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

Subject: Soil - Geophysical Assistance-GPR **Date:** 24 March 2009

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Purpose:
The Soil Staff of USDA-NRCS has developed ground-penetrating radar (GPR) soil suitability maps (GPRSSM) for most areas of the USA. These digital maps are based on physiochemical properties of soils. Two soil properties used in the preparation of GPRSSMs are clay content and clay mineralogy. Soils with clay fractions dominated by low cation exchange capacity clays (e.g., kaolinitic, gibbsitic, and halloysitic soil mineralogy classes) have lower electrical conductivity and are assumed to be less attenuating and depth restrictive to GPR. It is assumed that for soils with comparable clay and moisture contents, greater depths of penetration can be achieved in highly weathered soils of tropical and subtropical regions that have greater amounts of low cation exchange capacity clays and kandic or oxic horizons, than in soils of temperate regions that have greater amounts of high cation exchange capacity clays and argillic horizons. This study documents the relative performance of GPR on fine and very-fine textured Oxisols and Ultisols in Puerto Rico.

Participants:
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Activities:
All field activities were completed during the period of 23 to 26 February 2009.

Summary:

1. With the exception of Cerro Gordo soils, soils profiled with GPR in Puerto Rico were very attenuating and depth restrictive to GPR. These fine and very fine textured Oxisols and Ultisols have low potential for most GPR applications.

2. The use of advanced processing steps did not improve the resolution or improved the depth of observation in the profiled fine and very fine textured soils.

3. Results from this study would suggest that high amount of iron oxides in soils favors deeper GPR penetration and improved resolution of subsurface features. This is contrary to the findings of others and emphasizes the need for greater understanding of the affects of interacting soil properties and different soil mineralogy classes, especially sesquic, parasesquic, ferritic, ferruginous on the effectiveness of GPR.

4. With the exception of Cerro Gordo soil, the depth of penetration is restricted in all of these soils, where the maximum clay content in the Bo or Bt horizons ranged from 63.5 to 82.5%. In the preparation of GPRSSMs, the use of a textural adjustment (-1) for highly weathered soils dominated by low-activity clays with clay contents between 10 and 35 % appears appropriate.

5. As the effectiveness of GPR in very-fine textured soils with oxic or kandic horizons is considered very limited, the use of a mineralogy override (-1) can not be justified by the results of this study. However, earlier GPR work, which was completed on the Piedmont of North and South Carolina, suggests that GPR resolution and depth of penetration are improved in soils with low activity clays and lower clay content maximums (generally between 40 and 60 % clay). It is therefore recommended that the use of the mineralogy override (-1) for soils dominated by low activity clays be restricted to soils with clay contents between 10 and 60 % (medium and fine textured soils).

It was my pleasure to work in Puerto Rico and with members of your fine staff.

With kind regards,

James A. Doolittle
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Background:
The USDA-NRCS Soil Survey Staff has developed ground-penetrating radar (GPR) soil suitability maps (GPRSSM) for most areas of the USA at different scales and levels of resolution. These digital maps are based on soil taxonomic criteria and physicochemical properties of over 22,000 different soils. Factors used to prepare these maps include: soil taxonomic classification, clay content and mineralogy, electrical conductivity, sodium absorption ratio, and calcium carbonate and calcium sulfate contents. These maps can help GPR operators evaluate the relative appropriateness of using GPR, select the most suitable antennas, and assess the need and level of data processing. The ground-penetrating radar soil suitability map of Puerto Rico and the U. S Virgin Islands (GPRSSM_PR) is shown in Figure 1. The map uses different colors to represent the six GPR suitability indices and areas that are not digitized, have not been rated, or represent bodies of water.

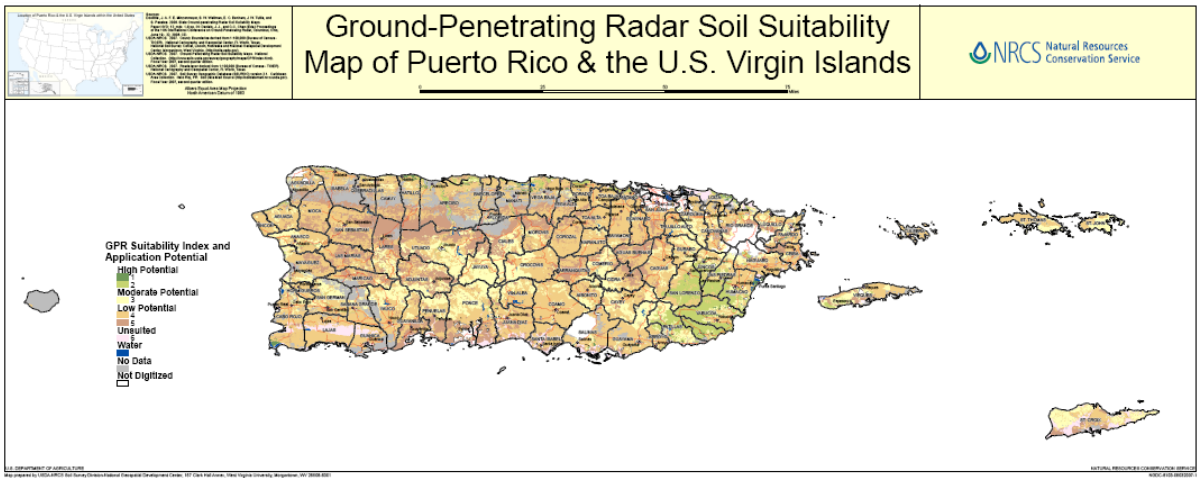

Figure 1. The ground-penetrating radar soil suitability map of Puerto Rico (GPRSSM_PR)

The penetration depth of GPR is determined by antenna frequency and the electrical conductivity of the profiled soil materials (Daniels, 2004). Soils having high electrical conductivity rapidly attenuate radar energy, restrict penetration depths, and severely limit the effectiveness of GPR. The electrical conductivity of soils increases with increases in water, clay and soluble salt contents.

Because of their high adsorptive capacity for water and exchangeable cations, clays greatly increase the electrical conductivity of soils and radar attenuation losses (Daniels, 2004). Variations in electrical conductivity, attenuation rates, and penetration depths have been attributed not only to clay content, but differences in the cation exchange capacity (CEC) associated with different clay minerals (Saarenketo, 1998). Soils with clay fractions dominated by high CEC clays (e.g., smectitic and vermiculitic soil mineralogy classes) are more attenuating to GPR than soils with an equivalent percentage of low CEC clays (e.g., kaolinitic, gibbsitic, and halloysitic soil mineralogy classes). It is assumed that for soils with comparable clay and moisture contents, greater depths of penetration can be achieved in highly weathered soils of tropical and subtropical regions that have kandic or oxic horizons than in less weathered soils of temperate regions that have argillic horizons. Compared with argillic horizons, kandic and oxic horizons have greater concentrations of low CEC clays (Soil Survey Staff, 1999).

Kandic and oxic horizons are products of intense weathering. Both kandic and oxic horizons have less than 10% weatherable minerals in the sand, silt or clay fractions. Kandic and oxic horizons have an apparent CEC of $\leq$ 16 cmol (+) per kg clay (by 1N NH_4OAC pH 7) and an apparent CEC of $\leq$12 cmol (+) per kg clay (sum of bases extracted with by 1N NH_4OAC pH 7 plus 1N KCl-extractable Al) (Soil Survey Staff, 1999). Oxic horizons show no indications of clay movement or clay films on surfaces of peds. Kandic horizons, however, show indications of clay movement and clay films on surfaces of peds. The kandic horizon, in essence, combines properties of both the

argillic and oxic horizon. While extensively mapped in Puerto Rico, the accurate classification of Oxisols and Ultisols and of oxic and kandic horizons, is often difficult in the field and requires measurements of CEC from laboratories.

In developing the attribute index values (AIV) and soil suitability indices (SSI) used to make GPRSSMs, a mineralogy override is used for highly weathered soils that are dominated by low activity clay minerals. Based on taxonomic criteria, a textural adjustment (-1) is applied to all soils that have kandic or oxic horizons and more than 10 percent clay. The objective of this study was to evaluate the performance of GPR and confirm SSI interpretations on several fine and very-fine textured Ultisols and Oxisols in Puerto Rico.

Equipment:
The radar unit used in this study 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. An antenna with a center frequency of 200 MHz was used in this study. With an antenna, the SIR-3000 requires two people to operate (see Figure 1). Jol (2009) and Daniels (2004) discuss the use and operation of GPR.

Figure 2. Wes Tuttle and Samuel Rios complete a radar survey with the SIR-3000 GPR, AG114 GPS, and 200 MHz antenna.

The RADAN for Windows (version 6.6) software program (GSSI) was used to process the radar records.[1] Basic processing steps included: header editing, setting the initial pulse to time zero, color table and transformation selection, display range gain adjustments. Most radar records were subjected to further more sophisticated

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

processing. The added processing included: signal stacking, migration, and range gain adjustments (see Daniels (2004) and Jol (2008) for discussions on these techniques).

An EM38 meter, manufactured by Geonics Limited (Mississauga, Ontario), was used in this investigation.[2] The meter weighs about 1.4 kg (3.1 lbs) and needs only one person to operate. No ground contact is required with this instrument. The EM38 meter has a 1-m intercoil spacing and operates at a frequency of 14,600 Hz. When placed on the soil surface, it has effective penetration depths of about 0.75 m and 1.5 m in the horizontal and vertical dipole orientation, respectively (Geonics Limited, 1998). The EM38 meter measures the EC_a of earthen materials, which is expressed in milliSiemens/meter (mS/m).

Study Site:
Each site is identified by its dominant soil. The taxonomic classifications of these soils (as sampled) are listed in Table 1. Pertinent physiochemical properties of the soil sampled near or at each site are listed in Table 2. In Table 2, data are listed only for the Bt or Bo horizons. Based on the CECs listed in Table 2, the sampled Consumo, Nipe, Cerro Goto, and Coto soils should be classified as Oxisols, while the sampled Daguey, Voladora, and Lares soils should be classified as Ultisols. As Consumo soil has a kandic horizon, it is an Ultisol. Table 3 lists the taxonomic classifications of these soils based on soil descriptions and laboratory characterization.

Table 1. Taxonomic classifications of the soil series recognized at the study sites.

Soil Series	Taxonomic Classification
Consumo	Fine, mixed, semiactive, isohyperthermic Typic Haplohumult
Daguey	Very-fine, kaolinitic, isohyperthermic Inceptic Hapludox
Nipe	Very-fine, ferruginous, isohyperthermic Typic Acrudox
Cerro Gordo	Fine-loamy, mixed, isothermic Typic Haploperox
Coto	Very-fine, kaolinitic, isohyperthermic Typic Eutrustox
Voladora	Very-fine, mixed, active, isohyperthermic Plinthic Haplohumult
Lares	Very-fine, mixed, semiactive, isohyperthermic Aquic Hapludult

Table 3. Summary of pertinent laboratory data for soils sampled near each study site.

Soil	Pedon ID #	Depth (cm)	Clay content (%)	CEC NH4 OAC meq/100 grams of clay	CEC Sum Bases meq/100 grams of clay
Consumo	S07PR097-001	10 to 43	53.5 to 63.5	12.7 to 14.8	8.9 to 9.8
Daguey	88PR097001	39 to 192	51.6 to 74.4	14.7 to 16.6	10.2 to 11.6
Nipe	S02PR-125-005	28 to 152	40.9 to 66.5	3.8 to 7.7	
Cerro Gordo	S07PR125-007R	28 to 206	18.9 to 35.4	1.8 to 8.5	
Coto	94PR005001	38 to 180	64.8 to 82.5	9.0 to 10.8	
Voladora[3]	87PR007006	17 to 160	33.9 to 68.7	25.6 to 34.0	19.1 to 29.7
Lares	S04PR-023-010	12 to 71	51.4 to 66.9	18.9 to 23.9	14.4 to 20.8

[2] Manufacturer's names are provided for specific information; use does not constitute endorsement.
[3] This sampling was not correlated to the Voladora soil series. By the current Voladora series concepts, this soil has not been characterized.

Table 3. Taxonomic classifications of the soil recognized at the study sites, based on laboratory data.

Soil Series	Taxonomic Classification
Consumo	Fine, mixed, semiactive, isohyperthermic Typic Kanhapludult
Daguey	Very-fine, parasesquic, isohyperthermic Typic Haplohumult
Nipe	Very-fine, ferruginous, isohyperthermic Typic Acrudox
Cerro Gordo	Fine-loamy, mixed, isothermic Typic Haploperox
Coto	Very-fine, kaolinitic, isohyperthermic Typic Eutrudox
Voladora	Fine, mixed, active, isohyperthermic Typic Haplohumult (not sampled)
Lares	Very-fine, mixed, semiactive, isohyperthermic Aquic Hapludults

Consumo Site:
The Consumo site (latitude 18.220169 N, longitude 67.144814 W) is located in a hay land on the campus of the University of Puerto Rico in Mayagüez. The site is located in an area of Consumo clay, 20 to 40 percent slopes (CoE). The very deep, moderately well drained Consumo soils formed in fine-textured residuum weathered from volcanic rocks on summits and side slopes of uplands. Though classified as a fine, mixed, semiactive, isohyperthermic Typic Haplohumult, the sampled Consumo pedon from this site, based on laboratory characterization, was reclassified as a fine, mixed, semiactive, isohyperthermic Typic Kanhapludult. The CEC of the sampled Bt horizon ranges from 12.7 to 14.6 meq/100 grams of clay (by 1N NH_4OAC pH 7). The clay contents of sampled Bt horizons range from 53.5 to 63.5 percent.

Daguey Site
The Daguey site (latitude 18.218492 N, longitude 67.1472361 W) is located in a pasture on the campus of the University of Puerto Rico in Mayagüez. The site is located in an area of Daguey clay, 12 to 20 percent slopes, eroded (DaD2). The very deep, well drained Daguey soils formed in fine-textured residuum weathered from volcanic rock on side slopes, ridge tops, and foot slopes of uplands. Though classified as a very-fine, kaolinitic, isohyperthermic Inceptic Hapludox, the sampled Daguey pedon, based on laboratory characterization, was reclassified as a very-fine, parasesquic, isohyperthermic Typic Haplohumult. The CEC of the Bt horizon ranges from 14.7 to 16.6 meq/100 grams of clay (by 1N NH_4OAC pH 7). The clay contents of sampled Bt horizons range from 51.6 to 74.4 percent.

Nipe Site:
The Nipe site (latitude 18.139167 N, longitude 67.162556 W) is located in an open field of Nipe clay, 5 to 20 percent slopes (NpD) near the intersection of Camino Quintana and Camino de Plan Bonito in Guanajibo. The very deep, well drained Nipe soils formed in iron-rich residuum weathered from serpentine bedrock on stable areas of ridges, hills, and mountains. A Nipe pedon, which was sampled on this site, is appropriately classified as a very-fine, ferruginous, isohyperthermic Typic Acrudox. The CEC of the sampled Bo horizon ranges from 3.8 to 7.7 meq/100 grams of clay (by 1N NH_4OAC pH 7). The clay contents of sampled Bo horizons range from 40.9 to 66.5 percent.

Cerro Gordo Site:
The Cerro Gordo site (latitude 18.153561 N, longitude 66.994597 W) is located in a wooded area in the Maricao State Forest. The site is located in an area of Cerro Gordo mucky peat, 2 to 20 percent slopes (CuB2) in San German about 3.3 km southwest of Maricao. The site has been disturbed by camping activities and a mucky peat surface layer was not observed. The very deep, well drained Cerro Gordo soils formed in iron-rich residuum weathered from serpentine bedrock on stable areas of mountains. In the control section, iron stone fragments are less than 35 percent (by volume). A Cerro Gordo pedon, which was sampled near this site, is appropriately classified as a fine-loamy, mixed, isothermic Typic Haploperox. The CEC of the sampled Bo horizon ranges from

1.8 to 8.5 meq/100 grams of clay (by 1N NH_4OAC pH 7). The clay contents of sampled Bo horizons range from 18.9 to 35.4 percent.

Coto Site:
The Coto site (latitude 18.471119 N, longitude 67.043483 W) is located in a recently disked research field at the USDA-ARS Isabela Research Station. The research field is located in an area of Coto clay, 2 to 5 percent slopes, eroded (CuB2) about 3.2 km southwest of Isabela. The very deep, well drained Coto soils formed in sediments weathered from limestone on uplands. A Coto pedon, which was sampled nearby, is appropriately classified as a very-fine, kaolinitic, isohyperthermic Typic Eutrudox. The CEC of the sampled Bo horizon ranges from 9.0 to 10.8 meq/100 grams of clay (by 1N NH_4OAC pH 7). The clay contents of sampled Bo horizons range from 64.8 to 82.5 percent.

Voladora Site:
The Voladora site (latitude 18.082722 N, longitude 67.169833 W) is located in an area of Voladora clay, 5 to 12 percent slopes (VoC). The site is in a pasture located about 2.5 km west of the center of Cabo Rojo. The very deep, moderately well drained Voladora soils formed in fine-textured volcanic and marine sediments on hills. Though classified as a very-fine, mixed, active, isohyperthermic Plinthic Haplohumult, a Voladora pedon, which was sampled nearby, based on laboratory characterization, was reclassified fine, mixed, active, isohyperthermic Typic Haplohumult. The CEC of the sampled Bt horizon ranges from 25.6 to 34.0 meq/100 grams of clay (by 1N NH_4OAC pH 7). The clay contents of sampled Bt horizons range from 33.9 to 68.7 percent.

Lares Site:
The Lares site (latitude 18.0960857 N, longitude 67.1432233 W) is located in a pasture of Lares clay, 0 to 5 percent slopes (LkA), about 1.0 km north-northeast of the center of Cabo Rojo. The very deep, somewhat poorly drained Lares soils formed in clayey marine sediments on alluvial fans and dissected terraces. A nearby, sampled Lares pedon is appropriately classified as a very-fine, mixed, semiactive, isohyperthermic Aquic Hapludult. The CEC of the sampled Bt horizon ranges from 18.9 to 23.9 meq/100 grams of clay (by 1N NH_4OAC pH 7). The clay contents of sampled Bt horizons range from 51.4 to 66.9 percent.

Survey Procedures:
At each site, a small metallic reflector (a vehicle hubcap) was buried in the soil at depths ranging from 39 to 57 cm. A short traverse line (generally about 4-m) was extended across the position of the buried reflector. Markers were placed in the soil at 1 m intervals along this traverse line and served as reference points on radar records. A 200 MHz was pulled along the traverse line to complete the radar survey. At most sites, multiple traverses were completed to optimize calibration and depiction of the buried artifact on radar records. At each site, additional, longer GPR traversed were completed to better characterize the soils.

At each site, the apparent conductivity (EC_a) of the soil was measured with and EM38 meter operated in the vertical dipole orientation (VDO).

Calibration of GPR:
Ground-penetrating radar is a time scaled system. This system measures the time that it takes electromagnetic energy to travel from an antenna to an interface (e.g., soil horizon, stratigraphic layer) and back. To convert the travel time into a depth scale, the velocity of pulse propagation or the depth to a reflector must be known. The relationships among depth (D), two-way pulse travel time (T), and velocity of propagation (v) are described in the following equation (Daniels, 2004):

$$v = 2D/T \qquad [1]$$

The velocity of propagation is principally affected by the relative dielectric permittivity (E_r) of the profiled material(s) according to the equation (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).

Table 4. For each site, the depth at which a metallic reflector was buried, and, using equations [1] and [2], the resulting v and E_r for the soil. In addition, the EC_a as measured with an EM38 meter operated in the VDO.

Soil Series	Depth (cm)	*v*	E_r	EC_a (mS/m)
Daguey	53	0.1004	8.8	3
Consumo	57	0.0999	8.9	3 to 6
Cerro Gordo	46	0.1206	6.1	-27
Nipe	48	0.9746	9.4	21 to 26
Coto	50	0.1080	7.6	27 to 30
Lares	40	0.1018	8.6	23 to 31
Voladora	48	0.1224	5.9	22 to 29

At each site, based on the measured depth to a shallowly buried metallic reflector, and using equations [1] and [2], the *v* and E_r of the upper part of the soil were determined (see Table 4). Differences in *v* and E_r are principally attributed to differences in soil moisture contents. As the dielectric properties of soils are temporally and spatially variable, all measurements provided in this report should be considered as approximations only.

Results:
Table 5 lists the current soil suitability indices for the soils that were traverse by GPR. The taxonomic classifications shown in Table 5 are based on laboratory characterization data from soil pedons that were sampled near each study site. Soils that are fine-loamy, fine, and very fine textured are assigned attribute index values (for their clay contents) of 3, 4, and 5, respectively. Soils with oxic or kandic horizons are assigned a textural adjustment (-1). In Table 5, the identified soil series are listed from top to bottom according to increasing SSI. This arrangement reflects increasing signal attenuation rates and more restricted GPR penetration depths.

Table 5. The sampled soils are rated based on their present GPR Soil Suitability Indices.

Soil Series	Taxonomic Classification	SIU
Cerro Gordo	Fine-loamy, mixed, isothermic Typic Haploperox	2
Consumo	Fine, mixed, semiactive, isohyperthermic Typic Kanhapludult	3
Voladora	Fine, mixed, active, isohyperthermic Typic Haplohumult	4
Coto	Very-fine, kaolinitic, isohyperthermic Typic Eutrudox	4
Nipe	Very-fine, ferruginous, isohyperthermic Typic Acrudox	4
Daguey	Very-fine, parasesquic, isohyperthermic Typic Haplohumult	5
Lares	Very-fine, mixed, semiactive, isohyperthermic Aquic Hapludult	5

Of the soils investigated, Cerro Gordo has the lowest SSI and is considered the best suited to GPR. Observations made in this study confirm this interpretation. Because of its medium texture (18 to 35% clay; SSI of 3) and the presence of an oxic horizon (textural adjustment of -1), Cerro Gordo soil is assigned a SSI of 2. Figure 3 is a representative radar record from an area of Cerro Gordo soils. In this radar record, the vertical and horizontal

scales are expressed in centimeters and meters, respectively. Radar records collected in this area of Cerro Gordo soils have remarkable resolution of subsurface features and rather surprising penetration depths (greater than 3 m). Radar records from all other investigated soils suffered high rates of signal attenuation, which resulted in very restricted penetration depths and reduced resolution of subsurface features. All other soils investigated in this study are fine or very-fine textured Ultisols or Oxisols.

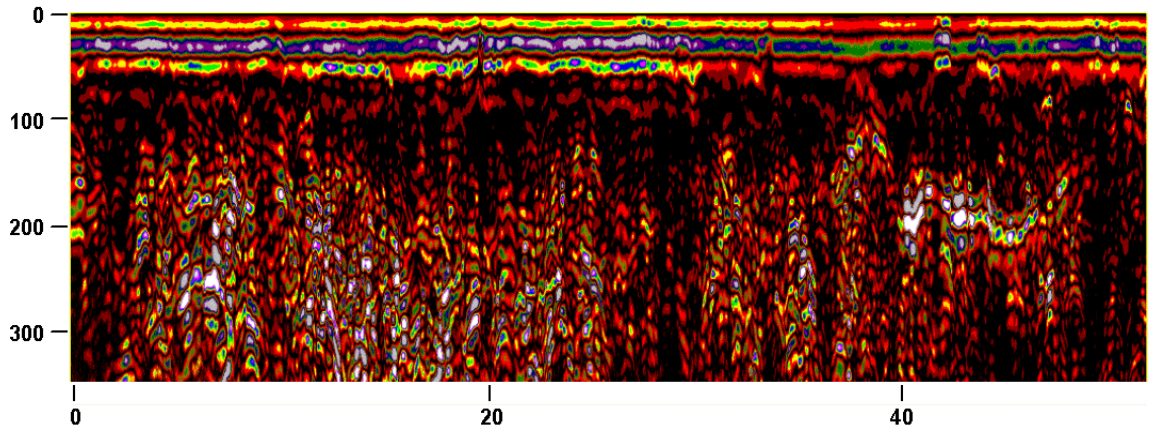

Figure 3. The high resolution and rather deep penetration depth (> 300 cm) for the Cerro Gordo soils supports the use of the mineralogy override for fine-loamy, highly weathered soils.

The radar record of the Cerro Gordo soil contains a large number of point reflectors. These reflectors represent relatively small, point reflectors; perhaps larger ironstone nodules and rock fragments. These reflectors could also represent a highly-irregular and weathered lithic contact. The seemingly, excessive scattering caused by these small-scale heterogeneities in the soil, is a source of signal attenuation that restricts penetration depths. In Figure 3, between the 40 and 48 m distance marks, and at depths of about 150 to 180 cm, a high amplitude, planar reflector is evident. This reflector may represent a petroferric or lithic contact. The SSI rating and the use of a textural adjustment (-1) for the moderately-fine textured Cerro Gordo series are appropriate.

The EM38 meter was difficult to calibrate and when lowered to the soil surface displayed negative EC_a. These characteristics are often experienced in soils with high magnetic susceptibility.

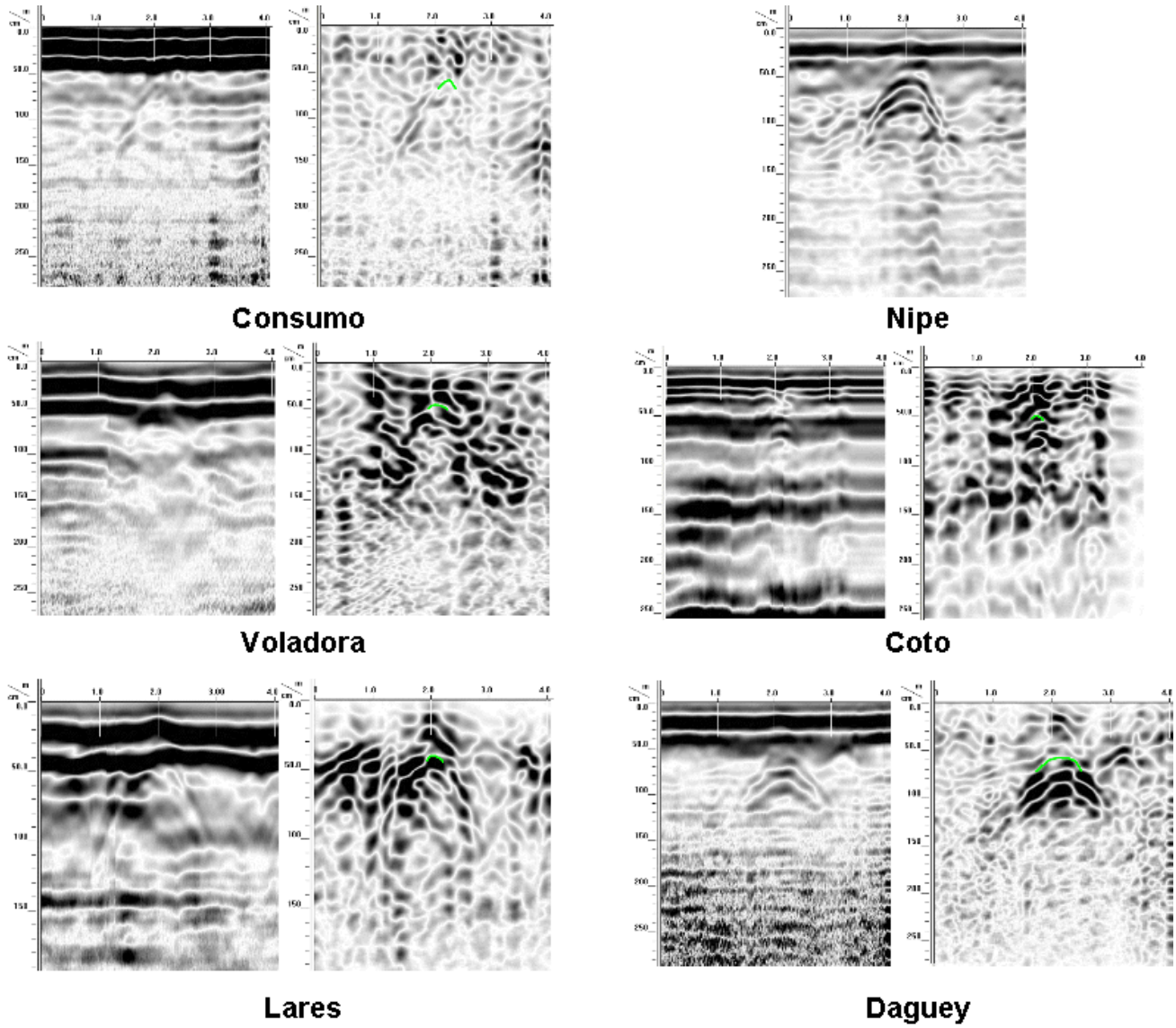

Figure 4. Relatively unprocessed and processed radar records from different soil sites in Puerto Rico.

Figure 4 contains a comparatively unprocessed radar record of Nipe soil, and five comparatively unprocessed and process radar records from the fine and very-fine textured soils investigated in this study. On each radar record, the vertical and horizontal scales are expressed in centimeters and meters, respectively. All radar records shown on this composite image were subjected to the following preliminary processing procedures: header editing, setting the initial pulse to time zero, color table and transformation selection, distance normalization, and display range gain adjustments. Additional processing was applied to the radar record shown on the right of each set of compound records. These processing techniques included signal stacking, horizontal high-pass filtration and range gain adjustments. Signal stacking is used to remove unwanted high frequency background noise (appears as "snow-like" noise on radar records). Horizontal high-pass (background removal) filter is used to remove bands of low-frequency ringing noise (mostly from the strong surface pulse). On most radar records, ringing noise obscured reflections from the relatively shallowly buried metallic reflector. Range gain adjustments were used to compensate for amplitude reduction caused by increasing signal attenuation with depth and by the application of added signal processing techniques.

Horizontal high pass filtration did reduce the level of unwanted background noise and improve the visibility of some near surface features, which had been masked by the strong surface reflection. In general, additional processing steps did not, however, improve the resolution or aid the identification of the shallowly buried artifact in these fine and very fine textured soils. The presence of weakly expressed diffraction tails did aid the identification of the buried artifact. Because of the expression of diffraction tails on hyperbolas produced by the buried artifact, I prefer the relatively unprocessed over the more highly processed radar records. With the application of additional processing techniques diffraction tails are removed, reduced in size, and/or segmented. On each of the more highly processed radar records (right-hand compound record) a green-colored line has been used to identify the approximate location of the buried artifact.

With the exceptions of Nipe and Daguey radar records, reflection patterns from the buried metallic reflector were poorly expressed on radar records (both relatively unprocessed and processed). Both Nipe and Daguey soils belong to the very-fine textural family. Unlike the other soils, Nipe and Daguey soils belong to the ferruginous and parasesquic mineralogy classes. The other soils belong to either the mixed or kaolinitic mineralogy classes. Soils belonging to the ferruginous mineralogy class have 18 to 40 % iron oxide (12.6 to 28 % Fe) (by dithionite citrate) in the fine earth fraction (Soil Survey Staff, 1999). Soils belonging to the parasesquic mineralogy class have a total iron oxide, by weight, plus percent gibbsite of more than 10 % in the fine earth fraction. In general, of the soils profiled with GPR in this study, those soils with higher total iron oxide contents (Cerro Gordo (15.8 to 20.5%), Nipe (15.0 to 17.5%) and Daguey (6.2 to 7.2 %) appear to provide (based on Figures 3 and 4) the best mediums for GPR applications.

Soils with high iron oxide contents often have high magnetic susceptibility and are attenuating and depth restrictive to GPR. The presence of iron and iron-bearing minerals are assumed to result in significant losses due to ferromagnetic relaxation processes (Olhoeft, 1994). Magnetic properties of soils are largely controlled by the presence, abundance, and oxidation state (which can be controlled by either oxygen or sulfur) of iron (Olhoeft, 1994). In this study, however, the presence of high amount of iron oxides in soils appears to favored deeper GPR penetration and improved resolution of subsurface features. This study lays emphasis on the need to better understand the affects of different soil mineralogy classes, especially sesquic, parasesquic, ferritic, ferruginous on the effectiveness of GPR.

The location of the buried metallic reflector, though less apparent on radar records collected in areas of Consumo, Voladora, Coto, and Lares soils, was known, and therefore could be identified. The use of advanced processing techniques, however, did not result in any greater illumination of the buried metallic reflector location. Buried at depths ranging from 40 to 57 cm, the metallic reflector could easily have been overlooked if its location were unknown in these soils.

Radar traverses were conducted over soils with textural control sections mostly within the fine and very-fine textured particle-size classes. With the exception of the Cerro Gordo soil, the maximum clay content of Bo and Bt horizons in these soils ranged from 63.5 to 82.5 %. For Cerro Gordo soil the maximum clay content was 42 % in the A horizon and 35.4 % in the Bo1 horizon. These soils have high clay contents, which even with dominance of low activity clays, are attenuating to GPR.

Other than the interface separating the surface layers from the subsoil, these soils lack contrasting soil layers that are detectable with GPR. The A/B horizon interface occurs within depth of 17 to 39 cm. With a 200 MHz antenna, features at these depths are too shallow to be resolved and are masked by the strong surface reflection.

The EMI responses over fine and very-fine textured soils were exceedingly variable with no consistent results that could be related to clay content or mineralogy.

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