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HIGH-RESOLUTION SEISMIC REFLECTION TO LOCATE DNAPL SOURCE ZONES AT HAZARDOUS WASTE SITES

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Acronyms and Abbreviations

2-D	two-dimensional
3-D	three-dimensional
AFB	Air Force Base
bgs	below ground service
CA	chloroethane
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CMP	common midpoint
CPT	cone penetrometer test
CVOC	chlorinated volatile organic compound
DCA	dichloroethane
DCE	dichloroethene
DNAPL	dense, nonaqueous-phase liquid
DOD	United States Department of Defense
EPA	United States Environmental Protection Agency
ESE	Environmental Science and Engineering, Inc.
ESTCP	Environmental Security Technology Certification Program
GC/MS	gas chromatograph/mass spectrometer
GP	Geoprobe®-installed microwell
gpm	gallon(s) per minute
LNAPL	light, nonaqueous-phase liquid
LSZ	lower saturated zone
ms	milliseconds
msl	mean sea level
NA	not applicable/not available
NAPL	nonaqueous-phase liquid
NAS	Naval Air Station
NASNI	Naval Air Station North Island
ND	not detected / not determined
NFESC	Naval Facilities Engineering Service Center
NMO	normal moveout

PCE	tetrachloroethene (perchloroethene)
PID	photoionization detector
ppb	parts per billion
ppm(v)	parts per million (by volume)
PRC	PRC Environmental Management, Inc.
RPM	Remedial Project Manager
RRI	Resolution Resources, Inc.
SCAPS	Site Characterization and Analysis Penetrometer System
SEG Y	Society of Exploration Geophysicists Format Y
TB	test boring
TCA	tricholorethane
TCE	trichloroethene
USZ	upper saturated zone
VC	vinyl chloride
VOA	volatile organic analysis
VOC	volatile organic compound
VSP	vertical seismic profile

Executive Summary

High-resolution, three-dimensional (3-D) seismic surveys were conducted and evaluated at four U.S. Department of Defense (DOD) installations to determine if the seismic reflection survey technique could be used to rapidly and effectively perform high-resolution site characterization and dense, nonaqueous-phase liquid (DNAPL) source detection and delineation. The four sites selected were Letterkenny Army Depot near Chambersburg, Pennsylvania; Alameda Naval Air Station, Alameda, California; Tinker Air Force Base, Oklahoma City, Oklahoma; and Allegany Ballistics Laboratory, Mineral County, West Virginia. The sites were selected based on sampling data that indicated the presence of DNAPL in the subsurface of each site. These sites are considered to be typical DOD sites possessing high levels of DNAPL contamination. They are also sites that have typical limitations with respect to drilling restrictions and with respect to the degree of uncertainty for where free-phase DNAPL currently occurs in the subsurface.

The steps involved in the high-resolution, 3-D seismic survey analyses performed at these sites consisted of site research and the generation of a conceptual geologic model that included the results of fracture trace analyses. First, vertical seismic profiles (VSPs) were collected; VSPs consist of down-hole field measurements of seismic wave velocities through a site's bedrock and soil strata. VSP data are used to help process the seismic survey data and to define the depth to a geologic horizon or other features of interest across the survey area. Then the 3-D seismic surveys were performed and the survey data were processed and interpreted. Data interpretation consisted of correlating the seismic data with the geologic model for each site to predict the depths of stratigraphic features (such as the top of bedrock) or to identify and locate fracture zones. Attributes within the seismic data also were evaluated to predict locations where DNAPL might occur in each subsurface. Validation drilling was performed to determine if geologic and DNAPL predictions were accurate. Most if not all applications of this technology require drilling and sampling to ground-truth all predictions, because all geophysically based subsurface predictions carry uncertainty.

Correlation of the seismic data with the geologic model for each site led to the identification of fracture and lineament traces beneath or associated with suspected contaminant source zones. Attribute analyses performed on the seismic data were focused on these areas and were used to identify anomalies in the data thought to represent DNAPL. Based on the geologic model for each site, vertical fractures or faults were believed to represent primary migration pathways for DNAPL. Therefore, anomalies beneath suspected source zones were assigned the highest probability of encountering DNAPL. Anomalies identified in fractures or other preferential pathways connected to the source but located laterally adjacent to the source, were assigned a moderate to low probability of encountering DNAPL.

A number of data anomalies were selected as targets for evaluation by conventional drilling and sampling techniques. Groundwater samples were collected and analyzed for the presence of volatile organic compounds (VOCs). DNAPL was considered to be present in the groundwater at a site if the solubility of a groundwater sample met or exceeded 10% of the solubility limit for any DNAPL constituent thought to be present. Predicted depths to stratigraphic features were compared to plus or minus 10% of the observed depth of the features.

The results of the drilling and sampling evaluation of targets indicated that the high-resolution, 3-D seismic surveys could not detect DNAPL contamination of any magnitude existing at these sites. Of the total of 27 targets evaluated for the presence of DNAPL, only one was found to contain DNAPL. More DNAPL-bearing targets may have been encountered had not logistical constraints prevented the testing of anomalies lying directly beneath the source zones. Anomalies beneath the source zones were thought to be more likely to contain DNAPL based on interpreted pathways and perceived migration routes, but in the processed seismic imagery, these anomalies were visually indistinguishable from other anomalies that did not lie beneath the source zones or spill areas.

The one target proven to contain DNAPL was the target at the LB6 location at Letterkenny Army Depot. At that location, DNAPL was encountered at the predicted depth, which, based on both the seismic data and drilling, was likely to be a fracture zone. None of the other targets at any of the three sites where validation drilling was conducted encountered DNAPL at the predicted target locations.

As expected, the seismic-based stratigraphic predictions (e.g., top of bedrock, presence of fracture zones, and depth to fracture zones) agreed more closely with observations made during drilling and sampling. However, during the (intrusive) verification sampling and analysis, DNAPLs were detected at only one of the locations where they were predicted to be present. During the attribute analysis, because of a lack of clearly unique DNAPL target anomalies, verification targets were selected based primarily on fracture locations and orientations linked to known or assumed DNAPL release points. Based on the results of this demonstration, it seems doubtful, given the types of conditions that DNAPLs are thought to typically accumulate and reside in the subsurface (e.g., in small, scattered pools and ganglia), whether this seismic method can distinguish between aqueous media and the DNAPLs and/or their dissolved-phase constituents.

Draft Final Report

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

Battelle Columbus Operations
and
Resolution Resources, Inc. (RRI)

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1. Introduction

This report describes the demonstration of the three-dimensional (3-D) seismic reflection survey technique to generate high-resolution, 3-D imaging of subsurface geologic, subsurface hydrogeologic, and subsurface contaminant source features at four selected United States Department of Defense (DOD) sites. The technique is designed to support the detailed characterization of DOD contaminated sites, particularly those impacted with dense, nonaqueous-phase liquids (DNAPLs).

The objective of this project is to verify that 3-D seismic reflection surveying is a viable method for rapidly and effectively performing DNAPL source delineation and high-resolution site characterization. Geophysical surveys could make it possible to more directly remediate source zones rather than contain and/or treat the dissolved-phase plumes that originate from these contaminant sources. This project was funded by the Environmental Security Technology Certification Program (ESTCP) at the Naval Facilities Engineering Service Center (NFESC) under Contract No. N47408-95-D-0730.

1.1 Background Information

Because of their physical properties, DNAPLs present unique challenges to site characterization and remediation. The high specific gravity and low viscosity of DNAPLs permit movement down through the water table; along preferential pathways such as faults, bedding planes, and sand channels; and through relatively higher zones of permeability in complex, porous geologic materials.

Typically, most of the contaminant mass at a DNAPL site is centered in the source zone. Unless the contaminant mass is removed from the source zone, permanent aquifer restoration to drinking water standards cannot be achieved in the near term. Heterogeneities in geology and DNAPL distribution can severely limit the performance of source zone remediation technologies. It is not possible to use conventional methods (such as drilling and sampling) to accurately characterize the heterogeneities through which DNAPL may migrate. Also, available contaminant remediation methods, such as pump-and-treat and cutoff-wall enclosures, are used for source zone containment, which often has higher long-term costs than contaminant removal technologies. In many instances, it can take several decades or longer to remove a plume (Pankow & Cherry, 1996).

1.2 Official DOD Requirement Statements

This work supports the following Navy Tri-Service Environmental Quality user requirement:

1.III.2.a Remote Sensing for Site Characterization and Monitoring

In addition to this broad requirement, Table 1 provides relevant Environment Safety and Occupational Health (ESOH) needs of DOD as specified by the Environmental Security Technology Requirements Group (ESTRG). These needs were identified by searching the FY97 DOD Environmental Technology Requirements Strategy website, available at http://xre22.brooks.af.mil/estrg/estrgPwdPage.htm.

1.3 Objectives and Scope of the Demonstration

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 as indicating the presence of free-phase DNAPL was set at 10% of the solubility of any potential DNAPL constituent. For

Table 1. Relevant ESOH Needs of DOD as Specified by ESTRG

Organization	Applicability	Identification Number	Description
		Army Needs	
Army-wide	Direct	A(1.1.k)	Develop Innovative Alternative (and Non-Invasive) Techniques for Subsurface Characterization (96-97)
		A(4.2.a)	Land Capability/Characterization
		Navy Needs	
Navy-wide	Direct	(1.III.1.k)	Improved field analytical sensors, toxicity assays, methods, and protocols to supplement traditional sampling and laboratory analysis
		(2.II.2.b)	Improved field analytical sensors, toxicity assays, methods, and protocols to supplement traditional sampling and laboratory analysis
	Related	(1.I.1.g)	Improved remediation of groundwater contaminated with chlorinated hydrocarbons and other organics
		Air Force Needs	
Air Force Flight Test Center	Related	1611	Treatment of Chlorinated Hydrocarbons
Arnold Engineering Development Center	Direct	701	In Situ Treatment for Dense, Nonaqueous-Phase Liquids
Odgen Air Logistics Center	Direct	246	New Technology to Identify and Quantify Chlorinated Organic Compound Concentrations for Installation Restoration Program Site Investigation/Remediation Monitoring
	Related	255	Improve Understanding of DNAPL Groundwater Transport to Accurately Predict Fate of Contaminants
		271	Fate and Transport of Chlorinated Solvent Plumes in Vadose Zone
		281	Hazardous Waste Treatment Technologies for Installation Restoration Program Site Remediation of the Plumes of Chlorinated Organic Compounds
Oklahoma City Air Logistics Center	Direct	130	Effective DNAPL Characterization, Monitoring, and Detection Technology
Sacramento Air Logistics Center	Direct	570	Improve Understanding of DNAPL Groundwater Transport to Accurately Predict Fate of Contaminants
	Related	557	Fate and Transport of Chlorinated Solvent Plumes in Vadose Zone
San Antonio Air Logistics Center	Related	641	Fate and Transport of Chlorinated Solvent Plumes in Vadose Zone

example, trichloroethene (TCE) has a solubility in groundwater of 1,100 parts per million (ppm), so the target was considered to contain free-phase DNAPL if 110 ppm was detected in groundwater samples collected from a target location. All four sites evaluated during this demonstration previously were found to contain levels of dissolved DNAPL 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.

The work was accomplished by performing 3-D seismic surveys at four sites suspected of having free-phase DNAPL in the subsurface (Table 2). The data collected and processed from the seismic surveys were used for the primary objective of generating predictions for subsurface contamination by identifying specific DNAPL target locations and depths. To meet the secondary objective of performing high-resolution site characterization, the data was also interpreted to predict depths to stratigraphic features.

Table 2. Demonstration Site Locations

DOD Installations	Sites
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

NAS = Naval Air Station.
AFB = Air Force Base.

DNAPL target locations were validated by drilling with an air rotary drilling rig down to the actual target depth and then collecting groundwater samples. The groundwater samples were analyzed by a certified environmental laboratory to determine if DNAPL was present at the 10% solubility limit.

These sites were selected because they possessed well-documented DNAPL contamination, while each site resides in a distinctly different geologic setting. 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 validated.

1.4 Regulatory Issues

Many sites at DOD installations are listed under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). These DOD installations are engaged in active

Installation Restoration Programs. Remedial Investigations are an integral element of the CERCLA process. A main objective of any Remedial Investigation is to determine the nature and extent of contamination at waste sites so that an effective remedial design can be implemented. High-resolution, 3-D seismic imaging supports these efforts by providing information on site geology. For example, the imaging can be used to help define the thickness of unconsolidated overburden or depth to bedrock. Imaging also can be used to determine the geometry (thickness, inclination, lateral extent, and degree and distribution of fracturing) of hydrostratigraphic units at a site. These capabilities of seismic imaging make it possible to identify the pathways that contaminants may have taken from their point of release to their points of exposure.

DNAPLs are a common contaminant type at many CERCLA sites. Because the physical properties of DNAPL may contrast with those of soils, rocks, and groundwater, high-resolution 3-D seismic imaging may be useful in directly detecting and delineating free-phase DNAPL.

1.5 Previous Testing of High-Resolution, 3-D Seismic Surveying

This demonstration was motivated by the result of two-dimensional (2-D) and 3-D seismic data collection by Resolution Resources, Inc. in 1994 during an investigation at Site 9, Naval Air Station North Island (NASNI), in San Diego, California. The work was performed under a Comprehensive Long-Term Environmental Action Navy contract and under the auspices of the Naval Environmental Leadership Program. 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 (121.1 million liters) 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 are believed to be the result of a known DNAPL presence. The accurate and detailed seismic image of the site significantly changed the previous site model.

Seismic profiles north of the source at NASNI were contrasted with profiles over the "fiery marsh" disposal area. An order of magnitude difference in the amplitude data was noted between the data collected over the source area versus data from the area to the north of the source area. The difference was attributed to the modification of the seismic signal by the presence of microscopic and macroscopic globules of DNAPL believed to be suspended in the pore space within a large tensional fault. There was no change in geology above and below the source that could account for the differences. In addition, vertical seismic profiles (VSPs) were performed in an upgradient clean well and in a highly contaminated well within the source area. The VSP data from the well in the source area showed modified amplitude and frequency effects when compared with the results in the upgradient well. Three borings that confirmed the seismic interpretation were later drilled at the site. DNAPL was not pooled on a confining layer as originally thought, but was isolated within a large tensional-faulted zone.

The 3-D seismic survey performed at NASNI showed that seismic imaging can delineate complicated structure and stratigraphy, a task which is essential in understanding contaminant migration pathways; and that seismic imaging may be able to detect the presence of DNAPL.

This work at NASNI was the first field evidence which suggested that DNAPL compounds attenuated the seismic signal. However, bench-scale studies such as those done by Wang and Nur (1990) and Geller and Myer (1994) have shown that seismic amplitudes are sensitive to concentrations of nonaqueous-phase liquids (NAPLs). These studies also represent a step toward the application of seismic measurements to NAPL detection in the field.

Investigations performed at the Savannah River Site in Columbia, South Carolina (Waddell and Temples, 1997) also indicated that, under certain conditions, free-phase DNAPL can be imaged using high-resolution seismic reflection. The Savannah River work compared actual field data to synthetic seismograms.

1.6 Report Organization

This report has been organized to follow as clearly as possibly the ESTCP final report guidelines for funded projects. Section 2 provides a description of the technology. Section 3 provides a description of each site where the 3-D seismic surveys were completed. Section 4 presents the overall demonstration approach and includes the results from the 3-D seismic surveys in the form of predictions for field verification sampling. Section 5 presents the results of the field verification efforts at each site in the form of a performance assessment and also includes a brief discussion on lessons learned and recommendations for further investigation. Section 6 presents a brief cost assessment. Section 7 presents the conclusions and Section 8 includes references cited. Appendix A lists the points of contact pertinent to this project. Appendix B summarizes information on data archiving procedures and on the demonstration plans. Appendix C is a table coordinating original validation borehole designators with the new and more consistent designators used throughout this report. Appendices D, E, and F present summary tables for chemical analyses, the borings logs, and the analytical laboratory reports, respectively, generated during the field verification efforts.

2. Technology Description

2.1 Description

Geophysical exploration is a 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.

2.1.1 Application and Evolution of Seismic Reflection Surveying. Since the 1930s, seismic reflection surveys have been performed in oil exploration to delineate subsurface structure. The early surveys (2-D, single-fold, continuous coverage profiling) provided large-scale structural information about the subsurface, but forced oil exploration teams to drill without a completely accurate image of the reservoir (much as is done in environmental engineering today). As the use of seismic surveys became more accepted and as funds were available for research, the technique evolved until it became an effective way to view and interpret large-scale subsurface geologic structural features (Bengstson, 1982). The advent of the 2-D, multi-fold, and common depth point surveying techniques, along with advances in instrumentation, computing power, and data processing techniques, greatly increased the resolution of seismic data and the accuracy of the subsurface images. However, the technique still yielded little information about the physical properties of the imaged rocks, or the pore fluids within them (Savit and Wu, 1982).

It was not until the introduction of 3-D reflection surveying in the 1980s that seismic images began to resolve the detailed subsurface structural and stratigraphic conditions that were missing or not discernable from previous types of data. Today, potential oil reservoirs are imaged in three dimensions, which allow seismic interpreters to view the data in cross sections along 360 degrees of azimuth, in depth slices parallel to the ground surface, and along planes that cut arbitrarily through the data volume. Information such as faulting and fracturing, bedding plane direction, the presence of pore fluids, complex geologic structure, and detailed stratigraphy are now commonly interpreted from 3-D seismic data sets.

In the environmental engineering industry, 2-D shallow seismic reflection imaging has been performed to map the overburden-bedrock interface at test sites since the 1970s (Hunter et al., 1989). In recent years, seismic reflection profiling has been applied to other geotechnical and environmental problems as well (Steeples and Miller, 1990). It was not until 1994, however, that the first high-resolution, 3-D seismic reflection survey was performed at a hazardous waste site (RRI, 1995). Since that time, thirty 3-D seismic surveys have been performed for environmental investigations.

2.1.2 Overview of Seismic Reflection Surveys. In a seismic reflection survey, acoustic energy is imparted into the earth with a seismic source. For this specific investigation, the ground surface was impacted with a sledgehammer or power-assisted weight drop to create the acoustic energy. 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 result, seismic reflections make it possible to map the stratigraphy below a site.

Areas of structural deformation such as faults and fractures also are sources 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 wavefronts propagate through the earth mechanically, as one particle moves and compresses the next particle. Section A of Figure 2 shows the wavefront of sound waves impinging on a geophone. 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 (section B of Figure 2). 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 (section C of Figure 2). The data in this investigation were digitized to 21-bit resolution, which means the analog geophone signal was broken into 2^{21}, or 2,097,152, levels. Data interpreters analyze the final processed wavelet (section D of Figure 2), which is the result of the post-survey data reduction process. These wavelets act as high-resolution, distortion-free representations of the subsurface.

2.1.2.1 3-D Seismic Surveys. Because 2-D data collection occurs along a line of receivers, the resultant image represents only a thin vertical plane below the receiver line. Unfortunately, this method does not always produce realistic interpretations of the geology. Seismic waves travel along expanding spherical wavefronts and therefore have surface area. A

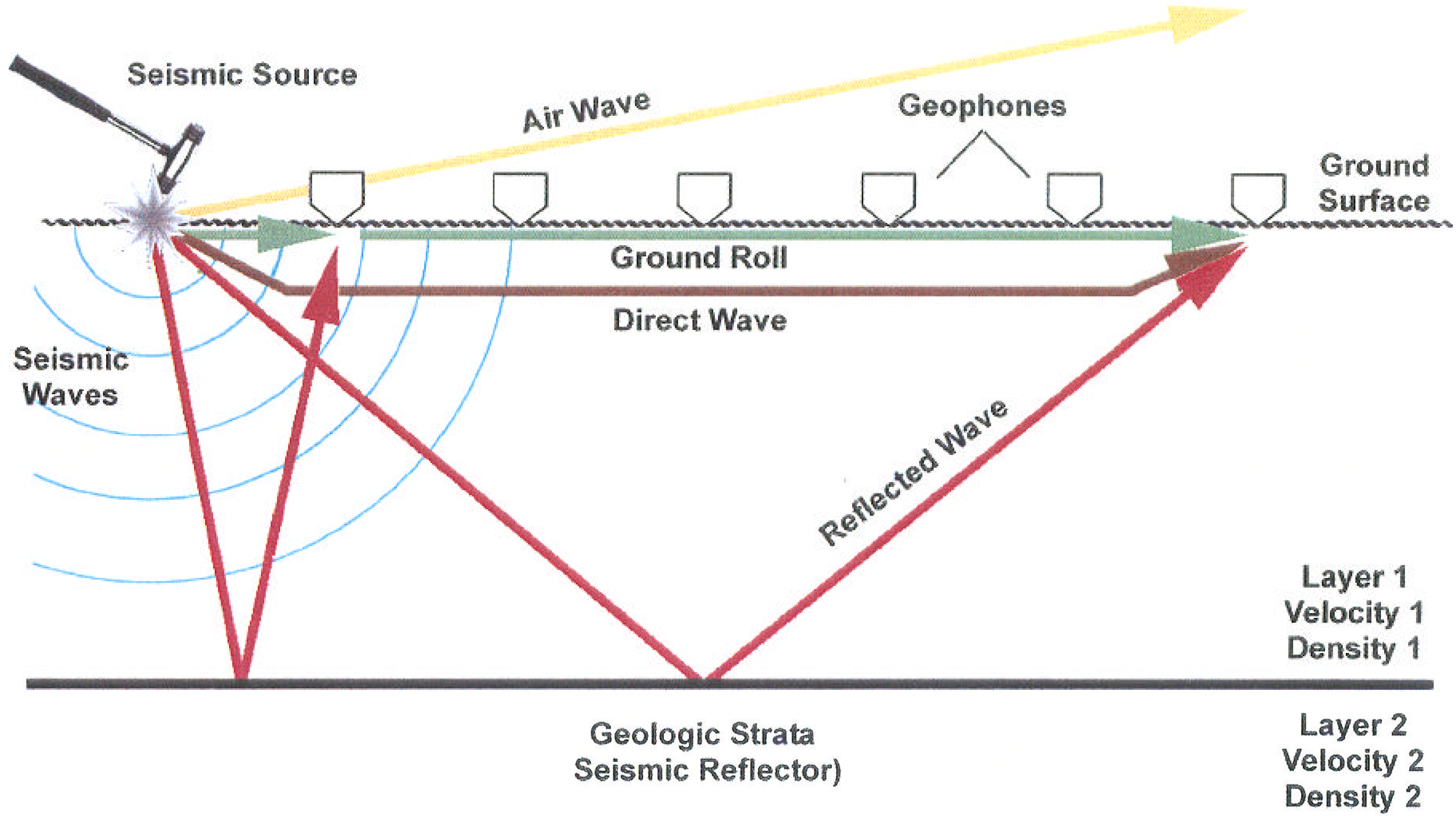

Figure 1. Seismic Reflection Surveying

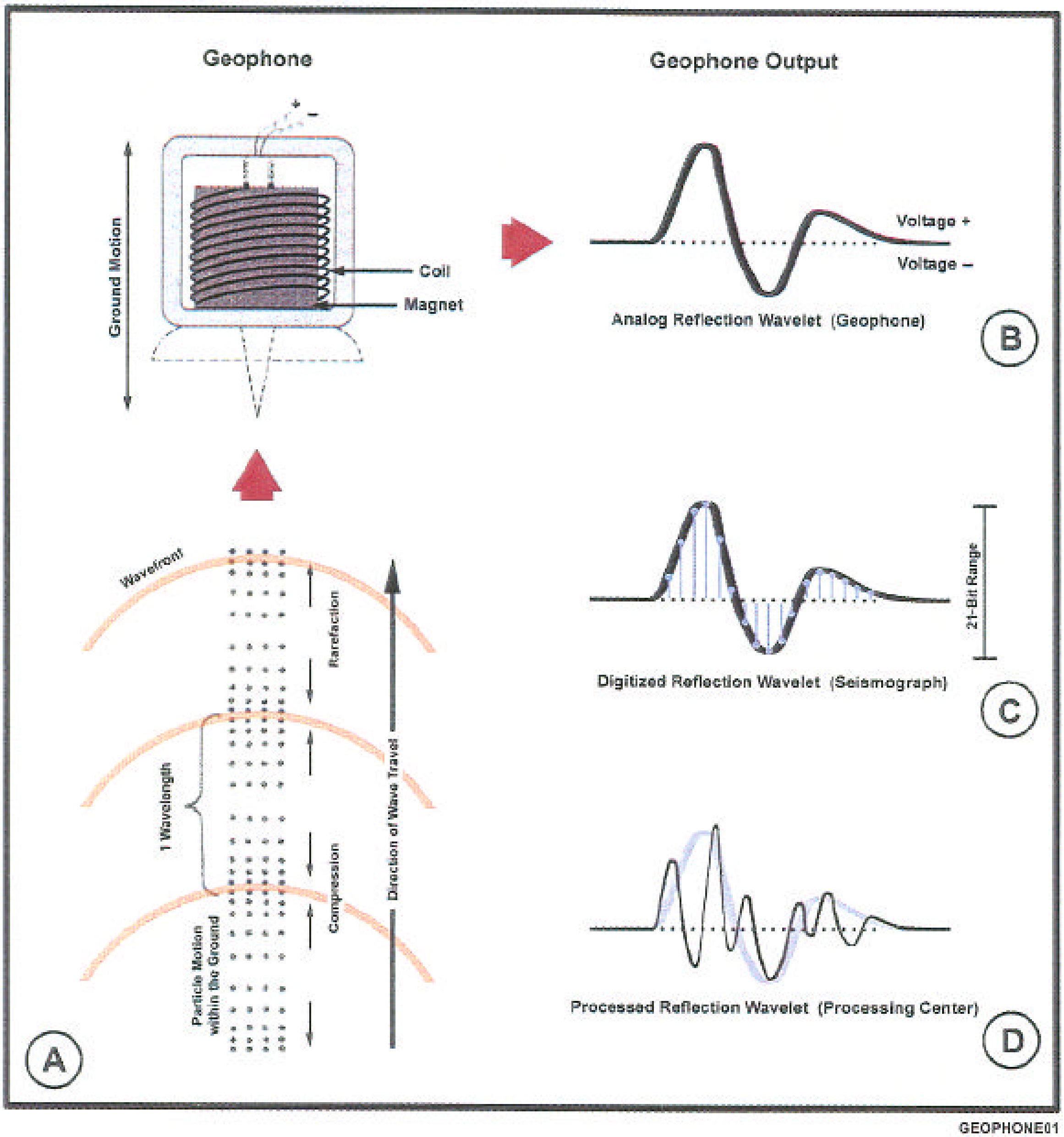

Figure 2. Compressional Waves, Geophone Schematic, and Seismic Waveforms

representative image of the subsurface is only obtained when the entire wave field is sampled. A 3-D seismic survey is more capable than a 2-D survey of accurately imaging reflected waves because it utilizes 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 was sampled from a range of different angles (azimuth) and distances (offset), as shown schematically in Figure 3.

Because oil reservoir exploration is a spatial, 3-D problem, 3-D seismic data collection, processing, and imaging has been advanced by all major oil companies. Locating and defining potential DNAPL accumulations presents a similar 3-D problem, although DNAPL targets are much smaller in size and are located at much shallower depths than are oil reservoirs.

2.1.2.2 Resolution Issues. The resolution of seismic data refers to the size at which a geologic feature is imaged: the higher the resolution, the smaller the feature. According to Hunter et al. (1989), structural resolution may be one meter where optimum conditions exist (including a fine-grained or saturated overburden allowing recorded frequencies of 300 to 500 hertz). In other words, at an arbitrary depth of 100 feet, it is possible to delineate features of a few feet or less in size. The use of 3-D seismic surveys makes possible the acquisition of such high-resolution data.

At many sites it is possible to characterize rather small subsurface changes in geology through the use of 3-D seismic surveys. DNAPLs are known to migrate through and accumulate in sand channels or fractures and faults, as opposed to less-porous competent bedrock. Therefore, maximizing the horizontal resolution of the seismic data is paramount to accurately imaging these laterally limited areas of preferred contaminant transport. Horizontal resolution of the seismic data is bounded by the Fresnel zone of seismic waves. The Fresnel zone is the total surface area on a reflector (e.g., a stratigraphic layer) from which the reflection energy recorded during a seismic survey could potentially have originated. A reflector with a surface area that is smaller in size than the Fresnel zone cannot be resolved.

Because the sizes of Fresnel zones increase with depth and decrease with the frequency of the seismic waves, the 3-D surveys in this investigation were designed to produce the highest frequency of reflected waves at the depths of interest. This approach minimized the size of the Fresnel zones, and increased the lateral resolution of the subsurface image. In addition, a data processing function called 3-D migration was used to further reduce the size of Fresnel zones. 3-D migration focuses the energy spread over the seismic Fresnel zone and collapses diffraction patterns caused by points and edges (such as fractures and faults), a process which can dramatically improve the horizontal resolution of 3-D seismic data. Figure 4 is taken from Brown (1996), and illustrates how the size of a hypothetical Fresnel zone of a 100-hertz reflection, from 0.100 seconds at a velocity of 5,000 ft/second, is reduced by 2-D and 3-D migration techniques. Note that the pre-migration Fresnel zone is quite large, and encompasses a circular area with a diameter of about 160 feet. 2-D migration reduces the area to an ellipse, with a major axis perpendicular to the 2-D survey line. A seismic image from the center of the diagram would include all data from within the yellow zone, not just below the survey line. However, 3-D

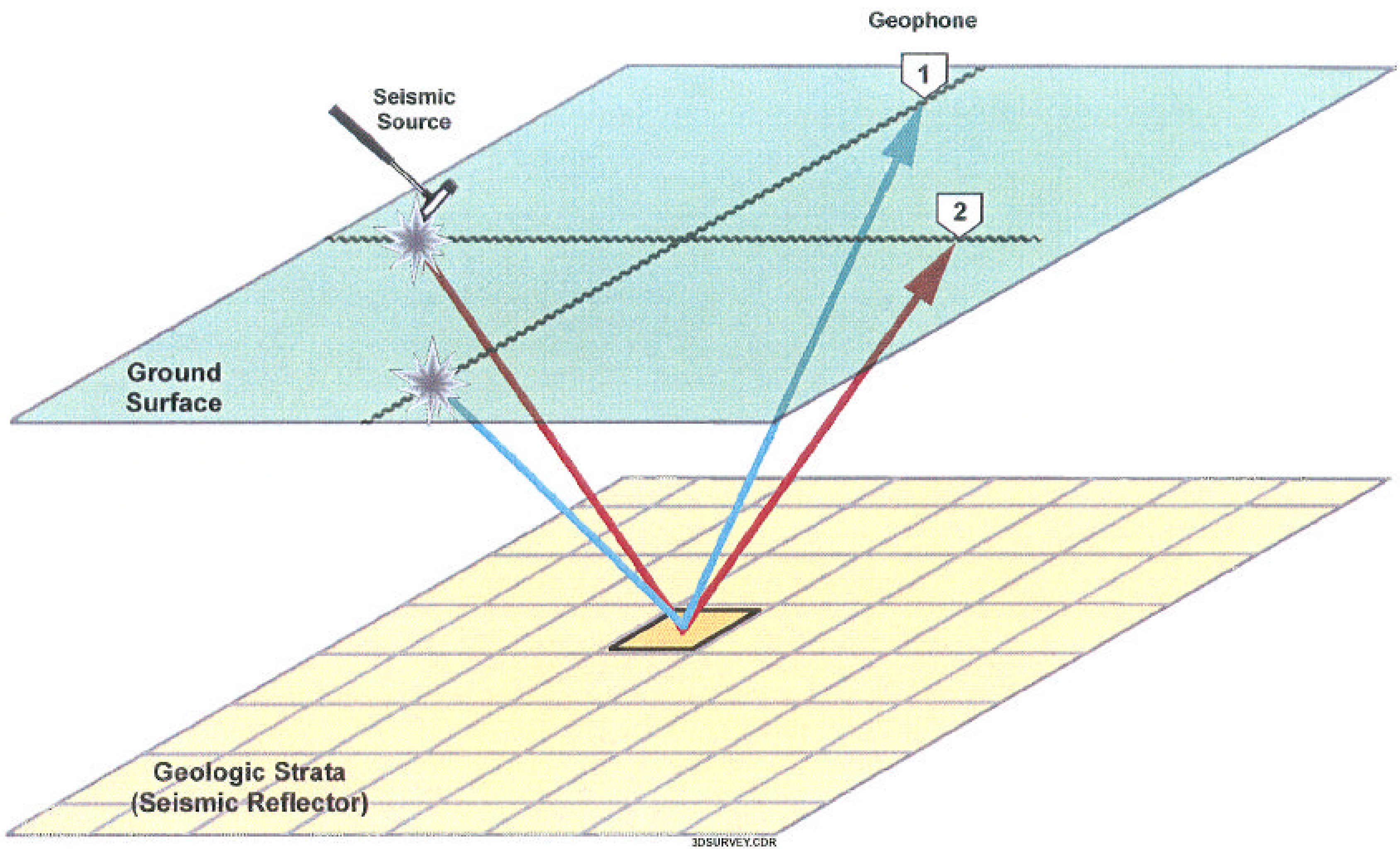

Figure 3. 3-D Seismic Survey

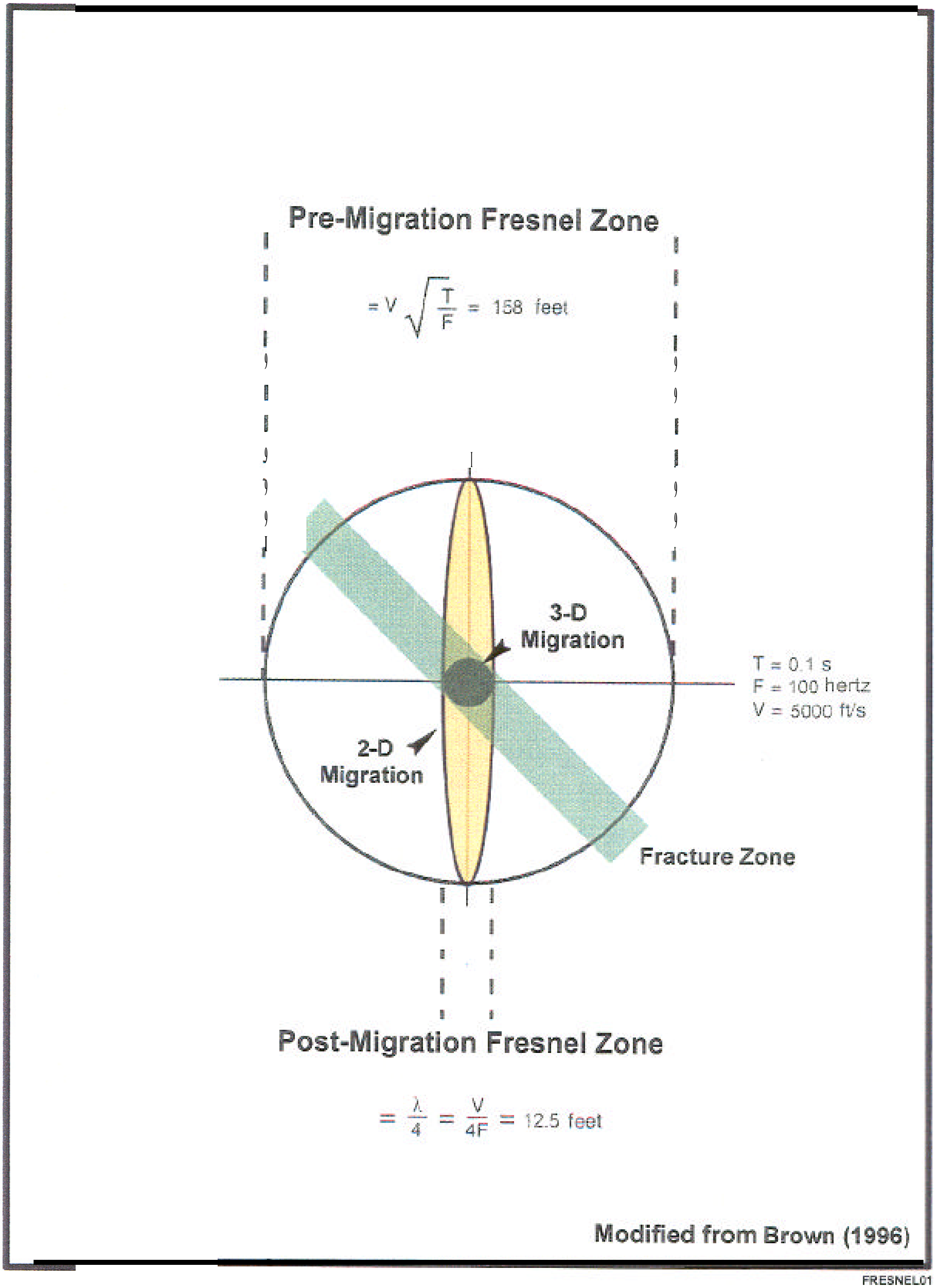

Figure 4. Effects of 3-D Seismic Data Resolution on Hypothetical Fresnel Zone

migration further reduces the area from the 2-D ellipse to a circle less than 13 feet in diameter. The 3-D migration improved the lateral resolution of the seismic image by reducing the size of the Fresnel zone by almost a factor of 30. If a fracture zone were present within the green shaded area on Figure 4, only 3-D migrated data could differentiate the zone.

Figure 5 shows the work of French (1974), who demonstrated the relative improvement in quality of migrated 3-D data in contrast with both migrated and unmigrated 2-D data. French collected 13 lines of seismic data over a model with two anticlines and a fault scarp (section [a] of Figure 5). Results from Line 6 of French's data are shown in sections (b), (c), and (d) of Figure 5. The raw data shows anomalous effects from neighboring structures: diffraction patterns from the fault block (red) and both anticlines (green and yellow) are apparent in the data, and make the section confusing and also incorrect. The image is improved with 2-D migration: Anticline 1 is correctly imaged because Line 6 passes over its crest, but Anticline 2 (which is visible on the section) is not actually beneath Line 6. Additionally, 2-D migration imaged the fault scarp with the wrong slope. Only the 3-D migrated section accurately delineates the true model geology. It should be noted that French's experiment exhibits a relatively simple system; sites with fractures and faults potentially containing DNAPL accumulations produce a much more confusing image that only 3-D migration could help clarify.

2.1.2.3 Attribute Analysis. As early as the 1970s, oil companies made use of the fact that high-intensity seismic reflections may be indicators of hydrocarbon reservoirs or oil-saturated porous or fractured rock. Amplitude anomalies, or bright spots caused by nongaseous, abnormally high or low velocity layers, often have distinguishing characteristics (Ostrander, 1984). Wang and Nur (1990) have performed extensive experiments on changes in velocities that are exhibited by rock samples saturated with different hydrocarbon liquids, and they have concluded that the seismic properties of rocks containing hydrocarbon-filled pores are different than those with water-filled pores.

Attribute analysis is a method of data manipulation and interpretation that can emphasize aspects of the geology not observable during the interpretation of conventional seismic sections. A standard seismic section or profile is a plot of particle velocity at a geophone versus time. Seismic data, however, cannot be completely characterized by these plots of this type because seismic signals are functions both of time and of frequency. Therefore, at any point in time, a seismic trace is dependent upon the amplitude and the phase of the individual frequencies that comprise its signal. Complex seismic trace attributes are a transformation of seismic refection data that separates a seismic trace into its amplitude and angular (phase and frequency) components. The mathematical transformation permits the construction of new data plots that highlight specified attributes of the seismic traces not observable on conventional sections.

A complex seismic attribute that may be useful for mapping fracture networks is the instantaneous amplitude (envelope) attribute. The envelope attribute is an exact measure (21-bit resolution) of seismic signal strength for each sample of the waveform (i.e., at each depth). It is known that a seismic signal travels further in solid rock than in fractured rock. It is true also that a signal is lost more rapidly in highly fractured media. In these instances the principal mechanism

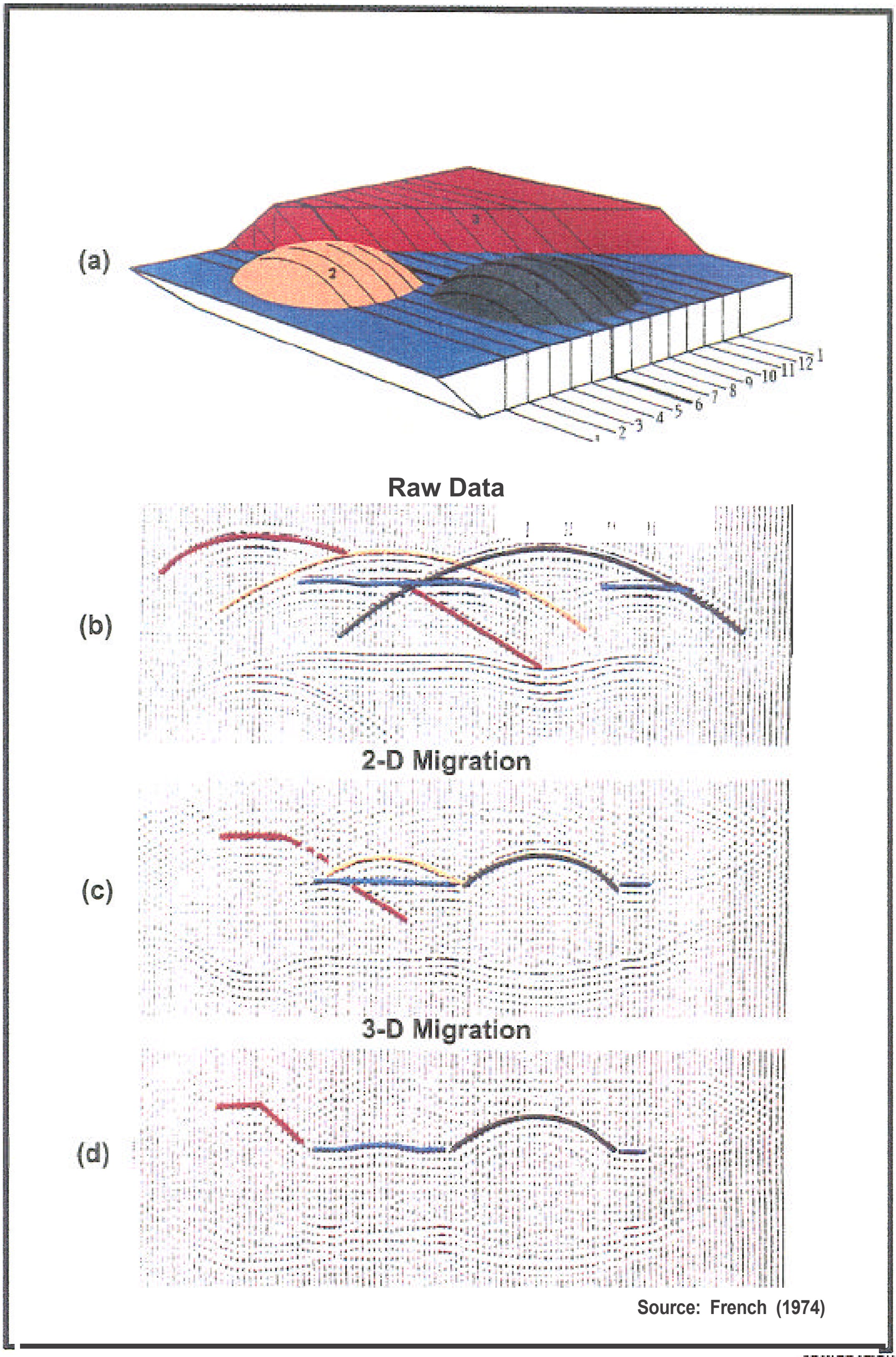

Figure 5. Comparative Effects of 2-D and 3-D Seismic Data Migration on Resolution Quality

for energy loss is the diffraction of seismic waves from irregular surfaces and absorption within the fractured zones. The envelope attribute can be used to highlight areas of amplitude variations in the seismic data, which may be caused by fracture zones within the subsurface. In fact, dramatic qualitative changes in waveform amplitudes and frequencies were observed at NASNI. During this demonstration, attempts were made to quantify similar changes in pore fluids with the use of instantaneous attribute analyses.

In addition to the fracture zones, larger than normal dim spots (low amplitude envelope attributes) may be produced by the presence of NAPL-impacted groundwater. The reason for the energy loss in these instances currently is not documented; however, it may be possible that at the molecular level seismic energy transmission would be enhanced by the mechanical link provided in a homogeneous fluid such as water; this theory is illustrated in Figure 6. Mixed fluids for example (microscopic globules of DNAPL and water), would provide less efficient molecular connections and thus less efficient seismic transmission than homogenous fluids.

2.2 Advantages of 3-D Seismic Technology

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 at up to five orders of magnitude more points than a traditional site characterization. Having a thorough understanding of the subsurface facilitates the location of monitoring wells and subsequent remedial efforts for optimum monitoring and contaminant removal. Seismic survey data must be tied to observations in the field (such as lithologic logs generated during the installation of monitoring wells) so that features observed in the seismic data can be accurately interpreted. Also, velocity models for the seismic data must be refined to match actual observations during drilling. In addition, seismic surveys are conducive to repetition over time.

There are some limitations inherent in the use of seismic surveys. For example, many lithologic variations in the subsurface may account for the observed anomalies in the seismic survey data. 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 somewhat from site to site. A well-developed model of the geology of the site is important to allow accurate survey design and analysis.

When compared with conventional site characterization techniques, seismic surveys provide several advantages. A problem with the conventional site characterization (when attempting to locate DNAPL accumulations) is the fact that vertical exploration boreholes are usually employed. Vertical holes 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

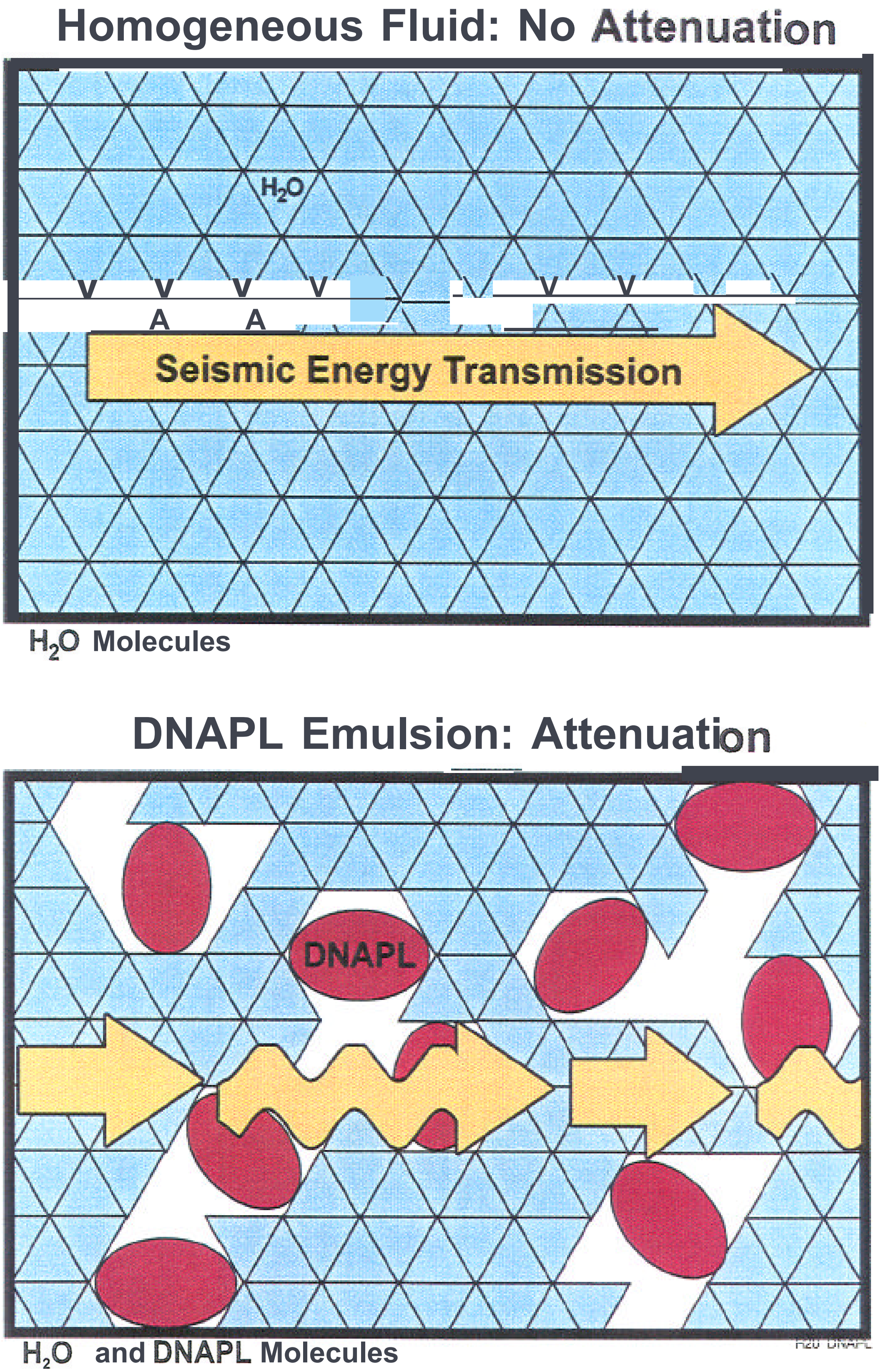

Figure 6. Seismic Energy Transmission in H_2O and DNAPL

(matrix) that may exist at the site. 3-D seismic surveys provide a means to evaluate vertical fracture systems.

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 3-D seismic surveys are non-invasive, much data can be gathered beneath source areas prior to drilling and sampling.

The fact is, at most potential DNAPL sites, we know very little or nothing about DNAPL distribution at depths below the source. The problem is compounded by the possibility that if DNAPL finds a permeable vertical pathway, and that pathway extends to depth, most investigations would not discover it. Once the DNAPL enters a vertical pathway it would remain localized around a small area and be difficult to intercept with drill holes. Most of the DNAPL at potential sites could be localized in areas and at depths that are never investigated using physical sampling. These same areas can be imaged with 3-D seismic surveys.

2.3 Factors Influencing Cost and Performance

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), and the degree of access allowed in and around the site. 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 than surveys targeting deeper features. In addition, the cost of processing the seismic data increases as the resolution required for the survey is increased.

3. Site/Facility Description

3.1 Background

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

- Letterkenny Army Depot, Pennsylvania: Area K – former waste disposal pits
- NAS Alameda, California: Building 5 – plating shop
- Tinker AFB, Oklahoma: Building 3001 – degreasing operation
- Allegany Ballistics Laboratory, West Virginia: 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 typical geological environments at sites where there was strong evidence of DNAPL contamination. However, it is important to note that at none of the four selected sites was free-phase DNAPL detected in the subsurface. In other words, none of the samples collected at any of the sites contained free-phase DNAPL, nor were there any active remediation programs to extract free-phase DNAPL. The following is a description of the geologic diversity represented by these sites:

- The Letterkenny Army Depot, Pennsylvania, 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 is also present in the region, creating karstic features such as caverns and sinkholes.
- The NAS Alameda, California, 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, Oklahoma, site is underlain by interfingering layers of sandstone, siltstone, and shales.
- The Allegany Ballistics Laboratory, West Virginia, site generally is underlain by 8 to 25 feet of silty clay and gravel alluvium overlying fractured bedrock of varying lithologies, including shale, sandstone, and carbonates.

3.2 Site/Facility Characteristics

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

3.2.1 Letterkenny Army Depot. Letterkenny Army Depot is located in central Pennsylvania, about 5 miles north of the city of Chambersburg as shown in Figure 7. 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) overhauling, 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 (United States Environmental Protection Agency – Environmental Photographic Interpretation Center Laboratory, 1987).

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 1,2-dichloroethene (DCE). This area is referred to as the disposal area and is shown in Figure 8.

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 feet. TCE was found at concentrations as high as 500 ppm; DCE was found at concentrations as high as 2,000 ppm. 1,1,2,2-tetrachloroethene (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.

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.

Five formations underlie Letterkenny Army Depot: the Martinsburg (Omp) shale, the Chambersburg Formation (Och) and St. Paul Group (Osp) limestones, the Pinesburg Station Formation (Ops) dolomites, and the Rockdale Run Formation (Orr) limestones and dolomites.

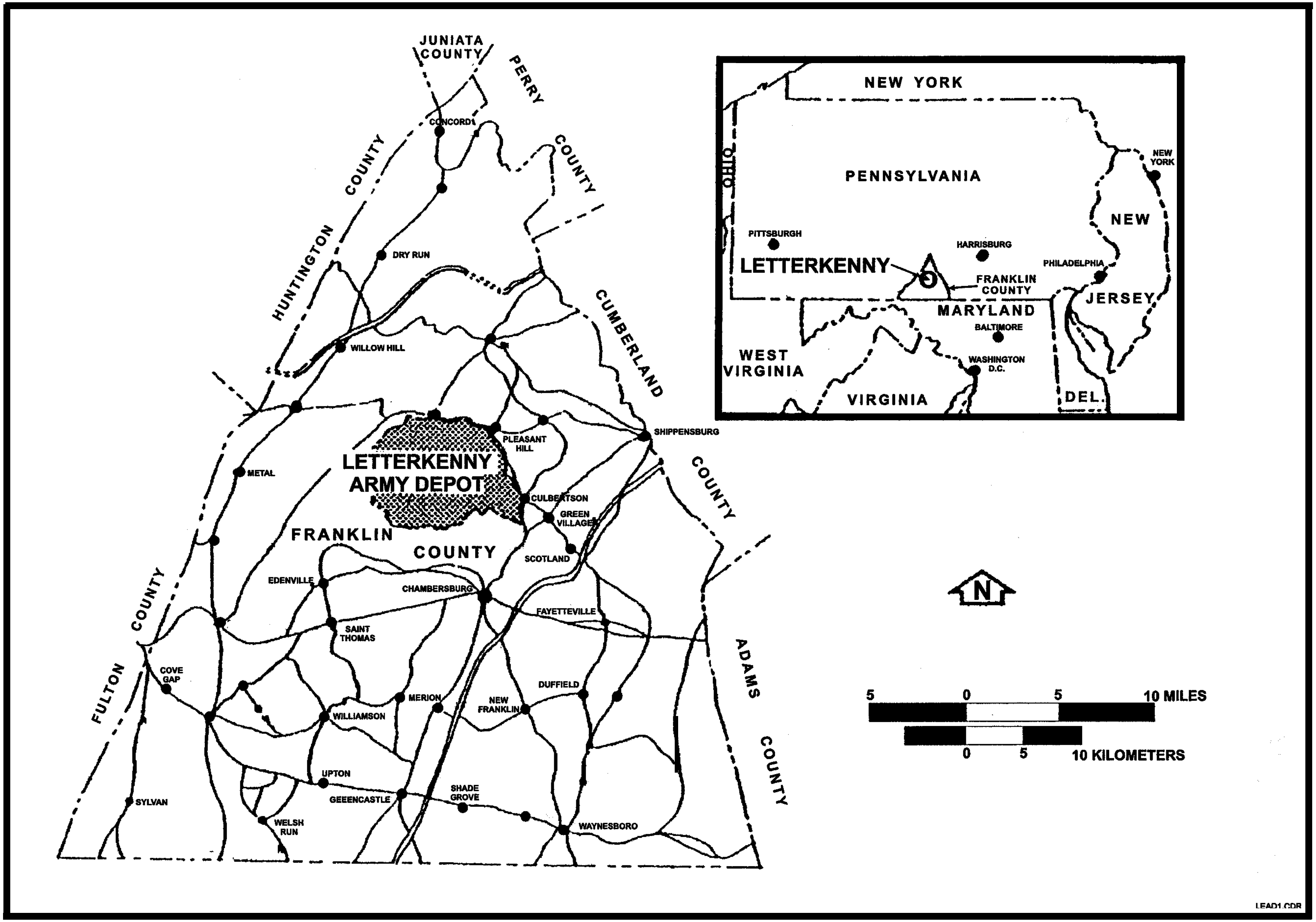

Figure 7. Location Map of Letterkenny Army Depot and Vicinity

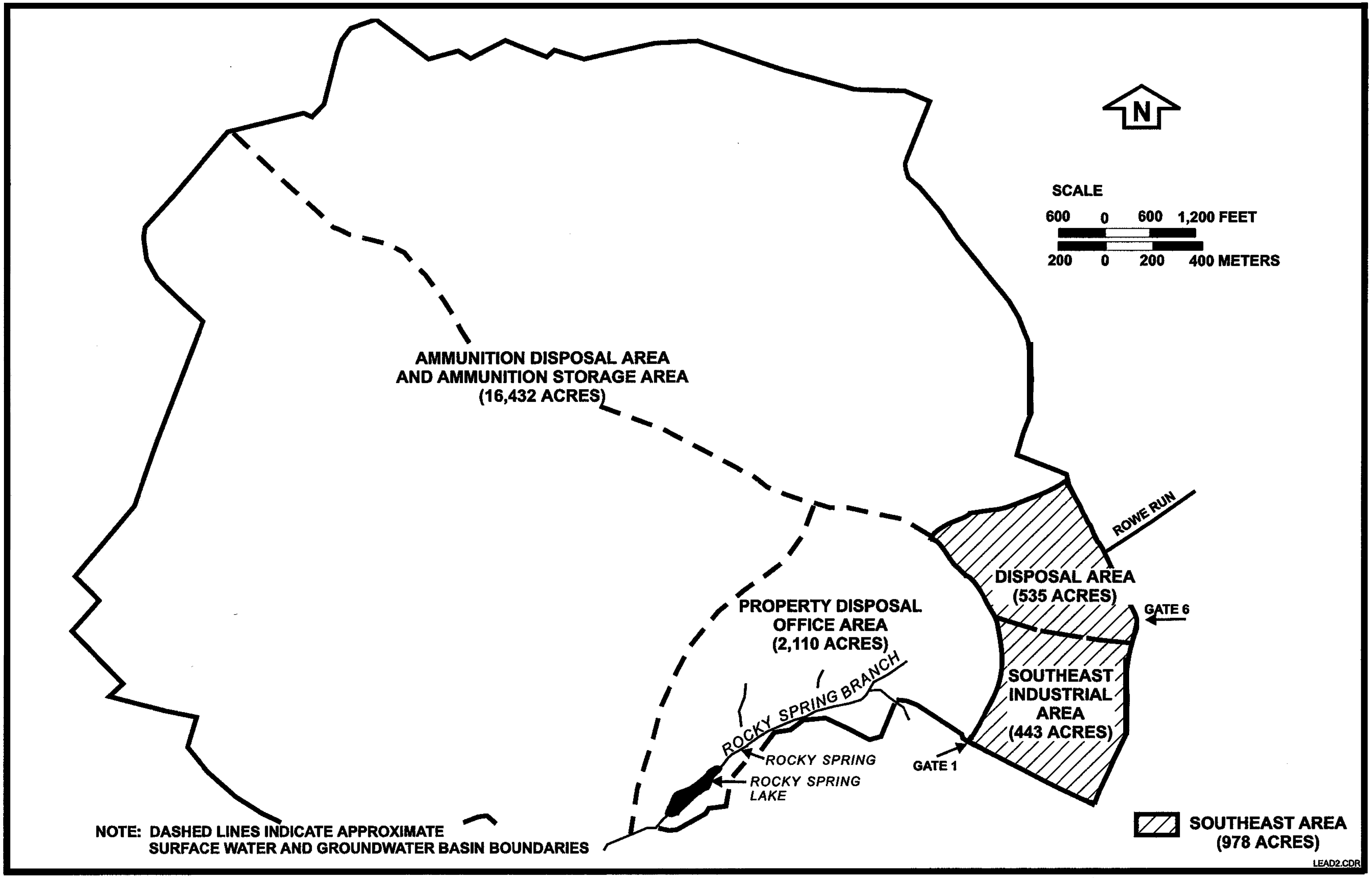

Figure 8. Southeast Area at Letterkenny Army Depot

The water-yielding characteristics of the formations range from good for the St. Paul Group and the Rockdale Run formations, with yields up to 225 and 410 gallons per minute (gpm), respectively; to fair for the Martinsburg (yields up to 150 gpm); to poor for the Pinesburg Station and the Chambersburg (yields up to 30 to 40 gpm, respectively).

The closest cross section to Area K, constructed from well information but not indicative of structure, is shown in Figure 9 (Environmental Science and Engineering, Inc. [ESE], 1993). This cross section is slightly south of Area K. It is oriented northeast-southwest and extends from East Patrol Road to the western edge of the SE Area. It shows pinnacled limestone bedrock overlain by clay. The approximate orientation of the Letterkenny Fault also is shown. The orientation, deformation, and faulting of bedrock controls groundwater flow and contaminant migration, because the limestone at the site has a low primary porosity. Groundwater and any contaminant releases migrate along folds, faults, and fractures. Solution channels or karst have developed along many of the fractures that are aligned predominately with the north-northeast geologic strike. Groundwater and contamination can move readily through these solution channels.

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.

3.2.2 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 10. 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 (PRC Environmental Management, Inc. [PRC], 1993).

The Army acquired the area now 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 NAS Alameda has been to provide facilities and support for fleet activities.

The 3-D seismic survey was completed within Site 5 at NAS Alameda. Site 5 covers 18.5 acres and includes Building 5. A plating shop is located within Building 5. The site is located in the central portion of the NAS just east of the airfield, as shown in Figure 11. It has been in operation since 1942, and is still partially occupied. Shops in the building were used for cleaning,

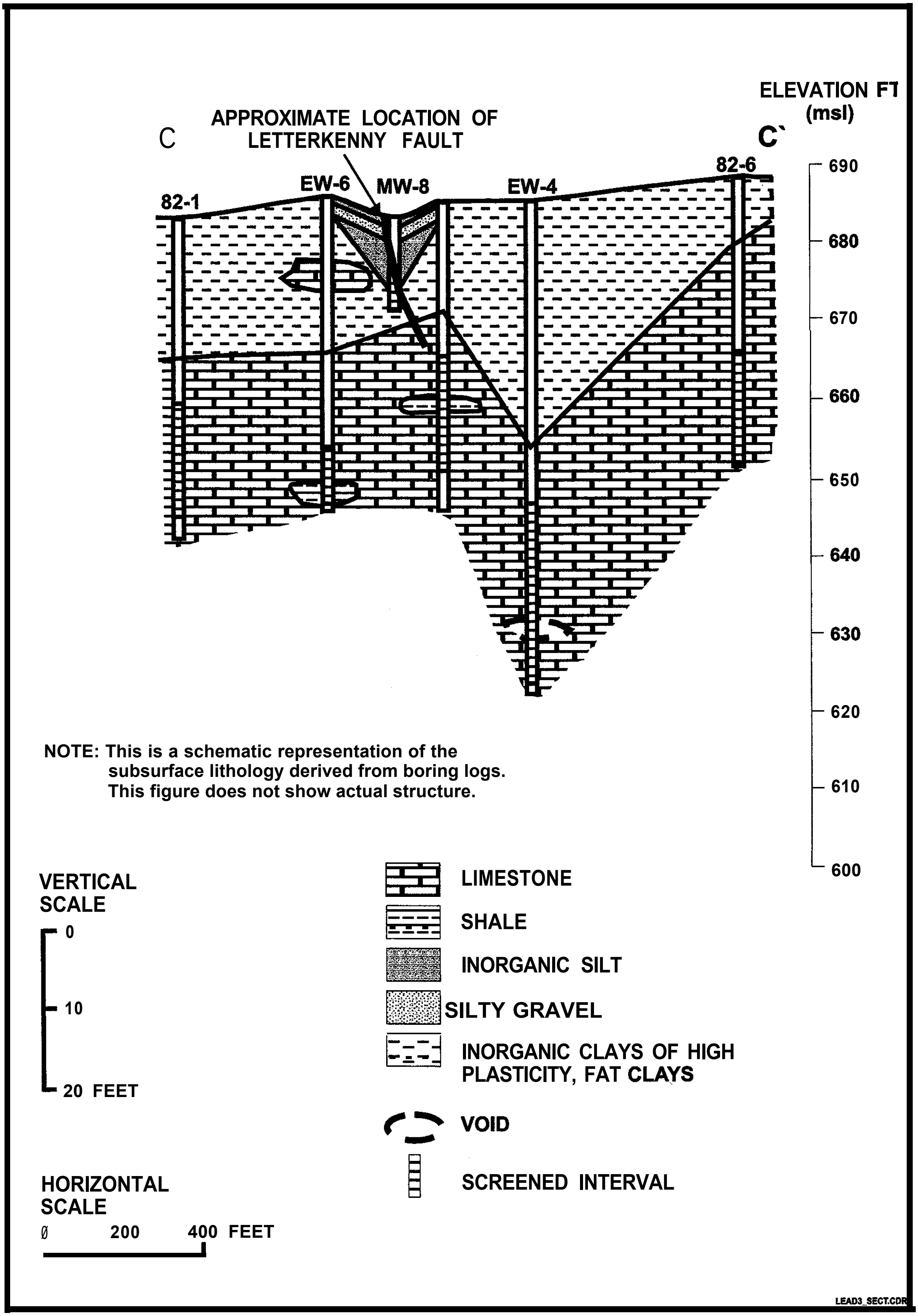

Figure 9. Geologic Cross Section C-C' South of Area K at Letterkenny Army Depot

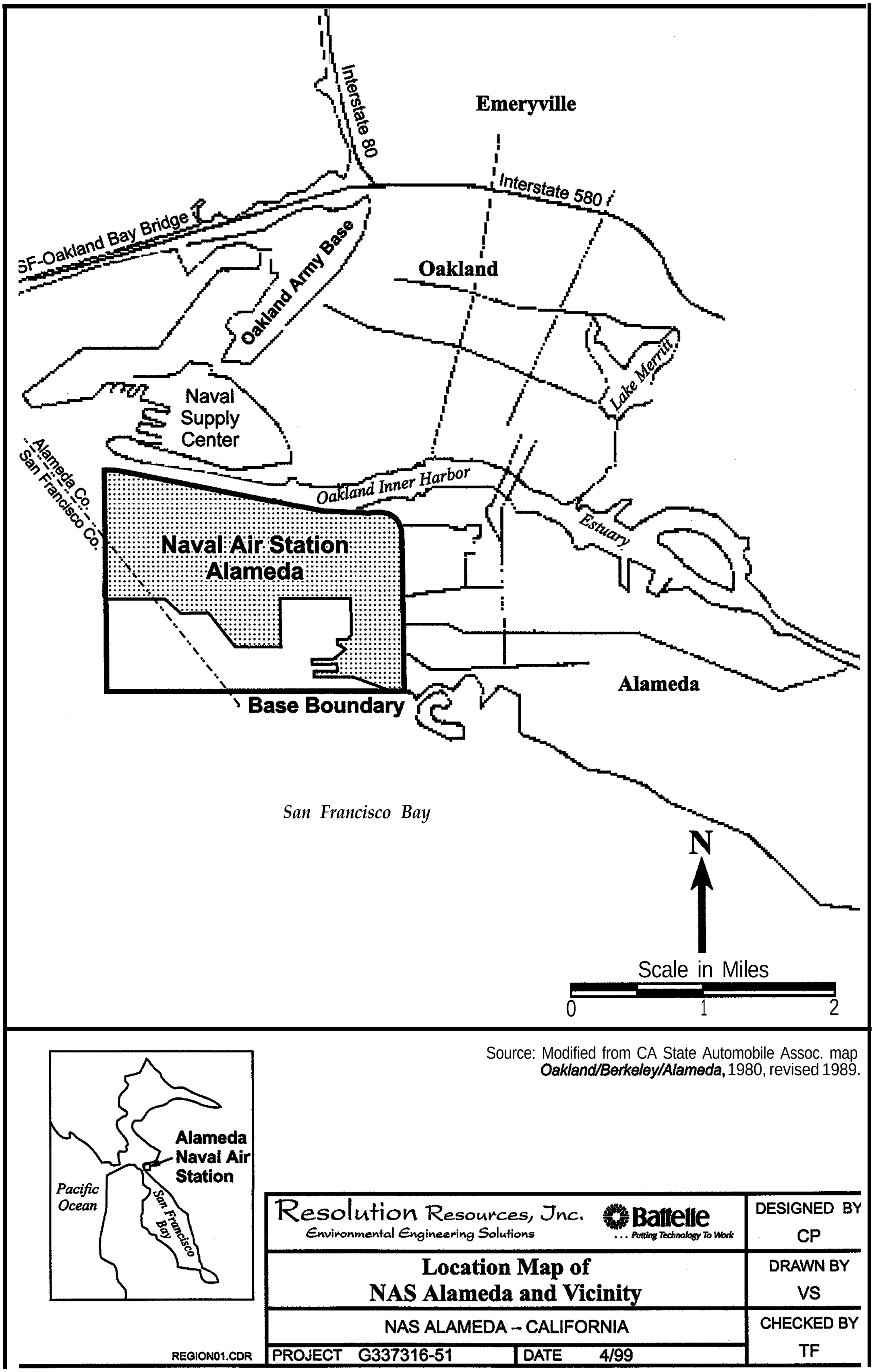

Figure 10. Location Map of NAS Alameda and Vicinity

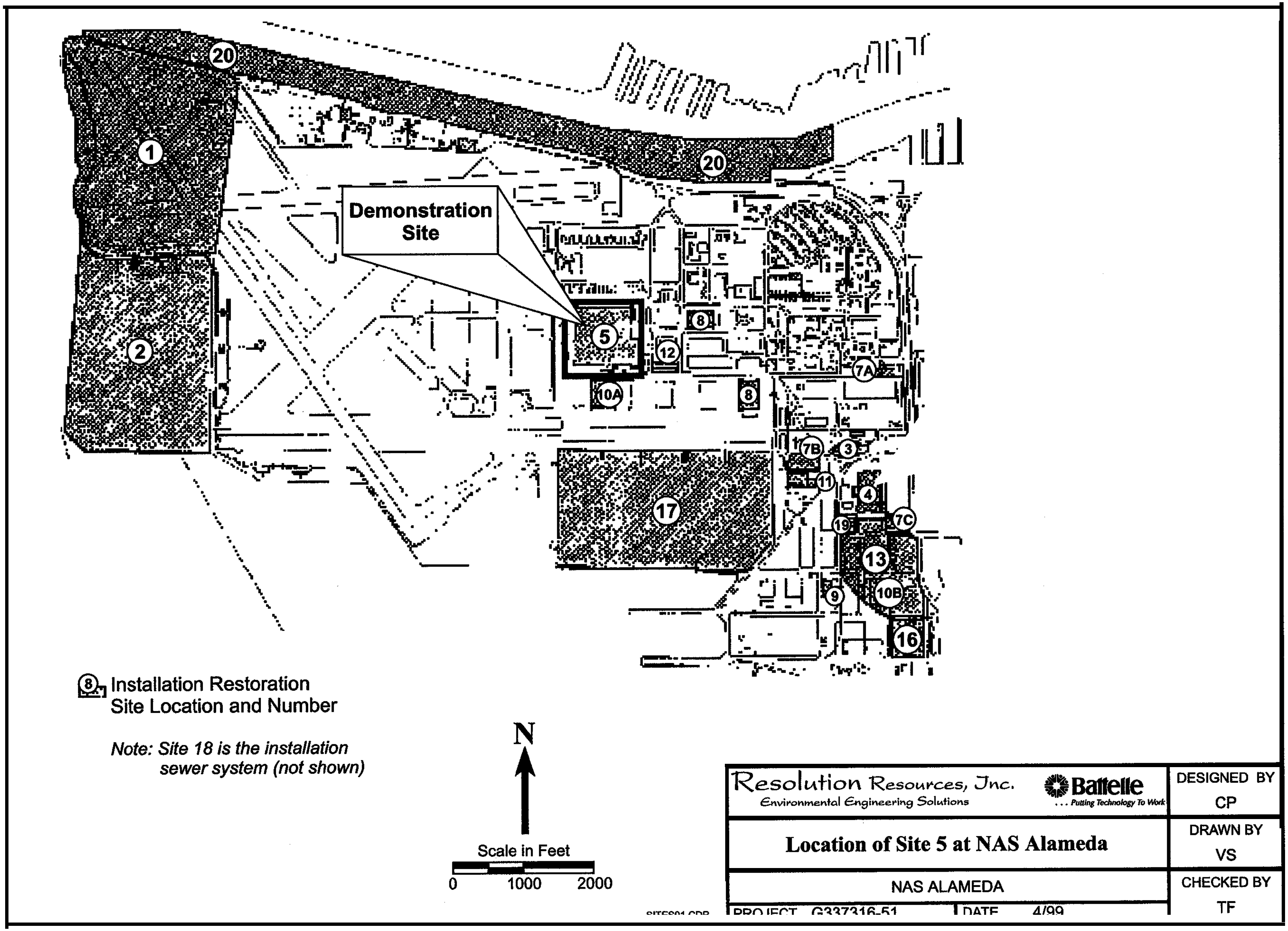

Figure 11. Location of Site 5 at NAS Alameda

reworking, and manufacturing metal parts; tool for maintenance; and for plating and painting operations.

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 (PRC and Montgomery Watson, 1994). 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.

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 feet 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 feet of unconsolidated sediments overlie Franciscan bedrock, according to boring logs from water supply wells installed as early as the 1940s.

The Bay Sediment is the youngest of the naturally occurring formations, and consists of Bay Sand and Bay Mud, according to information provided by PRC (Willoughby, 1996). The Bay Sand is gray with green or blue colors, and is comprised of fine to medium-grained sand or sandy silt, and loose to medium dense with shells. The Bay Mud also is gray, with green or blue hues and grades from clay to clayey silt, is soft to medium stiff, and has minor shells. The Bay Sediments are 130 feet thick, and are thickest in a paleochannel that trends nearly east to west across the middle of NAS Alameda. This channel cuts across the northern part of Building 5 and is north of the source areas of concern for this investigation. Bay Sediments are thin or absent in the southeastern part of the NAS. These sediments are Holocene in age and were deposited in an estuarine environment by deposition in channels that were eroded into older underlying sediments.

The Merritt Sand is older than the Bay Sediments and was deposited in the Late Pleistocene to Holocene. The medium grained sands are dense to very dense, and are brown, with yellow and red iron oxide stains, sometimes with minor clay. This eolian unit is up to 70 feet thick, and has been partially eroded by the paleochannel.

Beneath the Merritt Sand are dense interbedded blue to gray sands and clay of the San Antonio Formation. These sediments are discontinuously distributed across NAS Alameda and are thickest on the eastern half of the NAS, especially the southeast. These sands and clays were deposited in the Late Pleistocene and Holocene, most likely in a deltaic environment.

The oldest unit that has been identified by borings at the NAS is the San Antonio Formation Yerba Buena Mud. It is believed to underlie the entire NAS; however, sufficient borings to confirm this have not been drilled. These sediments also have been eroded by the paleochannel and are characterized by blue to gray, thick bedded, dense clay that was deposited in the Late Pleistocene in an estuarine environment. In general, deposition in the Bay Area has been influenced by recent (Holocene) changes in sea level. Figure 12 shows a cross section across the site from west to east illustrating the geologic units beneath the test site at NAS Alameda.

Groundwater was encountered in borings between 5 to 10 feet deep and flow is generally to the west and southwest. Two water-bearing zones, which are continuous, underlie NAS Alameda. The first water-bearing zone occurs in the dredge fill at a depth of about 5 or 6 feet. The deeper water-bearing zone is found in the Lower Pleistocene sediments. Both water-bearing zones are influenced by tidal fluctuations and are characterized by water problems associated with nitrates, saltwater intrusions, and naturally occurring mercury contamination from the bedrock formation. As a result, no groundwater presently is used as a water supply on Alameda Island.

3.2.3 Tinker AFB. Tinker AFB is located in Oklahoma County in central Oklahoma, approximately eight miles southeast of downtown Oklahoma City (Figure 13). The base encompasses 4,541 acres and contains approximately 500 buildings. Tinker AFB, as a worldwide repair depot, manages and maintains the following aircraft: B-1B, B-2, B-52, E-3, and the multipurpose 135 series. Also managed at the base are the SRAM, SRAMII, ALCM, and GLCM missile systems, as well as the United States Air Force Harpoon Missile. 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.

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. 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 also may have moved along joints and fractures that dip westward from below the pits under the building to the area west of the building.

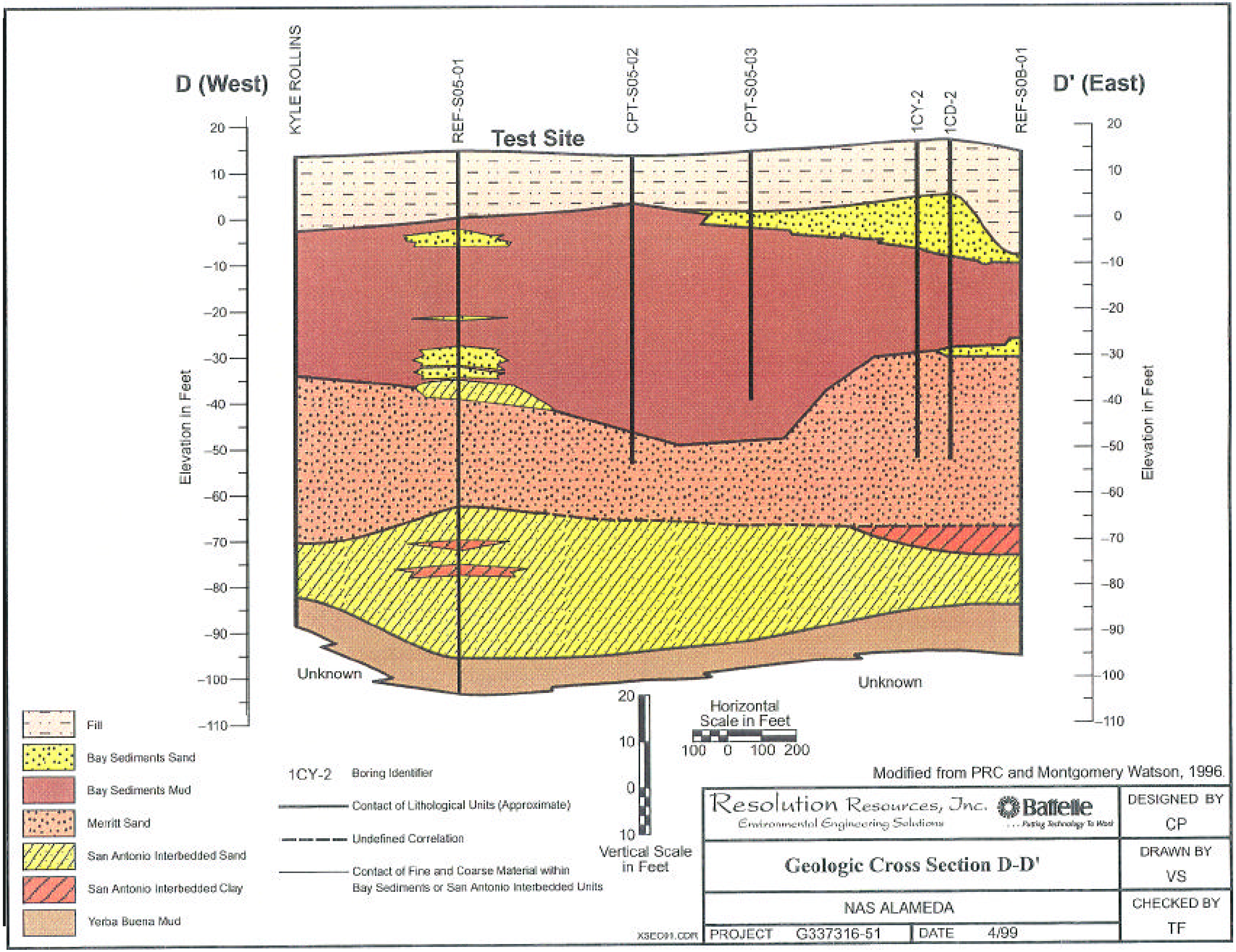

Figure 12. Geologic Cross Section D-D' at NAS Alameda

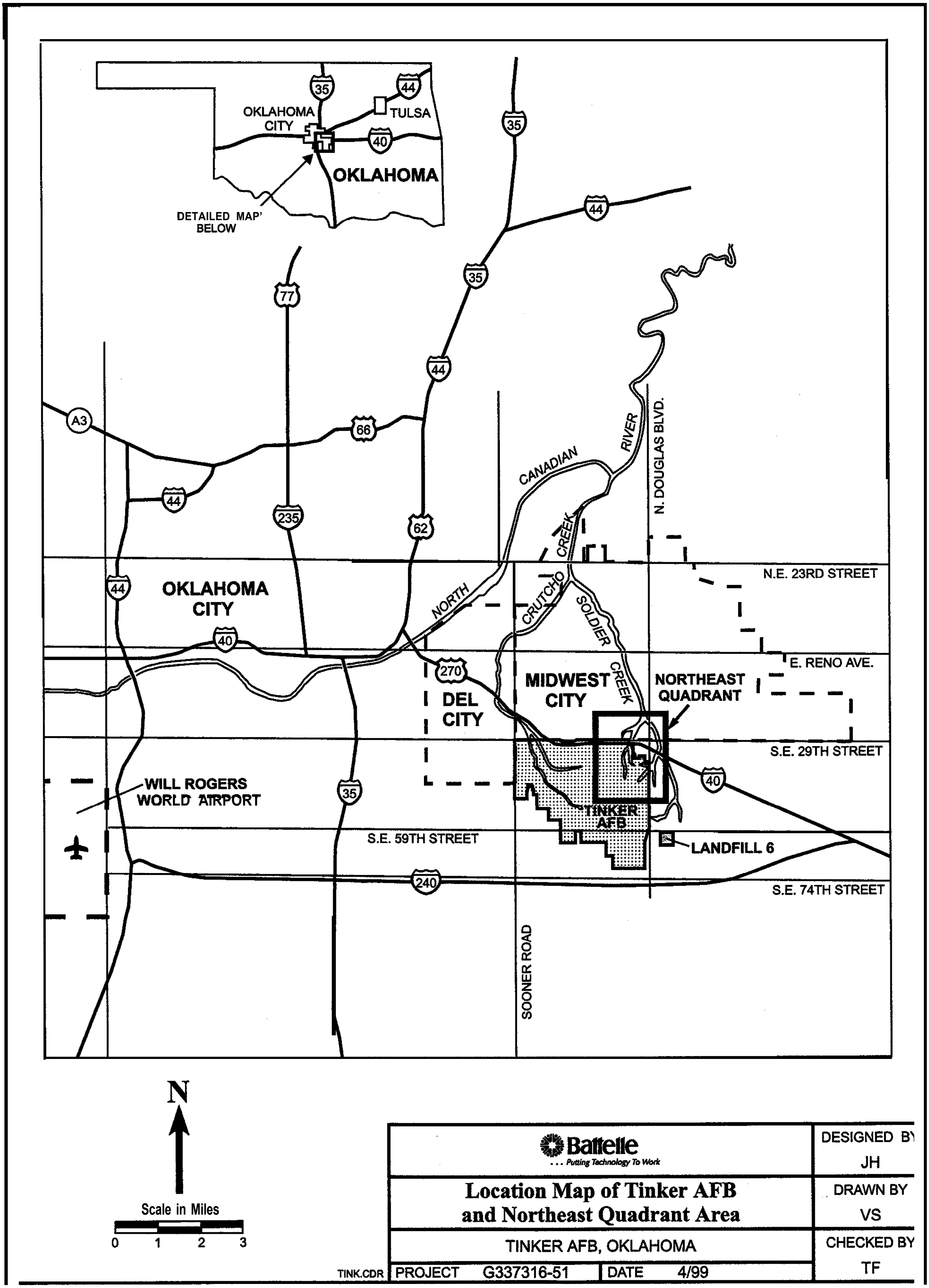

Figure 13. Location Map of Tinker AFB and Northeast Quadrant Area

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, which is shown on Figure 14, high concentrations of TCE were detected in the soils beneath and adjacent to the pit. The monitoring well clusters initially installed within Building 3001 are also shown on Figure 14. 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.

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 through Kansas 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.

The Nemaha Ridge consists of uplifted, block-faulted zones, each about 3 to 5 miles wide and 5 to 20 miles long. The ridge trends northeast/southwest throughout most of its length, but it abruptly changes near its terminus to a northwest/southeast strike. The end of the Nemaha Ridge is believed to be the Oklahoma City Anticline (see Figure 15). Most of the uplift along the ridge occurred during the convergence of the North American and African plates during the Pennsylvanian. As a result, most of the active faults do not extend up through the Permian units. Although faults may not extend to the surface, fractures (without vertical or horizontal movement) from these faults have propagated to the surface as evidenced by the Lineament Map of the Nemaha Uplift Region. Many of the lineaments (fractures, faults, or other linear surficial features related to structural geologic characteristics) correspond to stream traces and subsurface fault zones.

The main water-bearing units of the Central Oklahoma aquifer are the Permian-age Wellington Formation and the Garber Sandstone. These two units are grouped as a single aquifer because their lithologies and water bearing characteristics are similar. They are typified by interfingered, lenticular beds of sandstone, siltstone, and shale, deposited by shifting channels in a delta system. The sandstones are fine- to very-fine-grained and friable, with a matrix of red clay. Part of Tinker AFB is underlain by shales and siltstones of the Hennessey Group, which confines the aquifer in some areas. The combined maximum thickness of the Central Oklahoma Aquifer is 900 feet.

Groundwater beneath Tinker AFB's northeast quadrant generally is thought to flow to the west-southwest along regional dip. Localized variations in groundwater flow directions occur in the

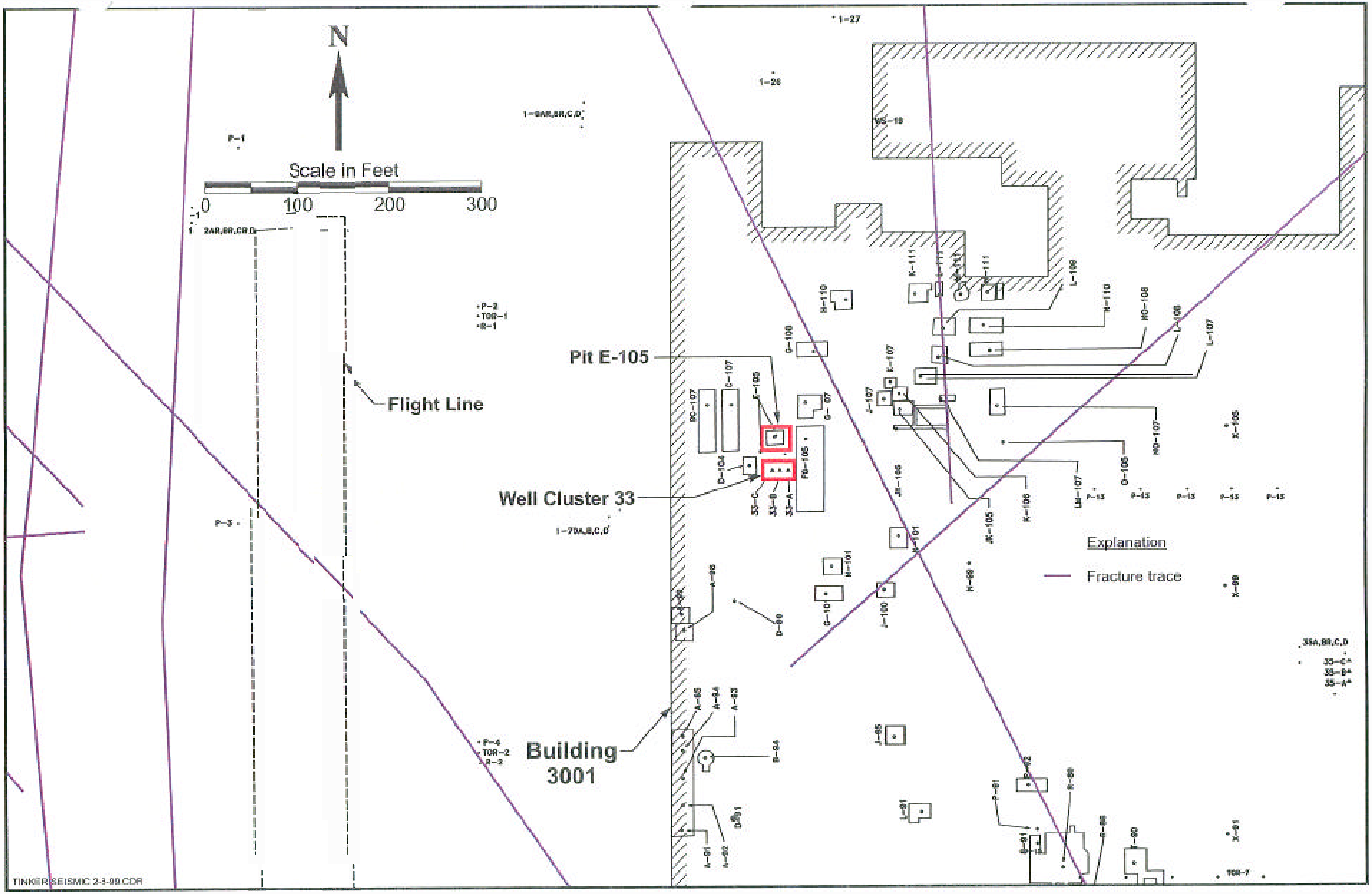

Figure 14. Demonstration Site Location at the North End of Building 3001 at Tinker AFB

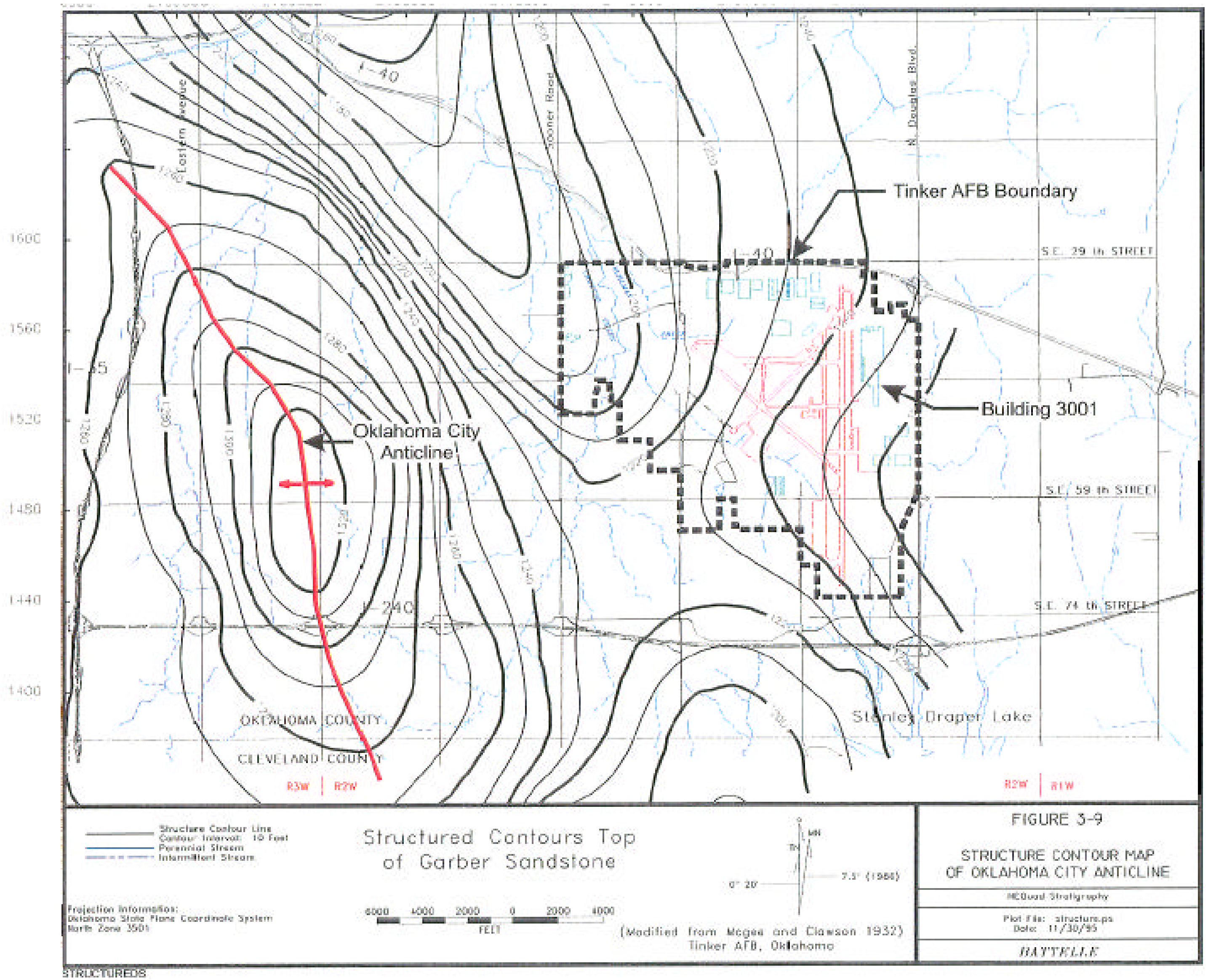

Figure 15. Structure Contour Map of Oklahoma City Anticline

vicinity of surface water drainages and where geologic units pinch out. Shallow groundwater beneath the northeast quadrant occurs under unconfined or water table conditions. As depth increases, the flow system transitions between semiconfined and confined conditions as a result of the presence of numerous low-permeability siltstones and mudstones within the aquifer.

Three major water-bearing and transmitting units underlie the northeast quadrant and the study area. A north-south cross section (shown in Figure 16) beneath the demonstration site illustrates the hydrologic units. Various hydrogeologic and modeling studies done at Tinker designate them as the upper saturated zone (USZ), lower saturated zone (LSZ), and production zone. These zones are separated by two distinct shale units, the Upper and Lower Shale, that represent the most significant semi-confining units beneath the northeast quadrant of the base. These two distinct shale units consist of a series of interbedded and interfingered shale lenses rather than a single, continuous shale layer. Together, these units comprise the five primary hydrostragraphic units occurring within the northeast quadrant.

3.2.4 Allegany Ballistics Laboratory. Allegany Ballistics Laboratory is a research, development, and production facility located in Mineral County, West Virginia. 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 are 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 17). 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.

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. Figure 18 is a northwest-southeast–trending cross section located north of Allegany Ballistics Laboratory that illustrates the deformation in the subsurface geologic units.

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 feet 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 feet, 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.

The alluvial deposits overlay fractured bedrock that consists of Silurian sedimentary lithologies of some sandstone and mostly shale and carbonates. When deposited, these beds were nearly flat

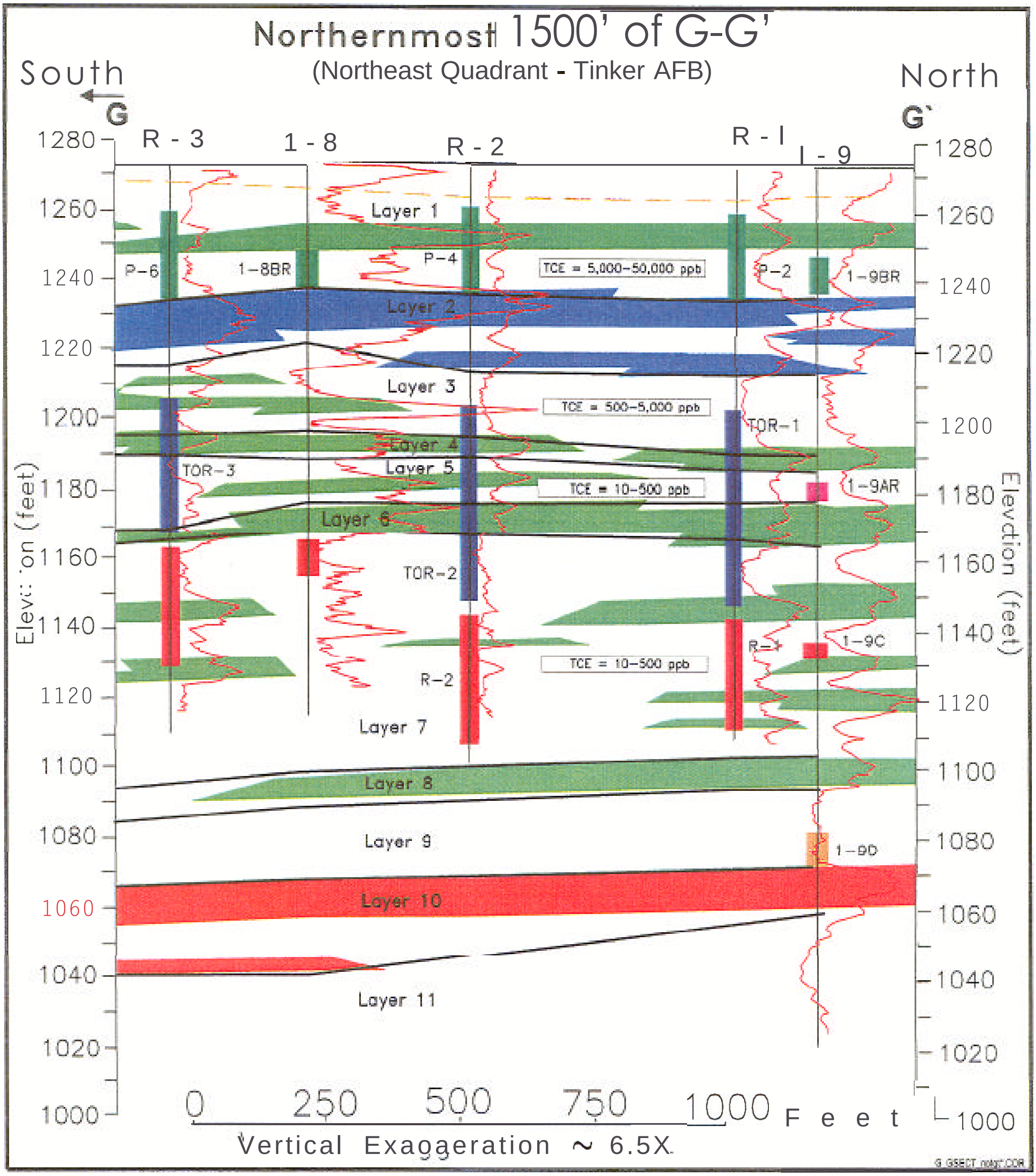

Figure 16. North-South Geologic Cross Section G-G` at Tinker AFB

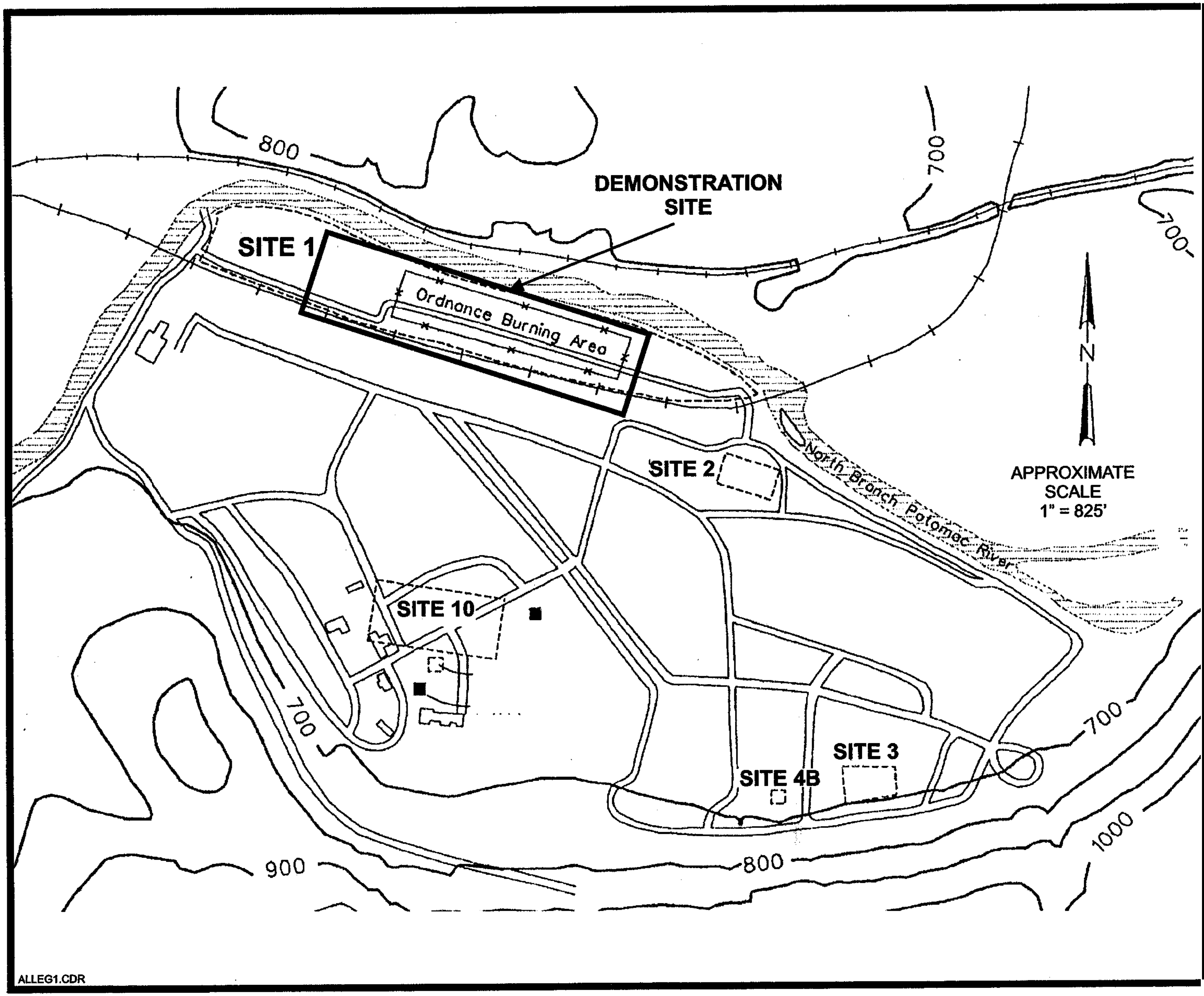

Figure 17. Location of Site 1 at Allegany Ballistics Laboratory

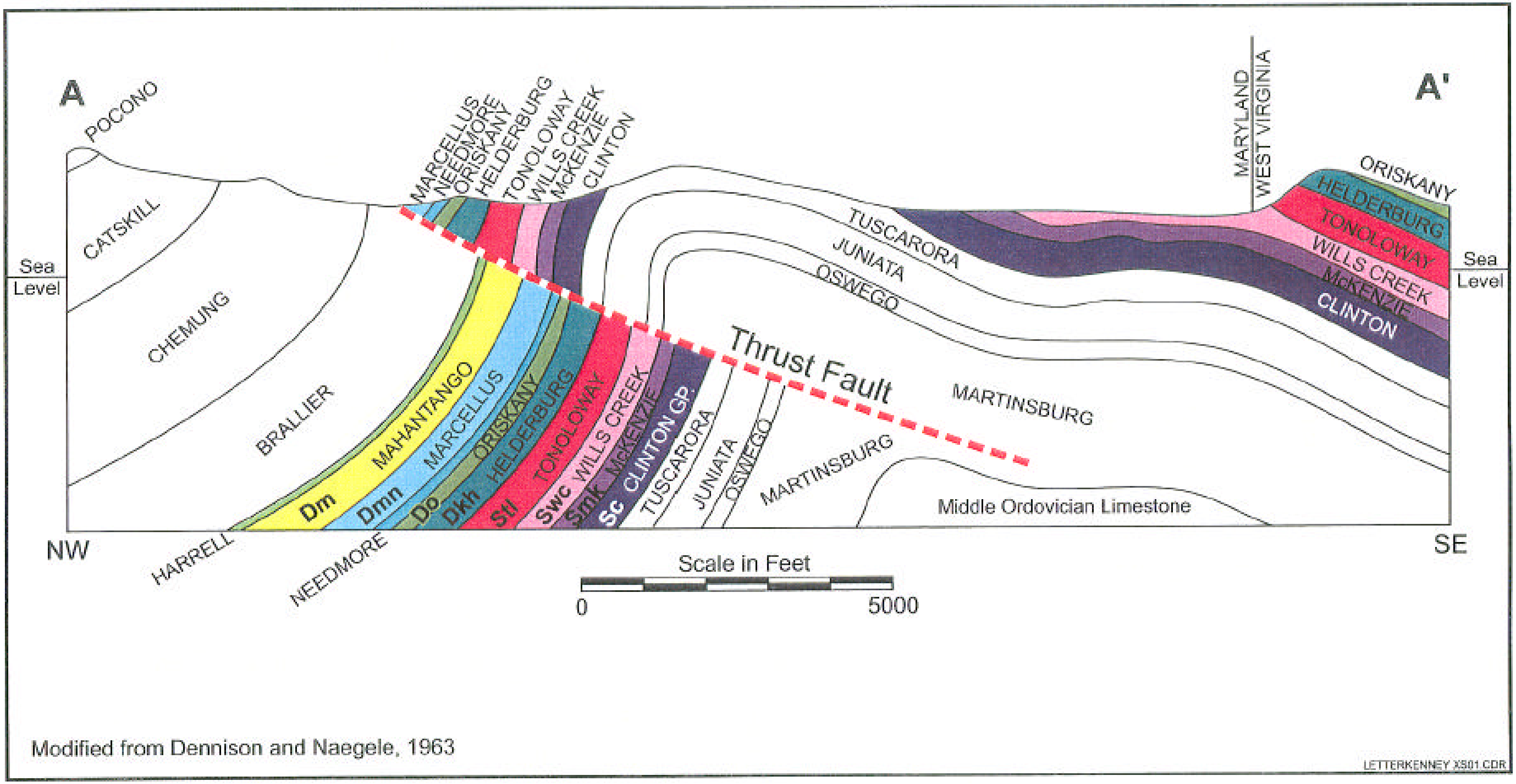

Figure 18. Cross Section A-A' Showing the Cresaptown Fault Near Allegany Ballistics Laboratory

but were folded and thrust westward as a result of plate collision to the east. Although the deformation was only in the sedimentary cover, basement structures still influence the overall structure and especially the fault and fracture network, even to the present-day surface, where two prominent sets of lineaments (four trends) can be seen on aerial photographs. Groundwater flow in the bedrock aquifer is through the secondary porosity and is controlled by fracture flow.

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 in the subsurface at Allegany Ballistics Laboratory Site 1. Potential sources of subsurface contamination include the following:

- The burning ground for ordnance
- Three inactive waste disposal pits
- 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 gravely 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. Demonstration Approach

ESTCP provided funding for this project. RRI and Battelle were responsible for various tasks included in the demonstration. RRI, in conjunction with NFESC, performed the initial selection of demonstration sites. RRI also designed and completed the 3-D seismic surveys at each of the sites and generated a list of predictions based on interpretation of the seismic data. Excel Geophysical Corp. performed the numerical processing and attribute analyses of the seismic data collected at each of the four sites. Battelle, in conjunction with RRI, was responsible for completing the verification sampling and compiling the final report. Battelle also was responsible for providing independent oversight for the entire project.

The four sites selected for this demonstration are:

- Letterkenny Army Depot, Pennsylvania: Area K – former waste disposal pits
- NAS Alameda, California: Building 5 – plating shop
- Tinker AFB, Oklahoma: Building 3001 – degreasing operation
- Allegany Ballistics Lab., West Virginia: Site 1 – former waste disposal pits

Seismic surveys were planned and implemented at all four sites selected for this demonstration, but validation drilling and sampling were performed only at the first three sites. At Allegany Ballistics Laboratory, survey validation consisted only of comparing the predicted depth to bedrock to actual bedrock depths measured during the drilling of a series of extraction wells that were installed after the survey was performed. The positioning of these extraction wells was not based on DNAPL targets interpreted from the seismic data.

4.1 Performance Objectives

The primary objective of this project was to demonstrate that high-resolution, 3-D seismic reflection surveys can be an effective method for detecting subsurface DNAPL contaminant source areas. 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 analyses of physical samples (groundwater) taken from within the surveyed regions. As a secondary objective, the surveys also were 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.

This demonstration project was accomplished by performing and evaluating 3-D seismic surveys at four DNAPL sites. The data collected and processed from the seismic surveys also was used to generate predictions for subsurface contamination and depths to stratigraphic features. The accuracy of the predictions was evaluated by comparing them with conventional site characterization data.

4.2 Sampling Procedures

Once the validation targets were identified, conventional drilling and sampling techniques were used to collect data to evaluate the seismic survey predictions in order to determine if DNAPL was actually present at any target under evaluation. Sampling procedures were fairly consistent across the three sites where validation drilling took place. In all cases, groundwater was bailed from the borehole or cone penetrometer test (CPT) push hole and stored in 40-mL volatile organic analysis (VOA) vials before they were analyzed by a certified laboratory. At the Letterkenny Army Depot and 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. The instrument operators at both Letterkenny Army Depot and NAS Alameda were professional chemists. At Tinker 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. Onsite Environmental is a certified environmental laboratory based in the State of California.

4.2.1 Letterkenny Army Depot. Sampling at Letterkenny Army Depot involved working in uncased (i.e., open-hole) bedrock boreholes. Typically, surface or top-hole casing was set to isolate the unconsolidated overburden and shallow groundwater-yielding interval(s) from the deeper target objectives. Sampling at Letterkenny Army Depot involved using 1½-in.-diameter × 36-in.-long weighted disposable Teflon™ bailers and nylon string. Samples were collected during the advancement of the boreholes and at the target depths. In the event that DNAPL might migrate into a completed borehole, several repeat samples were collected from each target depth for several days following the completion of each borehole. Drilling was performed using air percussion or air rotary methods, so little or no drilling fluids were added to the hole. To better understand whether contaminated zones of groundwater were being penetrated, groundwater samples were also collected at various depths at the end of flow line, where groundwater and cuttings discharged to a settling pit that was built temporarily next to the drilling rig. At the flow line, the 40-mL VOA vials were slowly filled with groundwater. However, because of the aeration of these flow line samples, they were not expected to show elevated concentrations of VOCs. The outflow air and groundwater also was monitored frequently for the presence of organic contaminants using a photoionization detector (PID). Samples were immediately carried to the on-site lab trailer where they were quickly analyzed, or temporarily stored in a refrigerator until analysis could be performed. Except at Tinker AFB, where samples were shipped to an off-site location, it was not necessary to use an acid preservative because the analytical turnaround time was far less than the standard seven-day time period.

4.2.2 NAS Alameda. For the NAS Alameda verification work, a Navy Site Characterization and Analysis Penetrometer System (SCAPS) unit was used. Temporary microwell points were installed for groundwater sampling. These microwell temporary completions had an expandable collar above the screen interval. When this collar was set, the screen interval was isolated from the overlying portion of the push hole, ensuring that a representative sample was being collected. A Geoprobe® rig also was used at the site to set temporary wells at a few locations that could not be accessed by the SCAPS unit. Once temporary microwells were installed, a small ½-in.-diameter bailer was used to retrieve groundwater samples. The microwells were not purged prior to sampling. Groundwater samples bailed from the microwells were collected in 40-mL VOA vials and hand-delivered to the on-site laboratory.

4.2.3 Tinker AFB. The same basic drilling and sampling procedures employed at Letterkenny Army Depot were applied at Tinker AFB. Drilling was performed using air rotary methods. Samples from target intervals were bailed from open hole completions. A shallower perched aquifer was cased off temporarily to prevent interference with the quality of groundwater collected from the target intervals. Groundwater samples also were collected from the outflow line as boreholes were being advanced. The perched aquifer present at the site was sampled prior to the setting of the temporary casing. The perched aquifer was known to contain elevated concentrations of chlorinated solvents. Results from these shallower groundwater samples confirmed that this high level of contamination was present.

4.2.4 Allegany Ballistics Laboratory. Investigation of seismic anomalies through drilling and sampling in the subsurface was not performed at Allegany Ballistics Laboratory. During preparation for the drilling and sampling, a paper validation study was completed to evaluate observed field data (such as the measured depth to top of bedrock and groundwater contaminant distributions) with respect to the 3-D seismic survey results. The complete evaluation is presented in the Draft report entitled *Existing Data Assessment and Paper Validation of the 3-D Seismic Survey at Allegany Ballistics Laboratory*, prepared by Battelle in June 1997 for the NFESC (Battelle, 1997a). The results of the paper validation effort are presented in the performance assessment in Section 5.1.4.4.

4.3 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 PID was utilized 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. Before use each day, it was calibrated to ensure that it was functioning properly and providing accurate readings. The PID was also checked periodically at the drill site by measuring its sensitivity to vapors from an indelible marking pen. The battery pack for the PID was recharged overnight. The PID was used to help select groundwater sampling points. Samples were collected when elevated readings were shown on the PID. The PID also was 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 CPT and Geoprobe® direct-push methods do not bring air, groundwater, or cuttings to the surface as the hole is being advanced. Therefore, 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, 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 common industrial solvents, PCE and TCE, and their degradation products: 1,2-dichloroethane (DCA), 1,1- and 1,2-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.

4.4 Physical Setup and Operation

This technology application consisted of conducting high-resolution, 3-D seismic reflection geophysical surveys, and then processing and interpreting the data to identify important subsurface features and anomalies.

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
- Vertical seismic profile, to obtain a velocity model for the site's subsurface stratigraphy
- Land survey
- 3-D seismic reflection survey and data collection
- 3-D data processing and interpretation
- Attribute analysis to delineate anomalies that may represent fractures and/or DNAPL.

4.4.1 Site Research and Generation of a Geologic Model. Site-specific geologic models were generated before the seismic surveys were performed. The geologic models were essential for a more complete understanding and interpretation of the 3-D seismic data sets. The development of the geologic models consisted of reviewing pertinent background information including previous site studies and reports on the facility and its history, regional geology and tectonics, hydrology and hydrogeology, site history, and contaminant distribution. Regional data from topographic maps and from geophysical measurements such as gravity, aeromagnetics, and seismicity were reviewed when available. A reconnaissance of the facility and the surrounding areas also was performed to better understand the regional geologic relationships and contaminant transport.

LandSat and historical aerial photographs also were consulted, and a fracture trace analysis was performed at the detailed site level on stereographic pairs of aerial photographs. The fracture trace analyses were used to evaluate how structural features observed on the surface from aerial photographs extended into the subsurface beneath a site. The available aerial photographs, including those at different scales and sun angles and from different seasonal time periods, were used to identify surface lineaments.

Lineaments are linear surface features that are identifiable primarily by subtle changes in the topography and shading of the ground surface as observed on stereographic pairs of aerial photographs. The vertical exaggeration inherent in stereo photographs aids in identifying linear topographic expressions. Lineaments cut across different surface terrain and often indicate a topographic expression where one side of the lineament is slightly higher than the other side, as though offset has occurred. Fractures and faults in bedrock or basement rocks often are expressed as lineaments that have subtle surface expressions. These features are propagated up through unconsolidated sediments to the surface as failure plains, a result that may be the result of minor occasional reactivation along the fractures and faults that occur as the result of seismic activity in the area. Materials that infill faults or fractures frequently have different shading than the surrounding surfaces that have never been fractured.

Investigators (Culbreth, 1988; Wobber, 1967; Parizek, 1976; and Rumsey, 1971) have found that lineaments can be identified in aerial photographs, even when sediments overlie the bedrock for hundreds of feet, and that they are manifestations of fractures or faults that have been propagated from bedrock to the surface through unconsolidated sediments and soil. The lineaments can be expressed by a variety of features (Hough, 1960), such as tonal changes in soil, changes in the directions of streams, straight segments in drainage patterns, or alignment of vegetation (because fractures are often more permeable, more water is available for enhanced growth of the plants). As a result of their work on LandSat imagery compared to outcrop patterns and geophysical data in Montana and Wyoming, Marrs and Raines (1984) concluded that the lineaments represented the surface expression of boundaries of crustal blocks that have been active throughout time.

The fracture trace analyses also were used to help interpret the seismic data sets. Linear features from the photographs often can be correlated with fractures or fault offsets found in the seismic data. The important lineaments at each site typically represented the vertical fracture matrix that included at least two sets of fracture directions approximately perpendicular to each other. The most often observed primary set of fractures were northwest-southeast and northeast-southwest trending. Also identified were nearly north-south and east-west trending sets. The vertical fracture sets are important because these fractures represent potential vertical migration pathways for DNAPL.

4.4.2 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, 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.

Multiple VSPs were performed at each site. The VSP data were collected in monitoring wells located within the boundaries of the 3-D survey grids whenever possible. The VSP surveys involved lowering a hydrophone into the well bore to a maximum depth, recording the data, and then raising the hydrophone in regular increments (typically 5 feet) to the top of the water surface. A hydrophone is a pressure sensor that can measure acoustic energy traveling in a liquid medium. The VSP signals were recorded with the same seismographs used to collect the 3-D surface data. A sledgehammer or weight-drop was used for the seismic source, which was impacted multiple times at each sensor depth. The source was positioned at a small horizontal distance away from the casing head to prevent accidental damage of the well casing. A geophone, which was pneumatically locked in place within the well bore, replaced the hydrophone as the seismic sensor when VSP data were collected in any dry portions of the well bore and above the water table. Note that the hydrophone was not locked in place within the well bore because it was already coupled acoustically to the rock surrounding the well through the water in the bore. Figure 19 shows a general schematic diagram that identifies the components of the recording system for the VSP.

The one-way travel time data acquired during the VSPs then was correlated to depth and changes in the stratigraphy in the boreholes. The time difference (i.e., one-way travel time) was measured as the difference between when the hammer or weight-drop hit the strike plate and when it was detected by the hydrophone/geophone. Subsurface seismic velocities then were calculated knowing both the travel time and the depth or distance to the sensor. One-way travel times were doubled, and slight corrections applied as a result of the offset between the wells and the source, to obtain two-way travel times. Two-way travel times were eventually used to convert travel time (in milliseconds [ms]) to depth (in feet) on the surface seismic sections. Since the surface sections plot reflections using two-way travel time as the vertical scale, the VSP data were used to provide reasonable values for actual depths to the bedrock horizons (expressed as reflections) and other features of interest on the seismic sections.

Although the well casing and grout have different acoustical properties than the surrounding rock, the wells do not adversely affect the VSP velocity data. The energy measured during the VSP surveys travels almost exclusively through the rock and soils, travelling through the well casing only at the receiver locations. In this study, the distance the seismic waves traveled through the well casings (a few inches) was so small, and the velocities of the well materials (steel, polyvinyl chloride, and concrete) were so fast in comparison to the distance traveled through, and the physical properties of the surrounding rock and soils, that the effect of the well casing on the travel times of the seismic waves was insignificant. In addition, the frequency and velocity of seismic waves traveling through the well casings were so high that they were easily identified in the seismic records. Any “tunnel waves” (seismic events caused by energy traveling down along the well casing) identified in the VSP data were removed during data processing.

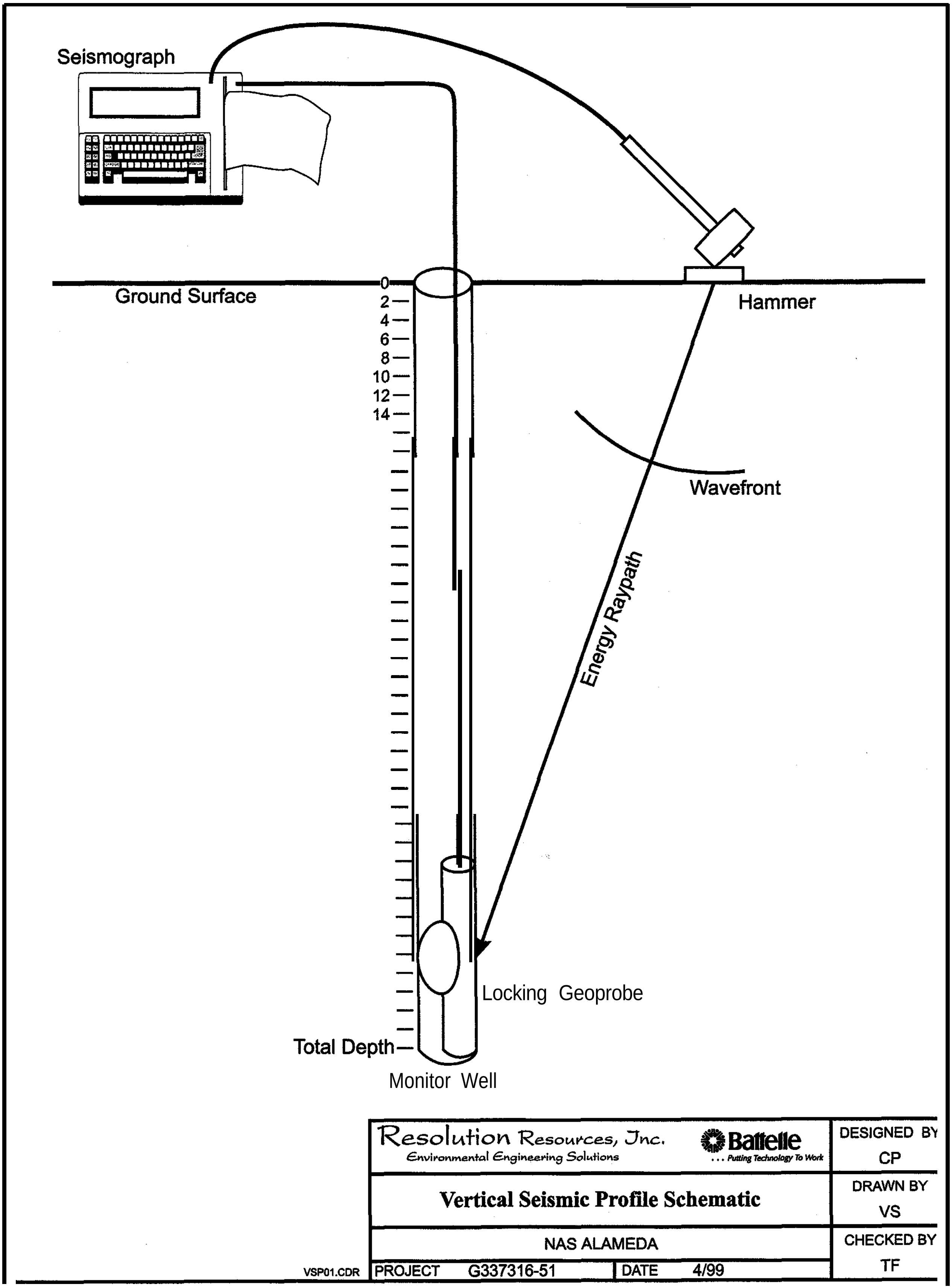

Figure 19. Vertical Seismic Profile Schematic

4.4.3 Land Survey. A land survey was performed before each 3-D seismic survey to accurately and precisely locate important site features and enable proper positioning of the pre-designed seismic survey grid relative to those features and to any anticipated target locations. The designed 3-D grid indicates the extent of the area to be characterized by the seismic survey. The size and orientation of the grid is determined by the estimated size of the contaminant source area and an estimate of the extent to which contaminants may have migrated laterally off of the site.

At each site a registered land survey team using an Electronic Distance Meter system located the positions of the receiver stations and source points with an accuracy of ±0.1 feet along the x, y, and z coordinates. The surveyed positions were recorded in the State Plane coordinate system appropriate for each site. Every station was marked either with a numbered flag on soil surfaces or with spray-paint on paved surfaces. The seismic cables, the geophones, and the other acquisition equipment then were placed at the marked positions. For the grid, locations for each receiver were flagged or spray-painted on the ground surface. Mean low sea level was used as the datum for the land survey of each site.

Accurate positioning of sensor and source point locations was extremely important in generating the highest quality seismic data. The high-resolution imaging benefits provided by 3-D seismic acquisition and 3-D migration processing techniques can only be achieved through precise control of survey grid geometry.

4.4.4 3-D Seismic Reflection Survey. Before the 3-D surveys began, the specific acoustic characteristics of each site were tested. The tests were used to select the recording parameters, which would optimize the quality of the acquired data. A "noise test" was conducted to determine the proper receiver-to-source geometry for the target depth. A source test was conducted to evaluate the number of stacks (the summation of repetitious source impacts) required to produce an acceptable signal-to-noise ratio. An analog filter test also was conducted to determine the best low cut and high cut filter settings for the seismic recording system. The analog filters helped to remove unwanted low and high frequency noise before the seismograph digitized the seismic data. Examples of low frequency noise include source-generated surface waves ("ground roll") and ambient seismic energy such as vehicle traffic. The most common source of high frequency noise is wind. The technical demonstration plans provide details on the recording parameters that were chosen during the tests. Details on the equipment utilized to perform the surveys also are presented in the demonstration plans.

The sizes of the 3-D surveys, the depths of concern, and surface conditions varied at the four sites. The geometry of the 3-D survey equipment was determined partially by technical factors such as the required depth of investigation, the shallowest zone of interest below ground surface, and the required resolution of the seismic imagery to be generated from the data. To delineate DNAPL source areas, a high-resolution 20-foot × 20-foot sensor (receiver) and source point grid was used at each site. Source lines were separated by 20 feet, and each source point along those lines were separated by 20 feet. Receiver lines were separated by 20 feet, and each geophone along those lines was separated by 20 feet. This geometry produced a subsurface bin size of 10 feet ×10 feet for each 3-D survey.

Bin size defines the spatial resolution of the data sampling in a 3-D survey. During data processing, bin size is used to equally grid all subsurface reflecting horizons. All data traces reflecting from a horizon within a specific bin area are combined (stacked) during processing. The stacking process outputs a data trace that uniquely represents the 2-D area of the subsurface defined by the bin. Small bin sizes and high fold (the multiplicity of reflections from within a bin) increase the resolution of 3-D seismic surveys. The 3-D surveys in this investigation were designed to have maximum fold (and therefore maximum resolution) over the areas of interest.

Data were acquired during the 3-D surveys with a systematic progression (Figure 20). During the surveys a 100-foot × 480-foot patch of geophones was active at all times. The active patch consisted of 6 receiver lines of 24 sensors each for a total of 144 "live" recording channels. Source lines were positioned along lines parallel to the sensor lines. A survey began when the first source point was impacted at a short distance (offset) from the first sensor position (#1) in the first receiver line (referenced as Line 1). A sufficient number of source impacts was summed (stacked) at the station to increase signal and to reduce noise. After each impact at source point #1, the analog data, produced by the 144 geophones, was transmitted by the common depth point seismic cables to the seismic recording system, where it was digitized, formatted, and stacked. Upon completion of all impacts at source point #1, the stacked data was then stored on the hard disk drives of the seismic system as a field record. The thermal printer on the seismograph also produced a plot of the data. The field record plots were monitored by the instrument observer, and were used as an aid for data quality control.

After data from source point #1 was acquired, the seismic source was then incrementally moved 20 feet along Line 1 to every source point located along the line. The same data collection procedure was followed at each source point. After the completion of all source points along Line 1, the source then was moved laterally 20 feet to Line 2. Data collection continued similarly along Line 2 with the source points being moved in 20-ft increments toward the starting point of the survey. Section A of Figure 20 illustrates the data acquisition procedure.

Following the collection of data from two consecutive rows of source points, the first two 24-channel receiver lines (Lines 1 and 2) were disconnected from the active 3-D patch and reconnected (as Lines 7 and 8) on the end of the patch. The second pair of receiver lines (Lines 3 and 4) then became the next source lines that were impacted. This "leap-frog" process was repeated throughout the survey until the active patch was "pushed" across the site. Sections B and C of Figure 20 illustrate the leap-frog acquisition process used during this investigation.

At the very beginning of each survey, and after the active patch was pushed through the end of the survey, some data points were collected using a different "static patch" configuration. In the static patch, the initial or final six receiver lines remained stationary throughout data collection. Source line locations and progression of source points were the same as previously described, with the exception that the receiver lines were not moved after two lines of source points were impacted. This method of data collection was required to achieve fold (density of data) at the

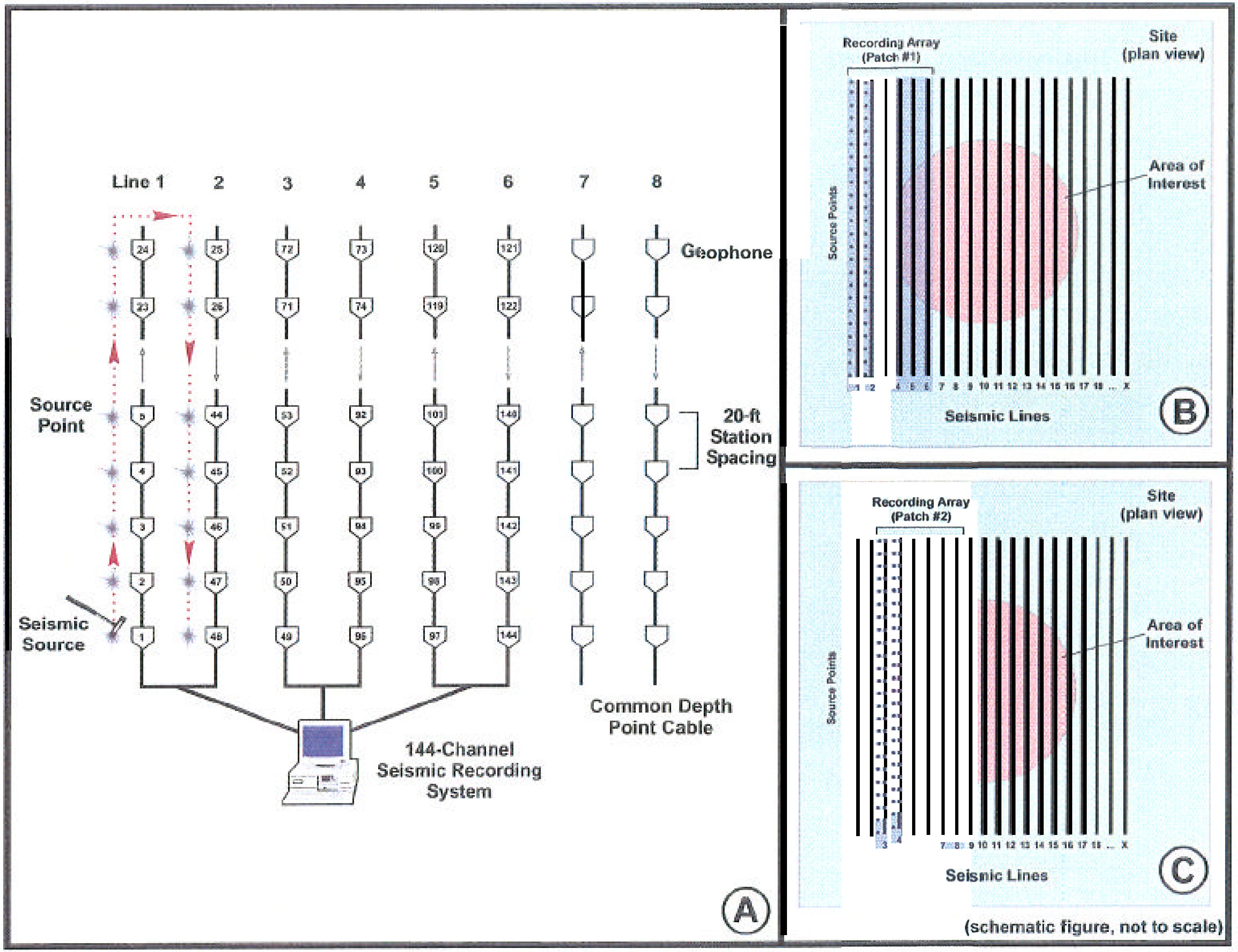

Figure 20. 3-D Data Acquisition Schematic

edges of the survey area, and where physical obstacles on the surface of the sites required a modification to the layout.

It should be noted that both data acquisition processes used during these surveys take advantage of asymmetric split-spread survey geometry. In a split-spread survey configuration, the geophones (receivers) are positioned at different distances (offsets) from each source location; they are not symmetrical about the source point. This pre-designed geometry was used to produce a better distribution of near offset receivers, which in turn yielded better data quality for the shallow reflectors. This geometry allowed the accurate imaging of reflectors as shallow as 10 feet.

4.4.5 3-D Data Processing and Interpretation. Data were transferred at the end of each day of the survey to a personal computer for archiving. After a 3-D survey was completed, a software program was used to convert the field data from the seismograph's recording format into an industry standard data exchange format, Society of Exploration Geophysicists Format Y (SEG Y). The SEG Y format can be recognized by advanced 3-D seismic data processing programs. The raw, or unprocessed, SEG Y files then were transferred from the personal computer onto 100-megabyte zip disks, and were delivered to Excel Geophysical Corp. (Denver, Colorado) where the 3-D data were processed.

Promax 3-D software (Excel Geophysical Corp.) and a UNIX workstation were used to complete the data processing. The following is a general description of the primary digital processing steps that were performed on the seismic data:

1. Edit Field Data.
   The SEG Y files were imported into the 3-D processing system and individually analyzed. All duplicates, excessively noisy traces, corrupted data traces, or traces with monofrequency signals (those with one primary frequency that did not contain a full spectrum of useful frequencies) were deleted. Any polarity reversals were also corrected at this time.

2. Create Geometry File.
   The coordinates of the source and receiver locations, which were measured during the land survey, were matched with the individual data traces. Corrections for any changes made in source or sensor positions during data collection (as detailed in the observer's log) were also made at this time. The spatial relationships among data collection points are required so the computer can correctly define the 3-D geometry of the subsurface.

3. Common Midpoint (CMP) Sorting (i.e., "Binning").
   The geometry files were used to combine the raw data traces into coherent 3-D data sets sorted into bins. Bins were used to grid the 3-D arrays, and are representative of geometric (typically square) areas within the subsurface. Data traces which had subsurface reflecting points located within a bin were sorted into sets

of traces called CMP gathers. The binning process transformed the data set from source-receiver coordinates into CMP-offset coordinates, which were required by the processing steps that followed.

4. Mute.
   Specific time-offset seismic events in the data sets were muted (deleted). These seismic events, which are characterized by high amplitude and strong coherency, include first arrival refractions, source-generated ground roll, and air blast.

5. Velocity Analysis.
   To attain geologic significance, seismic reflection data required conversion from a function of time to a function of depth. To achieve this conversion, a velocity model of the subsurface was created for each survey to correlate arrival times and depth across the sites. The models consisted of sets of correlated velocity-time pairs at different positions within the survey areas. A velocity model for the entire data volume of each 3-D survey was created by the computer, which spatially interpolated between analysis points.

   A technique called velocity animation was used to generate the initial velocity model for the surveys. Velocity spectra (seismic velocity as a function of travel time) were created for many CMP gathers; the gathers that were chosen represented a spatial sampling of a cross-section of the sites. The coherency of seismic reflection events across all data traces within the gathers then was analyzed. A multiplicity of different velocities was used to determine which root mean square velocities at which time (depth) produced the most coherent events on each gather.

   Velocity information obtained during the VSP profiles also was used in combination with the velocity spectra to increase the accuracy of the velocity model (Section 4.4.2).

6. Normal Moveout (NMO) Corrections.
   The first application of the velocity model was the NMO correction of the CMP gathers. NMO is the variation of arrival times of seismic reflection events resulting from increasing source-to-sensor separation (offset). All traces within a CMP gather have common subsurface reflecting points. These traces display events from the same subsurface reflectors, but the reflections occur at different arrival times because the acoustic energy has traveled greater distances to geophone positions with longer offsets.

   To remove the effects of NMO, a time correction (i.e., a translation of each trace within a CMP gather into a zero-offset position) was applied to each data set. The source-receiver geometry information and the velocity field were used to determine the appropriate NMO correction for all data traces within all CMP gathers.

As a result of the NMO correction, data traces were stretched in a time-varying manner, which caused the frequency content of the data to shift. Frequency distortion increased at extremely short arrival times (shallow depth) and large offsets. To prevent the degradation of the shallow events within the data sets, the highly distorted zones were muted from the affected traces.

7. Static Corrections.
   Before CMP stacking (Step 8) occurred, static corrections were calculated and applied to all data traces in each survey. The application of static corrections compensated for the effects of surface elevation differences among source and receiver locations. The static corrections adjusted the arrival times of all seismic events within the data set to the times which would have been observed had all the measurements been made on a flat plane (reference datum).

   The source-receiver station elevations were measured by the Electronic Distance Meter system during the land survey. The processing software interpolated elevations of stations not actually measured.

8. CMP Stacking.
   The CMP stack is the foundation of the multi-fold data acquisition process. Because all traces within the CMP gathers had been transposed to the same spatial location (the zero offset position), they could be "stacked." Stacking is the simple summation of the NMO corrected traces within each CMP gather. After stacking, each subsurface reflection point (i.e., CMP) was then represented by one trace, a composite of all traces within the gather.

   The stacking process increased the quality of the data sets by enhancing usable signals and removing noise. The signal strength of coherent (real) seismic events was increased during the trace summation, while the strength of incoherent or random events (including multiple reflections, ghost or imaginary reflections, and background noise) was greatly attenuated through destructive interference.

9. Digital Filtering.
   A digital band-pass filter was applied on all data traces to attenuate frequencies representing noise and non-reflection events.

10. Automatic Gain Compensation.
    The amplitude of signals on the data traces for each survey was increased to visually improve the data displays and aid interpretation. In general, the time-variant automatic gain compensation function applied to the data sets increased the amplitudes of late-arriving seismic events while leaving the amplitude of early events uncompensated.

After automatic gain compensation was applied, a trace balancing (amplitude equalization) scheme was used on the data sets to preserve the amplitude relationships among traces. Relative trace amplitudes were important for accurate interpretation of the data.

11. 3-D Migration.
    Migration functions impart 3-D seismic surveys the ability to accurately image complex subsurface geology. The 3-D migration functions were used because dipping stratigraphy, lateral velocity changes, and faults and fractures below the site, caused seismic reflections and diffractions to be recorded at positions within the seismic record different from their true subsurface positions. After applying migration functions, dipping events were moved back to their true subsurface position, and diffractions caused by faults/fractures were collapsed.

After the 3-D migration was completed, the seismic data set was completely processed and ready to be interpreted.

Micro-Seismic Technology's Kingdom Suite seismic analysis software was used to read and analyze the 3-D SEG Y files. This software, which is compatible with Microsoft® Windows, displays lines, crosslines, and arbitrary lines within the 3-D data volume, as shown schematically in section A of Figure 21. It is also possible to read the traces, extract selected time values, and display a depth (or time) slice. Time slices show the sites in plan view at different depths. The software was used to shade and display the traces in full color, which allows subtle changes in the geology to be more easily viewed and compared. The trace data were shaded using a 200-color rainbow scheme, with colors ranging from dark blue to white (section B of Figure 21). The color scheme presents the acoustic data as a series of layers of differing acoustic properties. The color scale was proportional to the voltage output of the geophone and to the ground motion sensed by the geophone. This is a result of the reflected wavefronts that arrive from geologic features. Very positive trace amplitude data were shaded white, and very negative values were shaded blue. In areas where the layers are more discontinuous, signals colored white or blue were disrupted and weak. The weaker signals were colored green, orange, or yellow.

During the evaluation of the data sets, each line, crossline, and time slice was reviewed and analyzed. Data interpretation began with the analysis of VSP wells because the reflection time to borehole lithology was known at these locations. During the data interpretation process, the geologic models generated for each site were continually referenced and compared with the seismic sections so that meaningful and geologically accurate interpretations could be generated.

In general, the lines and crosslines were most useful in analyzing stratigraphy represented by the reflector horizons. The time slices were very useful for assessing potential fracture directions (azimuths). Some time-depth data from the data volumes representing site-specific horizons of interest were imported into a surface mapping software program to contour surfaces of the horizons.

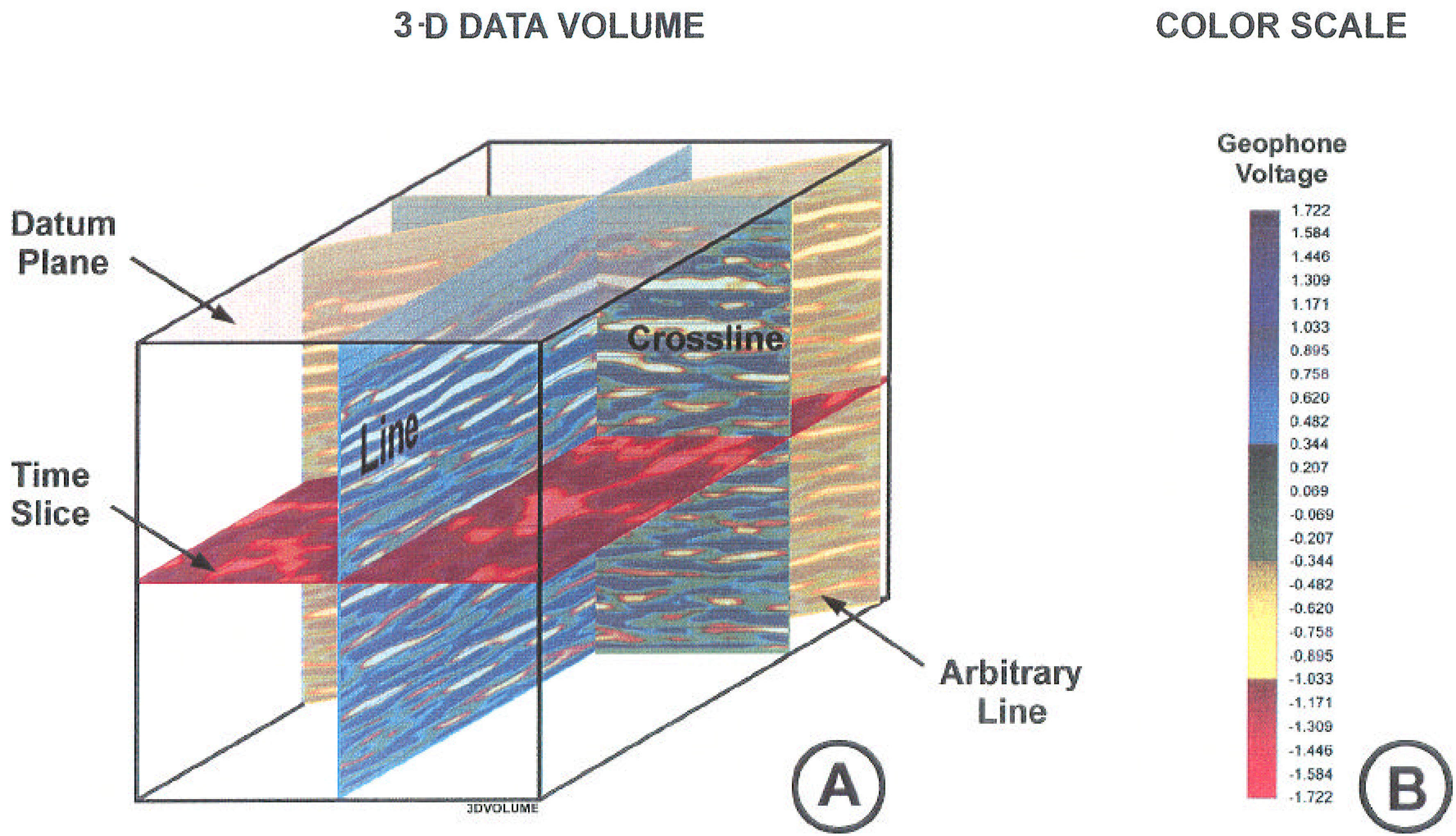

Figure 21. 3-D Data Volume Schematic and Seismic Plot Color Scale

Complex attribute analysis also was used to evaluate the data sets for instantaneous amplitude (envelope) attribute anomalies. Anomalies within the attribute plots that exhibited continuity with increasing depth, and which were limited in horizontal extent, were specifically targeted for analysis. It was believed that these anomalies might have indicated vertically fractured zones that were potentially impacted with DNAPL.

4.4.6 Attribute Analysis. A standard seismic section is a plot of the particle velocity at the geophone versus time. The line, crossline, and time slice figures are examples of these standard plots. Seismic data traces, however, cannot be completely characterized by these plots.

Seismic signals are functions of both time and frequency. Therefore, at any point in time an observed seismic trace is dependent upon the amplitude and phase of the individual frequencies that comprise its signal. A complex seismic trace attribute is a transformation that separates a seismic data trace into its amplitude and angular (phase and frequency) components. An attribute can emphasize aspects of the geology that were not obvious during the interpretation of the conventional seismic sections. Seismic attribute analysis can be applied to any line, crossline, or arbitrary line of the 3-D seismic data.

One of the most useful seismic attributes for mapping fracture networks is instantaneous amplitude, also known as envelope attribute. The envelope attribute is a polarity-independent measure of energy of each sample of the seismic data. Envelope amplitude can be plotted in color to highlight areas of amplitude variations, which can be caused by fracture zones or impacted groundwater.

It is well established that a seismic signal travels better and further in solid rock. It is also true that signal is lost more rapidly in highly fractured media (the principal mechanism for energy loss is the diffraction of seismic waves from irregular surfaces within the fractured zones). The envelope attribute provides a high definition map of fractured and jointed zones in the subsurface. Since the envelope seismic data are arranged in a 3-D cube, envelope attribute measurement is a good way to map fracture zones in all orientations and is the only available technique for the 3-D mapping of vertical fracture networks. Areas on the attribute plots that indicate vertical fracture zones are limited in horizontal extent and have large color changes that exhibit continuity with increasing depth.

If DNAPL is present, attenuation in the seismic signal (beyond what is expected by fracturing alone) often appears to be evident in the envelope attribute data. These “dim spots,” low amplitude envelope attributes, usually are observed just below and just downgradient of source areas. However, it currently is not possible to tell whether a particular attribute anomaly is a highly fractured zone that is not impacted by VOCs or is a less-fractured zone that is impacted by VOCs. Both possibilities may show the same changes in the acoustic signal. Currently, the only way to verify the source of the anomaly, DNAPL or otherwise, is through drilling and sampling.

Envelope attribute analysis was performed on the entire data sets, and large anomalies were evaluated. The analysis was used to determine recommendations for potential sampling locations and depths. Figure 22 shows the relationship of color scale on the envelope attribute plots to the degree of fracturing, and possibly the degree of fracturing and contamination.

The evaluation of the trace data (along the lines and crosslines and with depth) was used to correlate the 3-D seismic survey with the geologic model of each site. The correlation led to the identification of fracture and lineament traces and stratigraphic areas where free phase DNAPL contamination was most likely to occur. The attribute analysis performed on the seismic data then was focused within these areas to identify anomalies for further investigation by drilling and sampling. The areas (anomalies) proposed for investigation are referred to as targets or target well locations. Seismic plots were used to illustrate the location of a target well. The plots include the line, crossline, and attribute analysis in line and crossline. Seismic time slices at select two-way travel times were also used to explain the location of the target wells.

The targets were assigned a high, medium, or low confidence of encountering DNAPL. This qualitative ranking was based upon the following criteria: proximity of the anomaly to the source, structural location, occurrence within a fracture, and the anomaly size. For example, the characteristics of a target assigned a high confidence included a large anomaly within a fracture or structural low near the source of contamination. A target assigned a medium confidence of encountering DNAPL has these same characteristics, but the seismic anomaly was smaller or was connected to the source via a longer travel path. Targets assigned a low confidence represent anomalies near the source but not within an apparent preferential pathway, or small anomalies within structural lows or fractures indirectly connected to the source zones.

The 3-D seismic survey results for each of the four sites are briefly summarized below. Predictions for the potential locations of DNAPL at each of the sites also are presented. These locations represent the targets that were investigated by drilling and sampling to determine if DNAPL was present or absent. Complete discussions of the 3-D seismic survey results are presented in the technology demonstration plans for each site (Battelle, 1997b, c, and d; 1998a and b).

4.4.7 3-D Seismic Survey Results. The final output of data processing is a SEG-Y file of 3-D migrated trace data. The trace data were analyzed on a computer along lines, along crosslines, and from top to bottom along time slices. Micro-Seismic Technology's Kingdom Suite seismic analysis software was used to read and analyze the 3-D SEG Y files. This software displays lines, crosslines, and any set of traces representing a line crossing the data along an arbitrary azimuth (arbitrary line). It is also possible to read the traces, extract selected time values, and display a depth (or time) slice.

The software can shade and display the traces in full color, allowing the subtle changes in the geology to be more easily viewed and compared. The trace data were shaded using a 200-color rainbow scheme, with very positive trace amplitude data shaded white and very negative values shaded blue. The rainbow scheme presents the acoustic data as a series of layers of differing hardness. The colored scale is proportional to the voltage output of the geophone and to the ground motion sensed by the geophone as a result of the reflected wavefronts arriving from

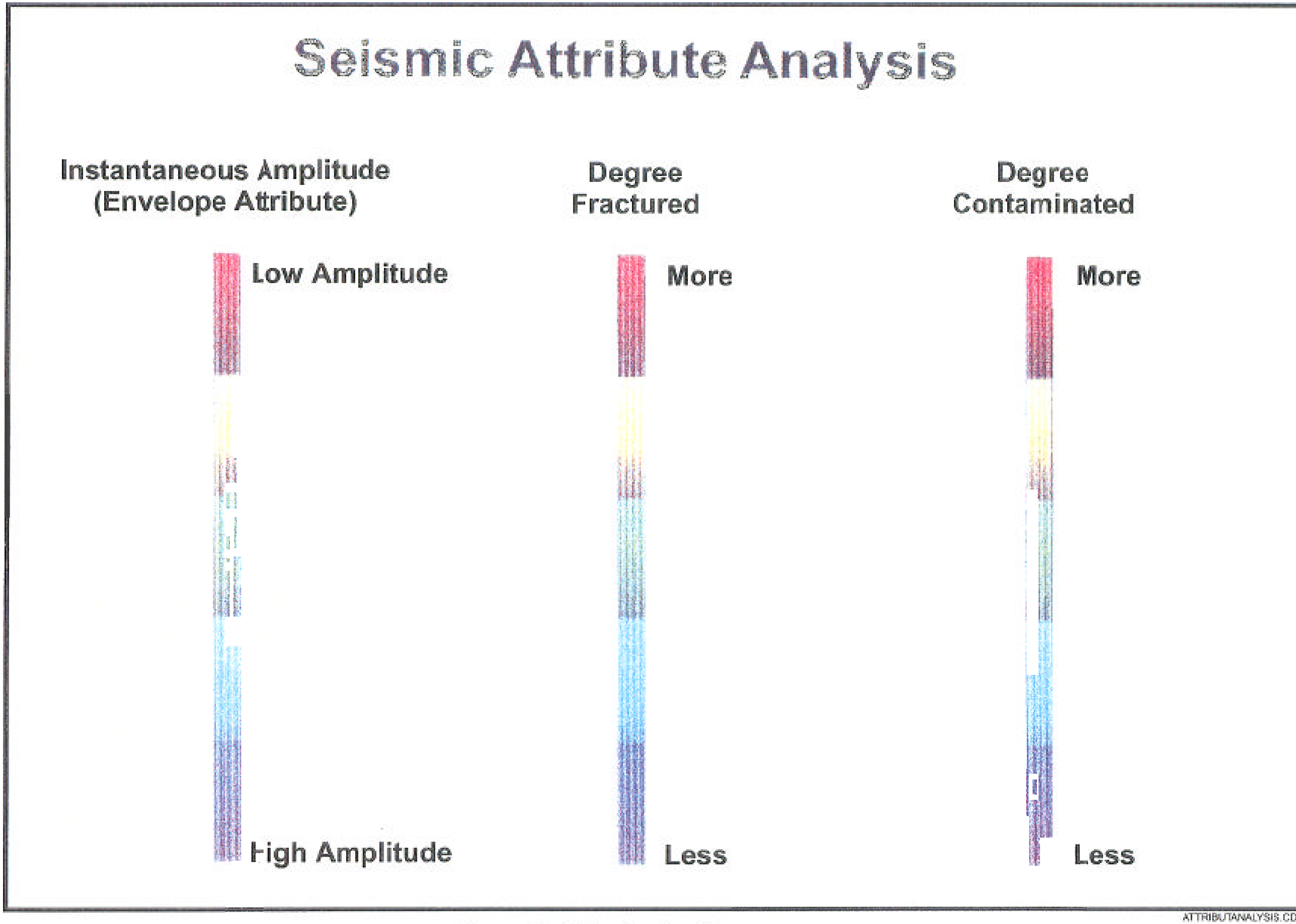

Figure 22. Seismic Attribute Analysis

geologic features. Positive deflections in amplitude (positive geophone voltage, shown as the color white) occur as the acoustic wave is reflected from the surface of softer layers. Negative deflections in the amplitude (negative geophone voltage, shown as the color blue) occur as the acoustic wave is reflected from the surface of harder layers. In areas where the layers are more continuous, the blue or white wavelets are strong and coherent. Where a fracture or fault occurs, the blue or white signals are disrupted and weak.

It is very important to note that the predictions (depths to features of interest) are based on the results of one or more VSPs completed in existing wells located within the survey area. The accuracy with which the VSPs represent conditions across the site governs the accuracy of the predicted depths at these locations. During drilling and sampling, seismic check shots were performed to refine the velocity model for each site and to refine the predictions, as necessary, during the field investigation.

4.4.7.1 Letterkenny Army Depot 3-D Seismic Survey Results. The 3-D seismic data set from Letterkenny Army Depot contains 7,500 traces, which are 10 feet apart and arranged as 75 lines trending northwest to southeast, each containing 100 traces. The traces also have been indexed as 100 lines trending southwest to northeast, each containing 75 traces. Figure 23 shows the seismic grid and other important site features. Note that the grid contains 75 rows of 100 columns, but the figure only shows every fifth line and crossline of the grid so that other site features also could be clearly shown.

The seismic survey results were used to make predictions at 10 locations with emphasis on the direct detection of DNAPL in the subsurface (Table 3). Locations 1-9 were selected as having a medium probability of encountering DNAPL at a predicted depth beneath ground surface.

Validation location LT-10 was a site selected near suspected contaminant sources as having a very low probability of encountering DNAPL. Source locations are specified by line and cross-line within the survey grid. The K-1 area is believed to be the main source of contamination of the soil and groundwater within the 3-D seismic survey. However, the K-2 and K-3 areas, as well as Area A (former dump site east of the survey) and Area B (former trash storage area), are in the disposal area and could be responsible for some of the anomalies which are present in the seismic data. For this demonstration, however, area K-1 was assumed to contain the source.

The seismic grid superimposed on the site features is shown in Figure 23. The K-1 area is bounded by seismic Lines 21 and 31, and Crosslines 42 and 62. It is not possible to drill within this area, because the area has been capped. Six targets were planned for evaluation (through the installation of temporary wells) as part of the demonstration at Letterkenny Army Depot. A total of 10 target locations were identified in the event that one or several of the targets could not be investigated. Each of the targets 1-9 were assigned a medium confidence of encountering DNAPL, primarily because none of the targets occur directly beneath the K-1 area. Each of the anomalies selected occur in preferential pathways such as fractures that pass directly beneath the K-1 area.

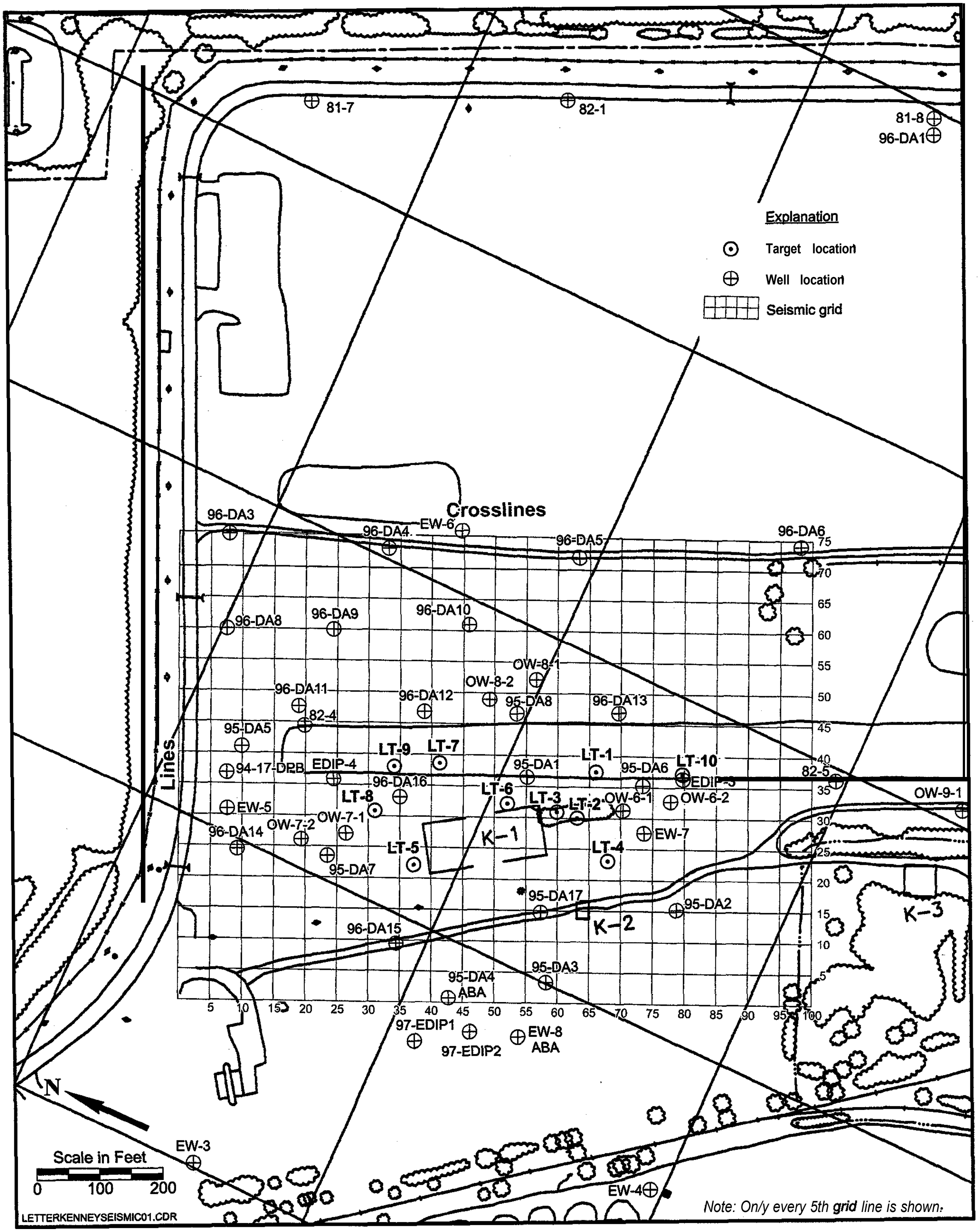

Figure 23. Letterkenny Army Depot Seismic Survey Grid and Target Locations

Table 3. Letterkenny Army Depot Validation Target Locations Based on Results from Attributes Analysis

Target Location	Seismic Location		Depth to Anomaly			Probability of Finding DNAPL	Discussion			
	Line	Crossline	Time (ms)	Projected Depth (ft bgs)	Drilled Depth (ft bgs)		Line	Crossline	Attribute	Time Slice
LT-1	38	34	145	330 Deep	340	Medium	Vertical fracture at Crossline 34; fracture is deep and apparent as shallow as 95 ms (~200 ft)	Voids present were created by fractures crossings joint sets	Large anomaly along a vertical fracture and within a void at the juncture of the fracture and joints	Time slice at 112 ms shows well would be drilled into a sink at the juncture of north-, northeast-, and northwest-trending fractures
LT-2	30	37	45	75 Shallow	85	Medium	Void at the juncture of 3 vertical/sub-vertical fractures and joints	Vertical fracture	Shallow anomaly between sub-vertical fractures; a trap forms as a result of joint planes, and along a vertical fracture	Time slice at 37 ms shows well would be drilled at the juncture of north-, northeast-, and northwest-trending fractures
LT-3	31	40	41	68 Shallow	78	Medium	Void at the juncture of 2 nearly vertical fractures	Vertical fracture	Shallow anomaly along a vertical fracture	Time slice at 37 ms shows well would be drilled at the juncture of northeast- and northwest-trending fractures
LT-4	23	32	61	120 Intermediate	140	Medium	Void at a vertical fracture	Vertical fracture	Large anomaly along a vertical fracture	Time slice at 37 ms shows well would be drilled at the juncture of north-, northeast-, and northwest-trending fractures
LT-5	23	63	33	37 Shallow	47	Medium	Down-dropped block between 2 vertical fractures, at the juncture of 2 joint planes	Vertical fracture	Large, shallow anomaly along thrust plane, and at the juncture of the plane with a vertical fracture	Time slice shows well would be drilled into a sink at the juncture of north-, northeast-, and northwest-trending fractures

Table 3. Letterkenny Army Depot Validation Target Locations Based on Results from Attributes Analysis (continued)

Target Location	Seismic Location		Depth to Anomaly			Probability of Finding DNAPL	Discussion			
	Line	Crossline	Time (ms)	Projected Depth (ft bgs)	Drilled Depth (ft bgs)		Line	Crossline	Attribute	Time Slice
LT-6	33	48	43	78 Shallow	88	Medium	Along joint plane and juncture of a vertical fracture	Along vertical fracture and joint planes	Medium sized anomaly shallow at vertical fracture location	Time slice shows well would be drilled into a sink at the juncture of north-, northeast-, and northwest-trending fractures
LT-7	39	59	148	340 Deep	350	Medium	Down-warped zone along a vertical fracture	Down-warped zone between 2 fractures; well is along vertical fracture within this zone	Large, deep anomaly along vertical fracture; small anomaly at 55 ms along same fracture	Time slice shows well would be drilled into a sink at the juncture of north-, east-, northeast-, and northwest-trending fractures
LT-8	31	69	41	65 Shallow	75	Medium	In folded zone at the juncture of vertical, northeast-trending fractures	At a low in a folded beds at the juncture of vertical, northwest-trending fractures	Two medium sized anomalies, one between 15-20 ms and the second between 30-25 ms, along vertical fractures	Time slice shows well would be drilled at the juncture of north-, northeast-, and northwest-trending fractures
LT-9	38	66	42	65 Shallow	75	Medium	At the juncture of vertical, northeast- and northwest-trending fractures	In vertical fracture within folded beds	Three small anomalies along vertical fractures separated by two northeast-trending fractures, and along northwest-trending fractures at the bottom	Time slice shows well would be drilled at the juncture of north- and northeast-trending fractures
LT-10	37	20	40	60 Shallow	70	Low	Relatively undeformed area	Relatively undeformed area	No anomalies present	Within a relatively unfractured block

bgs = below ground surface.

Four of the validation borings are shallow (0 to 150 feet), one boring is intermediate in depth (between 150 and 300 feet), and two borings are deep (more than 300 feet). Figures 24 through 28 are examples of the seismic analysis for proposed boring location LT-6. This analysis was performed and similar figures developed for each of the proposed targets at Letterkenny Army Depot and for each target identified at the other three sites. Figures 24 and 25 illustrate the seismic line and crossline traces for LT-6 used for correlation with the geologic model of the site. The location of the well and several fractures (shown as dark lines on the figures) are shown. The predicted top of bedrock has not been indicated on the figures. Figures 26 and 27 present the seismic envelope attribute along the line and crossline for LT-6. Figure 28 shows the seismic time slice at 37 ms for the shallow and intermediate targets at Letterkenny Army Depot.

In addition to estimating the likelihood of encountering DNAPL, the elevation of the top of weathered bedrock at each location was estimated from the 3-D seismic survey results. Table 4 includes the survey coordinates and top-of-bedrock predictions for the target borings at Letterkenny Army Depot. A map that depicted the surface topography of the top of the weathered bedrock surface also was generated from the interpretation of the seismic data.

Table 4. Letterkenny Army Depot Survey Coordinates and Weathered Bedrock Elevations at Proposed Validation Target Locations

Target Location	Seismic Location		Top of Weathered Bedrock		State Plane Coordinates	
	Line	Crossline	Time (ms)	Depth (ft bgs)	Northing (ft)	Easting (ft)
LT-1	38	34	27.50	22	247364.7	2031338.0
LT-2	30	37	31.25	25	247359.4	2031252.5
LT-3	31	40	33.75	27	247390.9	2031249.5
LT-4	23	32	26.25	21	247285.2	2031209.2
LT-5	23	63	33.75	27	247568.2	2031082.5
LT-6	33	48	33.75	27	247472.1	2031235.0
LT-7	39	59	41.25	33	247597.0	2031246.5
LT-8	31	69	32.50	26	247855.8	2031131.2
LT-9	38	66	32.50	26	247856.8	2031207.3
LT-10	37	20	28.75	23	247232.8	2031385.9

4.4.7.2 NAS Alameda 3-D Seismic Survey Results. Figure 29 shows the location of the seismic grid relative to features of Site 5 at NAS Alameda. The grid contains 71 lines trending east to west and spaced 10 feet apart, and 93 crosslines (or traces), trending south to north, with a total of 6,603 traces within the x, y grid. Each of these traces contains 1,520 time series samples, meaning that, acoustically, the site has been sampled at 10,036,560 locations.

Test wells were to be drilled and sampled originally at six locations to validate the seismic data. However, in an effort to investigate targets at or above the Bay Mud, a revised set of targets were identified for investigation using the Navy SCAPS unit. The original six target locations,

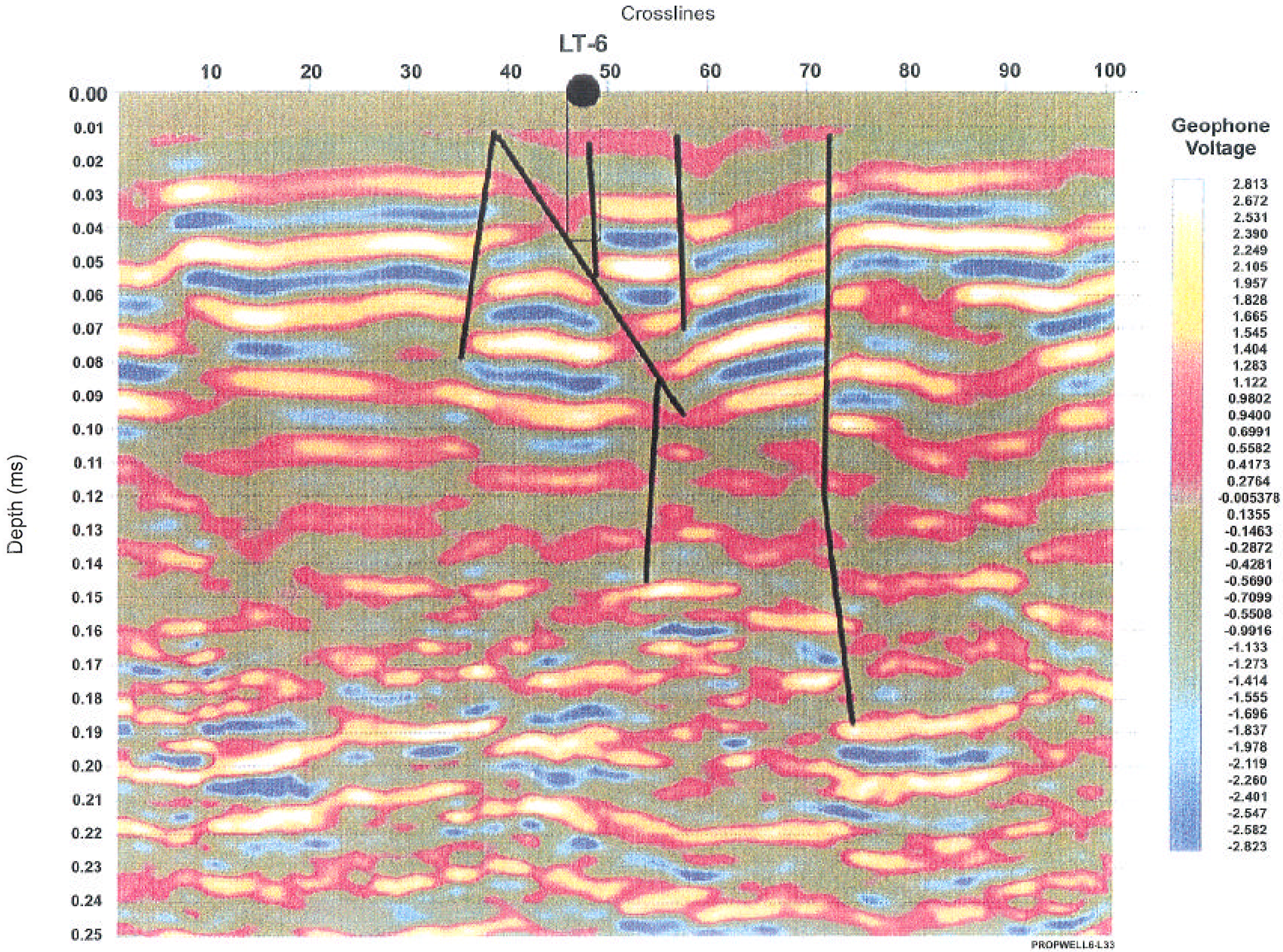

Figure 24. Validation Target LT-6, Line 33 at Letterkenny Army Depot

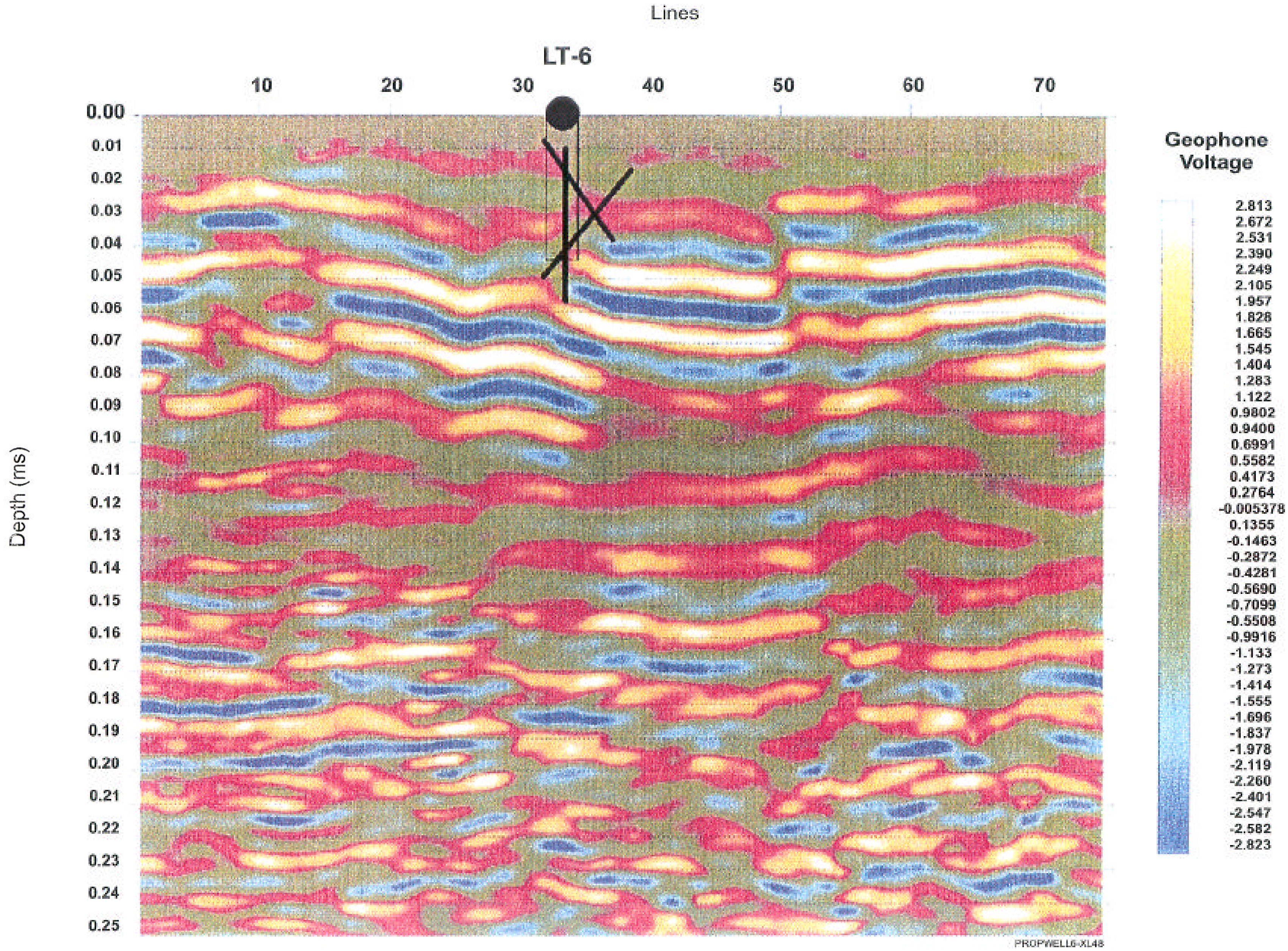

Figure 25. Validation Target LT-6, Crossline 48 at Letterkenny Army Depot

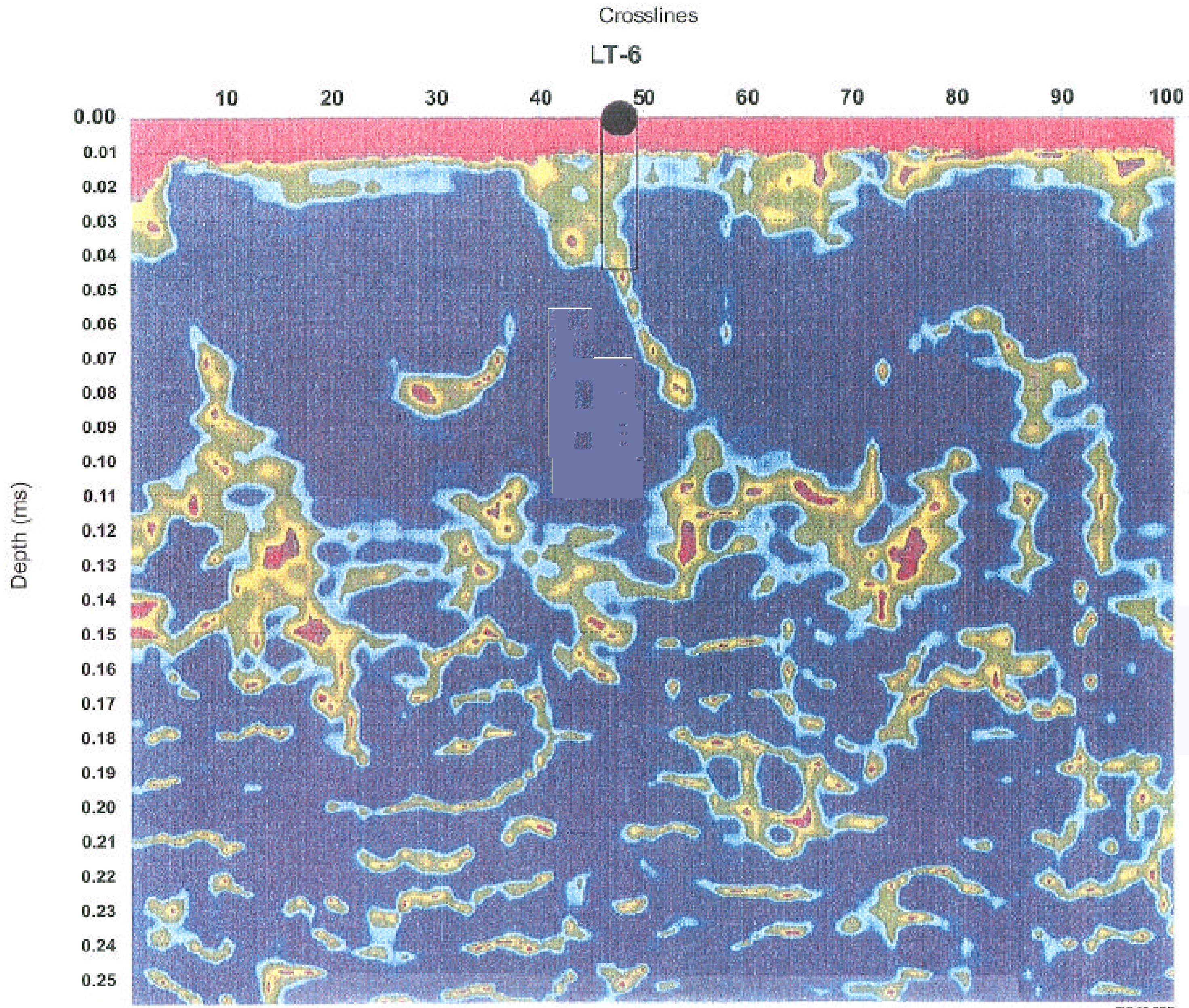

Figure 26. Envelope Attribute of Validation Target LT-6, Line 33 at Letterkenny Army Depot

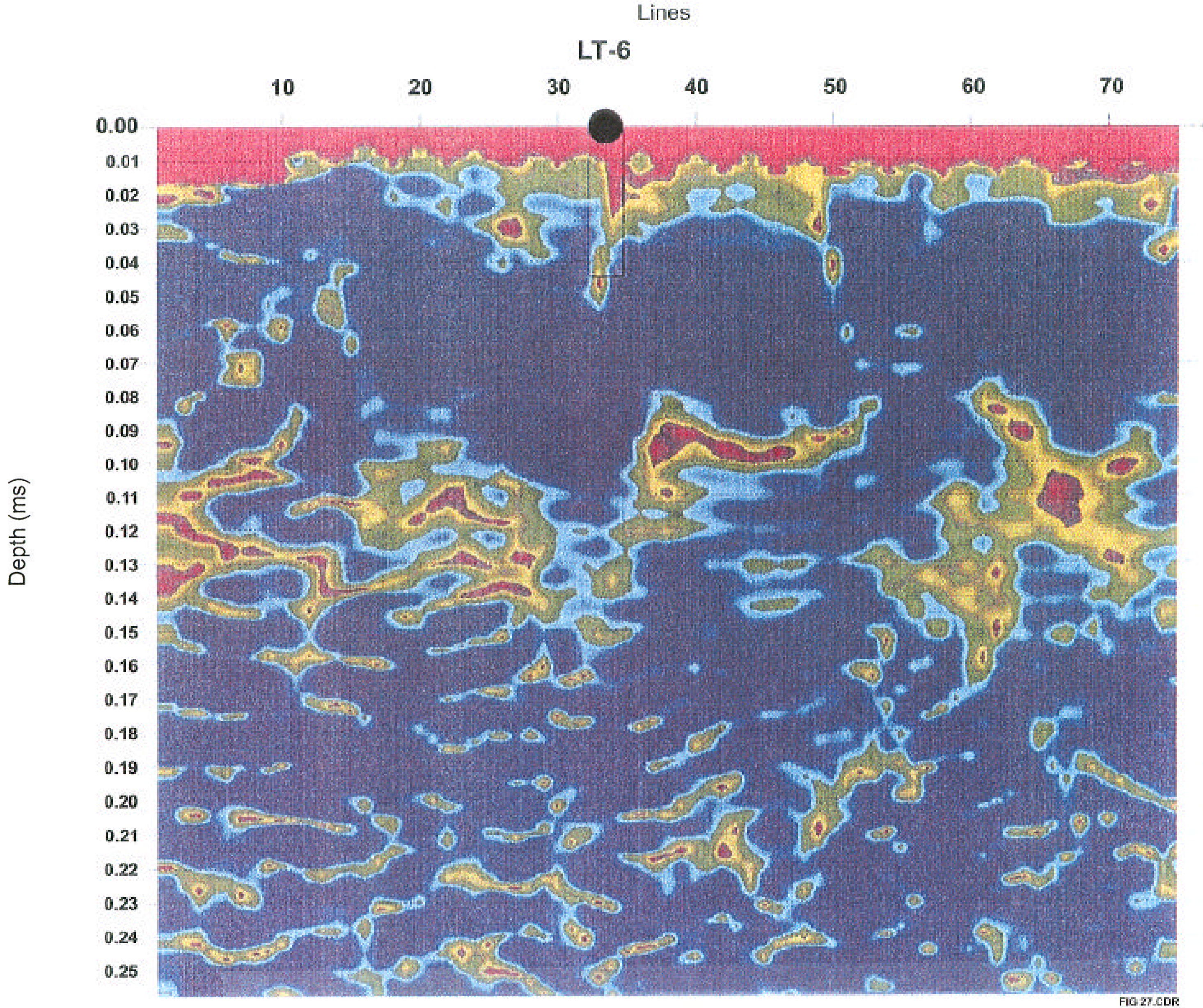

Figure 27. Envelope Attribute of Validation Target LT-6, Crossline 48 at Letterkenny Army Depot

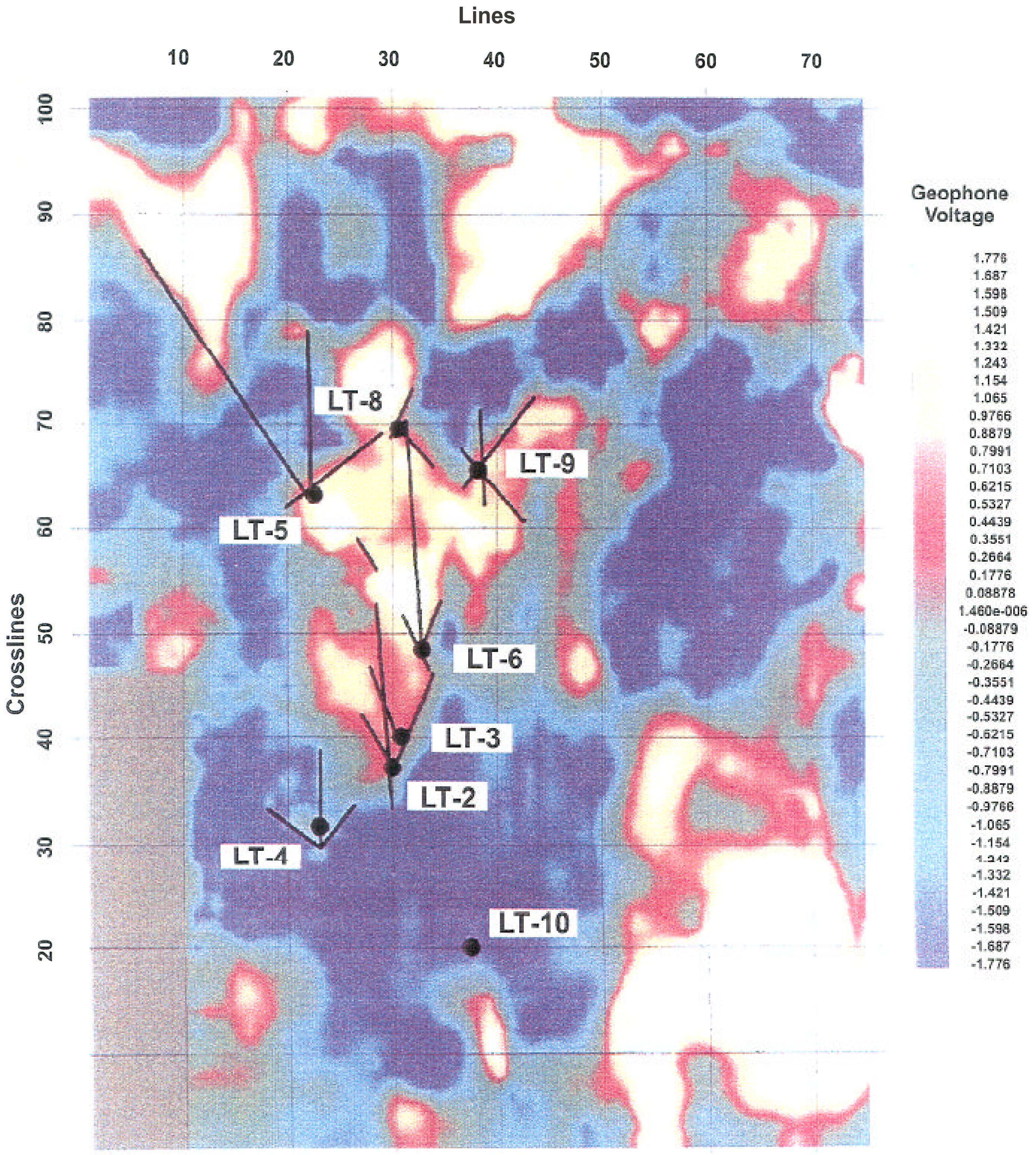

Figure 28. Time Slice at 37 ms at Letterkenny Army Depot

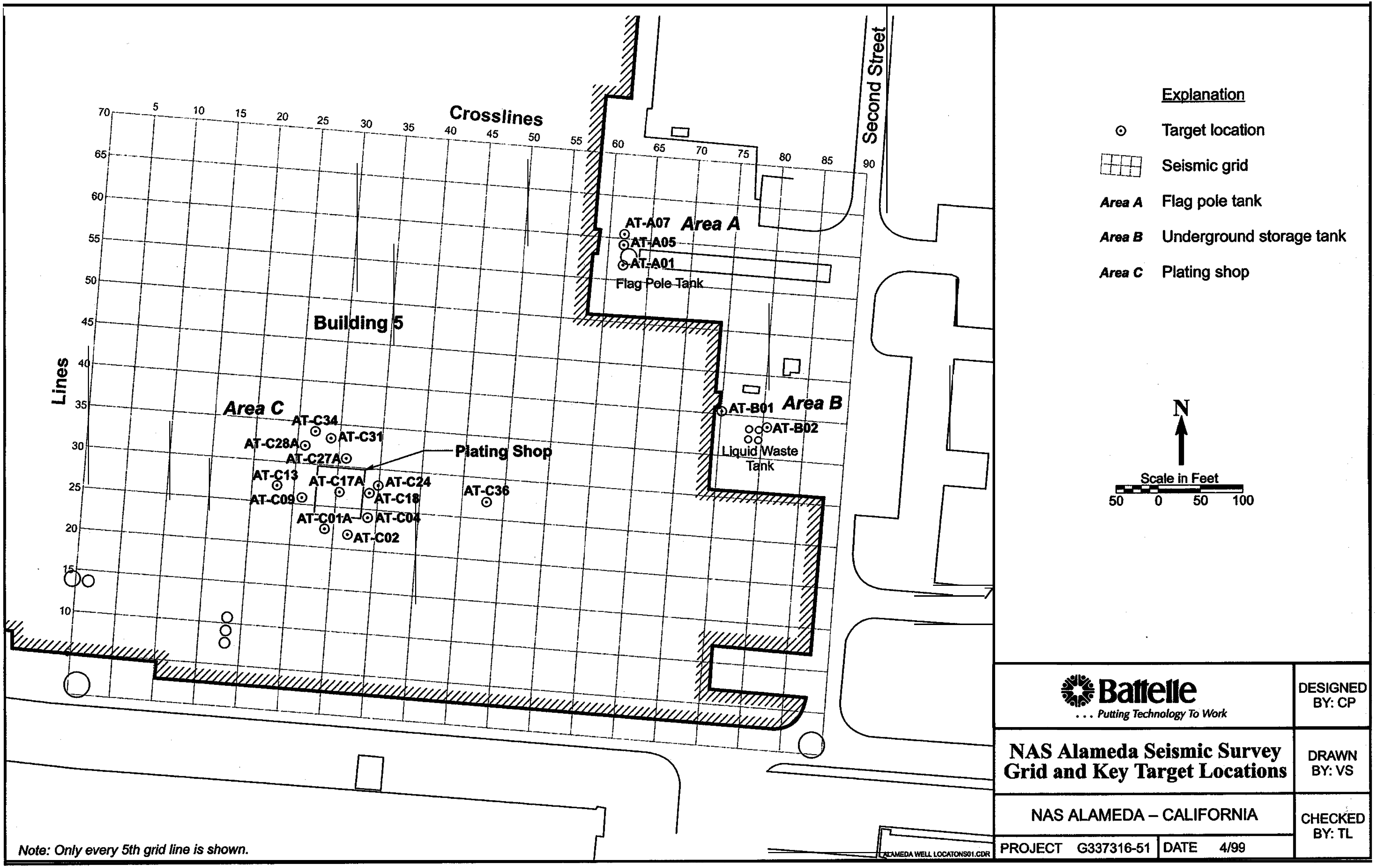

Figure 29. NAS Alameda Seismic Survey Grid and Key Target Locations

including DNAPL predictions, rationale, and stratigraphic predictions, are presented in Table 5 and in detail in the Addendum to the Draft Attributes Analysis and Verification Plan for Naval Air Station Alameda (Battelle, 1998a). Well points were installed using the SCAPS rig at two of these locations in Area C.

Table 5. NAS Alameda Survey Coordinates and Depths at Original Validation Target Locations

Target Location	Seismic Location		Layer 1		Well Depth		State Plane Coordinates		Probability of Finding DNAPL[a]
	Line	Crossline	Time (ms)	Depth (ft bgs)	Time (ms)	Drill (ft bgs)	Northing	Easting	
AT-B02	39	81	13	20	13	21	472649.84	1478984.54	Low
					31	72			Low
					44	113			Low
AT-A07	60	62	12	17	11	15	472871.50	1478815.75	Low
					14	22			Medium
					18	35			High
					21	45			Low
					28	65			None
					32	75			None
AT-C30	32	36	8	8	8	8	472616.82	1478540.23	Low
					20	42			Medium
					46	118			High
AT-C36	27	48	7	7	7	7	472557.81	1478645.67	Low
					20	42			Medium
					23	50			High/Free
AT-C37	27	31	8	8	11	15	472572.01	1478476.26	Medium
					31	72			High/Free
					49	127			High/Free
AT-C38	27	38	11	15	10	12	472566.16	1478546.02	Medium
					20	41			High/Free
					30	70			Medium
					38	94			High/Free

(a) None = 0-5 parts per billion (ppb).
Low = 5-1,000 ppb.
Medium = 1,000-10,000 ppb.
High = 10,000-1,000,000 ppb.
Free = Free product.

It was anticipated that direct push testing using a SCAPS unit could penetrate to about 50 feet bgs. Deeper targets were listed in the event that it was possible to penetrate deeper, or in case drilling was also performed and wells were installed.

Figure 29 shows the location of each potential SCAPS target tested by sampling through microwells (those lacking "GP" labels) on the seismic survey grid. SCAPS targets were located and posted on the map (Figure 29) according to the number of the seismic line on which they are located. The seismic grid coordinates and depth for each potential SCAPS target are provided in Table 6 for targets in Source Area 1 (plating shop), in Table 7 for targets in Source Area 2 (buried tank), and in Table 8 for targets in Source Area 3 (liquid waste tank).

A short discussion on why each target was selected based upon comparing interpreted stratigraphic information with attribute analysis is also provided in Tables 6 through 8.

In the area of the former plating shop, line 27 is especially important. The seismic profile for line 27 is present in Figure 30, while Figure 31 shows the envelope attribute of line 27. On line 27, significant anomalies are present on 10 crosslines. These anomalies range from small to large for this site, although the anomalies are not as large as many that are present at other installations that have been imaged. All of the targets that have been selected, except for a single target on crossline 42, are within a down-warped area, bracketed by a series of possibly compressional fractures. Within this area the contact with the Bay Mud is not distinct and may be absent. The target on crossline 42 is located at a vertical fracture, and the Bay Mud (blue) is clearly present to the east of this crossline, in a down-warped section 20 feet wide. This second down-warped, deformed "basin" extends to crossline 55. Four of the targets depicted on line 27 were evaluated during the validation. Validation probings were performed at the AT-C13, AT-C17, and AT-C18 locations. Results from these tests are presented in Section 5.

There are fewer anomalies at the location of the former buried tank near the flagpole. The main area of interest is from line 57 to 60 (30 feet), centered at crossline 62.

No seismic anomalies that would indicate the presence of DNAPL have been noted at the former liquid waste tank. However, line 40 in the area of the former potential source between crosslines 73 to 83 shows an anomaly that is flat-lying, and which may be indicative of stratigraphy, the water table, or light, nonaqueous-phase liquids (LNAPLs).

4.4.7.3 Tinker AFB 3-D Seismic Survey Results. The 3-D data set from Tinker AFB contains 3,264 traces. The grid contains 51 lines trending west to east, each containing 64 traces and spaced 10 feet apart. The traces have also been indexed as 64 lines trending south to north, each containing 51 traces. Figure 32 shows the seismic grid and other important site features. Note that the grid contains 51 rows of 64 columns.

The seismic survey results were used to make predictions at a total of 26 locations with an emphasis on attempting direct detection of DNAPL in the subsurface. Eight of the 26 selected locations were within Building 3001. These locations, which are considered most favorable due to their close proximity to known DNAPL release points, were not accessible for this validation exercise. However, six of the remaining 18 locations, all located just west of Building 3001 as depicted in Figure 32, are also thought to have some (low) probability of encountering DNAPL at the predicted depths beneath ground surface (see Table 9). Figures 33 through 36 are seismic profiles that show subsurface conditions along line 21 and crossline 44 in the area directly west of Building 2001. Validation target locations TT-1, -2, -3, and -4 are located along crossline 44.

Table 6. NAS Alameda Proposed SCAPS Targets at Source Area 1

Target Location	Seismic Location		Depth to Anomaly		Size of Anomaly	Discussion
	Line	Crossline	Time (ms)	Depth (ft bgs)		
AT-C01A	22	29	24	53	Large	Structural low at juncture of vertical and NE-trending fracture; Bay Mud may be absent in downdropped block, 40 feet wide from crossline 28 to 32.
AT-C02		32	24	53	Large	Structural low at juncture of vertical and NW-trending fracture.
AT-C03A	23	32	22	48	Large	At juncture of vertical and NW-trending fracture.
AT-C03B		41	25	55	Small	At juncture of vertical and NW-trending fracture.
AT-C03C		41	42	105	Medium	At juncture of vertical and NW-trending fracture.
AT-C04	24	34	20	40	Large	At juncture of NW- and NE-trending fractures.
AT-C05		39	11	15	Large	At juncture of vertical and NW-trending fracture.
AT-C06A		40	27	63	Medium	Along vertical fracture.
AT-C06B		40	39	98	Small	At juncture of vertical and NW-trending fracture.
AT-C07	25	35	24	53	Large	Within vertical fracture at juncture with NE-trending fracture zone. Bay mud appears to be obscure.
AT-C08		40	27	63	Medium	Within vertical fracture zone, down-dropped area.
AT-C09	26	26	22	48	Medium	At juncture of vertical and NW-trending fracture in area where Bay Mud appears to be breached.
AT-C10A		34	11	15	Large	Within vertical fracture in area where Bay Mud appears to be obscure.
AT-C10B		34	27	63	Medium	In trap below juncture of vertical and NE-trending fracture.
AT-C11A		40	12	18	Large	Along vertical fracture in down-dropped block.
AT-C11B		40	32	75	Small	Along vertical fracture in down-dropped block.
AT-C12	27	22	18	35	Small	Along vertical fracture at bottom of sandy fill at low in contact with Bay Mud.
AT-C13		23	18	35	Medium	Along small vertical fracture at juncture with compressional fracture at low in contact of fill with Bay Mud.
AT-C14		24	27	63	Medium	Along compressional fracture at top of Bay Mud.
AT-C15		27	27	63	Medium (two)	Along small vertical fracture that intersects NW-trending and NE-trending set of fractures. The first anomaly is the result of the two compressional fractures along the vertical fracture. The second anomaly is at the juncture of a NE- and NW-trending fracture.
AT-C16A		28	23	50	Large	Along vertical fracture, at juncture of NE-trending fracture zone.
AT-C16B		28	38	95	Small	Along vertical fracture, at top of confining zone.
AT-C17A		30	23	50	Large	Along vertical fracture zone.
AT-C17B		30	48	125	Small	Along vertical fracture zone at juncture of NE-trending fracture below sand lense.
AT-C18A		34	23-27	50-63	Medium	Along vertical fracture zone at juncture of NE-trending fracture.

Table 6. NAS Alameda Proposed SCAPS Targets at Source Area 1 (continued)

Target Location	Seismic Location		Depth to Anomaly		Size of Anomaly	Discussion
	Line	Crossline	Time (ms)	Depth (ft bgs)		
AT-C18B	27	34	37	90	Medium	At NE-trending fracture downgradient of vertical fracture to the east.
AT-C19A	(cont)	35	23	50	Medium	At juncture of vertical and NE-trending fracture.
AT-C19B		35	33	80	Medium	At juncture of vertical and NE-trending fracture.
AT-C20A		36	18	35	Large	Along vertical fracture.
AT-C20B		36	46	118	Medium	Within sand lens along vertical fracture.
AT-C21		42	27	63	Small	Four small anomalies along vertical fracture.
AT-C22A	28	26	16	30	Large	Within dropped down zone between 2 vertical fractures, Bay Mud appears to be obscured.
AT-C22B		26	24	53	Small	Within dropped down zone between 2 vertical fractures and at NE-trending fracture plane.
AT-C23		33	22-33	48-80	Medium	Along vertical fracture zone.
AT-C24		35	23	50	Medium	Along vertical fracture zone.
AT-C25A	29	29	12	18	Medium	In zone where Bay Mud appears to be absent, along vertical fracture.
AT-C25B		29	33	80	Medium	Deeper along vertical fracture at juncture of NW-trending fracture.
AT-C26		35	35	85	Medium	Along vertical fracture, below NE-trending fracture at juncture to NW-trending fracture.
AT-C27A	31	31	11	15	Medium	Along vertical fracture at juncture of NW-trending fracture.
AT-C27B		31	33	80	Medium	Along vertical fracture at juncture of NW-trending fracture.
AT-C28A	32	26	12	18	Large	Along vertical fracture.
AT-C28B		26	23	50	Medium	Along vertical fracture at juncture with NE-trending fracture.
AT-C29		30	35	85	Medium	Along nearly vertical fracture small anomaly appears at 12-18 ms, then a medium anomaly appears at juncture between vertical and NE-trending fracture.
AT-C30		36	22-49	48-128	Large	Migration of fluids along nearly vertical fracture and at juncture of NW- and NE-trending fractures over an interval of 69 feet.
AT-C31	33	29	18-48	35-125	Large	Along vertical fracture at interval between 3 NE-trending fractures.
AT-C32		32	29-33	68-80	Large	Along nearly vertical fracture at juncture with 2 NE-trending fractures.
AT-C33	34	21	11	15	Small	Nearly vertical fracture in down-dropped area.
AT-C34		27	18-23	35-50	Medium	Along nearly vertical fracture at juncture with NE-trending fracture.
AT-C35A		32	9	9	Medium	Along nearly vertical fracture at juncture with NE-trending fracture.
AT-C35B		32	24	53	Medium	Along vertical fracture just below juncture with NE- and NW-trending fracture.

Table 7. NAS Alameda Proposed SCAPS Validation Targets at Source Area 2

Target Location	Seismic Location		Depth to Anomaly		Size of Anomaly	Discussion
	Line	Crossline	Time (ms)	Depth (ft bgs)		
AT-A01	57	62	25	55	Medium	Along nearly vertical fracture, below juncture with NE-trending fracture.
AT-A02		62	45	115	Medium	Along nearly vertical fracture, below juncture with NE-trending fracture.
AT-A03	58	62	27	63	Large	Along vertical fracture at edge of downdropped block, at juncture of vertical fracture and NE-trending fracture.
AT-A04		62	50	130	Small	Along vertical fracture at edge of downdropped block, at juncture with NW-trending fracture.
AT-A05	59	62	23	50	Large	Along vertical fracture.
AT-A06		62	40	100	Small	Along vertical fracture above juncture of NE-trending fracture.
AT-A07	60	62	20	40	Medium	Along vertical fracture.
AT-A08		62	36	88	Small	Along vertical fracture.

Table 8. NAS Alameda Proposed SCAPS Validation Target at Source Area 3

Target Location	Seismic Location		Depth of Anomaly		Size of Anomaly	Discussion
	Line	Crossline	Time (ms)	Depth (ft bgs)		
AT-B01	40	75	7	7	Medium	Flat-lying, unlikely to be DNAPL, may be lighter than water.

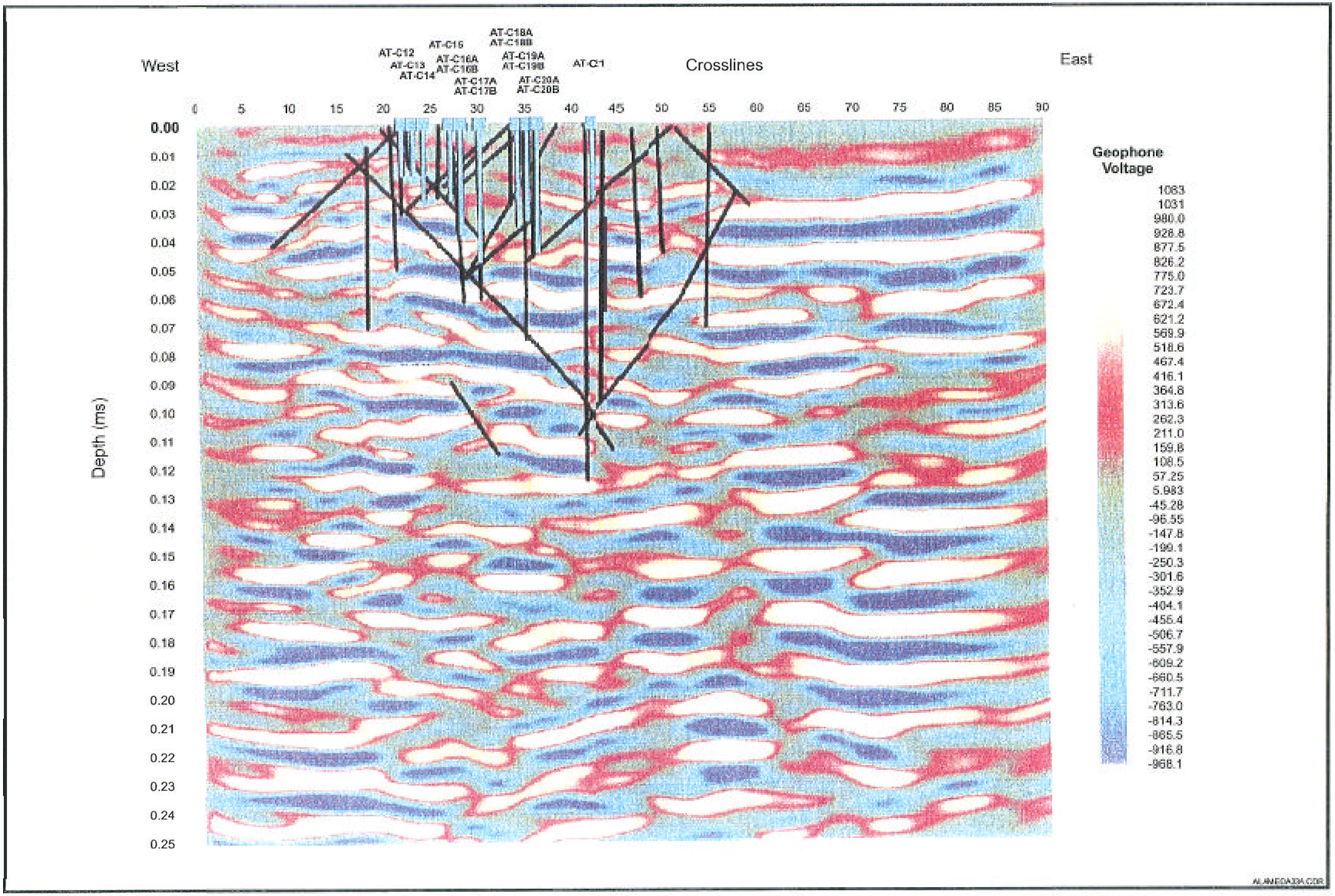

Figure 30. Validation Targets, Line 27 at NAS Alameda, Area C

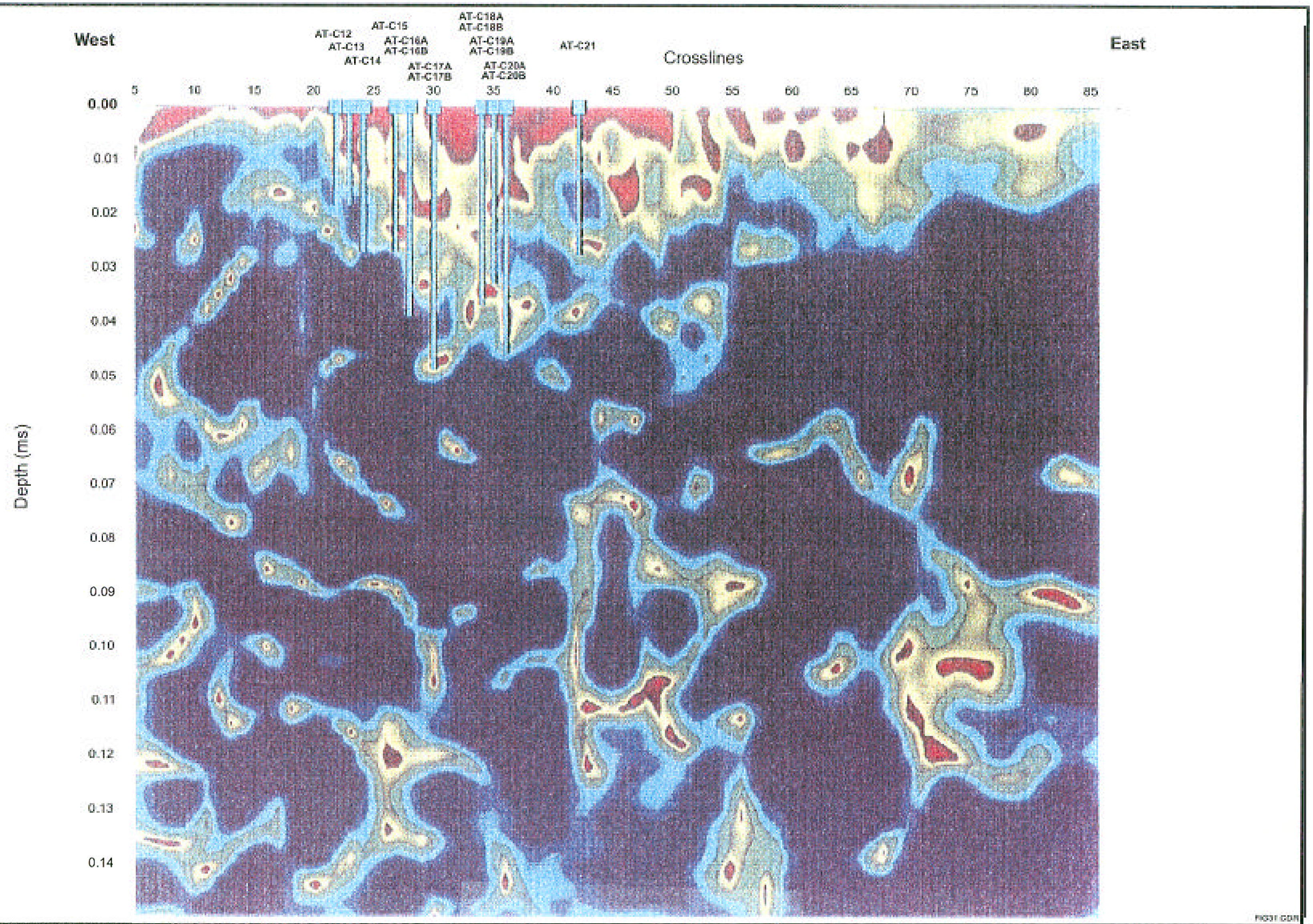

Figure 31. Envelope Attribute of Validation Targets, Line 27 at NAS Alameda Area C

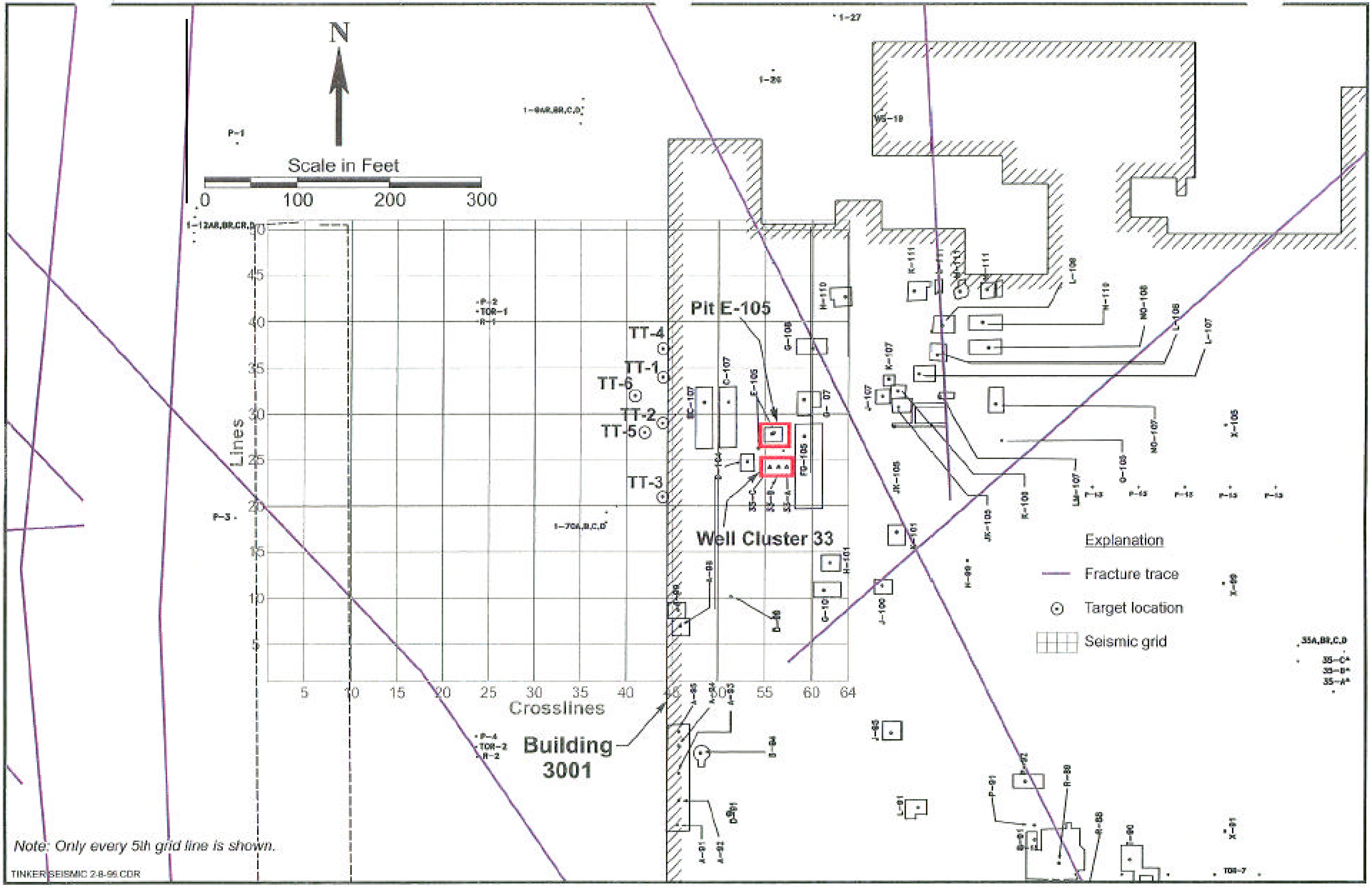

Figure 32. Tinker AFB Seismic Survey Grid and Target Locations

Table 9. Tinker AFB Validation Target Locations Based on Results from Attributes Analysis

Target Location	Seismic Location		Depth to Anomaly		Probability of Finding DNAPL	Discussion			
	Line	Cross-line	Time (ms)	Depth (ft bgs)		Line	Crossline	Attribute	Time Slice
TT-1	34	44	32	61	Low	Along vertical fault at juncture with joint and on the downthrown side of the fault block.	Along vertical fracture	Along vertical fracture at juncture of joint, in low at competent bed-rock surface, crossline attribute section shows there may be leak of fluids from the east	At juncture of north- and northeast-trending fault
TT-2	29	44	49	114	Low	Along vertical fracture intercepted by 2 joints trending northwest and northeast	Along vertical fracture in very fractured zone	Along vertical fracture in connection with jointing located at low in down dropped block	At juncture of northwest-, northeast-, and north-trending fractures
TT-3	21	44	61	165	Low	Along vertical fracture in very fractured area, in interconnection with 2 joints from the northeast	Along vertical fracture in very fractured area, in interconnection with 2 joints from northeast and 2 joints trending northwest	In low, along vertical fracture	At juncture of north-, northeast-, and north-trending fractures
TT-4	37	44	33	64	Low	Along vertical fracture, at low in possible confining layer, in inter-connection with 2 northeast-trending joints, some fluids could leak from northwest-trending fracture that intersects with vertical fracture at shallow depth of 15 ms.	Along vertical fracture in interconnection with northeast- and northwest-trending fractures, at possible confining layer	At possible bench in downthrown block	At juncture of north- and east-trending fractures
TT-5	28	42	28	230	Low	Along vertical fault in connection with northwest-trending joint and northeast-trending fault	Along vertical fracture in connection with large joints in fractures	Small anomalies along vertical fracture	At juncture of northeast- and northwest-trending fractures
TT-6	32	41	32	104	Low	At juncture of 3 fractures	Along vertical fracture in connection with multiple joints	Medium sized anomaly in connection with fracture	At juncture of northeast-, north-, and northwest-trending fractures

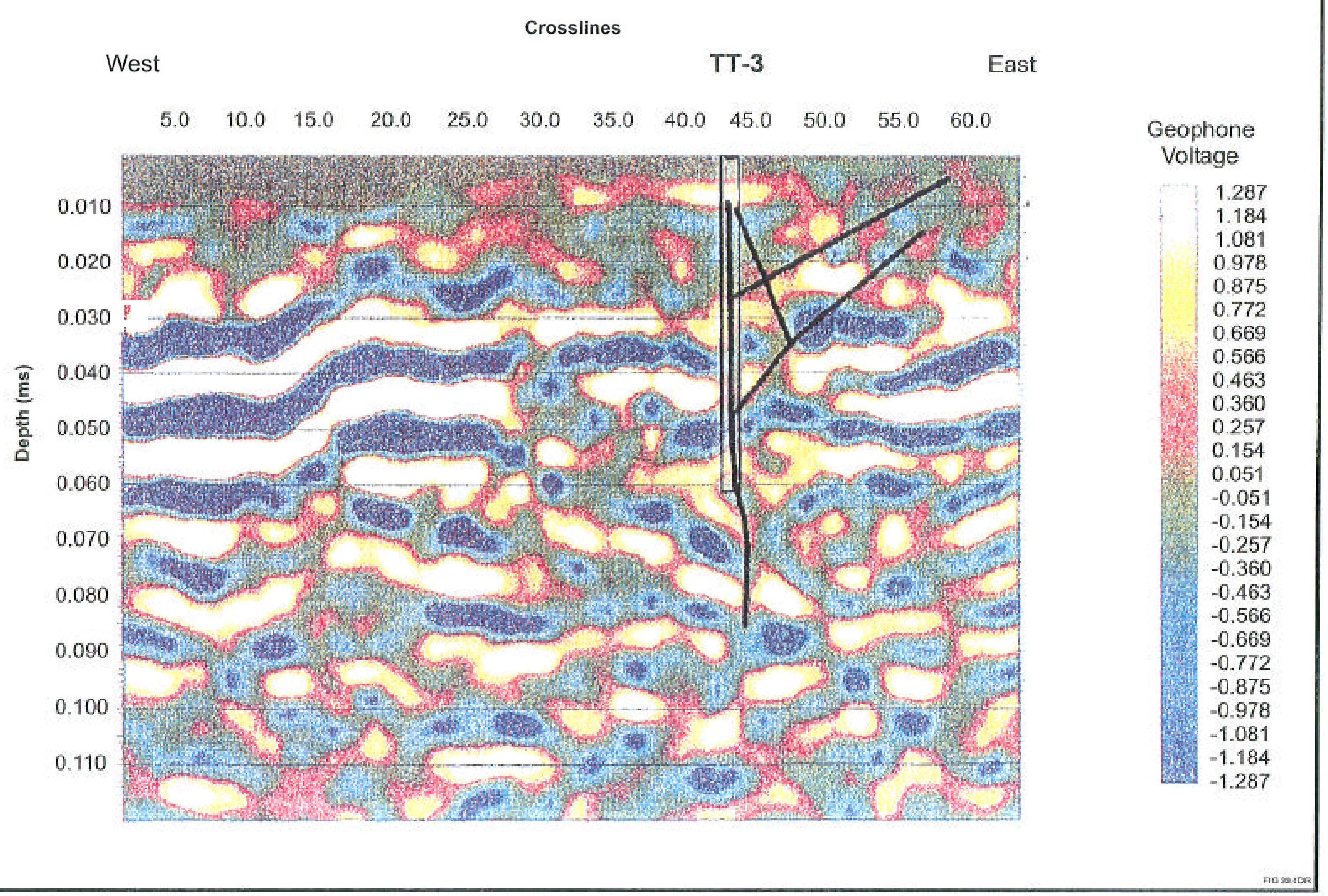

Figure 33. Validation Target TT-3, Line 21 at Tinker AFB

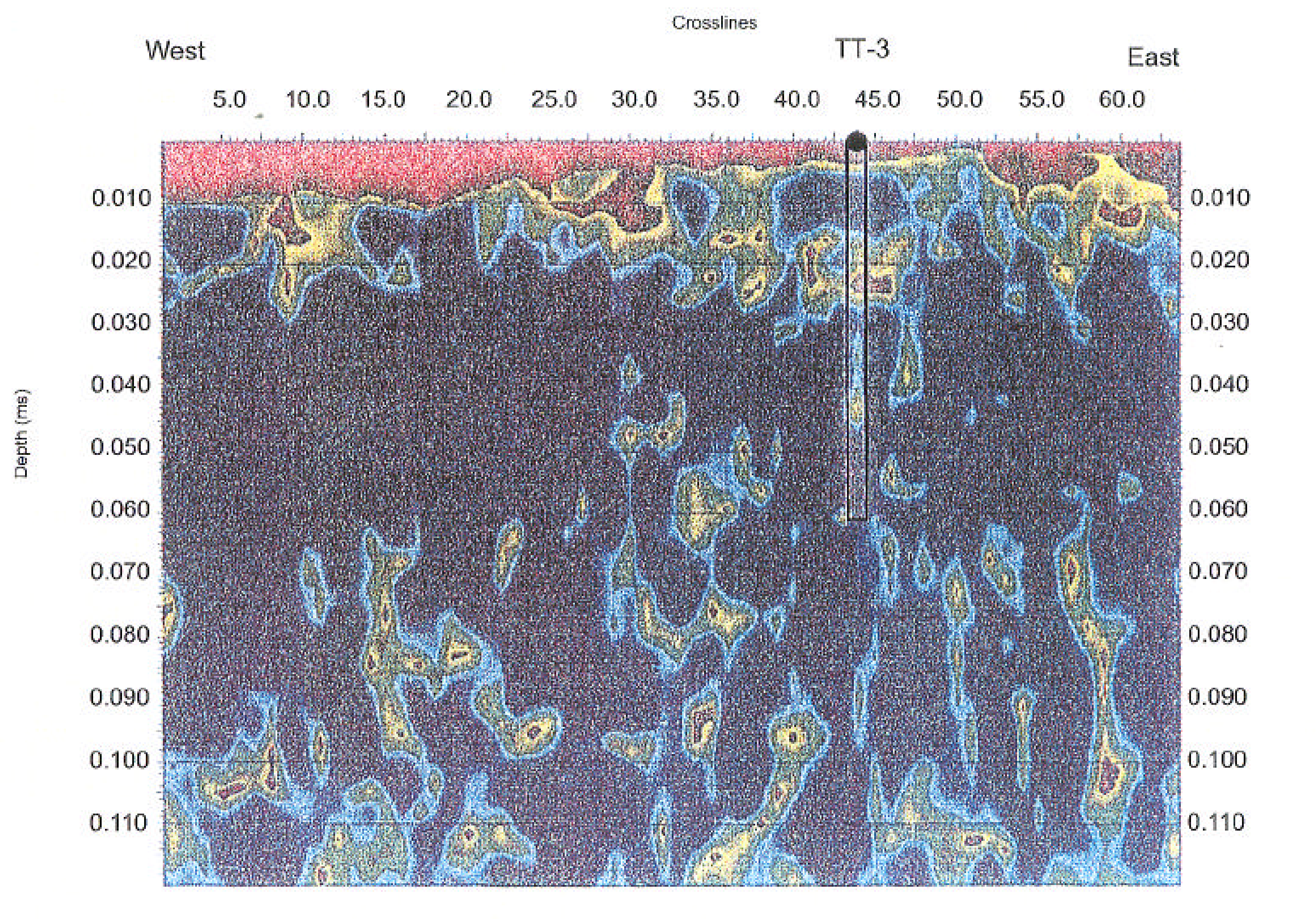

Figure 34. Envelope Attribute of Validation Target TT-3, Line 21 at Tinker AFB

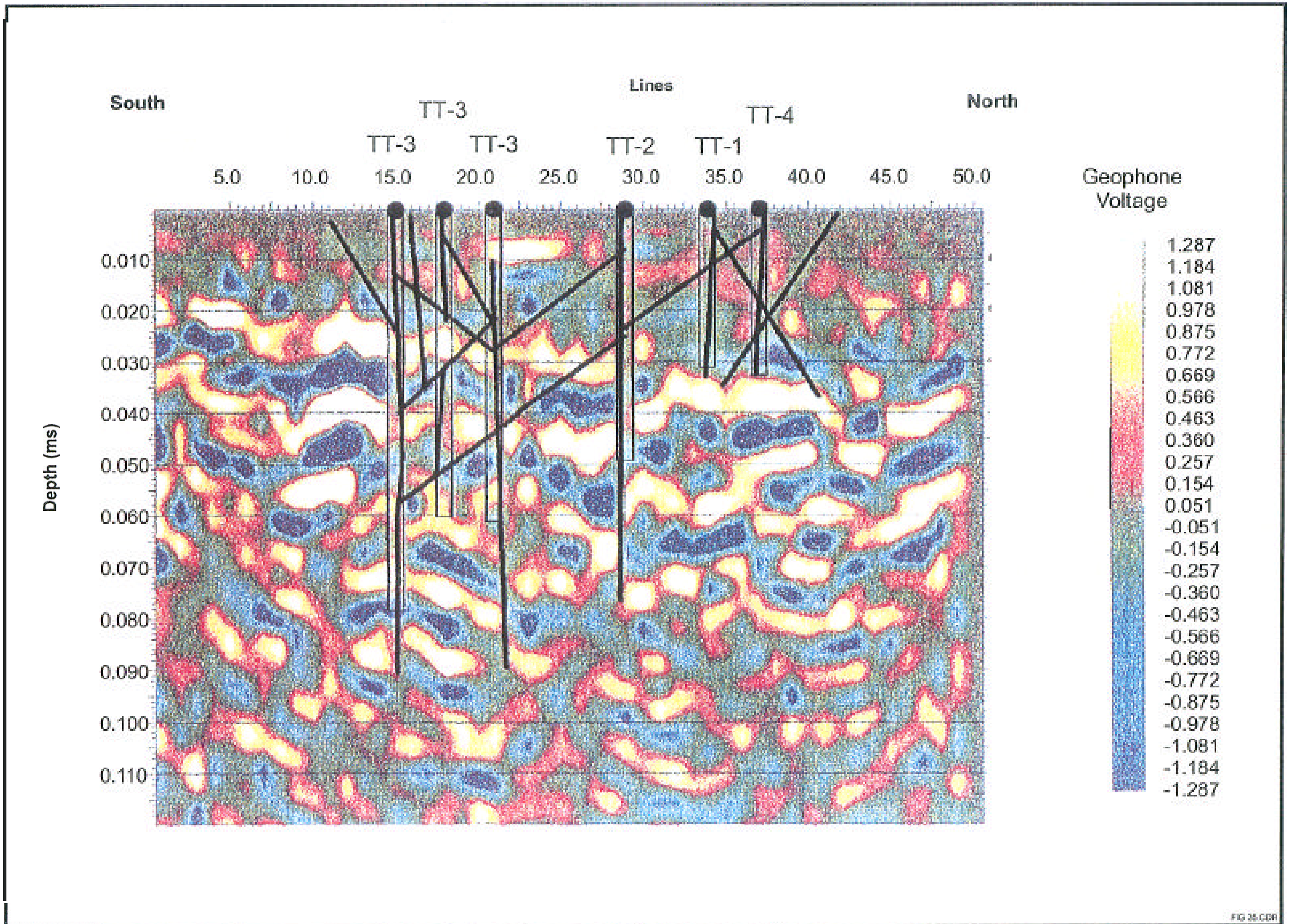

Figure 35. Validation Targets, Crossline 44 at Tinker AFB

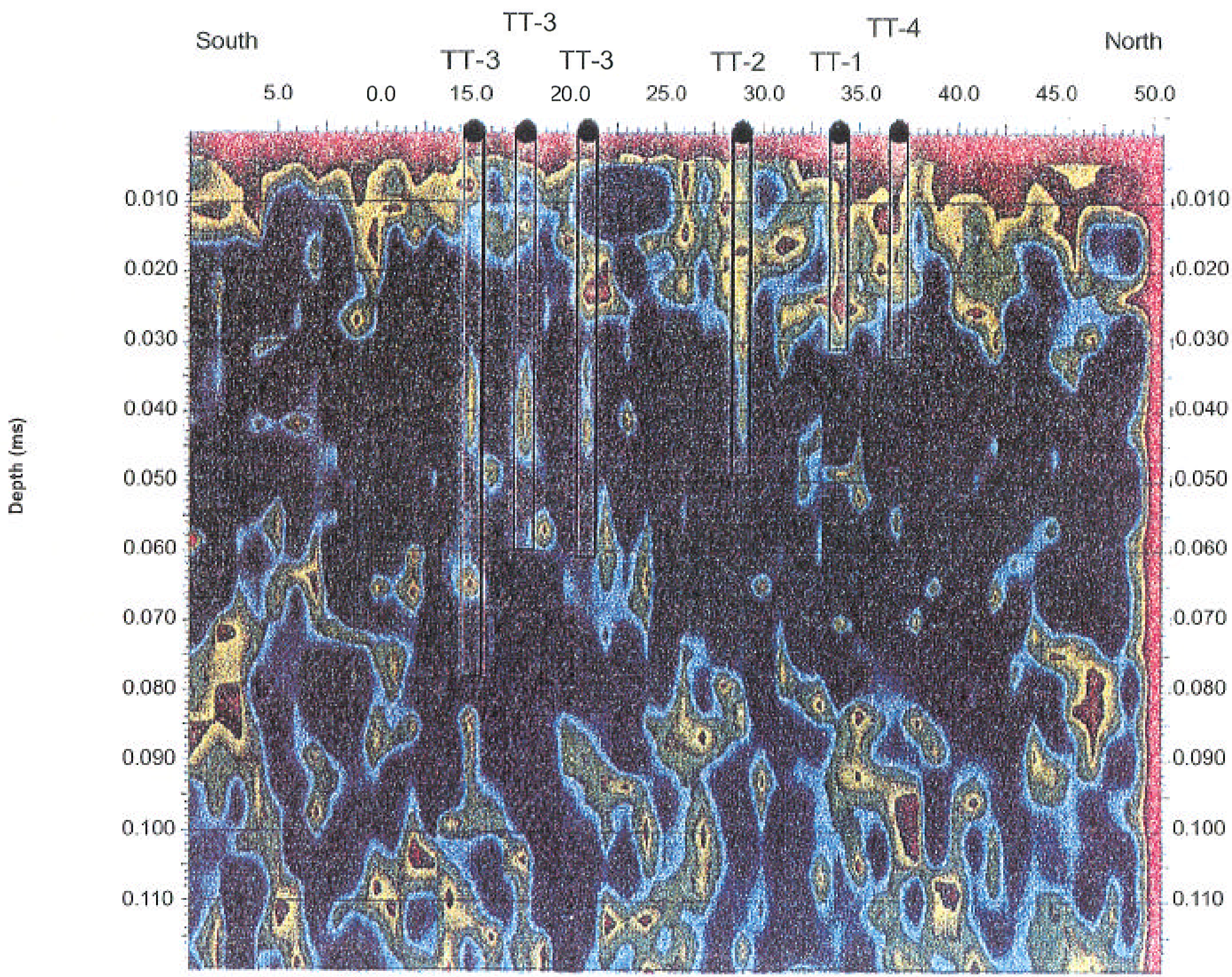

Figure 36. Envelope Attribute of Validation Targets, Crossline 44 at Tinker AFB

During the validation drilling, target locations TT-3 and TT-4 were successfully tested. Results from these tests are presented in Section 5.

Stratigraphic predictions also were made for the depth to the top of the first shale unit (referred to as the Upper Shale) at Tinker AFB. A top of Upper Shale topography map was constructed that is based upon a correlation of seismic survey results with stratigraphic data from a borehole geophysical log taken from a well within the survey area (well 1-70). Table 10 lists the surveyed coordinates and predicted depth to the top of the Upper Shale at each of the six proposed well locations.

Table 10. Tinker AFB Survey Coordinates and Depths to Top of Upper Shale at Proposed Validation Target Locations

Target Location	Seismic Location		Top of Upper Shale		State Plane Coordinates	
	Line	Crossline	Time (ms)	Depth (ft bgs)	Northing (ft)	Easting (ft)
TT-1	34	44	32.4	39	155719.8	2185034.7
TT-2	29	44	30.0	36	155669.8	2185035.5
TT-3	21	44	25.8	31	155589.8	2185033.9
TT-4	37	44	32.7	39	155749.8	2185032.3
TT-5	28	42	28.6	34	155659.8	2185013.9
TT-6	32	41	26.8	32	155699.8	2185004.3

4.4.7.4 Allegany Ballistics Laboratory 3-D Seismic Survey Results. The 3-D data set from Allegany Ballistics Laboratory contains 8,507 traces, which are spaced 10 feet apart and arranged as 47 lines trending west to east, each containing 181 traces. The traces also have been indexed as 181 lines trending south to north, each containing 47 traces. Figure 37 shows the seismic grid and other important site features. Note that the grid contains 47 rows of 181 columns. Results from the 3-D seismic survey (primarily describing the correlation with the geologic model of the site) originally were presented in June 1996 (RRI, 1996). Attribute analysis of the seismic survey was completed as part of this investigation to detect DNAPL directly. The seismic survey at Allegany Ballistics Laboratory was funded and conducted outside of this project.

No drilling and sampling was performed at Allegany Ballistics Laboratory to investigate the anomalies for the presence or absence of DNAPL. However, the targets that were identified are presented along with a very brief discussion of their selection. The technology demonstration plan for Allegany Ballistics Laboratory (Battelle, 1997b) presents a detailed discussion of the analysis of site geology, source areas, and the 3-D survey data used to select the targets.

The correlation of the 3-D seismic survey with the geologic model of the site led to the identification of fracture and lineament traces where high levels of TCE contamination were likely. The geologic units beneath Allegany Ballistics Laboratory are highly fractured and faulted.

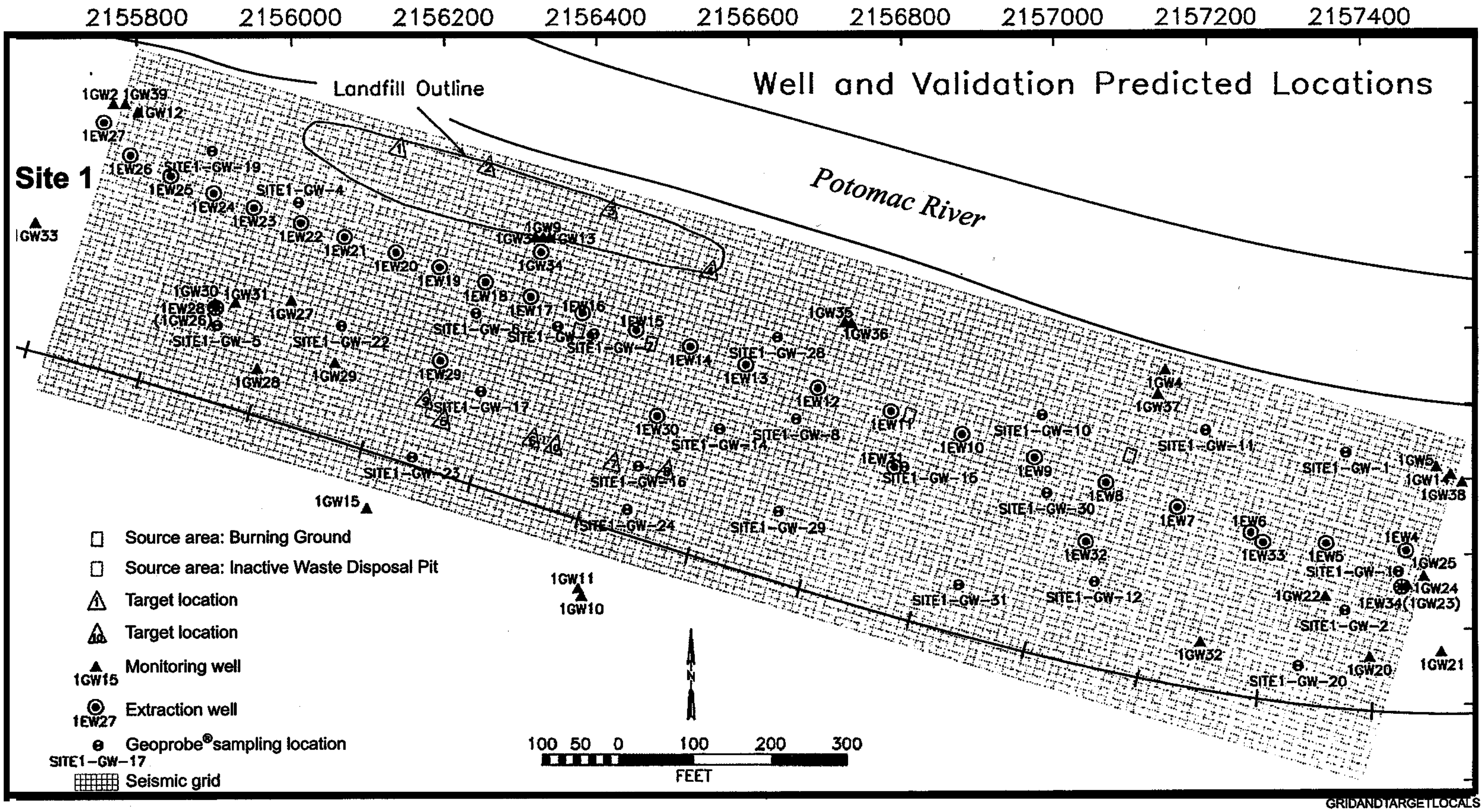

Figure 37. Allegany Ballistics Laboratory Seismic Survey Grid and Target Locations

Anomalies observed in the attributes were examined in conjunction with their proximity to sources and preferential pathways. Based on this analysis, eight locations initially were identified as having a high probability of encountering DNAPL. As a result of the paper validation effort (discussed in Section 5.1.4.4), these locations were updated and are listed as targets 1 through 8 in Table 11. Two additional targets (9 and 10) were identified as having a low probability of encountering DNAPL. The target locations also are indicated on Figure 37, and are listed in Table 11. Figure 38 is the seismic profile from line 10. Target location ALT-1 is located along this line.

Table 11. Allegany Ballistics Laboratory Validation Target Locations Based on Results from Attributes Analysis

Target Location and Drilling Order	Seismic Location		Depth to Top of Gravel		Depth to Top of Bedrock		Probability of Finding DNAPL	Discussion[a]
	Line	Crossline	Time (ms)	Depth (ft bgs)	Time (ms)	Depth (ft bgs)		
ALT-1	10	57	12	12	22	34	High	Near Pit 1 source area near the intersection of vertical fractures 3 and 20
ALT-2	18	53	10	11	24	39	High	Down gradient from Pit 1 and Pit 2 near fracture 3
ALT-3	14	85	12	12	25	40	High	Near fracture 29 and source area
ALT-4	41	28	NA	NA	NA	NA	High	Beneath landfill source area near fracture 6
ALT-5	12	64	9	5	22	34	High	Beneath source area Pit 2 on fracture 17 extension
ALT-6	41	37	NA	NA	NA	NA	High	Beneath source area along vertical fracture 8
ALT-7	45	49	NA	NA	NA	NA	High	Beneath source area along vertical fracture 12
ALT-8	13	82	12	12	24	37	High	Near Pit 3 with small seismic anomaly
ALT-9	12	91	11	10	23	35	Low	Near Pit sources but not on a fracture and on a structural high
ALT-10	12	67	10	9	23	35	Low	Near Pit sources but not on a fracture and on a structural high

(a) Refer to RRI Allegany Ballistics Laboratory report (RRI, 1996).
NA = Not available.

All pertinent information needed to describe each target location is also included in Table 11. The target locations are specified in the order in which they will be investigated. The size and position of the source of contamination believed to have caused the anomaly observed in the seismic data is identified. The locations of the target wells are specified by line and crossline numbers within the survey grid. The total depth of the boring, perforation depth, and depth to top of gravel, and top of bedrock are also included. Finally, a description of the target well location with respect to suspected sources and fracture traces is presented for each target. The

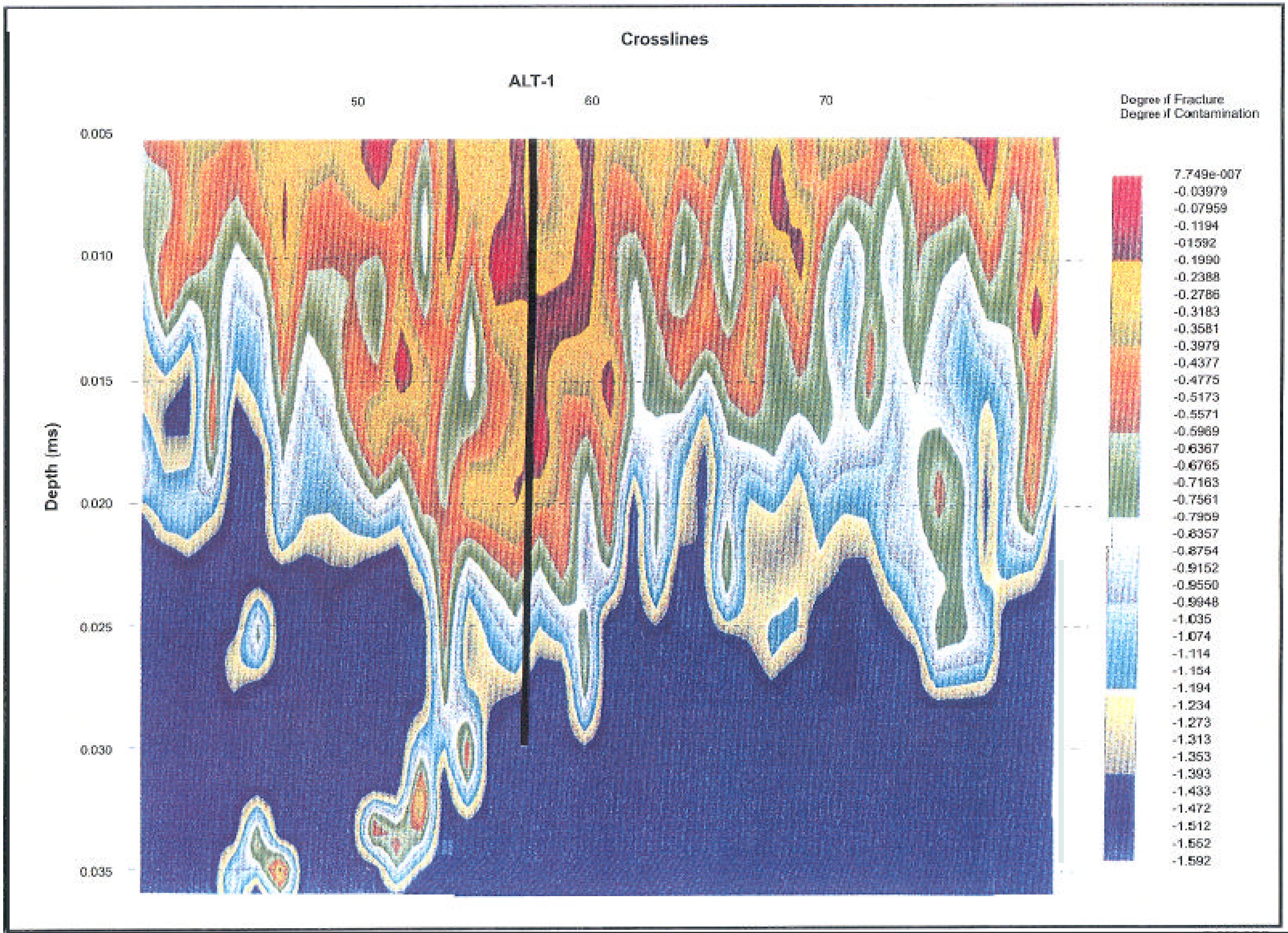

Figure 38. Envelope Attribute of Validation Target ALT-1, Line 10 at Allegany Ballistics Laboratory

perforation depth represents the predicted interval at which DNAPL is believed to occur. Similarly, the predicted depths to the top of gravel and to the top of bedrock are presented in Table 11. Table 12 lists the x and y coordinates (easting and northing), for field validation targets referenced to the Allegany Ballistics Laboratory plane coordinate system, and also lists the total depth bgs.

Table 12. Allegany Ballistics Laboratory Survey Coordinates and Depths to Field Validation Targets

Target Location	Total Depth (ft bgs)	State Plane Coordinates Northing (ft)	Easting (ft)
ALT-1	50	388,653	2,156,243
ALT-2	70	388,741	2,156,228
ALT-3	58	388,611	2,156,523
ALT-4	95	389,036	2,156,045
ALT-5	50	388,652	2,156,316
ALT-6	60	389,007	2,156,141
ALT-7	80	389,011	2,156,267
ALT-8	55	388,610	2,156,491
ALT-9	60	388,574	2,156,574
ALT-10	43	388,643	2,156,344

4.4.8 Quality Assurance During the Seismic Surveys. The quality of seismic data depended upon several factors: good coupling of the sensors to the ground, correct source/ receiver geometry, accurate documentation of field activities, good signal-to-noise ratio, and utilization of the correct recording parameters.

Data quality control was maintained in several ways. Stations were marked and flagged every 20 feet with an accuracy that was measured at ±0.1 feet. Coupling of the sensors to the ground surface was achieved by carefully placing spiked geophones in soil, or by attaching spike-less geophones to the concrete road surfaces with a bonding agent. In some cases it was necessary to dig a hole to place the sensor. The recording parameters were chosen based upon a noise test that was performed at the beginning of the survey. Before collecting data along each line, or if an interruption in data collection occurred (e.g., a pause in data acquisition for cultural traffic), a tap test was performed on specific geophones to assure that the correct geometry was maintained.

Before recording the data, the observer walked each line to ensure that all the geophones and cables were correctly placed and coupled. Field records were monitored, and if the signal-to-noise ratio was inadequate, additional source impacts were added. If any one of the 144 channels were found to produce bad data, the entire system, from patch panel through the cables to the geophones, was tested and repaired as required.

All field recording parameters, and any changes to parameters during data collection, were fully recorded for each station on each line throughout the survey in a detailed log maintained by the field crew manager or instrument observer. In addition to the line number, source point numbers, trace numbers, and offsets of the active spread, the observer's logs include: (1) sample rate; (2) record length; (3) record number; (4) recording station locations; (5) number of impacts vertically summed per source point; (6) field recording filters and gain settings; (7) recording instrument identifications, including make, model, and serial number; (8) layout geometry, dead traces, and trace polarity adjustments; (9) geophone type, model, and natural frequency; (10) tape storage media or disk number; and (11) weather conditions, cultural or systematic noise sources, or any other site conditions or events that impacted the data acquisition process.

5. Performance Assessment

This section presents the results from the drilling and sampling efforts to evaluate the targets discussed in Section 4 of this report. The objective of this work was to evaluate the likelihood that 3-D seismic reflection technique is capable of consistently finding DNAPL. As a secondary objective, the ability of the seismic technique to identify other features of interest (e.g., fractures and top of bedrock) was also evaluated because data on other site features are useful for site characterization.

Where present as a separate phase, DNAPL compounds generally are detected at less than 10% of their aqueous solubility in groundwater. Typically, dissolved contaminant concentrations greater than 1% of the aqueous solubility limit are highly suggestive of NAPL presence. This relatively low value is the result of the effects of non-uniform groundwater flow, variable DNAPL distribution, the mixing of groundwater in a well, and the reduced effective solubility of individual compounds in a multi-liquid NAPL mixture. In addition, concentrations less than 1% solubility do not preclude the presence of NAPL (Cohen et al., 1993).

Validation is the process of confirming that a target identified by the seismic survey as potentially containing DNAPL does in fact actually contain DNAPL. Drilling, groundwater sampling, and chemical analyses are performed to validate a target.

For this validation effort, sampling data indicated the presence of DNAPL if the level of contamination in a sample was at least 10% of the product's solubility in water. For example, the solubility of TCE in water is 1,100 mg/L (Pankow & Cherry, 1996); hence, for this effort, the presence of TCE as a DNAPL would be indicated by a TCE concentration greater than 110 mg/L. This measurement value is an order of magnitude greater than the established 1% "rule-of-thumb" value for DNAPL detection. Along with the collection of physical samples, the wells were logged to evaluate the accuracy of the stratigraphy predicted for the target locations.

5.1 Performance Data

Performance data were collected and evaluated during drilling and sampling at a number of attribute anomalies indicated by the seismic data and suspected to be the result of DNAPL. Interpretations of the seismic data in conjunction with the geologic model led to identification of structural elements and key anomalies, which are possible pathways and traps for DNAPL. Predictions for the presence of DNAPL at the target anomalies were evaluated against the 10% solubility limit for the respective contaminants. Predictions for the stratigraphic features of interest were considered successful if they fell within 10% of the measured depths of the features. Section 5.2 provides a discussion on whether these metrics allow for a realistic evaluation of this technology demonstration.

5.1.1 Sample Handling. During the validation drilling, the process for handling samples and analyzing the collected groundwater was also fairly conventional as compared to methods typically applied during environmental site characterization. At two of the sites, samples were carried to the on-site laboratory immediately after they were collected. At Letterkenny Army Depot, the on-site laboratory received the samples minutes after the vials were filled with groundwater. Samples were logged in at the laboratory on a chain-of-custody form and then placed in a refrigerator prior to analysis. At Alameda, the samples were stockpiled in an ice-chilled cooler over a three-day period until the mobile lab unit arrived and set up their analytical instruments. Then the samples were logged and stored in the same manner as at Letterkenny Army Depot. In the case of both Letterkenny Army Depot and NAS Alameda, the samples never left the study area prior to analysis, and many of the samples were analyzed within hours after they were collected. At Tinker AFB, samples were stored in a small refrigerator and then transferred to an ice-chilled cooler prior to overnight shipment to the lab. Once at the lab, samples were logged and then stored in a refrigerator prior to analysis.

5.1.2 Sample Matrix Considerations. The locations chosen for drilling and sampling were based on the results from the interpretation of the seismic data with respect to the model developed for the site. As described in the site technical demonstration plans, the correlation of the 3-D seismic survey data with the geologic model of the site led to the identification of fracture and lineament traces where high levels of DNAPL contamination were likely to occur within the subsurface. Anomalies observed in the attributes were examined in conjunction with their proximity to sources and preferred pathways. Based on this analysis, locations were identified as having a high probability of encountering DNAPL. These targets then were evaluated by drilling and sampling.

Although there were some instances where soil was sampled for chemical analysis during the validation effort, groundwater was the main target. However, soil and rock drilling cuttings and core were also collected during the validation exercises at Letterkenny Army Depot and Tinker AFB. Furthermore, outflow air and drilling fluids were also monitored with a PID as each borehole was advanced

5.1.3 Analytical Methods Employed and Special Considerations. The presence and concentrations of VOCs that were analyzed in the groundwater were quantified using a gas chromatograph/mass spectrometer (GC/MS)-based analytical method. EPA Method 8260 was used to perform the analysis. Applying this method with a properly calibrated GC/MS enables detection of the contaminants of concern at levels that are in the range of 1 to 10 ppb. (The threshold concentration level used to positively determine the presence of DNAPL is 110 ppm, or about one hundred thousand times higher than the detection limit of the GC/MS used to analyze groundwater samples.) The use of this analytical method was an effective approach to positively identify the presence of DNAPL in the groundwater samples, because the tuned and calibrated GC/MS with its ppb sensitivity could readily detect ppm target concentrations.

No significant special considerations related to these analyses were thought to impact the accuracy of the results. Qualified chemists employed by a certified laboratory utilized the lab instruments and applied this method. The instruments were properly calibrated prior to their use. The analytical method is routine. Target detection is assured given that the accuracy and precision of the instruments are at very low part-per-billion levels, while target concentrations are at levels of hundreds of parts per million.

Routine groundwater sampling methods were used to collect groundwater samples in the study. This was appropriate for the work at NAS Alameda, where sampling was performed in temporary microwells. The methods were also likely to be appropriate for the work at Tinker AFB, where borehole total depths were not excessive. However, borehole depths at Letterkenny Army Depot exceeded 700 feet in one well, which may have rendered this method inappropriate.

5.1.4 Analytical Results. Results from the groundwater sampling and analysis at the three sites where fieldwork was performed are presented in this section. A project-wide summary table, presented below as Table 13, lists the analytical results from samples collected from all 27 targets evaluated during the project. In the following subsections, activities and results are presented on a site-by-site basis, to document the validation drilling and sampling events that took place at each of the sites and the results from sample analyses of groundwater collected from target intervals.

As Table 13 indicates, 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 of the target intervals that were 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 are not high enough to imply that DNAPL is present and no DNAPL was observed at these locations as the drilling and sampling progressed at these locations. Samples from the remaining 23 targets that were evaluated did not exhibit DNAPL concentrations that come close to implying the presence of free-phase contaminants. The seismic anomalies that were targeted at these relative 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.

5.1.4.1 Letterkenny Army Depot. The field validation activities at Letterkenney Army Depot took a total of 23 working days to complete. This site was the most expensive and time consuming to validate because it is a bedrock site, and drilling conditions and target depths were much greater than the other two sites. There were five validation borings drilled at this site. The ultimate target depths in two of the borehole locations, LB-1 and LB-7, were found to be much greater than originally predicted by the seismic survey. These two borings were drilled to

Table 13. Summary of Chemical Results from the 27 Targets Tested During Seismic Demonstration

Target Borehole ID	Maximum CVOC Concentration Detected at Target Depth (ppb)	Target Confidence[a]	Target Reached	Presence of DNAPL in Target Validated
Letterkenny Army Depot				
LB-1	4,270	Medium	No (several hundred feet high)[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 (11 feet high)[b]	No
AB-2	ND	High	No (4 feet high)[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 (10 feet high)[b]	No
AB-7	ND	High	No (13 feet high)[b]	No
AB-8	300	High	No (2 feet high)[b]	Strong no
AB-9	ND	High	No (1 feet high)[b]	Strong no
AB-10	ND	Medium	Yes	No
AB-11	2,755	High	No (9 feet high)[b]	No
AB-12A	1,147	Medium	Yes	No
AB-12B	ND	Medium	Yes	No
AB-13	14	Medium	No (6 feet high)[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.
(b) Difference in feet between predicted target depth and 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 if targets actually were reached.
ND = Not detected.

depths of 340 feet and 740 feet, respectively. Because of these great depths, complications arose during borehole advancement and sampling. These complications prevented a thorough evaluation of downhole conditions. It is unlikely that the target was reached in LB-1 and uncertain if the target was fully evaluted in LB-7, but the samples that were collected do not show evidence of DNAPL. The LB-6 target was proven to contain DNAPL. This was a significant positive finding. Borings LB-2 and LB-5 were clearly proven to lack DNAPL at their target depths. A total of 96 groundwater samples were collected from the five boreholes. Screening also was performed with the use of a PID, so downhole conditions were carefully monitored.

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. Funks Drilling, Inc. was contracted to complete the borehole drilling. Onsite Environmental Laboratories, Inc. was contracted to provide analytical results for the collected samples. Chris Perry and Tad Fox from Battelle were on site to implement the drilling and logging process at each target location. They collected all groundwater samples for analysis during the advancement of the borings and after the completion of the respective validation target wells. They also monitored the progress of the lab work and compiled all analytical results provided by the lab. Brian Herridge and Mary-Linda Adams of RRI were on site to perform check shots. These check shots were used to correlate depths of stratigraphic horizons and/or fracture zones with two-way travel times from the seismic survey data. RRI also correlated the 3-D seismic survey results with observations made during drilling and sampling. Paul R. Stone, III, the site RPM, was on hand to provide his knowledge of past investigation work done at the site. He also provided some logistical support (e.g, backhoe services and use of his site trailer). Nate Sinclair of NFESC provided project oversight and technical assistance during the field validation.

A summary table of the groundwater chemical data from the Letterkenny Army Depot validation effort is presented in Table 14. As illustrated in Figure 39, a total of five boreholes were drilled at Letterkenny Army Depot, each to evaluate a different target anomaly. Groundwater sample results are plotted on Figure 40. 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 feet bgs. Groundwater samples were collected from various depths, usually in 20-ft increments, as each borehole was advanced.

The results from borehole LB-1 showed that carefully positioned wells can develop high yields when wells intercept fractures, however no DNAPL was discovered. The top of bedrock surface for well PW1 was predicted to occur at a depth of 22 feet. The measured depth to bedrock was 24.5 feet bgs. Test borehole LB-1 was drilled beyond the projected depth of the seismic anomaly, but VSPs performed as the hole was advanced indicated that the actual depth to the target anomaly was much greater than the 340 feet total depth. The hole was not drilled beyond 340 feet because a stainless steel sampler was lost and could not be retrieved from the hole. As shown in Table 14, a total of nineteen samples were collected from LB-1 at depths ranging from 28 to 330 feet bgs. These samples had concentrations of total chlorinated volatile organic compounds was 4,270 ppm at a depth of 280 feet. These data suggest that a deep source, or at

Table 14. Summary Chemical Data for Letterkenny Army Depot

Target Location Sample ID	CVOC Concentration (ppb)	Main Constituent(s)	Target Confidence	Target Depth (ft)	
				Projected	Actual
***LB-1*[a]**					
LB-1-28-1	240	DCE	Medium	330	340
LB-1-28-1C	168	DCE	Medium	330	340
LB-1-41-1	438	DCE	Medium	330	340
LB-1-61-1	139	DCE	Medium	330	340
LB-1-81-1	ND	NA	NA	330	NA
LB-1-101-1	280	DCE	Medium	330	340
LB-1-121-1	298	DCE	Medium	330	340
LB-1-141-1	355	DCE	Medium	330	340
LB-1-141A	512	DCE	Medium	330	340
LB-1-161-1	278	DCE	Medium	330	340
LB-1-181	436	DCE	Medium	330	340
LB-1-201	382	DCE	Medium	330	340
LB-1-220	438	DCE	Medium	330	340
LB-1-241	344	DCE	Medium	330	340
LB-1-261	229	DCE	Medium	330	340
LB-1-281	735	DCE	Medium	330	340
LB-1-280-122	4,270	DCE, TCE	Medium	330	340
LB-1 280-1221	546	DCE	Medium	330	340
LB-1-330-130	1,800	DCE	Medium	330	340
***LB-2*[b]**					
LB-2-25	530	DCE	Medium	75	90
LB-2-32-1	583	DCE	Medium	75	90
LB-2-32-C	230	DCE	Medium	75	90
LB-2-42-1	390	DCE, VC	Medium	75	90
LB-2-67-1	541	DCE	Medium	75	90
LB-2-75-1	800	DCE	Medium	75	90
LB-2-75B-1	403.6	DCE	Medium	75	90
LB-2-89.5	360	DCE	Medium	75	90
LB-2-89.5-127	328.5	DCE	Medium	75	90
LB-2-90-1	693	DCE	Medium	75	90
LB-2-90-2	782	DCE	Medium	75	90
LB-2-90D	633	DCE	Medium	75	90
LB-2-90-1220	626	DCE	Medium	75	90
LB-2-90-1220C	311	DCE	Medium	75	90
LB-2-90-1221	456	DCE	Medium	75	90
***LB-5*[b]**					
LB-5-25	310	DCE, VC	Medium	37	67
LB-5-34-1222	118	DCE	Medium	37	67
LB-5-38-126	360	DCE	Medium	37	67
LB-5-38-126	388.6	DCE, VC	Medium	37	67
LB-5-38-126B	345.7	DCE	Medium	37	67
LB-5-38-126B	380	DCE, VC	Medium	37	67
LB-5-47-127	251.3	DCE	Medium	37	67

Table 14. Summary Chemical Data for Letterkenny Army Depot (continued)

Target Location Sample ID	CVOC Concentration (ppb)	Main Constituent(s)	Target Confidence	Target Depth (ft) Projected	Target Depth (ft) Actual
LB-5[b] (continued)					
LB-5-47-127	260.6	DCE, VC	Medium	37	67
LB-5-67-126	378	DCE	Medium	37	67
LB-5-67-126	402	DCE	Medium	37	67
LB-5-67-126	355	DCE	Medium	37	67
LB-5-67-127	214	DCE	Medium	37	67
LB-6[b]					
LB-6-81	393,500	TCE	Medium	78	81
LB-6-81-C	2,933,000	TCE, PCE	Medium	78	81
LB-6-81-129	384,000	TCE, PCE	Medium	78	81
LB-6-81-1221	375,900	TCE	Medium	78	81
LB-6-81-DP1221	316,100	TCE	Medium	78	81
LB-7[c]					
LB-7-38-130	947	DCE	Medium	340	740
LB-7-40-129	1,100	DCE	Medium	340	740
LB-7-40-129	980.3	DCE	Medium	340	740
LB-7-53-130	1572	DCE, TCE	Medium	340	740
LB-7-53-130	1,229.3	DCE, TCE	Medium	340	740
LB-7-245-22FL	4113	PCE	Medium	340	740
LB-7-250-22	49,900	TCE, PCE	Medium	340	740
LB-7-250-22	29,197	TCE, PCE	Medium	340	740
LB-7-250-23A	27,600	TCE, PCE	Medium	340	740
LB-7-250-23A	15,500	TCE, PCE	Medium	340	740
LB-7-250-23C	27,200	TCE, PCE	Medium	340	740
LB-7-280-23	6,000	TCE, PCE, DCE	Medium	340	740
LB-7-340FL-24	ND	NA	Medium	340	NA
LB-7-340-25	4,200	DCE, TCE, PCE	Medium	340	740
LB-7-480-25	5,400	DCE, TCE, PCE	Medium	340	740
LB-7-565-26A	4,700	DCE, TCE, PCE	Medium	340	740
LB-7-565-26B	5,120	DCE, TCE, PCE	Medium	340	740
LB-7-565-26B	5,200	DCE, TCE, PCE	Medium	340	740
LB-7-565-29	5,500	DCE, TCE, PCE	Medium	340	740
LB-7-565-29-2	6,260	DCE, TCE, PCE	Medium	340	740
LB-7-565-29-2	6,100	DCE, TCE, PCE	Medium	340	740
LB-7-565-FLB	ND	NA	Medium	340	NA
LB-7-580-29FL	2,300	DCE, TCE, PCE	Medium	340	740
LB-591-29FL	560	DCE	Medium	340	740
LB-7-601-29FL	62	DCE	Medium	340	740
LB-7-609-29FL	59	DCE	Medium	340	740
LB-7-609-29FL	74	DCE	Medium	340	740
LB-7-610-210	230	DCE	Medium	340	740
LB-7-626-210FL	62	DCE	Medium	340	740
LB-7-648-210FL	62	DCE	Medium	340	740
LB-7-661-210FL	63	DCE	Medium	340	740
LB-7-667-210	59	DCE	Medium	340	740

Table 14. Summary Chemical Data for Letterkenny Army Depot (continued)

Target Location Sample ID	CVOC Concentration (ppb)	Main Constituent(s)	Target Confidence	Target Depth (ft)	
				Projected	Actual
LB-7[c] (continued)					
LB-7-667-2106	ND	NA	Medium	340	NA
LB-7-675-211FL	1,300	DCE, TCE	Medium	340	740
LB-7-675-211S	630	DCE	Medium	340	740
LB-7-680-211FL	58	DCE	Medium	340	740
LB-7-690-211FL	52	DCE	Medium	340	740
LB-7-720-211FL	69.6	DCE	Medium	340	740
LB-7-720A-211FL	631	DCE	Medium	340	740
LB-7-720A-211FL	41.1	DCE	Medium	340	740
LB-7-739-211	86.8	DCE	Medium	340	740
LB-7-740A-211	1,235	DCE, TCE, PCE	Medium	340	740
LB-7-740A-211	1,370	DCE, TCE	Medium	340	740
LB-7-740B-211	17,16.7	DCE, TCE	Medium	340	740
LB-7-740B-211	1891	DCE, TCE	Medium	340	740

(a) USPs indicate target was not reached and evaluated.
(b) Target successfully evaluated.
(c) Uncertain if target was reached by boring.
"C" and "D" = duplicate samples collected from a given borehole at a given depth.
NA = Not applicable.
ND = Not detected.
LB = Letterkenny validation boring location.
LB-2-90-1220 = Sample collected from LB-2 borehole at 90 feet drilled depth on 12/20/97.

least the lower portion of the well, has higher concentrations of VOCs than the upper portion of the well.

Test borehole LB-2 was drilled to a total depth of 90 feet bgs. The top of bedrock was predicted at a depth of 25 feet based upon interpretation of the seismic data and measured at 26.5 feet bgs during drilling. The anomaly at 90 feet bgs occurs at the juncture of fractures thought to represent a potential migration pathway for DNAPL. The target depth was originally projected to be 75 feet. At 90 feet, a VSP conducted in the borehole, indicated that the target had been successfully reached. A total of 15 samples were collected from LB-2 during the drilling. These samples were found to contain CVOC concentrations ranging from 230 to 800 ppb. Although DNAPL was not evident in the sample results, the target depth clearly represents a preferential fractured pathway, as indicated by water yields estimated in excess of 175 gpm from the investigation well.

Test borehole LB-5 was drilled to a total depth of 67 feet bgs. The top of bedrock was predicted at a depth of 27 feet based upon interpretation of the seismic data and measured at 17.5 feet bgs during drilling. The original projected depth of the target anomaly was 37 feet; however, a VSP indicated that the target had finally been reached and adequately tested by the borehole at 67 feet bgs.

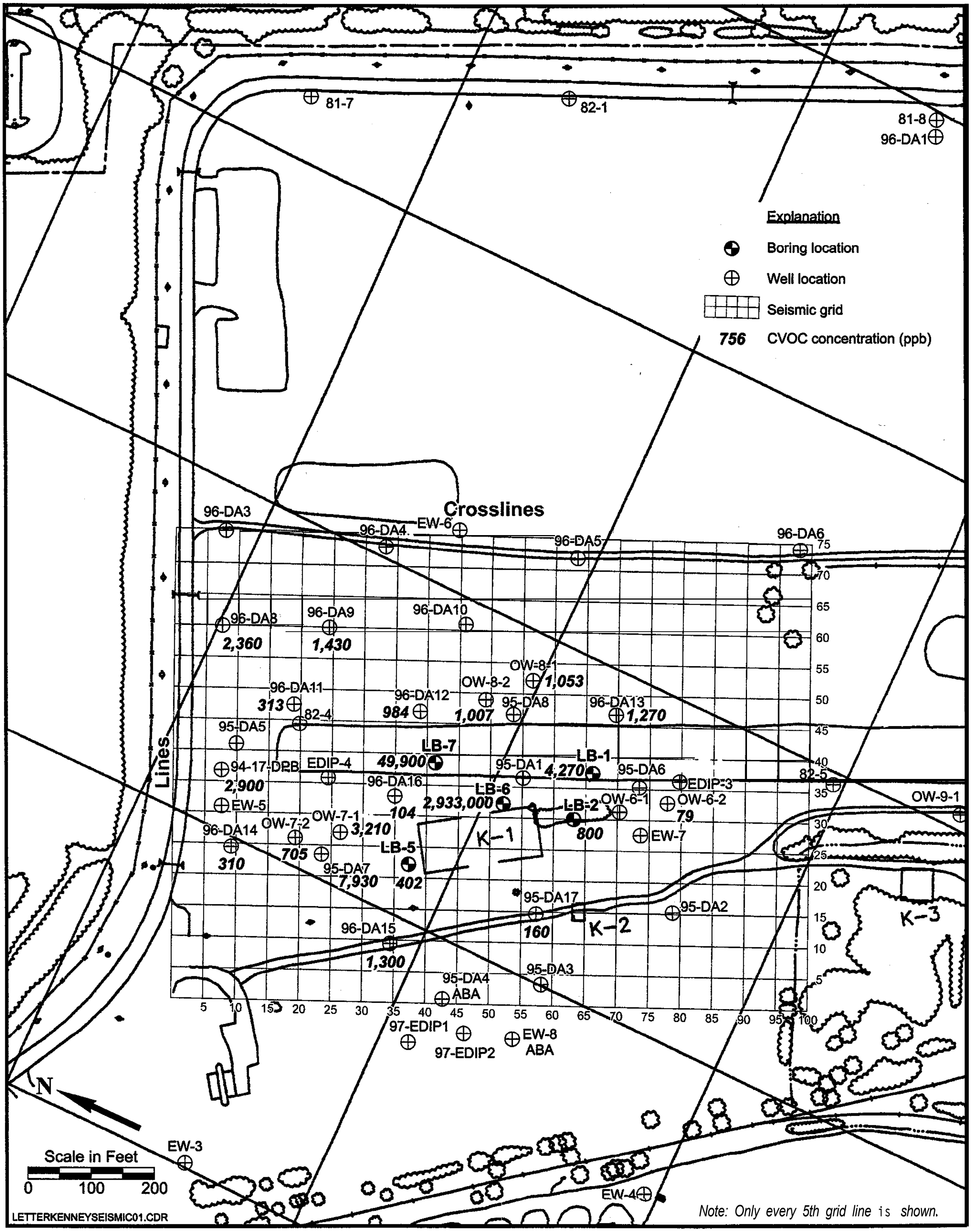

Figure 39. CVOC Concentrations at Letterkenny Army Depot Targets

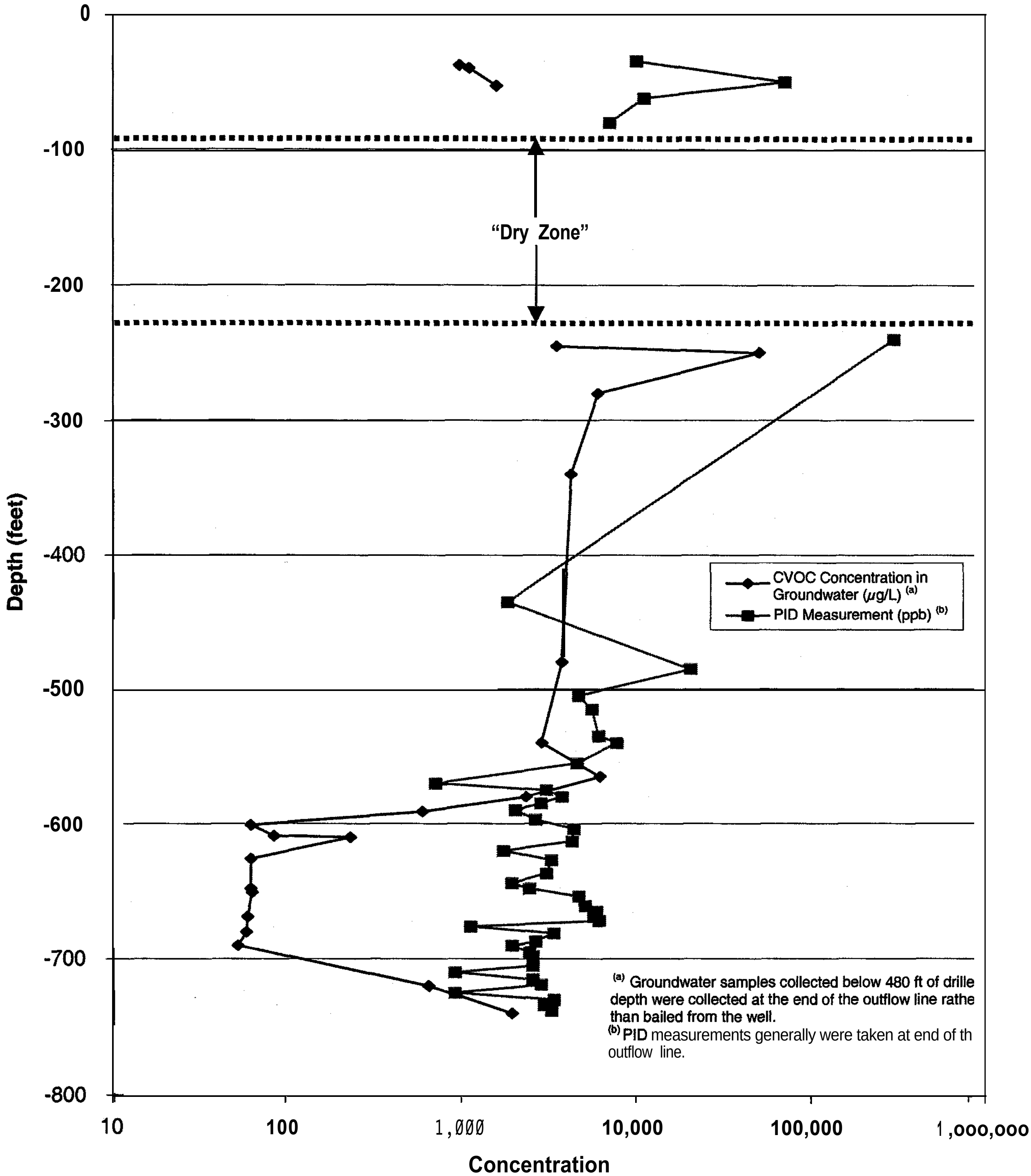

Figure 40. CVOC Concentrations in the Groundwater Along Discrete Sample Depths at Letterkenny Army Depot

There were a total of 12 samples collected during the advancement of this boring. CVOC concentrations measured in these samples ranged from 118 to 402 ppb.

Test borehole LB-6 was drilled to a total depth of 81 feet bgs. The top of bedrock was predicted at a depth of 27 feet based upon interpretation of the seismic data and measured at 18.75 feet bgs during drilling. The seismic anomaly was identified at a predicted depth of 78 feet bgs as a void at the juncture of three fractures and joints that acted to produce a trap for the DNAPL. Groundwater was not encountered in this borehole until drilling reached a depth of 76 feet bgs, as predicted by the seismic data because the drilling was through solid rock with little or no secondary porosity. While drilling at 76 feet bgs, a surge of water occurred suggesting the presence of the fracture zone as predicted by the seismic data. Elevated PID readings (490 ppm) started to occur about 5 feet above the trap at a depth of about 70 feet bgs. These PID readings were measured at the discharge point of the drilling rig's discharge or outflow line. There were no elevated PID detections above this depth. Free-phase DNAPL was encountered (roughly 3,000,000 ppb of CVOCs) in borehole LB-6. The presence and depth to this anomaly were accurately predicted by the seismic survey. Both free-phase DNAPL and LNAPL globules were observed in groundwater samples collected from this target zone. According to the site RPM, this was the highest level of contamination encountered at the site to date.

Test borehole LB-6 is located less than 200 feet from LB-1, which shows that conditions in the subsurface change rapidly from position to position at the site. In general, high groundwater yields were found where several fractures coalesce, but it was necessary to locate the structural or stratigraphic traps to find DNAPL.

Test borehole LB-7 was ultimately drilled to a total depth of 740 feet bgs, which was more than twice the originally projected target depth of 340 feet bgs. Drilling proceeded to such a great depth because the VSPs that were run as the hole was advanced indicated that the target anomaly was much deeper than originally anticipated. The difference between anticipated versus actual depths can be attributed to the fact that the actual velocity of seismic waves in this area of the bedrock was much higher than was assumed when the seismic data were interpreted and depths to anomalies were predicted.

The top of bedrock at LB-7 was predicted at a depth of 33 feet bgs based upon interpretation of the seismic data and measured at 27.5 feet bgs during drilling. As the borehole was advanced it became evident that the dense, microcrystalline limestone present at this location contributed to a higher seismic velocity than was found in the closest VSP well. Because high groundwater yielding fracture zones were encountered at shallow depths in the borehole, it was necessary to set three strings of casing to isolate these fracture zones from the deep part of the hole as it was being advanced.

A 40-ft length of 16-inch diameter casing was set at the top of the hole to control caving and to seal off inflowing groundwater that was entering the borehole at a rate estimated to be greater than 50 gpm. Once the 16-inch casing was grouted in place, the boring was deepened, and additional inflowing groundwater was encountered. A 10-inch diameter casing was installed to

80 feet bgs. Once the grout had set, drilling continued and the borehole was advanced. At 245 feet, as predicted on the seismic section, another high-yielding fracture zone was encountered. Groundwater discharge rates surged from the rig's outflow line and PID readings measured concentrations at 295 ppm. Samples bailed from this interval indicate that this zone was clearly contaminated (29-49 ppm). It was necessary to case off this zone by setting a 6-inch-diameter casing to 280 feet bgs to avoid the downward spread of contamination.

Drilling in borehole LB-7 continued at a slow rate of advancement as a result of the drilling rig. When the borehole reached a depth of 340 feet bgs, the drilling string was removed and a sample was bailed from the bottom of the hole. Results show total CVOC concentrations of 4,200 ppb. A VSP also was performed to check if the anomaly had been reached. The VSP results indicated that the bottom of the hole was still above the anomaly. The drillers switched to a new drill bit in an effort to increase drilling rate. The borehole then was advanced to 480 feet where the drilling string was again removed, a bailed sample was collected, and a VSP was run. The sample showed total CVOCs at 5,400 ppb. The VSP measured a travel time of 36 ms, which indicated that the target anomaly was still deeper. Drilling was restarted and the borehole was advanced to a depth of 565 feet. The drilling string was pulled out of the hole and a sample was bailed from the borehole. These results showed that total CVOC in the groundwater were 6,100 ppb. Efforts to perform a VSP at this depth were not successful. At first it was thought that there was an equipment problem either with the geophone or geophone cable, but because there were no equipment problems, it was concluded that an unknown exterior noise source was preventing good VSP readings. To compound the problems associated with conducting deep hole VSPs, evaluating downhole conditions based on the rig performance became more difficult as the hole was advanced to depths exceeding several hundred feet because the rig's drilling and lifting capabilities were being used at close to their maximum capacity. Changes in rates of drilling and water and cuttings outflow became more subtle and less easy to observe. It was also difficult to collect a bailed groundwater sample because hundreds of feet of drilling pipe had to be lifted from the hole each time a sample was to be bailed. It was not possible to sample through the drill pipe.

In an effort to evaluate downhole conditions, an increased number of PID readings and groundwater samples were collected from the discharge flow line as the target depth was approached. A profile plot of PID and groundwater sample results is presented in Figure 40 to show the chemical profile of the borehole.

The LB-7 was eventually drilled to a total depth of 740 feet. It was impossible to lower the geophone or bailers beyond a depth of 480 feet. The impediment in the borehole may have been a fracture zone or may have been a deviation in the hole, or by rubble that possibly entered the hole from that fracture zone. The fact that drilling occurred in a 6-inch casing also made it very difficult to keep the hole clear of cuttings and debris. Because of the fracture zone, no successful VSPs were conducted deeper than 480 feet.

The results from LB-7 suggest that the site is contaminated to a depth of at least 740 feet, a result which in itself indicates the presence of vertical pathways. Because the test well is located only about 100 feet east of the source area, and it appears that the contamination has migrated to a depth of at least 740 feet, a case could be made for nearly vertical migration pathways.

It is expected that VOCs in solution would move in the direction of groundwater flow rather than vertically, which is what has been observed during tracer tests. Evidence of contamination at a depth of at least 740 feet, 100 feet from the source area, may suggest that DNAPL is or was nearby at this depth.

The site velocity model was initially difficult to refine because of an unknown noise source, possibly from a pump and treat system located to the southeast. Interpretable VSP data was observed in LB-7 and LB-1 after an additional effort was made to collect representative data. The site velocity-depth model could only be evaluated to a depth of 480 feet bgs. An obstruction in the hole prevented the hydrophone element used for the VSP from being lowered to the full depth of the exploration hole. Using the site velocity-depth model, the anomaly identified in well LB-7 at 110 ms is about 850 to 900 feet deep. It suggests that more contaminated material may be present below the bottom of the test well. Test hole LB-7 was not advanced beyond 740 feet because of technical problems and budget constraints.

The center of the large anomaly in LB-7 is about 125 ms, which may be as deep as 1,200 feet according to the velocity model derived from the VSP. Because drilling was halted at 740 feet, this well cannot confirm or deny the presence of DNAPL.

5.1.4.2 NAS Alameda. The seismic survey conducted at NAS Alameda Building 5 encompassed three locations of concern, each with separate sources of contamination. Figure 41 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, 1998]). Area C consists of the plating shop located inside the building (identified as Source Area 1 in the Addendum [Battelle, 1998a]).

The site geology consists of approximately 15 feet of fill situated on top of the (clayey) Bay Mud confining layer. All of the contamination found at this site in the past was sampled from above the Bay Mud. Noteworthy sample detections which implied the presence of DNAPL were a groundwater sample containing 790 ppm of trichloroethane (TCA) collected from beneath the plating shop, and a soil sample containing 4,000 ppm of TCE collected at the former liquid waste tank site.

At Alameda it was possible to sample nearly all of the locations targeted by the seismic evaluation. Unfortunately, sample collection from beneath the Bay Mud (which is thought to be a confining layer) was not permitted. As a result, stratigraphic correlations between predictions from the seismic data and features observed during drilling at the site were limited.

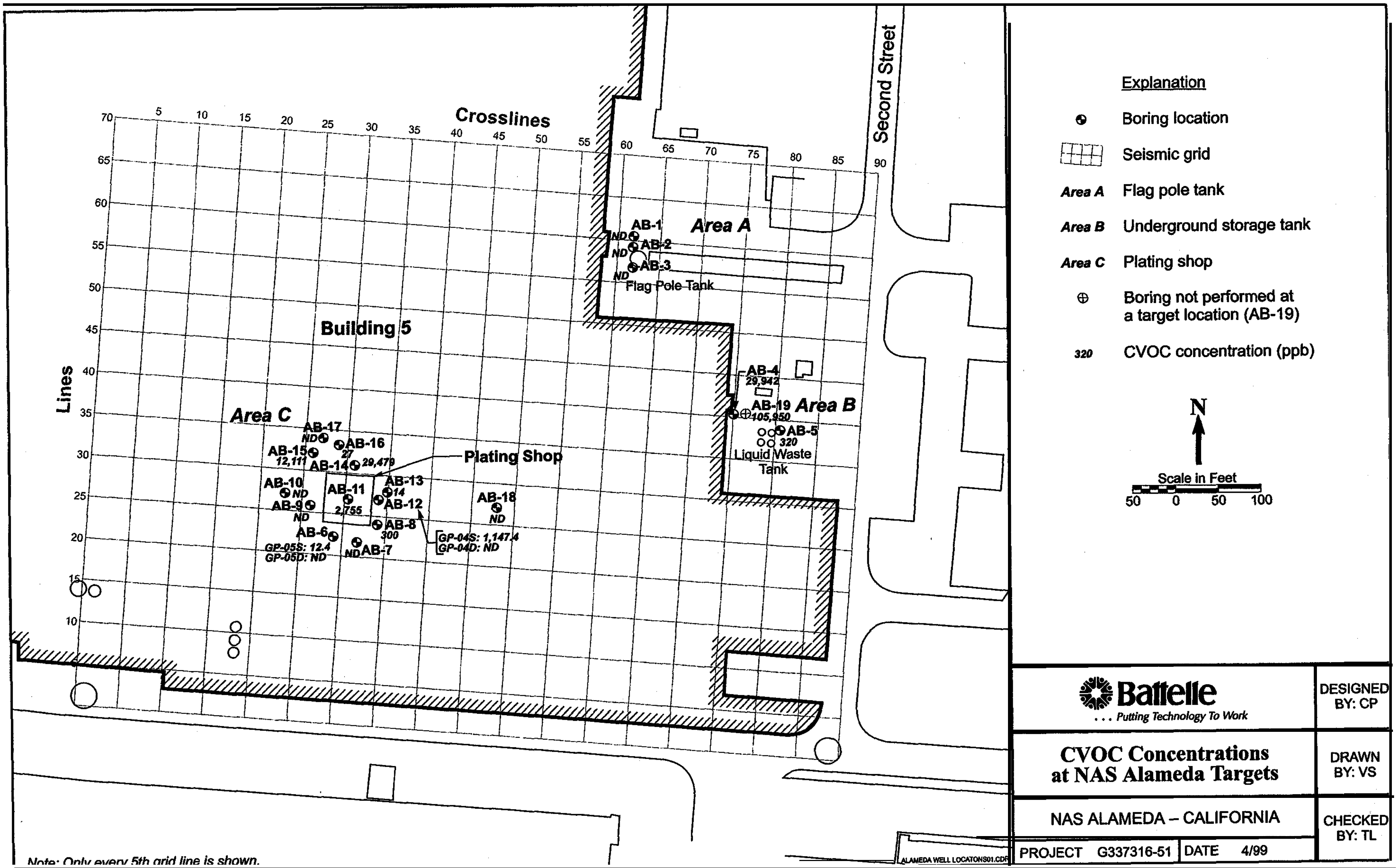

Figure 41. CVOC Concentrations at NAS Alameda Targets

Table 15 provides a summary of the sample results from NAS Alameda. The first column of the table lists the new validation boring designators for the field target locations. The second column lists the laboratory sample name. The target location as identified in the technology demonstration plan (Battelle 1997c) and in the Addendum to the Draft Attributes Analysis and Verification Plan for Naval Air Station Alameda (Battelle, 1998a) is included in the third column. The sample results, main constituent, and the target confidence are included in the next three columns. The last two columns present the screened interval for the target locations and the projected target depths derived from the seismic data.

Table 15. Summary Chemical Data for NAS Alameda

Target Location	Target Location Sample ID	Target Number[(a)]	CVOC Concen-tration (ppb)	Main Constituent(s)	Target Confidence	Target Depth Projected (ft)	Screen Interval (ft bgs)
Flag Pole Tank (Area A)							
AB-1	B5A-17-312	57A1	ND	NA	Medium	55	39-44
AB-2	B5A-16-311	59A1	ND	NA	High	50	39-44
AB-3	B5A-14-312	60A1	ND	NA	Medium	40	30-40
Liquid Waste Tank (Area B)							
AB-4	B5B-01-312	40A	29,942	DCE,TCE, DCA	Medium	7	5-10
AB-5	B5B-02-314	39A	320	DCE	Low	21	15-25
AB-19 [(b)]	B5B-TankOS-317	NA	105,950	TCE,DCA, TCA	NA	NA	5-10
Plating Shop (Area C)							
AB-6A	B5C-G5-313	22A	12.4	DCE	High	20	15-25
AB-6B	B5C-G5D-316	22A	ND	NA	High	53	33-43
AB-7	B5C-G3-313	22B	ND	NA	High	53	30-40
AB-8	B5C-03-313	24A	300	DCE	High	40	28-38
AB-9	B5C-G2-313	26A	ND	NA	High	48	37-47
AB-10	B5C-G1-313	27E	ND	NA	Medium	35	25-35
AB-11	B5C-Plating Shop	27I1	2,755	TCA	High	50	32-42
AB-12A	B5C-G4-313	27J1	1,147.4	DCA	Medium	20	15-25
AB-12B	B5C-G4D-316	27J1	ND	NA	Medium	50	36-46
AB-13	B5C-01-313	28C	14	CA	Medium	50	34-44
AB-14	B5C-06-313	31A1	29,484.7	DCA, CA	Medium	15	10-20
AB-15	B5C-05-313	32B1	12,111	DCA, CA	High	18	15-25
AB-16	B5C-07-313	33A	27	DCE	High	35	30-40
AB-17	B5C-04-313	34B	ND	NA	Medium	35	30-40
AB-18	B5C-G6-316	27C	ND	NA	Med/High	42&50	36-46

(a) IDs taken from Battelle 1997c, 1998a.
(b) The AB-19 location was not targeted as part of the validation as it was thought to be too shallow to contain DNAPL. However the seismic data did show the presence of an anomaly.

As mentioned in Section 4 of this report, only shallow targets above the Bay Mud were to be evaluated as part of this effort. Most of the subsurface characterization was performed using the Navy SCAPS truck, but locations that were inaccessible to the SCAPS truck were tested using a truck-mounted Geoprobe® rig. This method permitted the evaluation of more targets in a less disruptive manner and in such a way that minimal quantities of waste were generated. 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. One additional sample was collected from AB-19 at a location not selected from the evaluation of the 3-D seismic survey. In addition, the SCAPS truck generated soil classification and laser-induced fluorescence data at the 12 locations where it was utilized. The groundwater samples were analyzed with an on-site laboratory.

Four targets were investigated which are associated with very shallow anomalies (i.e., less than 25 feet bgs), two near the plating shop (Area C) and two near the former liquid waste tank (Area B). The anomalies were categorized based on their relative size as large and medium. Approximately 10 other very shallow anomalies were identified, but could not be investigated because of interferences from structural elements of the building. The remaining 16 targets investigated were associated with medium/large anomalies occurring 35-55 feet bgs. These were originally identified based on their location within vertical geologic features. A brief discussion of the targets investigated for Areas A, B, and C is presented below.

Three target locations (i.e., anomalies) were investigated at Area A. The locations ranged in depth from 40 to 55 feet and were classified based on their relative size as either medium or large anomalies. As shown in Table 15, only location AB-3 was completed to the target depth. Sample results from all three locations were below detection limits (at least some dissolved contamination in the samples would be expected if DNAPL were present). Therefore, the anomalies investigated at Area A are not believed to be the result of free phase DNAPL within fracture zones as one would expect.

One target, listed as boring AB-4 in Table 15, was investigated at the former liquid waste tank (Area B). In addition, two other locations, AB-5 and AB-19, were investigated. AB-5 was a target interpreted to contain little or no DNAPL. AB-19 was not selected from the interpretation of the seismic data. Instead, the location for AB-19 was selected because elevated fluorescence levels were detected in a previous SCAPS investigation performed at the former liquid waste tanks (Navy Public Works Center, 1998). The sampling results indicate that the highest levels of contamination (105,950 ppb) were detected at AB-19.

Significant contamination (29,942 ppb) was also detected at AB-4 located approximately 10 to 15 feet to the west of AB-19. Both samples were collected from microwells screened from 5 to 10 feet bgs. At AB-5, CVOC levels were measured at 320 ppb.

The results from Area B are generally in agreement with the predictions made from the interpretation of the seismic data. Both AB-19 and AB-4 were completed into a shallow, flat-lying anomaly, which RRI felt was too shallow to contain DNAPL. The shallow DNAPL ganglia found at the liquid waste tank area, located east of the building, is thought to be very small and perhaps a result of overfills. Nevertheless, it is present as a small, flat, shallow anomaly on the seismic data, and it turned out to be a small shallow DNAPL find.

A total of 15 groundwater samples were collected in the vicinity of the plating shop. Based on the conceptual model and seismic interpretation, it was thought that the greatest chance for finding DNAPL at Building 5, Area C, was directly beneath the plating shop. Location AB-11 was tested to evaluate a target that was directly beneath the footprint of the plating shop. This target was driven to refusal and screened at a depth of 42 feet bgs, about 8 feet above the predicted target depth. Groundwater from this location contained 2,755 ppb total CVOCs. Three other locations in the vicinity of the plating shop (AB-12A, AB-14, and AB-15) had total CVOC levels that were greater than 1,000 ppb. Each of these results was collected from relatively shallow screened intervals (25 feet or less bgs). The remaining samples each had total CVOC levels under 1,000 ppb, with many being below sample detection limits.

The anomalies seen on the seismic data below the metal plating shop could be caused by a number of factors. However, based upon the sampling results, it appears that DNAPL does not occur at Alameda Building 5, at least above the Bay Mud. If this conclusion is correct, then the NAS Alameda site cannot be used to evaluate seismic DNAPL exploration.

5.1.4.3 Tinker AFB. Battelle drilled and evaluated three targets at Tinker AFB 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. The targets that were evaluated by drilling and sampling are at locations TT-3, TT-4, and TT-6. Drilling also was performed at location TT-2, but unstable hole conditions prevented advancing this borehole to the target depth. 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 were no fractures linking the interval to the source area beneath the solvent pits.

Battelle performed the validation work of drilling and sampling at target locations west of Building 3001 at Tinker AFB from November 3 through 11, 1998. The target depth was successfully reached at three locations. Boreholes started at two additional locations were abandoned because of unstable near-surface drilling conditions. VSPs were performed in each of three completed boreholes to confirm that the projected target depths were correct. In each case, the projected target depths were found to be very accurate. This accuracy can be attributed to the good seismic velocity model developed at Tinker AFB from previous seismic surveys performed by RRI.

Each of the three target borings was cored, logged, and sampled, from ground surface to their respective target depths. All drilling was performed using an air rotary rig. The amount of groundwater outflow that was produced by the drilling was much less than at the Letterkenny Army Depot site. Lower groundwater production is the result of Tinker AFB's fine-grained, highly layered aquifer system, which is much less transmissive than the more massive, fractured limestone aquifer present at Letterkenny Army Depot.

The three boreholes drilled for validation at Tinker AFB were located at targets TB-3, -4, and -6 (see Figure 42). The targeted depths were 165, 64, and 104 feet, respectively. Corresponding depths drilled for the targets were 165, 68, and 108 feet, respectively. No fractures transmitting significant quantities of groundwater were encountered for the three targets. No obvious changes in the drilling rate or any unusual rig behavior were noted that might indicate that fractures were present. However, it is difficult to positively identify the presence of fractures using any drilling method, especially if the fractures are vertical as indicated by the seismic data. Only a few small fractures were observed in core samples. But core recoveries were rarely 100%, particularly in the less cohesive, sandy intervals. As a result, not all portions of the borehole were visually observed.

Sampling results from Tinker AFB are summarized in Table 16. No DNAPL or highly contaminated groundwater was detected while drilling any of the deeper intervals above the three targets. Efforts to detect DNAPL in the field consisted of general well-site observations, monitoring the groundwater and air outflow, and sniffing and logging the recovered core. As each test hole was advanced, outflowing groundwater, cuttings, and air were all carefully monitored for the presence of organics using a PID. Each core barrel was immediately "sniffed" with the PID. Core samples were then crushed and immediately sniffed again. While drilling was underway, in addition to monitoring outflow with a PID, groundwater was sampled and sent to a laboratory to for analysis with a GC/MS. Lab samples were collected from both the outflow line and the steel collection tray (Mud Pit). Upon reaching the target depth, samples were also bailed from the bottom of each borehole using a weighed bailer. A second bottom-hole sample of groundwater was bailed from the target depth after the borehole was allowed to sit open for about six hours.

Wireline logs were run in each of the three boreholes. The parameters that were logged included natural gamma ray, electrical resistivity, spontaneous (electrical) potential, and three-arm caliper. Results from wireline logging indicated that borehole lithology fit closely into the known site stratigraphy as it is depicted in the cross section, which is presented in Figure 43.

Upon completion of all drilling, sampling, and logging, it was decided that monitoring wells would not be constructed in any of the three boreholes because Tinker AFB did not want to assume possession of monitoring wells unless there was clear evidence that the wells could serve as DNAPL recovery wells.

Preliminary laboratory results indicate that none of the three targets contained TCE concentrations near the 110-ppm (10% solubility) cutoff level. In borehole TB-4, TCE was detected at 1,500 ppb (total CVOC = 1,620 ppb) at the target depth. In borehole TB-3, TCE was detected at 230 ppb at the target depth, and it was the only CVOC detected. In borehole TB-6, TCE was detected at 49 ppb (total CVOC = 56 ppb) at the target depth.

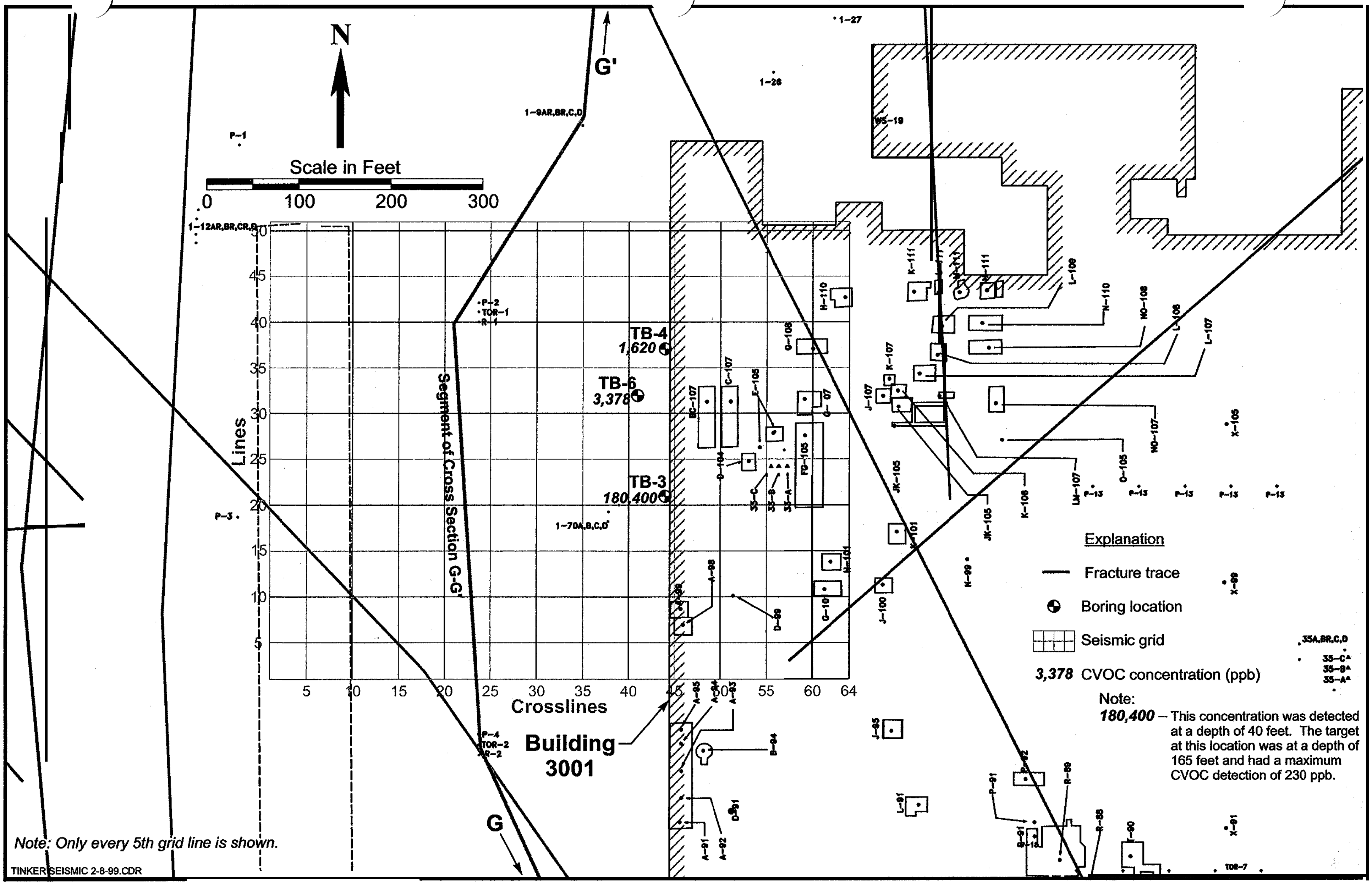

Figure 42. CVOC Concentrations at Tinker AFB Targets

Table 16. Summary Chemical Data for Tinker AFB

Target Sample ID	CVOC Concentration (ppb)	Main Constituent(s)	Target Confidence	Sample Depth (ft)	Target Depth (ft)	
					Projected	Actual
TB-2 [(a)]						
TB-2-40-116	1,237.5	DCE	Medium	40	114	ND
TB-2-40-116	1,239.0	TCE	Medium	40	114	ND
TB-2-40-116	1,940.0	TCE/DCE	Medium	40	114	ND
TB-3						
TB-3-40-116	180,400.0	TCE	Medium	40	165	165
TB-3-40-116	158,900.0	TCE	Medium	40	165	165
TB-3-85-118	5.0	TCE	Medium	85	165	165
TB-3-100-118	101.2	TCE	Medium	100	165	165
TB-3-109-118	4.1	TCE	Medium	109	165	165
TB-3-120-118	15.3	TCE	Medium	120	165	165
TB-3-140-118	160.0	TCE	Medium	140	165	165
TB-3-150-118	180.0	TCE	Medium	150	165	165
TB-3-165-118	230.0	TCE	Medium	165	Target Depth	
TB-3-165-119	180.0	TCE	Medium	165	Target Depth	
TB-4						
TB-4-MP40-116	535.7	DCE	Medium	40	64	68
TB-4-40-119	1,250.0	TCE	Medium	40	64	68
TB-4-61-119	1,620.0	TCE	Medium	61	64	68
TB-4-68-119	29.35	TCE	Medium	68	64	68
TB-6						
TB-6-40-119	3,378.0	TCE	Medium	40	104	108
TB-6-70-119	2.4	Methylene Chloride	Medium	70	104	108
TB-6-78-119	0.9	Methylene Chloride	Medium	78	104	108
TB-6-93-119	0.9	Methylene Chloride	Medium	93	104	108
TB-6-104-119	0.8	Methylene Chloride	Medium	104	104	108
TB-6-105-119	2.3	TCE	Medium	105	104	108
TB-6-106-119	56.0	TCE	Medium	106	104	108
TB-6-108-119	3.0	TCE	Medium	108	104	108

(a) TB-2 was abandoned at 40 feet because of unstable borehole conditions; target was estimated to be 114 feet bgs.
MP = Sample collected from mud pit rather than bailed from borehole.

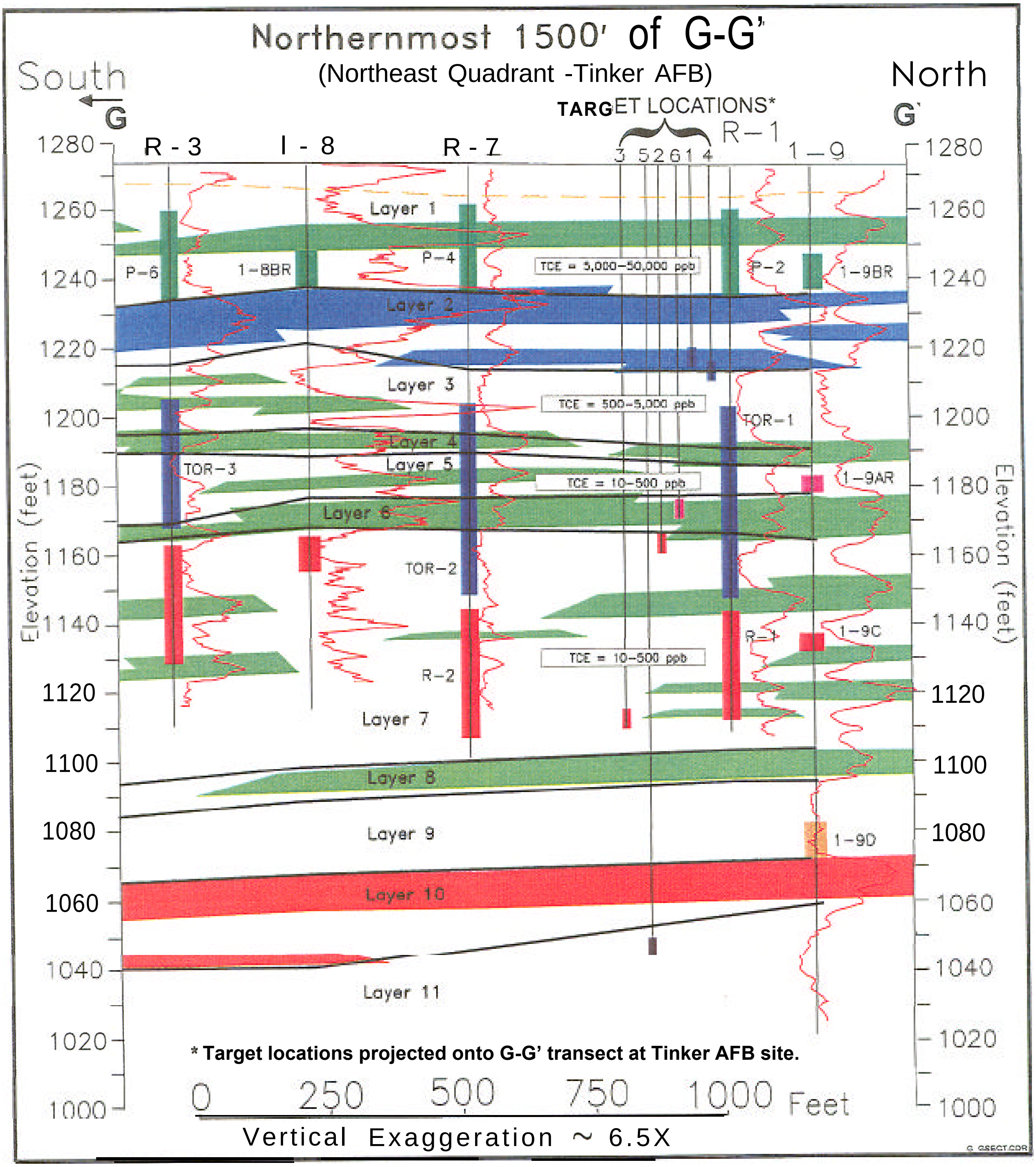

Figure 43. North-South Geologic Cross Section G-6' Showing the Locations and Depths of the Target Wells at Tinker AFB

As anticipated, based on existing RI data (see cross section in Figure 43), higher TCE concentrations were encountered in the USZ than at the target depths in the deeper LSZ. The USZ sample collected in TB-3 contained TCE at a concentration of 168 ppm, which is above the 110-ppm cutoff level and which was the highest detection found in any of the validation samples. A duplicate sample of this interval measured 151 ppm TCE. This location was not identified on the original plan as a target.

Part of the challenge associated with this sample is determining its spatial meaning. For example, how much volume of DNAPL is at this location? Is it large enough to "see" with the 3-D seismic method? The model suggests that most free product would travel vertically in a vertically fractured media. Therefore, most of the DNAPL detections laterally adjacent to suspected source areas may represent very small amounts of DNAPL that may not be visible within the resolution of this survey data. In addition, the USZ sample from TB-3 also indicates that lateral flow of contaminants (and possibly some flow of DNAPL) is occurring.

TCE was the predominant chlorinated constituent detected in all groundwater samples, although some samples contain significant quantities (<2 ppm) of other chlorinated constituents. The USZ was temporarily cased and sealed off in each borehole before drilling advanced downward toward the target depth. This casing, which was set and sealed to 40 feet bgs in each borehole, prevented cross contamination and enabled a more objective evaluation of each target.

The three targets that have been investigated at Tinker AFB during this field exercise were not the primary targets for validation. The interpretation of RRI, which included mapping potential fractures that served as migration pathways, indicated that the primary targets were located inside Building 3001 directly beneath the suspected source zones. However, Tinker AFB would not grant permission to drill inside the building because it would be very disruptive to mission activities. The secondary targets, outside of the building, were believed to have a lower chance of encountering DNAPL.

5.1.4.4 Allegany Ballistics Laboratory. An evaluation of the predictions from the 3-D seismic survey results was performed through a paper validation (Battelle, 1997a). The paper validation was completed in two steps. First, an assessment of the existing data was completed to ensure data quality and to identify any limitations of the data. Second, the existing chemical and sampling stratigraphic data were compared to the seismic survey data in an attempt to validate the interpretations and predictions made from the survey data.

The primary data used in the paper validation consisted of the following:

- Chemical and stratigraphic data collected during the Remedial Investigation (CH2MHILL, 1996a).

- Chemical and stratigraphic data collected during the installation of 33 wells as part of the Phase II aquifer testing investigation conducted by CH2MHILL (1997).

- Groundwater quality data collected from 24 locations during a Geoprobe® investigation completed as part of the Phase I aquifer testing (CH2MHILL, 1996b).

The data selected for the validation effort were not made available to RRI during their analysis of the seismic survey data. In addition to the data noted above, additional data from monitoring wells were included in the validation effort.

The assessment of the primary data used in the validation effort yielded the following conclusions:

- The chemical analysis for the Phase II wells is valid and can be used in the paper validation.

- The Geoprobe® data were not surveyed in, and the analytical data were not validated; therefore, they can only be used qualitatively in the paper validation.

- No signed, original lithologic logs are available; depth to bedrock was recorded in the field logbook.

- The drilling method precluded any logging of lithologies (top of gravel) in the alluvium.

- There is not enough information to ascertain the uncertainty associated with the determinations of depth to top of bedrock in the Phase II wells.

- Survey data are available for each of the Phase II wells.

- The lithologic data can be used in a qualitative fashion for the paper validation.

The validation effort consisted of comparing the chemical and stratigraphic data to the seismic survey data. The chemical validation was completed by asking RRI to make predictions (based on their analysis of the seismic data) regarding the presence of DNAPL at the locations of 12 wells and 8 Geoprobes®. RRI developed a table listing characteristics that may indicate the presence of DNAPL and then assigned each location a confidence level ranging from High 1 to Low 4 based upon the number of characteristics each location had. A confidence level of High 1 had all of the characteristics and strongly suggested the presence of DNAPL, whereas Low 4 had none of the characteristics and suggested the absence of DNAPL. All but two of the wells containing TCE concentrations greater than 11,000 ppb (1% TCE solubility) had at least one of the characteristics that may indicate the presence of DNAPL. Three of the locations had TCE levels of 110,000 ppb (10% TCE solubility) or greater, indicating the presence of DNAPL under the terms of this study. However, no locations in this paper validation effort were determined by RRI to have a high confidence of detecting DNAPL.

The determination that none of the locations used in this paper validation have a high confidence level of detecting DNAPL may be the result of several factors:

- The focus of the investigation was to identify the biggest targets and not to examine individual wells; therefore, the seismic survey may not have had the resolution to detect small fractures, discrete zones, or thin films contributing DNAPL to the wells.

- Some uncertainty is associated with the exact depth in feet for the seismic data as described in the discussion of the stratigraphic validation (Section 3.1 of this report).

- DNAPL may not be present at any of the wells used in this validation effort.

In addition, the Phase II well locations and sampling results were compared with respect to the locations of the fracture traces identified by RRI. The results of the comparison supported RRI's geologic model of the site. Six of these wells had TCE levels greater than 11,000 ppb. Of these six, five appeared to be located directly on or within fractures identified by the fracture trace analysis.

For the stratigraphic data, contour maps depicting the depth to top of gravel and top of bedrock were generated from the seismic data. The maps were then compared against the stratigraphic data with results listed in Table 4 of the Battelle paper validation (Battelle, 1998a). Only one top-of-gravel observation was available for comparison, and 41 top-of-bedrock observations were available for comparison with the maps. In general, the depths predicted from the seismic data were significantly lower than those the depth to bedrock presented in the Phase II aquifer testing report (CH2MHILL, 1997). In addition to the limitations noted in the assessment of the stratigraphic data above, several other possible explanations for the discrepancies between the observed and predicted stratigraphy are noted below:

- The site velocity model used to convert two-way reflection time to depth was developed from two VSPs in two wells. The accuracy of the site velocity model developed from the two VSPs is dependent upon the accuracy of the lithologic descriptions for those wells. As a result, the site velocity model may be slightly inaccurate; the model can be refined with the additional data from check shots during the drilling and sampling phase of the validation effort.

- The top-of-bedrock selected during Phase II investigation drilling may actually be weathered bedrock. The top-of-bedrock selection from the seismic data may be from competent, unweathered bedrock.

5.1.5 DNAPL Target Data Assessment. The results from this demonstration are somewhat inconclusive with regard to the use of 3-D seismic methods to identify anomalies caused by the presence of DNAPL. 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.

The Letterkenny Army Depot site possesses a typical fractured bedrock-controlled geologic setting. The seismic technology was found to be very 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, one supported by fracture trace analysis. The success at the PW6 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.

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. Still, it is difficult to conclude that seismic technology is insensitive to DNAPL because it is unclear if any DNAPL exists at NAS Alameda, and the extent of the DNAPL at Tinker AFB is also unknown. Prior to selecting Tinker AFB, site staff expressed their belief that DNAPL was present at high levels at the site.

Although a number of test borings were drilled at each site to test as many of the targets as possible within the areas that drilling and sampling could be performed, the technology evaluation suffered from several limitations. The primary limitation of this technology evaluation involves the site selection. It is still not known how extensive the DNAPL contamination is at any of the test sites.

The second limitation of this technology evaluation is that, based on the seismic anomalies, none of the best target locations were sampled because they were located deep or below the source areas. The geologic model developed by RRI for each of the sites indicates that each contain vertical fractures, and that DNAPL migration is primarily vertical within these fractures beneath the suspected source zones. But, because of this second 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.

The third limitation of this technology evaluation is that the budget did not allow adequate spatial sampling of the drilling and sampling plan (this is a problem with nearly all field evaluations). The fourth 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 degree, the seismic technique is sensitive to the presence of DNAPL.

5.1.6 Data Validity. Multiple samples were collected from many of the target intervals, especially at Letterkenny Army Depot. Several quality assurance/quality control samples were also collected to evaluate the accuracy and consistency of the GC/MS and proper application of the analytical method. The data have not been formally validated. However, the concentrations that were used to define the presence of DNAPL were approximately 100,000 times greater than the detection limit capabilities of the laboratory. Therefore, the data quality is believed to be sufficient to enable accurate conclusions regarding the presence or absence of DNAPL.

5.1.7 Data Assessment. Overall, a total of 27 anomaly-based targets were evaluated at the three different installations where drilling and sampling were performed during this study. The objective was to collect data from several geologically different sites and determine if there was overall success in finding DNAPL while also determining if any strengths and weaknesses are associated with any type of particular type of geologic setting.

5.1.8 Stratigraphic Comparisons. A second performance evaluation involved evaluating the success that surveys had at predicting important and useful subsurface geological features such as depth to bedrock, depth to faults or fracture zones, and the presence and depth to zones of higher porosity. Table 17 summarizes the results from the stratigraphic predictions that could be evaluated during the drilling and sampling at Letterkenny Army Depot and at Tinker AFB. At first glance, only one of the predictions for the Letterkenny Army Depot site (LB-2) is within 10% of the observed depth during drilling. Predictions at LB-1 and LB-7 are fairly close to those observed during drilling, but are not within ±10%. At target locations LB-5 and LB-6, the predictions were substantially different than the observed depths. In addition to the picks for the top of bedrock, fracture locations were predicted and confirmed in at least three of the target locations. The anomalies at LB-2 and LB-6 were found to occur in fractures as predicted. Another fracture was predicted at a depth of about 250 feet and confirmed at the LB-7 target location. Numerous other smaller fracture zones were noted during the drilling and sampling at Letterkenny Army Depot.

Overall, the results from Tinker AFB are in good agreement when comparing the seismic predictions for the top of the Upper Shale unit with the top picked from the borehole geophysical logs. However, only two predictions for the Tinker AFB site (TB-4 and TB-6) are within 10% of the observed depth during drilling. The predictions for the remaining three targets at Tinker AFB are nearly within 10% of the observed depth, and fall within the range of variability expected when interpreting seismic data and borehole geophysical logs.

Table 17. Results from Stratigraphic Predictions at Letterkenny Army Depot and at Tinker AFB

Target Location	Feature	Target Depth (ft)	
		Projected	Actual
Letterkenny Army Depot			
LB-1	Top of Bedrock	22	24.5
LB-2	Top of Bedrock	25	26.5
LB-5	Top of Bedrock	27	17.5
LB-6	Top of Bedrock	27	18.75
LB-7	Top of Bedrock	33	27.5
Tinker AFB			
TB-2	Top of Upper Shale	39	35 (gamma log)
TB-3	Top of Upper Shale	31	35 (gamma log)
TB-4	Top of Upper Shale	34	35 (gamma log)
TB-6	Top of Upper Shale	32	34 (gamma log)

The use of 3-D seismic surveys appears to be particularly well suited to sites such as Letterkenny Army Depot where the bedrock has been fractured and faulted, and where secondary porosity has been enhanced by dissolution along the fracture zones. Adequate site characterization of source zones at sites having similar geologic conditions (fractured and/or deformed bedrock) is difficult at best using conventional techniques. Figure 44 has been included to illustrate this point. The figure shows two photographs of an excavation to bedrock to remove contaminated overburden at the Industrial Wastewater Treatment Plant lagoon at Letterkenny Army Depot. Close examination of the photographs reveals the complexity associated with the bedrock surface and indicates that very large number of wells or borings would be needed to adequately characterize this area. 3-D seismic surveys represent a method that can be used to provide a much clearer understanding of the bedrock surface and preferential pathways through which contaminants may migrate. The degree to which a seismic image represents actual subsurface geology is dependent upon the complexity of both the site geology and the velocity model. Generally, more complex geologic features result in an equally more complex velocity model. If an insufficient number of VSPs have been run, greater error is present in the velocity model, which in turn, results in greater error in the seismic imagery. A brief discussion on the correlation of seismic data and observations from boreholes during drilling is presented below.

It is not unusual for the results from logging boreholes to be different from the seismic interpretation, especially when measuring the top of weathered bedrock. In general, the overall configuration of the bedrock surface mapped with seismic technique should correlate to a map created with sufficient drill hole data, but some differences should be expected.

There are several reasons why drilling and seismic data may not perfectly correlate. One reason is that the depth at which an auger meets refusal is a function of many factors, and the interpreted seismic depth of a reflector is also a function of many factors. In essence, the factors influencing drill refusal and seismic reflections are not the same (i.e., the acoustic top of the rock may not be the auger refusal top of the rock).

Photograph 1. IWTP Lagoon Closure Excavation View Looking East

Photograph 2. IWTP Lagoon Closure Excavation View Looking Southeast

Figure 44. Excavation to Bedrock at Letterkenny Army Depot (Source: ESE, 1993)

The weathered bedrock surface is often a gradation from soil to relatively hard rock. The properties of the rock surface may vary substantially, from spot to spot, over small distances. For example, the rock surface may change from one type of rock to another within a few feet. At Letterkenny Army Depot, the rock can change from hard limestone to soft shale across a few feet. The limestone changes from layer to layer (containing more or less shale) across several inches. The degree of fracturing within the bedrock changes every few feet. If an auger finds a suitable fracture or fracture intersection, it may advance several feet into the "bedrock" surface before refusal is encountered. If the fracture system is highly weathered, the auger could extend further.

A second reason is related to the migration of the seismic data and of the drill tool. The seismic data are migrated to collapse diffraction data and to adjust the reflectors back to the true positions of the events in the subsurface, and some difference between the seismic image and the "real" subsurface can occur. The drill tool similarly can drift, and although at some sites a shift would not cause a notable difference in drilling, at other sites, such as Letterkenny Army Depot and at Allegany Ballistics Laboratory, the surface of the bedrock can change many feet vertically across a few horizontal feet.

A final reason is that differences can occur between seismic depths and drilling depths, because of changes in the near surface velocities. The seismic depths to bedrock are interpreted by selecting a horizon and converting the horizon reflection time measurement to a depth value. The depth value is calculated by multiplying half of the echo time measurement by the layer velocity. Unfortunately, the velocity of near surface materials can vary substantially, even across small areas. To get an accurate seismic map of the top of rock, the velocities must be measured across the entire area. Although it is presumed that the velocities within the areas studied for this report do not change dramatically, the VSP and reflection data do suggest at least some variance within the study sites, and this variance will affect the accuracy of the bedrock depths which have been interpreted from the seismic data.

5.2 Technology Comparison

In general, the spatial sample density offered by most budgets and drilling techniques is inadequate to understand the heterogeneity in the subsurface. Conventional site assessment involves drilling and sampling a very small subset area within a larger site area. Budget considerations usually preclude sampling the site with very dense spacing of sample points, so a geologist must connect the data from boreholes spaced many tens or even hundreds of feet apart to assemble a site-wide interpretation or assessment. Unfortunately, many important features between the boreholes remain unknown. Vertical drilling is a good exploration tool when horizontal features (such as layers or fractures) exist. When the targets are high angle or vertical, such as vertical fracture systems, vertical drilling will yield very little useful information. If the vertical fractures form sets (as they often do) and are arranged in a system, very little information can be obtained by the installation of wells.

Detailed information about potential discrete pathways (such as the exact location of fractures or channels) are rarely understood, and exploration wells usually are installed based on a general area of interest. Test wells are most often installed where it is convenient to park the drill rig. Wells generally are not advanced at locations where drilling is inconvenient, such as in a ravine, under a power line, or below buildings; however, all these places may be and often are necessary places to drill. Information from logging and sampling the wells may present a false model of the site. If the contamination is migrating preferentially within a fracture, and the fracture is below a large ravine, then the necessary preparations to drill must be made.

Another drawback of characterization by test bores and wells is that in general, the well screens are often 10 feet or longer, and do not offer the resolution necessary to understand the discrete layering and fracturing that are important within a formation.

However, 3-D seismic imaging techniques have a clear advantage when compared to these drilling techniques (and budgetary concerns). At all of the demonstration sites for this study, the wells were irregularly spaced across the site, often with several hundred feet between them. The seismic data offered a fully stacked, high fold, 3-D migrated output trace every 10 feet on an even grid across the study area. Letterkenny Army Depot is an example of a site that has been well investigated by conventional means. Thirty-three wells drilled no deeper than 250 feet have been used to characterize the area, in contrast to more than 8,000 seismic traces arranged in a grid. The trace includes 1,500 depth samples, which is about one sample/foot, and the site was imaged to at least 1,000 feet.

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.

Electromagnetic techniques often are limited by the penetration into conductive overburden. The signal-to-noise ratio can be a problem because there are often large sources of electromagnetic noise at most environmental sites. With seismic techniques, on the other hand, it is always possible to get signal into the ground and to record data across travel paths that are several hundred feet into the earth and back. The standard practice of vertical stacking (multiple impacts) and horizontal stacking (common depth point fold shooting) has no comparison in electromagnetic, gravity, or resistivity techniques.

Radar data could be collected using 3-D techniques and 3-D migration could be used to clarify the image; however, radar measurements are at present limited to two dimensions, because radar still requires the use of several listening antenna with picosecond accuracy. Another problem is that a 100- or 200-channel radar recording system is too expensive to develop using existing technology. A recording system of this size is needed to get sufficient resolution required to detect small and subtle geologic features associated with DNAPL migration and accumulation. Finally, the depth penetration of radar is controlled by the conductivity of the surface layers and is often poor as a result.

Gravity is one of the lowest cost and lowest resolution techniques. The ability to measure small distortions in the total earth gravity field is limited by the accuracy of the instrumentation, presence of noise in the data, and the model definition.

Very low frequency is a very promising technique, which combines low cost with good resolution, especially on vertical fracture systems. It is still only a 2-D technique and contains 2-D distortions that cannot be removed. 3-D seismic imaging is the only technique which has evolved to a level that provides nearly distortion-free volumes of data which can be easily examined and interpreted using oil-exploration software.

5.3 Regulatory and Implementation Issues, Lessons Learned, and Recommendations

5.3.1 Regulatory Issues. Department of Toxic Substances Control regulators have supported the use of 3-D high-resolution seismic imaging at a number of sites. The California Environmental Protection Agency has had five surveys performed at Stringfellow National Priorities List site near Riverside, California. Thirty-five million gallons of liquid waste were disposed at this site. The New York State Department of Environmental Conservation recently funded the use of 3-D seismic imaging at a possible DNAPL site in Gowanda, New York. The seismic survey method was used in a residential neighborhood because of the noninvasive nature of the technique and to reduce the number of wells. The California Environmental Protection Agency's Regional Water Quality Control Board permitted Unisys Corporation to remove 47 recovery wells and replace them with three monitoring wells at Westlake Village, California, based on a 3-D seismic survey. Furthermore, based on 3-D survey results, the State of Florida and EPA Region IV are considering natural attenuation and the shutdown of a pump and treat system at the national Aeronautics and Space Administration's Wilson Corners site at Cape Canaveral Air Station, Florida.

In general, the detailed imagery provided by the 3-D seismic technique has met with favorable regulatory review in several other states, including Nebraska and Tennessee.

5.3.2. Technology Implementation

5.3.2.1 DOD Needs**.** The Naval Facilities Engineering Service Center will be developing a fact sheet that describes the appropriate uses and expected benefits of this seismic technology, particularly with respect to DOD needs.

5.3.2.2 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. As source areas are better understood, the ability to design and implement a more successful and efficient system to extract DNAPL from those source areas increases. The 3-D imagery can contribute knowledge of the nature and extent of the DNAPL source, either through the direct detection of the DNAPL or through a better understanding of the DNAPL migration pathways.

The 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 utilizes all available data, including 3-D survey data as well as conventional and often existing data. This process may also use data about the regional geology and geologic history, general information on hydrostratgraphy 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, hydrogeologic 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.

5.3.3 Lessons Learned. Several lessons were learned during this technology demonstration. First, the sites selected for the demonstration were not optimal, in that the presence of large known DNAPL sources were not clearly established and precisely defined, and that site selection, site research, and site planning needed to be addressed more thoroughly. It is not certain that sufficient amounts of DNAPL exist at any of the test sites to be detected acoustically. It also is not certain what volume of DNAPL is needed for positive acoustic detection, but the demonstration of this technology at a site with a well-established, large volume of DNAPL contamination likely would have produced more definitive results. The results from the four sites that hosted demonstrations are inconclusive because, although very limited DNAPL was found, it is not certain how much DNAPL actually exists at the sites.

In hindsight, several conclusions can be drawn about DNAPL at the sites. At Letterkenny Army Depot, there is a lack of strong evidence of a sizeable DNAPL target. Letterkenny Army Depot was selected on the basis of only one single sample that was collected from a fracture located close to a DNAPL source area, and the highest concentration of total VOCs detected in the 33 wells that had been previously installed at this site was 43,000 ppb. At NAS Alameda, the small amounts of DNAPL detected probably were a result of overfilling the underground storage tank at the site. The SCAPS system documented that the extent of this DNAPL pool was limited to a depth of about 11 feet below ground surface and a total thickness of 5 to 11 feet. And at Tinker AFB, although evidence of DNAPL was also found, the size of the free-phase DNAPL zone is still unknown, as it cannot be determined by this sole positive DNAPL detection.

Second, it would have been advantageous to thoroughly evaluate targets that were located directly below DNAPL sources or release areas. Seismic anomalies were typically the largest at these targets. With the exception of the tests at NAS Alameda, most of the best targets, the ones located below source areas, could not be evaluated. Test drilling of these best targets was not possible, primarily because of physical and logistical constraints, but also because of concerns about disrupting the source areas and spreading contamination. However, these types of obstacles are typical and they commonly make it difficult to access source locations. If the site selection process is limited to sites on installations where DNAPL presence has been well documented and where there are no surface obstructions, a more objective evaluation of this technology could be conducted, because the technology is used in conjunction with expert opinion and interpretation to identify the best targets.

Third, and more generally, any possible acoustic anomaly resulting from the presence of DNAPL may not be unique. A similar anomaly could be caused by another set of physical conditions or parameters in the subsurface. It is known that the envelope attribute is sensitive to degree of fracturing. If DNAPL causes an effect on the envelope attribute, it may not be possible to distinguish the DNAPL from a more fractured area.

5.3.4 Recommendations for Further Investigation. The results of this demonstration, though not totally conclusive, strongly imply that high-resolution, 3-D seismic reflection cannot directly detect DNAPL using state of the art technology. Overall, the four demonstration sites appear to possess high enough levels and large enough plumes of dissolved-phase DNAPL contamination to imply that those free-phase DNAPL sources are likely to be present. At the two sites 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.

Any further research, if pursued, should focus on evaluating the technology under more controlled conditions. For example, a bench scale or test site-scale evaluation might prove beneficial. Demonstration might also be beneficial at a site or installation where the presence of a large known DNAPL source has been clearly established and precisely defined.

The results from this demonstration imply that high resolution, 3-D seismic surveys are not effective at directly detecting DNAPL. However, 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. In non-bedrock settings, evaluation of other less fracture-dominated conceptual models may prove to be successful. 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.

6. Cost Assessment

The main activities and average cost elements in 3-D seismic surveys are listed in Table 18 below. These costs are typical for any survey of this nature. The costs are based on the efforts from three sites (Letterkenny Army Depot, NAS Alameda, and Tinker AFB). Additional costs that will likely be incurred include drilling and sampling to tie the seismic data to observations in the field and to confirm the presence of DNAPL within selected target anomalies. Drilling and sampling costs are contingent on 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 dependent upon the number and depth of targets investigated. Table 19 presents a breakdown of the cost of key activities related to the surveys and validation performed at three of the four demonstration sites. Work performed at Allegany Ballistics Laboratory was not included in this breakdown (also not factored into Table 18) because the majority of work was performed outside of this project.

Table 18. Average Cost Performance Data[a]

Cost Element	Cost
Site research/plan	$14,804
Seismic survey and VSP	$56,591
Data processing/interpretation	$19,478
Attribute analysis	$15,941
Plans and reports	$19,983
Total average costs	$126,797

(a) Excludes costs incurred at Allegany Ballistics Laboratory.

Table 19. Per Site Cost Breakdown by Activity

Activity	Letterkenny Army Depot ($)	NAS Alameda ($)	Tinker AFB ($)
Research and plan survey	15,709	12,834	15,871
Run survey and VSPs	53,200	71,655	44,920
Process and interpret data	21,938	25,415	11,082
Perform attribute analyses	16,241	15,682	15,900
Perform validation drilling and sampling	134,145	20,849	68,490
Perform laboratory analyses	45,050	20,400	22,100
Generate reports	13,993	37,532	8,424
Survey area (ft^2)	732,600	644,000	315,000
Estimated survey cost per ft^2 [a]	0.23	0.28	0.38
Estimated survey cost per acre[a]	10,018	12,197	16,553

(a) Excluding drilling and sampling.

Note: The following costs are not included in this summary: Demonstration plans, meetings, project management and reporting, miscellaneous materials, and activities conducted at Allegany Ballistics Laboratory.

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 feet for all three sites. Because of this, the site with a largest grid area (Letterkenny Army Depot) benefited by spreading the setup costs over a larger grid area, and thus had the lowest cost per unit area surveyed.

- Drilling and sampling costs were strongly influenced by each site's geologic setting. Drilling costs at Letterkenny Army Depot were much higher than at NAS Alameda or Tinker AFB 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 utilize 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 $2,000.00, was used at these sites. The laboratory throughput capacity was greater than the rate at which samples could be collected and delivered for analysis.

7. Conclusions

High-resolution, 3-D seismic reflection surveys were conducted at four DOD sites in an effort to identify subsurface DNAPL target zones. These surveys were also conducted to accurately image important subsurface geological features (such as structural and stratigraphic characteristics) that might influence the movement and accumulation of DNAPL in the subsuface. The four DOD sites where this technology was demonstrated and evaluated are Letterkenny Army Depot, NAS Alameda, Tinker AFB, and Allegany Ballistics Laboratory. The primary project objective, to validate the capability of this technology to directly detect free-phase DNAPL in the subsurface, was not realized. Anomalies identified within the seismic data sets collected at the four sites did not exhibit features that enabled a clear differentiation between those anomalies containing DNAPL and the anomalies caused by other factors (such as unrelated geologic characteristics). A total of 27 anomaly-based targets were drilled and sampled during the project validation. Only one of these targets was found to contain DNAPL. This successful target was based on an anomaly in the seismic imagery that appeared indistinguishable from other anomalies.

Key results from this project include the following:

- Of the 27 DNAPL targets that were evaluated at the three sites where active drilling and sampling were conducted, one target was proven to contain DNAPL. The target that tested positive for DNAPL was located in shallow fractured bedrock at Letterkenny Army Depot. This positive test was considered a significant success because 33 wells had been drilled at this site prior to the seismic survey, but no free-phase VOCs were detected.

- At NAS Alameda, one seismic anomaly observable in the data was interpreted to be a feature too shallow to be DNAPL-bearing, but the feature eventually was proven to contain free-phase DNAPL based on chemical analysis and video microscope investigations.

- At Tinker AFB, a drilled interval was found to contain high concentrations of dissolved DNAPL constituents; however, this interval was much shallower than the predicted target at the location. The target did not contain DNAPL, nor did the other two targets that were evaluated at this site.

- At Allegany Ballistics Laboratory, when other consultants drilled at locations based in part on the seismic data and photoanalysis developed from this ESTCP project, higher concentrations of VOCs were detected than had been previously found using conventional methods for locating extraction wells for remedial action.

In addition to the primary objective of directly detecting DNAPL, a secondary project objective was to evaluate the accuracy of depths-to-bedrock predictions made using the seismic surveys by comparing the predictions to the actual bedrock tops measured during drilling. Results and conclusions from this secondary evaluation are as follows:

- At Tinker AFB, stratigraphic depths were predicted very accurately during the 3-D seismic survey. The success at this site might be attributed partly to the velocity control provided from a previous 2-D seismic survey conducted at this site. The vertical velocity profile (i.e., VSP) data collected during the 2-D survey provided abundant control to enable very accurate predictions during the 3-D survey. These results demonstrate the need and value of VSP data. Greater amounts of VSP data and control enable more accurate depth-to-bedrock predictions and other stratigraphic and structural predictions.

- At Letterkenny Army Depot, discrepancies emerged between the depths to bedrock predicted by the seismic survey and the actual depths measured during drilling. The discrepancies were explained by the fact that the bedrock surface was very irregular and fractured, and that a fault which traverses the site contributes to the variability of acoustic velocities present at the site. The VSPs used to construct the model and to select projected target depths were shallower than some of the targets.

Based on this demonstration study, the following conclusions have been made:

- It is very unlikely that current state-of-the-art seismic technology can be used to directly detect DNAPL in the subsurface. No anomalies attributed directly to the presence of DNAPL are observable on processed seismic profiles from the four demonstration sites. No algorithms applied during numerical processing or attribute analysis during this project successfully delineated DNAPL-specific anomalies. Also, there appears to be no way seismic technology can be used to distinguish DNAPL-specific anomalies from anomalies caused by features such as unrelated variations in soil or bedrock lithology. It has not been proven that reflected seismic waves are actually impacted by the presence of DNAPL.

- State-of-the-art seismic imagery does not generate any observable differences between anomalies that lie directly beneath source areas and anomalies that are positioned laterally from source areas.

- Seismic surveys can be used to provide images of relevant geologic features below and in the vicinity of DNAPL release points. The surveys can help identify preferential DNAPL migration pathways within the subsurface from the point of release on the ground surface. The application of seismic technology seems particularly useful in fractured and faulted settings.

- Pathway analyses and interpretation must be performed on 3-D seismic imagery to identify either anomalies that qualify as either the targets that are most likely to represent or imply the presence of DNAPL, or local environments where DNAPL could be residing. Competent personnel must perform these types of analyses and interpretations. Success at finding DNAPL with the support of seismic images is dependent not only on the proper application of this technology, but also on the development of an accurate conceptual geologic model.

- Because DNAPL may not be detected directly using 3-D seismic imagery, any application of 3-D seismic technology to explore for DNAPL in the subsurface must be accompanied by a drilling and sampling program to ground-truth the pathway and migration interpretations. Drilling also is needed so VSPs can be collected to accurately interpret the depths to significant geologic features.

Uncertainties and restrictions were encountered during this project that may have impacted the success of encountering DNAPL targets. These uncertainties and restrictions are as follows:

- There was a lack of certainty that significant free-phase DNAPL actually was present at any of the four sites. Although each of the sites exhibits significant dissolved-phase DNAPL plumes, and all four sites have a history of using and disposing chlorinated solvents, it is not certain that any of the sites presently contain large volumes of free-phase DNAPL contamination.

- At the three demonstration sites where drilling took place, it was not possible to drill directly through and beneath the source areas. Based on the fracture-dominant conceptual models for all four sites in this project, the most favorable targets at all sites were thought to be located directly below the DNAPL release points. However, except at two locations at NAS Alameda, it was not possible to test these highest-priority targets. At Tinker AFB, the source areas were not accessible because of logistical constraints. Also, it was not possible to drill directly through and beneath the source areas at either Letterkenney Army Depot or NAS Alameda because of concerns that such drilling might breach important containment barriers or confining layers.

- The models developed by RRI are very fracture dominant, conceptualizing the downward migration of DNAPL along vertical fractures beneath the source zones at each of the four sites. Because target selection was based in large part on the conceptual geologic models developed by RRI for each site, the seismic technology and the conceptual models were tested together. It is possible that more DNAPL would have been found if alternate conceptual models were used, particularly models that considered more conventional structural or stratigraphic traps as possible settings where DNAPL might have accumulated. It also is possible that seismic imaging can detect structural and stratigraphic traps that are shallower and perhaps lateral to the source zones. Because RRI developed and employed conceptual models that centered on vertical fracture pathways, these models may be less appropriate for sites possessing primarily unconsolidated sediments (e.g., NAS Alameda).

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