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Subject: Soils -- Geophysical Assistance **Date:** 8 April 2008

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Purpose:
Ground-penetrating radar (GPR) was used to assess the depths to lithic gyprock, hypergypsic materials, petrogypsic and gypsic horizons; identify the presence of silicate-rich mantles; and provide documentation on map unit composition in Culberson County, Texas.

Principal Participants:
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Juan Herrero-Isern, Visiting Scientist, Texas Tech University, Plant & Soil Science Department, Lubbock, TX
Lynn Loomis, MLRA Project Leader, USDA-NRCS, Marfa, TX
Jim Rogers, Research Scientist, Texas Tech University, Plant & Soil Science, Lubbock, TX
Chanley Turner, District Technician, USDA-NRCS, Van Horn, TX

Activities:
All field activities were completed in Culberson County during the period of 5 to 9 March 2007.

Summary:

1. Global positioning system (GPS) technology has now been integrated with GPR. This integration allows the geo-referencings of individual radar scans. As several tens of scans are collected per second, the integration of GPS with GPR results in an unimaginably large geo-referenced data set and number of measurement points (a total of 169,709 were collected in Culberson County). With recent upgrading of the *RADAN* GPR processing software, depths to soil features can be readily calculated and exported into worksheets using an *Interactive 3D module*. The work in Culberson County, Texas, represents the first opportunity to conduct soil survey investigations with these technologies and to develop field protocol for their use. This report showcases these recent developments, which will have impact on how soil scientists will use GPR in the future to support soil survey operations.

2. In areas of gypseous soils, thin mantles of alluvial deposits are very attenuating and depth restrictive to GPR. In soils where this silicate-rich mantle is greater than 20 to 30 cm thick, the use of GPR is very restricted and not advised.

3. Within the Culberson Gypsum Plain, in areas that lack or have relatively thin (< 30 cm) alluvial mantles, GPR provides adequate penetration depths for soil investigations. However, even in these more favorable soils, GPR is unable to acceptably resolve the upper contact of gypsic and petrogypsic horizons, nor satisfactorily differentiate these two diagnostic subsurface horizons. Many of the propose soil series are shallow to petrogypsic horizons (Cavewell, Joberanch, Hollebeke, and Pokorny) and or gyprock (Elcor and Niemahr). Generally, features within the upper 40 cm of the soil profile cannot be adequately imaged with either a 200 or 400 MHz antenna. Without sufficient ground-truth

observations, the identification of these interfaces can not be confidently interpreted from radar records alone.

4. The interface separating hypergypsic soil materials from gyprock did provide relatively high-amplitude reflections that were identified and traced laterally across most portions of radar records. Gyprock provides a unique radar signature which aids identification.

5. On the Culberson Gypsum Plain, areas on radar record with no-*signal return* are associated with soils having silicate-rich alluvial mantles greater than 20 to 30 cm thick. Using the presence or absence of subsurface reflectors as an indicator of the mantle's thickness, GPR can be used to distinguish areas with and without thick silicate-rich mantles.

6. On the Culberson Gypsum Plain, GPR is suitable for determining the depth to gyprock in areas that lack relatively thick (> 20 to 30 cm) silicate-rich mantles. However, accurate depth determinations require auger and/or ground-truth pit observations to confirm interpretations and depth scales. As larger radar traverses and areas are often covered using the GPS options with GPR, variations in soil and dielectric properties can be larger, requiring greater ground control.

It is my pleasure to work in Texas and with Lynn Loomis. I wish to express my special thanks to Lynn for organizing the fieldwork, his kind fellowship, and willingness to share his knowledge.

With kind regards,

James A. Doolittle
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Study Sites:
All sites are located on the *Culberson Gypsum Plain* in MLRA 42 – Southern Desertic Basin, Plains and Mountain Native Range (USDA-NRCS, 2006). The Castile and Salado Formations (Late Permian-age) are exposed on over 250,000 hectares in Culberson County, Texas, and Eddy County, New Mexico (Lynn Loomis, personal communication) in an area known as the *Gypsum Plain* (Kirkland and Evans, 1976). The Castile and Salado formations weather to produce soils that have in excess of 80% gypsum. The World Reference Base for Soil Resources (WRB) uses *hypergypsic* to describe gypsic horizons with ≥60% gypsum (Herrero, 2004). These soils have been called "*gypseous*" (Texas Tech University and USDA NRCS, 2006). In contrast, soils that contain lesser amounts of gypsum (gypsum is a minor component) can have the textural modifier "*gypsiferous*." *Gypsiferous* is used for materials that contain ≥ 15 % by weight gypsum (Bob Engel, personal communication). Presently, gypsic and petrogypsic horizons are defined, but gypsum-rich soils are not adequately defined in Soil Taxonomy (Herrero, 2004). Herrero (2004) has noted that Soil Taxonomy does "not address sufficiently the advances in knowledge of the constitution, genesis, and behavior of gypseous horizons". The tentative taxonomic classifications of the proposed soil series study with GPR in Culberson County are listed in Table 1. Particle-size classes are not assigned to hypergypsic materials.

Table 1. Proposed taxonomic classification of the proposed soil series that were surveyed with GPR

Proposed Soil Series	Tentative Taxonomic Classification
Cavewell	hypergypsic, thermic Leptic Ustic Petrogypsids
Dillyhunt	fine-silty, mixed, thermic Ustic Haplocambids
Elcor	hypergypsic, thermic Lithic Ustic Hypergypsids
Hollebeke	hypergypsic, thermic Leptic Lithic Ustic Petrogypsids
Joberanch	hypergypsic, thermic, shallow Ustic Petrogypsids
Niemahr	loamy, mixed, superactive, thermic Lithic Ustic Haplocambids
Pokorny	hypergypsic, thermic Leptic Ustic Petrogypsids

Site 1:
The first site is located near the intersection of two farm roads. One, 860-m long GPR traverse line crossed this site. The GPR traverse line crossed an area between 31.5772° and 31.5800° N. Latitude and 104.4189° and 104.4247° W. Longitude. The area has been mapped as Joberanch and Dillyhunt soils. Both soils form in a mantle of alluvium overlying hypergypsic materials. These soils are very deep to gyprock. The proposed Joberanch series has a thin mantle (< 50 cm) of silicate-rich materials and is shallow (< 50 cm) to a weakly to moderately cemented petrogypsic horizon. The proposed Dillyhunt series has a thicker silicate-rich mantle, and gypsic and petrogypsic horizons within depths of 100 and 150 cm, respectively. Areas of the proposed Niemahr series were observed at this site. The Niemahr series forms in a thin silicate-rich alluvial mantle over hypergypsic materials, and is shallow to lithic gyprock.

Site 2:
The second site is located near an oil pad. Three GPR traverses were conducted at this site. These traverse lines ranged in length from about 140 to 180 m. The approximate location of the area traversed with GPR is between 31.6437° and 31.6455° N. Latitude and 104.3307° and 104.3316° W. Longitude. The site is on a karst-pitted, remnant platform. Soils are members of the proposed Dillyhunt, Pokorny, and Joberanch series. Dillyhunt and Joberanch soils occur where the mantle of silicate-rich alluvial materials fills depressions in the petrogypsic horizon. The Pokorny series forms in hypergypsic materials, lacks a silicate-rich surface mantle, and has a petrogypsic horizon within depths of 50 cm.

Site 3:
This site takes in a ridge of Cavewell and Hollebeke soils. Three GPR traverses were conducted at this site. These traverse lines ranged in length from about 190 to 325 m. The approximate location of the area traversed

with GPR is between 31.6283° and 31.6297° N. Latitude and 104.3263° and 104.3304° W. Longitude. The proposed Cavewell and Hollebeke series form in residual, hypergypsic materials weathered from gyprock. Both series lack a mantle of silicate-rich alluvial materials. Both Cavewell and Hollebeke series are shallow to a weakly-cemented petrogypsic horizon. Cavewell is deep (100-150 cm) and Hollebeke is shallow to a lithic contact of gyprock.

Site 4:
This site is located in an area of Pokorny and Joberanch soils. Site 4 is located on a broad upland area between 31.7454° and 31.7485° N. Latitude and between 104.445° and 104.446° W. Longitude. Two GPR traverses were completed at Site 4. The lengths of the two traverses were about 260 and 450 m.

Site 5:
This site is located on a ridge of Elcor soils. Site 5 is located between 31.7575° and 31.7584° N. Latitude and between 104.432° and 104.434° W. Longitude. The proposed Elcor series forms in hypergypsic materials and has lithic gyprock within depths of 25 cm. One GPR traverse was completed at this site. The length of the GPR traverse completed at this site was about 290 m.

Site 6:
This site is located on a broad upland in an area of Cavewell and Hollebeke soils. Site 6 is located between 31.7613° and 31.7624° N. Latitude and between 104.386° and 104.389° W. Longitude. Three GPR traverses were completed across this site. The lengths of the traverses ranged from about 55 to 285 m.

Site 7:
This site includes a recently sampled pit of Pokorny soil (Pedon ID S06-TX109-902). The site is in an area of Pokorny and Joberanch soils. This site will be included as a stop in the 2008 SSA Tour. One sinuous GPR traverse was completed at this site between 31.8699° and 31.8709° N. Latitude and between 104.330° and 104.331° W. Longitude. The length of the GPR traverse was about 200 m.

Site 8:
This site includes a recently sample pit of Hollebeke soil (Pedon ID: S06-TX109-901). The site is in an area of Cavewell and Hollebeke soils. This site will be included as a stop in the 2008 SSA Tour. One, 95-m long, GPR traverse was completed at this site. The traverse stretched between 31.8826° and 31.8827° N. Latitude and 104.326° to 104.327° W. Longitude.

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.

Radar records contained in this report were processed with the RADAN for Windows (version 6.6) software developed by GSSI.[1] Processing included: header editing, GPS positioning, setting the initial pulse to time zero, signal stacking, migration, and range gain adjustments. The coordinates of each radar scan were recorded with a Trimble AgGPS114 L-band DGPS (differential GPS) antenna (Trimble, Sunnyvale, CA).[1]

The National Soil Survey Center has recently upgraded its version of the RADAN (version 6.6) processing program. The upgraded version provides a setup for the simultaneous use of a GPS receiver, serial data recorder (SDR), and SIR-3000 system. This setup allows the automatic integration of GPR and GPS data. With this setup, each scan on radar records is geo-referenced. Geo-referenced radar records are imaged using the *3D*

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

QuickDraw Module of RADAN (version 6.6). In addition, using the *Interactive 3D Module* of the RADAN processing software, depths to soil horizons and features can be quickly, automatically, and accurately picked and outputted to worksheets (X, Y, Z format; containing latitude, longitude, and depths to a soil, stratigraphic, or bedrock feature). Using this module, data can be easily exported into GIS for plotting and visualization.

Survey Procedures:
Traverses were conducted with the SIR-3000 and a suitable antenna. The 200 MHz was preferred for field work in the rangeland settings of the *Culberson Gypsum Plain*. The 200 MHz antenna provided a more stable platform and remained more closely coupled with the ground surface than the smaller, lighter-weight 400 MHz antenna. Both antennas provided similar resolution of near surface features (neither could adequately discriminate features within the upper 40 cm). The 200 MHz antenna provided greater penetration depths. A Trimble AG114 global positioning system (GPS) receiver was used to collect the coordinates of each radar scan along GPR traverse lines. Each radar traverse was stored as a separate file (in this report, the file number will be used to identify a GPR traverse). Radar record was reviewed in the field and subsurface features identified. Ground-truth observations were made along several transect lines to confirm interpretations.

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 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] (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] (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 (temperature dependent) of water have the greatest effect on the E_r and v.

At several sites, based on the measured depth and the two-way pulse travel time to a known subsurface reflector, the velocity of propagation and the relative dielectric permittivity through the upper part of the soil profile were estimated using equations [1] and [2]. At Site 1 and 7, in areas of Dillyhunt and Joberanch soils, the estimated E_r was about 4.21 (v = 0.1452 m/ns). At Site 2, in an area of Pokorny, Dillyhunt, and Joberanch soils, the estimated E_r was about 4.45 (v = 0.1412 m/ns). At Site 5, in an area of Elcor soils, the estimated E_r was about 3.05 (v = 0.1746 m/ns).

Results:
Site 1: Area of Dillyhunt and Joberanch soils.
Figure 1 is a representative radar record that was collected with the 200 MHz antenna at Site 1. The white vertical lines at the top of the radar record represent the flagged reference points along the traverse line. In areas that lack or have a relatively thin (< 30 cm) alluvial mantle, GPR provided adequate penetration depths for soil investigations. However, even in these more favorable soils, GPR was unable to acceptably resolve the upper contact of shallow gypsic and petrogypsic horizons, nor satisfactorily differentiate these two diagnostic subsurface horizons. In many soils, gypsic and petrogypsic horizons occur at shallow depths and appear to grade laterally in degree of induration. As a consequence, these features are difficult to identify on radar records. Without sufficient ground-truth observations, the identification of these interfaces can not be confidently interpreted from radar records alone.

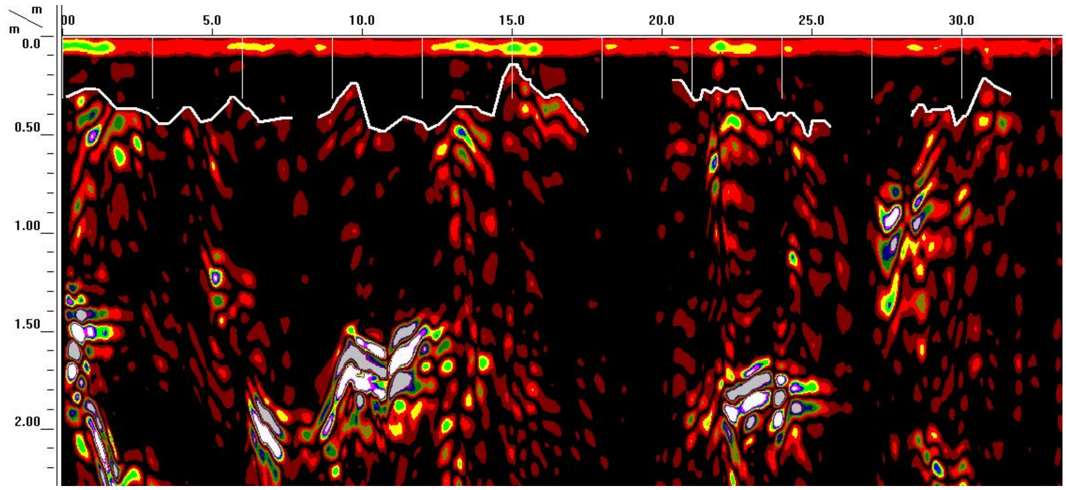

Figure 1. In this radar record from an area of Dillyhunt and Joberanch soils, the gyprock surface has been highlighted with a white line.

Variations in the amplitude of the surface pulse did provide some indication as to whether a petrogypsic or gypsic horizon was at or very near the soil surface. In general, the more cemented or indurated the surface materials, the stronger the amplitude of the reflected surface pulse. Where the surface pulse consists of higher amplitude reflections, a petrogypsic horizon was more likely to occur near the soil surface. Where the surface pulse consisted of lower amplitude reflections, a gypsic horizon or a thicker mantle of alluvial materials was suspected to occur near the surface. While these interpretations are generally reliable, it must be cautioned that other features (roots, rock fragments) can alter amplitudes within the surface pulse.

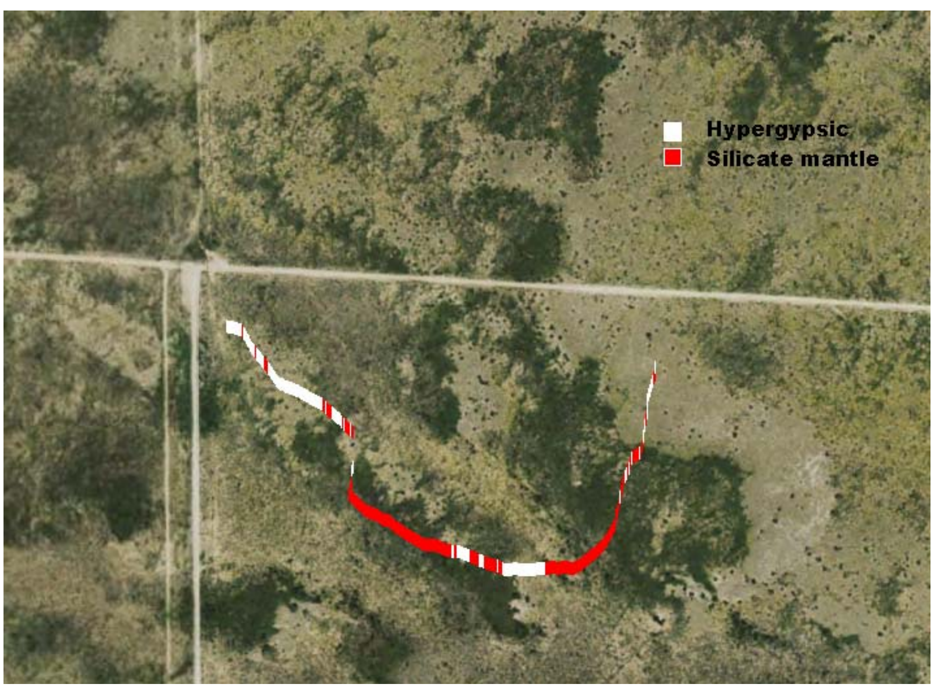

Figure 2. The location of a GPR traverse, which was conducted in an area of Dillyhunt and Joberanch soils, is shown on this Goggle Earth image. Colors are used to suggest areas of Dillyhunt (white) and Joberanch (red) soils.

Along the radar traverse shown in Figure 1, it was known that hypergypsic materials occurred at shallow depths. This aided interpretations. In Figure 1, a white line has been used to denote the interpreted depth to the gyprock. The placement of this line was assisted by six ground-truth observations. Along this traverse line, the average interpreted depth to gyprock was 41 cm, with a range of 18 to 73 cm. These depths are within the range of the proposed Niemahr series, which has a thin, silicate-rich surface mantle and lithic gyprock within depths of 50 cm.

Several areas of *no-signal return* are evident on the radar record shown in Figure 1. These areas occur beneath sections 17 to 20 m, 26 to 27 m, and 32 to 34 m. Beneath these sections of the radar record, reflections are exceedingly weak and no subsurface interface can be recognized. Areas of *no-signal return* are associated with thicker mantles of clay-enriched alluvial materials and deeper depths to hypergypsic materials. The clay content of the alluvial materials is relatively low, but sufficient to weaken the radar signal and limit the effective depth of penetration. Areas of *no-signal return* are characteristic of soils with silicate-rich mantles greater than 20 to 30 cm thick. The contact of the alluvial mantle with the underlying hypergypsic materials is masked by the strong surface pulse. Using the presence or absence of subsurface reflectors as an indicator of the alluvial mantles thickness, GPR was used to discriminate areas with and without thick silicate-rich mantles.

Figure 2 is a Goggle Earth image of Site 1. In this image, the location of the GPR traverse line is shown. Colors have been used to identify the presence and interpreted thickness of the silicate-rich mantle. Based on the aforementioned assumptions and reflection patterns, interpretations were made at 26,774 geo-referenced points on the radar record collected at this site. Soils with thick silicate-rich mantles occupy 53 % of the area traverse with GPR (see Figure 2). Soils with thicker silicate-rich mantles are easily identified in the field by changes in vegetal patterns. As can be noted in Figure 2, areas with thicker silicate-rich mantles generally support a more thriving stand of vegetation.

In soils with thicker silicate-rich mantles and deeper depths to hypergypsic materials, the depth of penetration was very restricted. Generally, radar records collected over these soils were devoid of meaningful subsurface reflections. The poor performance of GPR and the absence of subsurface reflections on radar records can be used to identify soils with thicker silicate-rich mantles. However, the presence and depths to gypsic and petrogypsic horizons or gyprock could not be identified and interpreted in these soils.

Site 2: Area of Pokorny, Dillyhunt, and Joberanch soils.

Three GPR traverse were completed at the “Oil Pad” Site or Site 2. Figure 3 is a three-dimensional (3D) block diagram showing the geo-referenced record from one GPR traverse line. This radar record has not been corrected for variations in surface topography. This record was collected with a 200 MHz antenna. The Universal Transverse Mercator coordinate system was used to geo-reference the location of each radar scan (observation point).

As evident in Figure 3, GPR provided adequate penetration depths (set for 2.5 m), but was unable to adequately resolve the upper contact of the gypsic and petrogypsic horizons. The interface between hypergypsic soil materials and gyprock did provide relatively high-amplitude reflections, which are more easily identified and traced across most portions of the radar records. In Figure 3, a large area of “*no-signal return*” is evident on the radar record. This area occurs at the base of a slope, in a draw, where the alluvial mantle is thicker and the vegetation is denser.

Figure 4 is a Goggle Earth image of Site 2. In this image, the locations of the three GPR traverse lines are shown. Colors have been used to identify the interpreted depths to gyprock according to soil depth classes. Black represents areas of *no-signal return* and areas with thicker silicate-rich mantles. These areas occupy about 13 % of the area traversed with GPR. Soils that lack or have a thin silicate-rich mantle occupy about 87 % of the areas traversed with GPR. Excluding the areas of *no-signal return*, Table 2 list the basic statistics for the three radar traverse shown in Figure 4. Table 3 lists the frequency distribution of soils that lack or have very thin silicate-rich mantles by soil depth classes for the three traverses. For each radar traverse, the average depth and the majority of observations were moderately deep (50 to 100 cm) to gyprock. Based on soil depth classes, the co-dominant soils in each traverse were shallow. While deep and very deep soils (>150 cm) soils did occur, they represent minor inclusions.

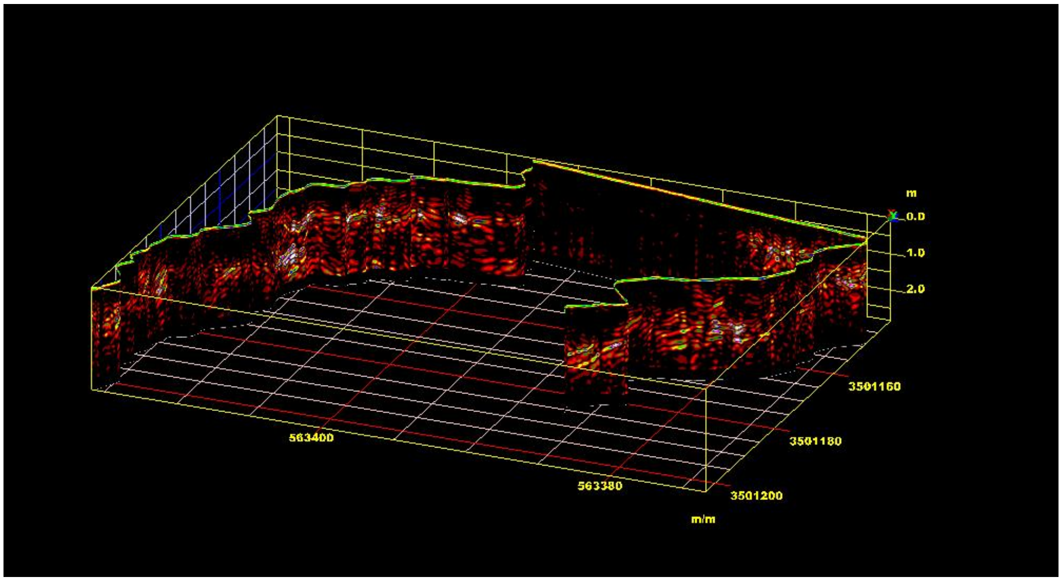

Figure 3. In this 3D rendition of a radar record that was collected in an area of Pokorny, Dillyhunt and Joberanch soils at Site 2, the contact of hypergypsic materials with the underlying gyprock can be seen.

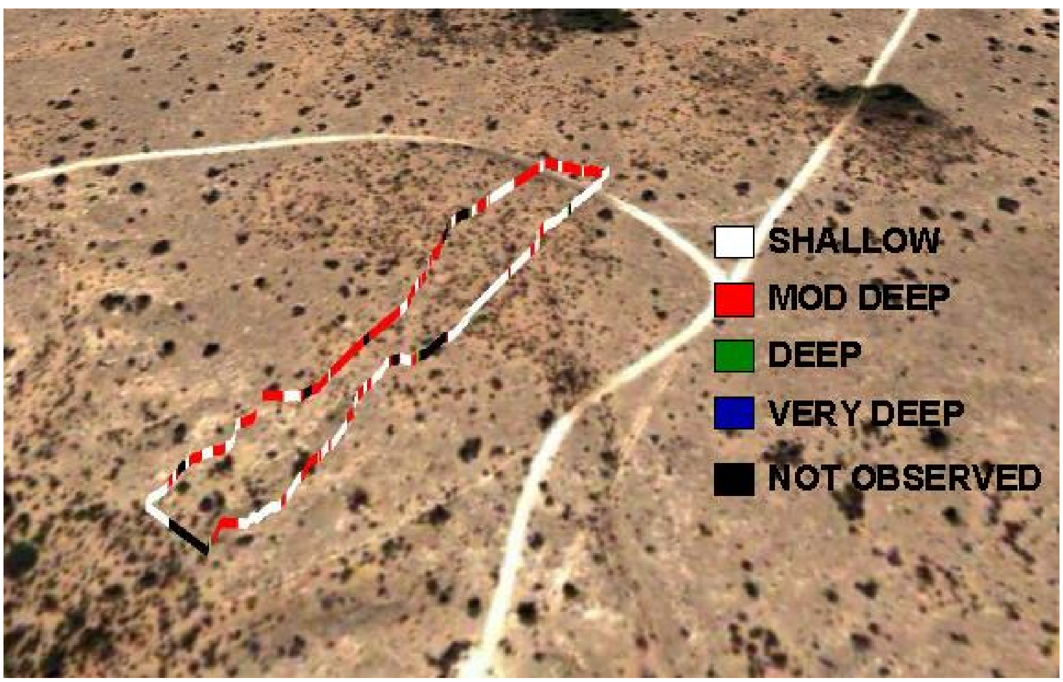

Figure 4. The locations of three GPR traverses that were conducted in an area of Pokorny, Dillyhunt, and Joberanch soils at Site 2 are shown on this Goggle Earth image. Colors are used to indicate the interpreted depths to gyprock.

Table 2. Basic statistics for the depth to gyprock along the three GPR traverse lines that were completed in an area of Pokorny, Dillyhunt, and Joberanch soils at Site 2. This data excludes areas of no-signal return.

	Obs.	Mean	Std. Dev.	Min.	25%-Tile	75%-Tile	Max.
LINE 19	3752	0.57	0.14	0.00	0.49	0.62	1.41
LINE 20	6060	0.87	0.62	0.00	0.50	0.92	1.48
LINE 21	4572	0.82	0.14	0.32	0.75	0.91	1.51

Table 3. Frequency distribution of observations based on soil depth criteria at Site 2. This data excludes areas of no-signal return.

	Shallow	Mod Deep	Deep	Very Deep
LINE 19	0.28	0.70	0.02	0.00
LINE 20	0.29	0.64	0.07	0.00
LINE 21	0.02	0.88	0.10	0.00

Site 3: Area of Cavewell and Hollebeke soils.

Site 3 is located on an upland area with vary sparse vegetation. In general, soils at this site lack or have a very thin mantle of silicate-rich alluvium and are well suited to GPR soil investigations. Figure 5 is a representative radar record collected with a 200 MHz antenna at Site 3. While GPR provided adequate penetration depths in areas that lack or have a relatively thin alluvial mantle, it was unable to acceptably resolve the upper boundary of the gypsic and/or petrogypsic horizons. As a consequence, without sufficient ground-truth observations, the identification of these interfaces could not be confidently interpreted from the radar records. In Figure 5, the contact of hypergypsic materials with the underlying gyprock has been highlighted with a white line. Within the hypergypsic materials, radar reflections are generally sparse and of low amplitudes. The gyprock is characterized by an abundance of higher-amplitude, inclined planar reflectors. In some areas patterns within the gyprock are more chaotic.

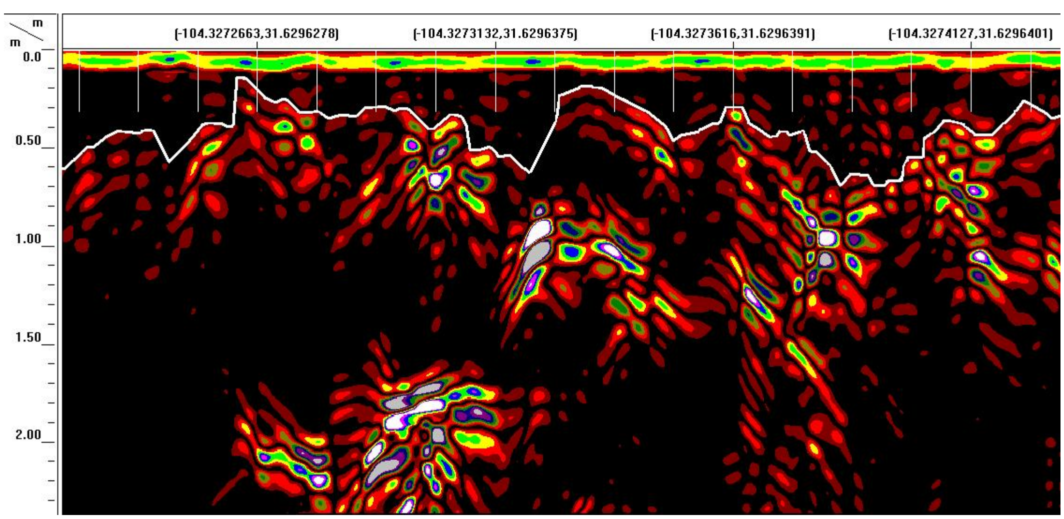

Figure 5. The white line in this radar record identifies the depth to gyprock in an area of Cavewell and Hollebeke soils at Site 3.

Figure 6 is a Goggle Earth image of Site 3. In this image, the locations of the three GPR traverse lines are shown. Colors have been used to identify the interpreted depths to gyprock according to soil depth classes. Black represents areas of *no- signal returns*. These areas are inferred to have thicker silicate-rich mantles. At this site, these areas occupy about 23 % of the area traversed with GPR. Soils that lack or have thin silicate-rich mantles occupy about 77 % of the areas traversed with GPR. Table 4 lists the basic statistics for the soils that lack thicker silicate-rich mantles along the radar traverses shown in Figure 6. Interpreted depths to gyprock averaged 47 cm, but ranged from about 0 to 2.1 m. Table 5 lists the frequency distribution of these soils along the three traverses according to soil depth classes. For each radar traverse, the majority of observations were shallow to gyprock. The co-dominant soils in each traverse are moderately deep to gyprock. While deep and very deep soils did occur, they represent minor inclusions.

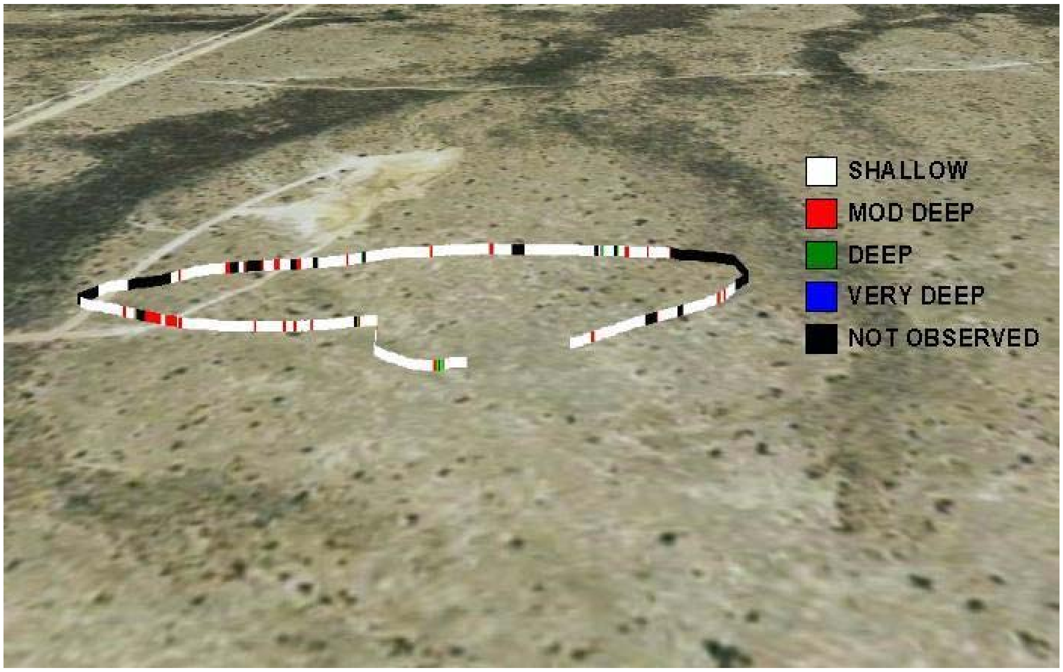

Figure 6. The locations of three GPR traverses, which were conducted in an area of Cavewell and Hollebeke soils at Site 3, are shown on this Goggle Earth image. Colors are used to indicate the depth to gyprock.

Table 4. Basic statistics for the depth to gyprock along GPR traverses conducted at Site 3. This data excludes areas of no-signal returns.

	FILE 22	FILE 23	FILE 24
Observations	13558	15072	12842
Average	0.44	0.54	0.41
Std. Deviation	0.20	0.24	0.22
Minimum	0.02	0.02	0.02
25%-Tile	0.31	0.38	0.26
75%-Tile	0.55	0.66	0.54
Maximum	1.41	2.11	1.27

Table 5. Frequency distribution of observations based on soil depth criteria at Site 3. This data excludes areas of no-signal returns.

	FILE 22	FILE 23	FILE 24
Shallow	0.67	0.53	0.70
Mod Deep	0.32	0.42	0.27
Deep	0.01	0.04	0.03
Very Deep	0.00	0.01	0.00

<u>Site 4: Area of Pokorny and Joberanch soils:</u>

In general, a relatively thin mantle of alluvium covers most of this site. Where the silicate-rich mantle is greater than 20 to 30 cm thick, radar records are plagued by areas of *no-signal return* and lack identifiable subsurface interfaces. The proposed Pokorny series forms in hypergypsic materials, lacks a silicate-rich mantle, and is more transparent to GPR.

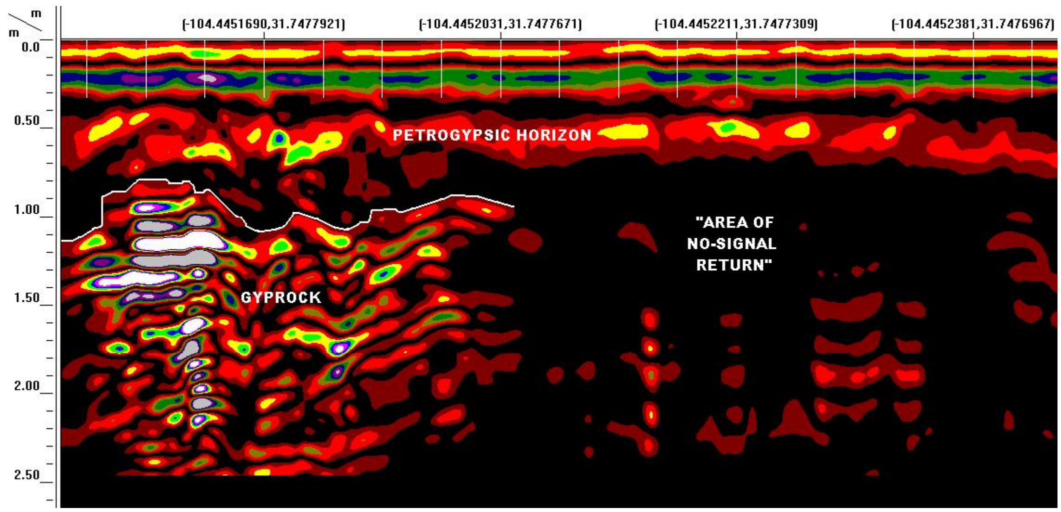

Figure 7. In this radar record that was collected in an area of Pokorny and Joberanch soils (Site 4), the relatively broad reflection patterns from a shallow petrogypsic horizon contrast with the narrower, better-defined patterns of the underlying gyprock.

Figure 7 is a portion of a radar record that was obtained at Site 4. Based on the radar imagery (or absence of), areas of Pokorny and Joberanch soils are assumed to respectively dominate the left-hand and right-hand portions of this radar record. The underlying gyprock provides a distinct and easily identifiable radar signature. Inhomogeneities (e.g., bedding and fracture planes, solution cavities) within the gyprock provide reflections of varying signal amplitudes. Pokorny soils are deep to gyprock. The left-hand portion of this radar record appears to be dominated by the moderately deep (Cavewell) soils. Areas of *no-signal return* are associated with Dillyhunt, Joberanch, and Niemahr soils. The proposed Dillyhunt and Joberanch soils are very deep to gyprock. The propose Niemahr soils are shallow to gyprock. Judging from the radar records from areas of this site that lack a silicate-rich mantle and are more suitable to GPR, a large proportion of the soils are moderately deep and deep to gyprock.

In the upper part of the radar record shown in Figure 7, a broad horizontal band is evident at a depth of approximately 50 cm. This represents the petrogypsic horizon. Generally, low to moderate signal amplitudes (colored in shades of red) characterize the petrogypsic horizon and suggest materials that do not contrast significantly with the surface layers. Scattered within this broad horizontal band are areas of higher signal amplitudes (colored in shades of yellow, green, blue). These areas may represent more strongly cemented materials, gyprock fragments, larger roots or animal burrows. While distinct on this radar record, reflections from shallower petrogypsic horizon often merge with and are obscured by the surface pulse. Without extensive ground-truth observations it is impossible to determine the degree of induration or whether an interface represents a petrogypsic or gypsic horizon.

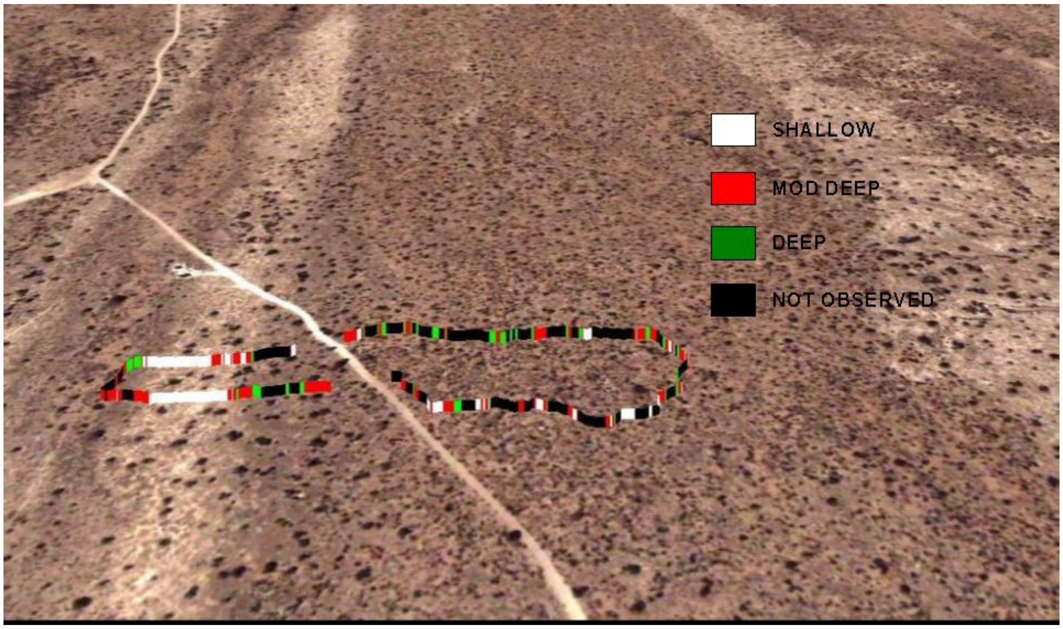

Figure 8. The locations of the GPR traverses, which were conducted in an area of Pokorny and Joberanch soils at Site 4, are shown on this Goggle Earth image. Colors are used to indicate the depth to gyprock.

Figure 8 is a Goggle Earth image of Site 4. In this image, the locations of two GPR traverse lines are shown. Colors have been used to identify the depth to gyprock according to soil depth classes. Areas of *no-signal return*, which represent areas with thicker alluvial mantles, are identified in black. These areas occupy about 21 % of the area traversed with GPR. Soils that lack or have a very thin silicate-rich mantle occupy about 79 % of the areas traversed with GPR. Table 6 list the basic statistics for the depth to gyprock along the two radar traverses shown in Figure 8. This data excludes areas of *no-signal return*. Table 7 lists the frequency distribution of observations by soil depth classes for all data collected along the two GPR traverse lines. Soils that are moderately deep to gyprock represent about 37 % of the areas traversed with GPR. Soils that are deep to gyprock represent about 29% of the traversed areas. While shallow soils did occur, they represent minor inclusions (about 14% of the area traversed). A majority of the shallow to gyprock soils are located on a more sloping area in the southern portion of the site (to the left in Figure 8). In Figure 8, this area of shallower soils is seen to support sparser vegetation. No very deep soils were interpreted along these traverses.

Table 6. Basic statistics for the depth to gyprock along the two GPR traverse lines that were completed at Site 4. This data excludes areas of no-signal return.

	FILE 6	**FILE 7**
Observations	13558	15072
Average	0.75	0.89
Std. Deviation	0.33	0.28
Minimum	0.06	0.11
25%-Tile	0.50	0.70
75%-Tile	1.03	1.10
Maximum	1.49	1.36

Table 7. Frequency distribution of observations based on soil depth criteria at Site 4.

	FILE 6	**FILE 7**
Shallow	0.18	0.08
Mod Deep	0.33	0.42
Deep	0.20	0.39
Not Observed	0.28	0.11

Site 5: Area of Elcor soils:
This site includes a well-define ridge that supports very sparse vegetation. The proposed Elcor series forms in hypergypsic materials. Elcor soils have lithic gyprock within depths of 25 cm. Gyprock and hypergypsic materials are well suited to soil investigations with GPR. Figure 9 is a 3D rendition of the radar record that was collected at this site. The Universal Transverse Mercator coordinate system was used to geo-reference the location of each radar scan (observation point). This radar record has not been corrected for variations in topography. In Figure 9, the contact between the hypergypsic materials and the underlying gyprock is fairly easy to identify and trace laterally across the radar record. The structure and geometry of bedding and fracture planes within the gyprock are readily apparent on the radar record shown in Figure 9.

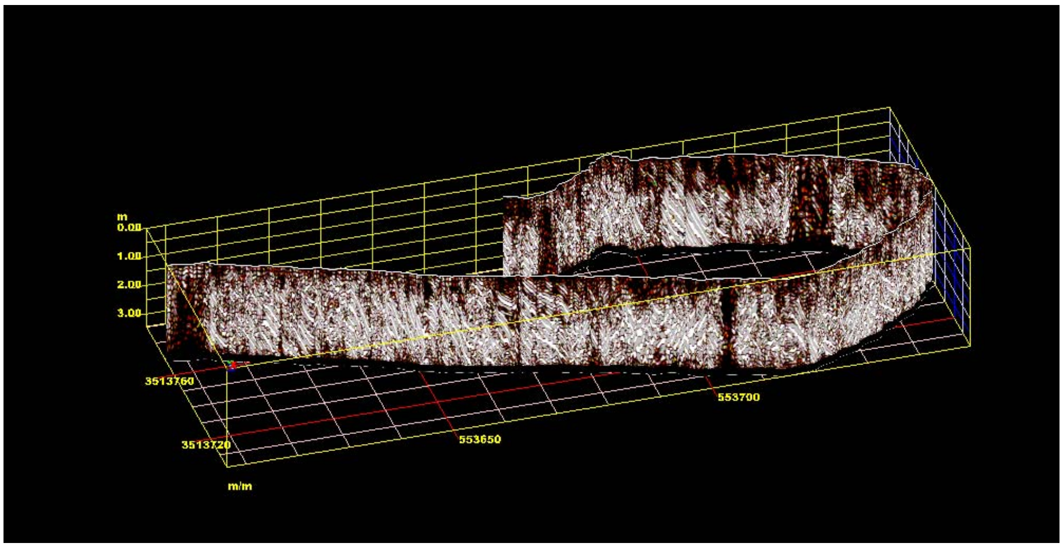

Figure 9. In this 3D rendition of a radar record that was collected in an area of Elcor soils, the structure and geometry of bedding and fracture planes within the gyprock can be seen.

Figure 10 is a Goggle Earth image of Site 5. The location of the GPR traverse line is shown on this image. Once again, colors have been used to identify the depth to gyprock. Areas of *no-signal return*, representing areas with thicker alluvial mantles are identified in black. These areas occupy less than 1 % of the area traversed with GPR. Table 8 list the basic statistics for the depth to gyprock along the radar traverse shown in Figure 9. This data excludes areas of *no-signal return*. Along this radar traverse, the average depth to gyprock was 0.55 cm with a standard deviation of 0.34. Table 9 lists the frequency distribution of observations by soil depth classes. The majority of observations are shallow (48 %) and moderately-deep (43 %) to gyprock. Deep and very deep soils represent about 8 % of the traversed area.

Table 8. Basic statistics for the depth to gyprock along the two GPR traverse lines that were completed at Site 5.

	FILE 8
Observations	22724
Average	0.55
Std. Deviation	0.34
Minimum	0.00
25%-Tile	0.32
75%-Tile	0.74
Maximum	2.40

Table 9. Frequency distribution of observations based on soil depth criteria at Site 5.

	FILE 8
Shallow	0.48
Mod Deep	0.43
Deep	0.08
Very Deep	0.00
Not Observed	0.01

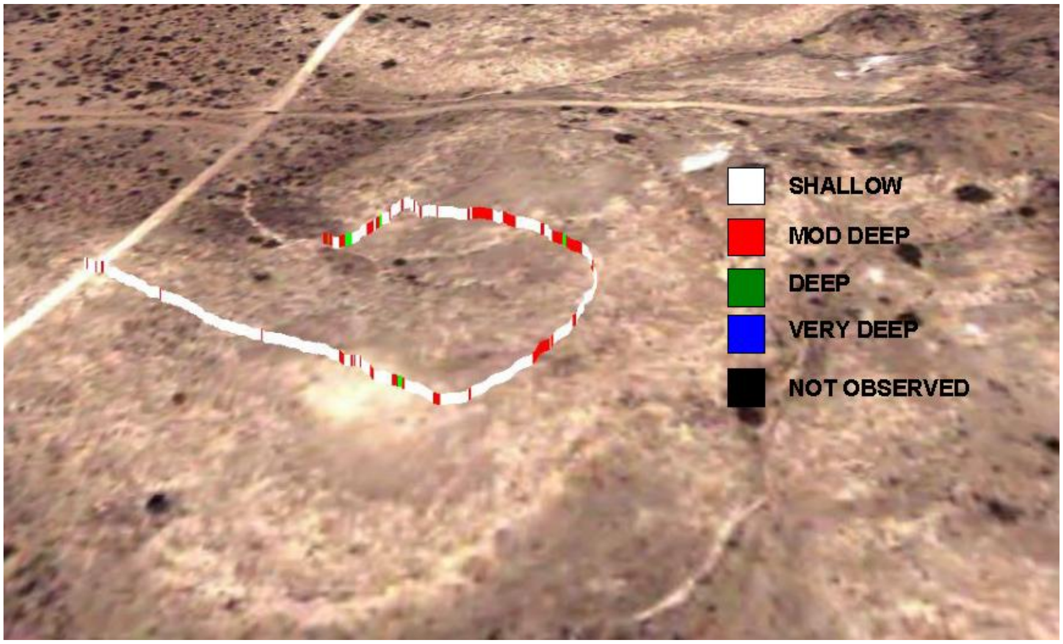

Figure 10. The locations of the GPR traverses, which were conducted in an area of Elcor soils at Site 5, are shown on this Goggle Earth image. Colors are used to indicate the depth to gyprock.

Site 6: Area of Cavewell and Hollebeke soils:

This is the second area (see Site 3) investigated with GPR that is mapped as Cavewell and Hollebeke soils. Compared with Site 3, Site 6 has more extensive areas with *no-signal returns*, which are inferred to represent thicker silicate-rich mantles.

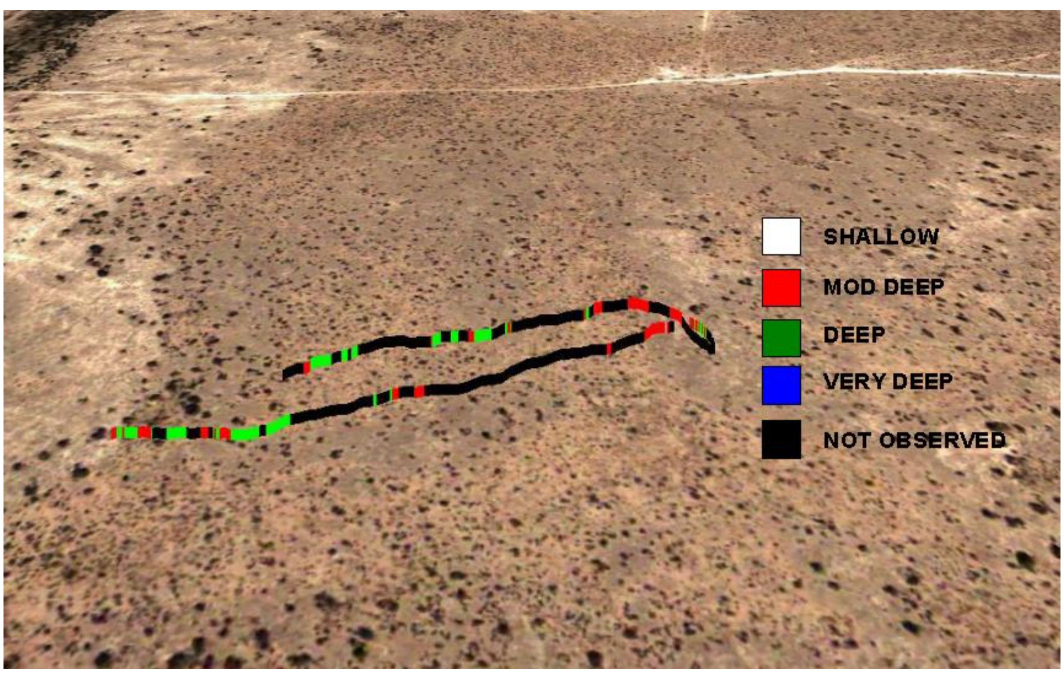

Figure 11. The locations of the three GPR traverses, which were conducted in an area of as Cavewell and Hollebeke soils at Site 6, are shown on this Goggle Earth image. Colors are used to indicate the depth to gyprock.

Figure 11 is a Goggle Earth image of Site 6. In this image, the locations of the three GPR traverse lines are shown. Colors have been used to identify the depth to gyprock according to soil depth classes. Black is used to represents areas of *no-signal return*. Table 10 lists the basic statistics for the depth to gyprock along the three radar traverse shown in Figure 11. This data excludes areas of *no-signal return*. Along the three radar traverses, the average depth to gyprock is 119 cm with a standard deviation of 0.211. Table 11 lists the frequency distribution of soils base on soil depth classes for the three traverses. Areas of *no-signal return* and presumably thicker silicate-rich mantles occupy about 67 % of the area traversed with GPR. Soils that lack or have a thin silicate-rich mantle occupy about 33 % of the areas traversed with GPR. Excluding the areas with *no-signal returns*, the majority of soils is deep (100 to 150 cm) to gyprock. Moderately deep and deep soils are minor inclusions along each traverse line. No shallow soils were interpreted at this site.

Table 10. Basic statistics for the depth to gyprock along the two GPR traverse lines that were completed at Site 6. This data does not include areas of no-signal return.

	FILE 9	FILE 10	FILE 11
Observations	16189	4722	13305
Average	1.21	1.15	1.16
Std. Deviation	0.22	0.15	0.22
Minimum	0.72	0.80	0.73
25%-Tile	1.03	1.09	1.00
75%-Tile	1.40	1.25	1.38
Maximum	1.68	1.55	1.51

Table 11. Frequency distribution of observations based on soil depth criteria at Site 6.

	File 9	File 10	FILE 11
Shallow	0.08	0.07	0.08
Mod Deep	0.24	0.23	0.22
Deep	0.02	0.00	0.05
Not Observed	0.66	0.70	0.65

Site 7: Area of Pokorny and Joberanch soils:

This site includes a sample pit for the Pokorny soil (Pedon ID: S06-TX109-902). A very twisting, 200-m long traverse was conducted across this site with a 200 MHz antenna. Figure 12 is a 3D rendition of the radar record along this traverse line. The Universal Transverse Mercator coordinate system was used to geo-reference the location of each radar scan (observation point). This radar record has not been corrected for variations in topography.

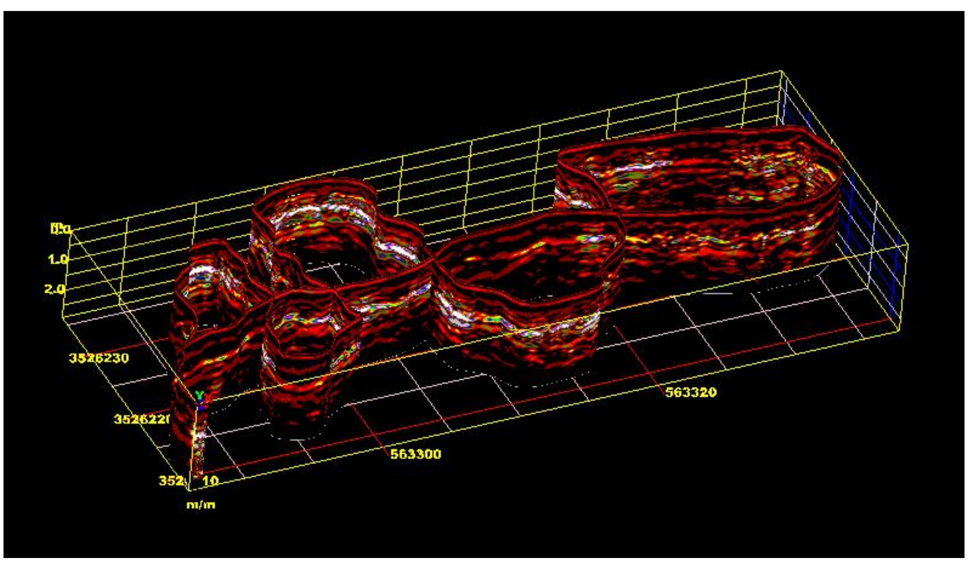

Figure 12. In this 3D rendition of a radar record that was collected in an area of Pokorny and Joberanch soils at Site 7, the continuous subsurface planar reflector is believed to represent a petrogypsic horizon.

In this area of Pokorny and Joberanch soils, the depth of penetration was about 2.5 m. Areas of *no-signal return* were not evident on the radar record (Figure 12), suggesting the absence of, or a very thin silicate-rich mantle, which would attenuate the radar signals and limit penetration depths. As can be seen in Figure 12, a continuous subsurface planar reflector is evident throughout the radar record. The average interpreted depth to this reflector is 93 cm with a range of 63 to 126 cm. This reflector represents the contact between two materials of different dielectric properties. This planar reflector varied in signal amplitudes suggesting lateral changes in the abruptness and/or the contrast in dielectric properties across the interface.

A closer look at the continuous subsurface planar reflector is provided in Figure 13. In Figure 13, the upper boundary of this reflector has been highlighted with a white line. Unlike the images from gyprock, this interface closely parallels the soil surface and has broader widths. The broader pulse widths suggest the attenuation of high frequency signal components and the transmission of lower frequency components. In addition, the absence of significant returns (other than signal multiples) below this interface also suggests attenuation. At previous sites, the gyprock provided a favorable medium for GPR and was characterized by multiple reflectors with narrow widths. The multiple reflectors were attributed to bedding and fracture planes and solution features. In Figure 13, the continuous subsurface reflector is therefore not suspected to represent the interface between hypergypsic materials and the gyprock that was so evident at the other sites. The interface highlighted in Figure 13 is believed to represent a petrogypsic horizon. If this continuous, planar reflector represents the upper boundary of the petrogypsic horizon, variations in signal amplitude along this interface could be related to differences in the degree of cementation or binding. This attribute, if confirmed and found to be reliable, may provide a means in some areas for the noninvasive determination of the presence and depth to petrogypsic and gypsic horizons. Gyprock was not imaged at this site.

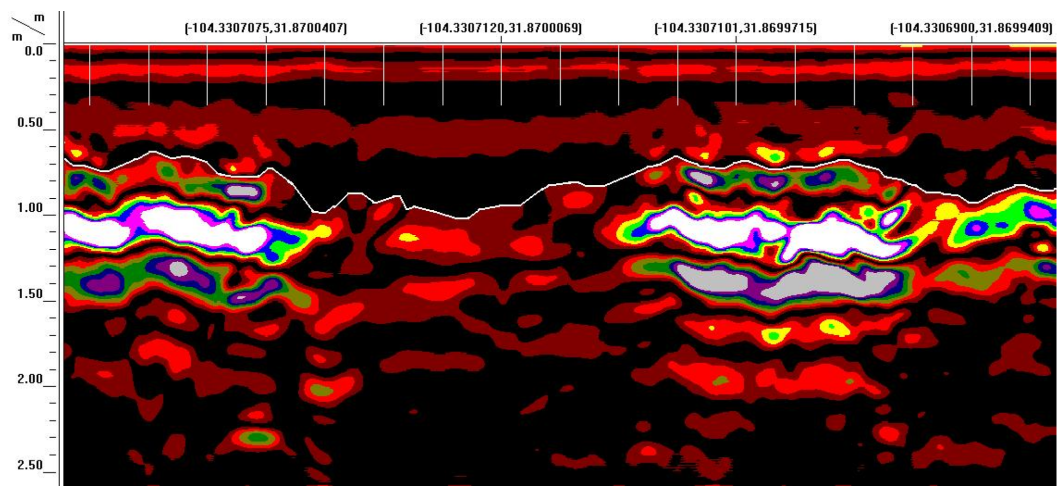

Figure 13. The white line in this radar record identifies the depth to petrogypsic horizon in an area of Pokorny and Joberanch soils at Site 7.

<u>Site 8: Area of Hollebeke soils:</u>
This site includes a sample pit for the Hollebeke soil (Pedon ID: S06-TX109-901). Hollebeke soils lack a silicate-rich mantle, have a weakly-cemented petrogypsic horizon, and are shallow to gyprock. A short 95-m traverse with a 200 MHz antenna was completed at this site. Figure 14 is a Goggle Earth image of Site 8 that shows this GPR traverse line. Colors have been used to identify the depth to gyprock according to soil depth classes. Only shallow and moderately deep soils were interpreted from the radar record.

In Figure 15, the underlying structure of the gyprock is evident on a 3D rendition of the radar record. The Universal Transverse Mercator coordinate system was used to geo-reference the location of each radar scan (observation point). This radar record has not been corrected for variations in topography. Within the gyprock, strata vary from slightly inclined to highly irregular or contorted. These characteristics help to define the gyprock and distinguish it from overlying hypergypsic materials and petrogypsic horizon. With the relatively low frequency 200 MHz antenna, it was difficult to clearly identify features within the upper 40 cm of the soil profile. Within depths of 0 to 40 cm, interpretations can be made, but are more ambiguous than interpretations made at deeper depths. Based on interpretations made 6347 points along this traverse line, the average depth to gyprock is 51 cm with a range of about 17 to 95 cm. The depth to gyprock did not vary greatly across this site. One-half of the observations had depths to gyprock between 39 and 60 cm. Along this GPR traverse lines soils were mostly moderately deep (55 %) and shallow (45) to gyprock soils.

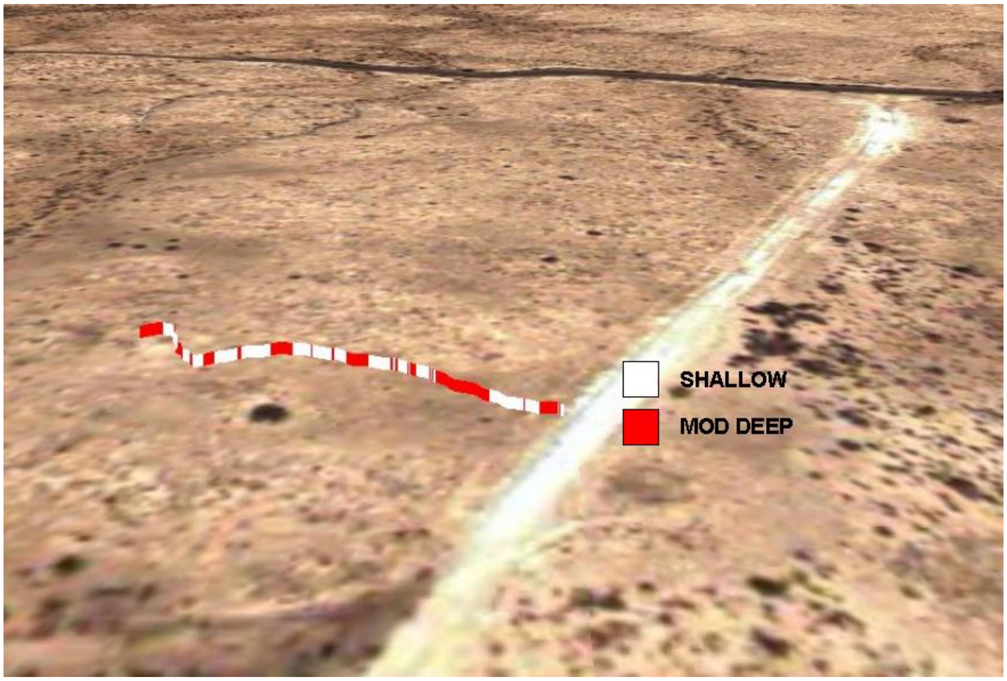

Figure 14. The locations of the GPR traverse line, which were conducted in an area of as Cavewell and Hollebeke soils at Site 8, is shown on this Goggle Earth image. Colors are used to indicate the depth to gyprock.

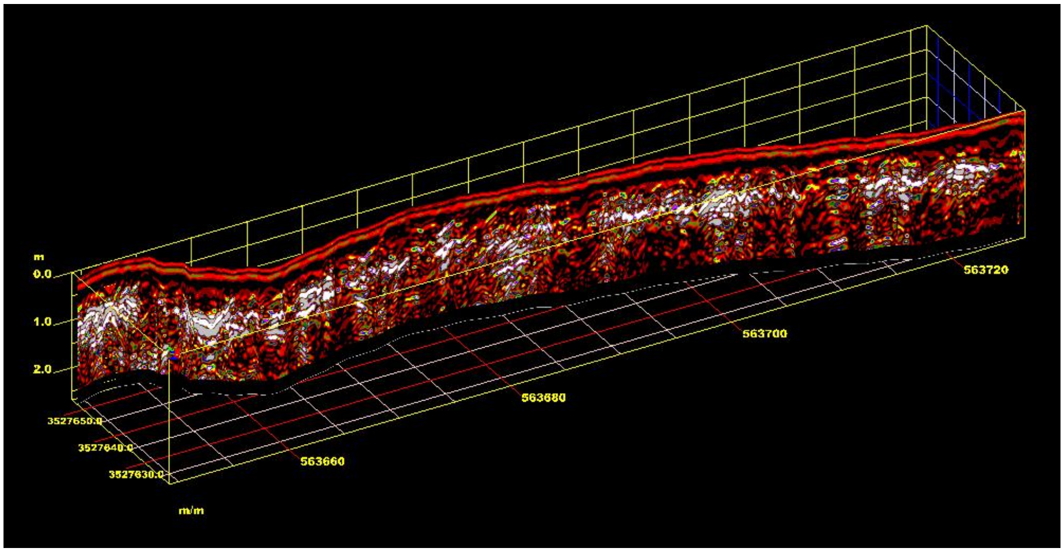

Figure 15. In this 3D rendition of a radar record that was collected in an area of Cavewell and Hollebeke soils, inclined to contorted strata provide a distinguishing signature for gyprock.

References

Daniels, D. J., 2004. Ground Penetrating Radar; 2nd Edition. The Institute of Electrical Engineers, London, United Kingdom.

Herrero, J., 2004. Revisiting the definitions of gypsic and petrogypsic horizons in Soil Taxonomy and World Reference Base for Soil Resources. Geoderma 120: 1-5.

Kirkland, D. W. and R. Evans, 1976. Origin of limestone buttes, Gypsum Plain, Culberson County, Texas. AAPG Bulletin 60(11): 2005-2018.

Texas Tech University and USDA NRCS, 2006. New Mexico and Texas Gypsum Soils Symposium/Study. Texas Tech University, Lubbock, Texas.

USDA-NRCS, 2006. Land Resource Regions and Major Land Resource Areas of the United States, the Caribbean, and the Pacific Basin. USDA Handbook 296, US Government Printing Office, Washington, District of Columbia.