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

Subject: SOI – Geophysical Field Assistance **Date:** 22 June 2005

To: Paul Benedict
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Purpose:
The purpose of this investigation was to evaluate the effectiveness of ground-penetrating radar (GPR) for determining the depth to bedrock in soil formed over different lithologies in the Black Hills Area of South Dakota

Participants:
Dan Brady, Soil Scientist, USDA-NRCS, Rapid City, SD
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Jim Doolittle, Research Soil Scientist, USDA-NRCS-NSSC, Newtown Square, PA
Larry Edland, Soil Data Quality Specialist, USDA-NRCS, Bismarck, ND
James Westerman, Soil Scientist, USDA-NRCS, Rapid City, SD

Activities:
All field activities were completed on 16 and 17 June 2005.

Summary:

1. GPR can be used effectively to determine depths to parent rock and the composition of map units (based on soil-depth criteria) on some soils within the Black Hills Area. On other map units the use of GPR provides no meaningful information and its use is considered ill-advised and inappropriate.

2. For those map units where GPR provides meaningful soil-depth information, its use is recommended. Compared with traditional methods of data collection, GPR is less labor intense, more efficient, and has been found to provide more accurate information on the depth to parent rock (Collins et al., 1989).

It was my pleasure to participate in this study and to work with Larry Edland and the soil staff located in Rapid City, South Dakota.

With kind regards,

James A. Doolittle
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cc:

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Background:
In many portions of the Black Hills, it is difficult to examine soil profiles and determine the depths to parent rock with traditional soil surveying tools. Traditional soil surveying tools (i.e., bucket auger, sharpshooter spade) are slow and tedious, thus limiting the number of observations that can be made in a specified time period. Tree roots, rock fragments, and irregular or weathered parent rock surfaces limit the effectiveness of these traditional coring tools. Doubts often arise as to whether auger refusal was caused by a large rock fragment or parent rock. Where soils are suitable, ground-penetrating radar (GPR) is an accepted tool for imaging the subsurface and determining depths to parent rock. In the absence of a satisfactory number of soil cores, excavations, or exposures, GPR can provide information on the underlying soil and parent rock (Davis and Annan, 1989; Morey, 1974; Olson and Doolittle, 1985). GPR provides a continuous record of the subsurface and is more convenient and effective than traditional soil surveying tools for determining the depth to parent rock and the composition of soil map units based on soil-depth criteria (Collins et al., 1989; Schellentrager and Doolittle, 1991). The purpose of this investigation was to evaluate the performance of GPR for determining the depth to parent rock on different soils and lithologies within the Black Hills Area.

Study Area:
Study sites were located on soils formed over different lithologies within the Black Hills Area. The taxonomic classifications of soils discussed in this report are listed in Table 1.

Table 1. Taxonomic classification of soils

Series	Taxonomic Classification
Citadel	Fine, smectitic, frigid Glossic Hapludalfs
Cordeston	Fine-loamy, mixed, superactive, frigid Cumulic Haplustolls
Gypnevee	Coarse-silty, gypsic, mesic Ustic Torriorthents
Heath	Fine, smectitic Ustic Argicryolls
Heely	Loamy-skeletal, mixed, superactive, frigid Typic Hapludolls
Judy	Fine, smectitic Ustic Argicryolls
Larkson	Fine, smectitic, frigid Typic Haplustalfs
Pactola	Loamy-skeletal, mixed, superactive, frigid Glossic Hapludalfs
Paunsaugunt variant	Loamy-skeletal, mixed, superactive Pachic Argicryolls
Rekop	Loamy, gypsic, mesic, shallow Ustic Torriorthents
Virkula	Fine-silty, mixed, superactive, frigid Glossic Hapludalfs

Study Site #1 is located in an area of Judy-Heath-Paunsaugunt variant complex, 2 to 25 percent slopes (map unit (M.U.) JhD) in Pennington County. The well drained, moderately deep Judy and very deep Heath soils formed in calcareous materials weathered from limestone and interbedded shale. Compared with Paunsaugunt soil (loamy-skeletal, mixed, superactive, frigid Lithic Haplustolls), Paunsaugunt variant soil has a thicker mollic epipedon, is cryic, and is moderately deep to limestone. Within the study site, Judy, Heath, and Paunsaugunt variant soils formed over Madison limestone. The site is located at 43.96242^{o} N. Latitude, and 103.96136^{o} W. Longitude. Site # 1 is in rangeland.

Study Site #2 is located in an area of Heely-Cordeston complex, 6 to 15 percent slopes (M.U. HfC) in Pennington County. The moderately deep, well drained Heely soil formed in residuum weathered from metamorphic parent rocks. The very deep, well drained Cordeston soil formed in alluvium. Within the study site, these soils formed in materials weathered from phyllite. The site is located at 44.03684^{o} N. Latitude, and 103.80309^{o} W. Longitude. Site # 2 is in rangeland.

Study Site #3 is located in an area of Virkula-Pactola complex, 2 to 15 percent slopes (M.U. 205C) in Lawrence County. The very deep and deep, well drained Virkula and Pactola soils formed in materials weathered from metamorphic parent rock. Within the study site, these soils formed over phyllite. The site is located at 44.20980^{o} N. Latitude, and 103.58785^{o} W. Longitude. Site # 3 is in woodland.

Study Site #4 is located in an area of Gypnevee-Rekop-Rock outcrop complex, 6 to 15 percent slopes (M.U. GvD) in Pennington County. The well drained, deep Gypnevee and shallow Rekop soils form in residuum weathered from reddish

sedimentary parent rock that is high in gypsum. Within the study site, these soils formed over the Spearfish formation. The site is located at 44.11033^o N. Latitude, and 103.30190^o W. Longitude. Site # 4 is in rangeland.

Study Site #5 is located in an area of Citadel-Larkin complex, 10 to 40 percent slopes (M.U. 20E) in Lawrence County. The very deep, well drained Citadel soil formed materials weathered from calcareous sandstone, limestone, and soft shale. The deep, well and moderately well drained Larkson soils formed in materials weathered from soft noncalcareous sedimentary deposits. Within the study site, these soils formed over the Minnelusa formation. The site is located at 44.36237^o N. Latitude, and 103.57970^o W. Longitude. Site # 5 is in forest.

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 and 400 MHz antennas were used in this study.

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

Survey Procedures:
Ground-penetrating radar traverses were completed along selected lines established within different soil polygons and across different landscape components. In forested areas, traverse lines were cleared of tree limbs and debris. Along each line, reference flags were inserted in the ground at intervals of about 3 or 6 m. Pulling the 200 MHz antenna along each line completed a GPR transect. Along each line, as the antenna was towed passed a reference point, a vertical mark was impressed on the radar record. These marks referenced known positions and served as observation points.

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:

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

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 moist at the time of the GPR surveys. At each site, a metallic reflector was buried at a known depth (about 40 to 48 cm) and used to calibrate the GPR. Based on the depth to this known buried reflector, hyperbola-matching processing techniques (the shape of a hyperbole is dependent on the velocity), and equation [1], an averaged pulse propagation velocity was determined for each site. The estimated velocity will vary spatially and with depth, but for most soil investigations is reasonably accurate.

Results:
<u>High Limestone Plateau Site (Pennington County):</u>
Because of the high clay content (>35%) of the principal component soils in the Judy-Heath-Paunsaugunt variant

complex, this area was portrayed on the *GPR Soil Suitability Map of South Dakota* as having low potential for GPR. The fine-textured Judy and Heath soils formed in calcareous residuum weathered from Madison limestone. Rates of signal attenuation are exceptionally high in these soils and, as a consequence, GPR penetration depths are severely restricted. In addition, because of low signal-to-noise ratios, the interpretive quality of radar records is generally poor.

Figure 1 is a 22-m portion of a radar record from an area of Judy-Heath-Paunsaugunt variant complex, 2 to 25 percent slopes. For soil/bedrock interpretations, the use of GPR in these soils is considered inappropriate. The radar record shown in Figure 1 is of poor interpretive quality. Except in areas where the underlying limestone is within depths of about 1 meter, the underlying parent rock is indistinguishable. In this area of Judy and Heath soils, the depth of consistent penetration is generally less than 60 cm. Point reflectors in the upper part of the radar record (see Figure 1) represent rock fragments. Ground-penetrating radar can not be used effectively in areas of Judy-Heath-Paunsaugunt variant complex, 2 to 25 percent slopes to map the soil/bedrock interface and determine soil depths.

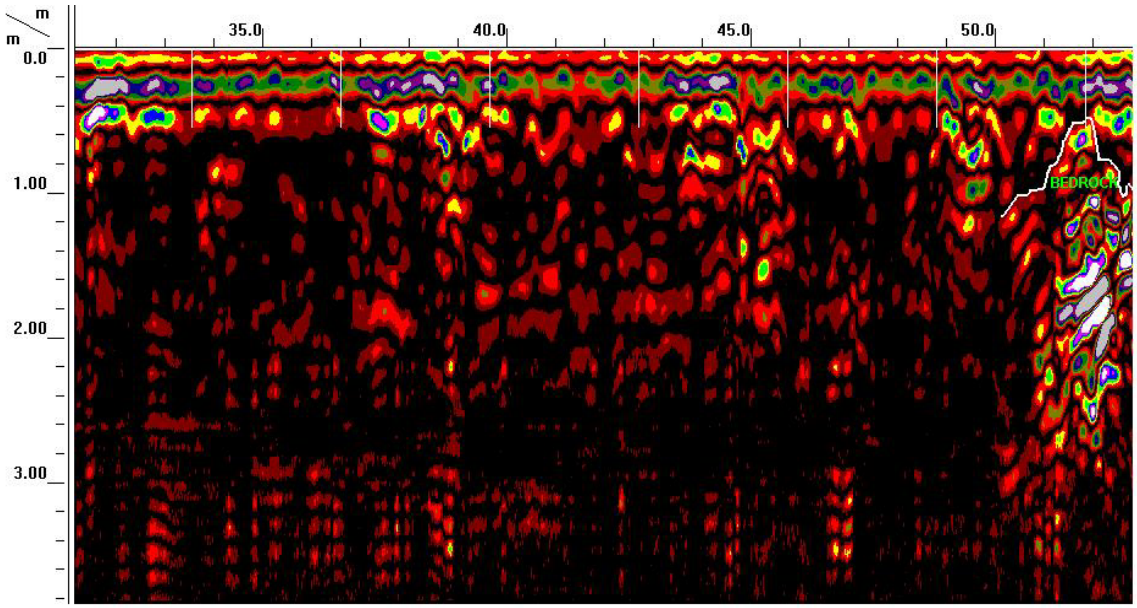

Figure 1. Radar record from an area of Judy-Heath-Paunsaugunt variant complex, 2 to 25 percent slopes.

<u>Site underlain by Metamorphic Parent Rock (Pennington County):</u>
This site is located in an area of Heely-Cordeston complex, 6 to 15 percent slopes, and is underlain by steeply dipping beds of phyllite. Soils are Mollisols. Because the clay content of the principal soil components averages between 18 and 35 percent, this area was portrayed on the *GPR Soil Suitability Map of South Dakota* as having moderate potential for GPR. Because of lower clay and moisture contents, parent rocks are typically less attenuating and more transparent to GPR than the soils that form in materials weathered from the parent rock.

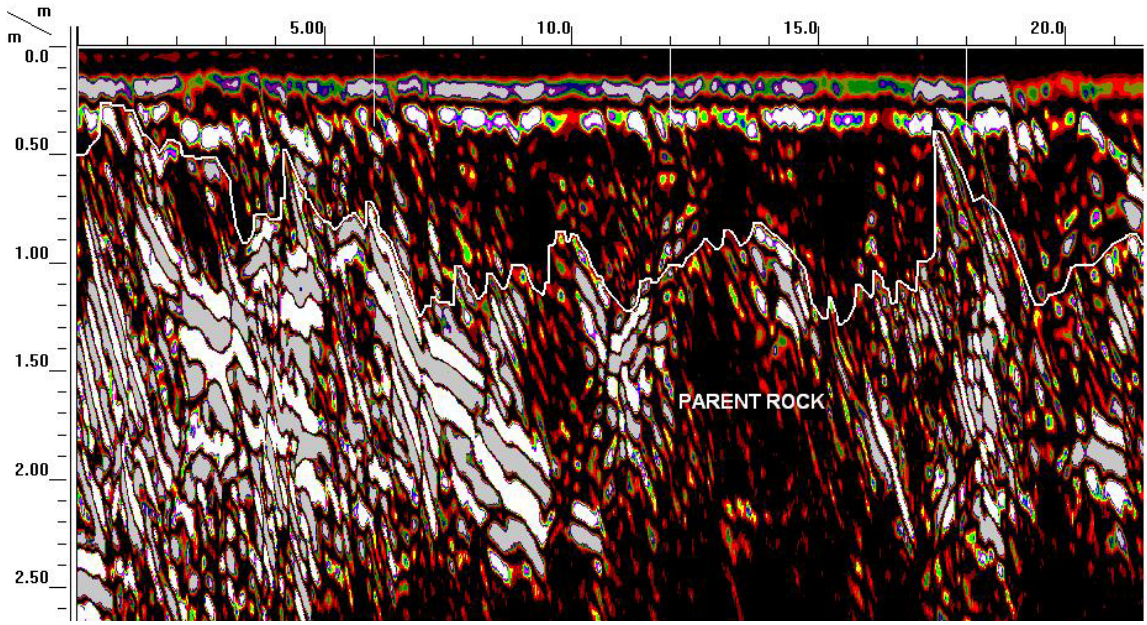

Figure 2. Radar record from an area of Heely-Cordeston complex, 6 to 15 percent slopes.

Figure 2 is a 22-m section of a radar record that was collected in an area of Heely-Cordeston complex, 6 to 15 percent slopes. The radar record is of exceptional interpretive quality. Because of differences in moisture and density, fracture and bedding planes are evident as high-amplitude reflectors in the underlying phyllite. In Figure 2, these bedding planes appear to be steeply dipping. This was confirmed by visual correlations with rock outcrops. The large number of point reflectors in the overlying soil represents larger rock fragments and testify to its fragmental character. In Figure 2, a white line has been drawn to represent the soil/bedrock interface.

Two GPR transects were hastily completed in this area of Heely-Cordeston complex, 2 to 15 percent slopes. Based on interpretations made at 40 observation points (in Figure 2, see white vertical line at the top of the radar record), the averaged depth to bedrock was 89.2 cm with a range of 31 to 151 cm. Based on soil-depth criteria, soils are shallow at 13 %, moderately deep at 50 %, deep at 35 %, and very deep at 3 % of these observation points. The transect data is included in the addendum to this report.

<u>Site underlain by Metamorphic Parent Rock (Lawrence County):</u>
This site is located in an area of Pactola-Virkula-Rock outcrop complex, 10 to 40 percent slopes. Soils are Entisols and develop over the Spearfish formation. Because the clay content of the principal soils averages between 18 and 35 percent, this area was portrayed on the *GPR Soil Suitability Map of South Dakota* as having moderate potential for GPR.

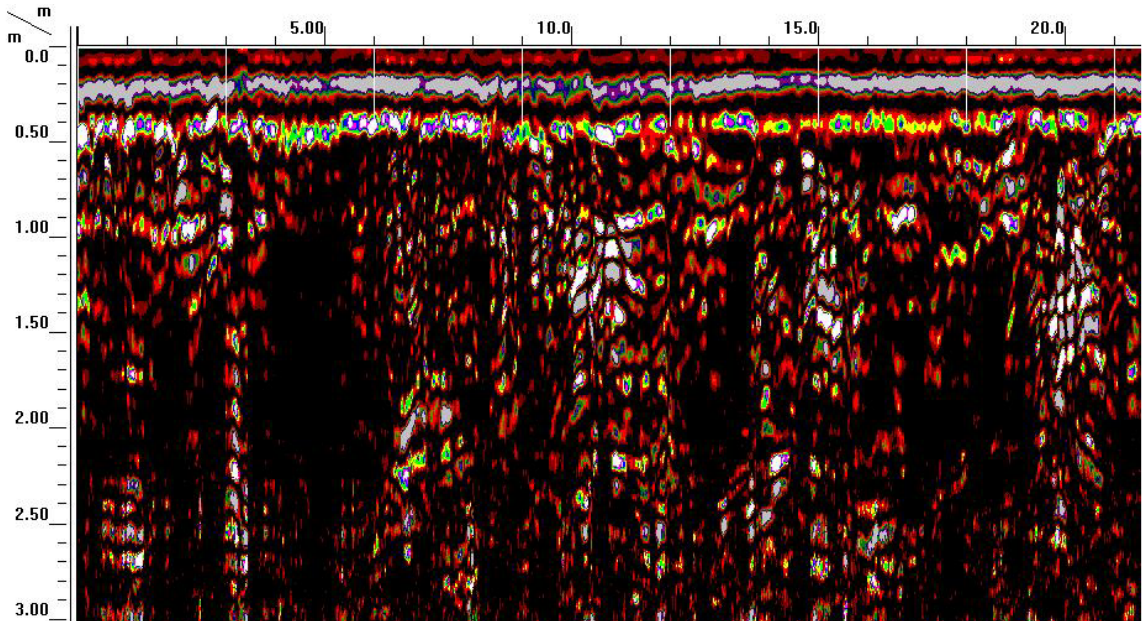

Figure 3. Radar record from an area of Pactola-Virkula-Rock outcrop complex, 10 to 40 percent slopes.

Figure 3 is a 22-m section of a radar record that was collected in an area of Pactola-Virkula-Rock outcrop complex, 10 to 40 percent slopes. The radar record is of poor interpretive quality and the soil/bedrock interface is ambiguous. Radar reflections provide some suggestion of inclined bedding planes, but are of low to moderate amplitudes and too segmented to provide a clear interpretation of the soil/bedrock interface. Because of poor interpretative quality of the radar records from this area, any interpretation of the soil/bedrock interface was considered ill-advised and too liable to errors.

<u>Site underlain by the Spearfish formation with Petrogypsic Horizons (Pennington County):</u>
This site is located in an area of Gypnevee-Rekop-Rock outcrop complex, 6 to 15 percent slopes. Soils are Entisols and form over the Spearfish formation. Gypnevee can contain 10-50 % gypsum and 3-25 % calcium carbonate, and has a salinity that ranges from 0 to 2 mmhos/cm. Rekop can contain 5-65 % gypsum, 5-40 % calcium carbonate, and has a salinity that ranges from 2 to 4 mmhos/cm. Because of their chemical composition, these soils were considered to have a low potential for GPR.

Figure 4 is a 18-m section of a radar record that was collected in an area of Gypnevee-Rekop-Rock outcrop complex, 6 to 15 percent slopes. The radar record is depth restricted and of poor interpretive quality. Where the petrogypsic horizon is within depths of 50 cm, it is distinguishable and some deeper lithologic features are evident on the radar record. However, where the petrogypsic horizon occurred at depths greater than 60 cm, the soil materials are highly attenuating to the radar's energy and subsurface features are indistinguishable. Because of the limited profiling depth and poor quality of radar records, the use of GPR in areas of Gypnevee-Rekop-Rock outcrop complex, 6 to 15 percent slopes, is considered inappropriate.

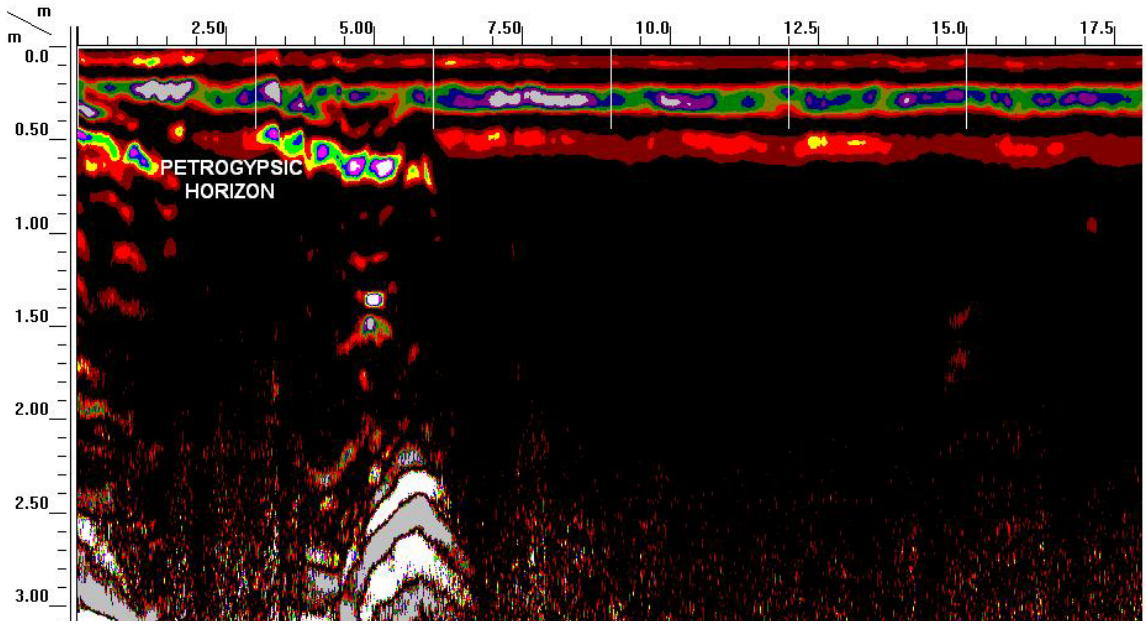

Figure 4. Radar record from an area of Gypnevee-Rekop-Rock outcrop complex, 6 to 15 percent slopes

<u>Site underlain by the Minnelusa formation (Lawrence County):</u>
This site is located in an area of Citadel-Larkin complex, 10 to 40 percent slopes. Because of the high clay content (fine-textured) and dominance of smectite clays minerals, these soils were initially considered to have a low potential for GPR. However, radar records from the selected site provided excellent and unambiguous imagery of the soil/bedrock interface. The Minnelusa formation is a complex of anhydrite, dolomite, limestone, shale, and sandstone members. It is probable that the selected site was over a more resistive member (i.e., sandstone) and consequently the soils were more favorable to GPR.

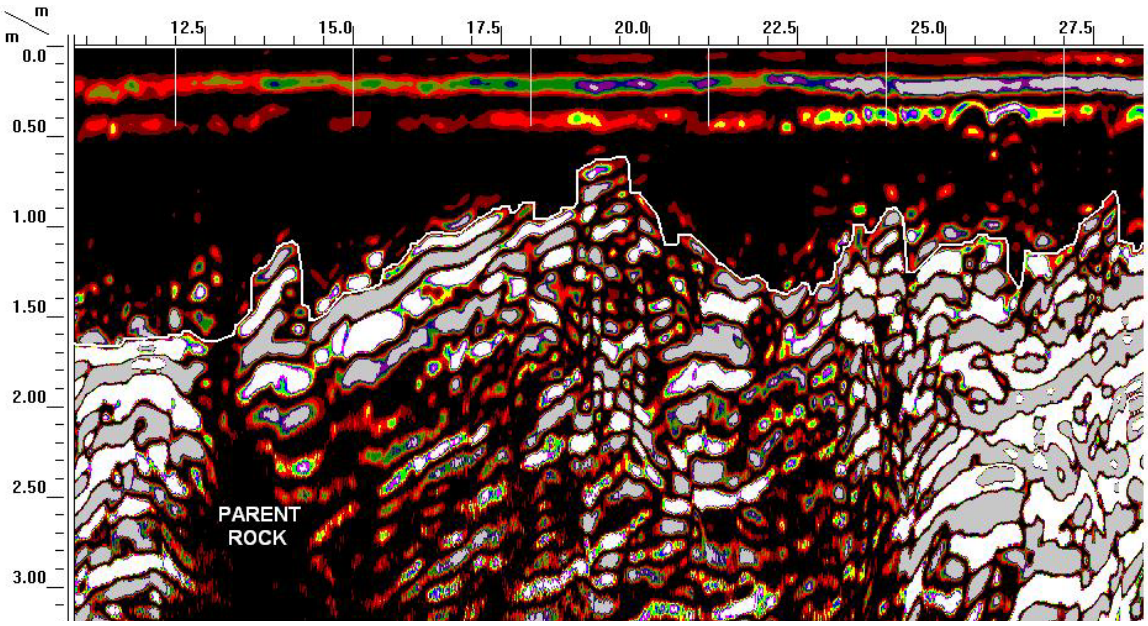

Figure 5. Radar record from an area of Citadel-Larkin complex, 10 to 40 percent slopes

Figure 5 is a 28-m section of a radar record that was collected in an area of Citadel-Larkin complex, 10 to 40 percent slopes. The radar record is of exceptional interpretive quality. Fracture and bedding planes are clearly evident in the underlying Minnelusa formation. Bedding planes are inclined and provide distinct, high-amplitude reflections on the radar record. Fracture planes appear as vertical zones of no signal returns or columns of aligned, point reflectors. Point reflectors in the overlying soil represent larger rock fragments and tree roots. Compared with the radar record obtained in the area of Heely and Cordeston soils (Figure 2), point reflectors are noticeably fewer in this radar record. Observations made in the field confirm this interpretation. In Figure 5, a white line has been drawn to represent the soil/bedrock interface.

Three GPR transects were completed in this area of Citadel-Larkin complex, 10 to 40 percent slopes. Based on interpretations made at 40 observation points, the averaged depth to bedrock was 113.6 cm with a range of 51 to 196 cm. Based on soil-depth criteria, soils are moderately deep at 43 %, deep at 49 %, and very deep at 8 % of these observation points. The transect data is included in the addendum to this report

References:

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Addendum:
Heely-Cordeston complex, 2-15% slopes (Pennington County):

Transect #1	Transect #2		
Obs[1]	**Depth**	**Obs**	**Depth[2]**
0	60	0	50
3	68	6	73
6	92	12	108
9	101	18	65
12	111	24	142
15	68	30	90
18	60	36	113
21	45	42	81
24	116	48	89
27	151	54	89
30	148	60	106
33	82	66	95
36	110	72	112
39	79	78	113
42	115	84	69
45	98	90	116
48	138		
51	40		
54	65		
57	33		
60	65		
63	31		
66	89		
69	93		

Citadel-Larkin complex, 10-40% slopes (Lawrence County)

Transect #1		Transect #2		**Transect #3**	
Obs	**Depth**	**Obs**	**Depth**	**Obs**	**Depth**
0	132	0	97	0	90
3	116	3	78	3	117
6	80	6	130	6	99
9	95	9	196	9	51
12	134	12	161	12	81
15	128	15	137	15	82
18	143	18	88	18	123
21	125	21	117	21	118
24	162	24	93	24	111
27	134	27	114	27	94
30	136	30	111	30	95
33	148				
36	95				
39	97				
42	94				

[1] "Obs" represents observation points; number represents the distance along traverse line in meters.
[2] Depth is in cm.