Cone-based geophysical imaging: A proposed solution to a challenging problem

ROSEMARY KNIGHT and ADAM PIDLISECKY, Stanford University, California, USA

There are many locations throughout the world where subsurface contamination impacts the natural environment, with potentially serious consequences for the quality of our water and for human heath. At U.S. Department of Energy (DOE) sites alone there are estimated to be "about 6.4 billion cubic meters of contaminated soil, groundwater and other environmental media" (DOE Environmental Management Science Program announcement 02-03). One of the initial steps in dealing with a contaminated site is that referred to as site characterization. During site characterization, measurements are made that allow for the development of an accurate model of the physical, chemical, biological, and hydrogeological properties of the subsurface. Such a model is required to design an appropriate plan for remediation of a contaminated site and can also be used, and continually updated, for short-term or long-term monitoring of the site. Site characterization can involve locating and identifying a known or suspected contaminant, and can also involve determining the properties of the subsurface controlling the fate and transport of the contaminant. The challenging problem we face, at many sites, is identifying an approach to site characterization that provides the required information about the subsurface while minimizing the risks associated with contacting the contaminated region.

The most common approach to site characterization involves drilling and directly sampling the near surface (top ~100 m) of the earth. Boreholes are used to extract samples for laboratory analyses, for borehole logging, and to conduct on-site testing. Examples of on-site testing include water sampling for the direct detection of contaminants and pump tests, slugs tests, and tracer tests to estimate hydraulic conductivity. While the borehole-based methods can provide direct and accurate measurement of subsurface properties of interest, they are limited in terms of the spatial density of the sampling (dictated by the number of boreholes) and the volume of the sampled region. This raises the concern that the acquired data are not sufficiently representative of the subsurface region of interest. In addition to these limitations in spatial coverage there is the risk, with any method requiring drilling, of directly contacting the contaminant. This could impact worker health and safety, and possibly further spread the contaminant in the subsurface. As a result, the cost of drilling boreholes at contaminated sites is very high.

The last 10 years has seen tremendous growth in the use of cone penetration testing (CPT) for characterization of unconsolidated sediments at contaminated sites. The great appeal of CPT is the fact that it is minimally invasive, which reduces the risks associated with contacting a contaminant. Rather than drilling a borehole to access and sample a subsurface region, a 36-mm diameter steel cylinder with a cone-shaped tip is pushed into the ground while making measurements with sensors mounted close to the tip. The cone is pushed into the ground using hydraulic rams mounted on a large truck, with the mass of the truck providing the reaction load (~30 tons). Given favorable ground conditions, the trucks have the capacity to push a cone to a depth of approximately 100 m. The trucks have equipment for decontaminating the cone as it is withdrawn and for grouting the remaining hole, so the potential for spreading any encountered contaminant is minimized. While CPT data can provide very useful information about subsurface properties (e.g., soil type, electrical resistivity, shear-wave velocity), the sampled region is the 5-50 cm immediately adjacent to the cone; i.e., the data set provided is a 1D depth profile at the cone-push location. As with borehole measurements, sampling such a small volume will generally be inadequate for accurately characterizing a heterogeneous region. In addition, parts of the sampled region are disturbed by the emplacement of the cone. For these reasons, reliance on CPT data could introduce considerable errors in the estimates of subsurface properties and in the prediction of subsurface processes, such as fluid flow and contaminant transport.

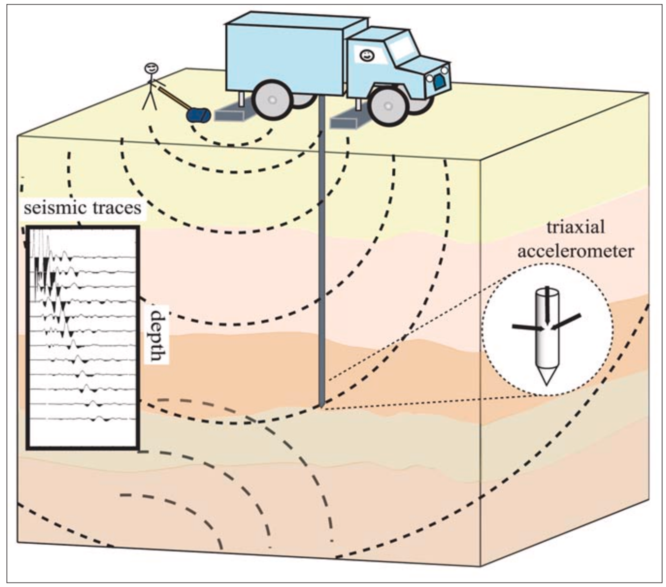

Figure 1. *Schematic of cone-based VSP experiment conducted at the Kidd2 site. A sledgehammer against the baseplate of the truck was used to generate SH-waves. A triaxial accelerometer mounted near the cone tip was the receiver.*

There is growing interest in the use of geophysical methods for site characterization at contaminated sites. Geophysics can provide high resolution images of large 3D volumes of the subsurface thus providing more extensive sampling of an undisturbed region than either borehole-based methods or CPT. Currently available are methods deployed from the surface of the earth such as ground-penetrating radar (GPR), reflection seismic, and electromagnetic methods; and methods deployed in boreholes such as cross-well seismic, electrical resistance tomography (ERT), and cross-well radar. The surface-based methods are fully noninvasive so there is no risk of disturbing subsurface contaminants. This has led to evaluation of their potential usefulness at DOE sites. For example, at the DOE Hanford site in southeastern Washington (USA), where efforts are underway to clean up subsurface con-

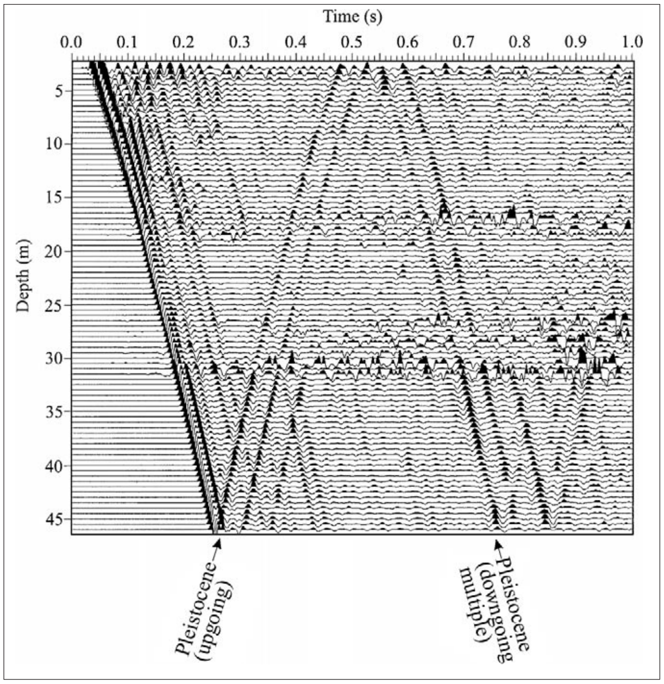

Figure 2. *VSP data collected using the cone-based system. A 30-150 Hz band-pass filter and spherical divergence correction have been applied to the data (from Jarvis and Knight, 2000).*

taminants, high-resolution (100 MHz) GPR images were used to obtain information about variation in water content, a factor that has a significant effect on contaminant transport. Unfortunately, due to electrically conductive material in the top few meters, GPR could only image to a depth of ~15 m below the earth's surface while the region of interest extends to the water table at ~50 m. This example illustrates one of the problems with surface-based methods: The geophysical properties of zones near the surface can prevent imaging to greater depths.

There are three other, more general, limitations in the use of surface-based geophysics as a stand-alone method for site characterization. Contaminated regions are commonly found underneath structures such as buildings, storage tanks or other infrastructure. With sources and sensors limited to surface locations, it is very difficult to accurately image the area below the structures. The second problem is the nonuniqueness in the inversion and interpretation of the data. In many cases data are required in the vertical direction, in order to obtain adequate depth resolution in the subsurface model that is derived from the surface-based measurements. The third problem is related to an issue common to all forms of geophysical measurement—the need to transform the subsurface model that we develop in terms of geophysical parameters (e.g., electrical conductivity, seismic velocity) to a subsurface model of the parameters of interest (e.g., volume of contaminant, water content, hydraulic conductivity). In order to do this we need to know the relationships between the two forms of parameters so that we can, for example, estimate water content from electromagnetic wave velocity, or contaminant concentration from electrical conductivity. At a site where we only have surface-based geophysical data, the tendency is to adopt very simple empirical relationships that, in general, will not be appropriate given the materials and nature of heterogeneity at the site. The use of these relationships can result in a level of uncertainty in the estimates of subsurface properties that is unacceptable given the risks and costs associated with the clean-up and management of contaminated sites.

The collection of geophysical data using boreholes for the deployment of sources and sensors can provide a means of addressing, and in some cases overcoming, the problems described above. By allowing for the placement of sources and sensors below the surface, it is possible to acquire and invert data to obtain a well-defined image of the region of interest. In addition, the drilling of boreholes means that samples of the geological material (cuttings, cores, plugs), fluid samples, and other forms of data can be collected and used to develop an understanding of the site-specific relationships between the geophysical parameters and the subsurface properties of interest. While there are clearly these advantages in using boreholes to obtain geophysical tomographic data, there still remain two important problems with all borehole-based methods: the risk of contacting or further spreading the contaminant, and the cost of drilling and casing a borehole.

The challenging problem that needs to be solved for site characterization in an area of known or suspected contamination: We need an approach to subsurface characterization that can provide the required information about the subsurface while minimizing the risks associated with contacting the contaminated region. None of the described methods, on their own, can achieve this. The solution to the challenging problem of site characterization is most likely to be an integrated approach that builds on the benefits of the various available methods.

A proposed solution. The solution we propose is the acquisition of geophysical images using cone penetration testing with geophysical sources and sensors mounted on cones. This approach combines the minimally invasive nature of CPT with the "away-from-the-cone" imaging capabilities of geophysical methods. It is less invasive and less expensive than using boreholes, but provides the level of 3D subsurface coverage that can currently only be obtained using boreholes. In addition, the integration of the geophysical imaging with the standard CPT measurements provides a way of developing site-specific relationships between geophysical parameters and subsurface properties.

There have been field tests conducted by Narbutovskih and colleagues where CPT was used as a way of placing electrodes in the subsurface for electrical resistance tomography. Their approach was to lower a string of electrodes through the steel cone-rod and then grout the electrodes in place. This is an illustration of how the use of CPT can reduce the costs and disturbance of borehole geophysics.

What we advocate is taking this to the next step by carrying the sources and sensors on the cones and developing the ability for on-site, optimization of the data acquisition stage. Rather than deciding on all cone-push locations at the start of data collection, carrying the sources and sensors on the cones allows us to use data collected in the field to obtain an approximate model of the subsurface and then use that model to determine the next sampling location and the density of sampling required over various depth intervals. This approach greatly improves the efficiency of the data acquisition by reducing the number of sampling locations. This, in turn, results in time and cost savings and lowers the risks associated with contaminant contact. Ultimately, we envision the development of fast-inversion algorithms that will allow us to collect field data with the real-time, on-site ability to update and define the experimental design.

The focus of our research effort is the development of cone-based seismic imaging and cone-based electrical resistivity imaging. The seismic work that we have conducted to date has involved the use of CPT to acquire a vertical seismic profile (VSP) and the integration of those data and other CPT data with seismic reflection common depth point data. Figure

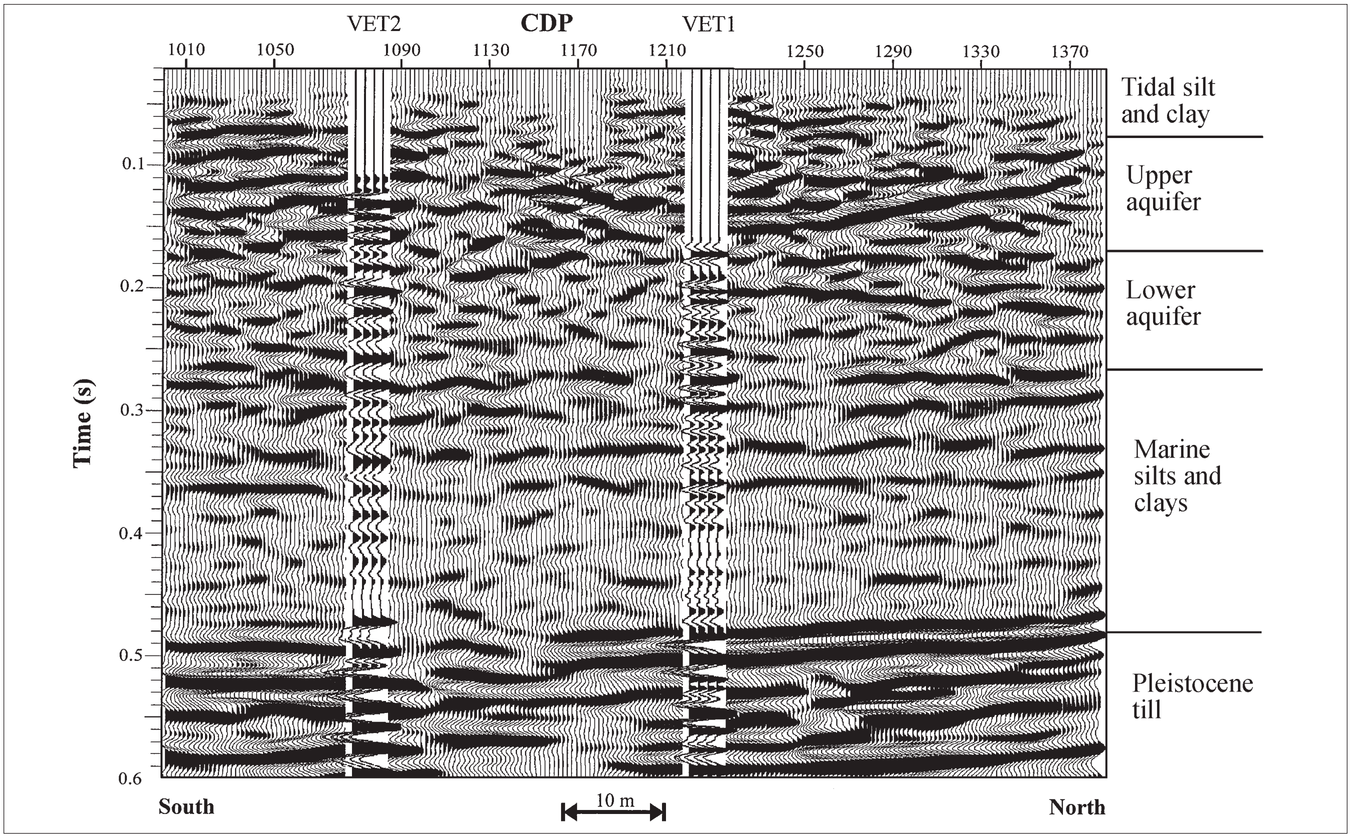

Figure 3. *Migrated SH-wave seismic reflection data, with the VET's (labeled VET1 and VET2) at the two cone-push locations (from Jarvis and Knight, 2002).*

1 shows schematically the way in which two cone-based VSPs were acquired by Jarvis and Knight at the Kidd2 test site on the Fraser River delta in southwestern British Columbia (Canada). The field experiment was conducted in collaboration with John Howie (University of British Columbia) using his CPT truck.

SH waves were generated using a large sledgehammer against the baseplate of the truck. The receiver was a triaxial accelerometer mounted on the cone which was pushed into the ground. The depths at which the cone was stopped to record VSP data were chosen to minimize field time and spatial aliasing; depth intervals ranged from 0.3 m to 3.0 m. The truck engine (which must be on to run the hydraulic system) was turned off before every measurement to reduce the noise. Two records were obtained with hammer blows in one direction, and two more with hammer blows in the opposite direction. The records from impacts in the same direction were stacked and the results were subtracted to enhance the signal to noise ratio of the SH-waves and reduce P-wave interference. The acquisition of 1D profiles of shear-wave velocity, by recording first arrivals with a cone-mounted accelerometer, is a standard CPT measurement. Our modification was to extend the typical record length from ~0.5 s to ~2 s so that we could obtain the later arrivals.

The data from one of the VSP surveys are shown in Figure 2. The high data quality is primarily due to the excellent accelerometer-ground coupling that the cone provides, as well as the absence of tube waves which interfere with borehole-acquired VSP data. The first arrivals are clearly seen along with an upgoing reflection from the top of a Pleistocene till and a downgoing free surface multiple. The data were processed and the VSP extracted traces (VETs) from the two VSP surveys were used in the inversion of SH-wave seismic reflection data at the site. Figure 3 shows the processed reflection data with the VETs inserted in the line. In addition to recording the SH-wave arrivals, the other cone-mounted sensors were used to make standard CPT measurements (tip resistance, sleeve friction, and pore pressure) which were integrated with the VSP and reflection data to develop a model of lithology and porosity variation at the site. This study is a compelling illustration of the way in which the combination of CPT and geophysics can be used to address characterization needs at contaminated sites in a way that is far superior to the use of either method on its own.

While this work demonstrates the successful acquisition of VSP data with a cone-mounted sensor, the real advancement that is needed for cone-based seismic imaging is the development of a cone-mounted source. As shown schematically in Figure 4, with a cone-mounted source pushed into the ground and receivers in a 2D array on the surface it would be possible to obtain, in a relatively short period of time, high resolution 3D coverage of a large volume of the subsurface.

Sandia National Laboratories, in collaboration with Applied Research Associates and Blackhawk Geoservices, have developed a prototype for a 48-mm diameter magnetostrictive source that can be housed in a modified cone tip (described in Grimm, 2001). The tip was designed to decouple from the push rod to isolate the source at the desired depth, then recouple to continue pushing. In field testing of this source, a standard 36-mm diameter cone was pushed to a depth of 30 m, then withdrawn, and the wider cone tip with the seismic source pushed into the open cone-hole. Geophones were permanently installed in a well at distances of 11.6 m and 18.9 m from two cone-push locations. A frequency sweep from 50 Hz to 1 kHz over 8 s was used with an attempt to flatten the spectrum as much as possible with the sweep design. Good signal-to-noise ratio data were recorded from each source location; however, the final spectrum was not flat and had several significant resonances, with the strongest at 250 Hz. Further testing and development of this source is

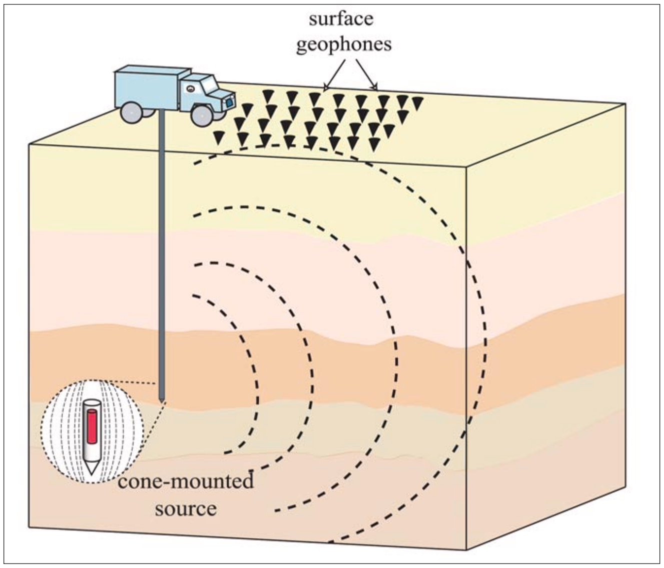

Figure 4. *Schematic illustrating the use of a cone-mounted seismic source.*

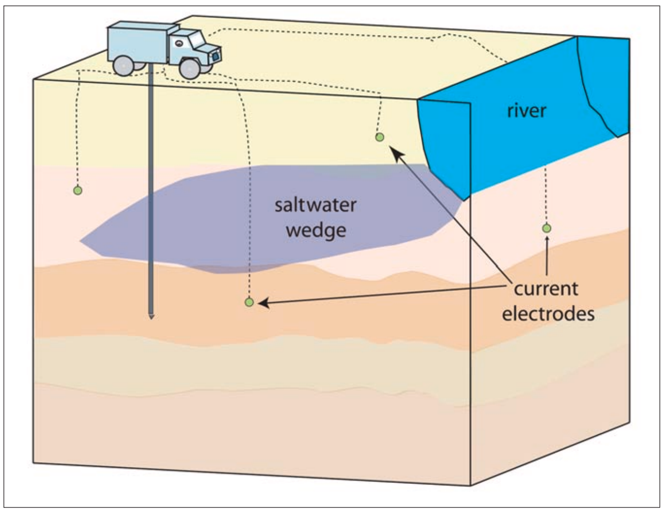

Figure 5. *Schematic showing the basic elements of the cone-based ERT experiment conducted to image a saltwater intrusion at the Kidd2 site. Permanent current electrodes were emplaced at subsurface locations. Two potential electrodes were located on the surface. The resistivity cone was adapted so that two ring electrodes near the cone tip were used for resisitivity logging and two were modified to serve as a single cone-mounted potential electrode.*

required to make this a viable surveying tool (Elbring, personal communication). The availability of a cone-mounted seismic source would dramatically change the way in which geophysical methods are used for environmental (and engineering) site characterization.

The other form of cone-based imaging that we are developing is cone-based electrical resistivity tomography. ERT has application at contaminated sites as a means of locating electrically conductive contaminants. In any application where subsurface resistivity data are required, it would be a significant advantage to have electrodes carried on a minimally invasive cone-based system that could be easily moved during the data acquisition stage. The use of cone-mounted electrodes would make it possible to select the optimal measurement locations as the subsurface imaging experiment progressed. The two key features —minimally invasive, and real-time experimental design—could significantly reduce the time, the costs, and the risks, associated with data acquisition.

We have recently developed a cone-based ERT system and tested it at the Kidd2 test site in British Columbia. The imaging target was a salt water plume, at a depth of ~10 m, that intrudes the fresh water aquifer beneath the site. Figure 5 is a schematic showing the basic elements of the field experiment. Nine disposable cone tips with attached electrical leads were emplaced at various subsurface locations to serve as permanent current electrodes. A dummy cone was advanced to the required depth and, upon retraction, the tip was left in place. We adapted for our experiment a standard resistivity cone which has four ring electrodes near the cone tip that are used for resistivity logging. We used two of the rings for resistivity logging, and modified the other two so that they served as a single cone-mounted potential electrode. Two other potential electrodes were installed on the surface. The cone was pushed to a depth of ~30 m at five locations with cone measurements of tip resistance, friction, pore pressure and resistivity made every 2.5 cm over the full depth range. The cone was stopped every 1-2 m to conduct the ERT measurements. This involved injecting current into pairs of the permanent current electrodes while measuring the potential drop between the cone-mounted electrode and a surface electrode. Measurements were made for 36 independent combinations of the current electrodes resulting in a total of approximately 8000 data points for the five cone-based ERT profiles. Upon completion of the experiment, the small current electrodes remained in place. At any later time, additional data could easily be acquired.

One of the issues that must be addressed in conducting cone-based ERT surveys is the effect of the cone on the data quality. ERT measurements involve making precise potential measurements which could be perturbed by the presence of the conductive cone. Because the cone is very small with respect to the volume we want to image, explicitly modeling the effect of the cone in the inversion algorithm is computationally expensive and was not attempted. Forward modeling suggested that for most parts of the model space the cone effect was negligible and could be ignored. However, developing effective techniques than can account for the effect of the cone on the ERT data will undoubtedly result in improved conductivity images.

A second issue that affected the data at the Kidd2 site was current channeling through the highly conductive salt-water wedge; for certain electrode configurations, this channeling pressed the power limitations of our resistivity unit, resulting in noisy data.

Figure 6 is a 2D slice from the results of preliminary 3D inversion of the ERT data acquired at the Kidd2 site. The 2D line bisects the survey site in an east-west direction. The starting model was a layered system, with conductivity values obtained from the CPT resistivity logs. As the inversion is nonlinear, these CPT data help to ensure we have a good starting model, from which we can calculate model perturbations using the ERT data. The resulting image is consistent with our knowledge of the site. We have laterally heterogeneous sands in the upper 10 m, saltwater intrusion from 10 m to 23 m, and a homogenous clay layer extending from a depth of 23 m to a depth of approximately 50 m. The image contains many features that were not included in the starting model, nor could be inferred from the CPT resistivity data. However, as these results are preliminary, further image appraisal must be done to determine the validity of these perturbations before concluding that they are representative of the subsurface heterogeneity at the site.

Conclusions. The characterization of a contaminated site is a critical step in the clean up and remediation of a site. Accurate

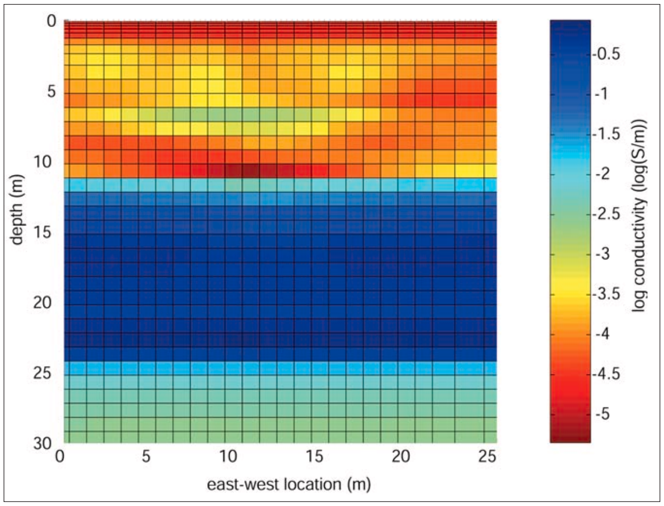

__Figure 6.__ A 2D slice from the preliminary 3D inversion of the cone-based ERT data acquired at the Kidd2 site. There are laterally heterogeneous sands in the upper 10 m, a saltwater plume from 10 m to 23 m, and a homogenous clay layer extending from 23 m to ~50 m.

information is needed about subsurface properties so that good decisions can be made for both short-term and long-term management. There are a number of methods currently in use for environmental site characterization ranging from direct but invasive borehole-based measurements to noninvasive measurements of geophysical parameters, which must be transformed to obtain the subsurface properties of interest. Despite the advances that have been made in characterization methods, we still face the challenge of acquiring the data that we need in a way that reduces the risks associated with contacting the contaminant. Our proposed solution, one solution, is to address this problem by integrating minimally invasive CPT methods with geophysics. By carrying geophysical sources and receivers into the subsurface on cones, we will be able to better use geophysical imaging in the characterization, clean up and management of contaminated sites.

Suggested reading. The work of Narbutovskih and colleagues is described in "Test results of CPT-Deployed Vertical Electrode Arrays at the DOE Hanford Site" by Narbutovskih, et al. (*Proceedings* of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, 1997). The studies involving the use of cone-based VSP data are described in the following papers: "Near-surface VSP surveys using the seismic cone penetrometer" by Jarvis and Knight (*Geophysics*, 2000). "Aquifer heterogeneity from SH-wave seismic impedance inversion" by Jarvis and Knight (*Geophysics*, 2002). The cone-mounted magnetostrictive source is described in: Integrated Geophysical Detection of DNAPL Source Zones by Grimm (Blackhawk Geoservices, Inc., *Final Report, SERDP Project CU-1090*, 2001). The cone-based ERT is described in: "Assessment of the use of cone-based resistivity imaging" by Pidlisecky et al. (*Proceedings* of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, 2003). TLE

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Corresponding authors: rknight@pangea.stanford.edu or apid@pangea.stanford.edu