Site characterization at the Groundwater Remediation Field Laboratory

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Environmental site assessment usually includes determining the geologic character of the subsurface *after* contamination has occurred. However, at the Groundwater Remediation Field Laboratory (GRFL), we acquired extensive geophysical and geotechnical data *before* planned contaminant releases happened. These prespill geophysical images provide background data for comparison with data acquired in the future. Additionally, a large amount of cone penetrometer (CPT) data provide in situ geotechnical measurements to compare with surface geophysics. The end product is a unique data set and an extensive analysis, resulting in a detailed description of the subsurface based on standard geophysical and geotechnical methods.

Site characterization for environmental cleanup provides the information needed to determine the extent and scope of a specific problem and to design remediation strategies. This can be expensive and hazardous when based primarily on in situ sampling by invasive techniques, such as monitoring wells or geologic coring. For example, boreholes must be closely spaced to insure that important features are found. Furthermore, drill holes may remobilize contaminants and provide conduits that may lead to further contamination. And, monitoring wells must be sampled for years to comply with environmental regulations. To reduce costs and to provide characterization over a wider area, geophysical methods often supplement drilling. Unfortunately, interpretation of surface geophysical data in terms of relevant physical properties is often difficult because of the scarcity of direct subsurface controls. Such controls, though, are present at the GRFL and provide an opportunity to study the relationship between in situ geotechnical measurements of physical properties with a variety of geophysical data.

The GRFL, administered by the U. S. Air Force's Armstrong Laboratory under the Strategic Environmental Research and Development Program, is located at Dover Air Force Base, Dover, Delaware.

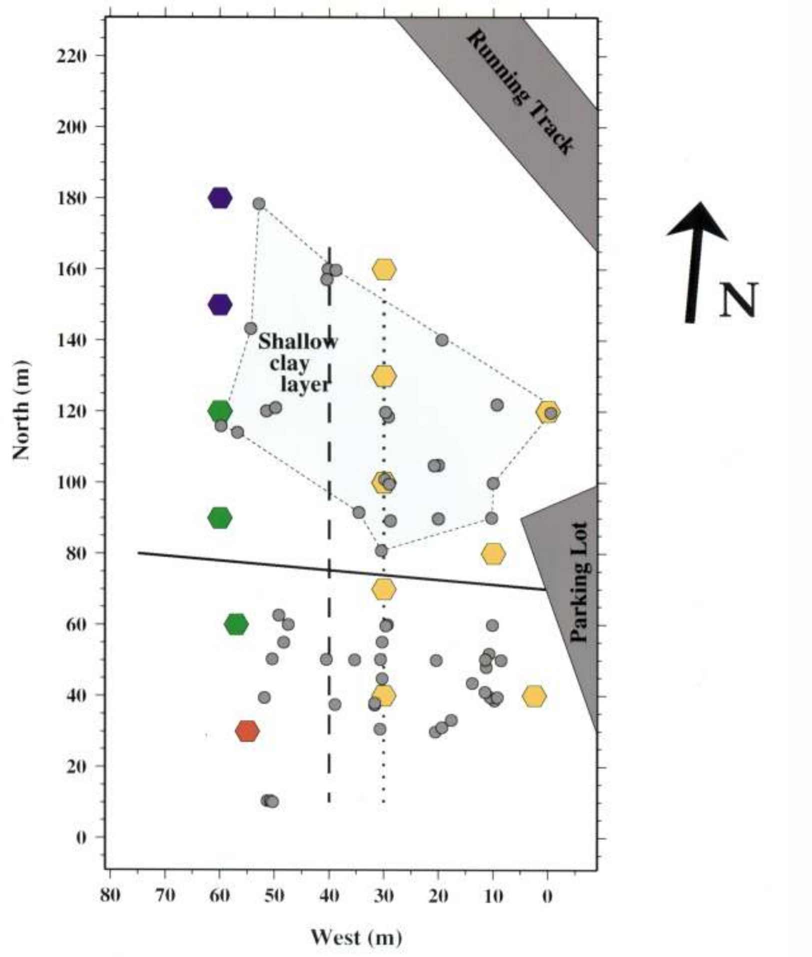


Figure 1. Location of some geophysical surveys. Hexagons = locations of the electrical resistivity soundings; colors are coordinated with Figure 6. Gray dots = locations of CPT pushes. Dashed line = the seismic reflection profile in Figure 2. The 20 MHz GPR profile in Figure 3 is coincident with this line. Dotted line = the 50 MHz GPR profile of Figure 4. Solid line = the seismic refraction survey in Figure 5. Terrain conductivity measurements cover the field (see Figure 7).

Various groups conducted complementary geophysical surveys of the site during 1995 and 1996, collecting ground penetrating radar (GPR) with pulseEKKO and SIR units at multiple source frequencies, shallow high resolution reflection and refraction seismic data, one-dimensional electrical resistivity surveys, and terrain conductivity measurements (Figure 1). We recorded high-resolution seismic reflection lines along north-south profiles separated by 10 m. Lines in a GPR grid were also separated by 10 m. The north-south seismic reflection lines were coincident with some GPR lines. Applied Research Associates simultaneously collected soil samples and performed CPT "pushes."

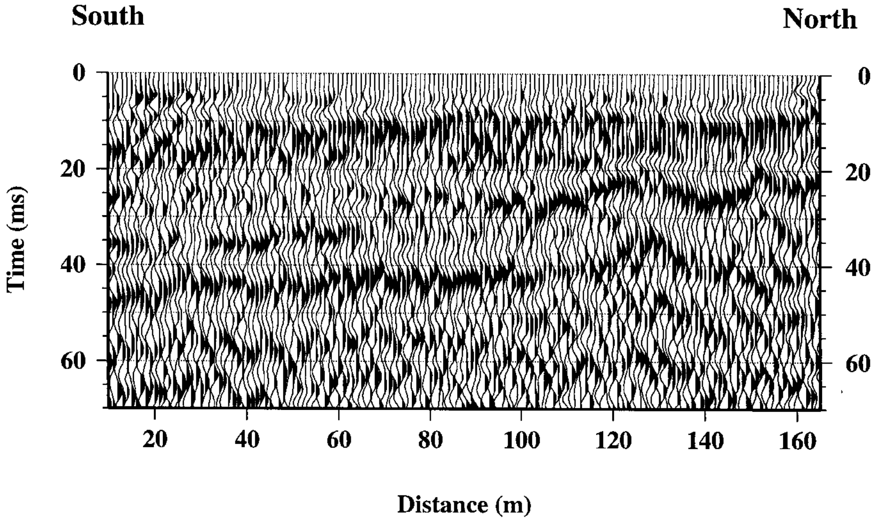


Figure 2. Seismic reflection data from the north-south profile along 40 m west. The reflector between 40 and 50 ms corresponds to the aquitard boundary. The reflector between 20 and 30 ms on the northern half of the section corresponds to a shallow clay layer.

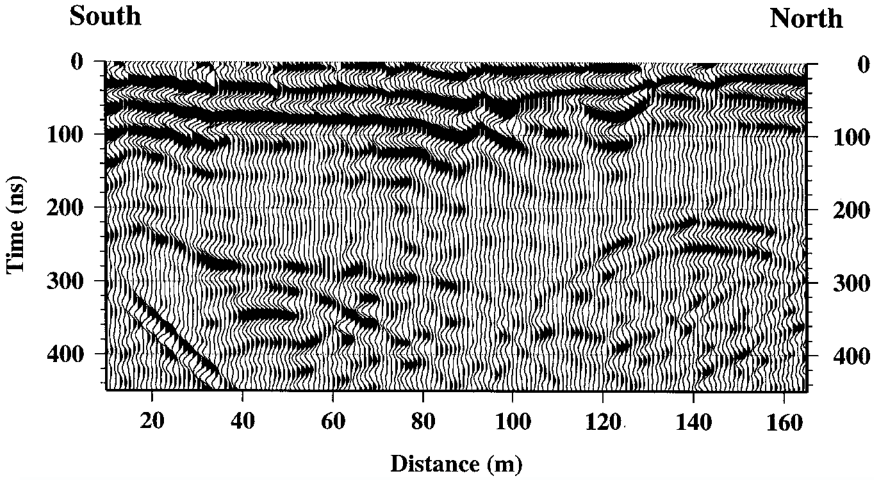


Figure 3. 20 MHz SIR-2 data along the same profile as the seismic reflection data in Figure 2. The prominent reflection between 200 and 300 ns that ends at about 90 m is the aquitard reflection.

Several shallow wells, previously drilled near the site, provide a detailed look at the medium to coarse grained sands and silt that comprise the local stratigraphy. An unconfined aquifer (water table at 7.3 m and bounded below by a clay aquitard whose depth is 9-14 m) defines the main hydrologic feature. Three main features of the aquifer provide targets for the geophysical surveys. The primary target is the sand-clay interface that marks the aquitard boundary at the base of the surface aquifer; the second is the water table; the third is a thin, shallow clay layer about 4 m below the surface in the northern portion of the GRFL. Imaging this clay layer, which was discovered by the CPT surveys, tests our ability to geophysically determine aquifer heterogeneity. The different geophysical techniques image these features with varying degrees of success.

Seismic and GPR. GPR works best in electrically resistive environments such as dry, unconsolidated sands with little clay. High resolution seismic reflection works best where high frequencies from the source propagate efficiently in the earth, such as in water-saturated conditions or in clay-rich materials. Not surprisingly, when one of these techniques provides high quality data, the other usually does not.

At the GRFL, we obtained good data from both techniques and we identified common reflections on the respective sections. A reflection is observed at 40-50 ms across most of the seismic reflection profile (Figure 2). In the GPR image (Figure 3), a reflection is observed at 200-300 ns. Using velocities determined from the GPR data, the reflector is about 11 m below the surface in the south and deepens to about 15 m in the middle of the section. We interpret this as the reflection from the base of the aquifer. The depth to the reflector in the seismic section is the same. These depths agree with the depth to the aquitard measured in the CPT surveys. Clearly, GPR and high resolution seismic adequately image the base of the aquifer.

In the seismic data, a shallower reflection at 20-30 ms is easily seen at 90-165 m (along the distance axis). Using the stacking velocities to estimate depth in the time section, this reflector is about 4 m deep and coincides with the northern shallow clay layer observed in the CPT data. A reflection from the shallow clay is not observed in the 20 MHz GPR data. However, in the 50 MHz GPR data (Figure 4), a reflection exists at about 4 m, because the shorter wavelengths in the higher frequency data can better resolve thinner layers. Again, the seismic and GPR data appear to image the same subsurface feature.

The first events in the GPR images are the air and ground waves. Unlike seismic velocities, EM velocities usually decrease with depth and the EM velocity in air, the speed of light, is much faster than in other materials. Thus, the waves traveling directly between the antennas are the first to arrive. Also, diffraction hyperbolas from nearby light towers and fences are easily seen in the GPR images. These conductive, metallic objects are strong reflectors and EM waves propagate with little attenuation in air, so reflections from above ground features are often present in GPR data. Even though GPR images appear similar to seismic reflection images, these differences are reminders that the two methods image different physical properties.

Seismic refraction is the only technique to image the water table (Figure 5). All other methods, including the in situ CPT probes, show little, if any, indication of it.

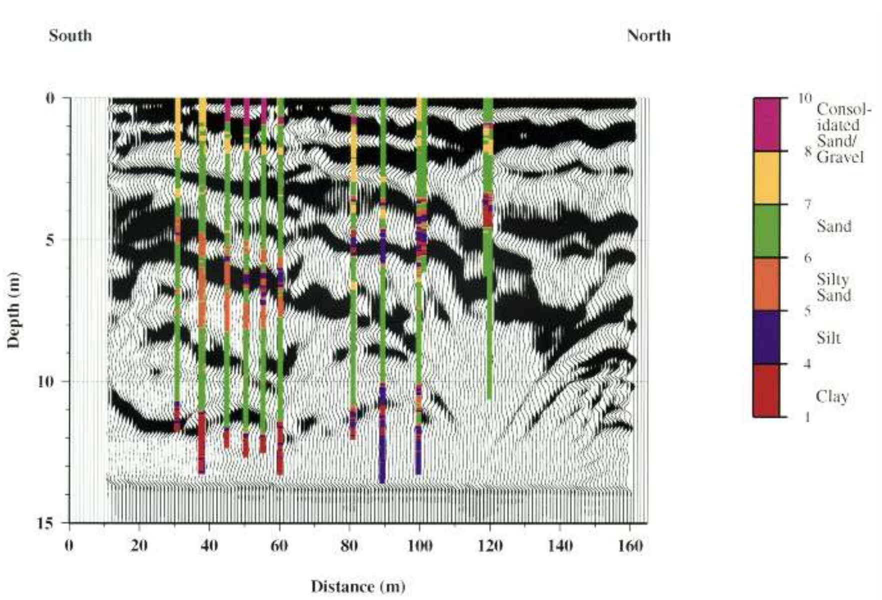


Figure 4. 50 MHz pulseEKKO IV data overlain by CPT soil classification interpretations. The color scale indicates the interpretation of the soil type. Data are from the north-south profile along 30 m west, 10 m to the east of the seismic reflection data in Figure 2.

Seismic refraction is a reliable method to determine depths to large velocity changes, such as depth-to-basement in aquifer studies. In the seismic refraction data, the direct wave has a slow velocity (about 400 m/s) which is not unusual for dry, unconsolidated sands at or near the surface. A refracted wave overtakes the direct wave about 20 m from the shot point. Based on a simple one-dimensional interpretation, the intercept time indicates that the refraction is from a depth of about 8 m — the approximate depth of the water table. Additionally, the refraction has an apparent velocity of 1600 m/s. This indicates that the refraction is from the top of the water table.

Electrical methods. We used two methods to measure electrical properties at the GRFL. The electrical methods complement GPR since they measure the resistivity or conductivity of the subsurface, whereas GPR data are primarily sensitive to changes in dielectric permittivity below ground level.

Kick Geoexploration acquired 14 resistivity soundings using a Schlumberger array at locations shown in Figure 1. Figure 6 shows apparent resistivity measurements from six soundings conducted approximately along a north-south profile at 60 m west. The sounding at the southernmost station has the highest apparent resistivity at AB/2 spacings less than 50 m. As the survey pro-

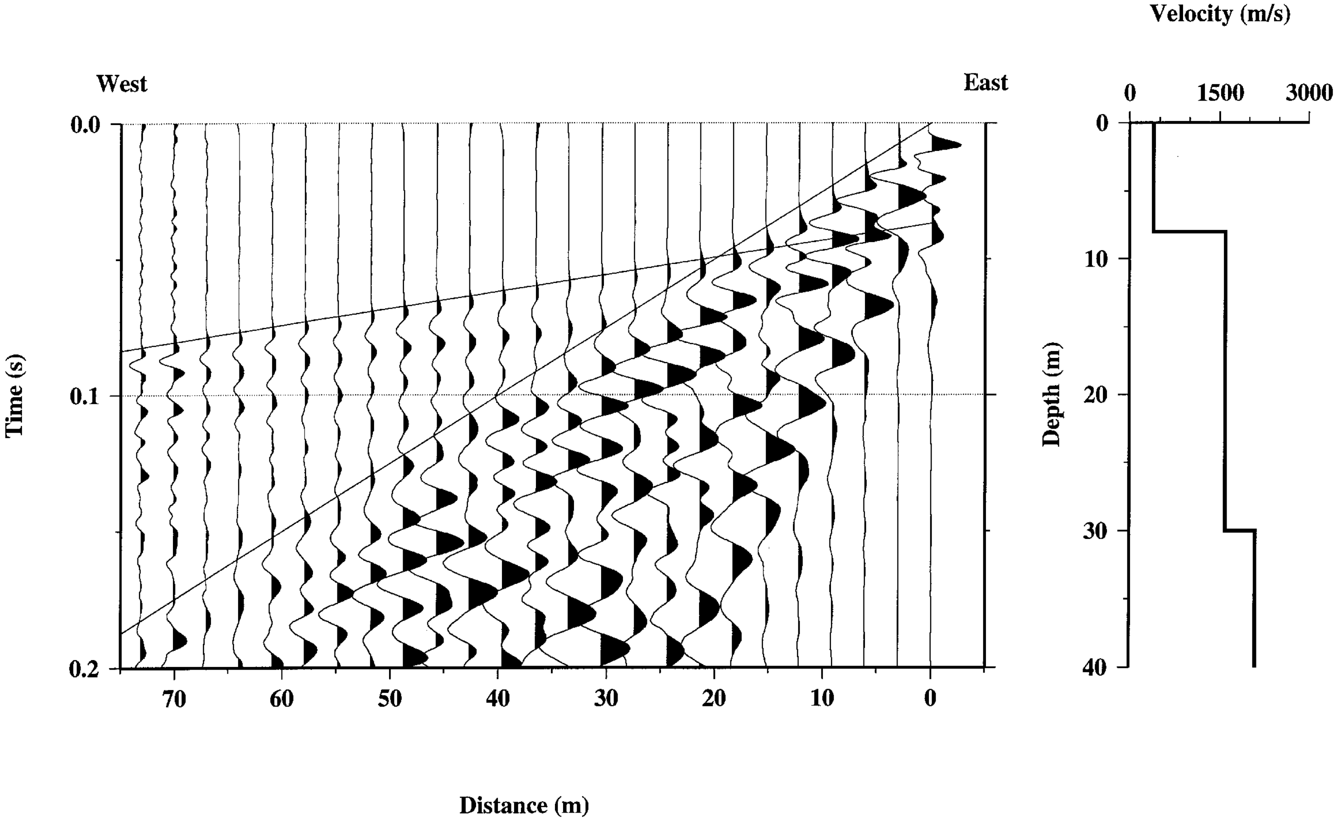


Figure 5. Seismic refraction data along an east-west profile. The thin, solid lines indicate the direct wave and the refracted wave. The one-dimensional velocity profile is presented on the right and clearly shows the water table at about 8 m. The velocity jump at 30 m is based on a weak, secondary arrival (not marked).

gresses to the north, apparent resistivities decrease, indicating that the subsurface is becoming more conductive.

Terrain conductivity surveys were acquired using EM-31 and EM-34-3 systems (Figure 7). They provided depth penetration of 6-15 m. These indicate that the northern section is more conductive than the southern end, which agrees with the resistivity data. Although many things can increase conductivity in the earth, the electrical methods suggest the shallow, electrically conductive clay layer first identified by CPT sampling.

Cone penetrometer. Applied Research Associates directly measured subsurface physical properties using CPT surveys, in which an instrument is pushed into the ground while readings are taken. CPT data are presented in terms of measured or calculated properties as a function of depth (Figure 8). The piezoelectric tool is the basic instrument. This device measures the sleeve and tip stresses and the pore pressure. With these geotechnical quantities, we can use empirical formulae to infer the soil type.

Other instrument packages, including a resistivity tool and a dielectric tool, were attached to the CPT stem. The former measures the resistivity with a small, four-electrode array. The dielectric probe measures the permittivity using resonant frequency. These data are direct samples of the ground beneath the GRFL and verify the surface geophysics.

Figure 4 shows 50 MHz GPR data overlain with soil classification based on interpretations of CPT data. The GPR reflection at 10-12 m corresponds with the top of the aquitard, a sand-to-clay transition. In the upper to middle section, the many radar reflections show a complicated subsurface stratigraphy with the structural trend dipping to the north. However, based on the CPT data, the structural trend could be interpreted as dipping to the south. Also, many reflections in the GPR data do not correspond to soil type changes interpreted from the CPT data. Interference of radar waves may cause part of the discrepancy. The CPT data has a vertical sampling interval of 5 cm, so some of the detail from the CPT is below the resolution level of 50 MHz GPR. In general, the geo-

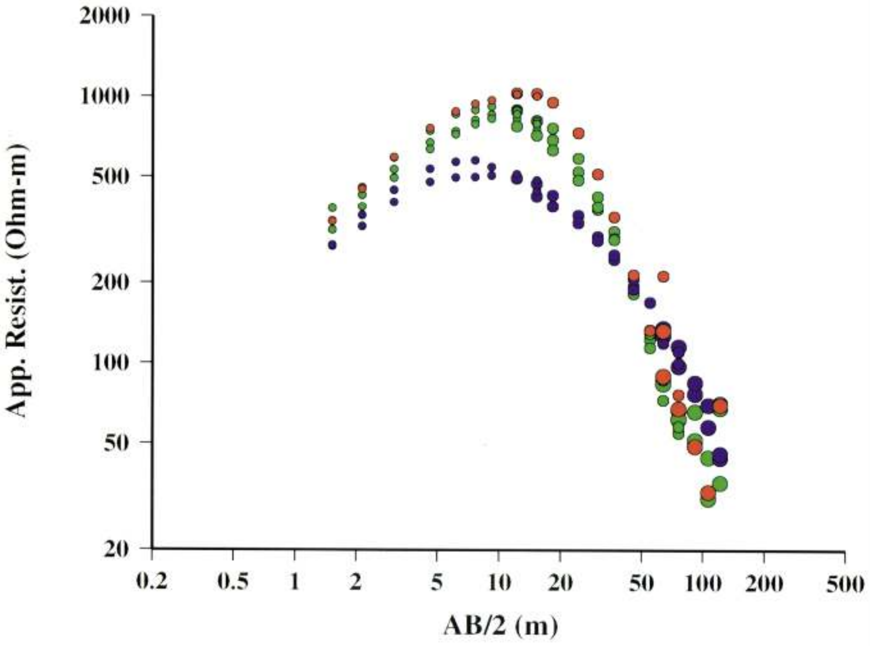


Figure 6. Resistivity soundings along a south-north profile near the western edge of the GRFL showing decreasing resistivity to the north. The data are plotted as apparent resistivities. AB is the separation distance of the electrodes. The colors are coordinated with the electrical resistivity locations in Figure 1. The increasing size of the symbols indicates increasing MN (potential electrode) separations.

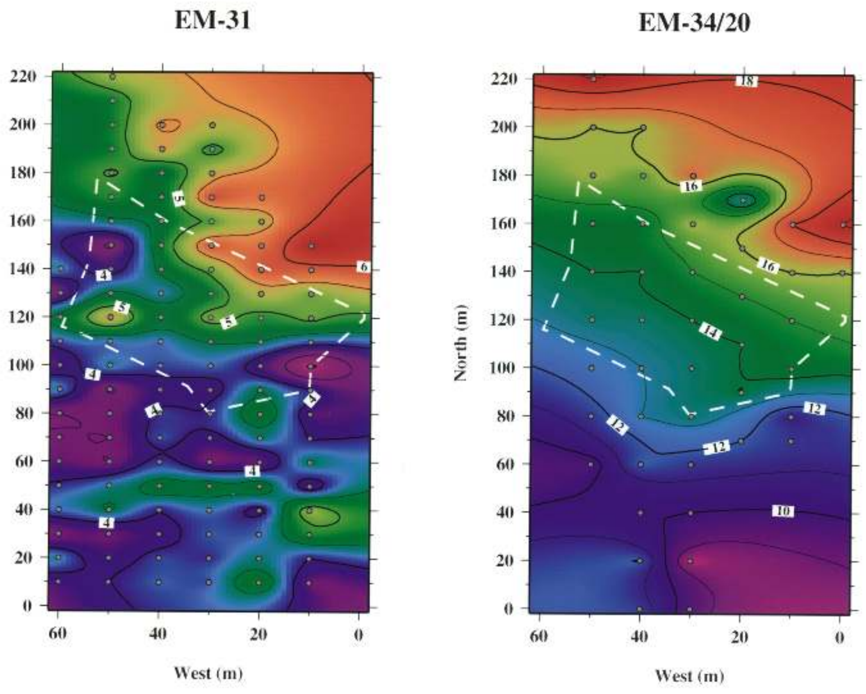
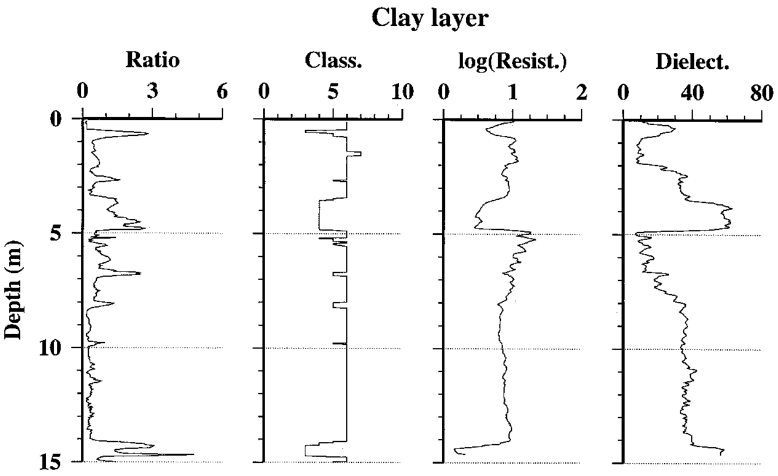


Figure 7. Quadrature component of EM-31 (left) and EM-34 (right) terrain conductivity measurements. The EM-34 data are for a coil separation of 20 m. The small dots on each plot are survey locations. The data contours are in mS/m. Each plot is color-scaled independently, but blues indicate relatively low conductivity and reds indicate relatively high conductivity, showing the higher conductivity in the north. The white dashed line is the known extent of the shallow clay layer from CPT sampling.



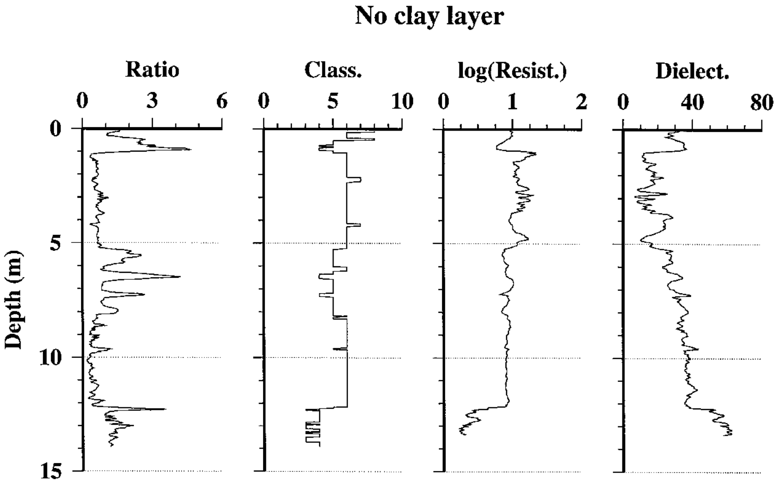


Figure 8. CPT measurements of different physical properties. The four upper plots are from a location within the shallow clay layer in the northern portion of the GRFL. The lower four plots are from the southern end of the GRFL away from the shallow clay layer. Note the presence of the shallow clay layer at a depth of 4-5 m in the upper plots. Ratio = corrected ratio between sleeve stress and tip pressure; Class. = soil classification index; log (Resist.) = log (resistivity); and Dielect. = dielectric permittivity.

physical and CPT interpretations match regarding large-scale features, but much work remains to correlate the physical properties measured or inferred by the different methods.

Conclusions. Our data from the GRFL show that the geophysical and geotechnical methods image similar features. Additionally, higher resolution methods like GPR show the complex, heterogeneous nature of the subsurface that interpretations based solely on a few wells or even quite a few CPT pushes may oversimplify. Interestingly, previous geological studies indicated a simple and homogeneous subsurface beneath Dover Air Force Base, a criteria for locating the GRFL. But subsequently acquired geophysical data clearly show the complicated nature of the shallow subsurface and the necessity of more continuous sampling than is provided by in situ measurements alone.

We continue to refine subsurface models based on joint interpretations of the GRFL data sets outlined in this paper and data not presented, such as high frequency GPR and data from other CPT tools. The complementary nature of the geophysical measurements should provide a more complete description of the subsurface. We are continuing to investigate the relationship between surface geophysical measurements and the in situ CPT measurements to determine if methods measuring similar physical properties (e.g., electrical resistivity soundings and CPT resistivity probes) result in similar subsurface models. Discrepancies in the details of separate interpretations may be due to unequal vertical and lateral averaging of the different techniques. We need a better understanding of fundamental differences such as this subsurface volumetric sampling before joint interpretation can become joint inversion for geologic structure of the shallow subsurface. **LE**

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