radar record has been subjected to additional signal stacking, horizontal high-pass filtration and range gain adjustments.

It is evident from the radar records shown in Figure 9 that advanced signal processing procedures have helped to reduce the level of background noise and have improved the interpretability of the radar record. In the lower record shown in Figure 9, a green-colored line has been used to indicate the interpreted depth to a subsurface interface, which is believed to represent the limestone bedrock. On this radar record, the interpreted depth to bedrock ranges from about 34 to 237 cm. In areas of the fine-textured Honobia soils, penetration depths and the general effectiveness of GPR were greater than anticipated. Although the clay content of Honobia soils is relatively high for GPR, the 2 to 3 m penetration depths of GPR suggest a greater proportion of low activity clay minerals.

Three radar traverses were conducted across an area of Bismarck-Honobia complex, 8 to 15 % slopes. Based on 8,865 interpreted measurements made along the three traverse lines, the average depth to bedrock is about 108.8 cm with a range of about 14.9 to 245.3 cm. Over one-half of these measurements were between depths of about 63.6 and 151.0 cm. Tables 3 and 4 summarize the results of these surveys. Table 3 lists the number of observations of the depth to bedrock for each traverse according to soil depth classes. Table 4 provides the frequency distribution of these observations also according to soil depth classes.

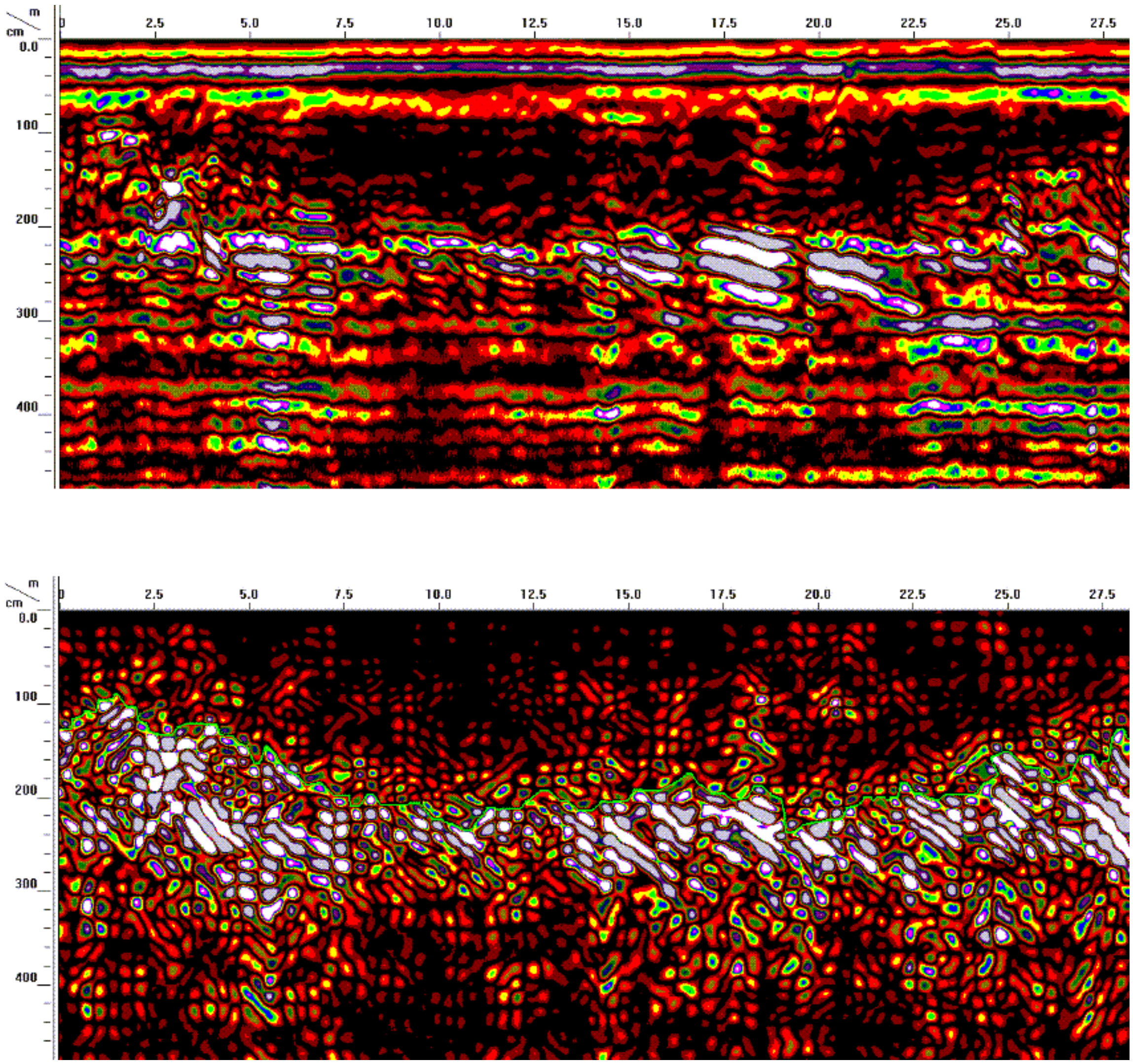


Figure 9. A relatively unprocessed (upper) and processed (lower) radar record from an area of Honobia soils.

Figure 10 is a Google Earth image of the area of Bismarck-Honobia complex, 8 to 15 % slopes, which was traversed with GPR. The locations of these traverse lines, as well as the interpreted depths to bedrock along these lines, are shown in this image. In the areas traversed with GPR, soils are shallow (12 %), moderately deep (39 %), deep (24 %), and very deep (25 %) to bedrock (colored red, orange, yellow, and green, respectively). Soils are dominantly (64 %) moderately deep and very deep to bedrock with included areas (36 %) of shallow and deep soils.

Table 3. These depths to bedrock statistics are for the GPR traverses completed in an area of Bismarck-Honobia complex, 8 to 15 % slopes (Montgomery County). Observations are grouped according to soil depth classes.

Depth Class	Traverse 1	Traverse 2	Traverse 3
0 to 50	837	212	20
50 to 100	1203	1243	1036
100 to 150	66	233	1776
>150	0	286	1953

Table 4. Frequency distribution of radar interpretations of the depth to bedrock in traversed areas of Bismarck-Honobia complex, 8 to 15 % slopes (Montgomery County). Interpretations are grouped according to soil depth classes.

Depth Class	Traverse 1	Traverse 2	Traverse 3
0 to 50	0.40	0.11	0.00
50 to 100	0.57	0.63	0.25
100 to 150	0.03	0.12	0.43
>150	0.00	0.14	0.48

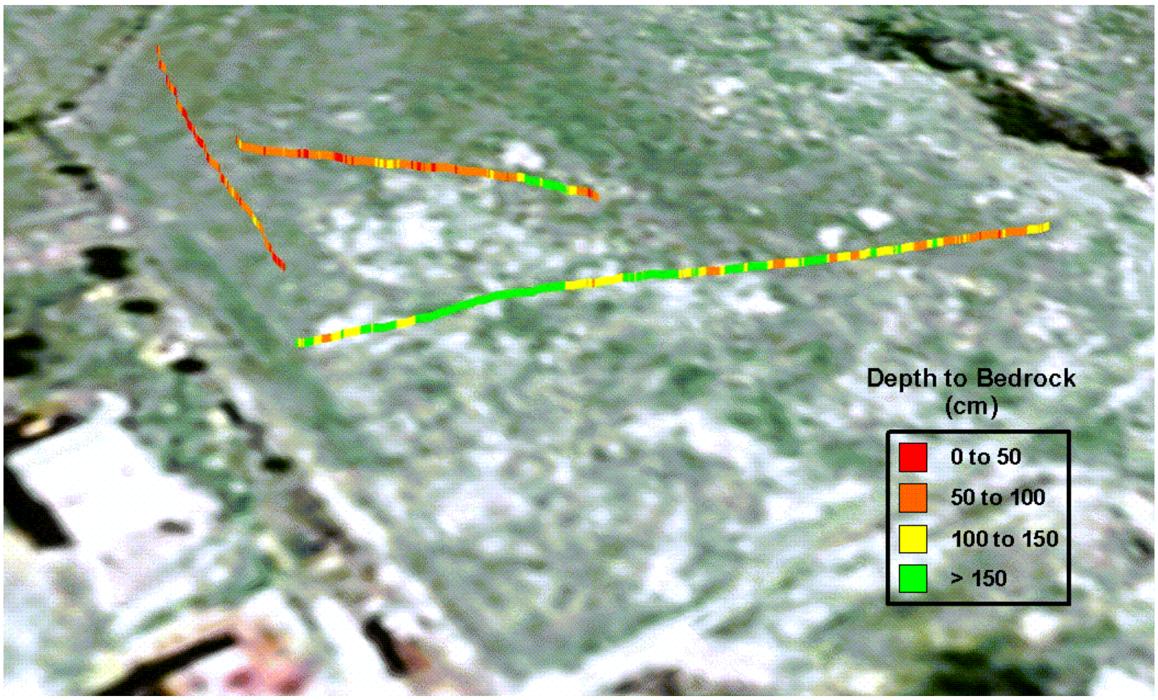
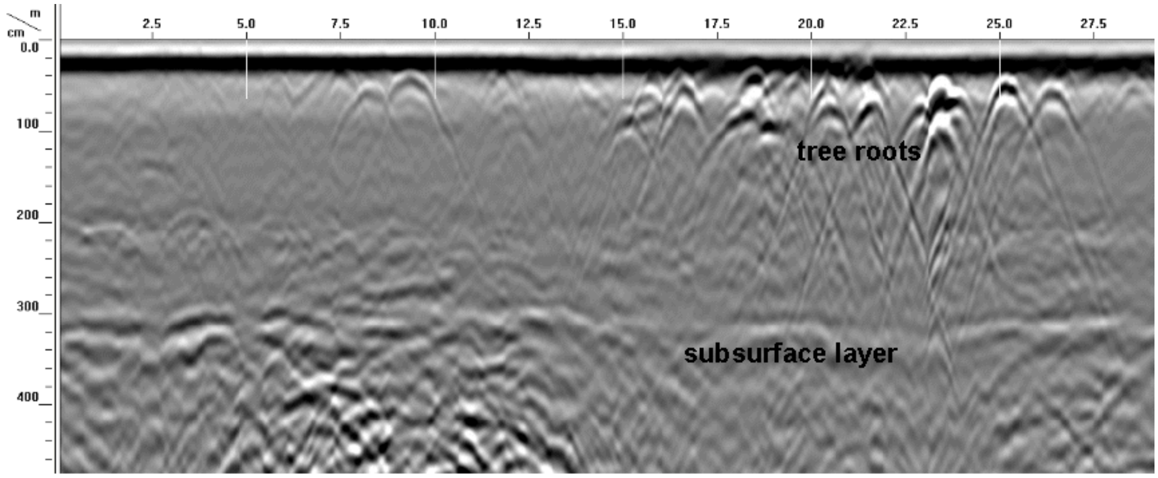


Figure 10. In this Google Earth image of Site 2 in Montgomery County, the locations of georeferenced GPR traverse lines are shown. Colors indicate the depths bedrock (all depths are expressed in cm).

<u>Nevada County Site:</u>
The Nevada County site is located in an area of Darden soils. The low clay and moisture contents of the sandy, excessively drained Darden soils are very favorable to GPR. In areas of Darden soils processing can be used to improve the imagery, but is neither essential nor required. In Figure 11, two renderings of the same section of a radar record are shown. Both radar records were subjected to the same basic processing steps of header editing, setting the initial pulse to time zero, color table and transformation selection, distance normalization, and display range gain adjustments. The lower radar record has been subjected to additional processing, which included signal stacking, migration and range gain adjustments. Radar antennas receive reflected energy from a complex 3D cone. Migration attempts to remove diffractions, distortion, dip displacement and out-of-line reflections (Neal, 2004). Migration algorithms are also used to improve signal-clutter ratio and to reconstruct and properly align inclined interfaces. In the upper part of the upper radar record shown in Figure 11, tree roots and buried artifacts produce hyperbolic reflection patterns, which can mask reflections from desired subsurface features and complicate interpretations. In the lower record, the effects of migration are evident in the removal of diffraction tails from the tree roots and buried artifacts. In addition, deeper soil interfaces have been reconstruct and are more properly align through migration In the lower radar record shown in Figure 11, additional range gain adjustments have been used to help emphasize subsurface features.



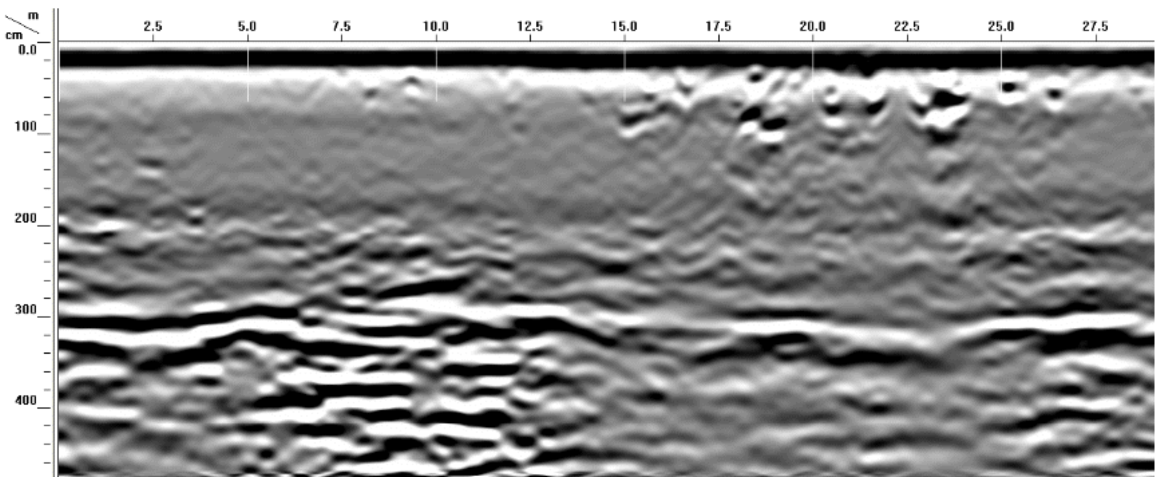


Figure 11. A relatively unprocessed (upper) and processed (lower) radar record from an area of Darden soils.

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