United States Department of Agriculture | **Natural Resources Conservation Service** | **100 Campus Boulevard Suite 200 Newtown Square, PA 19087-4585**

Subject: Soils -- Geophysical Assistance **Date:** 26 March 2007

To: Mike Risinger
MO9 Leader/State Soil Scientist
USDA-NRCS
W.R. Poage Federal Building
101 South Main Street
Temple, TX 76501-7682

Dr. Wayne Hudnall
Professor of Soil Science
Plant and Soil Science Department
Box 42122
Texas Tech University
Lubbock, Texas 79409-2122

Purpose:
The purpose of this study was to assess the influence of gpyrock and gypseous soils on the penetration depth and effectiveness of ground-penetrating radar (GPR). This work expands on earlier GPR studies, which were conducted on aeolian deposits derived from weathered gypsum crystals in the Tularosa Basin of New Mexico. In addition, electromagnetic induction (EMI) was used to characterize soils and soil properties at sites located in Culberson and Lubbock Counties.

Principal Participants:
Jim Doolittle, Research Soil Scientist, USDA-NRCS-NSSC, Newtown Square, PA
Wayne Hudnall, Professor, Plant and Soil Science Department, Texas Tech., Lubbock, TX
Lynn Loomis, MLRA Project Leader, USDA-NRCS, Marfa, TX
Annesly Nettininghe, PhD Candidate, Plant and Soil Science Department, Texas Tech., Lubbock, TX
Nicole Termini, Graduate Student, Plant and Soil Science Department, Texas Tech., Lubbock, TX

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

Summary:

1. Gypseous soils and gpyrock are well suited to ground-penetrating radar. This study confirms the non-limiting characteristics of gypsum and the high potential of gypseous soils and gpyrock to GPR. However, because of associated characteristics and properties (less intense leaching, prevalence of other soluble salts, greater quantities of inherited minerals from parent rock, and accumulations of specific mineral products of weathering), gypsiferous soils remain limiting to GPR. For GPR Soil Suitability maps (http://soils.usda.gov/), ratings could be improved if gypseous and gypsiferous soils are separately distinguishable.

2. A 400 MHz antenna can be used to provide high resolution radar records showing lithologic and solution features within gpyrock to depths of 2.5 to 3 meters. Lower frequency antennas can be used to extend this depth of penetration through gyprock.

3. In areas of gypseous soils, ground-penetrating radar can be effectively used to estimate the depth to lithic contact. GPR can also be used to differentiate gypseous soils based on soil depth criteria, presence of silicate mantles, and cementation of petrogypsic horizons.

4. In areas of gypseous soils, thin mantles that contain silicate clay minerals are very attenuating and depth restrictive to GPR. In soils where the silicate mantle was greater than 20 to 30 cm thick, the use of GPR is very restricted. EMI is a more suitable tool in these soils.

5. During my visit to Texas, difficulties were experienced transferring and processing GPS and EC_a data using the Trackmaker38, and Trackmaker38DD programs. The vendor, Geomar Software, Inc., examined the data and noticed that the Garmin GPS 76 receivers used by USDA were streaming too much unnecessary information into the Allegro field computer. They recommended collecting EC_a data at a faster rate (5 or 10 samples/sec). In addition, the use of NMEA Data: *GGA* should be specified in the Allegro (in GPS Port Setup dialog). Previously, selection has been *GGA/GSA* and the Garmin GPS receivers are not sending *GSA* data. Therefore, operators must insure that the *GSA Message* is *Disabled* on the TrackMaker38 programs while merging GPS and EC_a data and creating XYZ files. Responding to our needs, Geomar Software, Inc. has updated these programs with a newer version (version 1.65). Texas has an earlier version (1.59) of the Trackmaker38 software program, which needs to be updated by calling Geomar Software Inc. for the updated version.

It is my pleasure to work in Texas, with Lynn Loomis, Dr. Wayne Hudnall and his graduate students. I wish to express my special thanks to Lynn Loomis for organizing the fieldwork, his exception insight into gypseous soils, and his help in preparing this trip report.

With kind regards,

James A. Doolittle
Research Soil Scientist
National Soil Survey Center

cc:
B. Ahrens, Director, National Soil Survey Center, USDA-NRCS, Federal Building, Room 152, 100 Centennial Mall North, Lincoln, NE 68508-3866
M. Golden, Director of Soils Survey Division, USDA-NRCS, Room 4250 South Building, 14th & Independence Ave. SW, Washington, DC 20250
D. Hammer, National Leader, Soil Investigation Staff, USDA-NRCS, National Soil Survey Center, Federal Building, Room 152, 100 Centennial Mall North, Lincoln, NE 68508-3866
L. Loomis, Soil Scientist, USDA-NRCS, Marfa Soil Survey Office, 213 N Highland, Marfa, TX 79843
W. Tuttle, Soil Scientist (Geophysical), USDA-NRCS-NSSC, P.O. Box 974, Federal Building, Room G08, 207 West Main Street, Wilkesboro, NC 28697

Background:
The Castile and Salado Formations (Late Permian-age) are exposed on over 640,000 acres in Texas and New Mexico (Lynn Loomis, personal communication) in an area known as the *Gypsum Plain* (Kirkland and Evans, 1976). These formations weather to produce soils that have gypsum as their main component (> 80% gypsum). 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) are called "*gypsiferous*." These soils occur principally in arid and semiarid regions.

The penetration depth of GPR is dependent on the conductivity of the earthen materials being probed (Daniels, 2004). Soils with high electrical conductivity rapidly attenuate the radar signal and limit penetration depths. The electrical conductivity of soils is highly variable and increases with increase water, clay, and soluble salt contents. It is significant that only small amounts of water, clay, or soluble salts can increase the conductivity of soils to a level that significantly decreases the radar's penetration depths. In some areas (though especially in arid and semi-arid areas), high levels of calcium carbonate and/or calcium sulfate occur in soils. The presence of these compounds has been associated with high electrical conductivities and restricted GPR penetration depths. The degree to which calcium carbonates and sulfates affect the performance of GPR is largely undocumented.

In the preparation of GPR soil suitability maps the affects of calcareous and gypsiferous soils on the performance of GPR are recognized. In the methodology section, the following statements are made:

> *"Calcareous and gypsiferous soils are characterized by layers with secondary accumulations of calcium carbonate and calcium sulfate, respectively. These soils mainly occur in base-rich, alkaline environments in semi-arid and arid regions. High concentrations of calcium carbonate and/or calcium sulfate imply less intense leaching, prevalence of other soluble salts, greater quantities of inherited minerals from parent rock, and accumulations of specific mineral products of weathering (Jackson, 1959). These properties contribute to the higher electrically conductivity of calcareous and gypsiferous soils. Grant and Schultz (1994) observed a reduction in the depth of GPR signal penetration in soils that have high concentrations of calcium carbonate."*

Some of these statements refer to gypsiferous soils, but do not address gypseous soils. The purpose of this study is to assess the influence of gyprock and gypseous soils on GPR penetration depths and effectiveness.

Study Sites:
All sites are located in MLRA 42 – Southern Desertic Basin, Plains and Mountain Native Range (USDA-NRCS, 2006). Many of the sites visited in this study were also visited during the Gypsum Soil Tour of 2006. Each site is named for a local landmark. All sites except the first were located on the Brantley Moon Ranch. The named soils represent proposed soil series. Unless otherwise noted, these soils contain more than 80 percent gypsum throughout the profile and thereby qualify as hypergypsic materials. The taxonomic classifications of these proposed soils are listed in Table 1. Particle-size class has not been assigned to hypergypsic materials.

State Line Roadcut Site:
The *State Line Roadcut site* is located on top of a road cut along US 62-180 in Eddy County, New Mexico (32.01056^{o} N latitude, 104.49575 ^{o} W. longitude), about 1 mile northeast of the Texas-New Mexico state boundary. The underlying gyprock is a member of the Castile formation. Soils observed at this site are members of the proposed Hollebeke, Elcor, and Joberanch series. These soils form in residuum weathered from gpyrock. The Hollebeke series has a weakly cemented petrogypsic horizon within depths of 30 cm, and is moderately deep (50 to 100 cm) to a lithic contact of gyprock. The Elcor series is shallow (< 50 cm) to a lithic contact of gyprock. The Joberanch has a thin mantle (< 50 cm) of silicate-rich materials and is shallow over weakly to moderately cemented petrogypsic horizon.

Alligator Draw Site:
The *Alligator Draw site* is characterized by rugged breaks of moderate relief. The study site is located in

Culberson County, Texas (31.92407 ^{o} N latitude and 104.42149 ^{o} W. longitude). The site is sparsely vegetated, with more than 95% bare soil. The proposed Elcor series dominates this site. Adjacent to the breaks, on the floor of Alligator Draw, are areas of Dellahunt soils. The proposed Dellahunt series consists of very deep (> 150 cm) alluvial deposits that are dominated by silicate-minerals.

Water Tanks Site:
The *Water Tank site* is located on an undissected, karst-pitted platform remnant in Culberson County, Texas (31.92407^{o} N latitude, 104.42149 ^{o} W. longitude). The proposed Pokorny series has a moderately to strongly cemented petrogypsic horizon within depths of 30 cm depth. Included in mapping with Pokorny soils are areas of Dellahunt and Joberanch soils, which occur where silicate-rich materials fill depressions in the petrogypsic horizons.

Radio Tower Site:
The *Radio Tower site* is located on a long, smooth hillslope in Culberson County, Texas (31.94821^{o} N latitude, 104.33588 ^{o} W. longitude). The proposed Cavewell series dominates this site. The Cavewell series formed in residual material weathered from gpyrock. The Cavewell series has a weakly cemented petrogypsic horizon at depth of less than 30 cm, and is deep (100-150 cm) to a lithic contact of gpyrock. Included in mapping are small areas of Hollebeke soils.

Shipping Pen Gate Site:
This site is located in a large, shallow depression (dissolution collapsed trough) in Culberson County, Texas (31.90258^{o} N latitude, 104.36221 ^{o} W. longitude). The Orla-like soil supports a productive cover of alkali sacaton. In a sampled pit, the Orla-like soil has a thin veneer of silicate-minerals 5 cm thick, moderately cemented petrogypsic horizon at depth of 27 cm, densic gyprock at 110 cm, and lithic gyprock at 165 cm. It also contains accumulations of sodium sulfate salts (thenardite and/or mirabilite). Also included in mapping are small areas of Pokorny soil.

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

Proposed Soil Series	Tentative Taxonomic Classification
Cavewell	hypergypsic, thermic Leptic Ustic Petrogypsids
Dellahunt	fine-silty, mixed, thermic Ustic Haplocambids
Elcor	hypergypsic, thermic Lithic Ustic Hypergypsids
Hollebeke	hypergypsic, thermic Leptic Lithic Ustic Petrogypsids
Joberanch	hypergypsic, thermic, shallow Ustic Petrogpysids
Orla-like	hypergypsic, thermic Ustic Petrogypsids
Pokorny	hypergypsic, thermic Leptic Ustic Petrogypsids

Equipment:
The radar unit is the TerraSIRch Subsurface Interface Radar (SIR) System-3000, manufactured by Geophysical Survey Systems, Inc. (Salem, New Hampshire).[1] Daniels (2004) discusses the use and operation of GPR. The SIR System-3000 weighs about 9 lbs (4.1 kg) and is backpack portable. With an antenna, the system requires two people to operate. The 200, 400, and 900 MHz antennas were used in this investigation. In areas of gyprock and gypseous soils, the 400 MHz antenna provided the best balance of penetration depth and resolution of subsurface features. The 400 MHz antenna is recommended for soil and shallow lithologic surveys in areas of gyprock and gypseous soils.

Radar records contained in this report were processed with the RADAN for Windows (version 5.0) software program developed by Geophysical Survey Systems, Inc.[1] Processing included setting the initial pulse to time

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

zero, color transformation, marker editing, distance and surface normalization, filtration, migration, and range gain adjustments.

The EM38 and EM38DD meters were used in portions of this study. These meter are manufactured by Geonics limited (Mississauga, Ontario).[1] No ground contact is required with these instruments. Only one person is required to operate these meters. When placed on the soil surface, these meters have effective penetration depths of about 0.75 m and 1.5 m in the horizontal and vertical dipole orientation, respectively (Geonics Limited, 1998 & 2000). The EM38 and EM38DD meters weigh about 1.4 kg (3.1 lbs) and 2.8 kg (6.2 lbs), respectively. The EM38DD meter consists of two EM38 meters bolted together and electronically coupled. One meter acts as a master unit (meter that is positioned in the vertical orientation and having both transmitter and receiver activated) and one meter acts as a slave unit (meter that is positioned in the horizontal orientation with only the receiver switched on).

The DAS70 Data Acquisition System (developed by Geonics Limited) was used with the EMI meters to record and store both EC_a and Global Positioning System (GPS) data.[1] The acquisition system consists of an EMI meter, an Allegro CX field computer (Juniper Systems, North Logan, Utah), and a Garmin Global Positioning System Map 76 receiver (with a CSI Radio Beacon receiver, antenna, and accessories that are fitted into a backpack) (Olathe, KS).[1] When attached to the acquisition system, the EMI meter is keypad operated and measurements can be automatically triggered. The NAV38, NAV38DD, Trackmaker38 and Trackmaker38DD software programs developed by Geomar Software Inc. (Mississauga, Ontario) were used to record, store, and process EC_a and GPS data.[1]

To help summarize the results of the EMI survey, SURFER for Windows (version 8.0) software (Golden Software, Inc., Golden, Colorado), was used to construct two-dimensional simulations.[2] Grids were created using kriging methods with an octant search.

Survey Procedures:
Radar transect lines were established at each site. These lines traversed different landscape components and were variable in length. Each radar traverse was completed by pulling the antenna by hand along the transect line. Although, GPR provides a continuous profile of the subsurface, interpretations were restricted to reference points. For each transect, reference points were spaced at a uniform interval of 3-meters. At each reference point, the radar operator impressed an identifying mark on the radar record. Each radar transect was stored as a separate record. Each radar record was reviewed in the field and subsurface features were identified.

A *random walk* or *wild-cat* EMI survey was conducted with the EM38 meter at the *Orla-like site* in Culberson County and with the EM38DD meter at the *Playa site* in Floyd County. The EM38 meter was operated in the deeper-sensing (0 to 1.5 m) vertical dipole orientation. With each meter, only quadrature phase data were collected and expressed as values of apparent conductivity (EC_a) in milliSiemens/meter (mS/m). Both meters were operated in the continuous mode (measurements recorded at 1-sec intervals) with the DAS70 system. Using either the NAV38 or NAV38DD programs, both GPS and EC_a data were simultaneously recorded on the Allegro field computer. The meters were held about 3 cm (about 1 inch) above the ground surface and orientated with their long axis parallel to the direction of traverse. Surveys were completed by walking at a uniform pace, in a random or back and forth pattern across each site.

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

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

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

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

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

where C is the velocity of propagation in a vacuum (0.298 m/ns). Velocity is expressed in meters per nanosecond (ns). In soils, the amount and physical state of water (temperature dependent) have the greatest effect on the E_r and v.

Based on known depths to a buried reflector and hyperbola-matching processing techniques (the shape of a hyperbole is dependent on signal velocity), the velocity of propagation through the upper part of the soil was determined. With the 400 MHz antenna, in areas of gypseous soils, the estimated E_r ranged from 3.79 to 5.29 and the estimated v ranged from 0.13 to 0.15 m/ns. This information was used to depth scale the radar records. As the velocity of propagation is spatially variable, depth scales are considered close approximations, but are not exact.

Results:

State Line Roadcut Site:

In most areas of Hollebeke soil, the 400 MHz antenna provided favorable signal to noise ratios and suitable penetration depths. In general, subsurface features were well resolved and easy to interpret on radar records. Figure 1 is a 17.5-m section of a radar record from the *State Line Roadcut Site*. The depth scale is based on an estimated E_r of 3.79 and a propagation velocity of 0.153 m/ns. With a 400 MHz antenna, in this area of gypseous soils, the depth of penetration is about 2.5 to 3 meters through the gpyrock. A lower frequency antenna can be used in areas of gpyrock to extend the depth of penetration.

In Figure 1, the underlying gyprock is characterized by gently dipping, continuous, moderate amplitude planar reflectors. Multiple sets of bedding planes within the gyprock are evident in this record. In most rocks, GPR reflections are produced by lithologic and structural features (Aspiron and Aigner, 2000). Reflections are produced at interfaces separating layers with different lithologic properties (density, porosity, grain size, mineralogy, etc.) and/or water content (Corbeanu et al., 2001). Seepage, when it takes place, is more likely to occur in karstified portions of the gyprock that contain extensive fractures and cavities. Ground-penetrating radar has been used to identify structural features (e.g., bedding and fracture planes, karstified zones, and conduits) in limestone, but has not been documented in areas of gyprock. In Figure 1, the more intense and chaotic patterns of subsurface reflections near “A” suggests a potential karstified zone within the gyprock. This area and the area directly beneath the 2.5 m reference mark stand-out and contrast with the more repeatable linear patterns that are evident on other portions of this radar record.

At the *State Line Roadcut Site,* soils were shallow to gyprock. In Figure 1, a green colored line has been used to highlight the interpreted depth to the lithic contact. This interface is partially masked by the strong surface reflection.

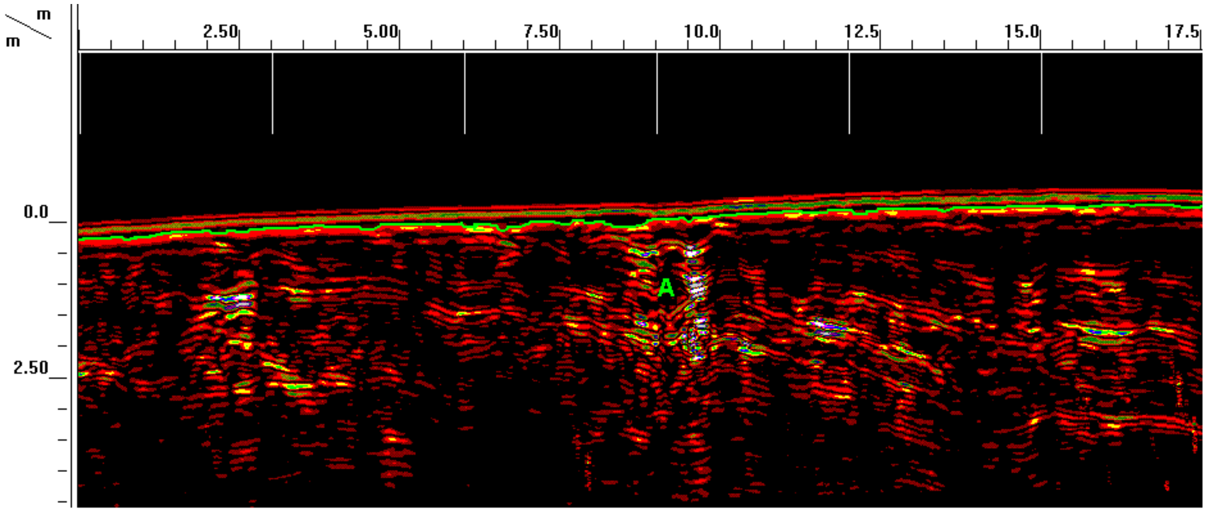

Figure 1. Contrasting lithologic layers and inhomogeneities within the gyprock are shown on this radar record from the *State Line Roadcut Site*.

<u>*Alligator Draw Site*</u>:
Similar results were obtained with the 400 MHz antenna at the *Alligator Draw Site* as were obtained at the *State Line Roadcut Site*. Along a radar traverse line from this site, a vein of Selenite was crossed with the 400 MHz antenna. In Figure 2, the linear, more steeply inclined vein of Selenite ($CaSO_4 \cdot 2H_2O$) is evident on the radar record. Selenite is a glassy, well-crystallized form of gypsum. The vein of Selenite contrasts sharply in signal amplitude and geometry with the surrounding gyprock. This vein of dissimilar material provides high amplitude reflections (colored white, blue and green on this record) and a distinct and easily recognizable pattern.

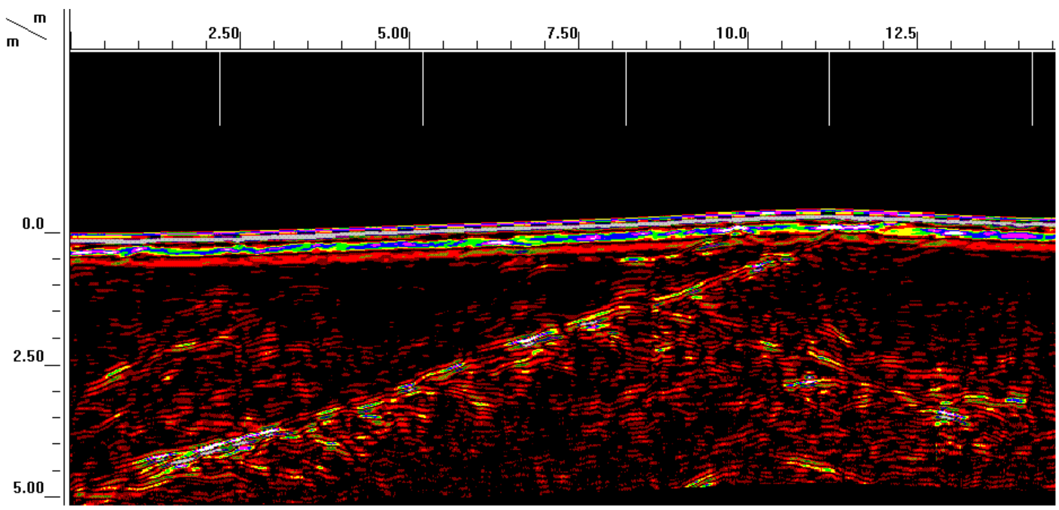

Figure 2. An inclined vein of selenite vein within the gyprock is evident on this radar record from the *Alligator Draw Site*.

In contrast with the *State Line Roadcut Site*, bedding planes within the gyprock appear more complex and less linear at the *Alligator Draw Site*. In different portions of the radar record shown in Figure 2, bedding planes appear to be inclined in different directions and distorted into convex–upwards, curvilinear forms. Olive (1957) described the Castile Formation as having "disorientated blocks and erratic dips." The radar images from this site are consistent with Olive's description.

<u>*Water Tank Site:*</u>
At this site, the GPR was calibrated to scan a shallower depth in order to discriminate differences in soil types.

This site is dominated by Pokorny soils. Included areas of Dellahunt and Joberanch soils have higher clay and silt contents, which attenuate the radar signal. The source of the clay minerals may be beds of contrasting lithologies (e.g., sandstone or limestone), laminations within the Castile Formation, or aeolian deposits. Soils with silicate-rich mantles are recognized by "*white-out*" zones or areas of no signal return. On radar records, the absence of subsurface reflections identifies areas of Dellahunt soils. Low amplitude and depth restricted subsurface reflections identifies areas of Joberanch soils. The abundance of moderate and high amplitude subsurface reflections identifies areas of Pokorny soils. Based on these criteria, soils were properly identified at 89 percent of the observation points (total of 41) along two radar traverse lines. While areas of Pokorny and Dellahunt soils were never confused or miss-identified, some areas of Joberanch and either Pokorny or Dellahunt soils were misinterpreted. As Joberanch has properties that may be viewed as transitional between Pokorny and Dellahunt soils, these errors are not unexpected. Greater experience and additional interpretative skills are needed to distinguish the Joberanch soil.

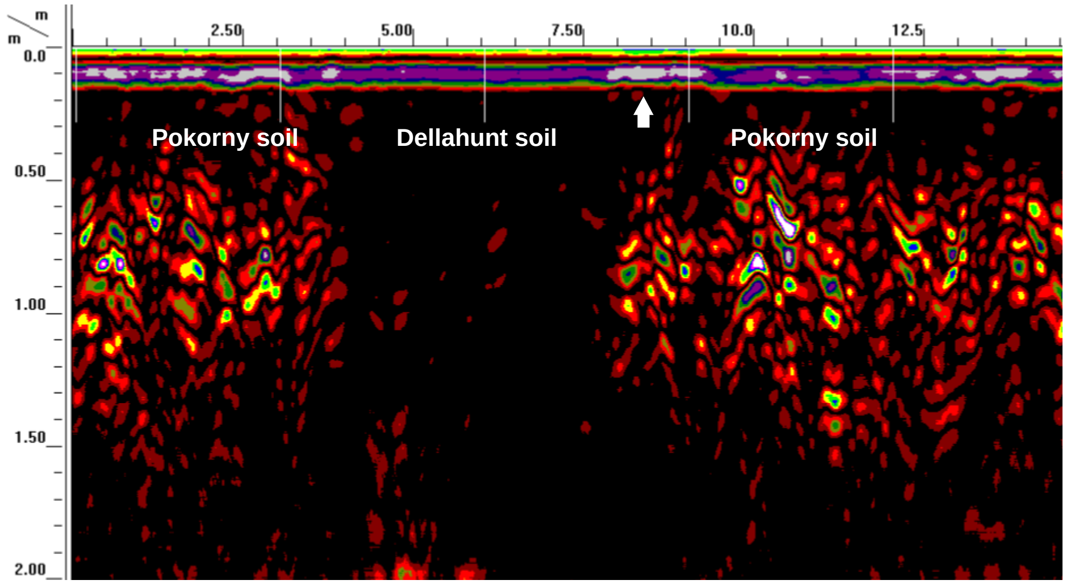

Figure 3. A *white-out* area occurs between the 3 and 9 meter distance marks and indicates an area of higher attenuation caused by clays and silts at the *Water Tank Site*.

The arrow in Figure 3 is pointing towards a segment of the surface pulse that has higher signal amplitudes (colored grey and light blue). The Pokorny series has a strongly cemented petrogypsic horizon that occurs at very shallow depths (within 5 to 13 cm). This horizon grades laterally into a more weakly cemented petrogypsic horizon (Joberanch soils) or descends beneath layers of silicate clays (Dellahunt soils). In Figure 3, soils with a very shallow and abrupt transition to a strongly cemented petrogypsic horizon have high amplitude surface and near surface reflections. Soils that have a less abrupt and more gradual (weakly to moderately to strongly cemented petrogypsic horizons) transition are expressed by lower-amplitude reflections (colored in shades of purple). Silicate-rich mantles that are greater than 15 to 20 cm thick result in the rapid attenuation of the radar signal, very limited penetration depths, and *white-out* areas on radar records.

<u>*Radio Tower Site*</u>:
Figure 4 is a 21-m section from a radar traverse conducted across the *Radio Tower Site*. In Figure 4, a green-colored line has been used to identify an irregular, but continuous subsurface interface. This interface varies in depth from about 25 to 80 cm and represents the soil/bedrock interface. Below the soil/bedrock interface, the gpyrock is characterized by inclined to rounded, segmented reflectors of varying signal amplitudes. Within the gpyrock, chaotic patterns suggest potential solution features or folding.

The dominant soils at this site are members of the proposed Cavewell series. The Cavewell soil has a weakly cemented petrogypsic horizon overlying gyprock. A weakly cemented petrogypsic horizon underlying a thin surface layer offers a weakly contrasting interface that will produce low amplitude reflections. In Figure 4, surface and near surface pulses provide mostly moderate signal amplitude reflections. A high amplitude (colored light blue) reflection appears only below the 6-m reference mark. This pattern is believed to represent a strongly cemented petrogypsic horizon the immediately underlies a thin surface layer. In other portion of the radar record, this interface has lower signal amplitude and is believed to represents a more weakly cemented petrogypsic horizon underlying the surface layers.

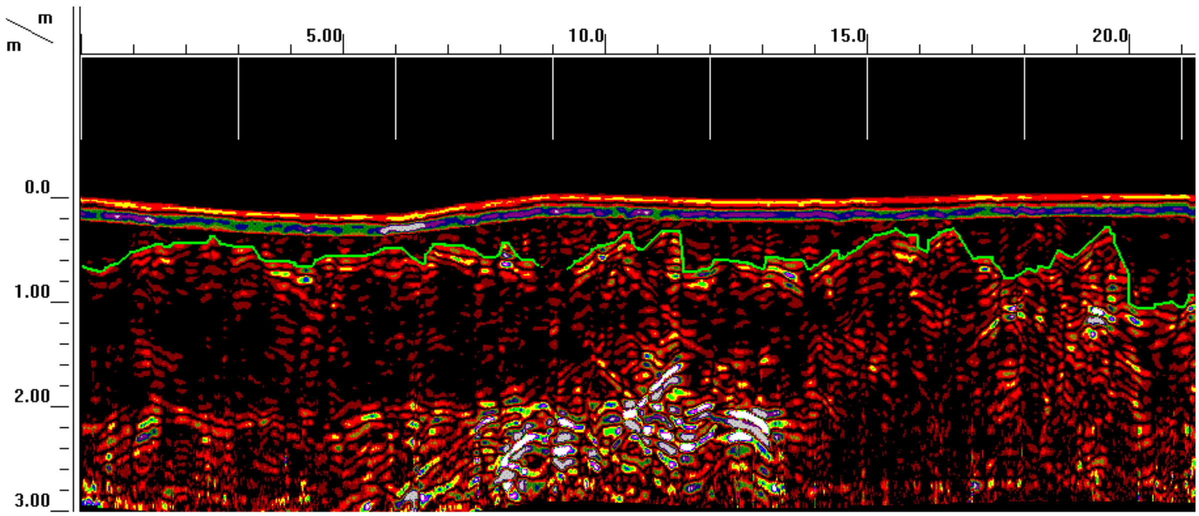

Figure 4. A green colored line has been used to identify the interpreted depth to unweathered gyprock along this radar record from the *Radio Tower Site.*

<u>*Shipping Pen Gate Site*</u>:
Portions of this site are salt-affected and inhospitable to GPR. A short transect with the 200 MHz antenna confirmed the unsuitability of this site to GPR. The collected radar record was extremely depth restricted and of poor interpretive quality. To better understand variations in soils and soil properties, an EMI survey was conducted across this site. In other surveyed areas of the proposed Elcor, Hollebeke, and Pokorny soils, EC_a was very low (1 to 5 mS/m) with some negative readings. Within the *Shipping Pen Gate Site*, EC_a averaged 27.9 mS/m with a range of 0.8 to 68.8 mS/m. One-half of the EC_a measurements were between 15.8 and 39.6 mS/m. The comparatively high EC_a values and large range are attributed to greater and more variable salt contents of the soils at *Shipping Pen Gate Site*.

Spatial EC_a patterns (measured with an EM38 meter that was operated in the deeper-sensing vertical dipole orientation) within the *Shipping Pen Gate Site* are shown in Figure 5. In Figure 5, the isoline interval is 5 mS/m. Higher levels of EC_a were measured in the western and southern portions of the survey area. These areas correspond with areas of sparser vegetation and noticeable salts on the soil surface.

Figure 6 is an alternate plot of spatial EC_a patterns within *Shipping Pen Gate Site*. This plot was prepared with the ESAP Software Suite for Windows (Version 2.35R) that was developed by the USDA-ARS, Salinity Laboratory (Riverside, CA). One of the statistical programs available in ESAP is the Response Surface Sampling Design (RSSD). This program generates an optimal sampling design based on the EC_a data. The optimal sampling design provides the best possible data points and information for generating predictive models of soil properties.

Based on the results of RSSD, 12 optimal sampling sites were identified (see Table 2). The locations of these sampling sites are indicated by blue-colored squares in Figure 6. At the sampling sites, EC_a ranged from about 1 to 68 mS/m. Soil samples were collected at each of these 12 sites for analysis at Texas Tech University Soil Laboratory. At each site, two samples were collected; one for the 0 to 30 cm and one for the 30 to 60 cm depth intervals. At some sites, gyprock occurred within the 30 to 60 cm depth interval. At these sites the sampled depth was to the lithic contact.

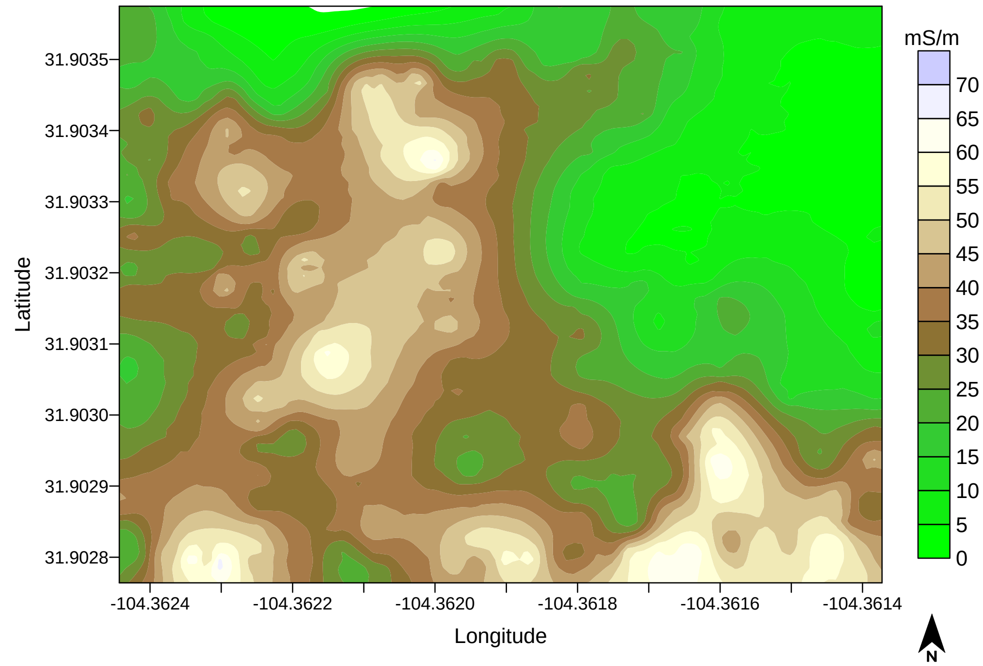

Figure 5. Spatial EC_a patterns measured with the EM38 meter in the vertical dipole orientation within the *Shipping Pen Gate Site*.

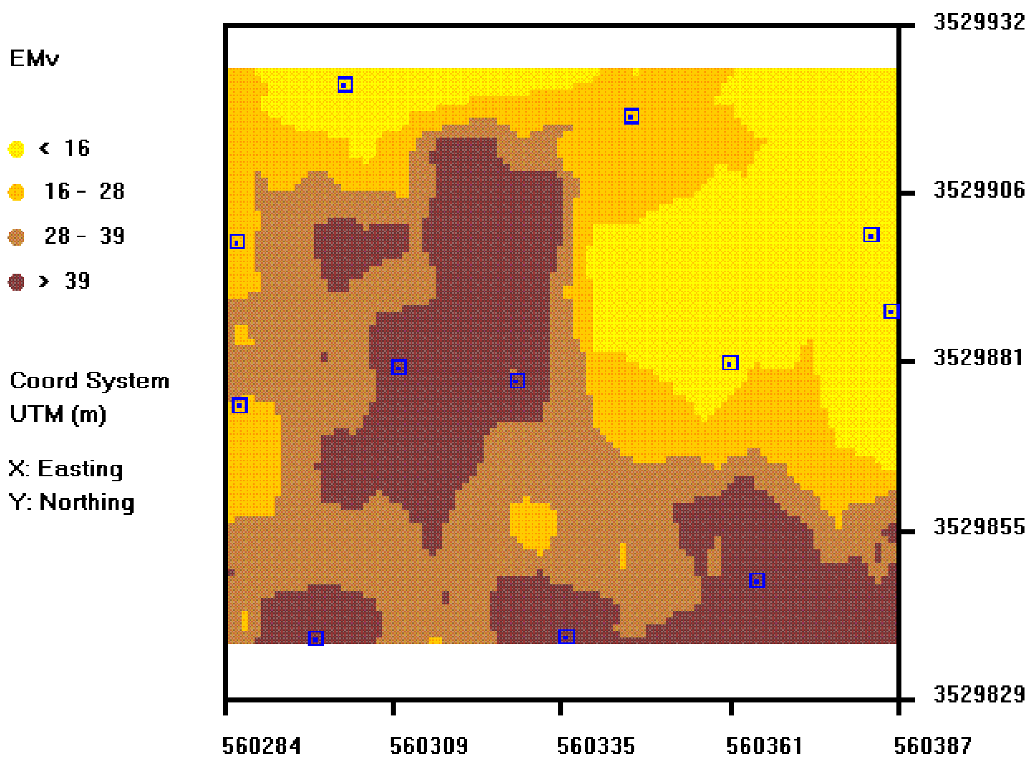

Figure 6. This plot of spatial EC_a patterns within the *Shipping Pen Gate Site* was prepared using ESAP Software Suite. The locations of 12 optimal sampling sites are shown.

Table 2. The locations and EC_a of the 12 optimal sampling sites within the *Shipping Pen Gate Site* that were generated by ESAP's RSSD program.

OBS	Long	Lat	Easting	Northing	EM38V
99	-104.36180	31.90351	560345.40	3529918.30	16.3
200	-104.36190	31.90280	560335.60	3529839.00	58.9
230	-104.36231	31.90279	560297.30	3529838.40	67.5
285	-104.36243	31.90334	560285.30	3529899.10	26.1
313	-104.36226	31.90356	560301.60	3529923.00	2.0
388	-104.36141	31.90335	560382.10	3529900.20	0.8
389	-104.36141	31.90333	560382.30	3529898.60	2.4
396	-104.36138	31.90324	560385.20	3529888.60	4.5
416	-104.36138	31.90299	560384.80	3529860.60	29.0
431	-104.36160	31.90287	560364.80	3529847.30	51.3
457	-104.36164	31.90317	560360.60	3529880.70	12.4
627	-104.36198	31.90315	560328.10	3529879.40	36.0
685	-104.36218	31.90317	560310.10	3529878.50	40.8

Playa Site:

An EMI survey was conduct at a Texas Tech University study site in Floyd County (34.09291 ^{o} N. Lat., 101.11528^o W. Long.). This site is referred to as the *Playa Site*. The *Playa Site* is in range and consists of a dried up playa bed and surrounding side slopes. The survey area is located on the southeast corner of the playa. Soil map units included within the survey area include Randall clay, 0 to 1 percent slopes, frequently ponded (map unit symbol RaA) and Olton clay loam, 1 to 3 percent slopes (map unit symbol OcB). The taxonomic classifications of these soils are listed in Table 3. The very deep, poorly drained Randall soils formed in clayey lacustrine sediments on the playa floor. The very deep, well drained Olton soils formed in loamy, calcareous, eolian sediments on the slopes that surround the playa.

Table 3. Taxonomic classification of the soils at the *Playa Site* in Floyd County.

Soil Series	Taxonomic Classification
Randolph	Fine, smectitic, thermic Ustic Epiaquerts
Olton	Fine, mixed, superactive, thermic Aridic Paleustolls

Table 4 provides the basic EC_a statistics for the EMI survey that was completed at the *Playa Site* with the EM38DD meter. Within the site, for measurements obtained in the deeper-sensing (0 to 1.5 m) vertical dipole orientation, EC_a ranged from 15.0 to 54.2 mS/m. In this dipole orientation, EC_a averaged 33.8 mS/m with a standard deviation of 10.2 mS/m. One-half of the EC_a measurements collected in the vertical dipole orientation were between 24.6 and 42.6 mS/m. Within this site, for measurements obtained in the shallower-sensing (0 to 0.75 m) horizontal dipole orientation, EC_a ranged from 5.0 to 45.5 mS/m. In the horizontal dipole orientation, EC_a averaged 24.8 mS/m with a standard deviation of 9.8 mS/m. One-half of the EC_a measurements collected in the horizontal dipole orientation were between 15.5 and 45.5 mS/m.

The spatial distribution of EC_a within the Playa site is shown in Figure 6. In each plot the isoline interval is 4 mS/m. The same color scale is used in each plot. The location of the playa and the area of Randolph soils are identifiable by the relatively high EC_a (> 26 mS/m in the vertical dipole orientation and >20 mS/m in the horizontal dipole orientation) in the north and northwest portions of the site. An intermittent stream channel enters the playa from the southeast and is identifiable by a sinuous pattern of higher EC_a. Higher-lying areas of Olton soils bound the playa on its southern and southeastern sides. Areas of Olton soils have lower EC_a (< 26 mS/m in the vertical dipole orientation and < 20 mS/m in the horizontal dipole orientation).

Table 4
Basic Statistics for the EC_a data that was collected with the EM38DD meter at the Floyd County Site.
(EC_a measurements are expressed in mS/m)

Dipole Orientation	Observations	Minimum	25%-tile	75%-tile	Maximum	Mean	Std. Deviation
Vertical	1515	15.00	24.63	42.63	54.25	33.76	10.22
Horizontal	1515	5.00	15.50	33.13	45.50	24.79	9.82

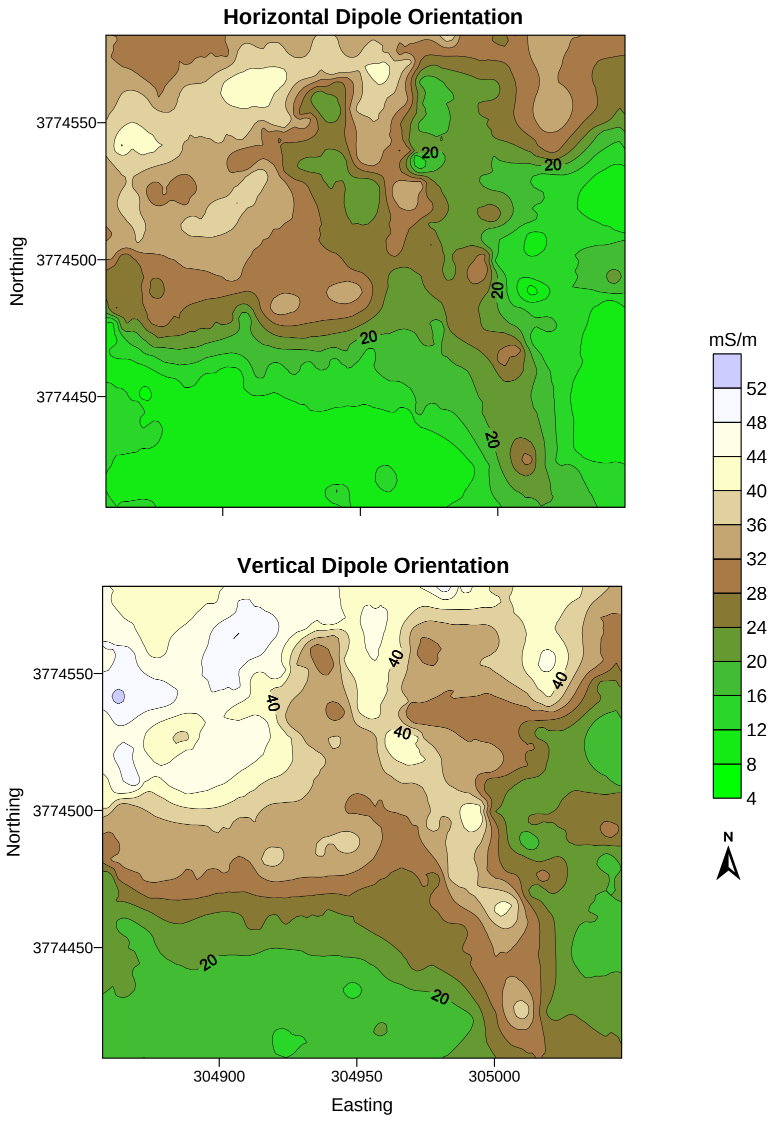

Figure 6. ***Data for these EC_a plots of the Floyd County site were collected with an EM38DD meter operated in the shallower-sensing, horizontal (upper plot) and the deeper-sensing, vertical (lower plot) dipole orientations.***

In some arid and semi-arid areas, EMI has been used to detect groundwater recharge and discharge areas and the distribution of soluble salts within soil profiles. In general, discharge areas have higher EC_a than recharge areas and salt profiles tend to be inverted. Cook and Williams (1998) noted that discharge areas tend to be characterized by shallow water tables and frequently have higher soluble salt concentrations in near surface soil horizons because of evaporative processes. Recharge areas have deeper water table and soluble salts are more effectively leached downwards (Cook and Williams, 1998).

Williams and Arunin (1990) found that multifrequency sounding or varying the dipole orientations are appropriate methods for determining whether the salt concentration increases or decreases with depth. These authors used a "salt ratio" to classify recharge and discharge areas. The salt ratio is the ratio of EMI measurements taken in the horizontal and vertical dipole orientation (V/H). A ratio greater than 1.0 would indicate increasing salt concentrations with depth and a recharge area. A ratio less than 1.0 would indicate decreasing salt concentrations with depth and a discharge area.
Figure 7 is a depiction of the Salt Ratio for the Floyd County Site. With the EM38DD meter, no observation was made in which the EC_a measurement in the horizontal dipole orientation (H) was greater than the EC_a measurement made in the vertical dipole orientation (V).

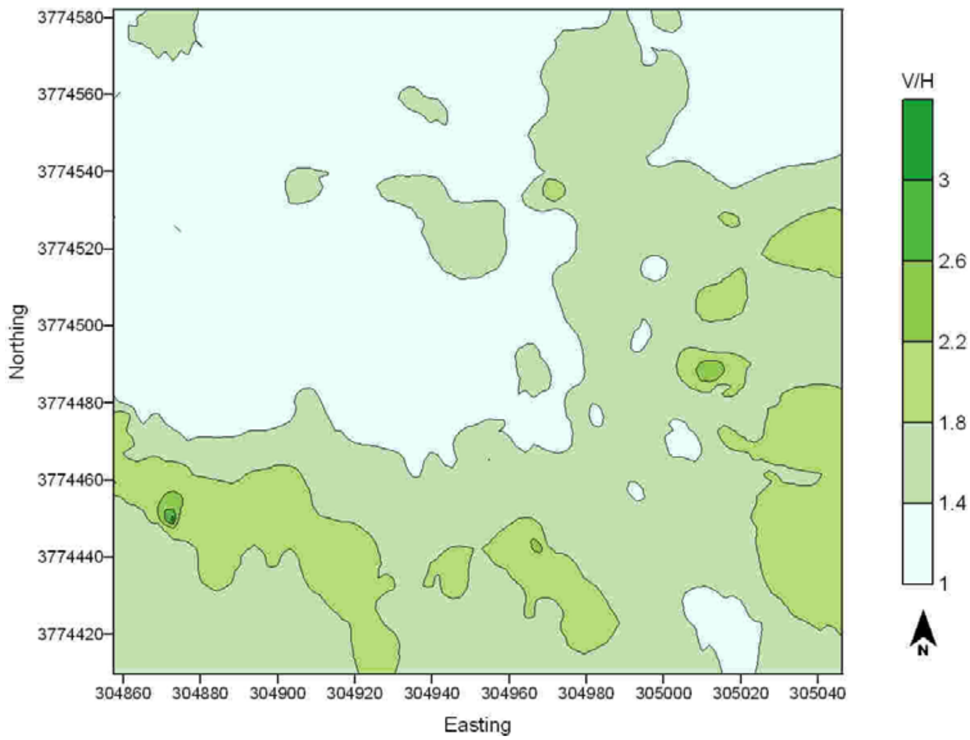

Figure 7. ***Plot of the Salt Ratio (EM38DD Meter -vertical dipole orientation (V) /horizontal dipole orientation (H)) for the Floyd County site.***

Cook et al. (1992) found that groundwater recharge rates are more strongly correlated with soil texture than with salt content. They noted that the range of environments in which EMI can be appropriately used for recharge/discharge assessments is limited. Restrictions are due to variations in clay and water contents of materials below 2 meters that often reduce or mask correlations. As an example, an area with relatively conductive soil materials overlying resistive stratigraphic layers or bedrock could be misinterpreted as a discharge area (Williams and Arunin, 1990). The conditions described by Williams and Arunin (1990) may be present at the *Playa Site*.

References

Aspiron, U. and T. Aigner, 2000. An initial attempt to map carbonate buildups using ground-penetrating radar: an example from the Upper Jurassic of SW Germany. Facies 42: 245-152.

Cook, P. G., G. R. Walker, G. Buselli, I. Potts, and A. R. Dodds, 1992. The application of electromagnetic techniques to groundwater recharge investigations. Journal of Hydrology 130: 201-229.

Cook, P. G. and B. G. Williams, 1998. The basics of recharge and discharge Part 8. pp 1-16. IN: Zhang, L., and G. Walker (eds.) Electromagnetic Induction Techniques. CSIRO Publishing, Collingwood, Australia.

Corbeanu, R. M., G. A. McMechan, R. B. Szerbiak, K. Soegaard, 2001. Prediction of 3-D fluid permeability and mudstone distributions from ground-penetrating radar attributes: Example from the Cretaceous Ferron sandstone member, east-central Utah. Geophysics 67(5): 1495-1504.

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

Geonics Limited. 1998. EM38 ground conductivity meter operating manual. Geonics Ltd., Mississauga, Ontario.

Geonics Limited. 2000. EM38DD ground conductivity meter: Dual dipole version operating manual. Geonics Ltd., Mississauga, Ontario.

Grant, J. A. and P. H. Schultz. 1994. Erosion of ejecta at Meteor Crater: Constraints from ground penetrating radar. In Proceedings Fifth International Conference on Ground Penetrating Radar (pp. 789-803). Kitchner, Ontario, Canada, June 12 – 14, 1994. Waterloo Centre for Groundwater Research and the Canadian Geotechnical Society.

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

Olive, W. W., 1957. Solution-subsidence troughs, Castle Formation of Gypsum Plain, Texas and New Mexico. Bulletin of the Geological Society of America 68: 351-358.

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.

Williams, B. G., and S. Arunin, 1990. Inferring recharge/discharge areas from multifrequency electromagnetic induction measurements. Technical Memorandum 90/11. CSIRO Institute of Natural Resources and Environment, Division of Water Resources. Canberra, Australia.