Comparison of Eight Innovative Site Characterization Tools Used to Investigate an MTBE Plume at Site 60, Vandenberg Air Force Base, California

Murray D. Einarson[1,2], Mario Schirmer[3], Parsa Pezeshkpour[1], Douglas M. Mackay[1], and Ryan D. Wilson[1]

[1]University of Waterloo, Department of Earth Sciences, Waterloo, Ontario, Canada
[2]Conor-Pacific/EFW, Palo Alto, California
[3]UFZ Centre for Environmental Research Leipzig-Halle, Leipzig, Germany

Abstract

Environmental assessment of contaminated sites often requires delineation of the pathways of contaminant migration. Often, the pathways are strongly affected by the subsurface geology. At Vandenberg AFB in California, an accidental release of gasoline containing MTBE occurred at a base gasoline station in 1994. Dissolution of the gasoline into groundwater has created a dissolved MTBE plume at least 1,700 feet long. The plume is flowing in a complex shallow alluvial aquifer system comprised of thin sand layers within a silt and clay matrix.

Portions of the aquifer containing the dissolved plume have been characterized in considerable detail in order to assess the occurrence, distribution, and flux of MTBE and other solutes within the dissolved plume. In one area(Transect B), the geology and plume geochemistry was assessed by collecting continuous stratigraphic and geochemical profiles at 40-foot intervals across the entire width of the MTBE plume. Eight innovative characterization tools were used in the subsurface investigation along Transect B, providing a unique opportunity to compare and contrast the various characterization tools.

The subsurface geology was investigated by collecting and logging continuous soil cores, performing cone penetration test (CPT) soundings, direct-push resistivity probes, Geoprobe® electrical conductivity probes, and surface dipole-dipole resistivity surveys. The groundwater geochemistry was assessed by collecting one time "snapshot" samples using a Geoprobe® sealed screen sampler and the Waterloo Groundwater Profiler™. Permanent, seven-zone multi-level monitoring wells have been recently installed along Transect B to assess the hydraulic head distribution in the shallow aquifer and to provide a way to monitor the plume geochemistry over time.

Characterization data along Transect B shows that the subsurface stratigraphy exerts a strong control on the distribution and flow of MTBE and dissolved electron acceptors in the shallow alluvial aquifer. Continuous soil cores were useful to provide samples needed to measure the physical properties of the various strata and to calibrate the CPT data. The CPT provided the most detailed, cost-effective information about the site stratigraphy. The multi-level monitoring system yielded important information regarding the vertical distribution of hydraulic head in the aquifer and on-going samples of groundwater for geochemical measurements.

Introduction

In early 1998, researchers from the University of Waterloo selected a former gas station (Site 60) at Vandenberg Air Force Base (VAFB) in Central California as the location for an API-funded field study of natural and enhanced attenuation of dissolved MTBE (Figure 1). Since then, detailed laboratory and field experiments have been undertaken to assess the feasibility of stimulating in situ biodegradation of dissolved MTBE (Mackay et al., 1999 [these proceedings] and Wilson et al., 1999 [these proceedings]). In addition, numerical simulations are being performed to better understand the characteristics and longevity of MTBE source zones (Durrant et al., 1999 [these proceedings]).

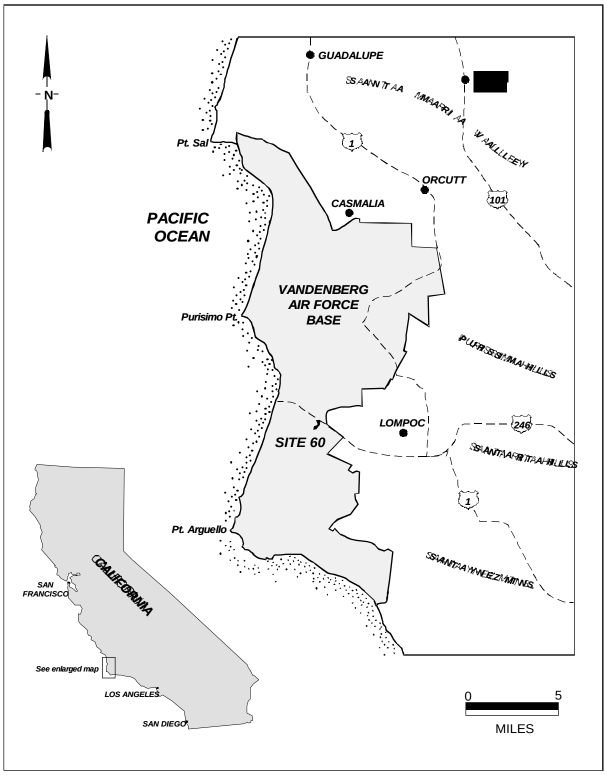


Figure 1. Location map

Prior to beginning the field experiments and computer simulations, detailed characterization of the hydrogeology of the site was performed. The site characterization utilized a number of innovative technologies due to the necessity of defining the stratigraphy, hydraulics, and groundwater geochemistry of the study area in considerable detail. Many of the technologies were used in parallel, providing an unprecedented opportunity to compare the various characterization tools and assess their particular strengths and weaknesses.

While the technologies were employed at many locations at the site, particular effort was spent delineating the subsurface geologic and geochemical conditions along a transect (Transect B) oriented perpendicular to the prevailing groundwater flow direction. Transect B is approximately 200 feet downgradient from the source zone, near the location of the small-scale pilot tests described by Mackay et al., 1999 (Figures 2 and 3). Detailed stratigraphic, hydraulic head, and groundwater chemical profiles were collected at closely-spaced points (maximum spacing of 40 feet) along Transect B (Figure 3).

Eight innovative subsurface characterization or monitoring technologies have been used to date at Site 60, VAFB. Comparison of these innovative characterization technologies along Transect B is the focus of this paper. These eight characterization tools are:

1. Dipole-dipole surface resistivity survey
2. Enviro-Core™ Soil Sampling System
3. Waterloo Piston Sampler™
4. Geoprobe® Electrical Conductivity Probe
5. CPT – Resistivity Probe
6. Waterloo Groundwater Profiler™
7. CMT Multi-Level Monitoring System™
8. Geoprobe® Membrane Interface Probe™

Release History and Plume Formation

A plume of petroleum hydrocarbons and MtBE resulted from leaking fuel storage facilities at a General Services Administration (GSA) gas station at VAFB. The GSA service station and associated subsurface contamination is referred to as Site 60. The service station, which historically dispensed diesel, leaded, and unleaded fuel, was taken out of service in 1994 after a significant fuel leak was noted. Reconciliation of inventory records suggested that a total of 572 gallons of unleaded fuel had been lost (Lee and Ro, 1998; see Figure 2 for the approximate location of the former fuel tanks, labeled as “source zone”). The underground storage tanks and piping were removed in 1995 via two excavations. Immediately after tank removal, the northern pit was partially filled with pea gravel. In late 1995, the southern pit and remaining 2 to 3 feet of the northern pit were filled with sand (Lee and Ro, 1998).

Based on investigations performed by consultants to the Air Force, the MtBE plume has been mapped as historically being from 250 to 300 feet wide and extending approximately 1,700 feet beyond the source area (Figure 2). A BTEX plume is also present at the site but apparently attenuates to below detection limits within 50-100 feet of the source.

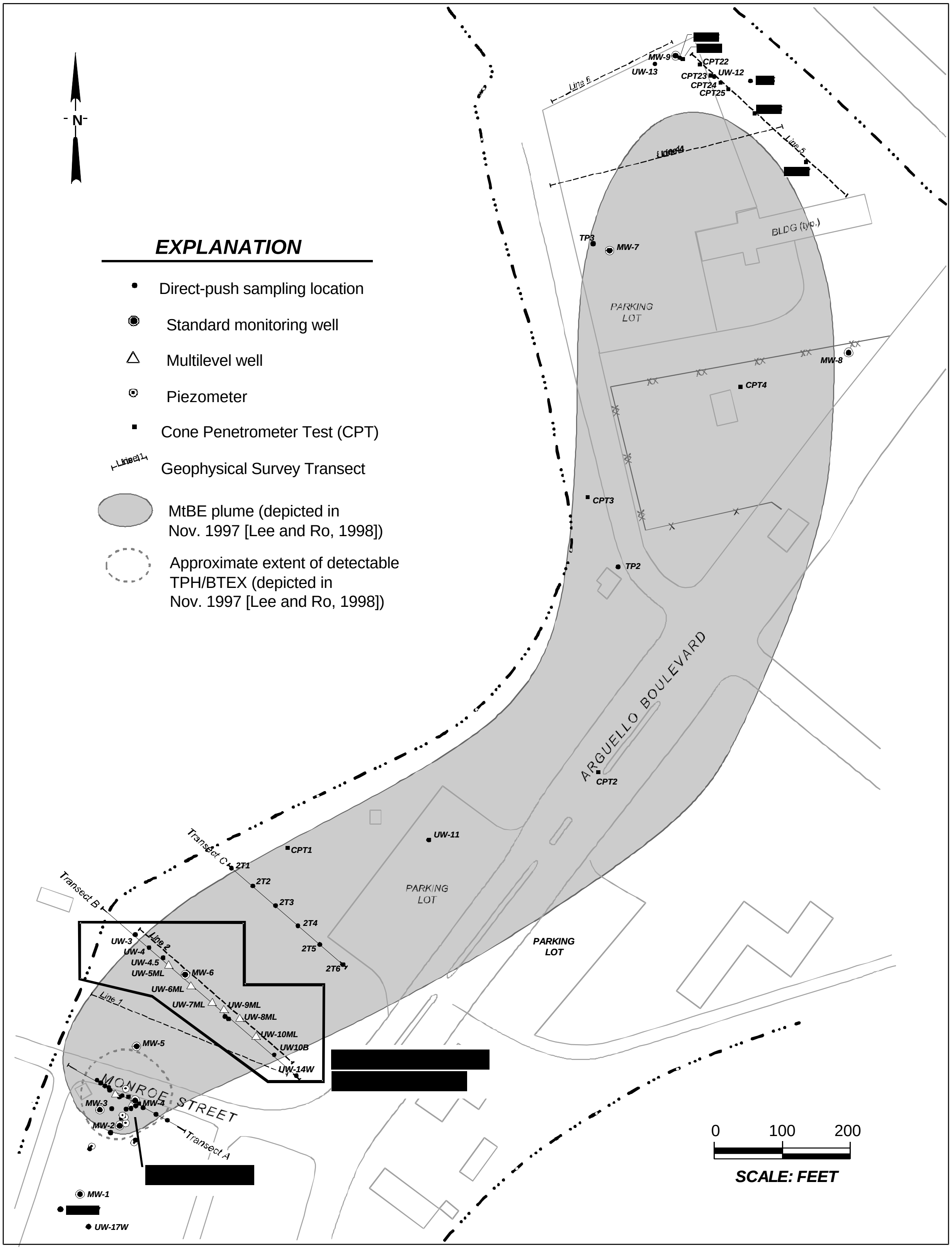


Figure 2. Map of Site 60, VAFB

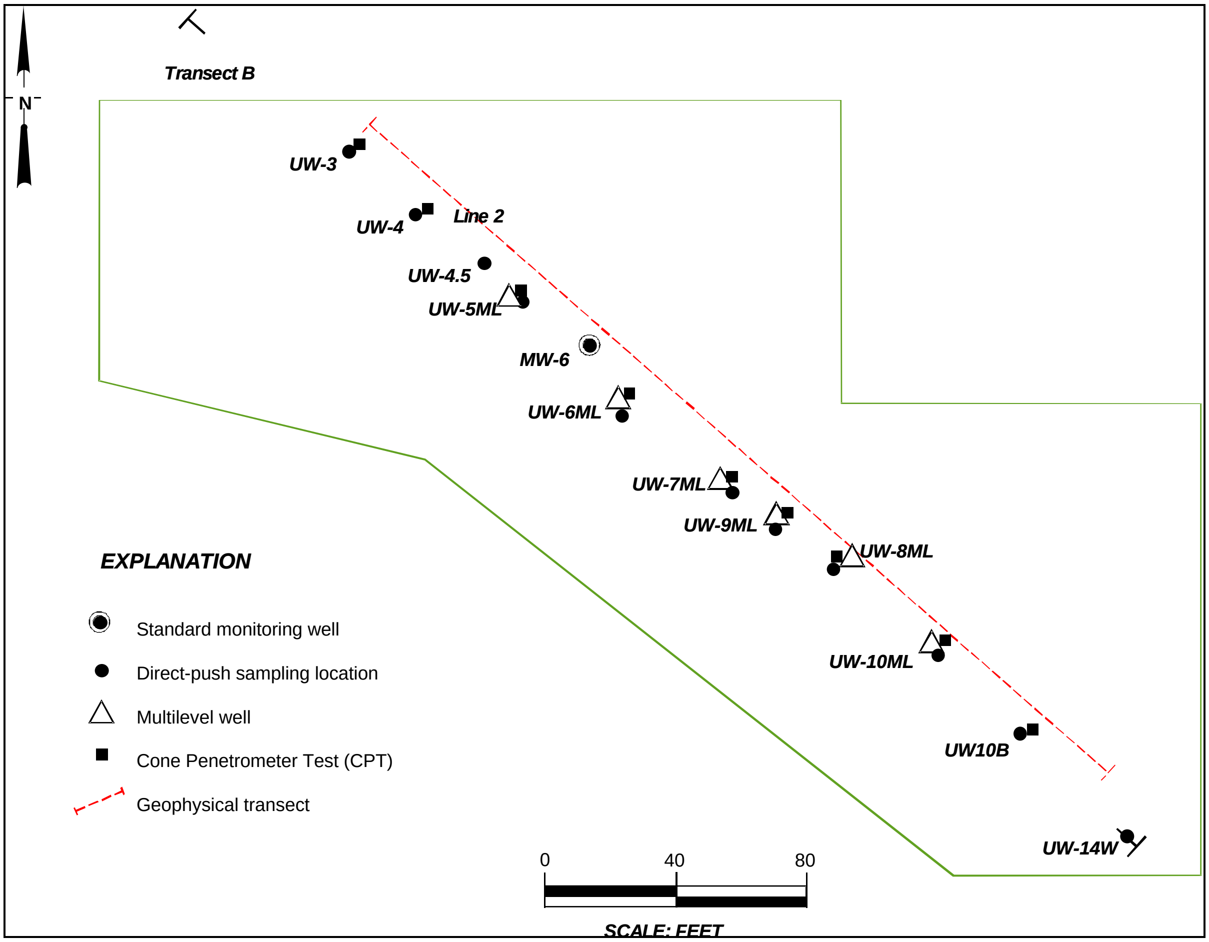


Figure 3. Transect B area

Hydrogeologic Setting

The Site 60 former service station is situated in Lompoc Canyon, a small north-trending canyon that feeds into the broad, west-trending Santa Ynez River valley 3 miles to the north. A heterogeneous mixture of sand, silt and clay alluvium fills the canyon, forming an alluvial wedge that thickens northward. Beneath the former service station, the alluvial fill is estimated to be approximately 40 feet thick; further north near the leading edge of the plume, the alluvium thickens to depths of up to 80 feet (Bright et al., 1997). The canyon alluvium is underlain by Miocene-age Monterey Formation siltstone, which is fractured and weathered at the ground surface in adjacent upland areas. A short distance south of the former service station, Lompoc Canyon ends abruptly at Lompoc Terrace, a flat coastal terrace eroded into the Miocene Monterey Formation bedrock by wave erosion prior to the last stages of uplift in the late Quaternary (Dibblee, 1950).

Groundwater occurs at shallow depths within the Lompoc Canyon alluvium, flowing northward to the Santa Ynez alluvial aquifer. Groundwater typically occurs at depths ranging from 5 to 8 feet, however groundwater rose to within 2 feet of the ground surface during the wet El Niño winter of 1998.

Near the former service station, groundwater flow to the northeast within the alluvial aquifer is indicated by measured hydraulic gradients and by the location of the dissolved MtBE plume mapped generally by Lee and Ro (Figure 2). Given the apparent length of the MtBE plume (1,700 feet) and a reported release date of 1994, the average groundwater velocity is estimated to be about 400 feet per year (1.1 feet per day). This groundwater velocity value is within the range of values calculated by Air Force consultants and University of Waterloo hydrogeologists. Approximately 1,000 feet downgradient from the former service station, the plume apparently bends toward the north, presumably due to preferred flowpaths within the alluvial fill. Note however, that there are few monitoring points upon which to define the exact location of the dissolved MtBE plume, and thus the areal extent of the plume may be different from that shown in Figure 2.

A shallow surface water drainage borders the plume to the west (Figure 2). This drainage is the current manifestation of the creek that originally flowed within Lompoc Canyon, but which has since been relocated to a man-made drainage ditch at the western margin of the canyon. The drainage ditch appears to form a hydraulic boundary for the dissolved MtBE plume (Figure 2). The source of water within the perennial creek is not known. The drainage ditch may be fed by discharges from the alluvial aquifer, however significant discharges to the ditch seem unlikely based on the preponderance of clay and silt within the alluvial fill adjacent to the drainage ditch measured during our Summer 1998 field activities. Alternatively, the drainage ditch may be fed by springs discharging from the Monterey Formation bedrock south of the former service station. Another man-made drainage ditch borders the leading-edge of the plume to the north (Figure 2).

Results of detailed subsurface characterization between the source zone and Transect B shows that a 3- to 6-foot-thick coarse-grained deposit underlies the entire Transect B study area at a depth of approximately 8 feet below ground surface (depth measured from ground surface to top of bed). This unit, which contains groundwater under confined conditions, is hydraulically connected to the former tank excavation and constitutes the primary pathway for dissolved MTBE migration from the source zone to a distance at least 100 feet downgradient from Transect B (the extent of this geologic unit beyond Transect C has not been determined [Figure 2]). This unit consists of coarse angular clasts of Monterey Formation within a sand and silt matrix and is considered to represent a broad Holocene-age debris-flow deposit. This deposit is referred to as the "upper sand zone" in this paper.

Description and Comparison of Eight Site Characterization Tools

Tools to Define Site Stratigraphy

<u>Dipole-Dipole Surface Resistivity Survey</u>

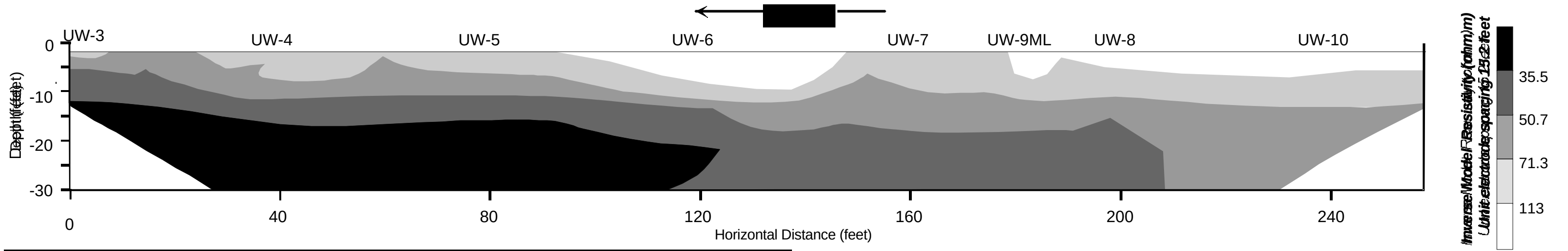
Surface geophysical (dipole-dipole resistivity) profiles were carried out along six transects (each about 300 feet long) including Transect B. This inexpensive investigation method allows rapid non-invasive screening of the electrical properties of the subsurface. The two-dimensional resistivity profiles can be interpreted and correlated to existing information from other investigation methods. With this correlation, additional resistivity transects can be evaluated, making it possible to identify continuous layering with preferential flow paths or heterogeneous patterns.

The geophysical equipment used at Site 60 consisted of an Advanced Geosciences, Inc. (AGI) Sting/Swift dipole-dipole array with an electrode spacing of 15 feet. The Sting/Swift uses a software-controlled electrode switching system to automate and simplify the surveying and subsequent data compilation.

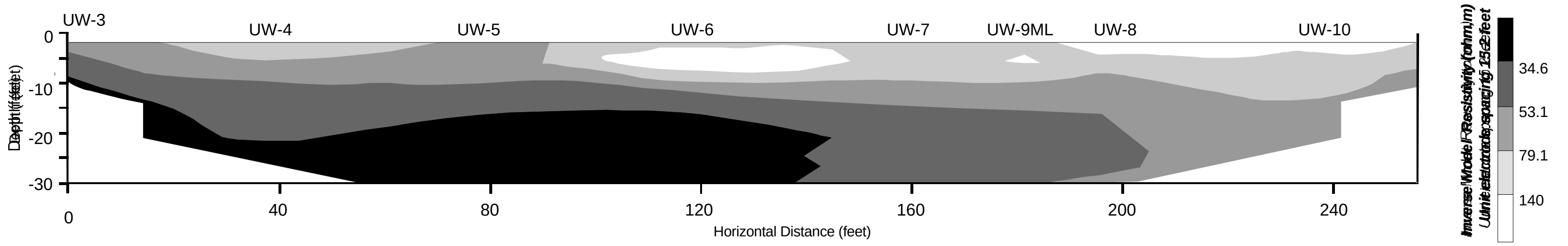
The collected resistivity data were analyzed using RES2DINV (Luke, 1998). Figure 4a shows the first results using the default options of the software combined with the following constraints:

1. Using combined Marquadt and Occam inversion methods;
2. Applying finer mesh for forward modeling;
3. Use of finite element method;
4. Layer thickness increases by 10%; ratio of thickness of the first layer to the unit electrode spacing is 0.34; factor to increase layer thickness with depth 1.25; no permission to exceed model parameters with respect to number of datum points;
5. No smoothness constrain on the model resistivity values and,
6. Logarithmic contour intervals.

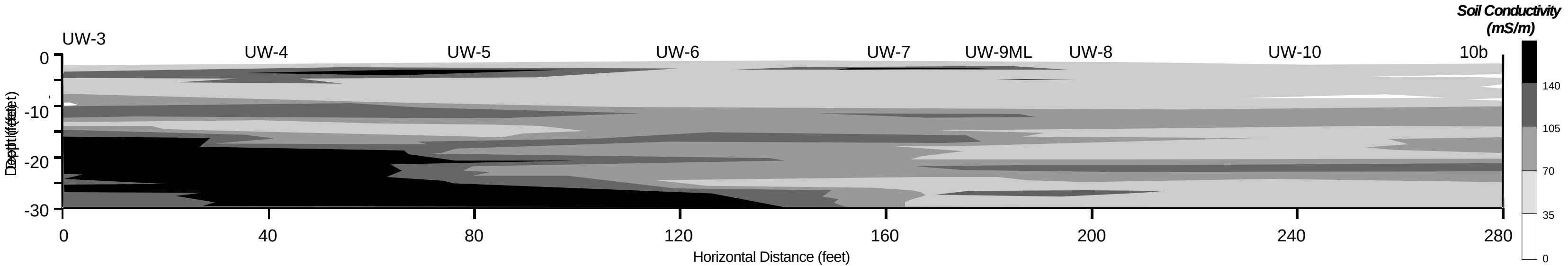
Figure 4a shows two shallow high resistivity patches at the center and right-hand (eastern) side of the pseudosection and the resistivity decreases with depth in a layered pattern. The two high resistivity patches



[redacted]



[redacted]



[redacted]

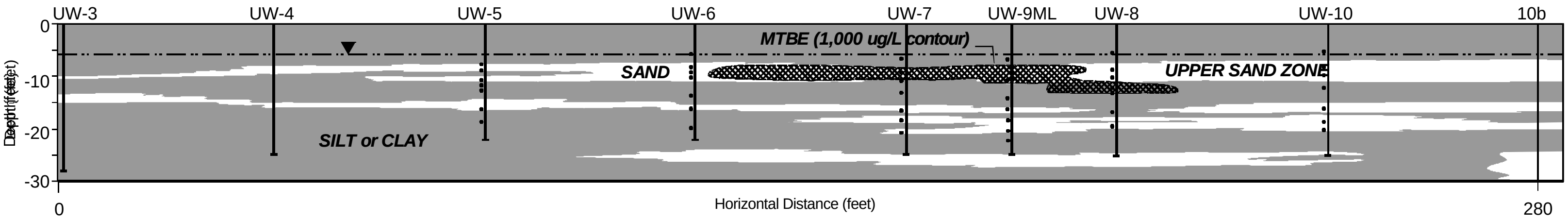


Figure 4d. Geologic cross section based on soil cores and CPT data

Figure 4. Data Comparision, Transect B

might be sand layers with low moisture contents and the low resistivity layer at the bottom could be interpreted as a continuous clay layer. Note that the low resistivity (high conductivity) zone appears to be much more prominent in the western portion of the pseudosection, consistent with the occurrence of preponderance of clay sediments beneath that part of the valley determined from the CPT, electrical conductivity (EC) probes, and the soil cores.

The data were further processed taking into account results of other site investigation methods, in particular the horizontal orientation of the sedimentary deposits obtained with CPT (Figure 4b). The revised plot shows a continuous high resistivity layer at the top center to the left of the section and confirms the low resistivity layer at the bottom part of the section.

Enviro-Core® Soil Sampling System

Continuous soil cores were collected at 10 locations to depths of 22 feet along Transect B (Figure 3). Sampling was performed by Precision Sampling, Inc., of San Rafael, California. Soil cores were collected using the dual-tube direct-push (DP) Enviro-Core sampling system (Einarson, 1995). With the Enviro-Core system, an outer drive casing is advanced along with the sample barrel. When the sample barrel is full, it is withdrawn, leaving the steel drive casing in place to seal the borehole. The outer drive casing is withdrawn only after the last sample has been collected. This prevents cross-communication of fluids in the borehole and eliminates the possibility that shallow soil could fall into the open borehole, potentially contaminating deeper soil samples. Two sizes of Enviro-Core sampling equipment were used along Transect B: 2.25 inch OD and 3.5 inch OD. Soil cores were logged in detail and some cores were preserved for physical and chemical testing.

Soil cores collected with the smaller-diameter Enviro-Core system yielded abundant samples for geologic logging and chemical analysis. However, the recovery of the soil cores collected with this system was often less than desired. This was especially true while trying to collect soil cores from (1) coarse-grained strata containing cobbles such as the upper sand zone and (2) a fine-grained cohesionless silt layer occurring at a depth of approximately 13 to 15 beneath the Transect B area. Core recovery with the small-diameter Enviro-Core system averaged approximately 60 percent. Because of the partial core recover, the existence and lateral continuity of the upper sand zone and the underlying “sensitive fine” layer was not recognized until CPT probes were advanced. A geologic transect along Transect B, drawn using core logs and CPT data, is depicted in Figure 4d.

Larger-diameter Enviro-Core sampling equipment was used to create the boreholes into which the CMT multi-level sampling wells were installed. With the larger-diameter Enviro-Core system, sample recover increased to approximately 80 percent.

Waterloo Piston Sampler™

Soil cores were also collected using the Waterloo Piston Sampler (Starr and Ingleton, 1992) at several locations at the site. The Waterloo Piston Sampler is a DP soil coring tool that uses an internal piston to seal the sampling tool as it is being advanced to the target depth. When the sampling depth is reached, the piston is released, and continued advancement of the tool forces soil to enter the sample barrel. The 5-foot-long sample barrel is retrieved when it is full, and the process repeated until the maximum sampling depth is reached. Soil cores collected with the Waterloo Piston Sampler were used primarily for lithologic logging and chemical analysis.

The Waterloo Piston Sampler proved to be a reliable tool to quickly collect continuous soil cores for geologic logging and geotechnical and chemical testing. The tool was used primarily in and around the source zone, where the upper sand zone contains less cobble-size clasts than in the vicinity of Transect B. Consequently, the recovery of soil cores was excellent, averaging over 90 percent in moist soil below a depth of 5 feet.

A log of the soil core collected from Boring SC-4/S-15 near the source zone is shown in Figure 5. This core was collected with the Piston sampler and yielded 100 percent recovery. The core log shown in Figure 5 was prepared by an experienced geologist using the Unified Soil Classification System (USCS). Lithologic descriptions were confirmed by grain size analyses of five core samples.

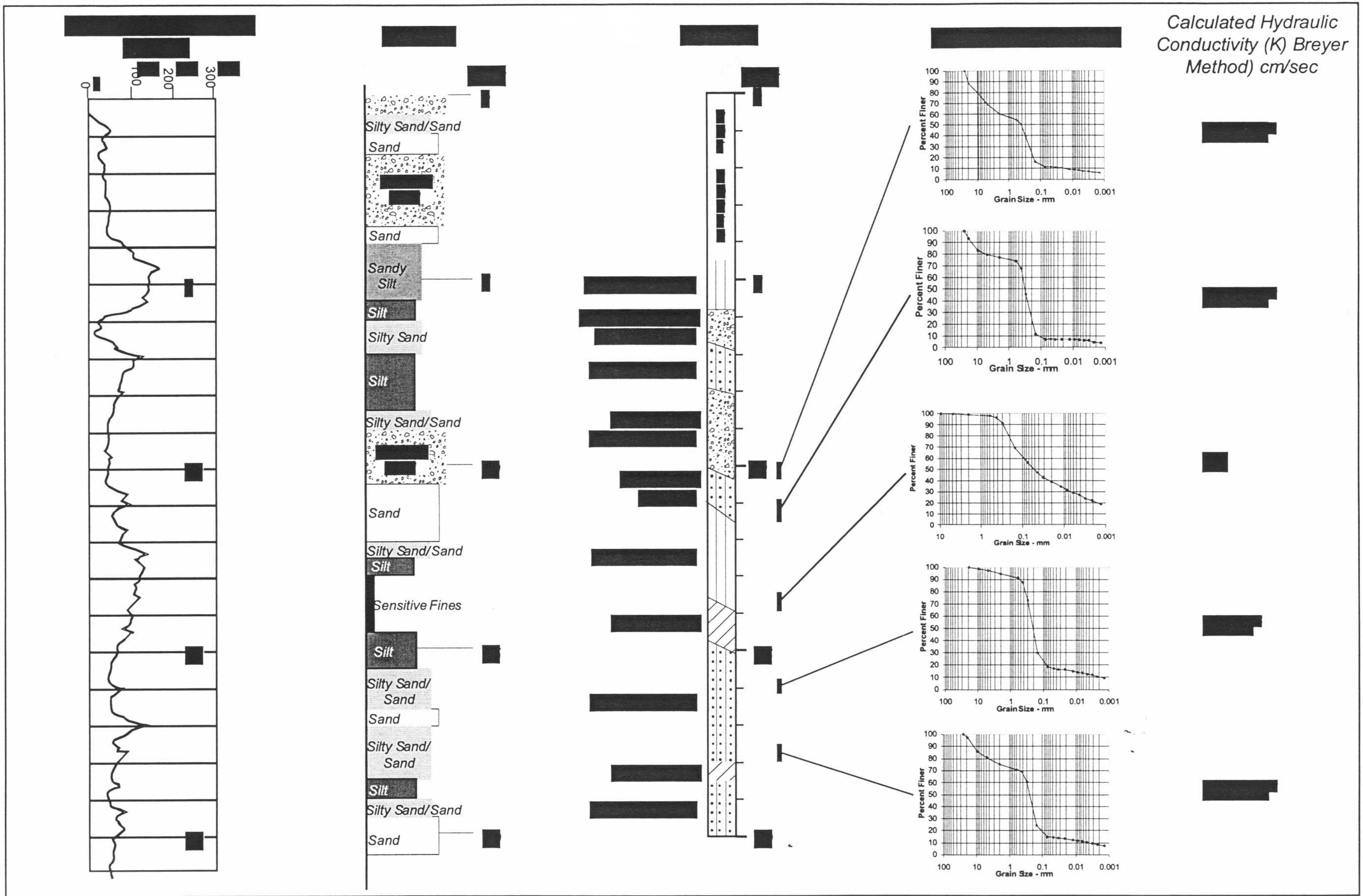


Figure 5. Data comparison, Boring SC-4/S-15 near source zone

Because of the complete recovery, this core log is presented along with the CPT and EC data from probes advanced just a few feet away from the core hole. Plots of grain size distribution and calculated hydraulic conductivity (K) values are also presented. Hydraulic conductivity values determined from the grain size distribution were calculated using the Breyer method for well-graded samples (Kresic, 1998). The calculated K values are generally consistent with values obtained by previous consultants and Durrant et al., 1999 (these proceedings).

Geoprobe® Electrical Conductivity Probe

Continuous profiles of electrical conductivity were measured adjacent to each core hole location along Transect B (Figure 3). Electrical conductivity measurements were made using Geoprobe's electrical conductivity profiling system (Christy et al., 1994). Positively-charged ions embedded within the sheet structure of clay minerals results in clay-rich sediments being better conductors of electricity than quartzo-feldspathic sand. Thus, intervals of high conductivity denote clay-rich sediments; low-conductivity intervals indicate sandy horizons. Strip charts of the conductivity profiles were printed at the site, along with kriged cross sections of the interpreted geology along the various transects (including Transect B; Figures 4c and 5).

The EC profile from location SC-4/S-15 in Figure 5 shows excellent correlation with the core log and the stratigraphy interpreted with the CPT tool. A low EC interval occurs adjacent to a coarse-grained unit at a depth of approximately 6 feet.

The kriged EC profile along Transect B is shown in Figure 4c. Note the abundance of highly conductive silt and clay beneath the western part of the transect, consistent with the soil core, CPT, and surface geophysical data. The presence and continuity of the upper sand zone at a depth of approximately 8 to 12 feet is clearly shown on the EC transect. The fine-grained confining unit overlying the upper sand zone (identified by CPT probes and soil coring) is not identified in the EC transect, however. This is likely due to low electrical conductivity of those fine-grained sediments resulting from low water saturation (the fine-grained confining unit is largely above the water table).

CPT-Resistivity Probe

Cone penetration testing (CPT) was performed to depths up to 100 feet at 45 locations at the site, including locations next to each of the core holes along Transect B. CPT was performed by Gregg In Situ, Inc., of Signal Hill, California. For this direct-push method, an integrated electronic cone system is applied that is advanced using a down pressure capacity of approximately 25 tons. The cone system measures tip resistance and sleeve friction. The ratio of sleeve resistance to tip resistance, referred to as the friction ratio, is used to interpret the soil types encountered (Chiang et al., 1992). In general, sandy soils have high tip resistance and low friction ratios, whereas clayey soils have low tip resistance and higher friction rations. The cones used during the investigation recorded tip resistance, sleeve friction and dynamic pore pressure at 5-cm intervals. In addition, soil resistivity was measured at the same locations. All parameters and strip logs of the interpreted stratigraphy were simultaneously printed on a printer and stored on a computer diskette for further analysis.

CPT proved to be a rapid and accurate way to collect critical lithologic data from the stratified sedimentary deposits underlying the Transect B study area. More than 1,300 feet of continuous stratigraphic profiles were collected in three field days, allowing complete three-dimensional characterization of the subsurface geology in the study area. CPT data were initially correlated with lithologic data from continuously-cored borings since CPT plots show the inferred geology based on the physical properties of the soil and not the actual lithology. Figure 5 reveals good correlation between the core log (SC-4) and the CPT probe (S-15), although the soil type interpreted by the CPT software is sometimes slightly different than the USCS description.

Perhaps the most valuable characteristic of the CPT logs is that the data represent quantitative and repeatable measurements of the soil properties. They are objective measurements indicative of lithology, unlike the sometimes subjective descriptions of soil cores recorded by geologists with different training and experience. As such, the CPT logs proved to be very useful in correlating strata and demonstrating that they are laterally continuous across the Transect B study area.

Tools to Define Groundwater Conditions and Contaminant Distribution

Waterloo Groundwater Profiler™

Depth discrete groundwater samples were collected adjacent to core holes at several locations along Transect B. The primary DP tool used to collect one-time groundwater samples was the Waterloo Groundwater Profiler (Pitkin et al., 1994). The Profiler allows the collection of multiple depth-discrete groundwater samples in a single push. With the Profiler, groundwater samples are collected through ports located at the bottom of the DP rods. Samples are extracted through Teflon® tubing that runs inside of the DP rods from the intake ports to the ground surface. Samples are collected in vials mounted upstream of the peristaltic pump in order to avoid negative biases caused by sorption of organic molecules to the peristaltic tubing. After a sample has been collected, the flow of water is reversed, and deionized water is pumped slowly down through the Teflon® tubing and out of the sampling ports. This flushes the old sample out of the tubing and keeps the ports from plugging. When the next sampling depth is reached, the flow direction is again reversed, pumping groundwater to the surface.

The Waterloo Groundwater Profiler was found to be of limited use in most parts of Site 60 due to the presence of interstitial fines that frequently plugged the external ports on the sampling tool. Sampling flow rates were typically very low. The tool often needed to be removed, cleaned, and reinserted in order to collect a sufficient volume of groundwater for chemical analysis. In some strata, e.g., coarse-grained, poorly-sorted sand, the tool yielded copious amounts of water in a short period of time. Our field team found that the best way to use the Profiler at Site 60 was to collect groundwater samples solely from coarse-grained zones identified from core logs or CPT plots.

Multiple depth-discrete groundwater samples were collected with the Profiler next to multi-level well UW-9ML. This was done to provide a very detailed profile of MTBE and electron acceptor concentrations in the vicinity of planned enhanced biodegradation pilot tests. Concentrations of MTBE and other solutes in samples collected with the Profiler compared very well to concentrations of the analytes measured in samples collected from the adjacent permanent multi-level monitoring well.

CMT Multi-Level Monitoring System

Following geologic characterization and one-time “snapshot” groundwater sampling of strata in the vicinity of Transect B, six permanent multi-level monitoring wells were installed along Transect B. Because of the presence of cohesive fine-grained sediments beneath Lompoc Canyon, traditional bundle piezometers could not be utilized. Traditional bundle piezometers are used when cohesionless sand collapses around the tubes, preventing short-circuiting of groundwater between the various intake ports.

Instead, a new type of permanent multi-level monitoring system, referred to as the Continuous Multi-Channel (CMT) Multi-Level System (Einarson and Cherry, 1999), was installed. The CMT system uses custom-made 1.7-inch-OD polyethylene tubing that is extruded with seven internal chambers. Ports were drilled into the various chambers at different depths and the chambers sealed below the ports with a polyethylene sealant. The ports were then screened with 0.007-inch stainless mesh to prevent fine sand from entering the ports. During construction, bentonite packers and sand packs were pre-formed around the tubing within fabric sleeves and thus lowered down the boreholes with the multi-level wells themselves. The wells, including the sand pack and bentonite seals, were built completely above the ground and were simply inserted into large diameter Enviro-Core drive casing to the bottom of the boreholes. The drive casing was then withdrawn, allowing water to flow into the boreholes, hydrating the bentonite. After about one hour, the bentonite packers had swelled, completely sealing the borehole between the various monitored intervals. A diagram of the construction of one of the multi-level wells, UW7-ML, is shown in Figure 6.

Fifteen multi-level wells were installed at Site 60 in three days. Each CMT multi-level well was custom built based on the stratigraphy defined by earlier continuous soil coring and CPT. This design allowed for the rapid installation of multi-level wells in a geologic formation that would not readily collapse around the emplaced well after the drive casing was removed.

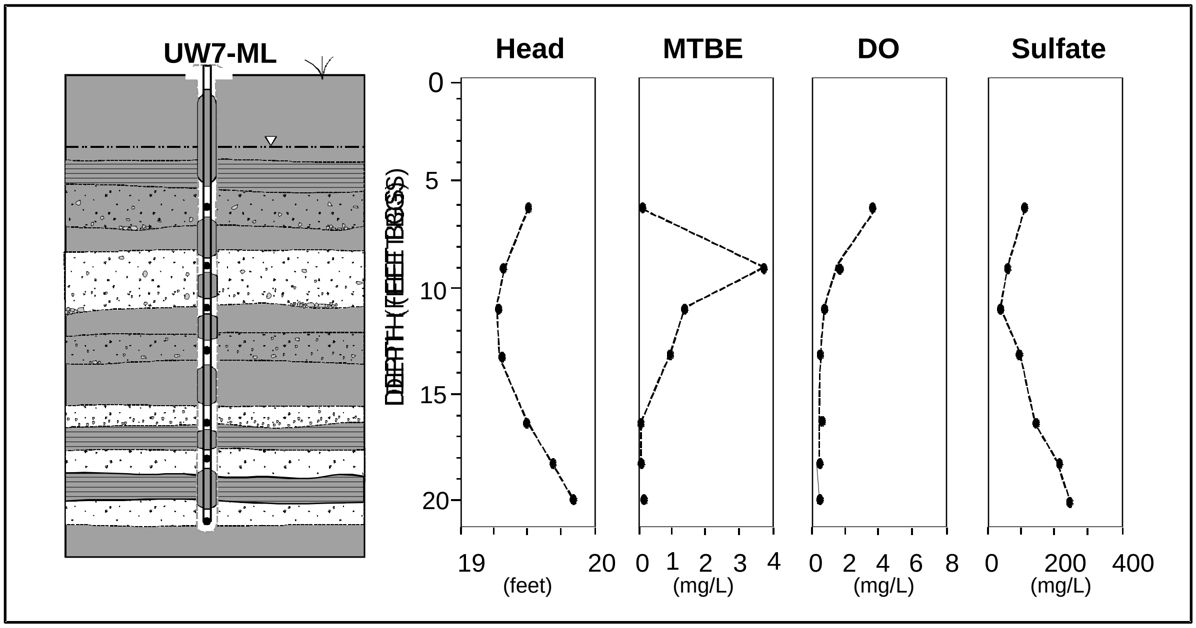


Figure 6. Data from multi-level well UW7-ML, April 1999

After installation, the multi-level wells were developed by purging with a peristaltic pump. Water levels were measured in the wells within one week of well development. Water levels were consistently different in each zone in the wells, indicating that the bentonite packer seals had swelled sufficiently to seal the borehole annulus between the various monitored zones. Most of the multi-level wells exhibit hydraulic head profiles similar to the one shown in Figure 6. As shown in that figure, an upward hydraulic gradient was measured in stratified deposits in well UW7-ML below a depth of 13 feet. This upward hydraulic gradient, which has been measured in subsequent monitoring events and in other multi-level wells along Transect B, is consistent with the regional hydrogeologic setting. Lompoc Canyon is located a few miles from the Pacific Ocean, in a regional groundwater discharge area. Upward hydraulic gradients, indicative of regional groundwater discharge, is therefore not unexpected. Interestingly, the upper units monitored by the UW7-ML exhibited a slight downward gradient in April 1999. This may be indicative of recharge of meteoric water during the winter rainy season. The presence of slightly oxygenated groundwater in the shallow zones may support this hypothesis, although the detection of oxygen in the shallow zones is more likely due to sampling error.

The concentration of MTBE in samples collected from the well in April 1999 ranges from nearly 4,000 ug/l in Zone 2 (the upper sand zone) to non-detectable concentrations in deeper zones 5, 6, and 7 (Figure 6). Based on data from even one multi-level well, the upper sand zone is clearly identified as the preferred pathway for MTBE migration in the vicinity of Transect B. When geologic and MTBE concentration data are plotted in a cross section drawn along Transect B, the importance of the site geology in controlling the occurrence and migration of the dissolved MTBE plume is apparent (Figure 4d). The MTBE plume (defined by the 1,000 ug/l contour) crossing Transect B is almost completely limited to the upper sand zone.

The Transect B multi-level wells are being monitored regularly to assess the temporal changes in hydraulic head, MTBE concentrations, and mass flux. Additional multi-level wells, constructed identically to the Transect B wells, are being used to monitor the results of small-scale field experiments being performed to stimulate the in situ biodegradation of MTBE (see Mackay et al., 1999).

Geoprobe® Membrane Interface Probe (MIP)

Geoprobe's Membrane Interface Probe (MIP) was advanced along with the electrical conductivity probe at each sampling location along Transect B and at locations in and around the source zone (Figure 2). The MIP allows semi-quantitative identification of contaminated zones without collecting a soil or groundwater sample.

Contaminants diffuse through a heated polymer membrane in the tip of the tool and are carried to a flame ionization detector (FID) whose signal is recorded every foot of penetration (Christy, 1996).

The MIP proved to be a useful tool to quickly delineate zones of residual hydrocarbon contamination near the source zone. However, the tool did not identify any MTBE along Transect B, even though analysis of groundwater samples collected with the Waterloo Groundwater Profiler and the CMT multi-level wells showed dissolved MTBE to be present in concentrations as high as 3,500 ug/l. Thus, the current version of the MIP tool does not appear to be sensitive enough to delineate dissolved MTBE plumes, at least in the range of concentrations found at Site 60. Geoprobe, Inc. has indicated that modifications to the tool are underway to enhance the tool's ability to detect dissolved MTBE.

Conclusions

Detailed characterization of a portion of Site 60, VAFB prior to initiating controlled field experiments provided a unique opportunity to compare several innovative characterization tools. Surface dipole-dipole resistivity surveys and intrusive Geoprobe® EC profiling were shown to be fast and inexpensive ways to identify general geologic units when there is a sufficient contrast in the electrical conductivity of the sediments. These methods are especially useful to interpolate the geology between areas where detailed subsurface data have been collected.

Characterization data along Transect B shows that the subsurface stratigraphy exerts a strong control on the distribution and flow of MTBE and dissolved electron acceptors in the shallow alluvial sediments. Continuous soil cores were useful to provide samples needed to measure the physical properties of the various strata and to calibrate the CPT data. The CPT provided the most detailed, cost-effective information about the site stratigraphy, in particular the lateral continuity of shallow water-bearing strata. The CMT multi-level monitoring system yielded important information regarding the vertical distribution of hydraulic head in the aquifer and on-going samples of groundwater for geochemical measurements.

Acknowledgements

Characterization efforts at Site 60 were funded by the American Petroleum Institute (API). We are particularly grateful to Bruce Bauman (API), Tim Buscheck (Chevron Research and Technology) and Gerrard Spinnler (Equilon Enterprises, Inc.) for their assistance since the very early stages of this project. We are also indebted to Denise Caron, Pablo Martinez, Jack Yamauchi, Ron MacLelland and others at Vandenberg Air Force Base for their encouragement and considerable in-kind support. We appreciate the interest and support of this project expressed by the Central Coast Regional Water Quality Control Board, in particular Bill Meece and Carol Kolb. Particular thanks is due to Precision Sampling, Inc., Geoprobe®, Inc., and Gregg In Situ, Inc. for their significant efforts and generous in-kind financial support.

References

Bright, D.J., D.B. Nash, and P. Martin, 1997. *Evaluation of Ground-Water Flow and Solute Transport in the Lompoc Area, Santa Barbara County, California*. U.S. Geological Survey, Water Resources Investigations Report 97-4056.

Chiang, C.Y., K.R. Loos, and R.A. Klopp, 1992. *Field determination of geological/chemical properties of an aquifer by cone penetrometry and headspace analysis*. Ground Water, Vol. 30, No.3: pp 428-436.

Christy, C.D., T.M. Christy, and V. Wittig, 1994. *A percussion probing tool for the direct sensing of soil conductivity*. In Proceedings of the 8th National Outdoor Action Conference, Las Vegas, Nevada. National Ground Water Association, Columbus, OH.

Christy, T. M., 1996. *A Driveable Permeable Membrane Sensor for the Detection of Volatile Compounds in Soil*. in: Tenth National Outdoor Action Conference and Exposition: Aquifer Remediation, Las Vegas, Nevada National Ground Water Association, Columbus, OH. pp 169-177.

Dibblee, T.W., Jr., 1950. *Geology of Southwestern Santa Barbara County, California, Point Arguello, Lompoc, Point Conception, Los Olivos, and Gaviota Quadrangles*. California Division of Mines Bulletin 150, June.

Einarson, M.D., 1995. *Enviro-Core™ – A new vibratory direct-push technology for collecting continuous soil cores*. In Proceedings of the 9th National Outdoor Action Conference, Las Vegas, Nevada. National Ground Water Association, Columbus, OH.

Einarson, M.D. and J.A. Cherry, 1999. *A New Low-Cost Multi-Level Monitoring System*. Manuscript in preparation.

Kresik, N., 1998. *Quantitative Solutions in Hydrogeology and Groundwater Modeling, Chapter 3*. Lewis Publishers, Boca Raton, Florida

Lee and Ro, 1998. *Draft Installation Restoration Program (IRP) Remedial Investigation Report for IRP Site 60, Vandenberg Air Force Base, California*. September. Lee and Ro, Inc., 1199 South Fullerton Road, City of Industry, CA 91748.

Luke, M.H., 1998. RES2DINV version 3.3 for WINDOWS 3.1 and 95: Rapid 2D resistivity and IP inversion using the least-squares methods (Wenner, dipole-dipole, pole-pole, pole-dipole, Schlumberger, rectangular, on land, underwater and cross-borhole surveys).

Pitkin, S.E., R.A. Ingleton and J.A. Cherry, 1994. *Use of a Drive Point Sampling Device for Detailed Characterization of a PCE Plume in a Sand Aquifer at a Dry Cleaning Facility*. Proceedings of the 8th Annual Outdoor Action Conference, Las Vegas, Nevada. National Ground Water Association, Columbus, OH.

Starr, R.C. and R.A. Ingleton, 1992. *A new method for collecting core samples without a drilling rig*. Ground Water Monitoring Review, Winter 1992, Vol 12(1), 91–95.

Biographical Sketches

Murray D. Einarson is a consulting hydrogeologist and part-time graduate student at the University of Waterloo. His work focuses on the fate and transport of dissolved solutes, and innovative, low-cost technologies for environmental site characterization and *in situ* remediation. He received a B.A. in geology from U.C. Santa Barbara in 1982 and has 14 years of environmental consulting experience. (Conor Pacific/EFW, 2650 East Bayshore Road, Palo Alto, CA 94303; phone: 650-843-3828, fax: 650-843-3815, email: murray.einarson@efwi.com)

Mario Schirmer, formerly a Postdoctoral Research Associate at the University of Waterloo, is a scientist at the UFZ Centre for Environmental Research Leipzig-Halle in Germany. He is working on multiscale aspects of biodegradation and dissolution modeling and is involved in large-scale field assessments of natural attenuation and remediation options. He obtained his Diplom in Geophysics in 1991 from the University Mining Academy Freiberg (Germany), worked at the University of Stuttgart (Germany) until 1993 and finished his Ph.D. in Hydrogeology in 1999 at the University of Waterloo. (UFZ Centre for Environmental Research Leipzig-Halle, Department Industrial and Mining Landscapes, Permoser Str. 15, 04318 Leipzig, Germany; phone: 011 49 341 235 2333; fax: 011 49 341 235 2126; e-mail: schirmer@pro.ufz.de)

Parsa Pezeshkpour, a Research Associate at University of Waterloo, is interested in the hydrogeological application of electrical resistivity tomography (ERT). He received his B.Sc. in geology (1986) and his M.Sc. in Hydrogeology (1991) from Shiraz University, Shiraz, Iran and received his Ph.D. from the University of Waterloo (1999). (University of Waterloo, Department of Earth Sciences, 200 University Ave. W., Waterloo, ON, N2L 3G1, Canada; Tel: (519) 885-1211 Ex. 5368; Fax: (519) 746-7484; email: ppezeshk@sciborg.uwaterloo.ca)

Douglas M. Mackay is a Research Associate Professor at the University of Waterloo. His work has included field tests of contaminant transport/transformation/remediation in groundwater, as well as laboratory studies of processes controlling field behavior. Recent research focuses on semi-passive methods of enhancing in-situ remediation of MTBE and other contaminants. (University of Waterloo, Department of Earth Sciences, Waterloo, ON, N2L 3G1, Canada; phone: 650-324-2809; fax: 650-324-2259; d4mackay@uwaterloo.ca).

Ryan D. Wilson is a Research Associate and Ph.D. student in the Department of Earth Sciences at the University of Waterloo, Waterloo, Ontario, N2L 3G1. His research interests include field and modelling studies of semi-passive remediation technologies and the behavior of gaseous tracers. Mr. Wilson received his B.Sc. in Geology from the Univerisity of Alberta in 1987, and his M.Sc. in Earth Sciences (Hydrogeology) from the University of Waterloo in 1993. . (University of Waterloo, Department of Earth Sciences, Waterloo, ON, N2L 3G1, Canada; phone: 519-888-4567 x 5372, fax: 519-746-7484, e-mail rdwilson@sciborg.uwaterloo.ca).