United States Department of Agriculture

Natural Resources Conservation Service

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Subject: -- Geophysical Assistance

Date: 29 September 2004

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Purpose:
The purposes of this investigation were to assess its effectiveness of GPR for characterizing petrocalcic layers and to evaluate the penetration depth and resolution of GPR in areas of gypsum sands.

Participants:
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Activities:
All activities were completed during the period of September 22 to 24, 2004. .

Results:

1. An area of Winks-Harrisburg association, 1 to 5 percent slopes, was traversed with GPR. In these soils, GPR can detect shallow and moderately deep petrocalcic horizon. However, in soils having solums with greater than 18 % clay, a 200 MHz antenna was unable to detect moderately deep or deeper petrocalcic layers. In areas with coarser-textured (< 18% clay) solums, the radar's energy was less rapidly attenuated and the penetration depth improved. Interpretations of the depth to petrocalcic horizon were obscured by high levels of background noise and clutter. Processing of radar records improves interpretations and is recommended.

2. A GPR survey was conducted with a 200 MHz antenna in an area that had been mapped as *Dune land, gypsum* within the White Sands National Monument, Otero County. With a 200 MHz antenna, radar reflections were observed to depths of 7 to 9 m. Ground-penetrating radar provides an excellent tool for charting the stratigraphy of dunes. The National Park Service may wish to consider the use of this tool rather than invasive and destructive trenches in any proposed dune genesis, hydro-geologic, and/or stratigraphic studies. Lower frequency antennas (10 to 100 MHz) are available that should provide greater penetration depths (see point 3 in *Results* for qualifications).

3. In general, at White Sands National Monument, GPR could not detect interfaces below the water table, which contained sufficient amounts of dissolved salts to attenuate the radar's energy. On interdune alkali flats, where the water table was at depths of less than 1-m, penetration was noticeably restricted. However, the radar signal did penetrate the water table in a toe slope area of the dune. The reasons for this singular improvement are unknown at this time.

4. The sands at White Sands National Monument are composed of sand-size gypsum particles. The affect of gypsum on the performance of GPR is unclear. A soil sample was collected at the study site and will be taken to the USDA- National Soil Survey Laboratory, Lincoln, NE, for analysis. Results of laboratory analysis will help assess the chemical, physical, and mineralogical parameters that affect the performance of GPR in sandy soils.

5. The mineral gypsum consists of two molecules of water. Gypsum present challenges to laboratory analysis. Because of its relatively high solubility, gypsum rapidly dissolves in particle-size and clay separation analyses. This creates problems as gypsum is removed in the process of dispersing the particles. Heating and laboratory preparation of samples can result in the rapid dehydration of the mineral. Dr Warren Lynn of the National Soil Survey Center suggests using the *bassinite procedure* and contacting Dr Tom Hallmark at Texas A&M University to obtain procedures for this analysis.

6. An EMI survey of the *Corralitos Site* provided a map of the spatial distribution of apparent conductivity. In general, EC_a increased with increasing depth of observation. This trend was attributed to greater moisture and clay contents at lower soil depths. Although comparatively low and invariable, spatial patterns of EC_a parallel the general slope of the alluvial fan and are believed to reflect principally variations in clay content. Further work with EMI is encouraged in New Mexico. The staff of the National Soil Survey Center will gladly assist your staff in evaluating the suitability of EMI for soil survey and investigation activities.

It was my pleasure to work in New Mexico, with Arlene Tugel, and members of the National Park Service and your fine staff.

With kind regards,

James A. Doolittle
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Equipment:

The radar unit is the TerraSIRch Subsurface Interface Radar (SIR) System-3000 (here after referred to as the SIR System-3000), manufactured by Geophysical Survey Systems, Inc.[1] The SIR System-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 System-3000 weighs about 9 lbs (4.1 kg) and is backpack portable. With an antenna, this system requires two people to operate. The use and operation of GPR are discussed by Daniels (2004). The 200 and 400 MHz antennas were used during this investigation.

Radar records contained in this report were processed with the RADAN for Windows (version 5.0) software program (Geophysical Survey Systems, Inc, 2003). [1] Processing included setting the initial pulse to time zero, color transformation, marker editing, distance and surface normalization, signal stacking, background removal, migration, and range gain adjustments.

Geonics Limited manufactures the EM38DD meter.[1] Geonics Limited (2000) has described the operating procedures for the EM38DD meter. The EM38DD meter has a 1-m intercoil spacing and operates at a frequency of 14,600 Hz. 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 dipole orientation and having both transmitter and receiver activated) and one meter acts as a slave unit (meter that is positioned in the horizontal dipole orientation with only the receiver switched on). The EM38DD meter provides simultaneous measurements in both dipole orientations. This meter is portable and needs only one person to operate. No ground contact is required with this meter. When placed on the soil surface, it has effective penetration depths of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively (Geonics Limited, 2000). Lateral resolution is approximately equal to the intercoil spacing. The meter measures the apparent conductivity (EC_a) of the underlying earthen materials. Values of EC_a are expressed in milliSiemens per meter (mS/m).

The Geonics DAS70 Data Acquisition System was used to record and store both EMI and GPS data. [1] The acquisition system consists of the EM38DD meter, an Allegro field computer, and a GPS receiver (Holux GM-210).[1] With the logging system, the meter is keypad operated and measurements were automatically triggered.

Ground-penetrating radar (GPR):

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., water table, 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):

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

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 (about 0.3 m/nanosecond). Velocity is expressed in meters per nanosecond (m/ns). The amount and physical state (temperature dependent) of water have the greatest effect on the E_r of earthen materials and therefore the velocity of propagation.

Petrocalcic Horizon:

[1] Trade names are used to provide specific information. Their mention does not constitute endorsement by USDA-NRCS.

The study site was located near a borrow pit (32.27507^o N. Latitude, 106.98489^o W. Longitude) west of Las Cruces. The area had been mapped as Winks-Harrisburg association, 1 to 5 percent slopes (Bulloch and Neher, 1980). The very deep, well drained Wink soil formed in calcareous, loamy, eolian or alluvial sediments. The moderately deep to a hardpan, well drained Harrisburg soil formed in residuum and eolian sediments from sandstone, shale, and volcanic ash. In these soils, the petrocalcic horizon typically occurs at depths of 50 to 100 cm. Wink is a member of the coarse-loamy, mixed, superactive, thermic Petronodic Haplocalcids family. Harrisburg is a member of the coarse-loamy, mixed, superactive, thermic Typic Petrocalcids. At the time of this investigation the soils were relatively dry.

Figure 1. An exposed petrocalcic layer in a borrow pit near Las Cruces.

Field Procedures:
A 24-m traverse line was established near the borrow pit. Survey flags were inserted in the ground at 2-m intervals along this line. These flags served as reference points. Pulling the 200 MHz antenna along this line completed the radar survey. As the antenna was pulled passed each reference point, the operator impressed a vertical mark on the radar record.

A metallic plate was buried along the traverse line at a depth of 48 cm. Based on the measured depth to this known reflector and equation [1], the velocity of propagation was an estimated 0.136 m/ns. The E_r was 4.77. Using a scanning time of 60 ns, a velocity of 0.136 m/ns, and equation [1], the maximum depth of penetration through these soils was and estimated 4.1 m. However, as will be discussed, the depth of observation was substantially reduced by the relatively high apparent conductivities of these soils.

Results:
In soils having solums with greater than 18 % clay, the 200 MHz antenna was unable to detect a moderately deep petrocalcic layer. In areas with coarser-textured (< 18% clay) solums, the radar's energy was less rapidly attenuated and penetration depths improved. However, interpretations of the depth to petrocalcic horizon were complicated by high levels of background noise and clutter.

Figure 2 is a portion of the radar record that was obtained with the 200 MHz antenna along the traverse line. The buried (48 cm) metallic reflector is evident as a series of small, high-amplitude hyperbolic reflectors immediately below the 12.0 m mark and to the right of "A." The upper boundary of the petrocalcic horizon has been interpreted and identified by a white line on this radar record. In Figure 2, the interpreted depth to the petrocalcic horizon ranges from 44 to 109 cm. As seen in Figure 2, meaningful information can only be discerned from the upper 1 to 2 meters, below these depths parallel lines of low frequency noise plague the radar record. Data processing was required to clarify interpretations. Even then, reflections are discontinuous and unclear, resulting in some ambiguous interpretations.

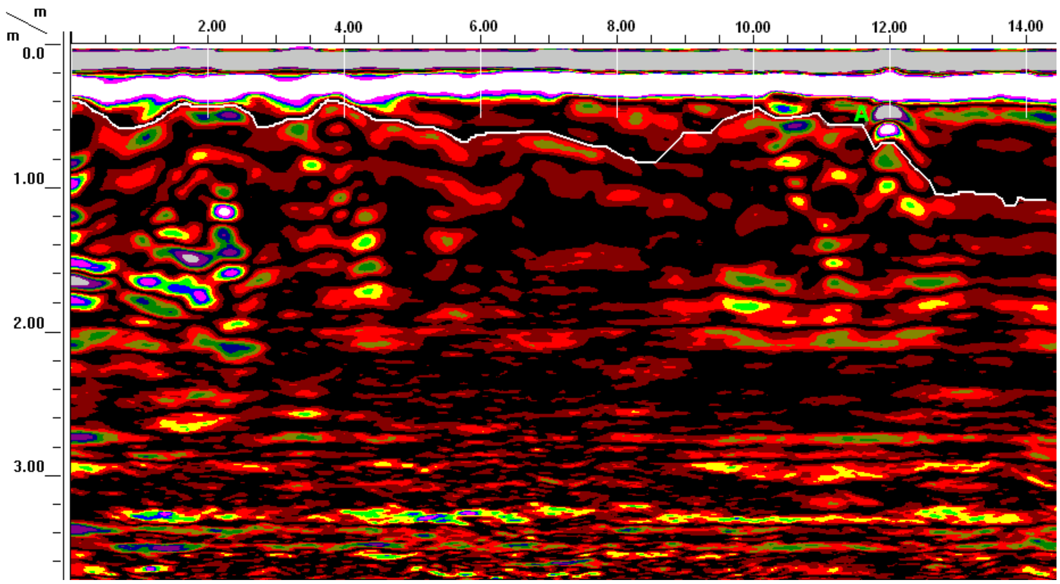

Figure 2. Radar record from an area mapped as Winks-Harrisburg association, 1 to 5 percent slopes.

White Sands National Monument:
Background:
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 increased water, clay, and soluble salt contents. It is significant that only small amounts of water, clay, or soluble salts are required to significantly increase the conductivity of soils and decrease the radar's penetration depths.

In excessively drained, sandy materials, GPR often achieves unsurpassed penetration depths and unmatched resolution of subsurface interfaces. Little consideration is often given to the chemical, physical, and mineralogical properties of these sandy materials. In sandy soils, the most significant form of signal loss and attenuation are related to the presence of saline pore waters and surface reactive clays (Schenk et al., 1993). The presence of even small amounts of clay will significantly increase signal attenuation and reduce the depth of penetration. In addition, mineralogical properties such as the concentration of heavy minerals are known to affect electromagnetic properties and GPR performance. In some areas (though especially in arid and semi-arid areas), high levels of calcium carbonate or calcium sulfate occur in soils. Soils with calcareous layers have been reported to severely limit the radar's penetration depth (Grant and Schultz, 1994).

The degree to which calcium sulfate affects the performance of GPR is undocumented. Gypsum or calcium sulfate ($CaSO_4 \cdot 2H^20$) is relatively soluble and is readily transported in surface or ground waters or deposited as aerosol dust. When present in large amounts, gypsum controls the properties of soils.

This study is being conducted by the National Soil Survey Center to assess the chemical, physical, and mineralogical properties of sandy aeolian deposits that affect GPR performance.

Study Site:
Radar surveys were conducted on a portion of a sand dune located in White Sands National Monument, Otero County, New Mexico. White Sands National Monument is located in the Tularosa Basin. This basin contains the world's largest gypsum dune field. The Tularosa Basin has no outlet and, in this arid environment, waters flowing into the basin evaporate leading to the deposition of large quantities of gypsum.

The study site was near a water monitoring site (32.82328^o N. Latitude, 106.26781^o W. Longitude) in White Sands National Monument. The area had been mapped as Active Dune, gypsum (Neher an Bailey, 1976). This miscellaneous map unit consists of shifting sands dunes that are relatively devoid of vegetative cover

Field Procedures:
A 60-m traverse line was established across a west-facing slope of a small dune. Survey flags were inserted in the ground at intervals of 5-m and served as reference points. The elevation of each reference point was measured with a level and stadia rod. Relief was about 4.7 m. Elevations were not tied to a benchmark; the lowest recorded point was chosen as an arbitrary 0.0 m datum. Surveys were completed with both a 200 and 400 MHz antennas.

Based on the measured depth to the water table at one reference points (observed depths of 1.32 m), the velocity of propagation through the unsaturated sands was an estimated 0.197 m/ns. The E_r was 2.3. Using a scanning time of 100 ns, a velocity of 0.197 m/ns, and equation [1], the maximum depth of penetration through the unsaturated sands is about 9.87 m. However, as shown in equation [2], the velocity of propagation is principally governed by the E_r of the profiled material(s), which will vary with water content. Below the water table, the sands are saturated and will have an E_r of between 15 and 30 (Daniels, 2004). This higher relative dielectric permittivity results in a slower velocity of propagation (0.05 to 0.08 m/ns) below the water table.

Figure 3 is a portion of the radar record that was obtained with the 200 MHz antenna. In Figure 3, the surface has been *terrain corrected* to improve the visual presentation. Through a process known as *surface normalization*, elevations are assigned to each reference point and the image is corrected for changes in elevation. Surface normalization adjusts the vertical scale to conform to changes in topography. After surface normalization, water tables appear as a horizontal or near horizontal reflectors.

The radar record obtained with the 200 MHz antenna was of good interpretive quality. Not only was the water table clearly distinguishable beneath this landscape, but also the geometry and structure of major stratigraphic boundaries were well expressed on the radar record. The water table, internal features and bedding planes within stratigraphic units are evident in this figure. Abrupt and contrasting differences in density, grain size, and moisture contents produce the high amplitude reflections that are apparent in Figure 3. The water table and major bedding planes slope downward towards the interior of the dune and away from the interdune alkali flat, which is located just beyond the right-hand border of this figure. Multiple reflections of the surface reflection and background noise clutters the lower part of the radar record (below about 8 m).

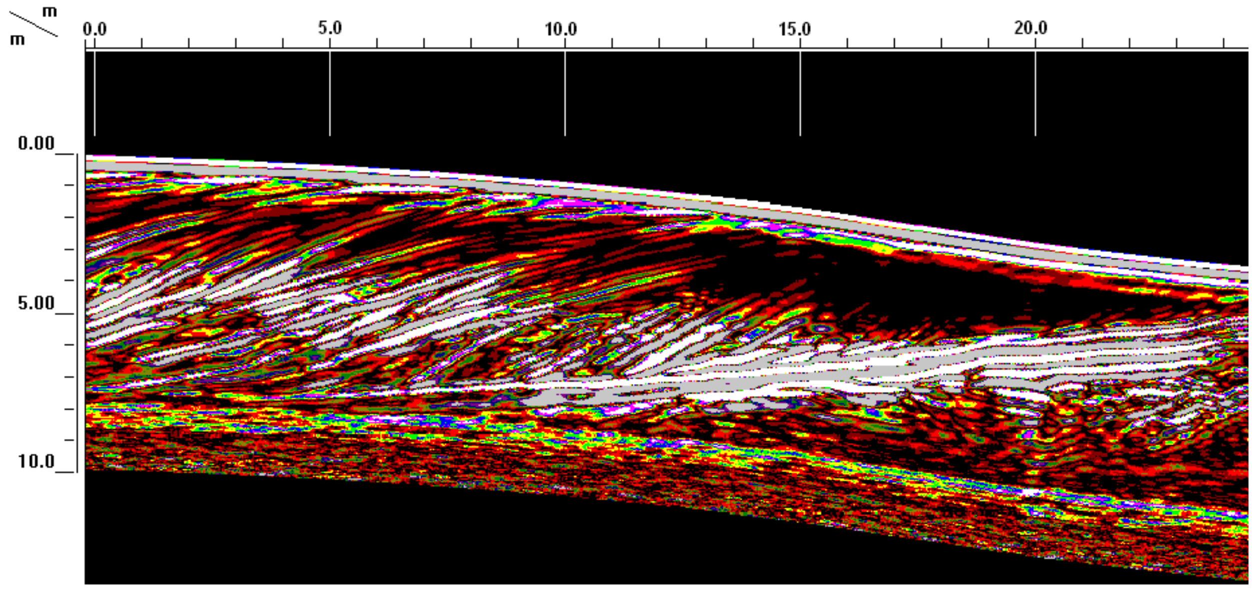

Figure 3. Radar record collected with the 200 MHz antenna in an area of Active dune, gypsum, White Sands National Monument, New Mexico.

The gradient of the water table beneath this west-facing slope, which apparently plunges from an alkali flat towards the dunes interior, was surprising. Across most of the radar record, the higher soluble salt content of the ground water affectively restricted penetration depths to the water table. However, beneath the toe slope of this dune, the radar's energy effectively penetrated the water table and imaged subsurface reflectors (In Figure 3, see reflectors that are evident below the water table at traverse line positions 15- to 25-m). The reasons for this increased depth of penetration in this area of the dune are unclear at this time.

During the course of this investigation, Bill Conrad showed me a reference to an article by McKee (1966). McKee studied the internal structure of a dune at White Sands National Monument by excavating two trenches across a 50 m long by 290 m wide 9 m high dune. This method struck me as being not only invasive, but very destructive. In future studies, researchers may wish to consider the use of GPR as a non-invasive tool will little impact to dunes.

Electromagnetic induction (EMI):
Electromagnetic induction uses electromagnetic energy to measure the apparent conductivity (EC_a) of earthen materials. Apparent conductivity is a weighted, average conductivity measurement for a column of earthen materials to a specific depth (Greenhouse and Slaine, 1983). Interpretations of EMI data are based on the identification of spatial patterns within data sets. Though seldom diagnostic in themselves, lateral and vertical variations in EC_a have been used to infer changes in soils and geologic materials.

Variations in EC_a are produced by changes in the electrical conductivity of earthen materials. The electrical conductivity of earthen materials will increase with increases in soluble salt, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976). The electrical conductivity of soils is influenced by the type and concentration of ions in solution, amount and type of clays in the soil matrix, volumetric water content, and temperature and phase of the soil water (McNeill, 1980).

Study Area:
The study area is known as the *Corralitos Site*. The site contains soil and ecological transects that were completed by Brandon Bestemeyer. The coordinates of the study area are shown in Figure 4. The area is in range and has

been mapped as Berino-Dona Ana association, 1 to 5 percent slopes (Bulloch and Neher, 1980). The well drained, deep Berino and very deep Dona Ana soils formed in mixed alluvium on fan piedmonts. Don Ana soils are calcareous throughout. Berino soils are not calcareous throughout. Berino is a member of the fine-loamy, mixed, superactive, thermic Ustic Calciargids family. Dona Ana is a member of the fine-loamy, mixed, superactive, thermic Typic Calciargids family.

Field Procedures:
The EM38DD meter was operated with the DAS70 Data Acquisition System and all measurements were georeferenced. The meter was operated in the continuous mode with measurements recorded at a 1-sec interval. For surveying, the meter was orientated with its long axis parallel to the direction of traverse and held about 2 inches above the ground surface. Walking at a fairly uniform pace across the study area completed the EMI survey.

Some negative EC_a were recorded with the EM38DD meter. These measurements were attributed to metallic artifacts (buried or littering the surface of the study area) and meter drift and calibration errors.

Spatial patterns of EC_a are known to be temporally variable (mostly related to changes in soil moisture and temperature). Temporal variation in soil moisture and temperature are expected to cause differences in measured conductivity. The conductivity of moist materials is linear proportion to temperature and changes at a rate of about 2.2% per degree centigrade (McNeill, 1980).

Results:
Table 1 summarizes the data collected with the EM38DD meter in the horizontal and vertical dipole orientation. A total of 2376 geo-referenced horizontal and vertical dipole orientation measurements were obtained over a period of about 2-hr. With the EM38DD meter, EC_a increased with increasing depth (measurements taken in the vertical dipole orientation were higher than measurements taken in the horizontal dipole orientation).

In the shallower-sensing, horizontal dipole orientation (0 to 0.75 m), EC_a averaged about 5.5 mS/m with a standard deviation of about 3.6 mS/m. One-half the observations had values of EC_a between about 3.2 and 7.5 mS/m. In the deeper-sensing, vertical dipole orientation (0 to 1.5 m), EC_a averaged 7.4 mS/m with a standard deviation of about 2.0 mS/m. One-half the observations had values of EC_a between about 6.0 and 8.5 mS/m. The increased EC_a with increasing depth was attributed to greater moisture and clay contents at lower soil depths.

Table 1. Basic Statistics for the EMI survey conducted with an EM38DD meter at the Corralitos Site.

	Horizontal Dipole	Vertical Dipole
Mean	5.5	7.4
Standard Dev.	3.6	2.0
Minimum	-13.5	3.6
Maximum	32.2	23.0
25% tile	3.2	6.0
75% tile	7.5	8.5

The data collected in the horizontal dipole orientation was low and considered too noisy. As a consequence, this data were not plotted. In the horizontal dipole orientation, the meter is most responsive to the material directly beneath the meter in the surface layers. The very low conductivity of the soil materials made the instrument more sensitive to interference from the operator and fluctuations in its height above the ground surface (affects the air column that is averaged into the measurement). In conducting this survey, the vegetation required constant adjustment in the height of the meter above the ground surface.

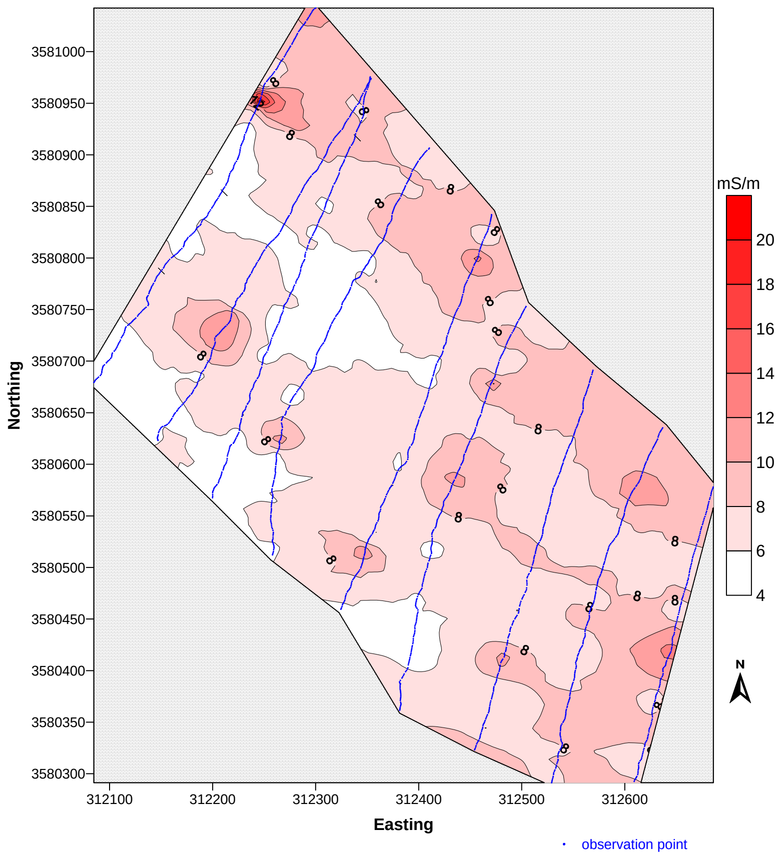

Figure 4. Spatial distribution of apparent conductivity collected with the EM38DD meter in the vertical dipole orientation at the Corralitos Site.

A plot of EC_a collected with the EM38DD meter in the vertical dipole orientation is shown in Figure 4. In this plot the isoline interval is 2 mS/m. Across most of the study area, EC_a is very low (averaged value of 7.4 mS/m) and relatively invariable (standard deviations of 2.0 mS/m). Although comparatively low and invariable, spatial patterns shown in Figure 4 conform to the general slope of this alluvial fan (slopes towards the south and southeast). Linear patterns are evident in the data and these patterns are orientated in a northwest to southeast direction. Soils with slightly higher clay contents were known to occur along the northern boundary of the study site. These linear patterns are believed to reflect principally variations in clay content. The high EC_a anomaly along the northwest border is an area of soils with surface layers that were noticeably saturated with water from recent rains. Higher moisture contents account for this anomaly.

While the results of the EMI survey appear favorable, more testing and ground-truth verifications are required to determine the appropriateness of this method for soil and vegetation mapping.

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