United States Department of Agriculture

NRCS

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Subject: Soils – Geophysical **Date:** 28 October 2013

To: Juan Hernandez
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Purpose:
Soil investigations using ground-penetrating radar (GPR) were completed at several sites in Aroostook and Penobscot counties. The purpose of these investigations was to verifying the depth to rock. The data collected in Aroostook County will be used to assess the suitability of three sites for the potential construction or expansion of irrigation water reservoirs. The radar data collected in Penobscot County was from three soil pedon sites (Kenduskeag, Adams variant, and Ragmuff). This data will be used by the Dover MLRA Soil Staff to confirm the depth to rock for the soil profiles, document map unit composition (based on soil-depth classes), and improve interpretative data.

Principal Participants:
Nicholas Butler, Soil Scientist, USDA-NRCS, Dover-Foxcroft, ME
Jim Doolittle, Research Soil Scientist, USDA-NRCS-NSSC, Newtown Square, PA
Mathew Dorman, Soil Scientist, USDA-NRCS, Dover-Foxcroft, ME
Robert Evon, Soil Survey Office Leader, USDA-NRCS, Dover-Foxcroft, ME
Greg Granger, Resource Soil Scientist, USDA-NRCS, Augusta, ME
Ken Hill, Soil Conservation Technician, USDA-NRCS, Presque Isle, ME
David Turcotte, Soil Scientist, USDA-NRCS, Dover-Foxcroft, ME

Activities:
All activities were completed on 24 and 26 September 2013.

Summary:

1. In Aroostook County, a shallow (0 to 50 cm) to moderately deep (50 to 100 cm), broken, weakly expressed interface; and a deeper, broken, interface consisting of higher-amplitude reflections were evident. The shallower and deeper interfaces were interpreted to represent a contact with firmer (densic) till and solid rock, respectively.

2. At the three reservoir sites in Aroostook County, the average interpreted depth to solid rock is 177 cm with a range of 28 to 291 cm. One half of the 40656 radar measurements had solid rock occurring between depths of 149 to 206 cm.

3. At the modal Kenduskeag soil pedon in southern Penobscot County, the depth to rock, based on GPR interpretations, is 175 cm and the soil is very deep as described. Traverses conducted in the surrounding area of the proposed very deep Kenduskeag and deep Wassookeag soils revealed that the bulk of the radar rock interpretations are within the moderately deep and deep soil-depth classes.

4. On a radar record collected near a sampled Adams variant soil pit, the depth to solid rock was interpreted to be 134 cm. Within the nearby soil pit, the depth of excavation was restricted by rock at a depth of 140 cm. The Adams variant soil is deep (100 to 150 cm) to solid rock. Based on radar interpretations, the soils along this traverse line and in the immediate vicinity of the Adams variant soil pit are deep to parent rock.

5. Based on GPR interpretations, the depth to rock near the Ragmuff soil pit was interpreted to range from 81 to 93 cm. Along a nearby GPR traverse line, soils are moderately deep to parent rock.

6. An Excel spreadsheet containing all radar traverse data has been forwarded to Bob Evon and Greg Granger.

It was the pleasure of Jim Doolittle and the National Soil Survey Center to be of assistance to you and your fine staff.

JONATHAN W. HEMPEL
Director
National Soil Survey Center

cc:
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GPR investigations in Aroostook and Penobscot Counties, Maine.
24 and 26 September 2013

Jim Doolittle

Purpose:
Ground-penetrating radar (GPR) investigations were completed at several sites in Aroostook and Penobscot counties. The purpose of these investigations was to verifying the depth to solid rock. Maine NRCS provides technical and financial assistance for the installation of high-efficiency center pivot irrigation sprinklers to replace older, less efficient, traveling gun irrigation systems. In Aroostook County, potato farmers are using supplemental irrigation to increase yields and improve the quality of their crops. In order to protect natural aquatic life, the State of Maine has enacted laws that regulate the withdrawal of water and establish minimum stream flows and lake water levels. As a consequence, Maine NRCS also provides assistance to farmers for the development of an alternative water source: a surface-water irrigation reservoir. Depth to solid rock is a major factor in excavation costs, available volume, and potential drainage and integrity of a surface-water irrigation reservoir. In this study, soil scientists used GPR to map and verify the depth to solid rock and assess the suitability of three proposed EQIP irrigation storage reservoirs sites: one, the expansion of a preexisting reservoir; and the other two, for new reservoirs.

Figure 1. A radar survey is conducted near an existing reservoir at the Flewelling Farm in Aroostook County, Maine.

In Penobscot County, GPR was used to verify the depth to solid rock at three soil pedon sites (Kenduskeag, Adams variant, and Ragmuff) and across the associated soil delineations. At each of these locations, the excavation of a soil pit was restricted by rock. MLRA soil scientists wanted to verify that these excavations were restricted by solid rock and not a larger “floater” rock. Multiple GPR transects

were also carried-out to document the composition (by soil-depth criteria) of the encompassing soil map units.

Equipment:
The radar unit is the TerraSIRch Subsurface Interface Radar (SIR) System-3000 (here after referred to as the 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 4.1 kg (9 lbs) and is backpack portable. With an antenna, the SIR-3000 requires two people to operate (Figure 1). Jol (2009) and Daniels (2004) discuss the use and operation of GPR. The scanning rate of the GPR was set to 40 scan/sec. A 270 MHz antenna was used in the investigations. This was the first time that this frequency antenna was used by USDA-NRCS.

The RADAN for Windows (version 7.0) software program (developed by GSSI) was used to process the radar records.[1] Processing included: header editing, setting the initial pulse to time zero, color table and transformation selection, signal stacking, horizontal high pass filtration, migration, and range gain adjustments (refer to Jol (2009) and Daniels (2004) for discussions of these techniques). The *Interactive 3D Module* of RADAN was used to semi-automatically "*pick*" the depths to the interpreted solid rock interface on radar records. The picked measurements were exported to a worksheet (in an X, Y, and Z format; including longitude, latitude, and depth to solid rock).

The SIR-3000 has a setup for the use of a GPS receiver with a serial data recorder (SDR). With this setup, each scan of the radar can be georeferenced (position/time matched). Following data collection, a subprogram within RADAN for Windows can be used to proportionally adjust the position of each radar scan according to the time stamp of the two nearest positions recorded with the GPS receiver. Where signals from an acceptable number of satellites are available, radar data can be georeferenced. A Pathfinder ProXT GPS receiver with Hurricane antenna (Trimble, Sunnyvale, CA) was used to georeferenced GPR data.[1] Position data were recorded at a rate of one reading per second.

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, rock surface) 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 light in a vacuum (0.3 m/ns). Typically, velocity is expressed in meters per nanosecond (ns). In soils, the amount and physical state (temperature dependent) of water have the greatest affect on the E_r and v. The relative dielectric permittivity ranges from 1 for air, to 78 to 88 for water (Cassidy, 2009). Small increments in soil moisture can result in substantial increases in the relative dielectric permittivity of soils (Daniels, 2004). Using a 100 MHz antenna, Daniels (2004) observed that

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

the relative dielectric permittivity of most dry mineral soil materials is between 2 and 10, while for most wet mineral soil materials, it is between 10 and 30. At the time of this investigation, soils were moist.

At Site 1 in Aroostook County, a metal plate was buried at a depth of 60 cm. The depth to this plate was used to scale the radar imagery. Based on the known depth and the two-way pulse travel time to this plate, the *v* and the E_r through the upper part of the soil profile were estimated using equations [1] and [2]. With the 270 MHz antenna, the estimated E_r was 12.8. The estimated *v* was 0.0840 m/ns.

At the Adams variant soil site in southern Penobscot County, a metal plate was buried at a depth of 40 cm and used to scale the radar imagery. Based on the known depth and the two-way pulse travel time to this plate, using equations [1] and [2], the *v* and the E_r through the upper part of the soil profile were estimated to be 0.0902 m/ns and 11.06, respectively.

At the Ragmuff site in southern Penobscot County, based on the known depth to rock and the two-way pulse travel time to this interface, using equations [1] and [2], the *v* and the E_r through the upper part of the soil profile were estimated to be 0.0694 m/ns and 18.68, respectively.

Variations in *v* and E_r among these sites are attributed to differences in soil moisture. It must be emphasized that within any site, *v* and E_r will vary spatially across the soil-landscape and with depth. This variability will affect the accuracy of soil-depth interpretations.

Study Sites:

Aroostook County:

Site 1 (near 46.6338 N, 67.8721 W) is located about 3.0 km east-southeast of Easton, Maine, and to the immediate east of a constructed reservoir on the Brett Flewelling Farm. The reservoir provides water for 70 acres of cropland. The reservoir is bounded on the west and south by a large wetland that is presently mapped in the Web Soil Survey as a miscellaneous area of Peat and Muck (Pa). Radar traverse were conduct across adjoining delineations of Caribou gravelly loam, 2 to 8% slopes (CgB); and Easton and Washburn silt loams, 0 to 2 % slopes (EeA). The very deep, well drained Caribou, poorly drained Easton, and very poorly drained Washburn soils formed in loamy supraglacial meltout till derived from shale and siltstone. The taxonomic classifications of these soils are listed in Table 1.

Table 1. Taxonomic classifications of recognized soils at the Aroostook County sites.

Soil Series	Taxonomic Classification
Burnham	Loamy, mixed, superactive, nonacid, frigid, shallow Histic Humaquepts
Caribou	Fine-loamy, isotic, frigid Typic Haplorthods
Easton	Fine-loamy, mixed, superactive, nonacid, frigid Aeric Endoaquepts
Monarda	Loamy, mixed, active, acid, frigid, shallow Aeric Endoaquepts
Washburn	Fine-loamy, mixed, nonacid, frigid Histic Humaquepts

Sites 2 and 3 are located on the Kingsbury Farm about 5.8 km south-southeast of Bridgetown, Maine. Site 2 (near 46.3764 N, 67.8303 W) is located in a densely wooded area (Figure 2, red). The area is mapped as Monarda and Burnham silt loams, 0 to 2 percent slopes (MoA). The very deep, poorly drained Monarda and very poorly drained Burnham soils formed in dense glacial till on lower slopes and depressions, respectively. These soils are shallow to dense glacial till. The taxonomic classifications of these soils are listed in Table 1.

Site 3 (near 46.3748 N, 67.8290 W) crosses a small forested gully at the base of merging slopes (Figure 2, yellow). Here, a single GPR traverse line crossed a delineation of Monarda and Burnham silt loams, 0 to

2 percent slopes (MoA). The adjoining, higher-lying cultivated areas are mapped as Caribou gravelly loam, 15 to 25 percent slopes (CgD).

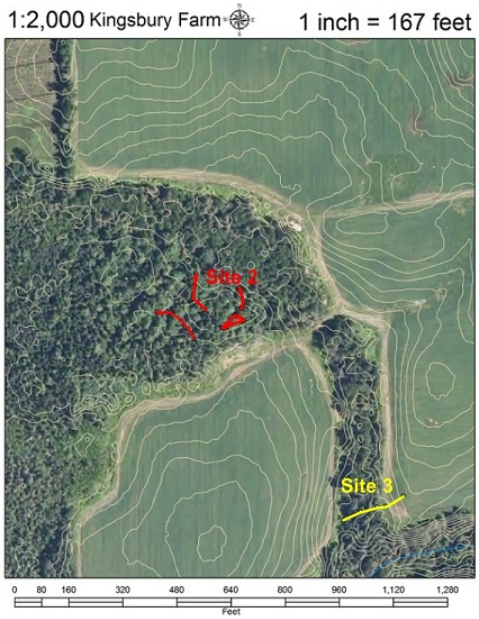

Figure 2. This image shows the locations of the radar traverse lines at Sites 2 and 3 in Aroostook County (courtesy of Greg Granger).

Penobscot County:

Site 1 (near 45.0057 N, 68.9929 W) includes the typical pedon for the proposed Kenduskeag soil series Kenduskeag is being established as a new soil series in the southern Penobscot County Survey. This site is located about 2.4 km east of East Corinth, Maine, in a delineation of Kenduskeag-Wassookeag complex, 1 to 8 % slopes, very stony (334B)[2]. The very deep, somewhat poorly drained Kenduskeag soils and the deep, moderately well drained Wassookeag soils formed in till over residuum weathered from limestone, which is interbedded with phyllite, calcareous metasiltstone, or pelitic limestone rock, on ground moraines. The proposed taxonomic classifications of Kenduskeag and Wassookeag soils are listed in Table 2. The excavation of the modal Kenduskeag soil pedon was restricted at a depth of 150 cm by rock. It was uncertain whether the restricting feature represents parent rock or a large rock fragment (*floater)* that was deposited by glacial ice. The purpose of the GPR investigation at this site was to verify the depth to rock and to confirm the very deep classification of Kenduskeag soil.

Site 2 (near 45.0889 N, 69.1406 W) includes a sampled pedon of Adams *variant* soil. The site is located about 3.6 km south-southeast of Garland, Maine, in southern Penobscot County. This site is located in a delineation of Adams-Nicholville association, 3 to 15 % slopes (300C)[3]. The very deep, excessively and somewhat excessively drained Adams soils formed in glacial-fluvial or glacio-lacustrine sand. However, the Adams variant is deep to rock. The very deep, moderately well drained Nicholville soils formed in water deposited material having a high content of silt and very fine sand. The taxonomic classifications of these soils are listed in Table 2.

[2] Presently in the Web Soil Survey, this site is mapped as Thorndike very stony silt loam, 2 to 8 percent slopes (TkB).
[3] Presently in the Web Soil Survey, this site is mapped as Thorndike very rocky silt loam, 8 to 15 percent (TkC).

Near Site 2, several GPR transects were conducted to help characterize the composition (by soil-depth criteria) of the soil map unit. A transect at the sampled pedon site was used to verify that refusal was caused by solid rock at a depth of 140, and that excavation was not limited by a large rock fragment.

Site 3 (near 44.9848 N, 68.8892 W) is the type location for Ragmuff soil. The soil pit is located about 1.65 km south of Hudson, Maine. This site is presently located within a delineation of Telos-Chesuncook-Elliottsville association, 1 to 8% slopes, very stony (340B) (proposing to replace Elliottsville with Ragmuff).[4] The moderately deep to densic contact and rock, moderately well drained Ragmuff soils formed in glacial till. The moderately deep, well drained Elliottsville soils formed in glacial till. The very deep, somewhat poorly drained Telos soils and the moderately well drained Chesuncook soils formed in dense glacial till. The taxonomic classifications of these soils are listed in Table 2.

Table 2. Taxonomic classifications for recognized soils at the southern Penobscot County sites.

Soil Series	Taxonomic Classification
Adams	Sandy, isotic frigid Typic Haplorthods
Chesuncook	Coarse-loamy, isotic, frigid Aquic Haplorthods
Dixmont	Coarse-loamy, isotic, frigid Aquic Haplorthods
Elliottsville	Coarse-loamy, isotic, frigid Aquic Haplorthods
Kenduskeag	Coarse-loamy, isotic, frigid Aquic Dystric Eutrudepts
Nicholville	Coarse-silty, isotic, frigid Aquic Haplorthods
Ragmuff	Coarse-loamy, isotic, frigid Aquic Haplorthods
Telos	Loamy, isotic, frigid, shallow Aquic Haplorthods
Thorndike	Loamy-skeletal, isotic, frigid Lithic Haplorthods
Wassookeag	Coarse-loamy, mixed, active, frigid Oxyaquic Eutrudepts

Survey Procedures:
At each site, multiple, GPR traverses were completed by pulling the 270 MHz antenna along the ground surface. Each radar traverse was stored as a separate file. Where overlying vegetation was sparse and open, the GPS option could be used with the GPR and radar scans were georeferenced. However, all GPS data suffered some degradation caused by poor geometry or satellite shading.

In Aroostook County, the GPS option was used and all radar data were georeferenced at Study Sites 1 and 3. Because of dense foliage, excessive satellite shading occurred and the radar data could not be georeferenced at Study Site 2.

All study sites located in southern Penobscot County were in forested areas. Prior to conducting radar traverses, ground cover and debris were removed to insure adequate coupling of the antenna with the soil surface and the elimination of most hindrances.

Results:
The large number of rock fragments in the soil profile, the irregular topography of the bedrock surface, and variations in the competency of the rock resulted in the general ambiguity of a continuous "geological" structure that could be clearly identified as the surface of the underlying solid rock.

In Aroostook County, on most radar records a shallow (0 to 50 cm) to moderately deep (50 to 100 cm), broken, weakly expressed interface; and a deeper, broken, interface consisting of higher-amplitude reflections were evident. Lacking ground-truth auger observations, it was assumed that the shallower interface represents the contact with an underlying layer of firmer (densic) till. The deeper interface was assumed to be the contact with solid rock.

[4] Presently in the Web Soil Survey, this site is mapped as Dixmont very stony silt loam, 2 to 8 percent slopes (DyB)

Site 1 Aroostook County:

Figure 3 is a representative radar record from Site 1 in Aroostook County. The two aforementioned interfaces have been identified on this radar record. The identities of these interfaces were not confirmed by borings. However, it is believed that the upper interface represents a layer of firmer till and the lower interface, the parent rock. On the portion of the radar record shown in Figure 3, the depth to firm till is shallow (0 to 50 cm) and moderately deep (50 to 100 cm). The depth to solid rock is very deep (> 150 cm).

Three traverses were completed to the east of an existing reservoir at Aroostook County Site 1. Based on 20127 *radar picks*, the average depth to rock was interpreted to be 1.76 m with a range of 0.53 to 2.91 m in the areas that were traversed by GPR. One-half of these measurements were between depths of 1.43 and 2.16 meters. As evident in Table 2, the bulk of the measurements are within the depth interval of 1.5 to 2.5 m.

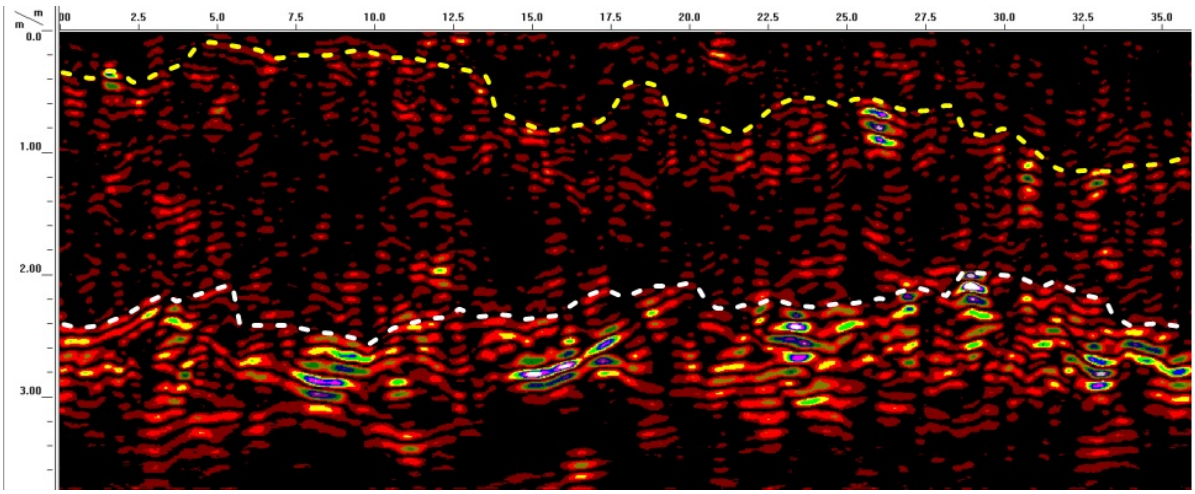

Figure 3. Two subsurface interfaces have been identified on this radar record from Site 1 in Aroostook County. The upper interface is believed to represent the contact with firmer till; the lower interface, the contact with parent rock.

Table 2. Frequency distribution of the depth to rock for the three GPR traverses completed at Site 1 in Aroostook County. Depths to rock are grouped in six, 50-cm depth intervals.

	5	7	8
0 to 0.5	0.00	0.00	0.00
0.5 to 1.0	0.04	0.00	0.06
1.0 to 1.5	0.26	0.02	0.50
1.5 to 2.0	0.46	0.61	0.42
2.0 to 2.5	0.23	0.37	0.02
2.5 to 3.0	0.01	0.00	0.00

Figure 4 is a *Google Earth* image showing the location and distribution of different soil-depth classes along the radar traverse lines that were completed across Site 1. Colors have been used to identify four different soil-depth classes (moderately deep (50 to 100 cm), red; deep (100 to 150 cm), yellow; very deep (150 to 200 cm), orange; and > 200 m, green). Although appearing forested on this *Google Erath* image, the area traversed with GPR was cleared of trees. The present reservoir is located to the

immediate west and south of these traverse lines. As evident in Figure 4, soils are deeper in the southern portion of the traversed area.

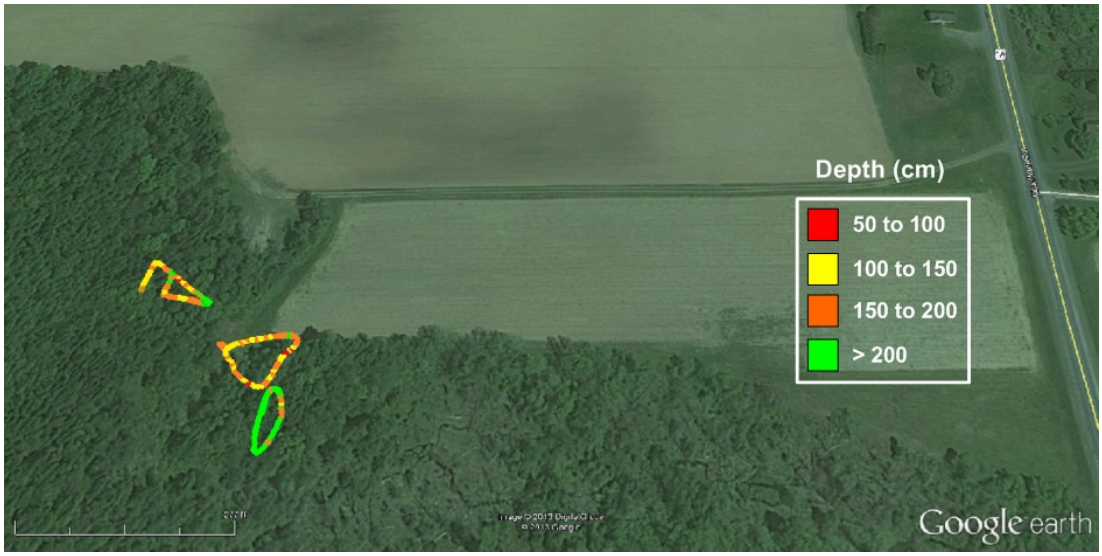

Figure 4. Interpreted soil-depth classes are shown on this Google Earth image of Site 1 in Aroostook County. The areas that were traversed with GPR were cleared subsequent to the collection of this image.

Site 2 Aroostook County:

Three traverses were completed in the densely wooded Site 2 (shown in Figure 2). The dense vegetation resulted in excessive satellite shading. As a consequence, the radar data could not be georeferenced at this site. Based on 16013 *radar picks*, the average depth to rock was interpreted to be 1.75 m with a range of 0.82 to 2.35 m in the traversed area. One-half of the recorded measurements were between depths of 1.56 and 1.99 meters. As evident in Table 3, the bulk of the measurements are within a depth interval of 1 to 2 m.

Table 3. Frequency distribution of the depth to rock for the four GPR traverses completed at Site 2 in Aroostook County. Depths to rock are grouped in five, 50-cm depth intervals.

	9	10	11	12
0 to 0.5	0.00	0.00	0.00	0.00
0.5 to 1.0	0.00	0.07	0.00	0.00
1.0 to 1.5	0.38	0.41	0.10	0.93
1.5 to 2.0	0.50	0.34	0.62	0.07
2.0 to 2.5	0.12	0.18	0.28	0.00

Site 3 Aroostook County:

Only one GPR traverse was completed at this site. Based on 4516 *radar picks*, the average depth to rock was 1.90 m with a range of 0.28 to 2.63 m in the area traversed with GPR. One-half of the recorded measurements were between depths of 1.79 and 2.19 meters. The vast majority of the interpreted measurements were between depths of 1. 5 to 2.0 m (36%) and 2.0 to 2.5 m (51%).

Figure 5 is a *Google Earth* image showing the location and distribution of soils by depth classes along the radar traverse line that was completed at Site 3. Colors have been used to identify the different soil-depth classes. Along this traverse line, soils are deepest in the lower-lying, forested area and shallowest on higher lying slopes within the cultivated field.

Figure 5. Interpreted soil-depth classes are shown on this Google Earth image of Site 3 in Aroostook County.

<u>Penobscot County:</u>

Kenduskeag pedon Site:

Figure 6 is a portion of a radar record that shows the Kenduskeag pedon site. On this radar record, all scales are expressed in meters. At the top of the radar record, a white, vertical, segmented line near the 35-m distance mark identifies the approximate location of the sampled Kenduskeag soil pit. At this point, the depth to rock is 175 cm and the soil is very deep. Two, high-amplitude *floaters* are also apparent to the right of this segmented line at depths of 123 and 153 cm. The soil pit was located in one of the deepest to solid rock segments of the entire traverse line. Along this traverse line the averaged depth to rock is 122 cm with a range of 64 to 188 cm. However, one-half of the *picked* 2625 depth measurements were between 104 and 133 cm.

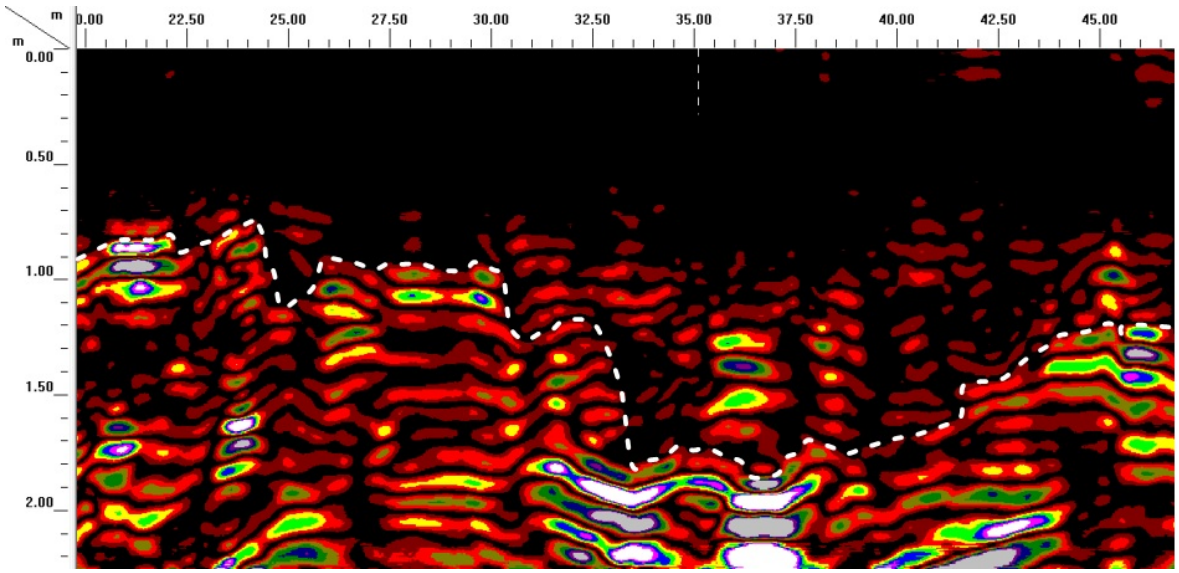

Figure 6. The white, vertical, segmented line at the top of this radar record identifies the location of the modal pedon for the Kenduskeag soil series.

Three GPR traverse lines were conducted in the area surrounding the Kenduskeag soil pit. Based on 11215 *radar picks* from this area, the average depth to rock was interpreted to be 101 cm with a range of 53 to 188 cm. One-half of the interpreted depths to solid rock measurements were between 86 and 114 cm. As evident in Table 4, in this area mapped as the very deep Kenduskeag and deep Wassookeag soils, the bulk of the measurements are within the moderately deep and deep soil-depth classes.

Table 4. Frequency distribution of the depth to rock for the four GPR traverses completed at the Kenduskeag soil site in Penobscot County.

	15	16	17
Shallow	0.00	0.00	0.00
Moderately Deep	0.98	0.18	0.81
Deep	0.01	0.68	0.19
Very Deep	0.01	0.14	0.00

Adams variant Site:

Site 2 contains a sampled soil pit for the Adams variant soil in southern Penobscot County. The Adam variant is deep to solid rock (the Adams series is very deep). Within this soil pit, the excavation was restricted by rock at a depth of 140 cm. Figure 7 is a portion of a radar record near the Adams variant soil pit. In this figure, the horizontal scale is expressed in meters, while the vertical scale is expressed in centimeters. At the top of this radar record, the white, vertical, segmented line near the 37-m distance mark identifies the location of the Adams variant soil pit. At this point, the depth to rock was interpreted to be 134 cm. Along this traverse line the averaged depth to rock is 116 cm with a range of 115 to 141 cm. Based on radar interpretations, the soils along this traverse line and in the vicinity of the Adams variant soil pit are deep to parent rock.

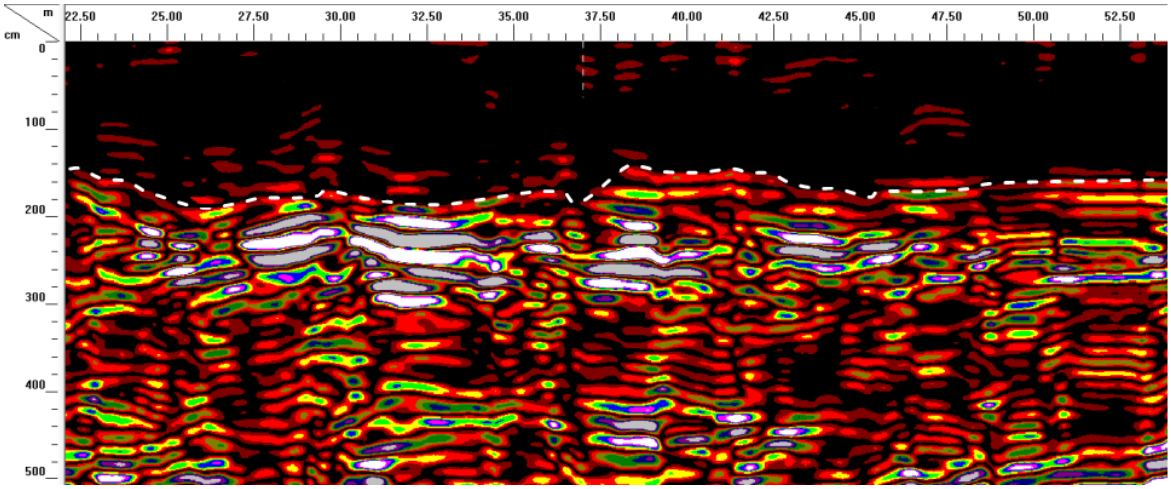

Figure 7. The white-colored, vertical, segmented line at the top of this radar record identifies the location of a sampled Adams variant soil pit in southern Penobscot County.

Eight GPR traverse lines were conducted along a trail and near the sampled Adams variant soil. Based on 38574 *radar picks*, in the area that were traversed by GPR, the average depth to rock was interpreted to be 90 cm with a range of 0 to 200 cm. One-half of these *radar picks* were between depths of 70 and 113 cm. As evident in Table 5, the bulk of the measurements are within the moderately deep (about 51%) and deep (about 37 %) soil-depth classes.

Table 5. Frequency distribution of the depth to rock for eight GPR traverses completed in an area of Adams variant soils in southern Penobscot County.

	19	20	21	22	23	24	25	26
Shallow	0.14	0.07	0.46	0.10	0.00	0.09	0.11	0.00
Mod Deep	0.34	0.31	0.50	0.72	0.33	0.50	0.69	0.05
Deep	0.42	0.62	0.04	0.18	0.67	0.41	0.20	0.95
Very Deep	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
>200	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

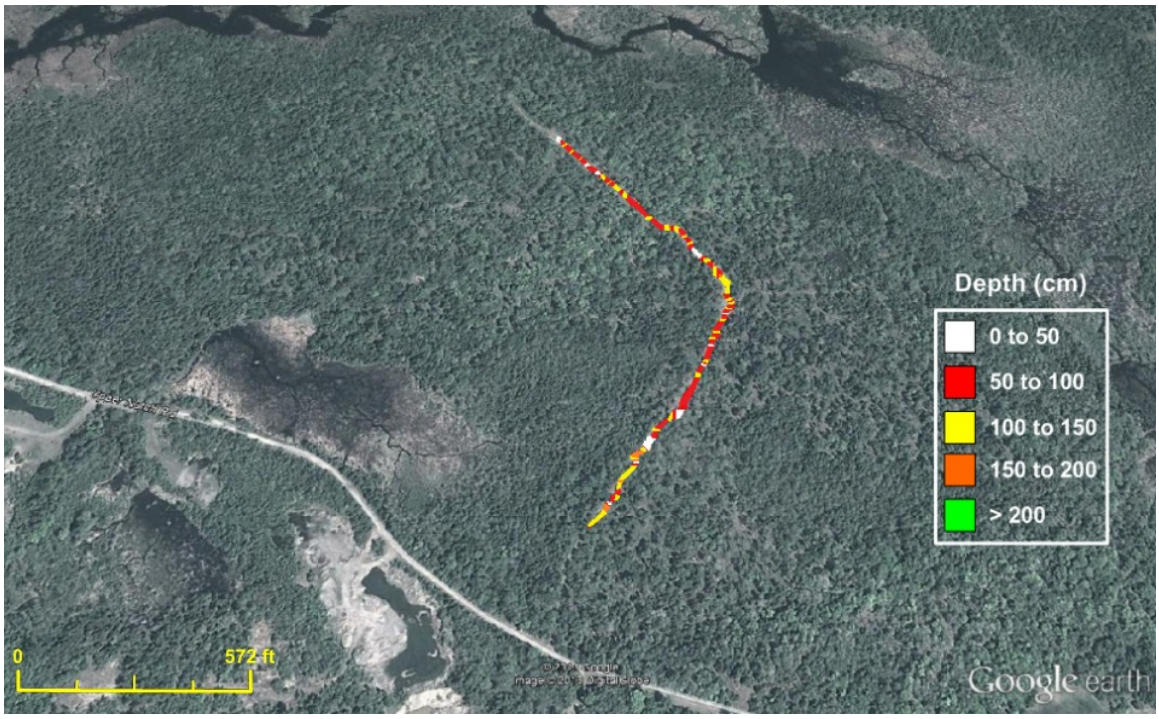

Figure 8. Interpreted soil-depth classes are shown on this Google Earth image of the Adams variant Site in Southern Penobscot County.

Figure 8 is a *Google Earth* image showing the location and distribution of soils by depth classes along the eight GPR traverse lines that were conducted in an area of Adams variant soil. Colors have been used to identify the different soil-depth classes. As evident in this image, soils are dominantly moderately deep and deep to solid rock.

Ragmuff Site:

This site contains the modal pedon for Ragmuff soil. The Ragmuff soil is moderately deep to densic contact and rock. Figure 9, is a portion of the radar record that was collected near the Ragmuff modal pedon site. In this figure, the horizontal scale is expressed in meters, while the vertical scale is expressed in centimeters. At the top of this radar record, the white, vertical, segmented lines at the 6.5- and 9-m distance marks includes the location of the Ragmuff soil pit. Between these points, the depth to rock was interpreted to range in depth from 81 to 93 cm. Along this traverse line the averaged depth to rock is 77 cm with a range of 60 to 96 cm. Based on radar interpretations, the soils along this traverse line are moderately deep to parent rock.

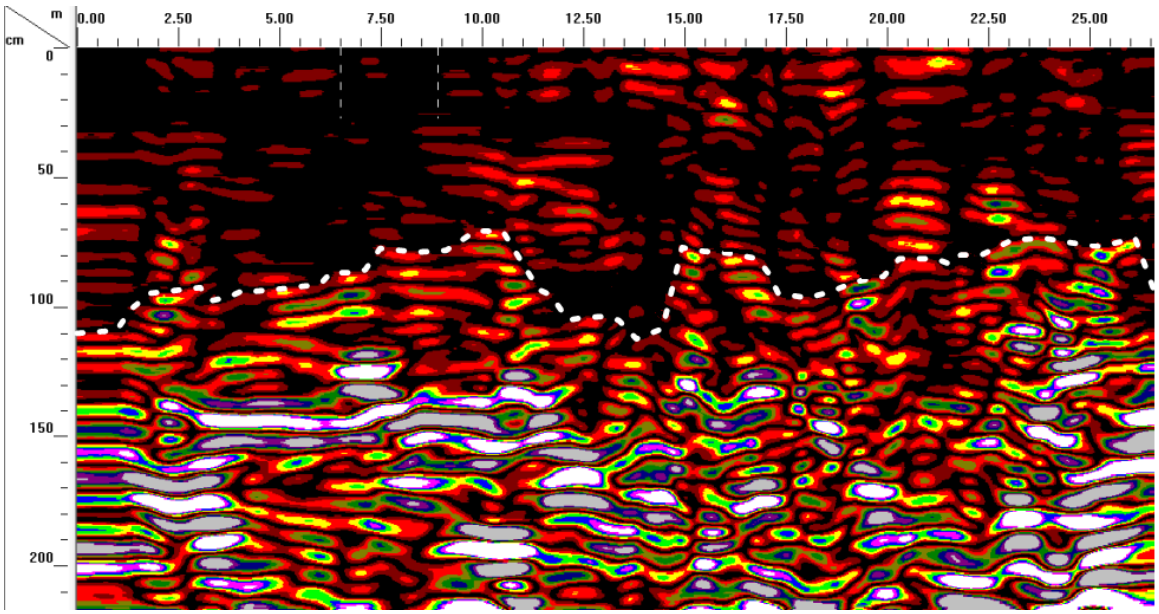

Figure 9. The two white-colored, vertical, segmented lines at the top of this radar record identify the location of the modal pedon for the Ragmuff soil in southern Penobscot County.

Four GPR traverses were conducted near the type location for the Ragmuff soil. Based on 15184 *radar picks*, the average depth to rock was 93 cm with a range of 27 to 161 cm. One-half of these measurements were between depths of 78 and 108 cm. As evident in Table 6, the vast majority of the measurements are within the moderately deep (61 %) and deep (36%) soil-depth classes.

Table 6. Frequency Distribution of the depth to rock for the four GPR traverses completed at the Ragmuff soil site in Penobscot County.

	27	28	29	30
Shallow	0.04	0.08	0.00	0.00
Mod Deep	0.91	0.46	0.50	1.00
Deep	0.05	0.46	0.49	0.00
Very Deep	0.00	0.00	0.01	0.00

Figure 10 is a *Google Earth* image showing the location and distribution of soils by depth classes along four GPR traverse lines located near the modal location for the Ragmuff soil. Colors have been used to identify the different soil-depth classes. As evident in this image, soils are dominantly moderately deep and deep to solid rock. In general the depth to solid rock deepens towards the west and in an upslope direction.

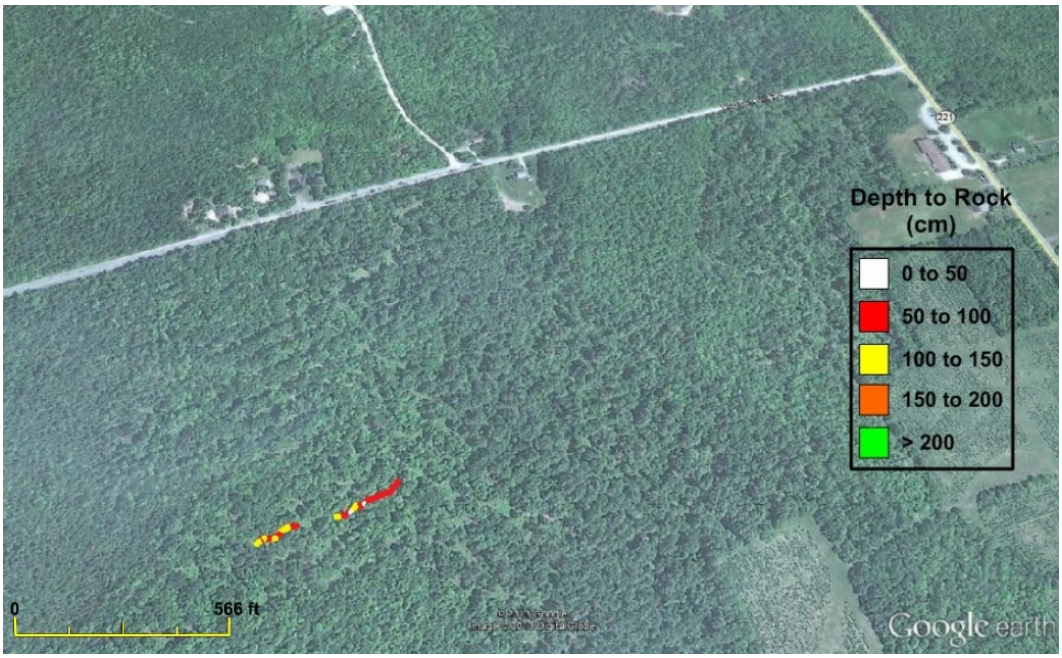

Figure 10. Interpreted soil-depth classes are shown on this Google Earth image of the Ragmuff Soil Site in southern Penobscot County.

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