ESTCP
Cost and Performance Report

(CU-9601)

High Resolution Seismic Reflection to Characterize and Plan Remediation at Hazardous Waste Sites

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ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

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LIST OF ACRONYMS

2-D	Two-Dimensional
3-D	Three-Dimensional
AFB	Air Force Base
CA	Chloroethane
CLEAN	Comprehensive Long-Term Environmental Action Navy
DCA	1,2-dichloroethane
DCE	1,1- and 1,2-dichloroethene
DNAPL	Dense Non-Aqueous Phase Liquid
DoD	Department of Defense
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
LIF	Laser Induced Fluorescence
NAS	Naval Air Station
NASNI	Naval Air Station North Island
NFESC	Naval Facilities Engineering Service Center
PID	Photoionization Detector
RPM	Remedial Project Manager
RRI	Resolution Resources, Inc.
SCAPS	Site Characterization and Analysis Penetrometer System
VC	Vinyl Chloride
VOC	Volatile Organic Compound
VSP	Vertical Seismic Profile

ACKNOWLEDGMENTS

Several individuals and organizations participated in this demonstration and provided review, guidance, and information that were valuable to the success of this project. Details of points of contact are provided in Appendix A.

- Mr. Mark Kram from the Naval Facilities Engineering Service Center (NFESC)
- Mr. Joey Trotsky from the Naval Facilities Engineering Service Center (NFESC)
- Mr. Chris Perry from Battelle Columbus Operations
- Mr. Brian Herridge from Resolution Resources, Inc.

Technical material contained in this report has been approved for public release.

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1.0 EXECUTIVE SUMMARY

This report presents cost and performance data for the three-dimensional (3-D) seismic reflection survey technique used to generate a high-resolution, 3-D imaging of subsurface geologic, subsurface hydro-geologic, and subsurface dense non-aqueous phase liquid (DNAPL) contaminant source areas at four selected Department of Defense (DoD) sites. This project was sponsored by the Environmental Security Technology Certification Program (ESTCP) and managed by the Naval Facilities Engineering Service Center (NFESC) Port Huneme, CA. NFESC contracted with Battelle Memorial Institute (Contract No. N47408-95-D-0730) to perform the project work. The four sites selected were Letterkenny Army Depot near Chambersburg, PA; Alameda Naval Air Station, Alameda, CA; Tinker Air Force Base, Oklahoma City, OK; and Allegany Ballistics Laboratory, Mineral County, WV. At Allegany Ballistics Laboratory, the seismic survey and an extensive sampling effort were funded and conducted outside of this project. Furthermore, at Allegany Ballistics Laboratory, only geologic predictions, and not DNAPL targets, were investigated.

The objective of the project was to verify that the 3-D seismic reflection survey is a viable technique for rapidly and effectively performing DNAPL source delineation and high-resolution site characterization. This objective would be met if 90% of the predictions for DNAPL contamination generated from the 3-D seismic survey results were verified to be correct, based on analysis of groundwater samples taken from within the surveyed regions. As a secondary objective, the surveys were also used to demonstrate high-resolution site characterization, by using the seismic output to interpret the depth to bedrock and the depth to fracture zones at several of the sites.

Seismic reflection imaging is based on the principle that acoustic energy (sound waves) will bounce, or "reflect," off the interfaces between layers within the earth's subsurface. These interfaces are subsurface anomalies which provide possible pathways and traps for DNAPL. In addition, it was believed that interfaces between the DNAPLs and surrounding materials can cause a reflection anomaly recognizable with this seismic technique. A 3-D seismic survey uses multiple points of observation. In a 3-D survey, a grid of geophones and seismic source impact points are deployed along the surface of the site. The result is a volume, or cube, of seismic data that is sampled from a range of different angles (azimuth) and distances (offset). The data is a high-resolution, distortion-free representation of the subsurface.

A complete seismic survey consists of the following components:

- Site research and generation of a geologic model
- Vertical seismic profile (VSP) generation to obtain a velocity model for the site's subsurface stratigraphy
- Land survey for proper position of important site features and data collection points
- 3-D seismic reflection survey surface geophysical data collection activities
- 3-D data processing and interpretation
- Attribute analysis to delineate anomalies that may represent fractures and/or DNAPL
- Confirmation drilling, sampling and analysis

The results of this demonstration show, at this time, that 3-D seismic surveys are not effective at directly detecting DNAPL. Of the 27 total targets evaluated at Letterkenny Army Depot, NAS Alameda, and Tinker AFB, only one target was found to contain DNAPL and, therefore, the project did not meet the objective of detecting DNAPL at 90 % of the targets. The only successful target was based on an anomaly in the seismic imagery that appeared indistinguishable from other anomalies believed to be caused by contrasts between geologic strata. The threshold concentration level used to positively determine the presence of DNAPL was 110 ppm. Overall, the four demonstration sites appear to possess high enough levels and large enough plumes of dissolved-phase halogenated organic contamination to imply that free-phase DNAPL sources are likely to be present.

This technology appears to be a useful tool for imaging subsurface conditions for the purpose of site characterization and for determining the most likely locations for DNAPL source zone migration and accumulation. As such, this technology may prove to be a highly effective source exploration tool, particularly in fractured bed-rock settings. During this demonstration, the interpretation of fractures and fracture geometry played the primary role in selecting targets. Greater emphasis on evaluating site stratigraphy and the identification of structural and/or stratigraphic traps might prove useful.

The estimated survey costs per acre at Letterkenny Army Depot, NAS Alameda, and Tinker AFB are \$17,859/acre, \$13,939/acre, and \$25,700/acre, respectively. Typical surveys will likely include drilling and sampling to link the seismic data to observations in the field, and to confirm the presence of DNAPL within selected target anomalies. Differences in drilling and sampling costs from site to site are contingent upon the amount of pre-existing well control present at any given site and on local market conditions and rates. Costs associated with these activities are also dependent upon the number and depth of targets investigated. Work performed at Allegany Ballistics Laboratory was not included in this breakdown because the majority of work was performed outside of this project.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY BACKGROUND

A previous seismic demonstration using two-dimensional (2-D) and 3-D seismic data collection by Resolution Resources, Inc. in 1994 was performed at Site 9, Naval Air Station North Island (NASNI), in San Diego, CA, under a Comprehensive Long-Term Environmental Action Navy (CLEAN) contract. A 3-D seismic survey, in conjunction with photoanalysis and a background review of the geology and site history, was performed at NASNI Site 9 over a topographically low area called the "fiery marsh," where an estimated 32 million gallons of liquid waste had been disposed. The 3-D seismic survey imaged the stratigraphy below the site, which consisted of faulted, unconsolidated marine sediments. The disposal area was actually a sag pond formed by the juncture of several faults. The seismic data, which were interpreted using complex seismic attribute analysis, also showed amplitude anomalies, which were believed to be the result of a suspected DNAPL source zone. Although not verified with confirmation drilling and sampling, the seismic image of the site significantly altered the previous site model. This unconfirmed effort suggested that seismic imaging may be capable of delineating complicated structure and stratigraphy, a task which is essential in understanding contaminant migration pathways. In addition, it suggested that seismic imaging may be used to detect the presence of DNAPL source zones.

2.2 THEORY OF OPERATION

Geophysical exploration is an indirect form of subsurface characterization in which physical measurements made at the ground surface provide information on specific features and conditions present in the subsurface. Seismic reflection imaging is based on the principle that acoustic energy (sound waves) will bounce, or "reflect," off the interfaces between layers within the earth's subsurface. This principle is analogous to the process of a human voice echoing off of a building wall.

In a seismic reflection survey, acoustic energy is imparted into the earth with a seismic source. After impact of the seismic source, the generated sound waves propagate and spread out along spherical wavefronts. The usable sound energy travels into the earth (signal), while some energy is lost into the air or along the ground surface (noise). Figure 1 shows a simplified cross-sectional view of a 2-D seismic recording system with some of the signal and noise ray paths associated with a reflection survey.

The earth is characterized by many subsurface layers, each possessing different physical properties. When sound waves traveling through the earth encounter a change in the physical properties of the material in which they are traveling, they will either reflect back to the surface or penetrate deeper into the earth, where they may be reflected at another interface. Some energy is always transmitted while some is reflected. Acoustic impedance is a measure of how seismic energy will react when it encounters a subsurface layer, one that is closely associated with the density of a given layer. Contrasts in acoustic impedance create seismic reflection interfaces. Subsurface reflections of seismic energy, therefore, most often occur at the interfaces between lithologic changes (for example, a transition from till to rock). As a seismic reflections make it possible to map the stratigraphy below a site.

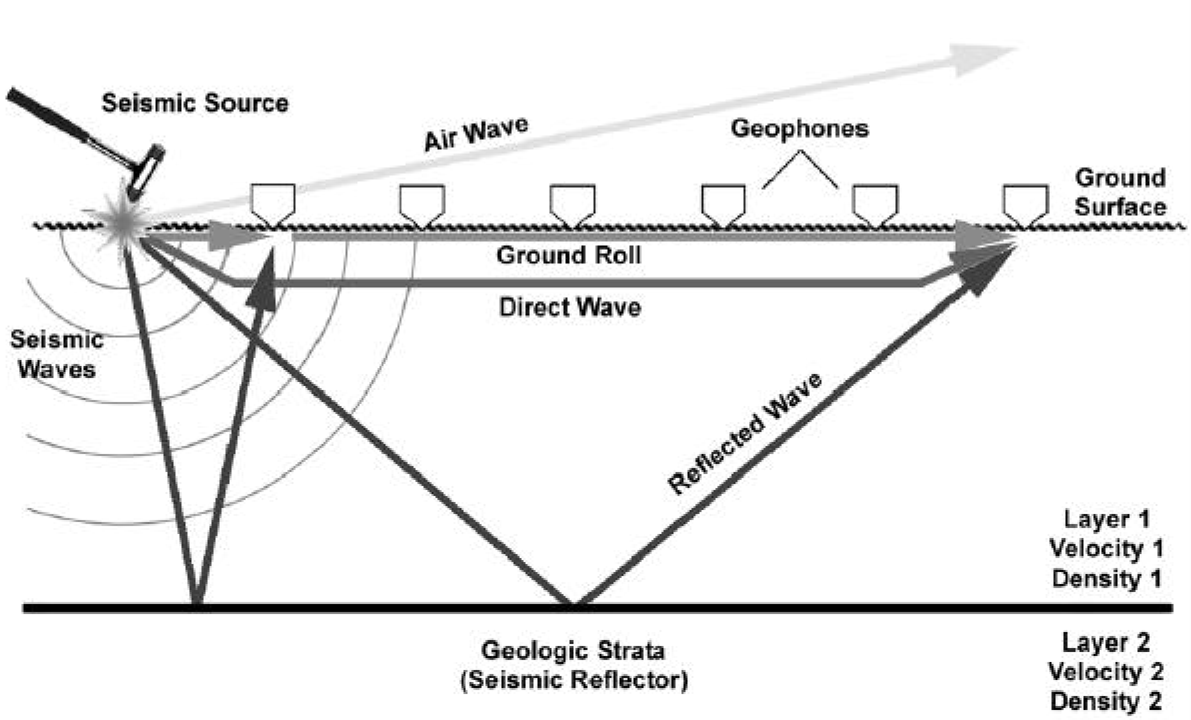

Figure 1. Simplified Cross-Sectional View of a 2-D Seismic Recording System. (Battelle, 1999)

Areas of structural deformation such as faults and fractures also are a source of seismic reflections. A fractured rock surface produces different reflections than a continuous rock surface. Acoustic energy is disrupted or "diffracted" by fractured rock surfaces in much the same way that a visual image is distorted in a shattered mirror. Identifying diffracted energy patterns is one way in which geologic structures such as faults and fractures can be mapped using seismic reflection surveys.

During this investigation, high-speed digital data recording systems (seismographs) and acoustic sensors (geophones) were used to measure the reflected sound waves. Compressional waves (p-waves) are a type of seismic wave. Compressional waves are so named because the wave-fronts propagate through the earth mechanically, as one particle moves and compresses the next particle. The particle motion in the earth moves the geophone body, which houses a magnet within a suspended coil inside the geophone. This action produces an analog voltage signal that is proportional to the ground motion. The seismograph then digitizes the analog signal by breaking the signal into discrete time samples, and creates a digital level (a numeric value) for the amplitude of the signal during that time sample. The data in this investigation were digitized to 21-bit resolution, which means the analog geophone signal was broken into 221, or 2,097,152, levels. Data interpreters analyze the final processed wavelet, which is the result of the post-survey data reduction process. These wavelets act as high-resolution, distortion-free representations of the subsurface.

2.3 COMPONENTS OF A 3-D SEISMIC SURVEY

A complete seismic survey consists of the following components:

- Site research and generation of a geologic model

- VSP generation to obtain a velocity model for the site's subsurface stratigraphy
- Land survey for proper position of important site features and data collection points
- 3-D seismic reflection survey surface geophysical data collection activities
- 3-D data processing and interpretation
- Attribute analysis to delineate anomalies that may represent fractures and/or DNAPL
- Confirmation drilling, sampling and analysis

It is important to include all components listed above when evaluating whether the 3-D seismic survey is appropriate for a particular site. If each component is not carefully considered, serious underestimates of time and cost requirements for this approach may be encountered. For instance, confirmation drilling and sampling are essential for using the seismic data. If not carefully considered, expenses for this critical component can outweigh the costs for collecting and processing the surface geophysical data.

2.4 ADVANTAGES OF 3-D SEISMIC SURVEYS

The primary advantage of seismic surveys is that they provide detailed 3-D characterizations of subsurface features that can be used to identify potential source zones and preferential pathways for contaminant migration. One strength of 3-D seismic surveys is that they are able to spatially sample the subsurface with up to five orders of magnitude more data points than a traditional, vertical borehole, site characterization effort. Having a thorough understanding of the subsurface facilitates the location of ground water sampling wells and subsequent remedial efforts for optimum contaminant removal.

2.5 LIMITATIONS OF 3-D SEISMIC SURVEYS

There are general limitations inherent in the use of seismic surveys. Most importantly, many lithologic variations in the subsurface can account for the observed anomalies in the seismic survey data. Therefore, seismic data may not be capable of directly identifying DNAPLs, but may reflect lithologic influences. There does not appear to be a method for filtering out anomalies due to stratigraphic signatures so that DNAPL signals can be unequivocally identified. Additional laboratory tests and modeling of seismic response are necessary to further delineate anomalies that may be associated with DNAPL from those that are simply the result of lithologic or structural variations. Survey data resolution depends in large part on the near-surface site conditions. Low-strength materials at the surface, including peat, organic sands, humus, and landfill debris, reduce the effectiveness of the technique. The quality of survey data will vary from site to site. Therefore, quality control with respect to resolution is difficult to assess, especially if different operators, hardware, or software are used. Another limitation is that the survey is not completely non-intrusive, since generation of VSP's typically require installation of wells. Related to this issue is that the resolution of the seismic technique (including the VSP component), in terms of identifying absolute DNAPL location, is difficult to assess without additional study. It is anticipated that under ideal conditions, optimal resolution is on the order of a few feet and greater. Given the observations that DNAPL migration pathways in unconsolidated materials can be on a micrometer to millimeter diameter scale, the seismic method may not yet be capable of yielding source zone location information with adequate resolution in unconsolidated materials. Therefore, depth values generated from seismic surveys may not yield resolution adequate to appropriately locate DNAPL source zones for situations where stratigraphic complexities exist, where DNAPLs exist in highly dispersed microglobules, or where preferential pathways in unconsolidated materials are undetectable.

2.6 TECHNOLOGY COMPARISON

Although new techniques are continuously being developed, the comparison discussion will only focus on conventional approaches employing drilling and sampling. 3-D seismic surveys provide a means to evaluate vertical fracture systems. An issue with conventional site characterization approaches (when attempting to locate DNAPL accumulations) is that vertical exploration boreholes are particularly ineffective at discovering vertical fracture systems. Even in the rare instances when vertical fractures are discovered, it is extremely difficult to integrate these infrequent observations and to thoroughly map the complete fracture system that may exist at the site. Another shortcoming of conventional site evaluation is the lack of evidence from deeper environments, especially below the source areas. Standard practices do not usually permit drilling into or through potential DNAPL source areas, especially when the source areas have been capped with clay. Because the surface data collection component of 3-D seismic surveys are non-invasive, data can be gathered beneath source areas prior to drilling and sampling.

Although other forms of geophysical characterization can contribute to the understanding of a site, they all lack one important feature possessed by 3-D seismic technology: the ability to use 3-D migration. 3-D migration removes distortions which so often make 2-D data (such as 2-D seismic reflection, radar, gravity, electromagnetic, or resistivity data) difficult to interpret. The effects from offline features and diffractions in 2-D work make it difficult to accurately interpret.

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The objectives of this project were to demonstrate the use of high-resolution, 3-D seismic reflection surveys to provide an effective method for conducting subsurface DNAPL source delineation and for performing high-resolution site characterization. The primary project objective (DNAPL source delineation) would be met if 90% of the predictions for DNAPL contamination (generated from the 3-D seismic survey results) could be verified to be correct, based on chemical analyses of groundwater samples taken from within target zones chosen within the surveyed regions.

The level of dissolved DNAPL contamination considered indicative of the presence of free-phase DNAPL was set at 10% of the solubility of any potential DNAPL constituent. For example, trichloroethene (TCE) has a solubility in pure water of 1,100 parts per million (ppm), so the target was considered to contain free-phase DNAPL if 110 ppm was detected in ground-water samples collected from a target location. All four sites evaluated during this demonstration previously displayed concentrations of dissolved halogenated organic contaminants in groundwater above the 10% cutoff levels.

In addition to evaluating this technology's ability to find DNAPL, the high-resolution, 3-D seismic method was tested for its ability to image shallow stratigraphic features by comparing the predicted depths of particular subsurface features to the actual depths measured during validation field efforts. Structural features such as fractures or faults also were evaluated based on whether they acted as conduits or barriers to transmit and accumulate DNAPL and to generally increase groundwater yields.

3.2 PHYSICAL SETUP AND OPERATION

This technology application consisted of conducting high-resolution, 3-D seismic reflection geophysical surveys which included processing and interpreting the data to identify important subsurface features and anomalies. Since every seismic survey used to identify DNAPL source zones and pathways will require confirmation sampling and analysis, this step is also considered an essential component of a complete survey.

The high-resolution, 3-D seismic reflection surveys applied at these sites consisted of the following steps:

- Site research and generation of a geologic model
- VSP generation to obtain a velocity model for the site's subsurface stratigraphy
- Land survey for proper position of important site features and data collection points
- 3-D seismic reflection survey surface geophysical data collection activities
- 3-D data processing and interpretation
- Attribute analysis to delineate anomalies that may represent fractures and/or DNAPL
- Confirmation drilling, sampling and analysis

The generation of VSP data is an important step which is briefly described below. All of these steps are detailed in the demonstration report by Battelle, 1999.

Vertical Seismic Profile. A VSP is a geophysical field test that measures accurate one-way seismic velocity values for exact depth intervals beneath a site. Soil and rock units are inherently heterogeneous and anisotropic, so they differ in their ability to transmit and reflect seismic signals. Physical characteristics such as mineral content, bulk density, degree of cementation, and pore fluid content and properties all impact the rate at which seismic signals travel through any volume of subsurface media, be it soil or rock. VSPs provide the means to calibrate or "tie" the 3-D surface seismic data to correct physical depths. Prior to collecting VSP data, the exact depth to features present on a seismic profile can only be assumed based on general estimates of seismic velocity values for the types of soils or rocks known or thought to be present beneath the site. Stratigraphic information from the boring log or a well, along with one-way travel time measured from the surface down to any soil or rock feature or contact of interest, provide data to correlate borehole geology with the surface seismic data.

The seismic survey is not complete without the VSP data, since the surface data collection activities produce data in units of time. The VSP data is required for conversion to depth units. Depth values generated from VSP surveys may not yield resolution adequate to appropriately locate DNAPL source zones for situations where stratigraphic complexities exist, where DNAPLs exist in highly dispersed microglobules, or where preferential pathways in unconsolidated materials are undetectable using these geophysical methods.

3.3 SAMPLING PROCEDURES

Once the validation targets were identified, conventional drilling and sampling techniques were used to collect water samples to evaluate the surface geophysical survey predictions and to determine whether DNAPL was actually present at any target under evaluation. Sampling procedures were relatively consistent across the three sites where validation drilling took place. In all cases, groundwater was bailed from the borehole or cone penetrometer test push hole and stored in 40 ml volatile organic analysis vials before they were analyzed. At the Letterkenny Army Depot and Naval Air Station (NAS) Alameda sites, a laboratory trailer was mobilized and set up at the site to perform very rapid analyses and to provide real-time results. At Tinker Air Force Base (AFB), samples were collected and stored in a refrigerator before they were shipped in a chilled cooler to the Pennsylvania laboratory of Onsite Environmental Laboratories, Inc.

3.4 ANALYTICAL PROCEDURES

Several procedures were employed during the validation drilling and sampling that helped to evaluate if DNAPL was encountered in the boreholes drilled at the demonstration sites.

A photoionization detector (PID) was used to scan soil and rock cuttings, groundwater samples, and outflowing air and groundwater for organic constituents. The PID used during validations was a Photovac Model 2020. The PID was used to help select groundwater sampling points. Samples were collected when elevated readings were shown on the PID. The PID was also used to monitor the mud pit or settling basin on a periodic basis when areas of interest and target intervals were being drilled. During the validation work at Alameda, the PID generally was not used because the cone penetrometer test and Geoprobe® direct-push methods were not used to bring air, groundwater, or cuttings to the surface as the push was being advanced. At Alameda there was no evaluation of downhole conditions until the groundwater was sampled from the microwells. Therefore, at

Alameda, reliance was placed solely on the laboratory analyses alone to determine the level of contamination in groundwater sampled from well points set in the target zones.

Laboratory analysis of groundwater samples was the primary analytical method used to evaluate target intervals. Because chlorinated hydrocarbons are the targeted constituents for this demonstration, the Environmental Protection Agency (EPA) Method SW-846-8260 was used to analyze groundwater samples. This method detects the presence of a wide range of chlorinated hydrocarbons including the most com-mon industrial solvents, PCE and TCE, and their degradation products: 1,2-dichloroethane (DCA), 1,1- and 1,2-dichloroethene (DCE), vinyl chloride (VC), and chloroethane (CA). These hydrocarbons were the primary contaminants of concern at the three sites where validation drilling and sampling was performed.

3.5 DEMONSTRATION SITE/FACILITY BACKGROUND

High-resolution, 3-D seismic reflection surveys were conducted at sites which previous sampling data implied were highly contaminated with DNAPL. 3-D seismic surveys were conducted at four different installations during this effort. The sites were selected by NFESC and Resolution Resources, Inc. (RRI) based on the needs, interest expressed by the remedial project manager (RPM) of each site, and on information pro-vided by the RPMs which suggested that DNAPL was present at their site. The installations and the respective sites were as follows:

- Letterkenny Army Depot, PA: Area K - former waste disposal pits
- NAS Alameda, CA: Building 5 - plating shop
- Tinker AFB, OK: Building 3001 - degreasing operation
- Allegany Ballistics Laboratory, WV: Site 1 - former waste disposal pits

The primary criterion for selecting these specific installations and sites was the opportunity to test the technology in a variety of geological environments where there was strong evidence of DNAPL contamination. At Allegany Ballistics Laboratory, the seismic survey was funded and conducted outside the scope of this project. Furthermore, at Allegany Ballistics Laboratory, only geologic predictions, and not DNAPL targets, were validated. The following is a description of the geologic diversity represented by these sites:

- The Letterkenny Army Depot site contains a thin clay overburden overlaying dense limestone and dolomite. This setting lies within a known geologic fault. A significant amount of bedrock also is present in the region, creating karst features such as caverns and sinkholes.

- The NAS Alameda site is located over a thick sequence of bay or coastal plain sediments, which consist of alternately layered sands and clays. Because it is situated in the San Francisco Bay area, this site has been exposed to considerable seismic activity.

- The Tinker AFB site is underlain by interfingering layers of sandstone, siltstone, and shales.

- The Allegany Ballistics Laboratory site is underlain by 8 to 25 ft of silty clay and gravel alluvium overlying fractured bedrock of varying lithologies, including shale, sandstone, and carbonates.

A brief description of the location and background for each site is presented below. More thorough descriptions of the four sites are presented in the Technology Demonstration Plans developed under this Delivery Order for each site (Battelle 1997b, c, and d; 1998a and b).

Letterkenny Army Depot. Letterkenny Army Depot is located in central Pennsylvania, about 5 miles north of the city of Chambersburg, as shown in Figure 2. In 1942, the Army acquired what had formerly been farmland, and used the site as an ammunition storage and shipment location during World War II. Since then, the installation has functioned in (1) over--hauling, rebuilding, and testing of wheeled and tracked vehicles and missiles; (2) issuance and shipment of chemicals and petroleum products; and (3) storage, maintenance, demilitarization, and modification of ammunition. In support of these operations, activities have included metal plating and degreasing, electronics, equipment overhaul, and washout/deactivation of ammunition, all of which have required the use of significant quantities of chlorinated solvents.

Letterkenny Army Depot is near the border between Pennsylvania and Maryland, and is located in the Great Valley section, known locally as the Cumberland Valley, of the Valley and Ridge physiographic province, which extends northeast to southwest across central Pennsylvania. The Area K former waste disposal pits, located within the southeast area at this installation, were employed in the disposal of used chlorinated solvents, primarily TCE and DCE.

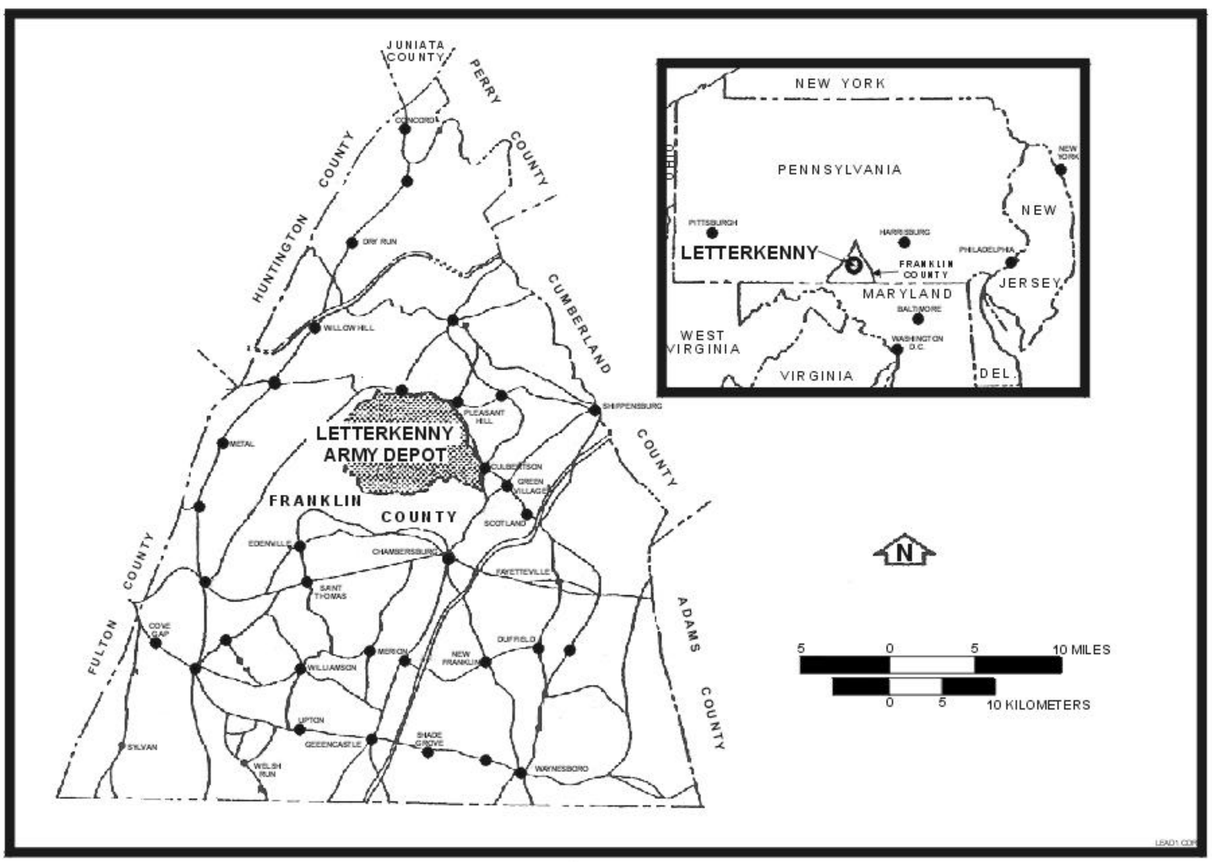

Figure 2. Location of Letterkenny Army Depot. (Battelle, 1999)

NAS Alameda. NAS Alameda is located on the northwest end of Alameda Island, in Alameda County, California. The island is located west of Oakland and on the eastern side of San Francisco Bay, as shown in Figure 3. NAS Alameda occupies 2,634 acres, partially on land and partially submerged, and is approximately two miles long and one mile wide. Land use in the area includes shipyards, military supply centers, residences, retail businesses, schools, and a state beach.

The Army acquired the area formerly occupied by NAS Alameda in 1930, and construction began the next year. In 1936, the area was transferred to the Navy and in 1941, more land was added to the air station. The primary mission of former NAS Alameda had been to provide facilities and support for fleet activities.

The 3-D seismic survey was completed within Site 5 at former NAS Alameda. Site 5 covers 18.5 acres and includes Building 5. A plating shop located within Building 5 had been in operation from 1942 to 1998. Shops in the building were used for cleaning, reworking, and manufacturing metal parts tool for maintenance and for plating and painting operations.

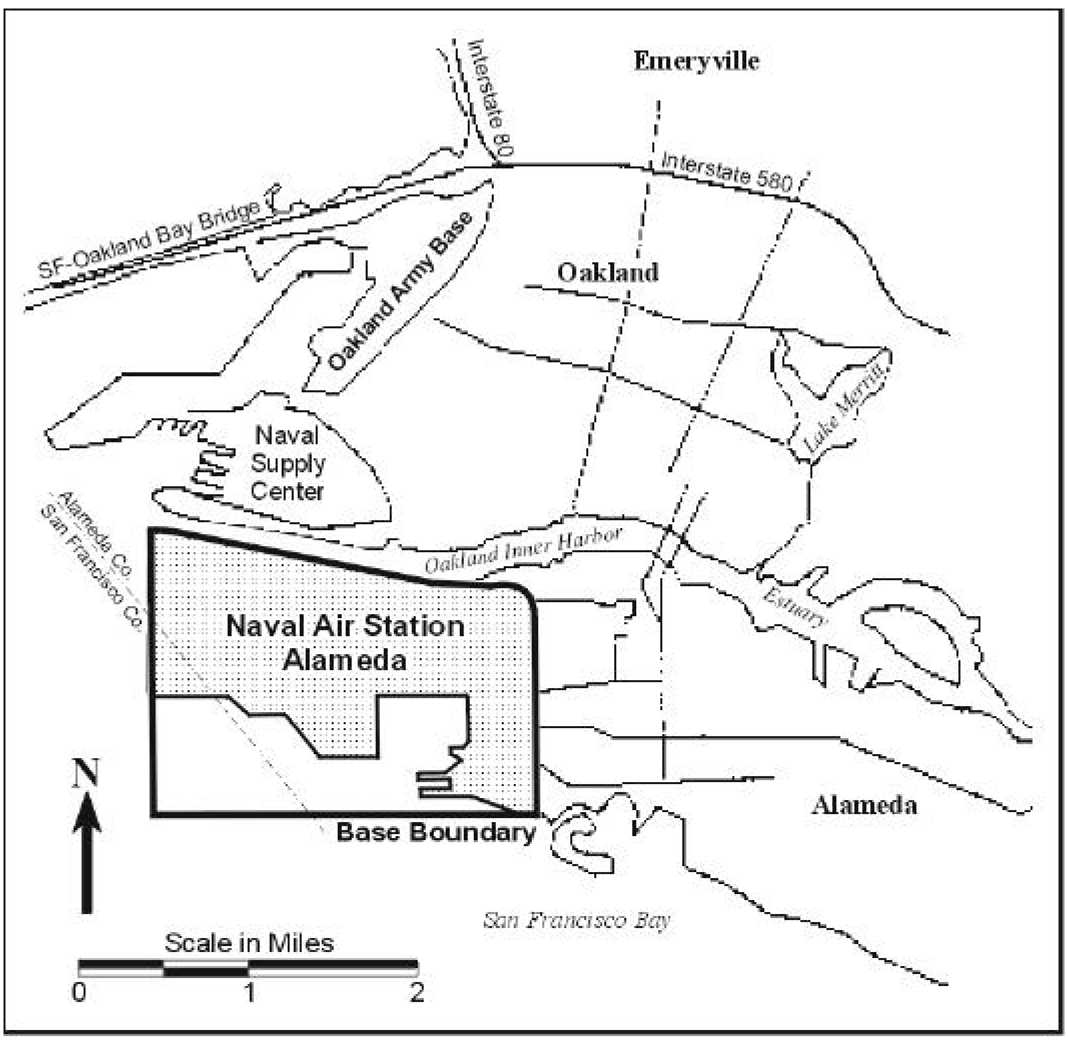

Figure 3. Location of NAS Alameda. (Battelle, 1999)

Tinker AFB. Tinker AFB is located in Oklahoma County in central Oklahoma, approximately eight miles southeast of downtown Oklahoma City (Figure 4). The Base encompasses 4,541 acres and contains approximately 500 buildings. Tinker AFB, as a worldwide repair depot, manages and maintains missile systems and aircraft. The base houses the Air Logistics Center and two Air Combat Command units, and is the main operating base for Airborne Warning and Control aircraft.

The degreasing operation at Building 3001 is located in the northeast corner of Tinker AFB. It has been in operation since the early 1940s. Past industrial practices within the building have resulted in contamination of surface soils and groundwater beneath and adjacent to the building.

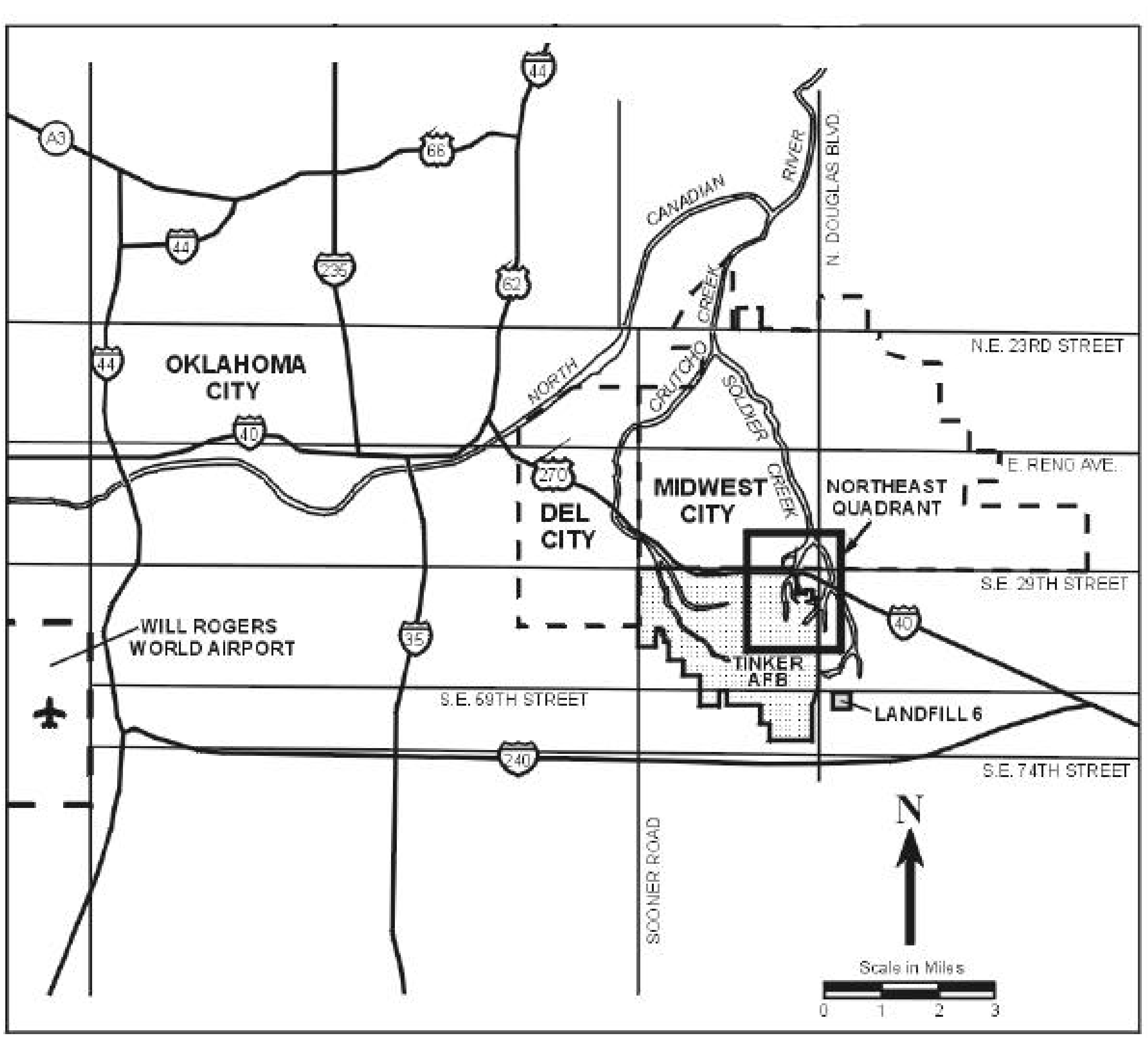

Figure 4. Location of Tinker AFB . (Battelle, 1999)

Allegany Ballistics Laboratory. Allegany Ballistics Laboratory is a research, development, and production facility located in Mineral County, WV. The facility is owned by the Navy and operated by Alliant Techsystems. Since 1943, Allegany Ballistics Laboratory has been used primarily for research, development, testing, and production of solid propellants and motors for ammunition, rockets, and armaments. The facility consists of two plants. Plant 1 occupies about 1,572 acres, most of which is in the floodplain of the North Branch Potomac River with the remaining acreage on forested, mountainous land. Site 1, the demonstration area, is located along the northern perimeter of Plant 1, adjacent to the North Branch Potomac River (Figure 5). Plant 1 is owned by the Navy and operated by Alliant Techsystems. Plant 2 consists of a 56-acre area adjacent to Plant 1 and is owned exclusively by Alliant Techsystems.

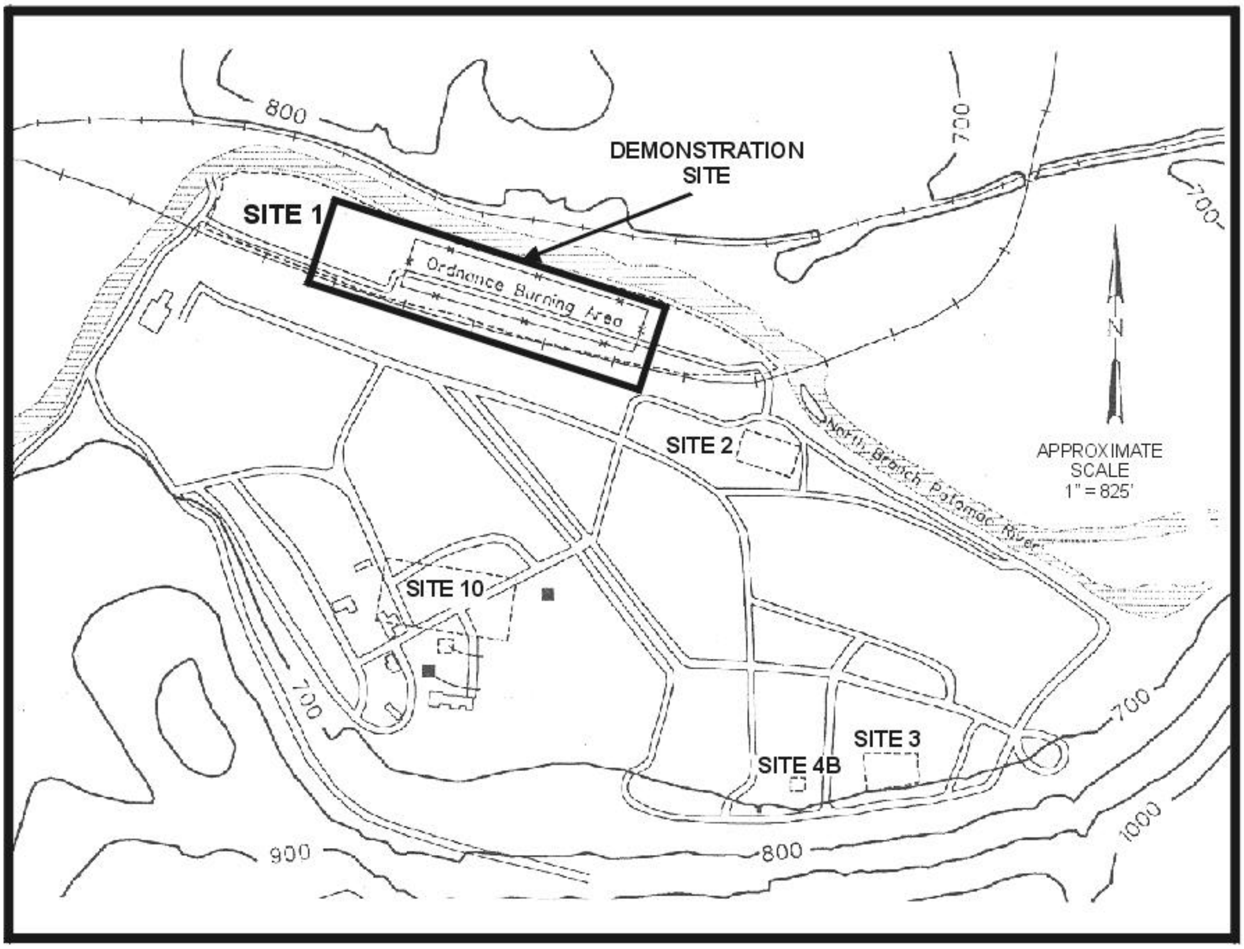

Figure 5. Location of Allegany Ballistics Laboratory. (Battelle, 1999)

Site-specific geology was documented during the well installations. The site is located on the flood plain of the North Branch Potomac River. The surface is underlain by 8 to 25 ft of silty clay and several feet of fill near the southern bank of the river. Beneath the silty clay is gravel, comprised of poorly sorted sand, pebbles, and cobbles within a matrix of clay and silt. The rock fragments are sandstone, quartzite, limestone, and shale. The thickness of the gravel varies between 6 to 24 ft, is generally saturated, and has been referred to as the alluvial aquifer. The river is the discharge source for groundwater flowing through the shallow alluvium.

3.6 DEMONSTRATION SITE/FACILITY CHARACTERISTICS

A brief description of the contamination and geologic characteristics for each site is presented below. More thorough descriptions of the four sites are presented in the Technology Demonstration Plans developed under this Delivery Order for each site (Battelle 1997b, c, and d; 1998a and b).

Letterkenny Army Depot. Structurally, Letterkenny Army Depot lies between the South Mountain Anticlinorium to the east and the Massanutten Synclinorium to the west. Deformation from folding and high-angle reverse faulting has occurred. Several major faults are present, which strike north to northeast and which dip to the southeast at steep angles as they traverse the demonstration area. The two faults which underlie Area K are the Pinola Fault and the Letterkenny Fault. The site contains a thin clay overburden overlaying dense miciritic limestone and dolomite. This setting lies within a known geologic fault. A significant amount of solution of bedrock also is present in the region, creating karstic features such as caverns and sinkholes.

In 1983, Roy F. Weston, Inc. completed four trenches and four soil borings to define Area K (Weston, 1984). Volatile organic compounds (VOCs) were detected in soil borings from depths of 6 to 22.5 ft. TCE was found at concentrations as high as 500 ppm; DCE was found at concentrations as high as 2,000 ppm. PCE and xylene also were detected at the high concentrations of 800 ppm and 700 ppm, respectively. Weston also conducted a soil-gas survey which indicated that total target VOC concentrations were above 100 ppmv within several areas. TCE was the most commonly detected VOC, at concentrations has high as 365 ppmv; trans-1,2-DCE was found as high as 500 ppmv. Concentrations of TCE, the most common chlorinated VOC in groundwater, have been as high as 114 ppm.

Considerable time and resources have been dedicated to characterizing this site during its remedial investigation. However, because secondary porosity (fractures and karst) serves as the predominant medium for groundwater flow and contaminant transport, it has been necessary to complete monitoring wells within these features to fully understand and effectively characterize this site. Successful well placement is hit-or-miss in this type of fracture-dominant setting. As a result, the nature and extent of contamination have not yet been completely determined. The lack of air photos and seismic images made it very difficult to locate fractures and to understand how contaminant migration is occurring within the existing fracture geometry. The fracture trace analysis and 3-D seismic imaging have contributed significantly to effective site characterization and further delineation of the nature and extent of contamination.

NAS Alameda. Alameda Island is located in one of the more seismically active portions of the Bay Area. It is located midway between the Hayward Fault to the east and the San Andreas Fault to the west. Most of NAS Alameda was built on artificial fill material dredged from San Francisco Bay, the Seaplane Lagoon, and the Oakland Channel. The fill is comprised mostly of silty sand to sand with clay and/or gravel, and contains wood, concrete, and metal. The fill is up to 40 ft thick in the western portion of the NAS, and thins to the east. It was placed hydraulically on Holocene Bay Mud in a submarine environment over a period of 75 years, beginning in 1900. About 400 to 500 ft of unconsolidated sediments overlie Franciscan bedrock, according to boring logs from water supply wells installed as early as the 1940s.

The plating shop was identified as an area of concern for this demonstration because of the high concentrations of VOCs in groundwater grab samples. Processes in the shop included degreasing caustic and acid etching metal stripping and cleaning and chrome, nickel, silver, cadmium, and copper plating.

The shop contains two paint bays and several paint spray shops. In addition to the plating shop within the building, two other areas outside of the building are of concern for this demonstration. The first area is to the east, near the flagpole, where an underground storage tank is located. This area is also where the highest level of VOC contamination has been found in wells.

Another possible area of concern may be the current location of the aboveground tanks, on the eastern side of the building but south of the flagpole. Historically, this was an area where wastes from the plating shop were temporarily disposed of or stored in a pit, which is believed to have been lined with concrete. These wastes were allowed to accumulate and were then siphoned off for disposal in portable tanks. It is likely that VOCs leaked into the groundwater from the pit. To date, no borings or wells have been drilled in this area. Information on solvent quantities at all three sources is lacking.

Tinker AFB. The rocks underlying Tinker AFB and the Oklahoma City area are Permian-aged. They are structurally underformed except for the block-faulted Nemaha Uplift and the related Oklahoma City Anticline. The Nemaha Uplift influences the structure in the area of Tinker AFB, extending 415 miles from Nebraska to Oklahoma. It is associated with the Mid Continent Geophysical Anomaly, which extends from Minnesota to central Kansas, and comprises an area that has a fairly high seismic risk classification.

Numerous compounds, including both VOCs and metals, have been detected in the groundwater. The major organic contaminant is TCE and its degradation products. For this study, TCE is the contaminant of concern. Free-phase DNAPL (i.e., TCE) may have seeped from the base of the pits downward until it became perched upon a low-permeability zone. Free-phase DNAPL may have also moved along joints and fractures that dip westward from below the pits under the building to the area west of the building.

The sources contributing to groundwater contamination beneath and adjacent to Building 3001 include the former solvent pits, industrial waste lines, improper tie-ins between storm sewers and wastewater lines, the North Tank Area, and Southwest Tanks. The former solvent pits within the northern end of Building 3001 are thought to be the main source of TCE contamination. At Pit E-105, high concentrations of TCE were detected in the soils beneath and adjacent to the pit. Well cluster 33, which was located just south of Pit E-105, has been plugged and abandoned. Some of the highest levels of TCE in groundwater under the northeast quadrant of the building were detected in well cluster 33. Because of this, the "footprint" of the seismic survey was placed to evaluate the area near Pit E-105, a likely source of TCE contamination. The area of the seismic footprint overlies some of the highest levels of TCE contamination in the groundwater at Tinker AFB.

Allegany Ballistics Laboratory. Allegany Ballistics Laboratory is located within the Valley and Ridge Province, which is a belt of severely folded and faulted-thrusted rocks that trends northeast to southwest, from New York to Alabama. This thrust zone is located in the Paleozoic Appalachian Basin, which extends westward to Ohio and eastward to the crystalline thrust sheets of the Piedmont

Physiographic Province. According to water-level measurements, a hydraulic connection exists between the alluvium and the fractured bedrock, and between the bedrock and the river.

Based on historical sampling data, TCE is the primary DNAPL contaminant of concern at Allegany Ballistics Laboratory Site 1. Potential sources of subsurface contamination include the burning ground for ordnance, three inactive waste disposal pits, and the former open burn area and landfill.

Potential conduits for the spread of DNAPL have been identified through the completion of a fracture trace analysis and a high-resolution, 3-D seismic survey. The conduits include fractures beneath the source areas, a gravel zone occurring above the bedrock, and fractures within the bedrock itself which conduct the DNAPL to potential sinks. The sinks may be either collection points (pools) or exit points where the DNAPL leaves the site (i.e., the north branch of the Potomac River or fractures in bedrock that allow the downward migration of the DNAPL).

4.0 PERFORMANCE ASSESSMENT

4.1 PROJECT RESULTS

The analytical results from samples collected from all 27 targets evaluated during the project are listed in Table 1 on page 18. For the three sites that underwent validation drilling and sampling, very few samples collected from target zones exhibited concentrations of DNAPL constituents in the part-per-million range, and only one sample exceeded the 110 ppm threshold level that implies the presence of TCE. This one sample was collected from the LB-6 test well at Letterkenny Army Depot. Also at Letterkenny, one sample collected from the LB-7 well measured almost 50 ppm, and two target samples collected at NAS Alameda contained concentrations at about 30 ppm. The samples from these four targets represent the highest concentrations of dissolved-phase constituents encountered in all seismic target intervals sampled.

At the LB-6 target, free-phase DNAPL was clearly present and visually identifiable during drilling and sampling. Concentrations from the remaining three targets were not high enough to imply that DNAPL was present and no DNAPL was observed at these seismic targets as the drilling and sampling progressed. Samples from the remaining 23 targets that were evalu-ated did not exhibit DNAPL concentrations that would imply the presence of free-phase contaminants. The seismic anomalies that were targeted at these relatively clean intervals are apparently the result of other geologic characteristics not related to contrasts in fluid properties (such as density and viscosity) resulting from the presence of free-phase DNAPL.

4.2 DATA ASSESSMENT

Although the results from this demonstration are relatively inconclusive with regard to the use of 3-D seismic methods for identifying anomalies caused by the presence of DNAPL, they suggest that the method can not be used to directly detect DNAPL source zones at these sites. Only one of the 27 tested anomalies (LB-6 at Letterkenny Army Depot) was found to contain DNAPL. A brief discussion of the results and limitations pertaining to the direct detection of DNAPL are summarized below. An extensive review of the drilling and sampling conducted at the target locations are detailed in the demonstration report by Battelle, 1999.

The Letterkenny Army Depot site possesses a typical, fractured bedrock-controlled geologic setting. The seismic technology was found to be successful at this site given that DNAPL was encountered in one of the four test borings drilled at the site. Prior to the validation drilling, more than 30 borings and monitoring wells had been drilled at Letterkenny Army Depot and none of them had encountered free-phase DNAPL. The anomaly at LB-6 did not possess characteristics that were unique and directly related to the presence of the DNAPL. Rather, the success at this anomaly (and at the Letterkenny Army Depot site in general) appeared to be the logical identification of prospective anomalies based on a good geologic conceptual model supported by fracture trace analysis. The success at the LB-6 anomaly appears to be a good demonstration of how the seismic method can contribute to the successful location of DNAPL sources. By identifying subsurface anomalies, the seismic method narrows the number of locations where drilling might be conducted to look for sources. However, the method was not necessarily successful at directly detecting the DNAPL based on anomalies cause by the contaminants. Therefore, false positives can be expected at sites consisting of fractured crystalline rock.

Table 1. Summary of Chemical Results.

Target Borehole ID	Maximum VOC Concentration Detected at Target Depth (ppm)	Target Confidence[a]	Predicted Target Reached	Presence of DNAPL in Target Validated
Letterkenny Army Depot				
LB-1	4270	Medium	No (actual depth several hundred ft higher)[b]	NA
LB-2	735	Medium	Yes	No
LB-5	389	Medium	Yes	No
LB-6	2,933,000	Medium	Yes	Yes
LB-7	49,900	Medium	No (very hard to test due to great depth)	NA
NAS Alameda[c]				
AB-1	ND	Medium	No (actual depth, 11 ft higher)[b]	No
AB-2	ND	High	No (actual depth, 4 ft higher)[b]	Strong no
AB-3	ND	Medium	Yes	No
AB-4	29,942	Medium	Yes	No
AB-5	320	Low	Yes	No
AB-6A	12	High	Yes	Strong no
AB-6B	ND	High	No (actual depth, 10 ft higher)[b]	No
AB-7	ND	High	No (actual depth, 13 ft higher)[b]	No
AB-8	300	High	No (actual depth, 2 ft higher)[b]	Strong no
AB-9	ND	High	No (actual depth, 1 ft higher)[b]	Strong no
AB-10	ND	Medium	Yes	No
AB-11	2,755	High	No (actual depth, 9 ft higher)[b]	No
AB-12A	1,147	Medium	Yes	No
AB-12B	ND	Medium	Yes	No
AB-13	14	Medium	No (actual depth, 6 ft higher)[b]	No
AB-14	29,485	Medium	Yes	No
AB-15	12,111	High	Yes	No
AB-16	27	High	Yes	Strong no
AB-17	ND	Medium	Yes	No
AB-18	ND	High	Yes	Strong no
Tinker AFB				
TB-3	230	Medium	Yes	No
TB-4	1,620	Medium	Yes	No
TB-6	56	Medium	Yes	No

[a] Interpreted/predicted likelihood that target contained DNAPL using the seismic survey method.
[b] Difference in feet between predicted target depth and actual depth above target to which a CPT or Geoprobe® screen was set to collect groundwater samples.
[c] At NAS Alameda it was not possible to run VSPs because the diameters of CPT and Geoprobe® holes are very narrow; therefore, it was not possible to confirm target depths or whether targets actually were reached.
ND = Not detected.

Field validation drilling and sampling efforts at Letterkenny Army Depot were initiated from December 15, 1997 through December 22, 1997 and were completed from January 22, 1998 through February 13, 1997. A total of five boreholes were drilled at Letterkenny Army Depot, each to evaluate a different target anomaly, as illustrated in Figure 6. The data indicates that the site is fractured vertically, which might suggest that DNAPL may exist at depth. The total depths of these boreholes ranged from 67 to 740 ft bgs. Groundwater samples were collected from various depths, usually in 20-ft increments, as each borehole was advanced.

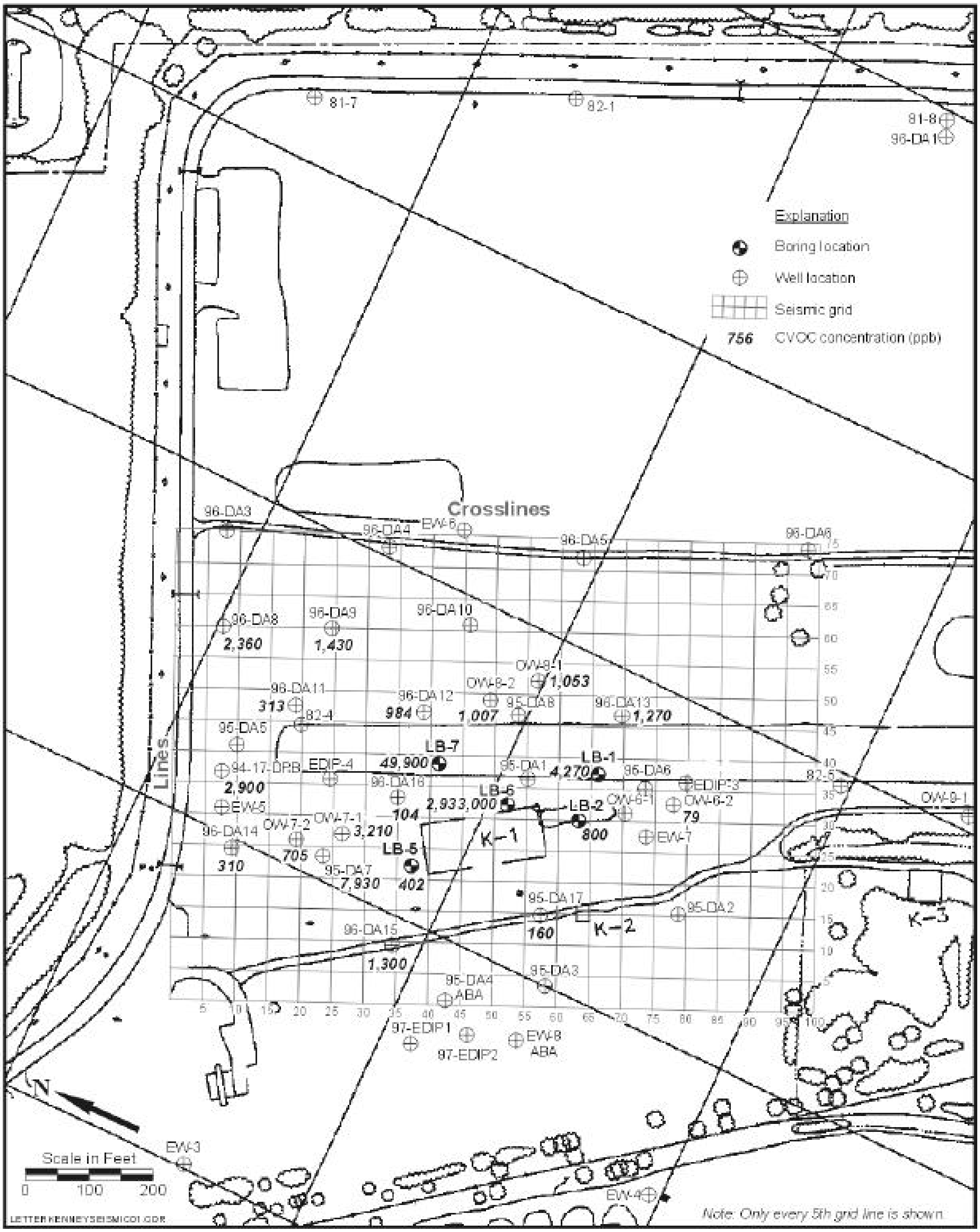

Figure 6. Location of Targets at Letterkenny Army Depot. (Battelle, 1999)

The seismic survey conducted at NAS Alameda Building 5 encom-passed three locations of concern, each with separate sources of contamination. Figure 7 is a map that illustrates the layout of locations and work that was performed in and around Building 5. The three locations were termed Areas A, B, and C during drilling and sampling. Area A consists of the underground storage tank located near the flag pole (identified as Source Area 2 in the Addendum to the Draft Attributes Analysis and Verification Plan for Naval Air Station Alameda [Battelle, 1998a]). Area B consists of the former liquid waste tank located east of Building 5 (identified as Source Area 3 in the Addendum [Battelle, 1998a]). Area C consists of the plating shop located inside the building (identified as Source Area 1 in the Addendum [Battelle, 1998a]). The validation effort was conducted during the week of March 9, 1998 and consisted of collecting 20 water samples from microwells installed at 20 target locations associated with seismic anomalies.

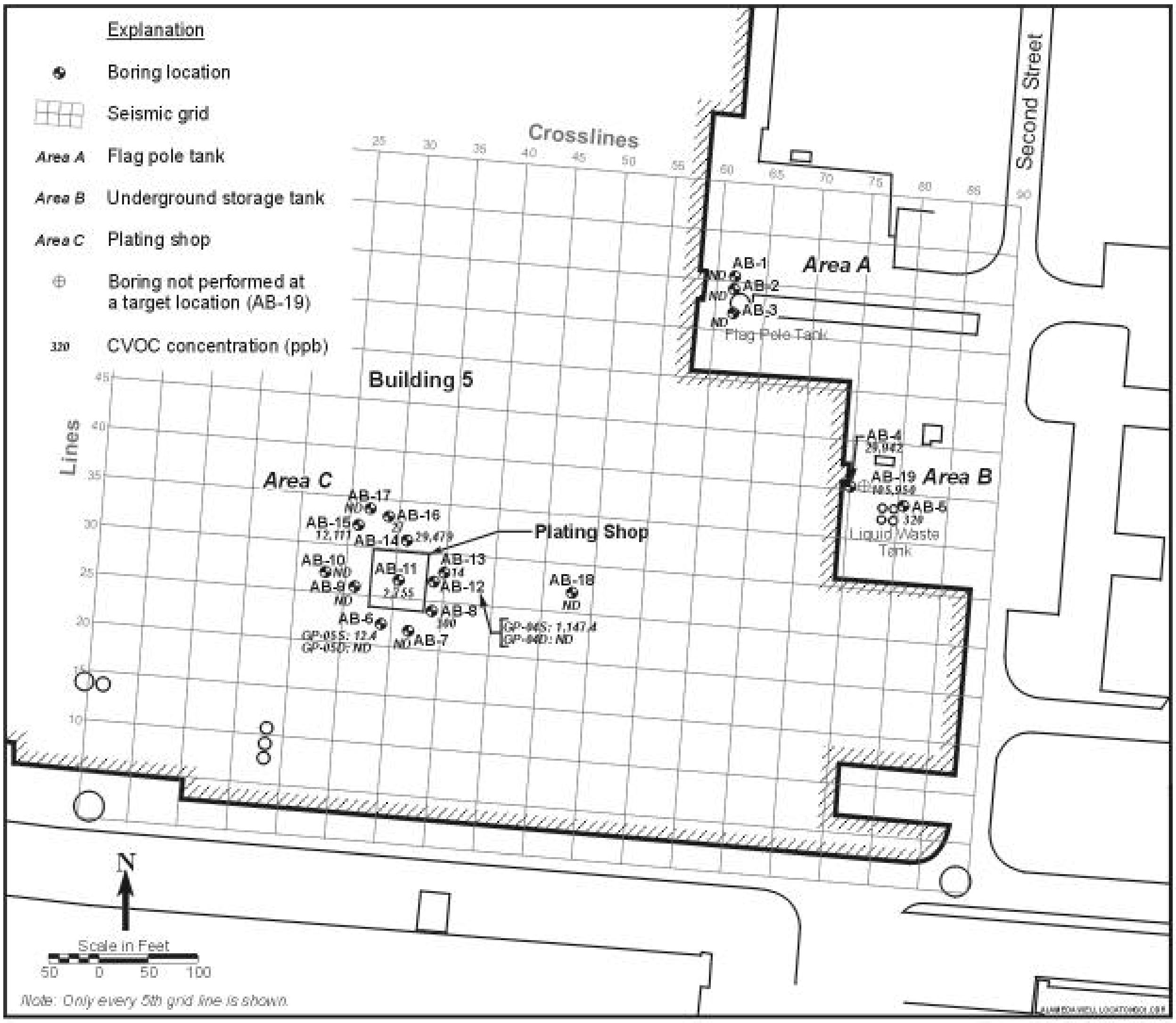

Figure 7. Location of Targets at NAS Alameda. (Battelle, 1999)

The three boreholes drilled for validation at Tinker AFB were located at targets TB-3, -4, and -6 (see Figure 8). Battelle drilled and evaluated the targets over the course of nine days in November 1998. All three targets were located immediately west of Building 3001, in the vicinity of and also downgradient from solvent pits within the building that are known to have released DNAPL to the subsurface and to groundwater. Although RRI strongly preferred to test several anomalies lying directly below the solvent pits within the building, it was not possible to drill within the building. Therefore, targets that are linked structurally to the area of the pits were selected instead. None of the groundwater retrieved from the target depths in the three borings were found to contain DNAPL levels exceeding single-digit ppb levels. However, groundwater collected from a shallower perched zone in the TT-3 boring was found to contain TCE at levels as high as 180 ppm, which exceeds the 110 ppb cutoff for assuming that DNAPL is present. Although an anomaly was present at this shallower depth on the seismic profile, the interval was not selected as a target by RRI because there was no fractures linking the interval to the source area beneath the solvent pits.

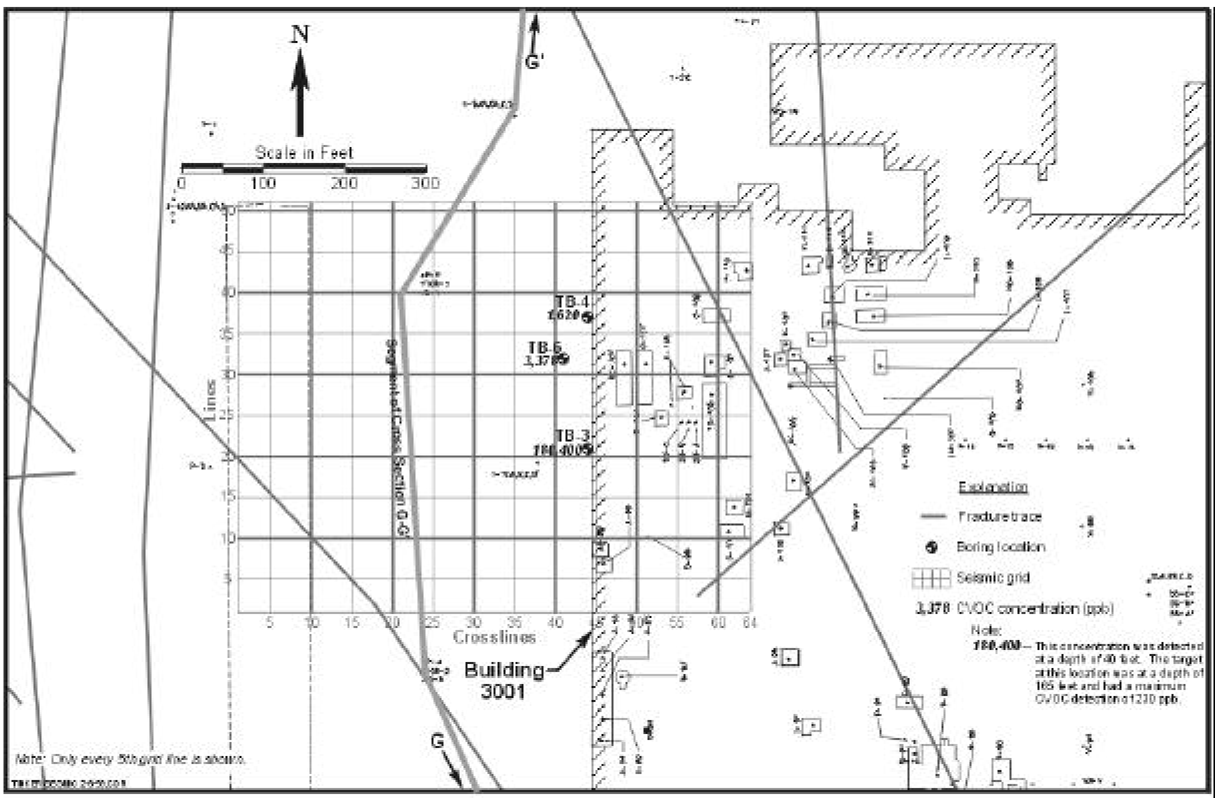

Figure 8. Location of Targets at Tinker AFB. (Battelle, 1999)

At NAS Alameda, the seismic technology was not successful at encountering DNAPL zones. Similarly, at Tinker AFB, the targets that were identified using seismic technology were not found to possess exceptionally high levels of contamination. In fact, at least one zone of very high contamination was encountered at a target location that was not specified as a DNAPL target. This result implies that many of the anomalies detectable using the seismic method are not related to the presence of DNAPL. Support for this stems from the recent (summer 1999) recovery of over 500 gallons of NAPL (mixed light and dense products) from the survey area at Alameda. Therefore, false negatives and false positives were encountered at these sites.

Although a number of test borings were drilled at each site to test as many of the targets as possi-ble, many of the best target locations were not sampled because they were located deep, beneath a confining layer, and/or below the source areas where push validation drilling was not possible due to physical and logistical constraints. The geologic model developed by RRI for each of the sites indicates that the sites contain vertical frac-tures, and that DNAPL migration is primarily vertical within these fractures beneath the sus-pected source zones. But, because of this sample access limitation, the fracture pathway hypothesis could not be fully tested. It is possible that the frequency of DNAPL detections would have been higher if drilling locations and targets had not been restricted to locations surrounding, but not within, the footprint of the source areas at Tinker and Alleghany Ballistics Laboratory. However, the Site Characterization and Analysis Penetrometer System (SCAPS) laser induced fluorescence (LIF) and GeoVis systems were used to verify the presence of DNAPL beneath a source at Alameda which was located within the domain of the 3-D seismic survey.

The second limitation of this technology evaluation is that the budget did not allow adequate for high enough sampling density to completely cover the target areas desired. This will potentially be a costly barrier to using this method, since confirmation samples are required.

The third limitation of this technology evaluation is that the seismic anomalies identified as a result of DNAPL may not be characterized by a unique response. That is, an anomaly caused by a fracture alone could resemble an anomaly caused by DNAPL or by DNAPL and the fracture. Because almost no DNAPL was discovered during this demonstration, it is difficult to evaluate if and to what extent the seismic technique is sensitive to the presence of DNAPL.

4.3 CONCLUSIONS

The results of this demonstration show, at this time, that 3-D seismic surveys are not effective at directly detecting DNAPL. Of the 27 total targets evaluated at Letterkenny Army Depot, NAS Alameda, and Tinker AFB, only one target was found to contain DNAPL and, therefore, the project did not meet the objective of detecting DNAPL at 90 % of the targets. The successful target was based on an anomaly in the seismic imagery that appeared indistinguishable from anomalies attributed to lithologic contrasts. The threshold concentration level used to positively determine the presence of DNAPL was 110 ppm. Overall, the four demonstration sites appeared to possess high enough levels and large enough plumes of dissolved-phase con-tam-ination to imply those free-phase DNAPL sources were likely to be present. At the site where DNAPL was clearly found, the seismic imagery could not clearly differentiate or delineate DNAPL zones from other subsurface characteristics that appear as anomalies on the seismic record.

This technology appears to be a very useful tool to image subsurface conditions for the purpose of site characterization and to help determine the most likely locations where DNAPL source zones may be present in the subsurface. As such, this technology may prove to be a highly effective source exploration tool, particularly in fracture bed-rock settings. During this demonstration, the interpretation of fractures and fracture geometry played the primary role in selecting targets. Greater emphasis on evaluating site stratigraphy and the identification of structural and/or stratigraphic traps might prove useful.

5.0 COST ASSESSMENT

The estimated survey costs per acre at Letterkenny Army Depot, NAS Alameda, and Tinker AFB are \$17,859/acre, \$13,939/acre, and \$25,700/acre, respectively. Typical surveys will likely include drilling and sampling to link the seismic data to observations in the field, and to confirm the presence of DNAPL within selected target anomalies. Differences in drilling and sampling costs from site to site are contingent upon the amount of pre-existing well control present at any given site and on local market conditions and rates. Costs associated with these activities are also dependent upon the number and depth of targets investigated. Work performed at Allegany Ballistics Laboratory was not included in this breakdown because the majority of work was performed outside of this project. Table 2 presents a breakdown of the cost of key activities related to the surveys and validation performed at three of the four demonstration sites.

Table 2. Cost Breakdown of Key Activities.

Activity	Letterkenny Army Depot (\$)	NAS Alameda (\$)	Tinker AFB (\$)	Average (\$)
Research and plan survey	15,709	12,834	15,871	14,804
Run survey and VSPs	53,200	71,655	44,920	56,591
Process and interpret data	21,938	25,415	11,082	19,478
Perform attribute analyses	16,241	15,682	15,900	15,941
Perform drilling and sampling	134,145	20,849	68,490	74,494
Perform laboratory analyses	45,050	20,400	22,100	29,183
Generate plans and reports	13,993	37,532	8,424	19,983
Total costs	300,276	204,367	186,787	230,476
Survey area (ft^2)	732,600	644,000	315,000	Ö
Estimated survey cost per ft^2	0.41	0.32	0.59	0.44
Estimated survey cost per acre	17,859	13,939	25,700	19,166

Note: Costs for ESTCP demonstration plans, meetings, project management and reporting, miscellaneous materials, and activities conducted at Allegany Ballistics Laboratory are not included in this summary.
Also note, 1 acre = 43,560 ft^2

The following details related to costs and activities for the work performed at the three demonstration sites is useful for planning any future seismic surveys:

- The setup configuration for each survey was the same for each of the three demonstration sites. Geophone spacing, line spacing, and source spacing all were set at 20 ft for all three sites. As shown in Table 2, the sites with the larger survey areas (Letterkenny Army Depot and NAS Alameda) benefited by spreading the setup costs over a larger area and thus had a lower cost per unit area surveyed than Tinker AFB.

- Drilling and sampling costs were strongly influenced by each site's geologic setting. Drilling and sampling costs at Letterkenny Army Depot (\$134,145) were much higher than at NAS Alameda (\$20,849) or Tinker AFB (\$68,490) because Letterkenny is situated in bedrock terrain, which is more costly to drill than other terrains. Furthermore, the depths drilled at Letterkenny were much greater than at the other two sites. Drilling costs at NAS Alameda were lowest because it was possible to use direct push methods at that site. Direct push methods are less expensive than conventional drilling methods.

- Analytical costs for the groundwater samples collected at Letterkenny Army Depot and NAS Alameda were controlled more by the rate at which the boreholes were advanced than by the number of samples that were collected and analyzed. An on-site laboratory, which charged a daily rate of $2,000, was used at these sites. The laboratory throughput capacity was greater than the rate at which samples could be collected and delivered for analysis.

6.0 IMPLEMENTATION ISSUES

The main benefit of applying 3-D seismic imaging to DNAPL remediation problems is the resulting likelihood of increased success in locating source areas, at least in certain types of geologic environments. The 3-D imagery can potentially contribute knowledge of the nature and extent of the DNAPL source through a better understanding of the DNAPL migration pathways. If successful, the lithologic data can also potentially assist with remediation system design.

This process of successfully and efficiently locating extraction wells to extract DNAPL and to eliminate a dissolved-phase groundwater plume also rests on the development of an accurate site model, an iterative process that uses all available data, including 3-D survey data, as well as conventional and often existing data. The 3-D seismic survey is enhanced by the quality of data obtained about the regional geology and geologic history, general information on hydrostratigraphy and structure, information on the site history and industrial practices that may have resulted in the release of contamination, results from borehole drilling and sampling, water levels, hydro-geologic tests, and trends in sample analyses and soil gas surveys. All data except for 3-D seismic survey data typically is gathered during a remedial investigation.

6.1 COST OBSERVATIONS

The cost of a 3-D survey depends on a number of factors including: the size of the source area, the size and depth of the area of concern, the resolution required to accurately image the target, the type of seismic source (energy input) required to image the target, the surface conditions at the site (geologic and cultural), the degree of access allowed in and around the site, and the ease with which water and soil sample collection can be achieved. The amount of pre-existing information on the site and the accessibility of that information also impact the cost of a survey. Surveys investigating shallower features require a more closely spaced sensor array and are therefore more expensive to process than surveys targeting deeper features. In addition, the cost of processing the seismic data increases as the resolution required for the survey is increased.

6.2 REGULATORY ISSUES

While the use of 3-D seismic techniques has been commonly accepted by regulators as a tool for locating potential contaminant migration pathways, it has not been used for the direct detection of DNAPL source areas. To date, the 3-D seismic imaging has not yet been successfully validated as a direct DNAPL source zone detection method. The California EPA Department of Toxic Substances Control regulators have accepted the use of 3-D seismic imaging at a number of sites for migration pathway analysis. For example, the California EPA has had five surveys performed at the Stringfellow National Priorities List site near Riverside, CA. The California EPA Regional Water Quality Control Board permitted Unisys to remove 47 recovery wells, and replace them with three monitoring wells at Westlake Village, CA, based on a 3-D seismic survey which determined the most likely locations for DNAPL source zone migration. In general, the detailed imagery provided by the 3-D seismic technique used for determining the most likely locations for DNAPL source zone migration has met with favorable regulatory review in several other states, including Nebraska, New York, and Tennessee.

6.3 LESSONS LEARNED

Several lessons were learned during this technology demonstration.

- The one target found to contain DNAPL was based on an anomaly in the seismic imagery that appeared indistinguishable from other stratigraphic anomalies. Therefore, it may not be possible to distinguish DNAPL from a more fractured area.

- Confirmation drilling and sampling costs can outweigh the surface geophysical data collection costs.

- At some sites, it may not be possible to access optimal drilling locations for VSP generation due to physical and logistical constraints.

- During this demonstration, the interpretation of fractures and fracture geometry played the primary role in selecting targets. Greater emphasis on evaluating site stratigraphy and the identification of structural and/or stratigraphic traps might prove useful.

- Based on the results from this project, any further research should focus on evaluating the seismic technique under more controlled conditions. For example, a bench scale evaluation might prove beneficial. A demonstration might also be beneficial at a site where the presence of a large known DNAPL source has been clearly established and precisely defined. Unless pooled by some geologic feature, the overall density contrast posed by DNAPL distribution may be imperceptible by the seismic technique. A detailed study should determine whether seismic can directly detect DNAPL source zones confined to configurations such as residual ganglia, microglobules, and narrow elongated distributions rendering low DNAPL saturation values. For low DNAPL saturation, which may be very common, it must be demonstrated that density contrasts can be identified using this method before it can be used on a wide basis for direct DNAPL detection.

- The technique has a higher potential for success at sites with geologic features dominated by fractures, especially fractured crystalline rock and karst topography. This is due to the observation that fractures which can serve as DNAPL contaminant pathways are more easily detected by the seismic technique in these settings.

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APPENDIX A

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