United States Department of Agriculture

Natural Resources Conservation Service

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Subject: SOI -- Geophysical Assistance **Date:** 4 September 2008

To: Joyce A. Swartzendruber
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Purpose:
Ground-penetrating radar (GPR) was used to determine depths to bedrock and document the composition (by soil depth class) of soil map units in Piscataquis and Aroostook Counties.

Participants:
Matt Dorman, Soil Scientist, USDA-NRCS, Presque Isle, ME
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Jeff Talskey, Soil Scientists, USDA-NRCS. Juneau, WI

Activities:
All field activities were completed during the period of 18 to 20 August 2008.

Summary:

1. Radar traverses were conducted across areas of several map units in Piscataquis and Aroostook Counties. Data from these traverses may be used by soil scientists to determine map unit composition (based on soil depth criteria) and names. In addition, the data contained in this report may help to confirm mapping concepts used by soil scientists.

2. Comparative studies were conducted with two antennas (center frequencies of 200 and 400 MHz) over different lithologies (slate and granite). In general, the soil/bedrock interface was more clearly expressed in soils underlain by granite. Soils formed over slat tend to have greater clay contents and are therefore more attenuating and depth restrictive to GPR than soils formed over granite. The slate is radar opaque and the soil/bedrock interface is more weakly expressed and ambiguous on radar records. Granite is more transparent to GPR.

3. I believe that the soil staff in Maine can benefit from a radar unit of its own to support soil survey operations. The soil staff in Maine was favorable to my suggestion. I shall seek advice and recommendations from the National Soil Survey Staff in the pursuit of my conviction.

As always, I deeply enjoy coming to Maine and working with your soil scientists.

With kind regards,

James A. Doolittle
Research Soil Scientist
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cc:

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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) discusses the use and operation of GPR. Antennas with center frequencies of 200 and 400 MHz were used in this study.

GPR data were processed using the RADAN for Windows (version 6.5) software package (GSSI; Salem, NH).[1] To insure consistent interpretations, all radar records were similarly processed. Processing included: header editing, setting the initial pulse to time zero, color table and transformation selection, range gain adjustments, signal stacking, migration, and high-pass filtration (see Daniels (2004) for more comprehensive discussions of these techniques). Signal stacking was used to remove high-frequency noise, which appears as "*snow*" on radar records (see Figure 1 B). Migration was used to reduce diffraction tails from hyperbolic reflectors (e.g., larger rock fragments and tree roots) and to more correctly position planar reflectors (see Figure 1 C). High-pass horizontal filters were used to remove parallel bands of reverberated signals and clutter (see Figure 1 D). These processing steps were applied to each radar record to improve interpretations.

Figure 1 illustrates the effects of these processing procedures on a radar record taken in an area of map unit 74B, Telos- Monarda-Elliottsville association, 0 to 8 % slopes. The radar record shown in Figure 1 was collected along a logging trail. In Figure 1 A, the surface reflection has been shifted and adjusted to time-zero for more accurate depth assessments. In Figure 1 B, signal stacking has been used to reduce high-frequency noise, which appears as "*snow*" on the radar record (shown in Figure 1 A). A horizontal low pass filter could also have been used to reduce "*snow*" noise and smooth the data. In Figure 1 C, migration has been used to focus scattered energy, reduce diffraction tails from hyperbolic reflectors, and improve the apparent geometry of steeply dipping interfaces. A high-pass filter has been used in Figure 1 D to remove parallel bands of ringing or reverberation noise. Note in Figure 1 D, how the thicknesses of road fill and the depths to the original soil surface (a) are apparent after the application of high-pass filtration, which removed the strong reverberations of the surface pulse.

A dash, red-colored line has been used in Figure 1 D to approximate the interpreted soil/bedrock interface. The clarity of the soil/bedrock interface is spatially variable. Near "b", this interface is represented by high amplitude reflectors. The shallowest, high-amplitude, planar reflectors were interpreted to represent the approximate location of the soil/bedrock interface. The underlying slate bedrock has several chaotic diffraction patterns which suggest fracturing. Near "c", the soil/bedrock interface provides a weaker, less clearly defined and more ambiguous interface. Here the interface is more difficult to trace laterally. The contrast in appearance of the soil/bedrock interface at "b" and "c" implies spatial differences in the composition of the overlying soil materials, the topography of this interface, and the composition and structure of the underlying bedrock. This example demonstrates the potential variability of soil/bedrock interpretations in Maine. In many areas the soil/bedrock interface can be picked with reasonable accuracy and confidence. In some areas, interpretations are more ambiguous and uncertain. However, with the limitations imposed by traditional soil sampling tools, greater quantities of soil data can be more easily collected with GPR, which, in my opinion, provides greater confidence in soil/bedrock interpretations.

Using the *Interactive Interpretation* module of the RADAN processing software, depths to the soil/bedrock interface were quickly, automatically, and reasonably accurately picked and outputted to a worksheet (X, Y, Z format; containing positions along traverse line, depths to bedrock, and other useful data).

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

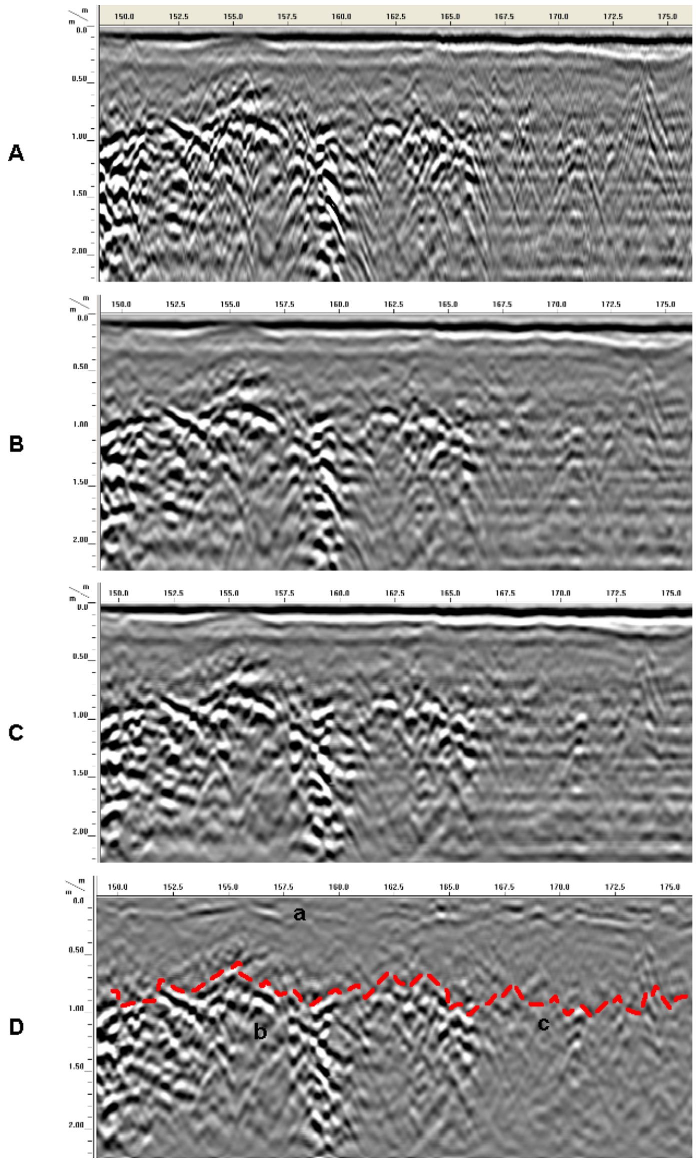

Figure 1. Processing steps used to improve interpretations of the depth to the soil/bedrock interface included time-zero adjustments (A); signal stacking (B); migration (C); and high-pass horizontal filtration (D).

Field Procedures:
It is very difficult to operate the GPR and collect radar records in the *Big Woods* of Maine, because of numerous stumps, felled debris, and dense vegetative growth. These features impair the movement of GPR antennas and produce unwanted reflections, which clutter radar records, mask reflections from the soil/bedrock interface, and impair interpretations. As a consequence of this inhospitable environment, GPR traverses are generally restricted to logging trails that have minimum cut and fill.

Each radar traverse was completed by pulling either the 200 or 400 MHz antenna by hand. Because of its smaller physical size and portability, the 400 MHz antenna is usually preferred for soil/bedrock investigations in the *Big Wood*. In addition, the 400 MHz antenna provided slightly superior resolution and clarity of the soil/bedrock interface. Radar data were collected at rates of either 40 or 48 scans/sec. Using the new *Interactive Interpretation* module of the RADAN, interpretations of the depth to the soil/bedrock interface were essentially made for each scan. This process produced very large data sets. Each radar traverse was stored as a separate file.

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., 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 (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 the equation (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 of water (temperature dependent) have the greatest effect on the E_r and *v*.

At most sites, hyperbola matching techniques were used to confirm the relative dielectric permittivity and the velocity of propagation. At some sites, these parameters were determined by comparing the interpreted depth to a known, buried metallic reflector (whose image was identified on a radar record) with the two-way travel time to this reflector on radar records. Based on the measured depth and the two-way travel time to the reflector, and equation [1], the velocity of propagation was estimated.

The relative dielectric permittivity and velocity of propagation varied with antenna frequency and with soils and landscape positions. In the investigated areas, relative dielectric permittivity ranged from 8.54 to 16.33. Noticeably high soil moisture contents accounted for the comparatively high E_r and low *v* that were estimated in this study.

Soils:
Table 1 provides the taxonomic classifications of soil series named in the mapping units that were traversed with GPR in Piscataquis and Aroostook Counties.

Table 1
Taxonomic classifications of soils traversed with GPR in Piscataquis and Aroostook Counties, Maine

Soil Series	Taxonomic Classification
Aurelie	Loamy, mixed, active, nonacid, frigid, shallow Aeric Endoaquepts
Brayton	Loamy, mixed, active, nonacid, frigid, shallow Aeric Endoaquepts
Burnham	Loamy, mixed, superactive, nonacid, frigid, shallow Histic Humaquepts
Colonel	Loamy, isotic, frigid, shallow Aquic Haplorthods
Dixfield	Coarse-loamy, isotic, frigid Aquic Haplorthods
Daigle	Loamy, isotic, frigid, shallow Aquic Haplorthods
Elliottsville	Coarse-loamy, isotic, frigid Typic Haplorthods
Lyman	Loamy, isotic, frigid Lithic Haplorthods
Monarda	Loamy, mixed, active, acid, frigid, shallow Aeric Endoaquepts
Rag Muffin	Coarse-loamy, isotic, frigid Aquic Haplorthods[2]
Telos	Loamy, isotic, frigid, shallow Aquic Haplorthods
Tunbridge	Coarse-loamy, isotic, frigid Typic Haplorthods

[2] Proposed soil series.

Results:
Study Areas in Piscataquis County:
Multiple transects were conducted in areas of the map units 78B, Telos-Monarda association, 1 to 8 % slopes, very stony; and 74B, Telos-Monarda-Rag Muffin association, 0 to 8 % slopes, very stony. These soils formed in dense tills and overlie slate. The very deep, somewhat poorly drained Telos and poorly drained Monarda soils are shallow to dense till. The Rag Muffin is a proposed soil series. The moderately well to somewhat poorly drained Rag Muffin soils is moderately deep to bedrock.

Table 2 summarizes the radar interpretations of the depth to bedrock for traverses conducted in areas that are underlain by slate. Radar traverses were collected on logging roads with minimum cut and fill. Traverses 8 thru 11 were conducted in an area of map unit 78B, Telos-Monarda association, 1 to 8 % slopes, very stony. These radar traverses were begun near $46^{o}00.037$ N. latitude and 69^{o} 30.330 W. longitude. Radar traverses 12 thru 16 were conducted in an area of map unit 74B, Telos-Monarda-Rag Muffin association, 0 to 8 % slopes, very stony. These radar traverses were begun near $46^{o}01.615$ N. latitude and 69^{o} 33.553 W. longitude. Soils in the traversed areas are dominantly deep (63%) and very deep (29%) to bedrock. No areas of shallow soils were observed along these radar traverses. The actual number of observations on which these statistics are based, is most remarkable (see Table 2, column 2). These numbers are extraordinarily large and hitherto unattainable by soil scientists using any method of investigation.

Table 2.
Frequency distributions (%) by soil depth classes of soils in areas of slate bedrock, Piscataquis County, Maine.

Transect	Observations	Shallow	Mod-Deep	Deep	Very Deep
8	4941	0	0	81	18
9	6697	0	0	47	53
10	4088	0	35	60	5
11	3372	0	8	66	26
12	3472	0	0	99	1
13	5375	0	21	69	10
14	5396	0	5	91	4
15	7752	0	1	46	53
16	6600	0	0	8	92

Table 3 summarizes the radar interpretations of the depth to bedrock for traverses conducted in areas that are underlain by granite. Once again, radar traverses were collected on logging roads with minimum cut and fill. Traverse lines 18 and 22 were conducted in an area of map unit 54C, Colonel-Dixfield-Brayton Association, 3 to 15 % slopes, very stony. Traverse line 20 was conducted in an area of map unit 54B, Colonel-Dixfield-Brayton Association, 0 to 8 % slopes, very stony. Traverse lines 19 and 21 were conducted in an area of map unit 94XC, Lyman-Tunridge complex, 3 to 15 % slopes, very stony. The very deep, poorly drained Brayton, somewhat poorly drained Colonel, and moderately well drained Dixfield soils formed in dense till on drumlins and till ridges. The shallow, somewhat excessively drained Lyman and moderately deep, well drained Tunbridge soils lack densic materials and formed on glaciated uplands. All of these radar traverses were begun along a logging trail near $46^{o}51.0005$ N. latitude and 68^{o} 44.120 W. longitude. Soils in the traversed areas are dominantly very deep (46%) deep (23%) to bedrock. Areas of shallow and moderately deep soils were observed on 12% and 19 % of the area along these traverse lines, respectively. However, shallow soils were only observed in areas of map unit 94XC, Lyman-Tunridge complex, 3 to 15 % slopes, very stony.

Table 3.
Frequency distributions (%) by soil depth classes of soils in areas of granite bedrock, Piscataquis County, Maine.

Transect	Observations	Shallow	Mod-Deep	Deep	Very Deep
18	5055	0	0	14	86
19	8761	22	55	23	0
20	7698	0	6	29	65
21	8706	39	22	33	6
22	9051	0	10	16	74

Aroostook County:
In Aroostook County, radar traverses were conducted in areas of Aurelie, Burnham, Daigle, and Elliottsville soils. These soils formed in dense tills and overlie slate. The very deep, poorly drained Aurelie and Burnham soils are moderately deep to dense till. Burnham has a Histic epipedon. The very deep, somewhat poorly drained Daigle soils are shallow to dense till. The moderately deep, well drained Elliottsville soils are not described as having densic layers.

Radar traverses were collected on logging roads with minimum cut and fill. Traverses 27 thru 30 were conducted in areas mapped as map unit Telos-Monarda-Elliottsville Association, 0-8% slopes, very stony. Radar traverses 27 and 28 were begun in an open area near 46^{o}51.005 N. latitude and 68^{o} 49.120 W. longitude. Radar traverses 29 and 30 were begun along a trail near 46^{o}43.647 N. latitude and 68^{o} 53.33 W. longitude. Traverses 31 and 32 were begun along a trail near 46^{o}40.005 N. latitude and 68^{o} 35.121 W. longitude. Traverse 31 was conducted in areas mapped as map unit 374B, Daigle-Aurelie-Elliottsville Association 0 to 8% slopes. Traverse 32 was conducted in an area of map unit 379A, Aurelie-Burnham variant Association, 0 to 3% slopes, respectively.

Table 4 summarizes the radar interpretations of the depth to bedrock for traverses conducted in the areas that are underlain by slate. Along these traverse lines, depths to bedrock were rather evenly distributed according to soil-depth classes, with 17 % shallow, 21 % moderately deep, 40 % deep, and 22 very deep.

Table 4.
Frequency distributions (%) by soil depth classes of soils in areas of slate bedrock, Aroostook County, Maine.

Transect	Observations	Shallow	Mod-Deep	Deep	V. Deep
27	4623	17	39	34	10
28	7267	1	6	54	38
29	5392	2	7	25	65
30	7839	56	41	3	0
31	10755	25	33	34	9
32	5859	0	0	90	10

GPR: Slate versus Granite:
Differences in lithology affect radar interpretations. Figure 2 contains two radar records; one collected over slate (upper record), the other over granite (lower record). On each record, a dashed, white-colored line has been used to identify the interpreted soil/bedrock surface. All scales are expressed in meters.

The slate is characterized by thin beds that are steeply inclined. Because of the large amount of shale fragments in the overlying soil materials, the dielectric contrast between the soil and the underlying slate is weakened, resulting in low to moderate amplitude reflections from the soil/bedrock interface (see Figure 2, upper record). In addition, the irregular bedrock surface scatters much of the propagated energy away from the antenna further reducing signal amplitudes. The slate is essentially radar opaque, with little to no internal reflections. Weakly expressed, vertical patterns of reverberated reflections identify larger fractures within the slate. Individual slate beds are too thin to be resolved with the 400 MHz antenna.

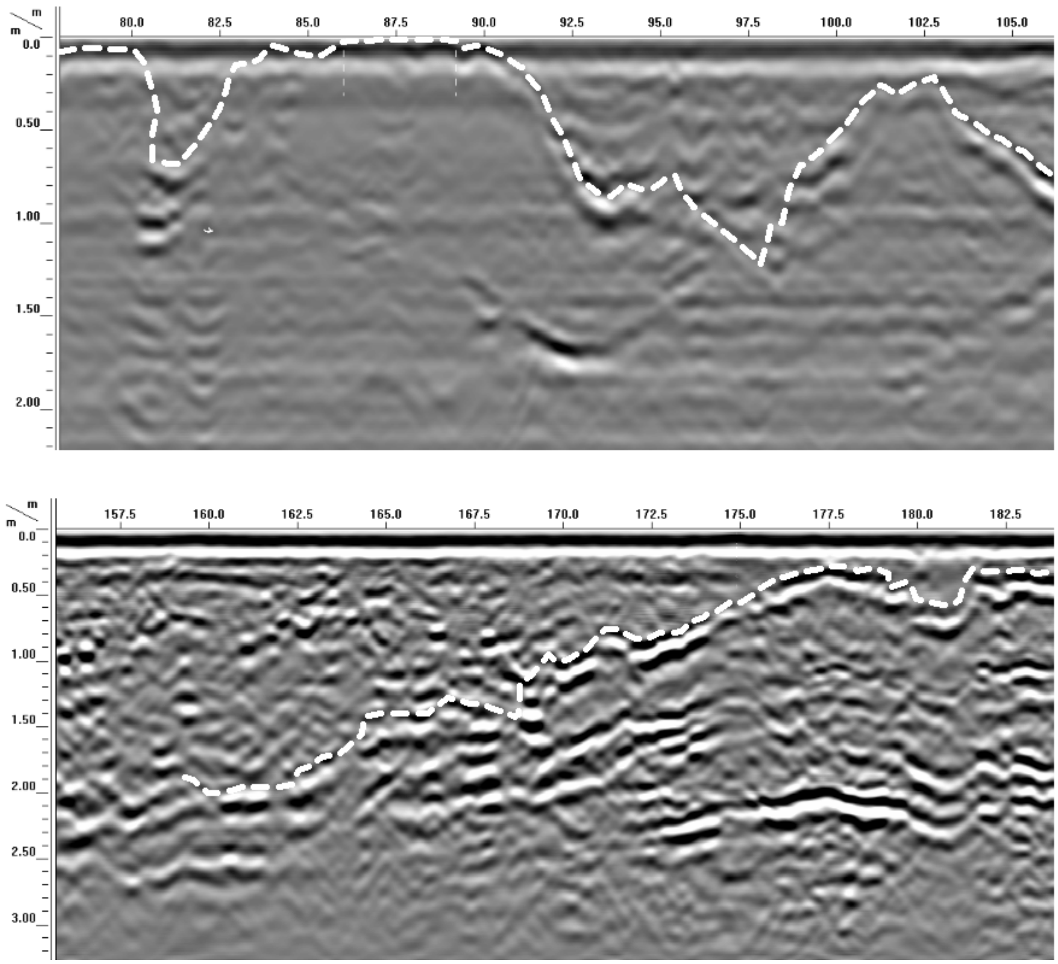

Figure 2. These radar records were collected over slate (upper) and granite (lower) parent rock.

Differences in the geometry, separation, and contents of fractures and bedding planes affect detection with GPR. Because of scattering losses, attenuation, wave length-scale heterogeneities, and geometric constraints, the number of fractures interpreted from radar data is generally considered an order of magnitude less than the number observed in outcrops (Lane et al., 2000). Closely spaced bedding and fracture planes are poorly defined as they often produce multiple, superimposed reverberations on radar records. Fractures and bedding planes with large dip-angles and/or irregular or rough interface surfaces can result in substantial scattering of the reflected wave front away from an antenna. Vertical interfaces reflect very little energy towards the antenna and are therefore difficult to detect with GPR. In addition, fractures and bedding planes with dip-angles greater than about 45 degrees are affected by spatial aliasing distortion and are not accurately imaged with GPR (Buursink and Lane 1999; Ulriksen, 1982).

The granitic bedrock is transparent and well suited to GPR. Both the 200 and 400 MHz antennas capture the horizontal to inclined fracture planes of the bedrock caused by exfoliation or glacial rebound. Hyperbolas and multiple scattering reflections suggest the probable locations of some, more vertically-inclined joints and fractures.

In bedrock, variations in electrical properties are associated with changes in water content (Davis and Annan, 1989). Abrupt changes in water content produce radar reflections. In crystalline bedrock, saturated fractures have higher amplitude reflections than air-filled or unsaturated fractures (Lane et al., 2000). However, not all fractures are detectable with GPR. GPR is generally insensitive to fractures with smaller widths (less than ½ to ¼ of the propagated wave length).

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