United States Department of Agriculture

Natural Resources Conservation Service

11 Campus Boulevard
Suite 200
Newtown Square, PA 19073

Subject: SOI – Geophysical Field Assistance

Date: 16 October 2001

To: Philip J. Nelson
State Conservationist
USDA-NRCS
125 South State Street
P.O. Box 11350
Salt Lake City, UT 84147-0350

Purpose:
The purpose of this investigation was initially to use ground-penetrating radar (GPR) to non-destructively determine depths to bedrock and assess soil-vegetation-landscape relationships in soils formed in eolian sands derived from Navajo sandstone within the Grand Staircase-Escalante National Monument (GSENM). These investigations support soil survey operations in Kane County and thesis research being conducted by Erin Bell, USDA-NRCS soil scientists and MS graduate student in soil science at Utah State University. Ensuing research redirected GPR activities to investigating the origins and development of lamellae in Ustic Quartzipsamments that formed in eolian sediments derived from Navajo sandstone. In addition, the feasibility of using GPR and electromagnetic induction (EMI) methods to support soil survey operations was also explored in different soils and areas of GSENM.

Participants:
Erin Bell, Soil Scientist Trainee, USDA-NRCS, North Logan, UT
Janis Boettinger, Assoc. Professor, Utah State Univ., Logan, UT
Bill Broderson, State Soil Scientist, USDA-NRCS, Salt Lake City, UT
Jim Doolittle, Research Soil Scientist, USDA-NRCS, Newtown Square, PA
Hays Dye, MLRA Office Leader, USDA-NRCS, Phoenix, AZ
Suzann Kienast, Soil Scientist, USDA-NRCS, Logan, UT
Sue Mayne, Range Conservationist, USDA-NRCS, Cedar City, UT
Victor Parslow, Soil Scientist, USDA-NRCS, Richfield, UT
Leland Sasser, Soil Scientist, USDA-NRCS, Price, UT
Tom Simper, Area Range Conservationist, USDA-NRCS, Cedar City, UT
Jay Skovlin, Soil Scientist, USDA-NRCS, Cedar City, UT
Kent Sutcliffe, Soil Project Leader, USDA-NRCS, Cedar City, UT

Activities:
All activities were completed during the period of 24 to 28 September 2001 and in accordance with the timetable developed by Kent Sutcliffe.

Results:

1. Ground-penetrating radar has proven to be highly effective in areas of coarse- and moderately coarse-textured soils of GSENM. Multiple radar traverses helped to confirm the ubiquity and expression of lamellae on different slope components within Erin Bell's research site. In addition, to 8 by 8 m grids were intensely surveyed with GPR. Data have been processed and will be used to construct 3D images of the grid sites. Bitmap image have been prepared of all radar traverses in Erin Bell's research site. These files have been mailed to Erin.

2. Areas of coarse-loamy or finer textured soils and/or calcareous soils were unsuited to GPR. In these soils, the depth of observation was acutely restricted and the resolution of subsurface interfaces was poor. In these soils, the use of GPR is inappropriate.

3. Studies demonstrated that EMI is not equally suitable for use on all soils in GSENM. However, results from some studies suggest that EMI can be effectively used to quantify and map soil and bedrock depths. In some areas, EMI measurements can supplement traditional soil mapping procedures. Electromagnetic induction provides comprehensive soil interpretations in areas where it is not practical to observe soils in a timely and cost-effective manner.

4. While the use of GPR and EMI can increase the number of observations and the quality of soil interpretations. However, these methods require experienced soil scientists to make proper interpretations. In addition, auger observations are required to verify interpretations.

5. An Excel spreadsheet with data collected in this study has been forwarded to Kent Sutcliffe and Erin Bell.

It was my pleasure to work in Utah and with members of your find staff.

With kind regards,

James A. Doolittle
Research Soil Scientist

cc:
B. Ahrens, Director, USDA-NRCS, National Soil Survey Center, Federal Building, Room 152,100 Centennial Mall North, Lincoln, NE 68508-3866
J. Boettinger, Associate Professor, Plants, Soils, and Biometeorology, Utah State University, 4820 Old Main Hill, Ag. Sci. Bldg., Room 354, Logan, UT 84322-4820
W. Broderson, State Soil Scientist, USDA-NRCS, PO Box 11350, Salt Lake City, UT 84147-0350
H. Dye, MLRA Team Leader, USDA-NRCS, 3003 N. Central Ave. Suite 800, Phoenix, AZ 85012-2945
C. Olson, National Leader, Soil Investigation Staff, USDA-NRCS, National Soil Survey Center, Federal Building, Room 152,100 Centennial Mall North, Lincoln, NE 68508-3866
H. Smith, Director of Soils Survey Division, USDA-NRCS, Room 4250 South Building, 14th & Independence Ave. SW, Washington, DC 20250
S. Sutcliffe, Soil Project leader, USDA-NRCS, Cedar City Field Service Center, Blackrock Village, 2390 West Highway 56 #14, Cedar City, Utah 84720

Equipment:
The radar unit is the Subsurface Interface Radar (SIR) System-2000, manufactured by Geophysical Survey Systems, Inc.[1] Morey (1974), Doolittle (1987), and Daniels (1996) have discussed the use and operation of GPR. The SIR System-2000 consists of a digital control unit (DC-2) with keypad, VGA video screen, and connector panel. A 12-volt battery powers the system. This unit is backpack portable and requires two people to operate. Both the 200 and 400 MHz antennas were used in this study. However, fieldwork revealed that the 400 MHz antenna provided the best balance of observation depth and resolution of subsurface interfaces. The range gain and filtration settings, and scanning times (40 and 60 nanoseconds) were varied based on desired observation depth and resolution of subsurface features. Hard copies of the radar data were printed in the field on a model T104 printer. All radar files have been saved to CD.

Field Procedures:
Multiple traverse lines of variable lengths were established at each site. Along each traverse line, survey flags were inserted in the ground at distances of about 10 m. Pulling the antenna along a traverse line completed a radar survey file. As the radar antenna was pulled passed each flagged position, the operator impressed a vertical reference line on the radar profile to identify the observation point. The radar profiles were printed and reviewed in the field.

Detail grids were established across two sites to help document the presence, depth, and form of lamellae for Erin Bell's research project. Figure 1 shows the two grids with the location, direction of advance, and radar file numbers.

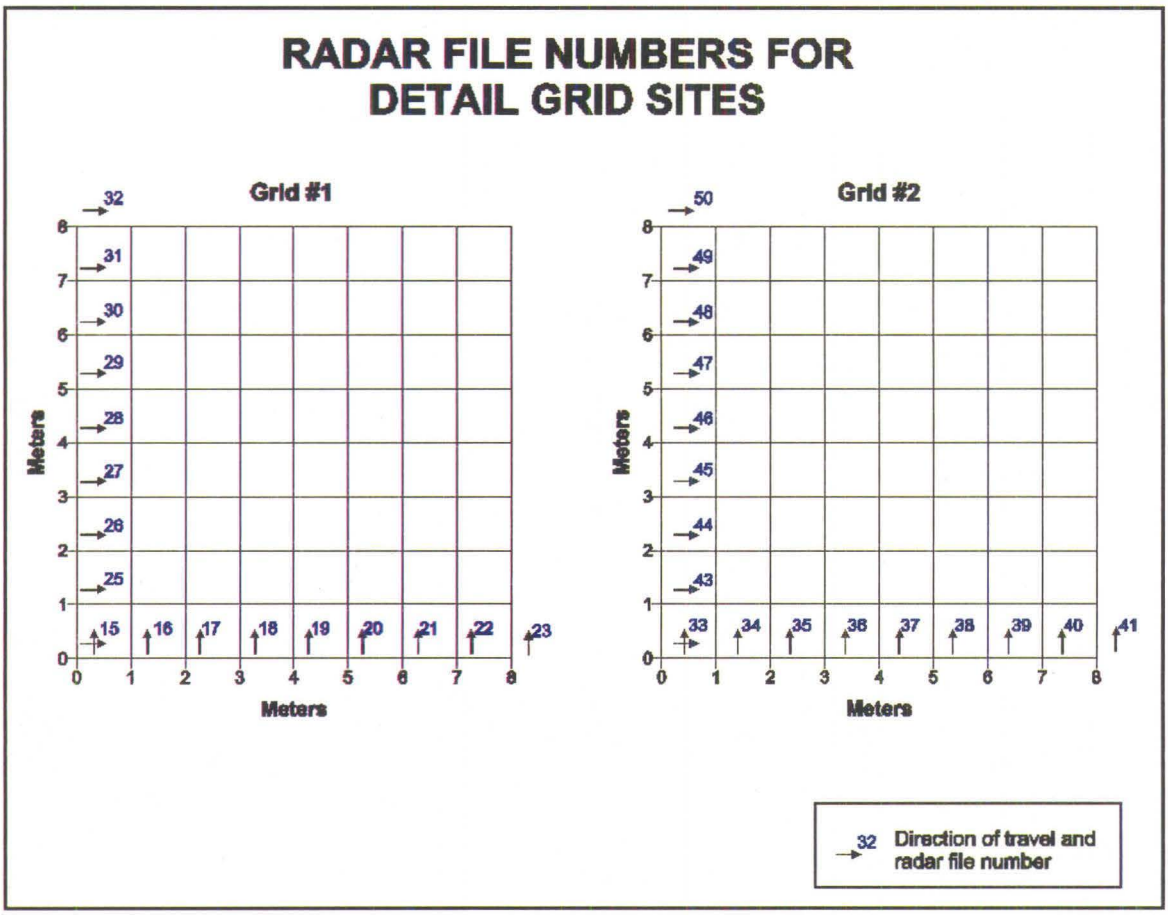

Figure 1. Locations and direction of radar traverse lines for two, 8 x 8 m grid sites. Numbering reflects radar file numbers.

Calibration of GPR:
Ground-penetrating radar is a time scaled system. This system measures the time that it takes electromagnetic energy to travel from the antenna to an interface (e.g., soil horizon, stratigraphic layer) and back. To convert the travel time into a depth scale, either the

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

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 (Morey, 1974):

$$v = 2d/t \qquad [1]$$

The velocity of propagation is principally affected by the dielectric permittivity (e) of the profiled material(s) according to the equation:

$$e = (c/v)^2 \qquad [2]$$

Where c is the velocity of propagation in a vacuum (0.3 m/nanosecond). Velocity is expressed in meters per nanosecond. A nanosecond is one billionth of a second. The amount and physical state of water (temperature dependent) have the greatest effect on the dielectric permittivity of a material.

Based on measured depths and two-way pulse travel times to subsurface interfaces, and equation [1], the velocity of propagation was estimated to be 0.137 m/ns. A scanning time of 60 nanoseconds was used in this investigation. Using equation [1] and a propagation velocity of 0.137 m/ns, the maximum depths of observation are about 2.7 and 4.1 m with scanning times of 40 and 60 nanoseconds, respectively.

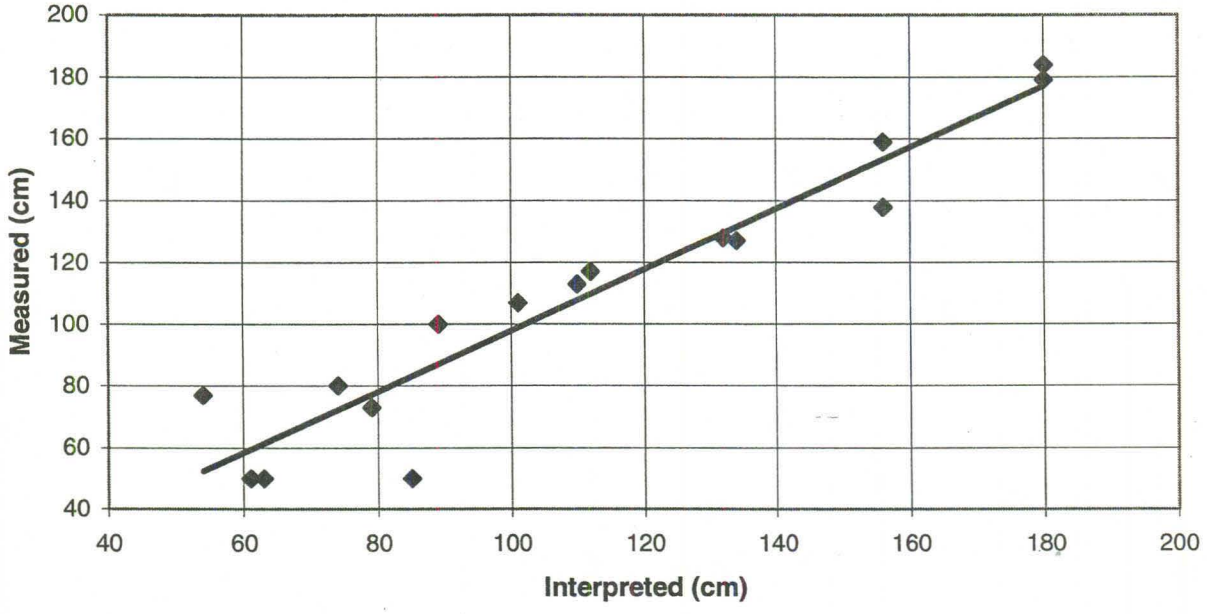

Figure 2. Relationship between interpreted and measured depths to subsurface interfaces. Interpreted depths were determined using equation [1] and a velocity of propagation of 0.137 m/ns. Measured depths were based on soil auger observations.

Figure 2 show the relationship between radar interpreted and measured depths to subsurface interfaces (lamellae or bedrock surfaces). Data were obtained from several observation points located on different soils and in different areas of GSENM. A strong ($r = 0.952$) and significant relationship (probability 0.001) exists between measured and interpreted depths.

Results:

GPR

Radar traverses were conducted in several portions of the GSENM in areas underlain by sandstone, siltstone, and limestone bedrock. Traverses were located principally in areas of Quartzipsamments and Torripsamments. These soils are fairly extensive (250,000 acres) within GSENM.

Figure 3 is a representative radar profile showing the soil/ bedrock interface. In general, the soil/bedrock interface produced an easily identifiable, continuous, high amplitude, subsurface reflector. The horizontal scale in Figure 3 is about 30 m. The maximum depth is about 4.1 m. Several roots are evident in the upper part of this profile. Bedding planes are evident in the Navajo sandstone. Some of these bedding planes cross the soil/bedrock interface. Within the soil, these *bedding planes* are more weathered, less indurated, and are often identified as lamellae.

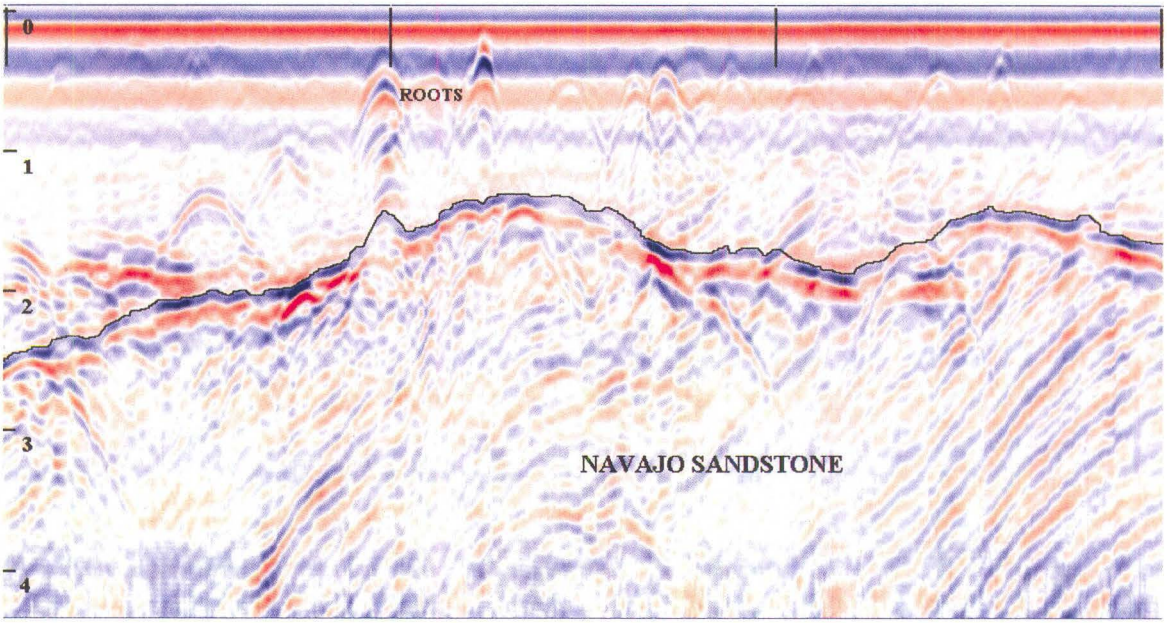

Figure 3. A representative radar profile of an Ustic Quartzipsamment. The soil/bedrock interface has been highlighted with a dark line. All depths are in m.

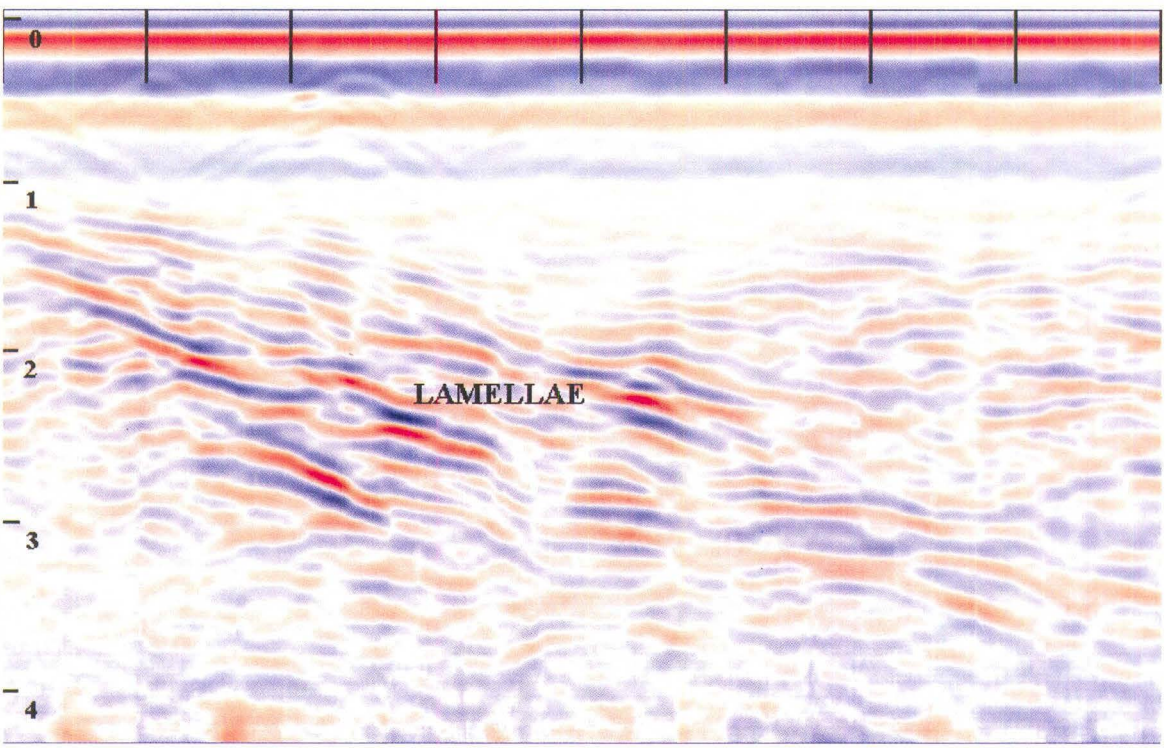

Figure 4. A representative radar profile showing bands of lamellae. All depths are in m.

Figure 4 is a representative radar profile from one of the grids showing lamellae. The horizontal scale in Figure 4 is about 8 m. The distance between each vertical observation mark is 1 m. The maximum depth is about 4.1 m. Numerous inclined lamellae are shown in Figure 4. In contrast to the reflection from the soil/bedrock interface (see Figure 3), reflections from lamellae are more discontinuous and of lower amplitudes. Often, as these incline reflectors approach the soil surface, signal amplitudes decrease. This trend is believed to reflect the effects of increased weathering.

Map unit 5151

Fieldwork was conducted on the Nephi Point quadrangle in areas of map unit 5151. Map unit 5151consists of deep and very deep Ustic Quartzipsamments formed in an Upland Mountain Big Sage ecological site with Pinyon and Junipers. These excessively drained upland soil formed over sandstone. Radar profiles revealed a continuous subsurface reflector that grades laterally from an argillic-like horizon to a Cr horizon composed of sandstone. The finer textured materials may represent mudstone or weathered shale. It is believed that this continuous interface was near the contact of two dissimilar beds within the Kayenta formation. One being mudstone or shale, the other being sandstone.

The interpreted depths to bedrock for each transect conducted with the GPR in map unit 5151 are shown in Table 1. Table 2 is a frequency distribution by soil depth classes of the data presented in Table 1. Based data from the areas traversed with GPR, map unit 5151 is composed predominantly of moderately deep and deep soils.

Table 1
Depth to Subsurface Reflector Identified on GPR profiles
In areas of Map Unit 5151
All depths are in cm

Observ.	File 60	File 61	File 62	File 63	File 64	File 65	File 66	File 67	File 68	File 69	File 70
1	0.77	0.66	1.08	0.80	0.83	0.83	0.98	0.87	1.20	0.79	1.59
2	0.97	0.62	0.86	0.72	0.80	0.91	1.10	0.86	0.94	0.80	1.15
3	0.89	0.86	0.73	0.97	0.78	1.05	0.94	1.13	1.13	0.90	1.09
4	1.01	1.19	0.73	0.89	0.81	0.84	0.84	1.04	1.35	0.87	1.22
5	0.91	1.45	0.74	1.03	0.64	0.79	0.98	1.37	1.42	0.80	1.20
6	0.74	1.01	0.82	0.58	0.58	0.84	0.74	1.47	0.76	0.79	1.30
7	0.58	1.03	0.61	0.81	0.57	0.74	0.84	1.39	0.58	0.89	1.36
8	0.50	0.98	0.70	1.02	0.77	0.77	0.89	1.52	0.59	0.75	1.19
9	0.54	1.11	0.92	1.01	1.02	0.78	0.83	1.26	0.54	0.74	1.12
10	0.57	1.10	1.12	0.79	0.85	0.76	0.91	1.27	0.63	1.50	0.76

Table 2
Depth to Subsurface Reflector Identified on GPR profiles
In areas of Map Unit 5151
Frequency Distribution by Soil Depth Classes

Transect #	Shallow	Mod Deep	Deep	Very Deep
61	10	80	10	0
62	0	40	60	0
63	0	80	20	0
64	0	70	30	0
65	0	90	10	0
66	0	90	10	0
67	0	20	70	10
68	0	60	40	0
69	0	90	0	10
70	0	10	80	10

Map unit 5126

Map unit 5126 consists of coarse-loamy soils formed in alluvium and in an Upland Mountain Big Sage ecological site. The site was located on the Nephi Point quadrangle. The radar was ineffective in these soils. Although these soils had less than about 10 percent clay, the clay content was sufficient and mineralogy adverse enough to severely limit the depth of penetration. Use of GPR in this and similar soils is not recommended because of severe attenuation and limited depth of penetration.

Coarse-loamy, Aridic Haplustalfs

The GPR was used to investigated an area of coarse-loamy Aridic Haplustalfs soil that formed over limestone bedrock. The site was located on the Pine Point quadrangle. The radar was ineffective in this soil. Depth of penetration was restricted because of

carbonate and clay contents. Some pedons were observed to have a sandy clay loam argillic horizons. The underlying bedrock interface was poorly expressed and ambiguous on most radar profiles.

Upland Sands Mountain Big Sage Bush Site

Radar traverses were also conducted on the Pine Point quadrangle in an area of Ustic Quartzipsamments that formed on dunes. These soils dominated an Upland Sand Mountain Big Sagebrush ecological site. Lower side and foot slopes were underlain by deep and very deep soils formed over limestone bedrock. Upper side slopes, summits, and deflation areas were underlain by greater than 2.75 m of sands that lack observable patterns or accumulations of lamellae.

Table 3
Depth to Subsurface Reflector Identified on GPR profiles
Upland Sand Mountain Big Sagebrush Ecological Site
All depths are in cm

Observation	File 74	File 75	File 76	File 77	File 78	File 79	File 81
1	1.58	>2.75	>2.75	>2.75	>2.75	>2.75	>2.75
2	2.12	>2.75	>2.75	>2.75	>2.75	>2.75	>2.75
3	2.72	>2.75	>2.75	>2.75	>2.75	2.55	>2.75
4	>2.75	>2.75	>2.75	>2.75	>2.75	2.53	>2.75
5	>2.75	>2.75	>2.75	>2.75	>2.75	2.32	>2.75
6	>2.75	>2.75	>2.75	>2.75	>2.75	2.15	>2.75
7	>2.75	>2.75	>2.75	>2.75	>2.75	>2.75	>2.75
8	>2.75	>2.75	>2.75	>2.75	>2.75	>2.75	>2.75
9	>2.75	>2.75	>2.75	>2.75	>2.75	2.40	2.72
10	>2.75	>2.75	>2.75	>2.75	>2.75	>2.75	1.80

Gypsic soil

GPR traverses were conducted across an area of gypsic soils. These soils were highly attenuating to GPR. In areas with less than 10 cm of soil, the bedrock was transparent to depths as great as 2.75 m. However, in areas where the depth to gypsum bedrock was greater than 10 to 15 cm, the soil was extremely attenuating and the bedrock was not discernible.

Map Unit 5155, Sanostee-Travessilla, dry complex, 2 to 8 percent slopes

Fieldwork was conducted on Smoky Mountain in areas of map unit 5155, Sanostee-Travessilla, dry complex, 2 to 8 percent slopes. These soils are on hills, structural benches, cuestas, and mesas. The well drained Sanostee soil formed in eolian material, alluvium and residuum derived from sandstone and siltstone. It is moderately deep to sandstone. Sanostee soil is a member of the fine-loamy, mixed, superactive, mesic Ustic Calciargids family. The shallow, well drained Travessilla soil formed in calcareous eolian sediments and material weathered from sandstone. Travessilla soil is a member of the loamy, mixed, superactive, calcareous, mesic Lithic Ustic Torriorthents family. Ecological sites have not been assigned. The radar was ineffective in this soil as the depth of penetration was severely restricted in these soils. The limited penetration depths. Were attributed to the contents of carbonates and clays in these soils.

EMI

In some areas, EMI can provide a relatively inexpensive, fast, and comprehensive means for mapping the depths to bedrock. This technique has been used to determine depths to bedrock (Bork et al., 1998; Doolittle et al., 1998; Palacky and Stephens, 1990; Zalasiewicz et al., 1985) and to locate water-bearing fault or fracture zones in bedrock (Beeson and Jones, 1988; Edet, 1990; Hazell et al., 1988; McNeill, 1991; Olayinka, 1990). These studies document the ease in which EMI can be carried out, the large quantities of data for site characterization and assessments that can be produced, and the application of this method over broad areas and soils.

Coarse-loamy, Aridic Haplustalfs

Electromagnetic induction was used determine the depth to bedrock in an area of coarse-loamy Aridic Haplustalfs soil that formed over limestone. The site was located on the Pine Point quadrangle. No correlation was found between EMI response and the depth to bedrock. This study demonstrated that EMI is not equally suitable for use on all soils. Generally, the use of EMI has been most successful in areas where subsurface properties are reasonably homogeneous and one property (e.g. salt, clay, or water content) exerts an overriding influence over soil electrical conductivity. In these areas, variations in apparent conductivity can be directly related to changes in the dominant property (Cook et al., 1989). In this study, the lack of correlation between apparent conductivity and the depth to bedrock was attributed to the high variability of the three parameters (moisture, clay, and soluble salt contents) that influenced EMI responses.

Map Unit 5155, Sanostee-Travessilla, dry complex, 2 to 8 percent slopes

Random traverses were conducted with the EM38 meter in areas of Sanostee-Travessilla, dry complex, 2 to 8 percent slopes. These traverses were located on Smoky Mountain. While ecological sites have not been assigned, appreciable quantities of spiny hopsage and blackbrush occur in areas of Sanostee and Travessilla soils, respectively.

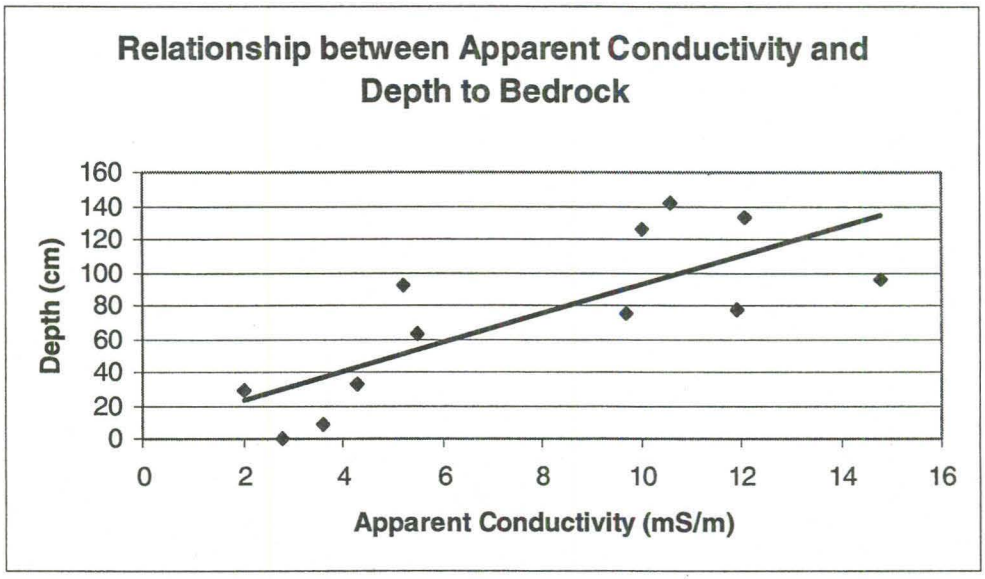

Figure 5. Relationship between apparent conductivity and measured depths to bedrock in an area of Sanostee-Travessilla, dry complex, 2 to 8 percent slopes

At the twelve sampling points, depths to bedrock were determined with an auger. Observed depths to bedrock averaged 40.3 inches and ranged from about 0 to 142 cm. A comparison of auger and EMI data collected at twelve sampling points is shown in Figure 5. A positive correlation ($r = 0.78$; 0.002 level) was obtained between depth to bedrock and the response of the EM38 meter obtained in the vertical dipole orientation. This relationship conforms to the basic conceptual model of the site: the medium-textured soil has higher clay, moisture, and soluble salt contents and is therefore more conductive than the underlying sandstone bedrock. Areas having greater depths to sandstone generally have higher EMI responses.

Data collected with the EM38 meter in the vertical dipole orientation at the twelve sampling points were used to develop the following predictive equation:

$$D = 5.529 + (8.731 * \text{EM38-V}) \qquad [3]$$

Where "D" is depth to sandstone bedrock, and "EM38-V" is the apparent conductivity measured with the EM38 meter in the vertical dipole orientation. Unfortunately, the intercept and slope used in Equation [3] are relatively large. These large coefficients will undoubtedly magnify small measurement errors.

Based on EMI measurements and predictive Equation [3], the depths to bedrock at each observation point along the transects were determine. The results are shown in Table 4. The preponderance of shallow and moderately deep soils is in accord with the soil and map unit delineated within the study site. The use of EMI is appropriate for determining the depth to bedrock in areas of Sanostee and Travessilla soils.

Table 5
Depth to Bedrock in Areas of Santostee-Travessilla Complex, 2 to 15 % Slopes
All depths are in cm

Observation	Transect 1	Transect 2	Transect 3
1	133.0	23.0	84.1
2	134.7	29.1	85.0
3	109.4	37.8	83.2
4	53.5	39.6	83.2
5	47.4	50.9	94.6
6	43.1	90.2	111.2
7	43.1	92.8	36.1
8	37.0	91.1	30.8
9	30.0	91.1	35.2
10	31.7	98.1	40.5
11		88.5	43.9
12		87.6	42.2
13		85.0	52.7
14		95.5	67.5
15		94.6	71.0
16			14.3
17			55.3
18			26.5
19			21.2
20			23.9
21			25.6
22			23.9
23			24.7
24			23.9
25			25.6

Table 5
Depth to Bedrock in Areas of Santostee-Travessilla Complex, 2 to 15 % Slopes
Frequency Distribution by Soil Depth Classes

Transect	Obs.	Shallow	Mod Deep	Deep	Very Deep
1	10	60	10	30	0
2	15	27	73	0	0
3	25	60	34	4	0

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