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

Subject: Soils – Geophysical Field Assistance **Date:** 22 November 2006

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Purpose:
Soils with high iron- and manganese-oxide contents have been reported by Blank and Rabenhorst (2006) in the Piedmont of Maryland. The purpose of this investigation was to use electromagnetic induction (EMI) and ground-penetrating radar (GPR) to help characterize these soils. This study focuses on the affects of different minerals on the response and effectiveness of these geophysical tools.

Participants:
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Martin Rabenhorst, Professor, College of Agriculture and Natural Resources, University of Maryland, College Park, MD

Activities:
All activities were completed on 6 November 2006.

Results:

1. Intuitive correlations among high ferromanganese contents, magnetic susceptibility, soil type, topography, and EMI response are possible within the study site. Anomalous apparent conductivity (EC_a) values were measured on higher-lying convex surfaces, known to have high iron- and manganese-oxide contents that are presently being associated with Letort soils. These anomalous spatial EC_a patterns are attributed to soils with higher ferromanganese contents and magnetic susceptibility. However, the supposed magnetic susceptibility of these soils has merely been inferred and was not properly measured. Further studies are recommended.

2. Radar records collected at the study site showed the presence of subsurface planar reflectors of varying amplitudes that suggest layers of saprolite (C horizon). This interpretation is contrary to core observations and justifies further examination of the residuum at this site.

3. Additional studies are recommended to confirm the interpretations made and to better understand the effects of high iron and manganese contents on the response of the both ground-penetrating radar and electromagnetic induction. If possible, I wish to return to this and other sites identified by Rebecca Blank next spring and conduct more extensive geophysical surveys.

I immensely enjoyed working with Dr Rabenhorst and Rebecca Blank in the field.

With kind regards,

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Background:
Some soils in the Northern Piedmont have exceptionally high Mn and Fe oxide contents (greater than 170 g kg^{-1} Fe and 100-150 g kg^{-1} Mn) (Black and Rabenhorst, 2006). These levels of Fe and Mn impart black colors (moist Munsell value and chroma commonly < 2/1) and unique physical and chemical properties to the soil materials. These soils occur in areas characterized by complex metamorphic geology, and have been associated with residuum weathered from marble and other calcareous parent rocks (Black and Rabenhorst, 2006). Ferromanganiferous soils are being investigated by the University of Maryland using various digital spatial data sets (including soil, geology, and topography surveys) that are supported with field reconnaissance assessments (Black and Rabenhorst, 2006). Geophysical methods are used in the present study to help characterize these soils and to map their spatial extent.

Equipment:
The radar unit is the TerraSIRch Subsurface Interface Radar (SIR) System-3000, manufactured by Geophysical Survey Systems, Inc. (Salem, New Hampshire).[1] Daniels (2004) discusses the use and operation of GPR. The SIR System-3000 weighs about 9 lbs (4.1 kg) and is backpack portable. With an antenna, the system requires two people to operate. A 200 MHz antenna was used in this investigation.

Radar records contained in this report were processed with the RADAN for Windows (version 5.0) software program developed by Geophysical Survey Systems, Inc (Geophysical Survey Systems, Inc, 2003).[1] Processing included setting the initial pulse to time zero, color transformation, marker editing, distance normalization, horizontal stacking, migration, filtration, and range gain adjustments.

An EM38 meter, manufactured by Geonics limited (Mississauga, Ontario) was used in this study.[1] This meter weighs about 1.4 kg (3.1 lbs) and needs only one person to operate. No ground contact is required with this instrument. The EM38 meter 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, 2006).

The Geonics DAS70 Data Acquisition System was used with the EM38 meter to record and store both EC_a and position data.[1] The acquisition system consists of the EM38 meter, an Allegro CX field computer (Juniper Systems, North Logan, UT), and a Garmin Global Positioning System (GPS) Map 76 receiver (with CSI Radio Beacon receiver, antenna, and accessories that are fitted into a backpack)(Olathe, KS).[1] When attached to the acquisition system, the EM38 meter is keypad operated and measurements can be automatically triggered. The NAV38 and Trackmaker38 software developed by Geomar Software Inc. (Mississauga, Ontario) was used to record, store, and process EC_a and GPS data.

To help summarize the results of the EMI surveys, SURFER for Windows, version 8.0 (Golden Software, Inc., Golden, CO), was used to construct the simulations of the EC_a data shown in this report.[1] Grids of EC_a data were created using kriging methods with an octant search.

Study Site:
The study site is located near the intersection of Green Valley and Keymar roads in Johnsville, northeast Frederick County, Maryland (see Figure 1). The site is located in the Northern Piedmont Major Land Resource Area (MLRA 148). The study site is in a cultivated field that is principally mapped as Glenelg-Mt. Airy channery loams, 3 to 8 percent slopes (GmB) (see Figure 1). The very deep, well drained Glenelg and the moderately deep, somewhat excessively drained Mt. Airy soils formed in residuum weathered mainly from hard mica schists and phyllites, or locally from granitized or chlorite schists. Also included in the lower-lying, eastern portion of the study site is a unit of Conestoga and Letort silt loams, 3 to 8 percent slopes (CoB). The very deep, well drained Conestoga and Letort soils formed in residuum on uplands. Conestoga soils formed in residuum weathered from micaceous limestones and calcareous schists. Letort soils formed in residuum weathered from interbedded micaceous limestones, graphitic phyllites and schists. Other than being classified into different cation-exchange

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

activity classes, Conestoga and Letort soils are differentiated by dominant chromas: Conestoga has a dominant chroma of 6 to 8; Letort has a dominant chroma of less than 5. In Frederick and Carroll Counties, the ferromanganiferous soils appear to occur principally in areas of Conestoga and Letort soils. However, the OSD for these soil series provide no mention of high Mn or Fe oxide contents. The taxonomic classifications of the named soil series mapped within the study site are listed in Table 1.

Figure 1. The approximate location of the study site has been identified with black-colored lines on this soil map of the study area.

Table 1
Taxonomic Classification of Soils

Soil Series	Taxonomic Classification
Conestoga	fine-loamy, mixed, active, mesic Typic Hapludalfs
Glenelg	fine-loamy, mixed, semiactive, mesic Typic Hapludults
Letort	fine-loamy, mixed, superactive, mesic Typic Hapludalfs
Mt. Airy	loamy-skeletal, micaceous, mesic Typic Dystrudepts

On the Geologic Map of Frederick County, Maryland (Maryland Geologic Survey, 1968), the study area is underlain by the late Precambrian, Swift Run formation. The Swift Run formation consists of "sericitic quartzite and phyllite; blue and green tuffaceous slate with white blebs, some white marbled with interbedded phyllite" (Maryland Geologic Survey, 1968). Within the general study area, a unit of the Swift Run formation is flanked by two units of the late Precambrian, Libertytown meta-rhyolite ("a purplish, bluish-black and red, fine-grained meta-rhyolite with feldspar phenochrysts; interbedded with blue and purple amygdaloidal meta-andesite; both rhyolite and andesite interbedded with blue, purple, and green phyllitic schist") (Maryland Geologic Survey, 1968).

Field Procedures:
A radar transect was completed by pulling the 200 MHz antenna by hand along a field boundary that forms the southern boundary of the study site. The transect line, though confined to a unit of Glenelg-Mt. Airy channery

loams, 3 to 8 percent slopes (GmB), traversed different landscape components. Although, GPR provides a continuous profile of the subsurface, interpretations were restricted to reference points. Reference points were spaced at a uniform interval of about 10 meters along the traverse line. At each reference point, the radar operator impressed an identifying mark on the radar record.

Three separate EMI surveys were conducted within the study site. These surveys varied in terms of spatial scales and levels of resolution. Two surveys were conducted (each in an orthogonal direction to the other) using a 5-m grid line interval. One survey was conducted using a 10-m grid line interval. The EM38 meter was operated in the vertical dipole orientation and in the continuous mode with measurements recorded at 1-sec intervals. The EM38 meter was carried at a height of about 3-cm above the ground surface with its long axis parallel to the direction of traverse. Data collection was facilitated by using the NAV38 programs with the Allegro field computer. Apparent conductivity (EC_a) data shown in this report are not temperature corrected.

Magnetic Susceptibility:

Typically the use of EMI focuses on the electrical properties of soils and other earthen materials and neglects the magnetic properties. In areas of moderate to high electrical conductivity, EC_a dominates the measured EMI response. Magnetic susceptibility (χ) may affect the data, but its effects will be significantly less than the effects of EC_a, and will not as a rule be noticed in the data. In most areas, it is generally assumed that the profiled earthen materials are non-ferromagnetic and have very low or immeasurable χ. During field calibration, the EM38 meter was calibrated on the summit of a low hill and in an area of extremely dark colored soil materials. It was observed following the "*instrument zero*" procedure that, as the EM38 meter was lowered from a height of 1.5 m, the conductivity decreased and became negative on the soil surface. This is unusual. During the *instrument zero* procedure, the EM38 meter is purposely held at a height above the surface where it no longer responds to the conductivity of the ground. As the meter is lower, the conductivity should rise. Following the "*final inphase nulling"* procedure, negative values were observed in the quadrature (conductivity) phase in areas of black-colored surface materials.

Magnetic susceptibility is a parameter of soils and earthen materials that is responsive to the presence of ferromagnetic materials. Many rocks and minerals are weakly magnetic and, in response to an applied magnetic field, can be magnetized producing what are know as "spatial perturbations" or "anomalies" in the earths magnetic field. Magnetic susceptibility is the ratio of the total magnetic moment per unit mass (M), measured in amperes per meter (A/m), to the applied magnetic field (H), also measured in A/m. This relationship is expressed by the equation (after Mullens, 1977):

$$M = \chi H \qquad [1]$$

A magnetometer is typically used to measure magnetic susceptibility. The magnetic properties of soils principally reflect the effects of soil mineralogy (Magiera et al., 2006). Soils with manifested magnetic properties are generally dominated by ferromagnetic minerals, maghemite, magnetite, and/or titanomagnetites (Mullens, 1977). Magnetic susceptibility depends on the concentration, size and shape of these minerals and the method of measurement (Mullens, 1977). Magnetic susceptibility has been associated with several soil properties including particle size, organic matter and soil moisture contents (Maier et al., 2006; Mullin, 1977).

Magnetic susceptibly varies at all spatial scales and levels of resolution. In most terrains, magnetic susceptibility is very low. In the presence of ferromagnetic materials, significant variations (by a factor of 2 or 3) in χ have been observed over distances as small as 2 to 3 meter (Butler, 2003). Magnetic susceptibility has been observed to vary with slope positions (de Jong et al., 2000), soil drainage (Maier et al., 2006), vegetation (Dearing et al., 1996). In addition, high values of magnetic susceptibility have been associated with human occupation (Dalan and Banerjee, 1996) and industrial pollutants (Fialová et al., 2006; Magiera et al., 2006). Magnetic susceptibility has been associated with pedogenesis (Fine et al., 1989), gleying (Vadyunina and Babanin, 1972), and hydric soils (Grimley et al., 2004; Grimley and Vepraskas, 2000). Magnetic susceptibility has also been used to distinguish soil types (Hanesch and Scholger, 2005; Dearing et al., 1996; Vadyunina and Smirnov, 1978).

Table 2
Magnetic susceptibility of some Rocks

Rock	10^8 χ/m^3 kg^{-1}	Coefficient of variation (%)
Basalt	1260	97
Diabase	1110	42
Rhyolite	525	89
Gabbro	427	54
Granite	220	162

Parent materials strongly influence soil magnetic susceptibility as either the source of lithogenic magnetic materials or the matrix that favors the formation of magnetic materials (Hanesch and Scholger, 2005). Lithology exerts a most profound effect on the magnitude of χ (Singer et al., 1996). Table 2 lists the χ of several rocks (after Mullins, 1977). Shenggao (2000) observed that the absolute value and profile distribution of χ in soils is strongly influenced by lithology. Shenggao (2000), in a study of χ in China, concluded that the magnitude of soil χ follows a lithologic procession of : basic igneous rocks (basalt, andesite, and granodiorite) > neutral and acid igneous and metamorphic rocks > sedimentary rocks.

Soils formed in residuum weathered from magnetically enriched parent rocks are natural enriched. Ferromagnetic minerals, maghemite, magnetite are resistant to weathering and will remain and become concentrated in residual soil materials (Magiera et al., 2006; Singer et al., 1996). *In situ* pedogenic processes can result in some enhancement of χ (Singer et al., 1996). Because of weathering processes and the selective sorting of heavy minerals, it is not uncommon for χ to be higher in residual soils than in the underlying parent rock (Butler, 2003). The concentration of magnetic materials in the weathered residuum accounts for what appears to be the magnetic enrichment of C horizons compare with the unweathered parent rock. Hanesch and Scholger (2005) noted that calcareous parent material with high pH values promoted the formation of magnetic materials in soils. However, soils with measurable χ can also develop from nonmagnetic parent rocks (Rivers et al., 2004). De Kimpe and others (2001) found that χ will vary with soil depth, particle size distribution, and mineralogical and chemical composition.

Magiera et al. (2006) observed a greater intensification of χ in the topsoil of forest than in grassland or arable soils. They attributed this difference to atmospherically deposited magnetic particles from anthropogenic sources in forest canopies and litter layers on forest soils. Anthropogenic sources are inferred when magnetic conductivity is relatively high in surface layers and decreases rapidly with increasing soil depth (Fialová et al., 2006).

The anomalous behavior of the EM38 meter within the study site suggests the occurrence of measurable levels of magnetic susceptibility in the soil. Magnetic susceptibility is a form of natural interference to electrical conductivity data. However, in a study conducted in Indiana, Butler and Llopis (1999) found no obvious correlation between EC_a measured with an EM38 meter and χ. In general, with an EMI meter, the inphase (I/P) rather than the quadrature phase (Q/P) component is used to detect metallic objects because it is more sensitive to χ and will produce more contrasting measurements (Bevans, 1996). Typically, in soils and earthen materials, higher levels of magnetic susceptibility result in the reduction of EMI measurements made in the inphase mode. Though not commonly used to measure magnetic susceptibility, the EM38 meter has been used to estimate a depth-weighted, averaged magnetic susceptibility measurement for the upper 0 to 50 cm of the soil (Butler, 2003) (Procedures used by Butler were not used in this study). Magnetic susceptibility is believed to have no significant effect on the quadrature component. While magnetic susceptibility was not directly measured in this study, it was inferred by anomalous (negative) EC_a measurements measured in the quadrature phase.

Interpretations:

Typically, for soil investigations, measurements are made with the EM38 meter in the quadrature phase rather than the inphase mode. Measurements made with the EM38 meter in the quadrature phase are considered inappropriate to measure χ. However, through visual correlation, it was observed that areas with negative EC_a measurements coincided with areas of dark colored surface layers suspected to be enriched with Fe and Mn. Duran (1984) suggested that interference to EC_a measurements caused by lithological sources can be partitioned into areas with differing background values. The accompanying plots (Figure 2 to 4) of EC_a measured with the EM38 meter did partition the study site into areas with and without dark colored surface layers. Areas with dark colored surface layers are associated with high levels of Fe and Mn oxides and are characterized by negative EC_a values.

Figure 2 is a plot showing the spatial EC_a pattern within the study site based on a 10-m grid line interval. The approximate locations of soil cores have been shown in this figure. Areas of negative EC_a are restricted to summit and shoulder slope components of a low ridge. These areas display dark colored surface layers and samples from cores extracted from these slope components have exceptionally high Mn and Fe oxide contents.

Apparent conductivity is variable across the area shown in Figure 2. Based on 4097 observations, EC_a averaged about 7.0 mS/m and ranged from about -32.5 to 33.5 mS/m. One-half of the measurements had an EC_a that was between about 4.1 and 10.5 mS/m.

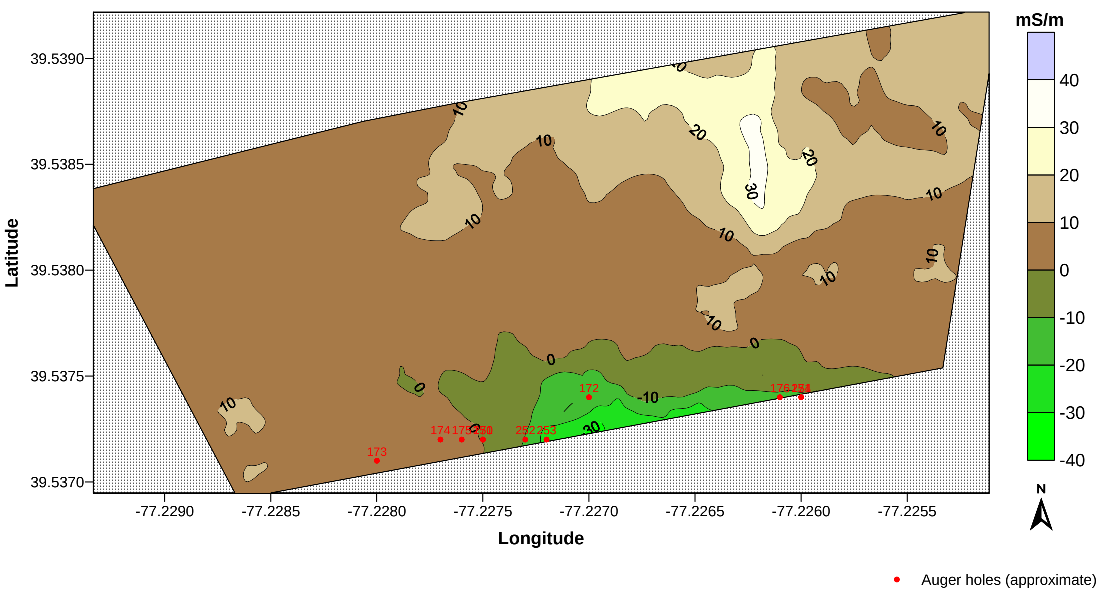

Figure 2. Plot of EC_a data collected on a 10-m grid interval.

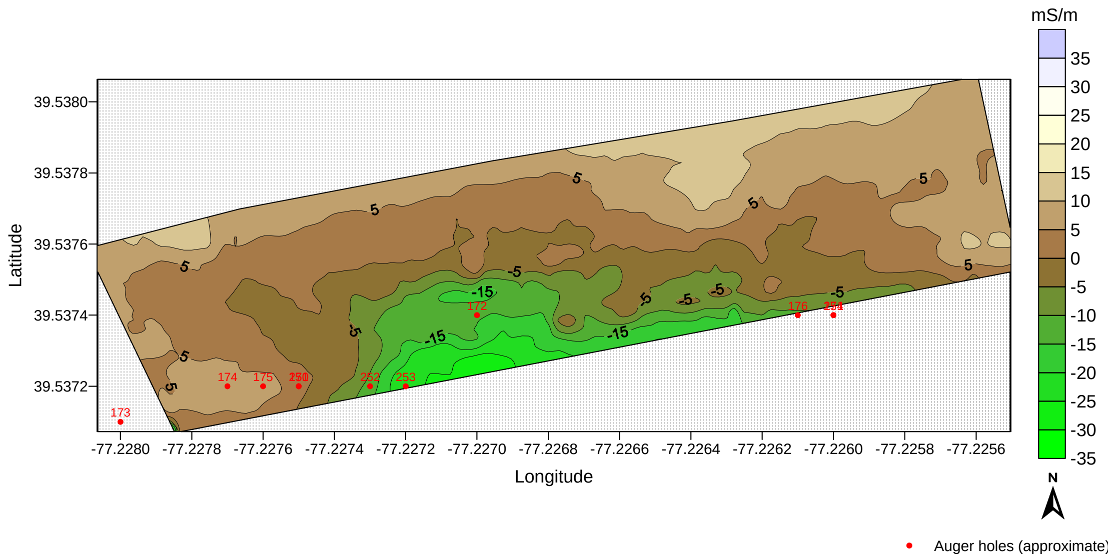

Figure 3. Plot of EC_a data collected on a 5-m grid line interval with traverses orientated east-west.

Figures 3 and 4 are plots of EC_a measured across more restricted portions of the study site using a 5-m grid line interval. The approximate locations of soil cores have been shown in Figure 3. In each of these surveys, the size and location of the area surveyed varied. Traverses were conducted in a general east-west and north-south direction in Figures 3 and 4, respectively. While variations in spatial patterns are evident in each plot, the area of negative EC_a, and presumably higher Fe and Mn oxide contents, remains very similar.

This preliminary study suggests that EMI can be use to detect and map anomalous areas believed to represent magnetic "hot spots" and to differentiate soils based on significant mineralogical differences.

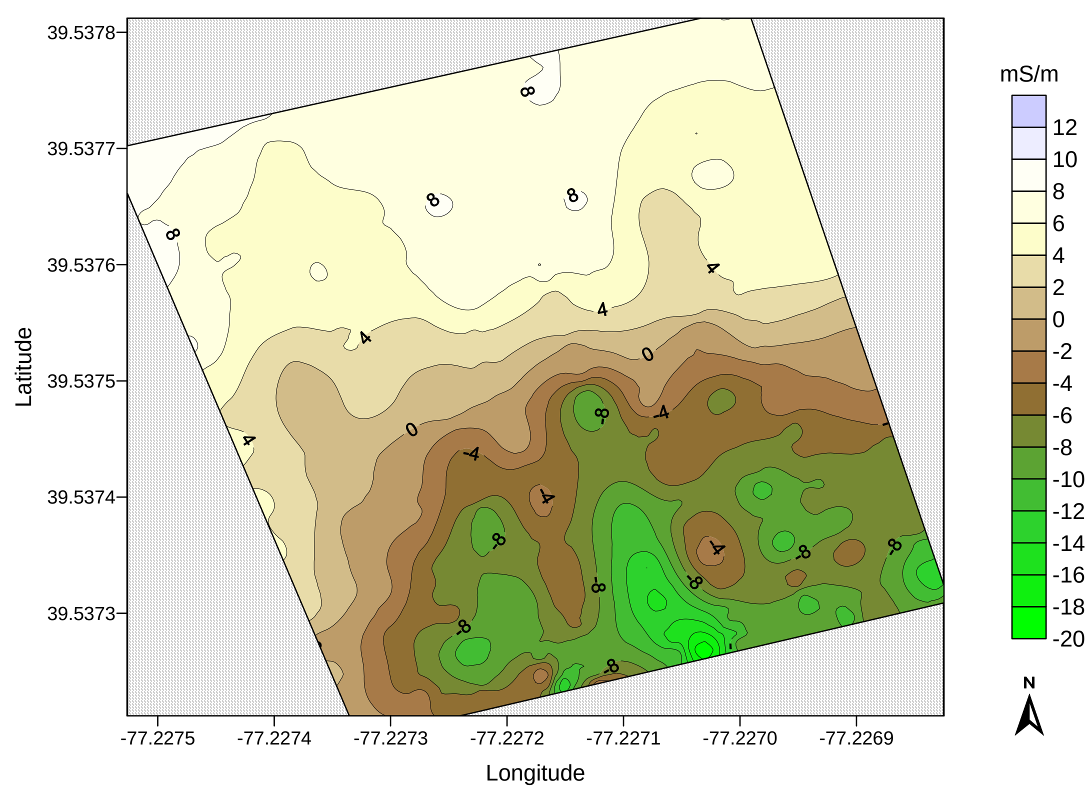

Figure 4. Plot of EC_a data collected on a 5-m grid line interval with traverses orientated north-south.

Ground-Penetrating Radar:
Based on the depth to a buried metallic reflector the velocity of pulse propagation was estimated to be about 12.3 m/ns through the upper part of the soil profile. This propagation velocity was used to depth scale the radar records. Figures 5 thru 7 show portions of radar record that was collected sequentially as the 200 MHz antenna was dragged from west to east along the traverse line. Unfortunately, elevation data were not collected at the time of the GPR survey, and consequently, the radar records can not be terrain corrected to show the approximate topography (the surface is incorrectly shown as being horizontal on each portion of the radar record). In these figures, the depth and distance scales are expressed in meters.

The portions of radar record (Figures 5 and 7) collected along lower back slope components were collected in areas of presumably Glenelg or Mt. Airy soils. The radar record (Figure 6) collected on the summit was in an area of black colored surface layers and presumably ferromanganiferous soils. The contrast in signal amplitudes between the soils on these two landscape components is most striking. Soils on lower back slope components (Figures 5 and 7) were more attenuating to the radar signal, more depth restricted, required the use of more extensive signal processing techniques, and displayed mostly weak to moderate subsurface reflectors (colored red and yellow on the radar record). Soils on the summit and in areas with black colored surface layers were less attenuating to the radar signal and deeper depths of penetration were obtained. Subsurface reflectors on summit area produced high amplitude (colored white, gray, pink, and blue on the radar record) reflections.

Subsurface reflectors shown on the radar records in Figures 5 thru 7 are dominated by planar, slightly inclined features. In general, these features are apparent at depths of 1 to 1.5 m. These reflectors suggest lithologic features such as bedding, fracture, or cleavage planes in parent rock. However, soil observations taken near the traverse line suggest significantly deeper depth to parent rock. The images recorded on these radar records suggest saprolite. Saprolite consists of coarse to fine textured, thoroughly decomposed igneous and metamorphic rock that has weathered in place. Saprolite can be excavated easily with shovel. Saprolite is characterized by preservation of original rock structure, foliation and jointing (Pavich et al., 1989). Ground-penetrating radar has been used to study weathered bedrock and the transition from weathered to hard bedrock (Aranha et al., 2002; Hubbert et al., 2001; Li, 1998). The confirmation of this interpretation will require excavated soil pits.

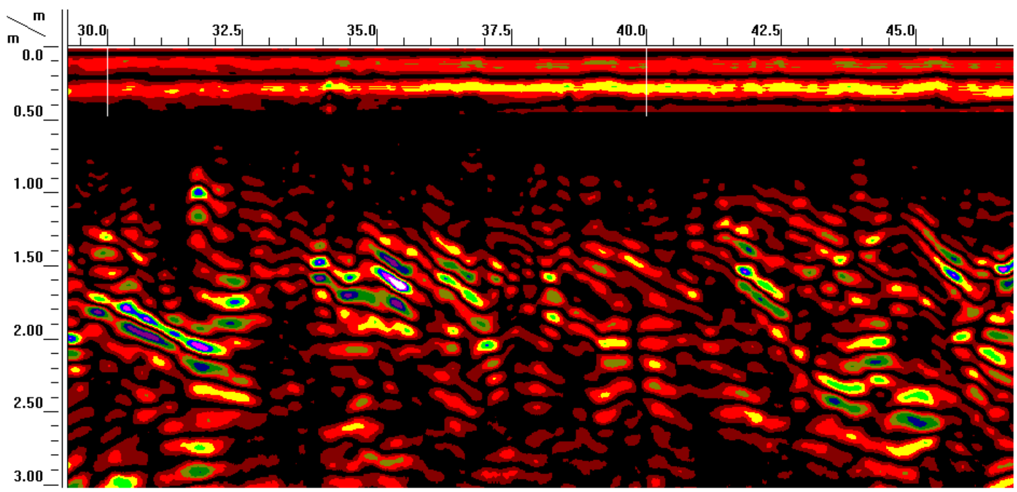

Figure 5. Subsurface features are evident beneath a lower back slope component along the western portion of the traverse line.

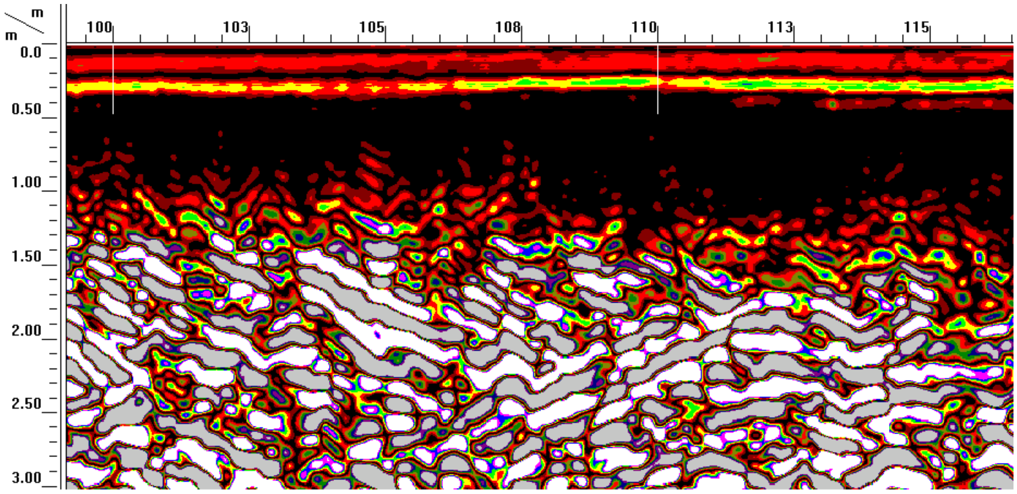

Figure 6. High amplitude subsurface features are well expressed beneath the summit component of the traverse line.

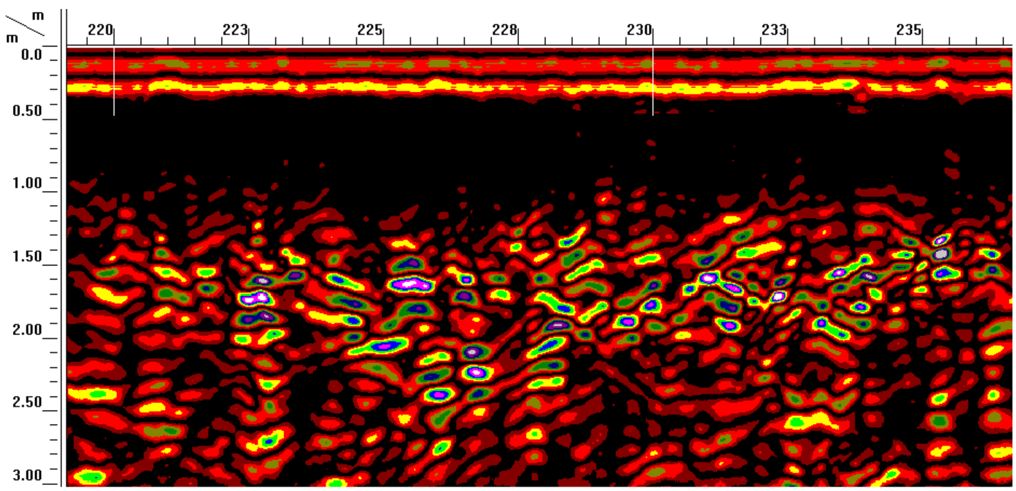

Figure 7. Subsurface features are evident beneath a lower back slope component along the eastern portion of the traverse line.

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