United States Department of Agriculture

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SUBJECT: SOI – Geophysical Assistance

January 10, 2014

TO: Carrie Mosley
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220 Davidson Ave., 4th Floor
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File Code: 330-7

Purpose:
The objective of this study is to collect information with ground-penetrating radar (GPR) on the depth to bedrock in areas mapped as complexes of Nassau soils in northwestern New Jersey. It is believed that the soils are deeper than presently mapped in areas of Nassau soils. The collected information will be used to justify changes in soil survey legend and interpretative data.

Participants:
Jim Doolittle, Research Soil Scientist, USDA-NRCS-NSSC, Newtown Square, PA
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Activities:
Field activities were completed on 10 to 12 December 2013.

Summary:

1. Data from 28 ground-penetrating radar traverses were collected in Sussex County over a two day period. These traverses provide copious, georeferenced data needed to validate bedrock depths in areas of the Nassau soils.

2. The collected data revealed that the extent of Nassau soils has been over-estimated and that the depth to bedrock is actually deeper than mapped in the areas traversed with GPR. At the three sites surveyed in Sussex County, based on 85,691 radar depth measurements, the distribution of soils according to soil depth classes is 13 % shallow (< 1.67 ft), 59 % moderately deep (1.67 to 3.33 ft), 27 % deep (3.33 to 5.00 ft), and 1 % very deep (> 5.00 feet). Nassau soils are shallow to bedrock.

3. Ground-penetrating radar interpretations are largely based on the experience of the interpreter and the expression of the soil/bedrock interface appearing on radar records. Because of the large number of rock fragments in Nassau and Manlius soils and the weathered and highly irregular bedrock surface, radar reflections from the soil/bedrock interface are often not continuous and clear. Although radar interpretations are considered a close approximation of the actual depth to bedrock, uncertainties will remain until future development of more sophisticated, automated mapping techniques to successfully replace present knowledge-based approaches.

4. In a comparative study of three antennas (200, 270, and 400 MHz) it was found that the continuity of a highly irregular boundary (e.g., soil/bedrock surface) becomes more distinct when the antenna frequency is sufficiently reduced so that the wavelength of the propagating radar pulse is long compared to the dimensions of overlying rock fragments and irregularities in the soil/bedrock boundary.

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

/s/ Jonathan W. Hempel

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Director

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Technical report on ground-penetrating radar (GPR) investigations conducted in areas of Nassau soils in Sussex County, New Jersey, on 9 to 12 December 2013.

James A. Doolittle

Background:
Nassau (loamy-skeletal, mixed, active, mesic Lithic Dystrudepts) soils are relatively extensive in the Valley and Ridge Province of northwestern New Jersey (MLRA 144A; New England and Eastern New York Upland, Southern Part) (see Figure 1). The somewhat excessively drained Nassau soils formed in glacial till (predominantly the *Kittatinny Mountain till*) and are shallow (< 1.67 ft) to Martinsburg shale (Ordovician age). In New Jersey, Nassau soils have been mapped on approximately 75,900 acres. Nassau is commonly mapped in complex with Manlius soils (Figure 1). The moderately deep (1.67 to 3.33 ft), well drained to excessively drained Manlius soils formed in channery till. Manlius is a member of the loamy-skeletal, mixed, active, mesic Typic Dystrudepts taxonomic family.

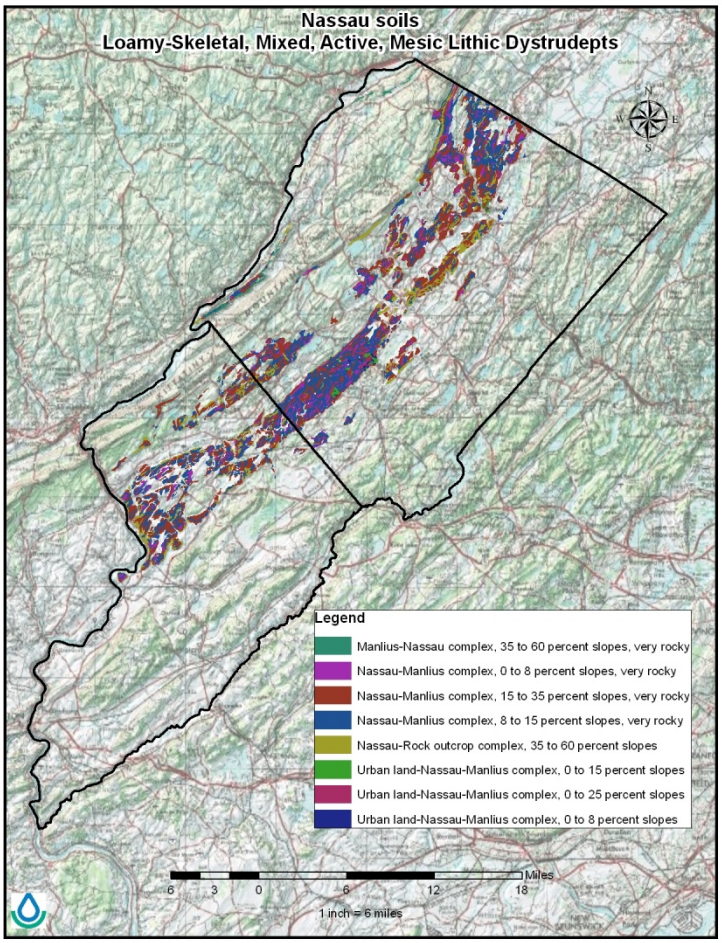

Figure 1. The areas mapped as complexes of Nassau soil in Warren and Sussex Counties, New Jersey, are shown on this map.

The large number of rock fragments in Nassau and Manlius soils limits the depth, accuracy, and number of observations that can be made with spade and auger. Transect data, collected using these traditional soil survey tools, are limited in depth, extent, and number of observations. Ground-penetrating radar (GPR) can quickly and easily provide the large, georeferenced data sets that are needed to help overcome

issues of data insufficiency and incorrectness, and validate differences in depths to bedrock. Ground penetrating radar has been used extensively to chart bedrock depths (Nováková et al., 2013; Gerber et al., 2010; Sass 2007; Sauer and Felix-Henningsen, 2004; Collins et al., 1989; Davis and Annan, 1989), changes in rock type (Davis and Annan, 1989), fractures and joint patterns (Mysaiah et al., 2011; Theune et al., 2006; Porsani et al., 2006 and 2005; Nascimento da Silva et al., 2004; Lane et al., 2000; Pipan et al., 2000) and faults (Demanet et al., 2001).

Manlius and Nassau soils are well suited to GPR because of their relatively shallow depth to electrically resistive bedrock, and comparatively low moisture, clay and soluble salt contents. Previous GPR field investigations (January 2012), which were conducted in Warren County, revealed that the extent of Nassau soils was over estimated and that the depth to bedrock is actually deeper than mapped. In the 2012 field study, based on data collected along 39 radar traverse lines, the distribution of soils according to soil depth classes is 9 % shallow, 65 % moderately deep, 23 % deep (3.33 to 5.00 ft), and 3 % very deep (> 5.00 feet).

This study expands the amount of information on the depth to bedrock in areas that are mapped as complexes of Nassau soils. Data will be used to justify recommendations for changes in soil survey legends and interpretative data.

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. Jol (2009) and Daniels (2004) discuss the use and operation of GPR.

The 200, 270, and 400 MHz antennas were used in this study. However, after initial calibration trials, the 270 MHz antenna was selected as the most appropriate antenna. The 270 MHz antenna provided the best over-all balance of depth of investigation (DOI) and resolution of the soil/bedrock interface. Both survey cart and survey wheel were used in this investigation. These distance-calibrated devices with encoders provide control over signal pulse transmission and data collection along radar traverse lines (see Figure 2).

The RADAN for Windows (version 7.0) software program (GSSI) was used to process the radar records.[1] Processing included: header editing, positioning the initial pulse to time zero, color table and transformation selection, horizontal high pass filtration, signal stacking, and migration (refer to Jol (2009) and Daniels (2004) for discussions of these techniques). The Interactive 3D Module of RADAN was used to semi-automatically picked the depths to the soil/bedrock interface. The picked data were outputted to a worksheet (in an X, Y, and Z format; including longitude, latitude, and depth to bedrock).

Recent technological advances allow the integration of GPR and global positioning system (GPS) data. The SIR-3000 system has a setup for the use of a GPS receiver with a serial data recorder (SDR). With this setup, each scan on radar records can be georeferenced (position/time matched). During data processing, a subprogram within RADAN 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. A Garmin Global Positioning System Map 76 receiver (with a CSI Radio Beacon receiver, antenna, and accessories that are fitted into a backpack) was used to georeferenced data collected with the SIR-3000 system (see Figure 2)[1].

[1] Trade names are used for specific references and do not constitute endorsement.

Figure 2. Edwin Muñiz conducts a GPR survey with the SIR-3000 mounted on a survey cart. The center frequency of the antenna (red box) is 400 MHz.

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., bedrock, soil horizon, stratigraphic layer) and back. To convert the two-way 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):

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

In equation [2], C is the velocity of propagation in a vacuum (0.984 ft/ns). The velocity of pulse propagation is expressed in feet per nanosecond (ns). In soils, the amount and physical state (temperature dependent) of water have the greatest effect on the E_r and v.

Based on the measured depths and the two-way pulse travel times to a known subsurface reflector (metallic plate), average velocity of propagations and relative dielectric permittivity through the upper part of soil profiles were estimated using equations [1] and [2]. At the time of this study, soils were moist and snow covered (see Figure 2), but not frozen. The estimated E_r varied between 7.4 and 9.5. The average v ranged from 0.3618 to 0.3192 ft/ns. Typically, a different velocity is not determined for each soil horizon or layer, but a mean value is used for all layers and soils within a site. This introduces error into soil-depth predictions, whereas a layer-based velocity calibration would, if feasible, improve the quality of depth predictions. However, even if layer-based velocity calibrations are used, v and E_r will vary spatially with soil conditions and the antenna being used.

Survey Area:
Three sites, each located in an open field, were selected in northwestern New Jersey. Figure 3 contains the soil maps for these survey areas. These soil maps are from the Web Soil Survey[2]. All sites are located in areas that are mapped as Nassau-Manlius complex, 8 to 15 percent slopes, very rocky (NauCh). However, Site 1 includes a small area mapped as Nassau-Manlius complex, 15 to 35 percent slopes, very rocky (NauDh).

Site 1 (41.0423 N, 74.7952 W) is located off of Long Hill Road, about 0.75 mi east-northeast of Fredon Township and 2.5 mi southwest of Newton, New Jersey. Site 2 is located off of Walnut Road, about 0.5 mi west-southwest of Knowlton, New Jersey. Site 3 (41.2676 N, 74.5904 W) is located off of Quarry Road, about 2.8 mi south of Union, New York, and 2.8 mi northeast of Wantage, New Jersey.

Figure 3. These soil maps from the Web Soil Survey show the three fields that were surveyed with GPR. All fields are located in areas mapped as Nassau-Manlius complex on 8 to 15 % slopes, very rocky (NauCh).

GPR Procedures:
Multiple GPR traverses were completed across each site. A 400 MHz antenna was used at Site 1. A 270 MHz antenna was used at Sites 2 and 3. Each radar traverse was stored as a separate file. Surveys were conducted by moving the antenna over the ground surface.

[2] Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at http://websoilsurvey.nrcs.usda.gov/. Accessed [12/17/2013].

Each radar record was processed in RADAN 7.0. Following processing, the depth to bedrock was semi-automatically *picked* on each radar record using the Interactive 3D Module of RADAN. These measurements were grouped according to recognized soil depth classes (shallow: < 1.67 ft; moderately deep: 1.67 to 3.33 ft; deep: 3.33 to 5.00 ft; and very deep: > 5.00 ft).

Results:

Site 1:

Twelve radar traverses were completed across Site 1 providing a total of 33,882 soil depth measurements. Based on these measurements, the average depth to bedrock is 2.89 ft with a range of 0.37 to 5.19 ft. One-half of the measurements are between 2.20 and 3.51 ft. Based on the averages from these 12 traverses, the depth to bedrock was largely moderately deep (63%) and deep (28%). Soils that are shallow to bedrock and represent the Nassau series only comprised 8 % of the traversed area. Tables 2 lists the frequency distribution of measurements by soil depth classes for each of the radar traverses completed in Site 1. Figure 4 is a *Goggle Earth* image of Site 1 showing the distribution of soils based on soil depth classes. In this image, the locations of the GPR traverse lines are shown. Colors have been used to identify the different soil depth classes.

Table 2. Frequency distribution (%) of observations according to soil depth classes for the 12 GPR traverses completed in Study Site 1.

	1	2	3	4	5	6	7	8	9	10	11	12
Shallow	0.00	0.00	0.06	0.00	0.11	0.09	0.10	0.12	0.36	0.09	0.06	0.00
Mod Deep	0.55	0.24	0.86	0.17	0.77	0.68	0.77	0.79	0.56	0.85	0.81	0.53
Deep	0.45	0.75	0.08	0.82	0.12	0.23	0.13	0.09	0.09	0.06	0.13	0.47
Very Deep	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 4. Variations in the depth to bedrock across Site 1, as interpreted from radar records, are shown on this Google Earth image (courtesy of Brian Jones of GSSI).

Site2:

Eight radar traverses were completed across Site 2 providing a total of 24,777 soil depth measurements. Based on these measurements, the average depth to bedrock is 2.86 ft with a range of 0.20 to 5.88 ft.

One-half of the measurements are between 2.28 and 3.45 ft. Based on the averages from the 8 traverses, the depth to bedrock was largely moderately deep (62%) and deep (31%). Soils that are shallow and very deep to bedrock comprise only 6 and 1% of the traversed areas.

Tables 3 lists the frequency distribution of measurements by soil depth classes for each of the radar traverses completed in Site 2. Figure 5 is a *Goggle Earth* image of Site 2 showing the distribution of soils based on soil depth classes[3]. In this image, the locations of the GPR traverse lines are shown. Colors have been used to identify the interpreted depth classes.

Table 3. Frequency distribution (%) of observations according to soil depth classes for the 8 GPR traverses completed in Study Site 2.

	18	19	20	21	22	23	24	25
Shallow	0.00	0.24	0.06	0.05	0.07	0.05	0.02	0.01
Mod Deep	0.42	0.72	0.67	0.83	0.78	0.70	0.68	0.17
Deep	0.58	0.04	0.27	0.13	0.15	0.25	0.31	0.78
Very Deep	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04

Figure 5. Variations in the depth to bedrock across Site 2, as interpreted from radar records, are shown on this Google Earth image (courtesy of Brian Jones of GSSI).

Site 3

Eight radar traverses were completed across Site 3 providing a total of 27,032 soil depth measurements. Based on these measurements, the average depth to bedrock is 2.46 ft with a range of 0.00 to 5.62 ft. One-half of the measurements are between 1.70 and 3.16 ft. Based on the averages from the 8 traverses, the depth to bedrock is largely moderately deep (57%) with lesser proportions of shallow (23%) and deep (19%) soils.

Tables 4 lists the frequency distributions of measurements by soil depth classes for each of the radar traverses completed at Site 3. Figure 6 is a Goggle Earth image of Site 3 showing the distribution of soils

[3] Three radar traverses are not shown in Figure 5 because of poor GPS reception.

based on soil depth classes. In this image, the locations of the GPR traverse lines are shown. Colors have been used to identify the soil depth classes.

Table 4. Frequency distribution (%) of observations according to soil depth classes for the 8 GPR traverses completed in Study Site 3.

	26	27	28	29	30	31	32	33
Shallow	0.51	0.25	0.24	0.03	0.21	0.04	0.20	0.31
Mod Deep	0.49	0.57	0.49	0.28	0.68	0.75	0.76	0.58
Deep	0.00	0.18	0.27	0.64	0.11	0.21	0.04	0.11
Very Deep	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00

Figure 6. Variations in the depth to bedrock across Site 3, as interpreted from radar records, are shown on this Google Earth image (courtesy of Brian Jones of GSSI).

Comparative Study of Antennas in area of Manlius and Nassau soils:
One of the most important decisions made in every GPR survey is the selection of a suitable antenna frequency that will provide both an acceptable depth of investigation (DOI) and resolution of subsurface feature (Conyers and Goodman, 1997). In general, antennas with lower frequencies provide greater DOI, but poorer resolution of subsurface features. Conversely, higher frequency antennas provide lesser DOI, but greater resolution of subsurface features. These relationships are known as the "range-resolution trade-off" (Davis and Annan, 1989). Typically, radar operators will select the antenna with the highest frequency that will attain the required DOI (Conyers and Goodman, 1997). Altering the antenna center frequency permits the selective enhancement of the subsurface responses at different scales.

In areas of Nassau and Manlius soils, the 200, 270, and 400 MHz antenna provide satisfactory DOI (> 7 ft) for soil investigations. Therefore, a major concern of the radar operator is the resolution and continuity of the soil/bedrock interface on radar records. Resolution is defined as the smallest discontinuity or separation that can be discerned between discrete targets. In order to be resolved, the thickness of a layer or feature must be the same dimension as the wavelength, or the travel time through the layer to be equal or greater than the pulse duration (Annan, 2001).

As radar pulses propagate downward through the soil, they expand to form a conical "footprint" area from which reflections are received. The more distant a feature is from the antenna, the wider the footprint area and the lower the horizontal resolution. In order for a feature (e. g., bedrock surface, rock fragment) to be resolved at a given depth, its cross-sectional area needs to be about the same size as this footprint area. Horizontal resolution depends on the velocity of pulse propagation, pulse width, and the distance from the antenna. In soils with higher dielectric permittivity and lower velocity of propagation, the conical radiation pattern is more focus; resulting in higher horizontal resolution with all antennas. However, because of the depth-increasing conical radiation pattern, horizontal resolution will decrease with increasing distance from an antenna (Annan, 2001). Higher frequency antennas provide greater horizontal resolution than lower frequency antennas. Lower frequency antennas cannot resolve small features and discontinuities in soils. Accordingly, reflections from smaller rock fragments and small-scale irregularities in the bedrock surface can be filtered-out of radar records by using a lower frequency antenna. Using a lower frequency antenna can improve the apparent continuity of discontinuous of irregular interface.

Vertical resolution is dependent on the wavelength of an antenna. For two separate reflections to be distinguishable on a radar record, they must be separated in time by at least ½ the pulse width. If two features and/or interfaces, such as the bedrock surface and an overlying rock fragment, are separated by less than this amount they will be indistinguishable and interpreted as one event (Annan, 2009). The wavelength is determined by dividing the propagation velocity (v) by the antenna frequency (f).

$$\lambda = v/f \qquad [3]$$

Using the *v* that were estimated in this study (range of 0.3618 to 0.3192 ft/ns), wavelengths for the 200, 270, and 400 MHz antennas are shown in Table 4. The wavelengths provided in this table are for the estimated minimum and maximum propagation velocities. Features must be separated in Manlius and Nassau soils by at least ½ these wavelength to be discerned as separate features. These propagation velocities are relatively fast (perhaps due to the inclusion of air pockets in the refilled soil materials that overlain the buried metallic reflector), but will decrease with increasing soil depths.

Table 4. Theoretical wavelengths (λ) for antennas operating at different frequencies and scanning soils at different propagation velocities. Theoretically, the vertical resolution will be ½ these λ.

	0.3168 ft/ns	0.3192 ft/ns.
200 MHz	1.81ft	1.6 ft
270 MHz	1.34 ft	1.18 ft
400 MHz	0.90 ft	0.80 ft

The interpretation of the soil/bedrock interface on radar records is based on the experience of the interpreter. In complex mediums such as soils, there are no unmistakable reflections. The "visibility" and "apparent continuity" of the soil/bedrock interface will depend on its reflectivity, structure, depth; and the amount of clutter in the overlying soil material. Variations in reflected signal amplitudes will affect the recognition and apparent continuity of the soil/bedrock interface. In northern New Jersey, the bedrock surface is often inclined and highly irregular. If the bedrock surface slants away from the antenna, more energy will be reflected away (scattered) from the antenna and a very low amplitude reflection will be recorded. Conversely, if the bedrock surface is slanted towards the antenna, more energy will be focused on the antenna and a high amplitude reflection will be recorded.

In the glaciated areas of northwestern New Jersey, the bedrock is folded and faulted, and overlain by a relatively thin regolith that contains numerous rock fragments of various sizes. Rock fragments produce reflection hyperbolas that can interfere with, mask reflections from, and disrupt the apparent continuity of the bedrock surface on radar records. Smaller rock fragments, and discontinuities and irregularities in the bedrock surface can be resolved on radar records collected with higher frequency antennas. These features are difficult to detect with lower frequency antennas. Discontinuities and irregularities in the bedrock surface will be "averaged-out" on radar records recorded with lower frequency antennas having larger wavelengths. This averaging can make the continuity of the soil/bedrock surface more recognizable in areas with highly folded or faulted bedrock.

A brief study was conducted comparing the resolution and reflection continuity of radar data collected with 200, 270 and 400 MHz antennas. The study site (40.9216 N, 75.0731 W) is located off of Walnut Road about 0.3 miles west of Delaware Lake and 1.0 mi east of Columbia in Warren County. The site is located in an area that is mapped as Nassau-Manlius complex, 8 to 15 percent slopes, very rocky (NauCh).

The GPR records were collected along an 80 foot traverse line with each antenna. A radar record was acquired for each antenna using the same settings (60 scan/sec; 12 scan/ unit; active automatic gain function with 4 break points; and a range of 60 ns). Depth scales were based on the depth to a reflector buried (at 17 inches) near the traverse line. The radar records were identically processed and displayed.

Along the traverse line, the expression and continuity of the soil/bedrock interface was rather poor. This was fortunate, as a comparative study of the responses of different antennas in soils with well-expressed and continuous soil/bedrock interface would provide less meaningful information. Figure 7 contains three radar records that were collected using the 200 MHz (top), 270 MHz (middle) and 400 MHz (bottom) antennas. In each of these radar records, the soil/bedrock interface is unclear and indistinguishable, because it is highly irregular and segmented with very poor horizontal continuity.

On the three radar records shown in Figure 7, increasing levels of resolution and detail are apparent as the center frequency is increased. However, decreasing the antenna center frequency results in an increase in the apparent continuity of the soil/bedrock reflections as unwanted clutter (from rock fragments in the soil and inhomogeneities such as fracturing and folding in the rock) is reduced. On the radar record that was collected with the 200 MHz antenna (top plot in Figure 7), few reflection hyperbolas are evident in the soil and the continuity of the soil/bedrock interface is more apparent. Inclined, white-colored lines have been drawn on the 200 MHz radar record to indicate the upper-most portions of coherent bedding planes as they extend upwards into the soil profile. In general, higher frequency antennas provided greater resolution of soil features (e.g., soil horizons and rock fragments), whereas lower frequencies antennas provided better continuity of soil/bedrock interface. Similar results have been reported by Jol et al. (2002).

Changing the center frequency of a GPR system permits selective enhancement of subsurface responses. In particular, the continuity of gradational or highly irregular boundaries (such as the bedrock surface under skeletal soil materials) may become more distinct when the center frequency is sufficiently reduced so that the wavelength of the propagating radar pulse is long compared to the thickness or irregular soil/bedrock.

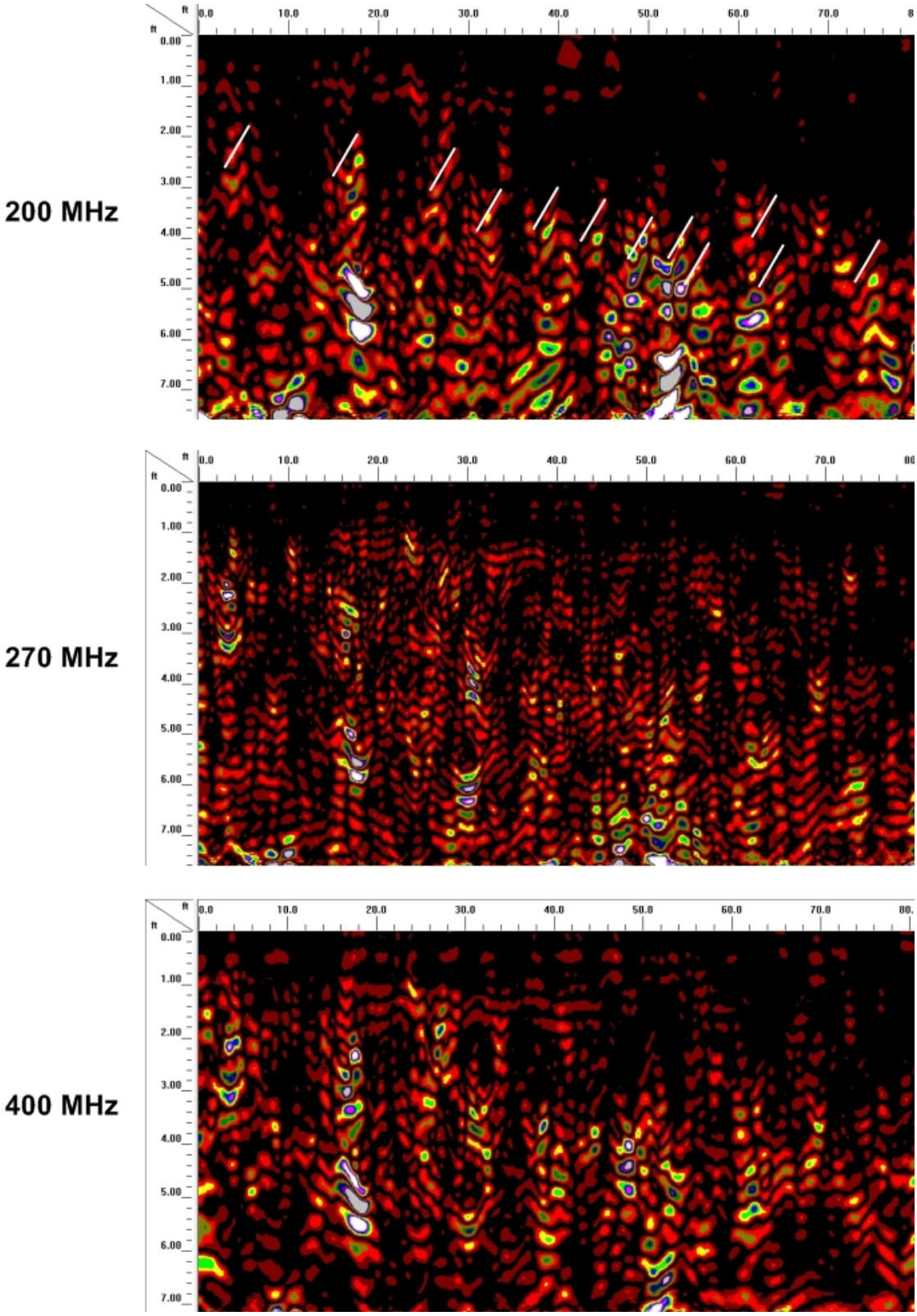

Figure 7. GPR records collected along n 80 ft test line using a 200 (top), 270 (middle) and 400 (bottom) MHz antenna in an area of Manlius and Nassau soils.

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