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

Subject: Soils – Geophysical Field Assistance **Date:** 2 November 2003

To: David Smith
State Soil Scientist/MLRA Office Leader
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Purpose:
The purpose of this investigation was to evaluate the use of electromagnetic induction (EMI) and ground-penetrating radar (GPR) to assist with the survey of Johnson Valley Off-Highway Vehicle Open Area Soil Survey.

Participants:
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Activities:
All activities were completed during the period of 26 to 30 October 2003.

Results:

1. Ground-penetrating radar provided radar records of good interpretative quality and satisfactory penetration depths. Soil, stratigraphic, and lithologic features were distinguishable on radar records in areas dominated by sandy and coarse-loamy, often calcareous soils. However, GPR failed to adequately resolve and provide unambiguous interpretations of key diagnostic features within these soils. In areas of saprolite, GPR failed to consistently distinguish the Cr horizon. Soil features that have weakly expressed or gradation properties, such as the Cr horizon, are often difficult to detect with GPR.

2. EMI appears to be a satisfactory quality control and mapping tool for soil survey operations in the Mohave Desert. EMI can provide a large number of observations in a short period of time. Because of the larger number of observations, maps prepared from EMI data can provide higher levels of resolution and more comprehensive coverage of sites and landforms than soil maps prepared with conventional methods. Differences in EMI response have been related to differences in soil properties and soils. EMI data can be used to provide a measure of map unit composition and variability, and to guide soil scientist in their selection of observation points.

3. The availability of computers, global positioning systems (GPS), geographical information systems (GIS), and geophysical tools are changing the way we map soils. These advancing technologies need to be better integrated and made more easy to use by soil scientists.

We appreciate the opportunity to work in California and with members of your fine staff.

With kind regards,

James A. Doolittle
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cc:
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Equipment:
The radar unit is the TerraSIRch SIR (Subsurface Interface Radar) System-3000, manufactured by Geophysical Survey Systems, Inc.[1] Morey (1974), Doolittle (1987), and Daniels (1996) have discussed the use and operation of GPR. The SIR System-3000 consists of a digital control unit (DC-3000) with keypad, color SVGA video screen, and connector panel. A 10.8-volt Lithium-Ion rechargeable battery powers the system. This unit is backpack portable and, with an antenna, requires two people to operate. The antennas used in this study have center frequencies of 70 and 200 MHz.

The RADAN for Windows (version 5.0) software program was used to process the radar records (Geophysical Survey Systems, Inc, 2003).[1] Processing included color transformation, marker editing, distance normalization, surface normalization, time-zero adjustment, and range gain adjustments.

The instruments used in this study included the Dualem-2 meter, the EM38 and EM38DD meter, and the GEM300 sensor. No ground contact is required with these devices. Lateral resolution is approximately equal to the intercoil spacing. The Dualem-2 meter, EM38DD meter, and GEM300 sensor have 2, 1, and 1.3 m intercoil spacings, respectively. All of these devices are portable and require only one person to operate.

Dualem Inc. manufactures the Dualem-2 meter.[1] Taylor (2000) has described the principles of operation for this meter. The Dualem-2 meter consists of one transmitter and two receiver coils. One receiver coil and the transmitter coil provide a perpendicular (P) geometry. The other receiver coil provides a horizontal co-planar (HC) geometry with the transmitter coil. This dual system permits two depths to be measured simultaneously without rotating the coils. The depth of penetration is “geometry limited” and is dependent upon the intercoil spacing, coil geometry, and frequency. The Dualem-2 operates at a frequency of about 9800 Hz. It provides penetration depths of 1.3 and 3.0 m in the P and HC geometries, respectively. The meter is keypad operated and measurements can either be automatically or manually triggered.

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

Geonics Limited manufactures the EM38 and EM38DD meters.[1] Geonics Limited (1998 and 2000) has described the principles of operation for these meters. The depth of penetration is "geometry limited" and is dependent upon the intercoil spacing, coil geometry, and frequency. These meters operate at a frequency of 14,600 Hz. They have effective penetration depths of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively (Geonics Limited, 1998 and 2000). The EM38DD meter consists of two EM38 meters bolted together and electronically coupled. One unit acts as a master unit (meter that is positioned in the vertical dipole orientation and having both transmitter and receiver activated) and one unit acts as a slave unit (meter that is positioned in the horizontal dipole orientation with only the receiver switched on).

The GEM300 multifrequency sensor is manufactured by Geophysical Survey Systems, Inc.[1] Won and others (1996) have described the use and operation of this sensor. This sensor is configured to simultaneously measure up to 16 frequencies between 330 and 20,000 Hz with a fixed coil separation (1.3-m). With the GEM300 sensor, the penetration depth is considered "skin depth limited" rather than "geometry limited." The skin-depth represents the maximum depth of penetration and is frequency and soil dependent: low frequency signals travel farther through conductive mediums than high frequency signal. Theoretical penetration depths of the GEM300 sensor are dependent upon the bulk conductivity of the profiled earthen material(s) and the operating frequencies. Multifrequency sounding with the GEM300 supposedly allows multiple depths to be profiled with one pass of the sensor.

The Geonics DAS70 Data Acquisition System was used to record and store both EMI and GPS data.[1] The acquisition system consists of an EMI meter, Allegro field computer, and Trimble AG114 GPS receiver. With the logging system, the meter is keypad operated and measurements can either be automatically or manually triggered.

To help summarize the results of this study, the SURFER for Windows, version 8.0 (developed by Golden Software, Inc.) was used to construct two-dimensional simulations.[1] Grids were created using kriging methods with an octant search.

Ground-Penetrating Radar:
Ground-penetrating radar is a time scaled system. The system measures the time it takes electromagnetic energy to travel from an antenna to an interface (i.e., soil horizon, stratigraphic layer) and back. To convert travel time into a depth scale requires knowledge of the velocity of pulse propagation. Several methods are available to determine the velocity of propagation. These methods include use of table values, common midpoint calibration, and calibration over a target of known depth. The last method is considered the most direct and accurate method to estimate propagation velocity (Conyers and Goodman, 1997). The procedure involves measuring the two-way travel time to a known reflector that appears on a radar record and calculating the propagation velocity by using the following equation (after Morey, 1974):

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

Equation [1] describes the relationship between the propagation velocity (V), depth (D), and two-way pulse travel time (T) to a subsurface reflector. During this study, the two-way radar pulse travel time was compared with measured depths to known subsurface interfaces within each study site. Computed propagation velocities were used to scale the radar records.

Results:
Rock Outcrop-Cougarbutte Association, 2 to 15 % slopes:
A 20 m traverse line was established across an area of this map unit. The very shallow, somewhat excessively drained Cougarbutte soil formed in granitic residuum and colluvium on pediments. Clay content ranges from 8 to 14 percent. Depth to paralithic contact ranges from 6 to 20 cm. Cougarbutte is a proposed soil series. Cougarbutte is a member of the loamy, mixed, superactive, calcareous, thermic, shallow Typic Torriorthents family. The approximate location of the traverse line was Zone 11, 0519868 E and 3814242 N (NAD83). Survey flags were inserted in the ground at intervals of 2 meters and served as reference points. Surveys were completed with the 400 and 200 MHz antenna at scanning times of 250 and 350 ns.

Based on a measured depth (45 cm) to a buried metallic reflector, the velocity of propagation through relatively dry sands was estimated to be about 0.16 m/ns. The dielectric permittivity was 3.2. Using a scanning time of 70 ns, a velocity of 0.16 m/ns, and equation [1], the maximum depth of penetration through dry sands is about 5.9 m.

The radar records obtained with the 400 and 200 MHz antenna were of generally poor interpretative quality. The dry, coarse-textured soil had similar dielectric properties to the underlying granite bedrock. The upper part of the bedrock was highly weathered producing an often gradational boundary of increasing density and hardness with increasing depth. As a consequence, the reflection coefficient across the soil/bedrock interface was small producing a weak and often indistinguishable subsurface reflection. The high calcium carbonate content of these soils attenuated the radar energy and restricted penetration depth.

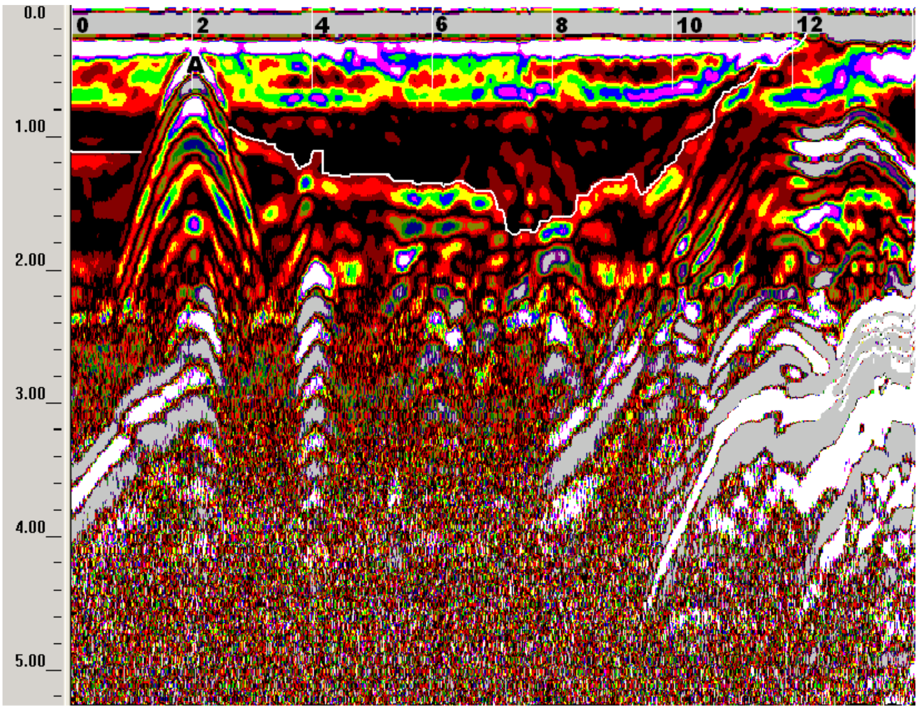

Figure 1. Radar record form an area of Rock Outcrop – Cougarbutte Association, 2 to 15 % slopes. The depth scale is expressed in m.

Figure 1 is a radar record that was collected with the 200 MHz antenna in an area of Rock Outcrop-Cougarbutte Association, 2 to 15 % slopes. The short, vertical lines at the top of the radar record represent the equally spaced (2-m) reference points along the radar traverse. A depth scale is provided along the left-hand margin of this figure. A metallic reflector (see *A* in Figure 1), buried at a depth of 45 cm, produced a strong hyperbolic reflection that was used to depth scale the radar record. A red line has been used to highlight the soil/bedrock interface. This interface produced a weak and difficult to identify subsurface reflection. Between reference points 0 and 2, this interface was very weak and indistinguishable. Between reference points 12 and 14 m, the bedrock was exposed at the surface. Veins of dissimilar mineralogy produce the high amplitude, planar reflections within the bedrock.

At 5 reference points the measured depths were compared with the interpreted depths to bedrock. A high (r = 0.819) and significant (0.001 level) correlation was found between the measured and interpreted depths to bedrock. Measured depths to bedrock ranged from 45 to 140 cm. The average difference between interpreted and measured depths to bedrock was 16.2 cm, with a range of 1 to 29 cm. These results confirm the accuracy of GPR in areas that have strong and identifiable subsurface interfaces. However, strong and identifiable soil/bedrock interface were infrequently observed on radar records from the study area.

The weak and often indistinguishable reflection from the soil/bedrock interface limited the usefulness of GPR in this map unit. The high calcium carbonate content of these soils is believed to be responsible for high rates of signal attenuation that limit penetration depths.

<u>Bluepoint loamy fine sands, 2 to 8 % slopes:</u>
Radar traverses were conducted in an area of Bluepoint loamy fine sands, 2 to 8 % slopes, to evaluate the depth of penetration and the resolution of subsurface interfaces that is achievable with GPR in slightly alkaline to strongly alkaline, sandy soils. The very deep, somewhat excessively drained Bluepoint soil forms in eolian deposits from mixed rock sources on dunes and sand sheets. Bluepoint is a member of the mixed, thermic Typic Torripsamments family. The traverse was located on a convex sand sheet northwest of Means Lake in the southeast ¼ Section 24, T. 4 N., R. 4 E. The survey was completed with the 200 MHz antenna at scanning times of 250 and 350 ns.

Based on a measured depth (50 cm) to a buried metallic reflector, the velocity of propagation through relatively dry sands was estimated to be about 0.20 m/ns. The dielectric permittivity was 2.3. Using a scanning time of 80 ns, a velocity of 0.2 m/ns, and equation [1], the maximum depth of penetration through dry sands is about 7.8 m.

The radar records obtained with the 200 MHz antenna were of generally good interpretative quality. Abrupt and contrasting differences in density and grain size produced high amplitude reflections. 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). Conductive, alkaline or saline ground waters cause severe signal loss and limit penetration depths. In the absence of carbonates, soluble salts, or saline groundwater, GPR will penetrate deeply and perform well in most coarse textured soil materials. However, the presence of even small amounts of clay will reduce the depth of penetration as this fraction greatly increases pulse attenuation (Harari, 1996). In some arid and semi-arid areas, high levels of calcium carbonate occur in soils. Though less attenuating than saline and sodic soils, soils with calcareous layers severely limit the depth of penetration (0.5 to 1 m) (Grant and Schultz, 1994)).

Figure 2 is a radar record that was collected with the 200 MHz antenna in an area of Bluepoint loamy fine sands, 2 to 8 % slopes. The short, vertical lines at the top of the radar record represent the equally spaced (5-m) reference points along the radar traverse. A depth scale is provided along the left-hand margin of this figure. A metallic reflector (see *A* in Figure 2), buried at a depth of 50 cm, produced a strong hyperbolic reflection that was used to depth scale the radar record.

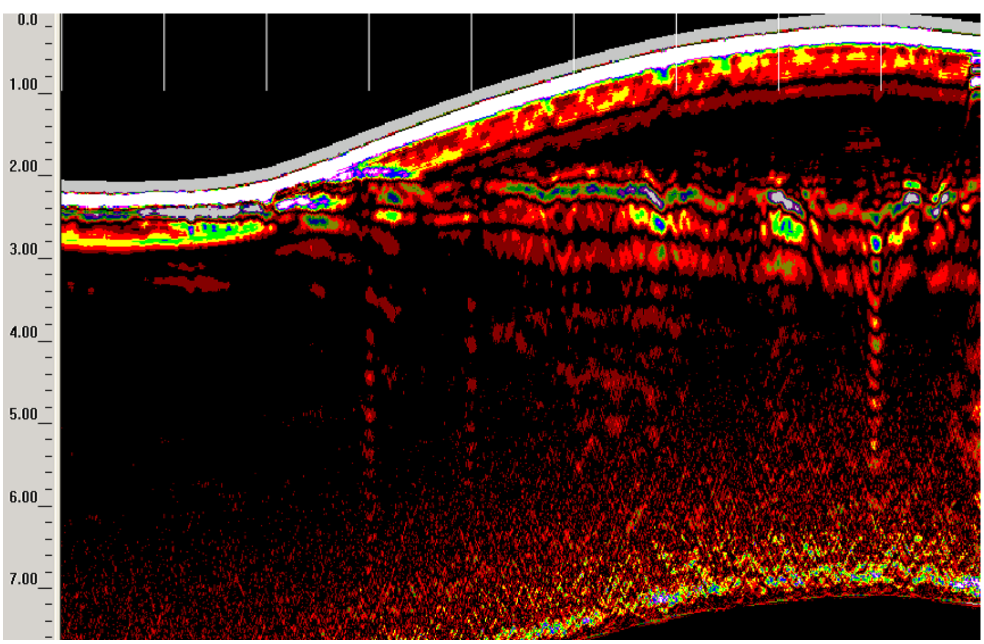

Figure 2. This radar record is from an area of Bluepoint loamy fine sands, 2 to 8 % slopes.

Electromagnetic Induction:
Electromagnetic induction is a noninvasive geophysical tool that can be used for soil and site investigations. Advantages of EMI are its portability, speed of operation, flexible observation depths, and moderate resolution of

subsurface features. Results of EMI surveys are interpretable in the field. This geophysical method can provide in a relatively short time the large number of observations that are needed to comprehensively cover sites. Maps prepared from correctly interpreted EMI data provide the basis for assessing site conditions, planning further investigations, and locating sampling or monitoring sites.

Electromagnetic induction uses electromagnetic energy to measure the apparent conductivity 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). Variations in apparent conductivity are caused by changes in the electrical conductivity of earthen materials. The electrical conductivity of soils is influenced by the type and concentration of ions in solution, volumetric water content, temperature and phase of the soil water, and amount and type of clays in the soil matrix (McNeill, 1980). The apparent conductivity of soils increases with increases in soluble salts, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976).

Electromagnetic induction measures vertical and lateral variations in apparent electrical conductivity. Values of apparent conductivity are seldom diagnostic in themselves. However, relative values and lateral and vertical variations in apparent conductivity can be used to infer changes in soils and soil properties. Interpretations are based on the identification of spatial patterns within data sets. To assist interpretations, computer simulations of EMI data are normally used. To verify interpretations, ground-truth measurements are required.

<u>Daisy-Gravesumit-Canjon complex, 2-4 % slopes:</u>
On Tuesday, EMI surveys were conducted in an area of Daisy-Gravesumit-Canjon complex, 2 to 4 % slopes. The very deep, well drained Daisy and Gravesumit soils, and the somewhat excessively drained Cajon soil formed in dominantly granitic alluvium on alluvial fans and fan remnants. Clay contents range from 8 to 18 percent. Daisy is a member of the loamy, mixed, superactive, thermic Arenic Calciargids family. Gravesumit is a member of the coarse-loamy, mixed, superactive, thermic Typic Calciargids family. Cajon is a member of the mixed, thermic Typic Torripsamments family.

Based on auger and GEM300 sensor measurements made at six observation points, a negative relationship was found to exist between EMI measurements and the depth to the argillic horizon. Stronger relationships were found in the vertical dipole orientation than in the horizontal dipole orientation. At an operating frequency of 9810 Hz, correlation coefficient of -0.57 and -0.52 existed between the depths to the argillic horizon and measurements made in the vertical and horizontal dipole orientations, respectively. At an operating frequency of 14790 Hz, correlation coefficients of -0.58 and -0.48 existed between the depths to the argillic horizon and measurements made in the vertical and horizontal dipole orientations, respectively.

Survey procedures were simplified to expedite fieldwork. Two parallel, 60-m lines that were spaced about 120 m apart were laid out. Dimensions of the grid was 60 by 120 m (about ha) with the long axis athwart the alluvial fan. Along each of the two lines, survey flags were inserted in the ground at intervals of 5 m. These flags served as grid line end points and provided ground control. Walking at a fairly uniform pace between similarly numbered flags on opposing sets of parallel lines in a back and forth pattern across each grid area completed a survey. The EM38 meter (operated in the vertical dipole orientation) and the dualem-2 meter were operated in the continuous mode with measurements recorded at 1-sec intervals. Surveys were conducted in the continuous mode with both the EM38DD held about 1 to 2 inches and the Dualem-2 meters about 40 inches above the ground surface with their long axis parallel to the direction of traverse.

A total of 1268 measurements were recorded with the EM38 meter. Measurements were comparatively low and invariable suggesting fairly uniform soil properties across most of the site. Apparent conductivity averaged 11.6 mS/m with a range of 7.2 to 20.1 mS/m. Half of these observations had values of apparent conductivity between 10.2 and 12.5 mS/m.

Figure 3 is a plot showing the distribution of apparent conductivity measured with the EM38 meter in the vertical dipole orientation. Although the slope is slight, linear patterns extend across the survey area in essentially parallel with the slope. The orientation of these linear patterns suggests variations in alluvial deposits on this fan pediment.

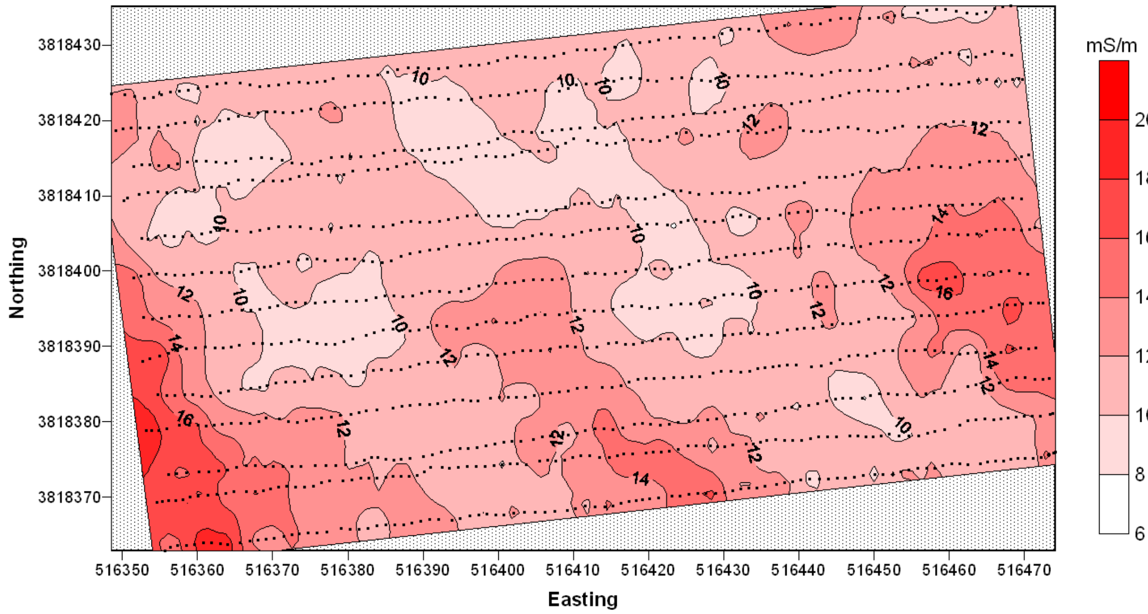

Figure 3. Spatial patterns of apparent conductivity in an area of Daisy-Gravesumit-Canjon complex, 2 to 4 % slopes, as measured with the EM38 meter in the vertical dipole orientation.

<u>Cajon-Daisy-Noagua Association, 2-8 % slopes:</u>
On Thursday, EMI surveys were conducted in an area of Cajon-Daisy-Noagua Association, 2-8 % slopes. The very deep, well drained Daisy and Gravesumit soils, and the somewhat excessively drained Cajon soil formed in dominantly granitic alluvium on alluvial fans and fan remnants. Clay contents range from 8 to 18 percent. Daisy is a member of the loamy, mixed, superactive, thermic Arenic Calciargids family. Gravesumit is a member of the coarse-loamy, mixed, superactive, thermic Typic Calciargids family. Cajon is a member of the mixed, thermic Typic Torripsamments family.

Traverses were conducted in an upslope-downslope direction from the apex of a remnant alluvial fan. The EM38DD meter was operated in the continuous mode with measurements recorded at 1-sec intervals. The EM38DD was held about 3 inches above the ground surface with its long axis parallel to the direction of traverse. Walking at a fairly brisk and uniform pace, the EM38DD meter recorded 786 geo-referenced measurements in about 1.25 hours of recording time.

In general, apparent conductivity was comparatively low and invariable suggesting fairly uniform soil properties across most of the site. In the deeper-sensing, vertical dipole orientation, apparent conductivity averaged 10.93 mS/m with a range of 0.6 to 44.4 mS/m. However, half of these observations had values of apparent conductivity between 6.59 and 12.44 mS/m. As seen in Figure 3, apparent conductivity increases towards the west (left-hand portion of plot) and in a downslope direction. The high values along the western boundary are attributed to greater amounts of soluble salts and clays in the soil profile.

Ground-truth auger observations were made at points selected from the EMI plot and range of measurements. Conductivity appeared to be inversely related to the depth to argillic and directly related to the amounts of fines in the soil profile. A profile of Arizo soil was associated with an apparent conductivity of 8.5 mS/m. A profile of Cajon soil was associated with an apparent conductivity of 12.4. In this profile sands were observed to a depth of 122 cm, the depth of auger refusal. Profile of Cajon loamy substratum was associated with an apparent conductivity of 20.2 and 38.4 mS/m. In the former profile, loamy sands were observed to a depth of 148 cm. A Btk horizon was present at a depth of 148 cm. In the latter profile, the higher apparent conductivity could be attributed to the shallower depth (100 cm) to loamy Bt horizon. The soil was calcareous above the Bt horizon. However, soluble salts are believed to be the causal factor for the higher apparent conductivity.

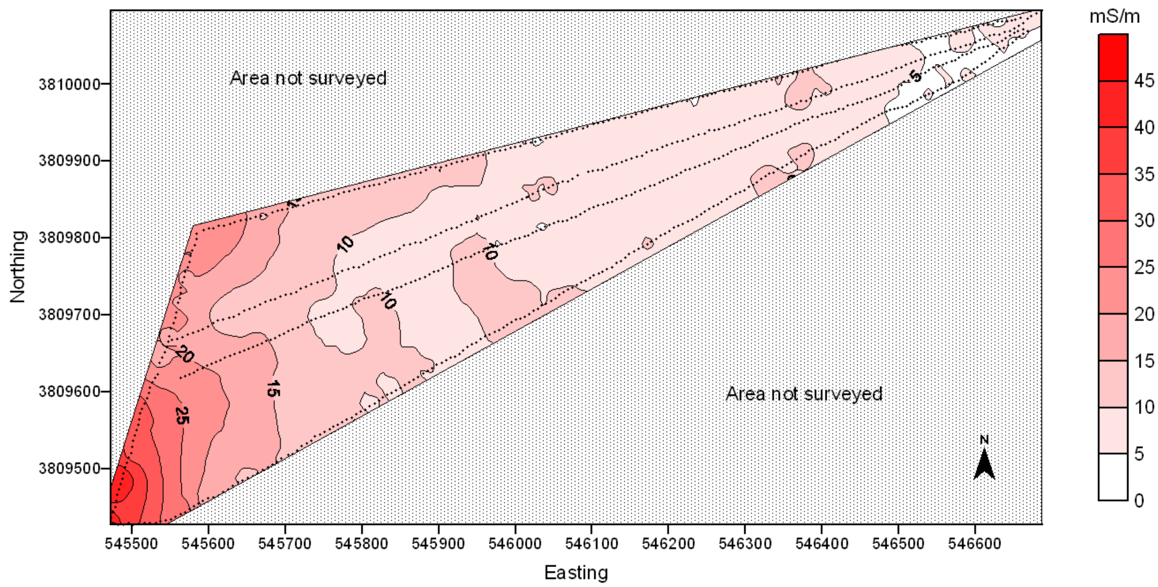

Figure 4. Spatial patterns of apparent conductivity in an area of Cajon-Daisy-Noagua Association, 2 to 8 % slopes, as measured with the EM38 meter in the vertical dipole orientation.

References:

Conyers, L. B., and D. Goodman. 1997. Ground-penetrating Radar; an introduction for archaeologists. AltaMira Press, Walnut Creek, CA. 232 pp.

Daniels, D. J. 1996. Surface-Penetrating Radar. The Institute of Electrical Engineers, London, United Kingdom. 300 p.

Doolittle, J. A. 1987. Using ground-penetrating radar to increase the quality and efficiency of soil surveys. 11-32 pp. In: Reybold, W. U. and G. W. Peterson (eds.) Soil Survey Techniques, Soil Science Society of America. Special Publication No. 20. 98 p.

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. 33 p.

Geophysical Survey Systems, Inc. 1998. GEM-300 Multifrequency Electromagnetic Profiler. Operating System Version 1.0. MN37-097A. North Salem, NH. 67 p.

Grant, J. A. and P. H. Schultz. 1994. Erosion of ejecta at Meteor Crater: Constraints from ground penetrating radar. 789-803 pp. IN: Proceedings Fifth International Conference on Ground-Penetrating Radar. June 12 – 14, 1994, Kitchner, Ontario, Canada. Waterloo Centre for Groundwater Research and the Canadian Geotechnical Society. 1294 p.

Greenhouse, J. P., and D. D. Slaine. 1983. The use of reconnaissance electromagnetic methods to map contaminant migration. Ground Water Monitoring Review 3(2): 47-59.

Harari, Z. 1996. Ground-penetrating radar (GPR) for imaging stratigraphic features and groundwater in sand dunes. Journal of Applied Geophysics 36: 43-52.

Kachanoski, R. G., E. G. Gregorich, and I. J. van Wesenbeeck. 1988. Estimating spatial variations of soil water content using noncontacting electromagnetic inductive methods. Can. J. Soil Sci. 68:715-722.

McNeill, J. D. 1980. Electromagnetic terrain conductivity measurements at low induction numbers. Technical Note TN-6. Geonics Ltd., Mississauga, Ontario. 15 p.

Geophysical Survey Systems, Inc, 2003. RADAN for Windows Version 5.0; User's Manual. Manual MN43-162 Rev A. Geophysical Survey Systems, Inc., North Salem, New Hampshire.

Morey, R. M. 1974. Continuous subsurface profiling by impulse radar. p. 212-232. IN: Proceedings, ASCE Engineering Foundation Conference on Subsurface Exploration for Underground Excavations and Heavy Construction, held at Henniker, New Hampshire. Aug. 11-16, 1974.

Pannel, J. P., J. M. Yentery, S. O. Woodyard, and R. E. Mayhugh. 1973. Soil Survey of Alamosa County, Colorado. USDA-Soil Conservation Service in cooperation with the Colorado Agricultural Experimentation. U. S. Government Printing Office, Washington, DC.

Rhoades, J. D., P. A. Raats, and R. J. Prather. 1976. Effects of liquid-phase electrical conductivity water content and surface conductivity on bulk soil electrical conductivity. Soil Sci. Soc. Am. J. 40:651-655.

Schenk, C. J., D. L. Gautier, G. R. Olhoeft, and J. E. Lucius. 1993. Internal structure of an aeolian dune using ground-penetrating radar. Spec. Publs Int. Ass. Sediment. 16: 61-69.

Taylor, R. S. 2000. Development and applications of geometric-sounding electromagnetic systems. Dualem Inc., Milton Ontario. 4 p.

Won, I. J., Dean A. Keiswetter, George R. A. Fields, and Lynn C. Sutton. 1996. GEM-2: A new multifrequency electromagnetic sensor. Journal of Environmental & Engineering Geophysics 1:129-137.