RICE UNIVERSITY

**Using Elastic-Wave Seismic Data to Image an Ultra Shallow Buried
Paleochannel**

by

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*Forse un mattino andando in un'aria di vetro,
arida, rivolgendomi, vedrò compirsi il miracolo:
il nulla alle mie spalle, il vuoto dietro
di me, con un terrore di ubriaco.*

*Poi come s'uno schermo, s'accamperanno di gitto
alberi case colli per l'inganno consueto.
Ma sarà troppo tardi; ed io me n'andrò zitto
tra gli uomini che non si voltano, col mio segreto.*

E. Montale

ABSTRACT

Using elastic-wave seismic data to image an ultra shallow buried paleochannel

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This thesis is a case study concerning the application of reflection and refraction seismic methods to a very specific instance: mapping an extremely shallow underground feature in the framework of groundwater contamination and remediation ongoing at Operable Unit 2, Hill Air Force Base (UT). The target is the bottom of a paleochannel eroded in a clay layer at a depth of 10-15 m from the topography and filled with a mix of sands, clays and gravels, which have different compaction and water saturation. The channel acts as contaminant trap for dense non-aqueous phase liquids, therefore a detailed map of its geometry, lateral boundaries and depth is crucial to the remediation effort. The clay-rich sediments that cover much of the study area preclude any effective use of the most commonly utilized ground-penetrating radar.

Here I present the results of the processing of a 3-D reflection dataset acquired in 2000 over the buried channel, showing that it is possible to image and delineate the geometry and depth of the very shallow structure using reflection seismic techniques. The resulting contour map of the buried channel can be directly used to plan injection/extraction well placements in the ongoing groundwater remediation program. The outcome is in good accordance with the available well data in the deepest, critical part of the buried paleochannel, where the contaminant is concentrated. The map of the channel obtained

from the reflection seismic data, although taking advantage of the available borehole information, eliminates the need for many wells.

In addition, I designed and performed a 2-D elastic-wave seismic survey at the same site in 2005, using three-component sources and receivers. The processing effort resulted in horizontally polarized shear-wave and P-wave stack sections across and along the channel. Despite the less efficient seismic source, the S-wave images are superior to the correspondent P-wave images. Finally, after inverting the first arrival traveltime of both P- and S-wave data, I obtained maps of the V_p/V_s ratio and equivalent Poisson's ratio along the acquisition lines. These maps highlight areas with different sand and shale content, allowing distinguishing lithology changes in the subsurface.

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Acronyms

AGC:	AUTOMATIC GAIN CONTROL
CMP:	COMMON-MIDPOINT
CPT:	CONE PENETRATION TEST
DCE:	DICHLOROETHYLENE
DNAPL:	DENSE NON-AQUEOUS PHASE LIQUID
EPA:	ENVIRONMENTAL PROTECTION AGENCY
FAST:	FIRST ARRIVAL SEISMIC TOMOGRAPHY
GPR:	GROUND-PENETRATING RADAR
HAFB:	HILL AIR FORCE BASE
LNAPL:	LIGHT NON-AQUEOUS PHASE LIQUID
OU:	OPERABLE UNIT
PCE:	PerCHLOROETHENE
S/N:	SIGNAL-TO-NOISE
SEG:	SOCIETY OF EXPLORATION GEOPHYSICISTS
TCE:	TRIChLOROETHYLENE
USAF:	UNITED STATES AIR FORCE
USDA:	UNITED STATES DEPARTMENT OF AGRICULTURE
VSP	VERTICAL SEISMIC PROFILE

CHAPTER I

Introduction

Accurate characterization of groundwater contamination sites is crucial for any successful design of effective and cost-efficient remediation strategies, especially when scarcely soluble, dense contaminants are involved. In addition, degradation and pollution of groundwater is becoming an increasingly serious problem. In natural subsurface systems dominated by heterogeneity, the delineation and even the detection of contaminants can be extremely difficult. As a result, several invasive and noninvasive technologies for the characterization of contaminated sites have been developed. Boreholes, trial pitting and cone penetration tests are common investigations at contamination sites, but have inherent lateral sampling limitations as well as the potential to spread contaminants by opening migration pathways through low-permeability zones.

Alongside these intrusive techniques, seismic methods are now beginning to be applied to groundwater contamination problems. In fact, seismic techniques are non-intrusive and can provide spatially continuous information regarding shallow subsurface structures (Steeple, 2001).

Seismic methods probe volumes rather than providing discrete point measurements, which can be an advantage in characterizing a site with small, dispersed pockets of contaminants. Although the resolution is generally too low to directly detect disconnected blobs of pollutant in the subsurface, geophysical techniques can be used to characterize and differentiate the geologic units that would be likely to harbor a contaminant or control its movement. Direct mapping of DNAPL by means of seismic is currently under

investigation. Seismic methods have applicability in a wide range of shallow environments, and particularly in areas where the target depth or the soil and/or hydrologic conditions preclude effective use of ground-penetrating radar (GPR), such as areas of high electrical ground conductivity caused by near-surface clay soils.

DNAPL

In general, a dense non-aqueous phase liquid (DNAPL) is defined as a heavier-than water organic liquid that is only slightly soluble in water. The acronym was first introduced in the United States during litigation proceedings in New York State in the late 1970s. Chlorinated solvents, such as perchloroethene (PCE), trichloroethylene (TCE), and dichloroethylene (DCE), are typical DNAPLs (Bedient et al., 2000). The high volatility of these solvents originally prompted their disastrous disposal practice. It was in fact considered ‘acceptable practice’ to spread them onto dry ground to allow them to evaporate, without recognizing the ability of DNAPLs to infiltrate rapidly into the subsurface, causing soil and groundwater pollution.

Groundwater contamination by DNAPLs has been recognized as a serious environmental problem. DNAPLs have been widely used for many decades, and have been introduced into the ground by spills and leaking storage and disposal facilities. Upon release, DNAPLs sink until their residual level, i.e. discrete blobs and ganglia of liquid that are disconnected from each other, are held in place by capillary force preventing further movement, or an impermeable layer (aquiclude) is reached, at which point pooling and lateral spreading may occur (**Figure 1.1**). DNAPLs are typically characterized by low solubility and are resistant to biodegradation and natural attenuation (Lucius et al., 1992;

Pankow and Cherry, 1996). They are, however, slightly soluble in water, and can persist for many decades. Some DNAPLs are highly toxic and even small amounts can present a long-term source of groundwater pollution and pose an unacceptable risk to human health or the environment. In some cases (e.g. TCE) the maximum contamination level allowed in drinking water is as low as 5 ppb.

Figure 1.1: A DNAPL spill (modified from: Bedient et al., 2000). DNAPL spilled at the surface migrates downward, leaving residual saturation behind, until it reaches the water table. After spreading laterally, the DNAPL moves downwards through the saturated zone.

DNAPL contaminated sites tend to be more complex than light non-aqueous phase liquid (LNAPL) or aqueous contaminated sites because the physical and chemical characteristics of dense, scarcely soluble contaminants add additional complexity to heterogeneous geology and hydrogeology at most sites. While LNAPL contamination is usually constrained to the top of the water table and above, and aqueous phase contamination follows the hydrology of the site, DNAPL movement is controlled by gravity and capillary pressure of sediments, and can move against the hydraulic gradient. DNAPLs, particularly if comprised of chlorinated solvents, usually present a much more formidable remediation challenge than LNAPLs.

Furthermore, DNAPL is probably a significant source of groundwater contamination at almost all chlorinated-solvent-contaminated sites, but it is rarely detected in site-monitoring wells (EPA, 1993).

Finally, DNAPL migration pathways are governed by the structure of the porous medium, dictating which holes the liquid will penetrate, and DNAPL pools tend to form above finer grained horizons that provide the necessary capillary resistance to support the DNAPL accumulation. Therefore, without a comprehensive knowledge of the geometry of the subsurface, it is very difficult to predict the migration and accumulation of the dense contaminant beneath the water table.

Hence, geophysical techniques potentially can have a big impact on this challenging problem by imaging possible structural and/or stratigraphic traps for contaminants and by providing high resolution mechanical property maps of the shallow subsurface.

COMPRESSIONAL-WAVE SHALLOW REFLECTION SEISMIC

The first examples of recorded reflections shallower than 50 m were published half a century ago, by the U.S. Geological Survey (Pakiser et al., 1954, Pakiser and Warrick, 1956; Warrick and Winslow, 1960). Depth-to-bedrock investigations were tested using a specially constructed portable shallow reflection seismograph. Digital seismographs were not yet available, and the method was not strongly pursued until the late 1970s and early 1980s.

A classic paper by Hunter et al. (1984) developed the optimum window technique, first used for constant-offset surveying but now adopted in typical common-midpoint (CMP) processing. At that time, however, the high cost of seismographs, computer, and processing systems limited the seismic investigation of the shallow subsurface.

Early work by Steeples illustrates the usefulness of compressional-wave (P-wave) reflection data for near-surface applications, while pointing out the difficulties occurring with frequency dependent attenuation, ground roll noise, and static corrections (Steeple and Miller, 1990).

It is only in the past decade that high-resolution seismic reflection profiling has become an important non-invasive tool for determining the physical properties and geometry of the upper 100 m of the subsurface. Shallow reflection seismic surveying is now fairly commonplace in academia, and it is becoming significant in the environmental industry as well (Geophysics Special Section -Shallow seismic reflection papers, 1998; The Leading Edge Special Section - Near-surface problems and solutions, 2004).

Although profiles are often sufficient for mapping relatively simple and continuous geological features, reliable knowledge of the size and geometries of complex reflectors

may be difficult to obtain on the basis of sparse 2-D datasets alone. In addition, seismic wave propagation is a 3-D phenomenon, especially when geological interfaces show a complicated topography. As pointed out by Lanz et al. (1996) in one of the first publications about 3-D high-resolution seismic reflection survey, out-of-plane reflections and diffractions may lead to serious misinterpretations of 2-D seismic profiles.

In spite of this, three-dimensional shallow reflection seismic investigations are not very common, somewhat surprising considering the popularity of 3-D seismic reflection surveying in the exploration for hydrocarbons.

One major deterrent to the widespread use of shallow 3-D reflection surveys is its inherently high cost. In addition, few engineering companies concerned with investigations of the near surface currently have the necessary equipment and expertise to collect and process shallow 3-D seismic reflection data.

In assessing their results, Siahkoohi and West (1998) emphasize the need for a uniform distribution of offsets and azimuths in the CMP bins. The scheme applied by Bker et al. (2000) in a 3-D investigation of near-surface glacial sediments, required wide offset and azimuth ranges, together with small bin sizes and high-fold acquisition strategy. High subsurface coverage is also essential to minimize or eliminate source-generated noise in the earliest parts of seismic data, and simultaneously preserve the shallowest reflections (Spitzer et al., 2003).

3-D seismic reflection methods are reliable and valuable tools for the detailed mapping of near-surface targets. Although the major lithological units are usually identified on 2-D seismic reflection profiles, much more detailed images of the subsurface structures and greater confidence in the interpretation can be accomplished from 3-D data. However,

this requires a dense spatial sampling of the wave field at short source-receiver offsets, i.e. large numbers of shots and receivers closely spaced, and consequently high acquisition costs.

Nevertheless, the development of towed land streamers systems (van der Veen et al., 2001) and portable geophones arrays (Bachrach and Mukerji, 2001) during the past few years has demonstrated the feasibility of acquiring high-quality data while minimizing manpower and field time, consequently reducing the cost of the acquisition. Thus, it is realistic to expect that high-resolution 3-D seismic reflection surveying will soon become common practice in the detailed assessment of hydrogeological/engineering sites with complex geology.

Although case studies on shallow 3-D seismic reflection techniques applied to areas characterized by both unconsolidated sedimentary sequences and crystalline environments have been published (Schmelzbach et al., 2006; Bachrach and Mukerji, 2005; Spitzer et al., 2003), these take into consideration targets usually much deeper than 20 m. Moreover, the source and receiver spacing used in the seismic acquisition are most often in the order of meters, not decimeters, the complexity of the subsurface is limited, and seismic is commonly combined with other geophysical techniques to reduce ambiguity. Thus, the dataset presented here is unique, due to the particular application to a groundwater contamination and remediation site, the complexity and depth of the target limited to less than 20 m, and the high resolution of the survey resulting from the dense distribution of sources and receivers.

SHEAR-WAVE SHALLOW REFLECTION SEISMIC

While shear wave (S-wave) applications languished in the oil industry in the 1990s, the near-surface seismic exploration community was putting SH-waves to use in high-resolution imaging of targets at depths of less than 100 m. A well recognized advantage of S-wave data in many shallow environments was the improved vertical resolution, due to the much lower velocity of shear-waves compared to compressional wave, especially in water-saturated sediments, resulting in shorter wavelengths than P-waves in a given frequency band. A second significant advantage was the lack of sensitivity of the shear modulus to fluid saturation, allowing scientists to “see” below the water table.

Hasbrouck (1991) utilized a hammer-impact source to evaluate the feasibility of using shallow-depth, seismic shear-wave methods to detect various underground features.

Goforth and Hayward (1992) presented a case where, by using shear waves to profile the alluvium/bedrock interface, it was possible to avoid the water table and ground roll problems associated with compressional profiling.

In spite of the benefits over P-wave, surveying with shallow S-wave reflections has not been widespread, due to a number of experimental drawbacks. Separating S-wave reflections from the Love waves that usually arrive at the same time on seismograms has been and continues to be the major obstacle to progress in this area (Robertsson et al., 1996).

Nonetheless, in the last few years, near-surface applications of S-waves have received increasing attention. Carr et al. (1998) presented migrated S-wave sections, showing that shear wave images are not only feasible in unconsolidated materials, but can provide additional information about structural relationships within till units. Young and Hoyos

(2001) illustrated a simple, near surface horizontally-polarized shear wave (SH-wave) study, revealing a shale boundary incised by channels approximately 1 m in thickness, possibly filled by gravel lenses, which could not be seen on P-wave records. SH-wave seismic reflection data, collected over a shallow aquifer, were exploited by Jarvis and Knight (2002) to investigate the use of such data in hydrogeological applications. Pugin et al. (2004) constrained the hydrogeological model of a shallow aquifer by combining SH-wave and P-wave high-resolution seismic reflection data. In addition, the cost of acquisition was effectively reduced using towed land streamers.

Finally, Rabbel et al. (2004) provided an example of the use of multi-component survey, a technique already established as state of the art in industrial applications, but very uncommon in shallow acquisition.

Shear-wave reflection seismic data acquired at the site allows the elastic parameters of the shallow subsurface to be determined, serving as natural complement to available compressional-wave data.

OUTLINE

This thesis is intended to test and illustrate the ability of elastic wave seismic methods to map a very shallow (< 20 m) buried channel, in the framework of groundwater remediation. The main objective is to test high-resolution seismic methods to characterize the shallow subsurface and identify structural/stratigraphic traps for contaminants. As a case study, a further aim is to expand and improve the understanding of the subsurface environment developed from well data at a particular site, by retrieving information immediately usable for the remediation effort, such as the accurate geometry and depth of

the underground features and the mechanical properties of the shallow subsurface. Lastly, this thesis intends to be a tutorial about the processing of shallow seismic reflection data, presenting a detailed description of the different techniques used to solve particular problems in the data, and the results obtained.

The data presented in this thesis were acquired at Hill Air Force Base, Ogden (UT) in two different experiments, during the summer of 2000 (3-D dataset) and the fall of 2005 (2-D profiles). The first seismic survey recorded vertical component data only, and was processed as a compressional wave survey, while the second survey made use of both P-wave and S-wave sources, recorded on three-component (3-C) geophones. The focus of this thesis is primarily on the reflection dataset, although refraction data were also acquired at the site, and first arrival traveltime tomography applied to the 2-D data.

Following this introduction covering the background on the subject and the motivation of the thesis, I provide an overview of the area of interest including a brief history of the site, the object of the study and the available borehole information, in **chapter two**.

I describe the acquisition, processing and depth migration of the 3-D reflection seismic data in **chapter 3**. Two main aspects deserve specific attention: the first is the processing sequence, tailored to attenuating source-generated noise and enhancing the signal to noise ratio of the seismic records, in order to suppress coherent events in the stacked volume.

The second is the depth migration of the stacked volume, which benefits from an independently constructed velocity model.

Chapter 4 deals with the acquisition and processing of the 2-D profiles obtained with compressional and shear-wave sources. A particular emphasis is placed on the horizontally polarized shear-wave images, and on the S- and P-wave velocity models (V_s

and V_p) obtained from the seismic refraction data and their use to characterize the shallow subsurface.

The overall conclusions and interpretations are discussed in **Chapter 5**, along with correlation of the different seismic results and borehole data.

CHAPTER II

Site Background

SITE HISTORY

Hill Air Force Base (HAFB) is located in northern Utah, about thirty miles north of Salt Lake City and about five miles south of Ogden, just west of the Wasatch Front mountain range (**Figure 2.1**). The aircraft maintenance and repair activities at HAFB have generated waste including chlorinated and non-chlorinated solvents and degreasers, fuels and other hydrocarbons, acids, bases, and metals. These chemicals were historically disposed of in open pits and landfills on the Base; this activity was discontinued in 1980. The U.S. Environmental Protection Agency (EPA) placed HAFB on the Superfund National Priorities List in 1987. At present there are 11 contaminated geographic areas at HAFB, known as Operable Units (OU), encompassing one or more hazardous waste sites, and many of them extend off Base into the surrounding communities.

One of these units, OU-2, also known as “chemical disposal pit 3”, consists of at least two unlined disposal trenches, a few meters wide and approximately 20 to 30 meters long, which were used from 1967 to 1975 for the disposal of unknown quantities of chlorinated organic solvents from degreasing operations, primarily TCE. The pits lie above an alluvial aquifer. The estimated volume of waste solvents disposed in the trenches exceeds 40,000 liters and may exceed 400,000 liters, and is approximately 70% TCE (EPA, 2003).

The solvents migrated downward through the vadose zone (i.e. the unsaturated zone above the water table) into the shallow aquifer. This shallow, unconfined aquifer is

composed of a heterogeneous mixture of sand and gravel and is contained in a buried paleochannel eroded into thick clay deposits (**Figure 2.2**).

Figure 2.1: *The area of interest is located in northern Utah, west of the Wasatch Front mountain range (inset). Chlorinated organic solvents were disposed off in unlined trenches (red spot), and migrated into the shallow aquifer. A steep escarpment with a relief of about 90 m leads from HAFB to the Weber River Valley. Contamination extended downgradient (N-E direction) into a rural area that relies on groundwater for its needs. Distances are in kilometers.*

A large volume of DNAPL remains in the subsurface, predominantly as an immobile or "residual" phase, retained as ganglia by capillary forces in the aquifer's pore spaces, and also as a mobile phase pooled in topographic lows on the surface of the clay aquiclude (USAF, 1998).

The paleochannel crosses OU-2 approximately north-south, and the base of the channel is presently at 10-15 m depth beneath the topography. Contaminated soils and the pooled DNAPL are the source of shallow groundwater contamination extending approximately 500 meters downgradient, and beyond the HAFB boundary.

A steep, terraced, northeast-facing escarpment leading from the Base to the Weber River Valley below separates the on-Base portion of OU-2 from the off-Base portion. There is about 90 meters of relief between HAFB and the valley. Downgradient seeps and springs have also exhibited contamination.

Figure 2.2: *Schematic reconstruction of the paleochannel (courtesy of C. A. Zelt).*

BOREHOLE LOGS

As part of the site characterization, a set of geotechnical investigations had been performed at the contamination site previously. The primary focus of these activities was the delineation of the buried paleochannel. Due to the limited areal extent and saturated thickness of the aquifer, and the density of the DNAPL, the correct position and topography of the buried channel were considered of critical importance in determining where to position the remediation wells.

The morphology and depth of the top of the clay layer has been constructed by interpolating soil-boring logs, gamma logs and cone penetration test (CPT) logs from monitoring wells. This image shows a buried channel approximately 10-15 m below the surface, with a north-south trend (**Figure 2.3**). The bottom of the channel has depressions that can serve as deeper ponds for the solvent.

Because the well locations were adjusted on the basis of the information obtained from previous logs, the monitoring wells are concentrated in the central part of the channel, while the rest of the area has fewer and sparser data points. Moreover, the logs are clustered in a few parts of the channel, representing the deepest ponds.

A geostatistical approach to modeling the channel morphology that is more rigorous than linear interpolation, is weighting nearby data points by some power of their inverted distance, a process described by ordinary kriging. Kriging is an interpolation technique commonly used in the field of geostatistics in which the value of a property at an unsampled location is estimated from values at neighboring locations (Davis, 2002). Kriging estimates require prior knowledge in the form of a model of the semivariogram or the spatial covariance.

Figure 2.3: Contour map of the depth of the clay layer defined by linear interpolation of logged value (soil boring logs, gamma logs, CPT logs) from monitoring wells (white circles). The datum is 1431 m a.s.l.

The semivariogram describes the spatial correlation of the observations and it is used to fit a model of the spatial correlation of the observations (**Figure 2.4**). Kriging is based on the assumption that the parameter being interpolated represents a regionalized variable, intermediate between a truly random variable and a completely deterministic variable, where points that are near each other have a certain degree of spatial correlation, but points that are widely separated are statistically independent. The end result of kriging is the best estimate for all the unsampled locations in a field achieved by minimizing the error variance, in the least-squares sense, at each location. The Kriging model has the advantage, over other interpolation and smoothing methods, to allow estimating the prediction error and appraise the quality of the spatial estimation.

The morphology and depth of the top of the clay layer imaged by ordinary kriging of log values from monitoring wells (**Figure 2.5**), shows a buried channel very similar in direction and geometry to the one imaged by linear interpolation.

Figure 2.4: *Experimental semivariogram (blue circles) and fitted model (red line) for depth of clay layer. The model is exponential with range=48.7 and sill=1.33.*

Figure 2.5: Contour map of the depth of the clay layer predicted by kriging using logged value (soil boring logs, gamma logs, CPT logs) from monitoring wells (white circles). The datum is 1431 m a.s.l.

However, the topography of the top of the clay layer appears smoothed and only one deep pond is present on the bottom of the channel.

The uncertainty about the estimated value, in this case the contoured surface of the clay layer, is measured by the kriging variance, a parameter that quantifies the accuracy of the prediction and provides a basic validation of the kriging performance.

The map of the kriging variance (**Figure 2.6**) highlights the central area as the more statistically reliable, while moving toward the sides of the paleochannel means an increased variance, i.e. less confidence in the model.

Additional cross-validation schemes include the distribution of the deviations for the mean (Q1) and the distribution of deviations for the standard deviation (Q2), both good indicators of the performance of the kriging. The estimate is considered acceptable if the Q1 and Q2 values fall in the set confidence range (95%). In our case, this condition is satisfied by both schemes (**Figure 2.7**).

The kriging analysis was performed using the software package “EasyKrig 3.0”, running as a MATLAB® toolbox and shared freely for noncommercial uses.

LITHOLOGY BOREHOLES

From the seismic point of view, what makes this site interesting and challenging at the same time, is the extreme heterogeneity of the shallow sediments, exemplified in lithology boreholes drilled in the area of interest at quite close distance from each other (**Figure 2.8**).

The surficial sediments are comprised of the Provo alluvium, which consists of silt, sand, and gravel in a cut-and-fill stratigraphy.

Figure 2.6: Kriging variance map for the depth of the clay layer, as a parameter for measuring the quality of the Kriging model by quantifying the accuracy of the prediction. The higher the variance is, the less accurate the contour map. The very central part of the channel is the most accurate. The white circles are the observations. The black dash line represents the limit of the 3-D seismic survey performed at HAFB in 2000.

The alluvium is up to 15 m thick and derived from igneous, sandstone, limestone, and quartzite rocks. The sediments are moderately to strongly calcareous, and the clast size exhibits little lateral continuity (USDA, 1999).

Figure 2.7: (top) Distribution of the deviations for the mean $Q1$ and (bottom) distribution of deviations for the standard deviation $Q2$, are indicators of the performance of the kriging. Both values fall inside the 95% confidence limits and are therefore considered statistically significant. (PDF = Probability Distribution Function)

The Provo alluvium is underlain by the Alpine formation, a thick silty clay unit with sporadic patches of fine sand and silt. Because of the very low hydraulic conductivity ($\sim 10^{-8}$ cm/s), the Alpine clay acts as an aquiclude, in our case as a contaminant trap.

Consequently, the clay surface morphology is the target of our study.

The very top of the alluvium is characterized by caliche, a hardened deposit of calcium carbonate that cements together other materials, including gravel, sand, clay, and silt.

Caliches, also known as desert hardpans, occur in arid or semi-arid regions.

The unique characteristics of the shallow underground at the groundwater contamination site are extremely important, because they control the seismic response. The very large mechanical heterogeneity is an exceedingly complicated seismic medium, with large-scale velocity fluctuations both laterally and vertically. A further complication is that the seismic response seems to be controlled by the saturation profile and not by a sharp boundary as defined by the phreatic surface (i.e. the water table). The extra-hard ground, aside from attenuating the seismic waves, made it difficult to properly couple the geophones with the terrain, and pre-drilling was required for the geophone shafts.

ADDITIONAL INFORMATION

Supplementary information obtained by monitoring wells are the water table depth and the depth of a clean sand layer (**Figure 2.9**). The water table data refer to the 2005 seismic experiment, and were collected during the experiment. Although the water table is assumed to be around 10 m below the surface, no data exist for the 2000 seismic experiment. The shallow aquifer is confined into a containment wall installed around the apparent DNAPL source zone at OU-2 in the spring of 1997, and therefore the water

table is mainly controlled by precipitation and remediation operations. As for the sand layer, the number of data points is limited and a correlation extended to the area of interest is difficult.

Despite drilling about 140 wells in an area ~50x100 meters, the remediation site is still not characterized well enough to complete the cleanup in a cost-effective way. In fact, besides the cost, the most common invasive techniques (drilling and cone penetration test) have intrinsic lateral limitations and can potentially spread the contaminants by opening migration pathways through low-permeability zones. In contrast, seismic methods provide a valuable non-invasive tool, especially when other tools such as GPR are not effective. These considerations prompted testing seismic techniques at HAFB.

Figure 2.8: Lithology logs located in the northern part of the area of interest (modified from: USAF, 1998). The top 10-14 m are comprised of the Provo alluvium, which consists of silt, sand, and gravel in a cut-and-fill stratigraphy. The alluvium is underlain by the Alpine formation, a thick silty clay unit which acts as an aquiclude. The 10 m depth contour of the channel as imaged by interpolated well data is shown on the well locations map as reference.

Figure 2.9: (a) Water table and (b) clean sand layer interpolated from borehole data. The water table depth data refer to the 2005 experiment (red lines). The black dashed line represent the limits of the 2000 seismic experiment. Depth are from a datum at 1431 m a.s.l.

CHAPTER III

3-D Reflection Seismic Data

A set of seismic investigations of the shallow subsurface (less than 20 m) were performed at HAFB by Rice University, in order to expand and improve the understanding of the subsurface environment developed from well data at OU-2. In particular, a 2-D seismic experiment (three lines) was conducted in 1998. A more extensive seismic survey was carried out in 2000, encompassing 3-D reflection and refraction seismic, six down-hole check shots, and a survey combining 2 borehole vertical seismic profiles (VSP) and a surface reflection profile. The whole set of experiments took into consideration P-waves only, and several studies resulted from the analysis, processing and interpretation of the acquired seismic data, by applying both standard processing techniques (Dana, 2003) and research level inversion methods (Gao et al., 2006; Zelt et al., 2006; Azaria, 2003).

The purpose of the seismic surveys was to image the buried paleochannel in the framework of the ongoing groundwater remediation effort at the site, and in broader terms, to develop high-resolution seismic methods for characterizing the shallow subsurface and identifying structural/stratigraphic traps for contaminants.

The subsurface at the groundwater contamination site proved to be an extremely heterogeneous and complicated seismic medium, with large-scale velocity fluctuations both laterally and vertically combined with a particularly shallow target depth and uneven water saturation. The measured seismic compressional velocities in the upper 15 m vary from about ~250 m/s at the surface to 1500 m/s (water velocity) at about 14 m depth (a factor of 6). Laterally the velocities at any depth can vary by a factor of 2. These are

enormous variations for most seismic imaging schema, considering that the behavior of shallow seismic reflections is critically tied to the near-surface velocity structure. Such lateral velocity variations require at very least depth migration to accurately image the alluvium-clay layer boundary. In addition, one of the goals of collecting seismic reflection data, essential for the remediation effort, was to obtain an image in depth of the subsurface.

In a complex medium, the accuracy of any seismic image in depth strongly relies on the accuracy and detail of the velocity model used in processing and migration. The previous processing made use of the stacking-velocity models, smoothed and depth converted, for migration after stack. The critical step is to convert stacking velocities using Dix's equation (Dix, 1955). When structural dips and lateral velocity gradients are small, seismic time sections can be converted to depth sections using the velocity function calculated during velocity analysis. However the degree of accuracy of the resulting interval velocity is directly affected by the accuracy of the stacking velocities and the amount of structural dip and lateral velocity variation. Consequently, in our specific case such a converted velocity field is not an accurate representation of the seismic velocity field required by migration.

In contrast, inverse methods provide a powerful tool to build a relatively complex velocity model that is very close to the migration velocity model (Schultz, 1999). This has the advantage of eliminating a number of velocity analysis processing steps difficult to perform in poor signal resolution datasets. Hence, the rationale behind this new effort on already processed and interpreted data was the intent to use the available 2-D

waveform tomographic velocity fields to post-stack depth migrate the stacked 3-D reflection seismic volume.

The task of depth-migrating the seismic dataset required a reprocessing of the seismic data specifically focused on removing unwanted signals, in particular surface waves, and enhancing the reflections. In fact, migration is extremely sensitive to random and coherent noise present in the seismic record. For this reason, records at the low-velocity, small-time end of the shallow reflection spectrum often do not respond favorably to migration. Furthermore, migrating diffractions from shallow targets can cause an overall lowering of the coherency of a stacked seismic section, because the diffraction tails can easily be lower in amplitude than the ambient noise.

An additional limitation is that depth migration after stack can remove the effect of a complex medium provided the input section (stack) accurately represents a zero-offset section. When the complex overburden causes ray path distortions that generate anomalous, non-hyperbolic moveout patterns in pre-stack data, post-stack depth migration does not produce a completely accurate image of the subsurface, even when the velocity-depth model is known accurately. Departure of the stacked section from the true zero-offset section, in fact, imposes a limitation on the accuracy of the image we get from post-stack depth migration (Yilmaz, 2001).

These drawbacks are balanced by the potential benefits of post-stack depth migration. Post-stack depth migration is appropriate for cases with significant ray bending at layer boundaries, significant vertical velocity gradients, and strong lateral velocity variations with sharp changes in reflector curvatures (Yilmaz, 2001). Moreover, migration can be represented as the application of a “smearing” operator to each single point on the

unmigrated section. The operator distributes the single-point amplitudes in unmigrated space over “spheroidal and ellipsoidal” migration trajectories corresponding to the zero offset traveltime path of influence on the migrated section. Thus, the smeared amplitudes accumulate on the migrated section, adding constructively where reflectors occur and destructively where no reflectors occur. The data to image space transformation gives continuity to reflections that often appear with jigsaw patterns on the stacked volume. Finally, the available borehole logs offer the unique opportunity to evaluate the results of the seismic processing and post-stack depth migration, compare and corroborate the validity of the approach to solve groundwater contamination problems, and highlight the limitations of the method.

DATA ACQUISITION

The acquisition parameters (**Table 1**) were designed taking into account previous on-site experience and expected results, equipment availability, and logistic limitations.

The seismic survey has dimensions of approximately 36x92 m and the shape of a rectangle, except for the very southern part where it becomes a parallelogram to adjust for obstacles. The survey was centered on the paleochannel as determined by boring logs (**Figure 3.1**).

The field layout is a non-orthogonal (or slanted) brick pattern, where the source lines are at an angle of 45° from the receiver lines (**Figure 3.2**). Each patch has 6 active receiver lines with a spacing of 2.1 m. The source points for each patch lie in the center of the patch between two adjacent receiver lines. The source line spacing is 2.1 m and repeats every other patch. Both the receiver and the source station intervals are 0.35 m in the

inline direction. The source points are stretched out in the source line direction, consequently the midpoints fall into the center of the bins using a natural bin size of 1/2 the source/receiver increment (0.175 m).

Due to the limited number of active receiver lines (6), the recording geometry has a narrow azimuth, leading to an even distribution of offsets. The offset distribution is skewed toward the short and mid offsets, with no gaps. The range of azimuths is limited and focused in the inline direction (**Figure 3.3**).

The 3-D reflection data were acquired along 45 east-west receiver lines, each approximately 36.5 m long (**Figure 3.4**).

Table 1. Acquisition parameters for the 3-D seismic survey		
	Nominal	Actual
Survey dimensions	3363 m ²	3331 m ²
Survey shape	Rectangle	Rect.-Paral.
Rec. inline direction	EW	
Rec. inline interval	2.1 m	
Rec. spacing	0.35 m	
Number of rec. points	4725	4520
Length of rec. lines	36.4 m	36.05 m
Source line direction	NE-SW	
Source line interval	2.1 m	
Source spacing	0.5	
Number of source points	4752	3126
Length of source lines	2.5	
Number of rec. lines	45	
Number of chan. per line	120	104
Patch	6x120	6x104
Geophones	40 Hz	
Source	.223 rifle	
Hole depth	0.3 m	
Bin size	0.175x0.175 m	0.2x0.2 m
Number of traces	3402000	1816958
Record length	200 ms	
Sample rate	1 ms

Figure 3.1: 3-D Seismic survey limits (dash line) and contour map of the deepest part of the paleochannel, as reconstructed interpolating the borehole (circles) data. The contour lines highlighted are at 10, 12, and 14 meters depth from 1431 m a.s.l.

Figure 3.2: (a) The acquisition patch is a 45° slanted pattern, with receiver and source lines at 2.1 meters of distance. The source lines repeat every other patch. (b) The source/receiver spacing is 0.35 m. The midpoints fall into the center of the bins, using natural 0.175 m square bins (black grid).

Figure 3.3: The acquisition geometry leads (a) to even population of offsets in CMP bins that is skewed toward short offsets, and (b) to a narrow range of source-receiver azimuths focused inline.

Figure 3.4: Acquisition layout of the 3-D seismic experiment, overlain on the elevation map of the area of interest. Black and magenta dots represent the actual position of the sources and receivers, respectively. Gaps and shifts in the source/receiver position are due to bad shots and obstacles on the ground.

The slanted acquisition geometry has a maximum source-receiver offset of about 36 m and maximum nominal fold of 52 traces, in 0.175 m square bins. Because of source and receivers gaps due to bad shots and obstacles such as propane tanks, pipelines, cement well pads and trailers, the actual fold is non-uniform. Moreover, in some areas (e.g. inline 1120 and adjacent), the actual fold drops significantly (**Figure 3.5**).

The seismic data were acquired using about 630 REF TEK 125A single-channel seismic recorders with 40 Hz geophones. Because of the extra-hard soil, most of the geophones were planted into pre-drilled holes. The seismic source was a .223 caliber rifle fired ~20 cm downhole into a pre-drilled and “plastic bag cased” hole.

The trace length was 200 ms, the sample rate 1 ms, and 120 channels were assigned to each of the 6 active receiver line, for a total of 720 nominal channels per shot gather. Of these, on average 104 were actually recorded, for a total of 624 active channels per shot.

DATA PRE-PROCESSING

The seismic data available were already converted to SEG-Y format (Barry et al., 1975), a standard format defined by the Society of Exploration Geophysicists (SEG), time zero corrected and sorted into common-shot gathers. Moreover, the bad shots were removed from the dataset and the trace headers populated with the main header words.

Therefore, the first step in the actual processing sequence (**Table 2**) was the geometry installation and subsequent full population of the trace headers. Defining the geometry and correctly filling the trace headers is a tedious but important process. In fact, most of the processing steps are not properly executed when the trace headers are incorrect.

Figure 3.5: *Actual fold of the CMP gathers obtained with a normal bin size of one half the receiver distance (0.175 m).*

The coordinates of sources and receivers are in Easting and Northing (m), and referenced to the local Utah Coordinate System of 1927. Because of the relatively low importance of the absolute coordinates and to give a better perception of the distances involved, the coordinates presented in the figures have been scaled.

Table 2. Processing flow for the 3-D seismic dataset. The steps highlight in gray were already applied to the data			
	Type	Parameter	
Formatting	SEG-Y		
Time correction	Time zero		
Sorting	Common source gather		
Editing	Bad shot killing		
Coordinates installation			
Geometry installation			
CMP Binning	Flex Bin	Bin size:	0.2x0.2 m
Trace killing			
Trace muting	Top mute	Ramp:	10 ms
Trace equalization		Time gate:	200 ms
		Scalar:	Mean
Amplitude scaling	AGC	Length:	75 ms
		Scalar:	RMS
Bandpass filter	Butterworth single filter	Phase:	Minimum
		Frequency:	160/12-400/12 db/oct
Groundroll removal	Coherent noise attenuation	Filter length:	11 traces
		Frequency/Velosity:	10/160-400/240 Hz/m/s
Air wave attenuation	Air blast attenuation	Velocity:	331 m/s
		Time gate:	10 ms
Deconvolution	Predictive deconvolution	Operator length:	40 ms
		Prediction lag:	8 ms
Bandpass filter	Butterworth single filter	Phase:	Minimum
		Frequency:	140/12-420/12 db/oct
Static correction	Elevation statics	Final datum:	1431 m asl
		Replacement velocity:	Variable
Velocity analysis	Constant Velocity Stacks		
NMO Correction		Stretch mute:	10%
Stack	3-D		
Deconvolution	Predictive deconvolution	Operator length:	36 ms
		Prediction lag:	6 ms
Band pass filter	Butterworth single filter	Phase:	Minimum
		Frequency:	100/12-350/12 db/oct
Trace equalization		Time gate:	200 ms
		Scalar:	Mean
Depth migration	3-D poststack	Method:	Explicit finite-difference
		Maximum dip:	50 degrees
		Interval velocity:	Tomography

Trace binning

Due to obstacles, shifts in the source and receiver positions and small size bins, the common-midpoint (CMP) fold varies significantly in the 3-D survey. This variation degrades velocity analysis, stacking, and migration. Moreover, in some parts of the area of interest the fold drops considerably and consequently so does the signal-to-noise (S/N) ratio. Likewise, the offset distribution, well arranged considering the entire dataset, presents significant gaps when single gathers are evaluated. In the attempt to maintain a more uniform CMP fold and offsets distribution, flex-binning (bin fractionation) was applied to the dataset (Cotton and Sanders, 1983).

A trace may contribute to a CMP if the trace's midpoint falls within the boundaries of a square centered on the CMP (bin). Generally, the size of each bin is maintained equal to half the receivers' distance (natural bin size), and each trace assigned to one specific CMP gather. In our case, the bin size was enlarged by ~15%, from 0.175 m to 0.20 m. Moreover, the bin centers were maintained, thus the bins overlap (**Figure 3.6**) and some traces were assigned to more than one CMP gather.

The new binning results in a much more uniformly distributed fold, and most importantly, the entire area of interest has now a significant fold with no gaps and drops (**Figure 3.7**). Offset gaps were also filled. After testing, flex-bins were preferred to super bins (non overlapping, 0.35x0.35 m bins), because the former method better preserve the lateral resolution and gives overall a superior result. Beside a more consistent and uniform number of traces in the CMP gathers, trace-bin effectively enhanced the CMP gathers in terms of coherent signal (**Figure 3.8**).

Figure 3.7: *Actual fold of the CMP gathers obtained with flex-binning (0.2 m).*

Figure 3.8: CMP gathers (a) before and (b) after flex-binning. The red lines are the common traces. The data have been band pass filtered and gained. Note that the offsets are all positive because of the 3-D arrangement. Events are recognizable (arrows).

Noisy traces must be zeroed both because they decrease the S/N ratio of the final section, and most importantly because they may contain single samples with very large amplitudes (spikes), which adversely affect frequency filtering and stacking.

Similarly, all data samples muted are set to zero up to the specified mute time (top mute), picked on each of the shot gathers. If the direct wave is not removed from the seismic record, it stacks constructively and generates coherent noise on the final section. A mute ramp of 5 ms was used to smooth the transition from live data to muted data samples and to prevent undesirable side effects in the following application of filters.

The traces to be killed and the top mute time gate were selected on equalized, gained and bandpass filtered shot gathers, but then applied as first step in the processing sequence.

Zeroed traces were removed from the dataset before staking.

Trace balancing

In order to reduce the amplitude variations between traces in common source gathers, trace equalization was applied (**Figure 3.10**). The tool computes and applies a trace-to-trace amplitude balancing function. The equalization scalar was computed on a mean basis in a 200 ms window for each trace and applied to the entire trace (new amplitude value = old amplitude value / scalar).

Amplitude scaling

With the purpose of improving relative amplitudes in time and offset, an automatic gain control (AGC) was applied to the data (**Figure 3.11**). Amplitude corrections are needed to compensate for waveform spreading, inelastic attenuation, and transmission losses.

Figure 3.9: Single receiver line of common-shot gather after trace killing and top mute. The traces are normalized so that the relative amplitudes between the samples are maintained.

Figure 3.10: Single receiver line of common-shot gather after trace editing and trace equalization. The amplitude differences between the traces are reduced.

Figure 3.11: Single receiver line of common-shot gather after trace editing, trace balancing and amplitude recovery. The deepest part of the shot is now recovered.

AGC automatically varies the gain applied to trace samples as a function of the sample amplitude within a certain time window. Although AGC alters the amplitude content of the seismic record, it is a simple and robust method for amplitude recovery for structural intent, when the resulting loss of true amplitudes is acceptable, as in our case.

After testing, a 75 ms window was selected for gain computation, and the RMS amplitude in the window was the basis for the scale factor calculation. The gain scalar was applied to the sample at the center of the AGC window.

DATA PROCESSING

Processing flows are as widely variable as seismic data. In order to optimize the final stacked section, the flow was tailored to the particular problems of the data, specifically strong coherent noise and low S/N ratio. In fact, a first look at typical unprocessed shot gathers shows that the most prominent feature is the high-amplitude ground roll, which in the vertical component P-wave seismic data is typically composed of Rayleigh waves. The first approach to improve the S/N ratio was to attenuate noise in a domain in which signal and noise could be separated. Both frequency filtering, i.e. attenuating noise that has a different frequency content than the reflections, and frequency-wavenumber ($f-k$) filtering, i.e. attenuating noise that has a different spatial relationship (slope) than reflections, were tested on the data.

The second method to improve the S/N ratio was correcting for temporal shifts between the traces. Elevation static corrections were used to compensate for temporal shifts caused by deviations from the datum plane of the source and receivers during the recording process.

The last step to improve the S/N ratio was stacking. Theoretically, the S/N ratio increases as the square root of the fold of the seismic data, assuming that the reflection information is embedded in random noise. However, coherent noise not removed successfully from the data stacks constructively during the stacking procedure and generates reflection-like, artificial events on the final stacked section. In order to avoid these types of pitfalls, a conservative approach to processing was adopted. Specifically, we eliminated coherent noise events even at the expense of a final image that is poorer quality (Steeple and Miller, 1998).

Bandpass filter

Since ground roll typically has high amplitude and a lower dominant frequency than near surface reflections, the power spectrum of the raw data is not an effective tool for choosing the frequency filter parameters (**Figure 3.12a**). The spectrum is, in fact, dominated by the surface wave response. As an alternative, trial and error of overlapping bandwidth or narrow band filters is the best method to determine frequency filters for shallow reflection data (Baker, 1999).

Therefore, the preprocessed shot gathers were examined using a wide range of filters, to determine the frequency content of the signal (**Figure 3.13**). The highest frequency correctly sampled in the data is constrained to 500 Hz (Nyquist frequency) by the sample rate of 1 ms.

A minimum phase Butterworth bandpass filter from 160 to 400 Hz was considered the filter that best attenuates noise and brings out reflections, and was applied to the data.

Figure 3.12: Average power spectrum of single receiver line of a common-source gather (a) after trace killing and top mute, (b) after trace editing, equalization, AGC, bandpass filtering and coherent noise attenuation, and (c) after preprocessing, processing and predictive deconvolution. Note how the low-frequency groundroll dominates the raw data. After bandpass filtering the dominant frequency is about 170 Hz. Deconvolution flattens and broadens the data frequency content.

Figure 3.13: Test for the frequency filter. Signal content of one receiver line of a shot-gather in the frequency range of (a) 20-140 Hz, (b) 140-260 Hz, (c) 260-380 Hz, and (d) 380-500 Hz. Most of the coherent signal is encompassed in the 140-380 Hz frequency range. Ground roll, although predominant at frequencies below 140 Hz, is present even at higher frequency. Very high frequencies are spatially aliased and no coherent signal can be detected.

The roll off (slope) on either side of the pass band was set to 12 db/octave to avoid the Gibb's effect (i.e. ringing that greatly distort the data).

Bandpass filtered shot gathers show that the ground roll has been attenuated by the frequency filter, and the main reflection singled out (**Figure 3.14a** and **Figure 3.15**). In addition, coherent phases that cannot be removed by frequency filtering due to the overlapping frequency contents, such as the airwave and noise from the groundwater remediation equipment, can be discriminated on the seismic record.

Although greatly attenuated, ground roll is still present in the shot gathers after bandpass filter. Additional processing was required to remove or attenuate the coherent noise from the seismic record.

Coherent-noise attenuation

Both the bandpass filtered data and the equivalent f-k spectrum clearly reveal the presence of three different kinds of coherent noise affecting the seismic record, and specifically ground roll, airwave and remediation noise (**Figure 3.14**).

Ground roll is identified by the characteristic low but dispersive phase velocity. Because of the tapering of the bandpass filter, some low frequencies are still present in the data.

Different methods to remove or attenuate ground roll were evaluated.

Muting (Baker et al., 1998), besides requiring picking a time window on shot records, was detrimental to records because of the loss of part of the main reflection, due to the overlap of the two phases.

Spatial filters like f-k filtering and trace mixing, while increasing the coherency of the reflections, generated strong artifacts and enhanced aliased phases present in the data.

Figure 3.14: (a) Single receiver line of bandpass-filtered shot gather, and (b) relative f - k spectrum. Both the time series and the spectrum highlight different kinds of coherent noise, specifically remediation noise (N), airwave (A), and groundroll (G). In the f - k domain they occur in different positions based on their velocity and frequency. These noise trains overcast in part the main reflection (R).

Moreover, a good control of the f-k filtering parameters requires a high S/N ratio for the reflections of interest and a separation of phases in the f-k domain, requirements not met by the present dataset.

More sophisticated techniques to remove surface waves like tau-p transformation (Spitzer et al., 2001) and wave-equation datuming (Larkin and Levander, 1996), which require considerable manpower for a correct application, are very sensitive to the aliased phases present in the data, and therefore were not applied to the data. Refer to **Appendix A** for a comparison between the results of the different techniques tested for ground roll attenuation.

As an alternative, coherent noise attenuation (Hornbostel, 1991) proved to be effective in attenuating the residual ground roll from the common source gathers, without introducing artifacts in the data, or deteriorating the reflection signal. Coherent noise attenuation applies a spatial filter in the frequency-offset domain to attenuate linear coherent noise in common source ensembles, given a frequency-velocity pair. After testing, the values of 10-400 Hz for the frequency, and 160-240 m/s for the velocity, were picked.

Airwave is a source-generated noise, typically high frequency, broadband, and easily identified because of its constant velocity in the range of 330-340 m/s, depending on elevation, air pressure, temperature, and wind.

In order to remove the airwave still presents on some of the records after top muting and bandpass filtering, air blast attenuation was applied. This tool seeks out anomalous energy on a trace-by-trace basis using a pilot velocity and an approximate energy envelope width. This strong energy, when found, is attenuated down to an amplitude

level similar to the surrounding data. After testing, values of 331 m/s for the airwave velocity and 10 ms for the energy envelope width were used.

An important benefit was that air blast attenuation could be applied to the entire dataset even if the airwave noise trains were strong on some records but non-existent just few records away, because the process leaves all the traces that are not contaminated by noise untouched.

Remediation noise is linear coherent noise probably generated by remediation equipment or personnel/vehicular activity at the site. These noise trains are well behaved because of the relatively low amplitude, the narrow band, and the non-dispersive constant velocity. Furthermore, this kind of noise is present only locally, and on a limited number of shot gathers. Remediation noise was removed from the seismic record using coherency noise attenuation, with parameters adjusted on a case-by-case basis.

The successful attenuation of ground roll, remediation noise and airwave has the dual effect of enhancing the continuity of the main reflector in the shot gathers, while removing non-reflective coherent events (**Figure 3.16**). The power spectrum of a sample common-source gather after bandpass filtering and coherent noise attenuation, shows a usable bandwidth from 100 to 300 Hz, although the spectrum is unbalanced and is dominated by a frequency of about 180 Hz (**Figure 3.12b**).

Deconvolution

In order to remove the effect of the unwanted residual source-propagation signatures from the seismic record, in particular reverberations, statistical deconvolution was applied to the data. A combination of autocorrelation, deconvolved data, and the

deconvolved spectra were used to determine the parameters and test the effectiveness of the procedure. Final parameters include 8 ms prediction lag, 40 ms filter length, and 0-160 ms time gate for the filter design. Furthermore, a surface consistent scheme (Levin, 1989) was employed, because it appeared to lessen the detrimental effect of noise and non-stationarity on the deconvolution.

Surface consistent deconvolution is based on the concept of surface consistent spectral decomposition (Taner and Coburn, 1981). In such formulation, each trace is decomposed into the convolutional effects of source, receivers, offset and the Earth's impulse response, thus explicitly accounting for variations in the wavelet shape caused by near-source and near-receiver conditions, and source-receiver separation. After the components are separated, the deconvolution operator is designed using the power spectra from the source and receiver components, uses a least-squares approach.

Particular attention was placed on checking the performance of deconvolution across the entire dataset, and minimizing disruption of the coherent signal. In fact, deconvolution can be very detrimental of the seismic signal when applied blindly.

The deconvolved data are not only sharper, but the similarity of the wavelets is improved (**Figure 3.17**). In addition, the power spectrum of the deconvolved data is now much more balanced, as anticipated, and broadened especially toward the higher frequencies (**Figure 3.12-C**).

Static corrections

The topography at the site has a maximum elevation change of 3.0 m, although in most of the survey area the differences in elevation are smaller (**Figure 3.4**).

Figure 3.15: *Single receiver line of common-shot gather after preprocessing and bandpass filtering.*

Figure 3.16: *Single receiver line of common-shot gather after preprocessing, bandpass filtering, coherent noise attenuation, and air blast attenuation.*

Figure 3.17: *Single receiver line of common-shot gather after preprocessing, bandpass filtering, coherent noise attenuation, air blast attenuation, and predictive deconvolution.*

Considering the scale of the seismic experiment and the low velocity of the near surface layer, such elevation differences are non-trivial. The standard method for correcting for elevation changes is to shift each source and receiver in time to a flat datum. The datum plane is usually located either at the lowest or at the highest location in the profile. In our case, the datum was placed at an elevation of 1431 m a.s.l., to avoid shortening the arrival time of the extremely shallow reflections. In addition, the datum is consistent with the tomography model used for migration.

The velocity of the layer between final datum and topography (replacement velocity) was selected following two criteria. Firstly, a constant velocity of 400 m/s, determined by measuring the average velocity of the direct arrival on the shot gathers across the survey area, was used. Secondly, a variable replacement velocity extrapolated from the available waveform tomography velocity model, was applied (**Figure 3.18**). The model shows important velocity variations in the area, especially higher velocities in the south and lower velocities in the north. We expect static correction to be important in these parts of the survey (where elevation changes are larger and velocities very low).

The comparison of the results shows that although the static corrections are generally small, the difference is subtle but not trivial in area of high elevation difference and low velocity (**Figure 3.19**). The variable replacement velocity gives better results.

Small trace-to-trace variations in arrival times due to very localized velocity variations remaining after datum statics in a CMP gather are generally corrected by means of residual statics. Surface consistent residual static corrections were calculated for the normal move-out (NMO) corrected CMPs, along time gates centered on the main reflector.

Figure 3.18: *Replacement velocity used for the elevation static calculation. The near-surface velocity model is derived directly from the available waveform tomography velocity field (Gao et al., 2006).*

Figure 3.19: Receiver line of shot-gather (a) before static correction and after static correction calculated with (b) a constant and (c) a variable replacement velocity. Receiver elevations and time-shifts are plotted above the traces in black and red, respectively. Note how the reflector indicated by the arrow changes shape depending on the replacement velocity used.

The temporal width of such gate was always kept sufficiently large (> 20 ms), and the maximum allowed shift at each station was less than or equal to 2 ms.

In spite of the conservative processing approach, after testing different parameters, the residual statics were not applied to the CMPs, to avoid artificially induced or overly forced coherency in the data. The non-robustness of the residual static solution was corroborated by low autostatics quality factors. These quality factors, ranging from 0 to 1, are based on correlation coefficients of input traces against the pilot trace. If a source or receiver static exhibits a very low quality factor relative to its neighbors, such as 0, a low reliability for the computed static is implied.

The preprocessing and processing sequences were tested on a number of sample shot-gathers acquired in various parts of the survey area and are shown for the sample gathers in **Figure 3.20**.

Velocity analysis

Velocity analysis is an extremely important step in the processing sequence. Reflections are in fact not correctly expressed on the final stacked section without a correct stacking velocity field.

Although the quality of the data at this phase was considerably improved with respect to the original data, there were still areas where determining the optimal stacking velocity of the reflections using velocity spectrum analysis and interactive velocity analysis was difficult.

Figure 3.20: Summary of the processing flow applied to the data. Entire shot gather (6 receiver lines) after (a) trace editing, trace balancing and amplitude recovery, (b) after preprocessing and bandpass filtering, (c) after preprocessing, bandpass filtering and coherent noise attenuation, and (d) after preprocessing and processing.

Likewise, sequentially picking hyperbolas on CMP gathers was made problematic by lateral velocity variation, non-uniform fold, and limited offset of the events.

Moreover, the use of reflection hyperbola in the more consistent source gathers is not a valid alternative in our case. Fitting hyperbolas to shot gathers yields to a correct stacking velocity only when the subsurface is horizontally stratified and isotropic. Stacking velocities are approximately the RMS velocity, provided the reflectors are horizontal and the velocity varies only with depth (Sheriff, 1991).

Stacking velocity is not a physical velocity, although it is related to the true velocity of the material, and in the case of flat layers strictly applies to the hyperbola that best fits a reflection in a CMP recording.

Perhaps the easiest and most robust method to use with shallow reflection data is constant velocity stacks (CVS) plots, an approach that is also quite efficient considering the relatively small volume of data. In addition, using CVS allows for the picking of velocities for maximum coherence on entire reflections rather than piecemeal velocity picking using other methods.

Constant velocity stacks were used to estimate velocities in correspondence of 45 inline profiles, approximately every 2.1 m of spacing in the crossline direction.

As first test, the minimum and maximum boundaries of the NMO velocities was set from 100 to 1500 m/s, in order to cover a broad range of velocities.

For the final analysis, CVS in the interval of 200 to 1000 m/s were produced and carefully studied to determine the velocity field. A velocity step size of 40 m/s was adequate to get the best stack result (**Figure 3.21**).

Figure 2.21: Example of constant-velocity stack panels used for the velocity analysis (inline 1060). The normal-moveout velocity is specified on each panel. The stretch mute is set to 10%.

The velocity picks were chosen to bracket the reflection with the NMO velocity of interest, rather than at the time of the reflection, so as to avoid differences between CVS and stacked wavelet due to the linear interpolation between velocity picks.

The final stacking velocity model was smoothed over 13 CMPs (2.1 m) in the inline direction, and over 25 CMPs (4.2 m, or two receiver lines) in the crossline direction, in order to reduce large velocity gradients that may cause distortion effects (Miller and Xia, 1998).

Finally, NMO corrected CMP gathers, after CVS velocity analysis but before stacking, were displayed to make sure that the coherent events were flattened.

Stacking

After applying the normal moveout correction, the CMP gathers were stacked. Even if the assumption of hyperbolic reflection events is valid only when lateral velocity changes are small, a fairly good final stacked section is not completely precluded in case of non-hyperbolic events, and the negative effects of strong lateral velocity gradients are far less severe with small station spacing, like in our case (Baker et al., 1999).

A 10% stretch mute was applied during the NMO correction process to mute the frequency distorted reflection information, which will degrade the final stacked section (Miller, 1992).

A quick, convenient way to evaluate changes in the amplitude of the seismic data is to display time slices through the stacked 3-D cube. In our case, the structure of the paleochannel is well delineated in the horizontal slice at 50 ms (**Figure 3.22**). A simple 2-D median spatial filter has been applied (3x3 samples) and 3 samples have been

stacked vertically. The approximate depth is 12-13 m. The seismic response weakens in the southernmost part of the survey, where the fold is reduced (see **Figure 3.7**).

The 3-D seismic time slice also reveals a linear spatial pattern in the data, aligned in the E-W direction, an acquisition footprint due to the particular distribution of source-receiver azimuths.

Post-stack processing

Post-stack processing is quite critical, with strong influence on the quality of the final outcome. Bearing in mind that the desired final product of the processing effort is the depth migrated image of the paleochannel, a more aggressive predictive deconvolution with 6 ms prediction distance and a 36 ms filter length was applied to the traces after stack. In addition, the attenuated ground roll and lower frequency content due to stacking procedure allowed for a more robust 100-300 Hz bandpass filter. Finally, trace balancing and AGC were reapplied to the stacked data, given that lateral variations in amplitude adversely affect the migration process. No spatial filter was applied at this point, so as not to introduce lateral coherency and create a “wormy” aspect in the stacked data.

3-D DEPTH MIGRATION

The need to migrate very shallow, high-resolution seismic reflection data is a function of depth and geometry of the target, near-surface velocity, and spatial and temporal sampling interval (Black et al., 1994). If dips are small, conventional stacked sections provide a normal incidence representation of the subsurface.

Figure 3.22: *Horizontal time slice through the final stacked volume at 50 ms. A simple median 2-D spatial filter with 3x3 samples has been applied horizontally, while vertically 3 samples (3 ms) have been stacked. The horizontal lineation is an acquisition footprint related to the azimuthal content of the data. A weak response in the south part of the survey corresponds to a lower than average, non-uniform fold of the CMPs (see Figure 2.7).*

Moreover, for shallow reflectors involving very low seismic velocities, the maximum distance and depth moved by migration can be only a few CMP traces or time samples, respectively. In such a situation, migration makes no detectable change in the stacked data. However, in our specific case the slopes of the paleochannel are significantly steep and the velocity of the near-surface sediments relatively high in spite of the depth, because of the water saturation (~ 1000 m/s for clay layer), and the spatial sampling is particularly small (0.175 m). Consequently, the maximum potential change is many traces or time samples in magnitude, and migration is necessary to produce a geometrically accurate image of the buried paleochannel.

Migration can produce poor results if the data have a low S/N ratio, and if the velocity structure is poorly determined or very complicated (Yilmaz, 2001). Therefore, besides a processing sequence designed to maximize the signal response and minimize the noise, an adequate velocity model is needed. The interval velocity in depth used for the depth migration was directly derived from the waveform tomography inversion of the seismic data along the 45 receiver lines (Gao, 2004). The 2-D velocity profiles were combined and extrapolated in a 3-D cube, then smoothed vertically over 1 m, and horizontally along one receiver line (2.1 m) in the inline direction and two receiver lines (4.2 m) in the crossline direction, respectively (**Figure 3.23**).

3-D post-stack depth migration was applied to the stacked volume. A finite-difference algorithm (Claerbout, 1985), implemented using an explicit scheme with 50 degrees dip accuracy was preferred because of its ability to handle the velocity variations. In addition, finite-difference migration is more robust in handling velocity errors. In particular, when using velocities greater than those of the true medium, overmigration is not as

pronounced as it is with other algorithms. This characteristic fits quite well with the tomography model. To avoid artifacts, a 0.1 m step size was used for the depth migration, far less than the aliasing sample interval. In order to produce the full 3-D cube of stacked traces needed for migration, dead traces were filled-in, padding each empty CMP position with a zeros trace, and creating a volume matching the velocity cube.

Figure 3.23: Interval velocity cube used for the 3-D post-stack depth migration of the seismic data. Forty-five 2-D waveform tomography velocity models (Gao et al. 2006) were combined in a velocity volume and smoothed. The 1000 m/s velocity contour can be used as proxy for the approximated depth of the clay layer. The depth is relative to a datum at 1431 m a.s.l.

RESULTS

The depth-migrated volume of seismic data represents a three-dimensional image of the subsurface that can be directly interpreted. Moreover, a quantitative evaluation of the result is possible through a comparison with the available borehole logs. The 3-D seismic survey was designed so that inlines and crosslines illuminate the target across and along its main axis, respectively.

Sections cutting EW across the paleochannel show a topography of the top of the clay layer remarkably similar to the one measured by borehole logs (**Figure 3.24**). In spite of the artifacts generated at the edges of the survey by the migration process, the top of the clay layer is visible, and in good agreement with the borehole data in the bottom part of the channel, although the shape appears smoothed and the steep edges are consistently gentler than the well-based image.

The overall good agreement in both geometry and depth of the channel between seismic and well data is emphasized in a N-S section, cut along the buried channel axis (**Figure 3.25**). The agreement with the well logs is very satisfactory along the bottom, gentle dipping channel in geometry and depth. However, the accuracy of the seismic image degrades where the degree of dip is higher.

The extent of reliability of the migrated image is reiterated by slices at different depths in the migrated volume, where small features at the bottom of the paleochannel appear only partially resolved (**Figure 3.26**).

By picking the reflector assumed to be the top of the clay layer on each of the 527 inlines, it is possible to reconstruct the topography of the buried paleochannel as imaged by reflection seismic (**Figure 3.27**). Finally, the elevations of the top of the clay layer

obtained with seismic and with borehole logs can be compared. The absolute difference between the two datasets confirms that the accuracy of the seismic image is limited to the central, deepest part of the paleochannel, below ~12 m of depth (**Figure 3.28**).

The smoothed geometry and depth inaccuracy on the sides of the paleochannel are possibly related to the inherent limitation of post-stack migration to resolve steep dips. In addition, monitoring wells are concentrated in the central part of the channel, often clustered in few spots, while the rest of the area has very few and sparse data points. Consequently, there is an uncertainty in the borehole image. However, the contaminant DNAPL is assumed to be ponding on the seismically well-resolved bottom of the buried channel, thus, the shallow part of the channel is not as critical.

The contour map of the deepest part of the paleochannel is an asset of great importance, because it allows locating the dense contaminants and designing an effective remediation system. The map of the buried channel obtained from reflection seismic data can be directly used to plan injection/extraction well placements in the ongoing groundwater remediation program, eliminating the need for many wells.

Figure 3.24: A set of sections cutting EW across the paleo-channel (inlines) extracted from the depth migrated cube show the shape of the channel as imaged by seismic data. The line in color represents the depth of the clay layer as inferred from the borehole logs, (left) by linear interpolation and (right) by kriging.

Figure 3.25: N-S section out of the depth migrated cube (crossline 80), and bottom of the paleochannel as imaged by (top) linear interpolation of the borehole logs and (bottom) kriging. The 10, 12, and 14 m depth contour lines are displayed.

Figure 3.26: Horizontal slices of the depth migrated volume. The depth of the clay (left) interpolated and (right) kriged from borehole logs contour is overlain on the seismic image for comparison. Two samples (0.2 m) have been stacked vertically.

Figure 3.27: Contour map of the depth of the clay layer as reconstructed after picking the reflector on each of the 527 inlines in the migrated volume. The map is plotted using a 0.5 m grid. While the geometry of the paleochannel appears consistent with the one imaged using borehole logs, the steep slopes of the buried channel appear smoothed in the seismic image.

Figure 3.28: Map of the absolute difference between the depth of the clay from the boreholes and from the seismic image. Both the (a) linear interpolation and (b) kriging are shown. The map is plotted using a 0.5×0.5 m grid. Depth differences vary in 0.1 m steps. The 12 m depth contour line is shown in white.

CHAPTER IV

2-D Elastic Wave Reflection Profiles and Tomography

The geometry and depth of the dense contaminant's trap has been successfully imaged by means of 3-D P-wave reflection seismic data. However, a full characterization of the near surface is not achievable using P-waves only. Hence, in September 2005 at HAFB, OU-2, we collected an elastic-wave survey using three-component (3-C) sources and receivers. The shear-wave data complement the P-wave data already acquired and processed, since the shear modulus is insensitive to fluid saturation. Moreover, horizontally polarized shear-wave (SH) records are generally cleaner than P-wave sections due to the absence of mode conversions. Shallow seismic data were recorded along two 2-D profiles, across and along the central part of the buried paleochannel (**Figure 4.1**), in the east-west direction (line EW) and north-south direction (line NS). The reflection data processing was aimed at obtaining shear-wave and compressional-wave images of the subsurface. Independently, we generated accurate S-wave and P-wave velocity models from the inversion of the traveltimes of the first arrivals.

DATA ACQUISITION

The seismic data were acquired using 60 groups of three identical single-component 40 Hz geophones. The geophones were mounted on a single spike in a Gal'perin configuration, i.e. at an angle of 35.3° to the horizontal and at 120° relative to each other (Gal'perin, 1984). Refer to **Appendix B** for more details on the Gal'perin receiver mount.

Figure 4.1: 2-D seismic profiles (red lines) and contour map of the deepest part of the paleochannel, as reconstructed interpolating the borehole (circles) data. The black dashed line is the limit of the 3-D seismic survey. The contour lines highlighted are at 10, 12, and 14 meters depth from 1431 m a.s.l.

The three-component units were leveled with respect to the vertical direction, and oriented horizontally such that one of the three geophones in the Gal'perin cluster was consistently parallel to the line of acquisition. Deviations in the receiver unit from either the vertical or the horizontal, in fact, results in an incorrect vector rotation from Gal'perin to Cartesian coordinate system. Because of the extremely hard and gravelly soil, receiver planting was difficult and holes had to be pre-drilled for the spikes.

The cables associated with each component of motion were color-coded and connected to three different cable take-outs per receiver location. The data were recorded on three different 60 channels Geometrics Stratavisor seismographs, one for each component.

The 3-C groups were 0.5 m apart, for a total length of each profile of 29.5 m (**Table 3**).

Both shear and compressional-wave sources were used and recorded along the same profiles (**Figure 4.2**). As an S-wave source, we used a 2 lb hammer to horizontally strike a steel-capped wooden beam weighted by three people, to ensure coupling and to avoid slippage with the ground. The strikes were taken in orthogonal and parallel directions to the seismic line. Strikes in opposite direction were recorded with the aim of attenuating the P-wave component and increase the SH signal.

As a P-wave source, we used a 12 lb hammer to vertically strike a trailer hitch ball planted in the ground. This unusual device, after testing at the site, proved to be more signal-noise effective than a traditional metal plate.

The source was placed in between adjacent receivers, with a spacing of 0.5 m. For both sources, we stacked 12 hammer blows per shot, to enhance the S/N ratio and to remove the effects of occasional misdirected blows.

The 2-D profiles were referenced to already mapped boreholes of known position, for the source and receiver coordinates. Elevations were taken from the 3-D survey.

In terms of person-hours, a crew of 8 people completed the seismic experiment in 3 days.

DATA PRE-PROCESSING

The seismographs employed recorded the seismic data in SEG-Y format. The trace length was 1 s, with a zero-time delay of 250 ms, and a sample interval of 0.5 ms.

Due to the Gal'perin mounts and separate recording instruments acquisition setup, the seismic records were not directly interpretable at this stage. Some basic manipulation and preprocessing was needed, prior to any further processing step. The three different datasets were merged and arranged in common-source gathers.

Table 3. Acquisition parameters for the 2-D profiles		
	P-wave source	S-wave source
Number of profiles	2	2
Group spacing	0.5 m	0.5 m
Number of groups	60	60
Number of channels	60x3	60x3
Length of profiles	29.5 m	29.5 m
Source spacing	0.5 m	0.5 m
Number of shots/line	61	61
Staked strikes/shot	12	12
Number of components	3	3
Geophones	40 Hz	40 Hz
Source	Trailer hitch ball	Wooden beam
Hammer weight	12 lb	2 lb
Bin size	0.25 m	0.25 m
Number of traces/line	10980	10980
Record length	1000 ms	1000 ms
Zero-time delay	250 ms	250 ms
Sample rate	0.5 ms	0.5 ms

Figure 4.2: Acquisition setup for the 2-D (top) shear-wave and (bottom) compressional-wave seismic experiment at Hill Air Force Base. 60 three-component Gal'perin receiver groups were deployed with 0.5 m spacing, and each of the 61 shots was simultaneously recorded by three 60-channel seismographs.

Polarity conventions and nomenclature

Polarity conventions and nomenclature support a right-handed coordinate system with the Z axis pointing downwards (Brown et al., 2002). The X axis pointed in the north direction for the NS profile and in the east direction for the EW seismic line. When looking down from above the geophone, a positive angle from the X axis to the Y axis is in the clockwise direction (**Figure 4.3**).

The data were processed such that on the final sections a peak corresponds to an impedance increase (SEG reverse polarity). The SEG recommended nomenclature for multicomponent acquisition was followed thereafter (**Figure 4.4**).

Vector rotation

Because the Gal'perin coordinate orientations do not coincide with the wave mode polarizations, this arrangement requires a coordinate change before processing. In the field, the quality control and interpretation of the field records is not straightforward, each trace showing a mixture between P (compressional), SV (vertically polarized shear-wave) and SH (horizontally polarized shear-wave) wave fields. It is only following the coordinate transformation that the different components show the expected different characters (**Figure 4.5** and **Figure 4.6**).

After rotating the records obtained with Gal'perin mounted geophones into an earth referenced X, Y, Z coordinate system, the components were separated and the traces were sorted into common-shot gathers. Geometries were installed at this stage.

Additional elements related to the vectorial rotation of the seismic components from Gal'perin to Cartesian coordinate system are presented in **Appendix B**.

Figure 4.3: Horizontal orientation of the components and polarity convention in the Gal'perin and Cartesian coordinate systems for the (left) NS seismic line and (right) EW seismic line. The vertical component Z is pointing downward.

Figure 4.4: Multicomponent acquisition nomenclature for sources and receivers (modified from: Garotta, 2000).

S-WAVE SOURCE - Before rotation

S-WAVE SOURCE - After rotation

Figure 4.5: Example of shear-wave shot gather (top) as recorded in the field and (bottom) after vector rotation of the components. Note that the transverse component (Y) does not contain the airwave (arrows), as expected.

P-WAVE SOURCE - Before rotation

P-WAVE SOURCE - After rotation

Figure 4.6: Example of compressional-wave shot gather (top) as recorded in the field and (bottom) after vector rotation of the components. Note the strong ground roll (arrow) appearing on the vertical (Z) component, as expected.

HORIZONTALLY POLARIZED S-WAVE DATA

The transverse component (Y) of the S-wave source shot gathers (SH-transverse) was extracted and processed in order to obtain SH-wave images of the subsurface along the two seismic profiles. A minimal amount of preprocessing was required to attenuate the monopole radiation and enhance the dipole radiation of the shear component of the source, improving the shear-wave S/N ratio.

Summation of SH-transverse components

In general terms, it is very difficult to generate S-waves without simultaneously generating P-waves. If a horizontal impact is used to generate SH-waves, as in this case, a technique often used in land surveys is to negatively stack strokes with opposite polarity, in order to attenuate the pressure-wave component. In fact, each of the two strokes results in a seismic record containing both P-waves and SH-waves. By adding the two records, after reversing one's polarity, P-wave components cancel out and only the sum of the two SH components remains (Helbig, 1987).

Misalignments in the traces pairs, due to heterogeneities, scattering and trigger errors, were corrected before summation by applying a static shift to the traces (**Figure 4.7**). The time corrections were calculated by means of crosscorrelation between pair of traces associated to the same receiver. Although the mis-ties were generally limited to few samples, some channels did not exhibit a reasonable correspondence between opposite blows. Consequently, a range of plus or minus 5 ms was set for the static correction, and all the pairs falling outside this threshold were discarded. Overall, about 6% of the total

number of traces were inconsistent in opposite directions and were killed in the EW line (Figure 4.8). In the NS line about 8% of the traces were zeroed (Figure 4.9).

Figure 4.7: Portion of a shot gather showing (a) pair of traces from opposite strikes and (b) relative crosscorrelation revealing the misalignments. (c) Opposite strikes recorded at channel 19 are not consistent. (d) Same portion of shot gather after traces alignment and (e) associated crosscorrelation. (f) Opposite strikes are finally stacked, while the inconsistent channel is zeroed.

Figure 4.8: (a) Overall time differences between same-channel traces from opposite strikes for the EW line, and crosscorrelation of the traces pairs in a sample shot gather (b) before and (c) after alignment. The blue line marks a killed trace. The portion of data shown in Figure 4.7 is highlighted in brown.

Figure 4.9: (a) Overall time differences between same-channel traces from opposite strikes for the NS line, and crosscorrelation of the traces pairs in a sample shot gather (b) before and (c) after alignment. The blue lines mark killed traces.

Processing of SH-transverse data

The processing flow (**Table 4**) was kept to a minimum number of steps, although carefully performed, and consisted of top muting, amplitude recovery, bandpass filtering, deconvolution, elevation static correction, NMO correction, stacking and migration. Particular attention was placed on checking the consistency of possible reflections through processing, considering the low S/N ratio of the data. For this purpose, the traces were sorted into CMP gathers, where events were more recognizable.

Table 4. Processing flow for the 2-D seismic dataset, S-wave source, transverse component			
	Type	Parameter	
Formatting	SEG-Y		
Sorting	Common shot/component		
Vectorial rotation	Galperin to Cartesian		
Sorting	Common shot gathers	Component:	Transverse (Y)
Summation	Stack of opposite strikes		
Trace killing	Strikes consistency	Lag:	> 5 ms
Geometry installation			
Zero-time correction	Constant time delay	Static shift:	-250 ms
Trace killing		Bad channel:	Channel 1
Trace muting	Top mute	Ramp:	10 ms
Trace equalization		Time gate:	500 ms
		Scalar:	Mean
Amplitude scaling	AGC	Length:	100 ms
		Scalar:	RMS
Bandpass filter	Butterworth single filter	Phase:	Minimum
		Frequency:	20/12-120/12 db/oct
Sorting	Common receiver gathers		
Deconvolution	Predictive deconvolution	Type:	Ensamble
		Operator length:	36-54 ms
		Prediction lag:	8-12 ms
Bandpass filter	Butterworth single filter	Phase:	Minimum
		Frequency:	20/12-140/12 db/oct
Static correction	Elevation statics	Final datum:	1431 m asl
		Replacement velocity:	150 m/s
Sorting	CMP gathers		
Velocity analysis	Hyperbola fitting		
NMO Correction		Stretch mute:	10%
Stack	2-D		
Trace equalization		Time gate:	300 ms
		Scalar:	Mean
Depth migration	2-D poststack	Method:	Explicit finite-difference
		Maximum dip:	50
		Interval velocity:	0-150/15-450 m-m/s

Following a static bulk shift of -250 ms to account for the time zero delay present on the seismic records, the direct and refracted waves were muted out where distinct from the reflections. A mute ramp of 10 ms was used.

The traces were balanced using a trace equalization computed on a mean basis in a 500 ms window. An AGC computed in a 100 ms window was applied to recover the amplitude losses in time. The RMS amplitude in the gain window was the basis for the scale factor calculation. The gain scalar was applied to the sample at the center of the AGC window.

At this point, the frequency content of the seismic records was evaluated by examining both power spectra and frequency filter panels (**Figure 4.10** and **Figure 4.11**). Most of the useful energy is in the frequency band 20-100 Hz, a band much lower and narrower than comparable P-wave experiments, but consistent with other shear-wave source shallow experiments. Consequently, the data were bandpass filtered using a minimum-phase Butterworth filter from 20 to 120 Hz. The slope on either side of the pass band was set to 12 db/octave. The raw data show mainly surface waves (**Figure 4.12a** and **Figure 4.13a**), and possibly a very shallow reflection at about 50 ms (3-4 m). A dramatic improvement in S/N ratio is obtained after the application of the top mute and the bandpass filter (**Figure 4.12b** and **Figure 4.13b**).

At this stage, the traces were sorted into common-receiver gathers, and an ensemble predictive deconvolution was successfully applied to the seismic data (**Figure 4.12c** and **Figure 4.13c**). All previous attempts to determine the correct deconvolution parameters and test the effectiveness of the procedure on the shot gathers were ineffective. On the other hand however, grouping the seismic traces by geophone instantly revealed the

presence of a strong ringing on the records. Such geophone-dependent coherent noise appeared to be consistent on each receiver, but slightly variable from geophone to geophone, so as to be disguised in the common-source gathers (**Figure 4.14**). Additional information and details about the ringing in the seismic data are presented in the **Appendix C**.

The advantage of having the data sorted in receiver gathers is twofold. Firstly, it made the problem evident. Second, it allowed tailoring the deconvolution parameters to the different receivers and effectively removing the unwanted reverberation from the seismic record. An ensemble predictive deconvolution, which computes a single deconvolution operator for all traces in the input receiver gather, was chosen as the preferred scheme. Final parameters included 8-12 ms prediction lag, 36-54 ms filter length, and 0-300 ms time gate for the filter design. The seismic traces were resorted in common-midpoint gathers after deconvolution. Elevation static corrections were applied to compensate for topographic variations along the profiles and to reference the 2-D lines to the same datum previously adopted (1431 m a.s.l.). A constant velocity of 150 m/s, based on direct arrivals, was used as replacement velocity. The maximum elevation change differs considerably between the two acquisition lines, being about ~0.5 m along the line EW, but only ~0.2 m along the line NS. Considering the extremely low velocity of the near surface layer, such small variations turn into non-negligible time corrections for sources and receivers. In fact, while the maximum relative shift between stations is only ~1.4 ms (~3 samples) in the NS profile, it reaches ~ 3.3 ms (~7 samples) in the EW profile (**Figure 4.15**). No residual static correction, usually used to compensate for such very small time differences between the traces, was applied to the CMP gathers.

Figure 4.10: (top) Power spectrum of CMP gather of line EW (a) before and (b) after top mute. Note how the dominant frequency (arrow) shifts toward the higher frequencies. (bottom) Signal content of the same gather for different frequency ranges.

Figure 4.11: (top) Power spectrum of CMP gather of line NS (a) before and (b) after top mute. Note how the dominant frequency (arrow) shifts toward the higher frequencies. (bottom) Signal content of the same gather for different frequency ranges.

Figure 4.12: Three adjacent CMP gathers from the SH-transverse data along the EW line (a) after amplitude recovery, (b) after top mute and frequency filtering, and (c) after predictive deconvolution performed on common-receiver gathers.

Figure 4.13: Three adjacent CMP gathers from the SH-transverse data along the NS line (a) after amplitude recovery, (b) after top mute and frequency filtering, and (c) after predictive deconvolution performed on common-receiver gathers.

Source gathers

Receiver gathers

Figure 4.14: Comparison between same positions (a) common-source gathers and (b) common-receiver gathers from the SH-transverse dataset, revealing the strong receiver-dependent ringing present in the seismic record.

Figure 4.15: (top) Elevation and (bottom) static corrections for the receivers of (a) EW line and (b) NS line, respectively. The replacement velocity is 150 m/s. The final datum is 1431 m a.s.l.

Velocity analysis of the data was performed by fitting hyperbolas directly to the reflection of interest on processed CMP gathers. NMO corrected CMPs were then analyzed and the velocity readjusted (**Figure 4.16**). This direct picking method is efficient when there is only one reflection and the number of CMP gathers is limited, as in our case.

Figure 4.16: Example of CMP gathers of (a) line EW and (b) line NS after NMO correction with different constant velocities. The velocity that flattens the main reflector the best (red arrow) is picked as correct.

The limited lateral variation in the velocity picking made smoothing of the velocity model unnecessary.

Stacking of SH-transverse data

The processed CMP gathers were stacked, following NMO correction using the stacking velocity model. A stretch mute as low as 10% was applied during the NMO correction process.

The final SH stack sections are presented in **Figure 4.17**. The reflector interpreted as top of the clay layer is evident on both the profiles. On the EW line, acquired in a direction perpendicular to the main channel axis, the reflector appears at a two-way traveltime (TWT) ranging from ~70 to ~130 ms. On the line NS, acquired alongside the channel axis, it appears as sub-horizontal reflection at approximately 120 ms. The mis-tie between the seismic sections at the crossing point is minimal. On the crossing section (line EW), the deepest part of the structure gives rise to what appear as diffractions (a “bow-tie”) on the stack section, more evident on the east side of the section (left).

It is possible to distinguish a reflection at about 50 ms, although not continuously along the profiles, particularly on the EW line. This exceedingly shallow signal, perceivable on the unstacked common-midpoint gathers, might be related to a superficial thin layer of caliche (desert hardpan), highly cemented, overlaying the unconsolidated mixture of clay, sand and gravel, or layering within the sediments covering the paleochannel. Shallower arrivals have been muted on the CMP gathers and are not present in the final stacked section. The deeper portion of the stack images displays some coherent events, consistent with reflection signals present on some of the unstacked gathers at about 250 ms.

However, these are most likely out-of-plane and/or multiple arrivals. In fact, the maximum offset in the profiles (~ 30 m) paired to the acquisition geometry, does not allow a confident reconstruction of any deeper reflector.

Figure 4.17: Final SH-transverse data stack sections (a) along the EW profile, and (b) along the NS profile. The number of traces in each stacked CMP is plotted beneath each seismic section.

Depth migration of SH-transverse stacks

Finally, the SH-wave stack sections were depth migrated using an interval velocity model varying vertically from 150 m/s at surface to 450 m/s at 15 m of depth. The 2-D post-stack depth migration was performed by an explicit finite-difference algorithm with 50 degrees dip accuracy.

The migrated SH-wave sections (**Figure 4.18**) show a geometry and depth of the clay layer that is similar to the one derived using the well data. Moreover, the depth of the aquiclude is consistent at the intersection of the two lines. On the EW profile, the bottom of the paleochannel appears shifted towards the west by about 3 m. However, the slope gradient matches the well data. In addition, minor depressions along the channel bottom appear correctly imaged on the NS profile. The incorrect position of the channel might be related to a significant lateral variation in the velocity of the medium, not taken into account by the simple velocity gradient used for the depth migration. The comparison between the final time sections and the depth migrated sections displayed at equivalent scales, highlights the effect of migration in relocating the main reflector, particular evident in the EW line, which crosses the buried channel, where dips are considerable (**Figure 4.19**).

VERTICAL COMPONENT OF P-WAVE DATA

The vertical component (Z) of the compressional-wave source shot-gathers (P-vertical) was extracted from the dataset and processed in order to obtain P-wave images of the subsurface along the two acquisition profiles.

SH-TRANSVERSE DATA

Figure 4.18: Depth-migrated stack sections (a) along the line EW and (b) along the line NS. The dashed yellow line marks the depth of the clay layer as inferred from the borehole logs. The semi-transparent panels indicate low-fold zone (<10 traces/CMP).

Figure 4.19: SH-transverse images: comparison between (top) stack section and (bottom) depth migrated image along (a) the EW line and (b) the NS line. The scale of the images is comparable.

Although the data quality is generally superior to the comparable S-wave data, handling the seismic records proved to be particularly challenging, due to the strong ground roll combined with the very shallow reflector and a limited offset.

Processing of P-vertical data

The processing sequence adopted (**Table 5**) is similar in fashion to the one used for the SH-transverse data, although modified to deal with the ground roll present on the records.

Table 5. Processing flow for the 2-D seismic dataset, P-wave source, vertical component.			
	Type	Parameter	
Formatting	SEG-Y		
Sorting	Common shot/component		
Vectorial rotation	Galperin to Cartesian		
Sorting	Common shot gathers	Component:	Vertical (Z)
Editing	Bad shot killing		
Geometry installation			
Zero-time correction	Constant time delay	Static:	-250 ms
Trace killing		Bad channel:	Channel 1
Trace muting	Top mute	Ramp:	10 ms
Trace equalization		Time gate:	500 ms
		Scalar:	Mean
Amplitude scaling	AGC	Length:	75 ms
		Scalar:	RMS
Bandpass filter	Butterworth single filter	Phase:	Minimum
		Frequency:	100/12-400/12 db/oct
Groundroll removal	Coherent noise attenuation	Filter length:	11 traces
		Frequency/Velocity:	10/160-400/260 Hz/m/s
Deconvolution	Predictive deconvolution	Operator length:	40 ms
		Prediction lag:	8 ms
Bandpass filter	Butterworth single filter	Phase:	Minimum
		Frequency:	100/12-400/12 db/oct
Static correction	Elevation statics	Final datum:	1431 m asl
		Replacement velocity:	300 m/s
Sorting	CMP gathers		
Velocity analysis	Hyperbola fitting		
NMO Correction		Stretch mute:	10%
Stack	2-D		
Trace equalization		Time gate:	300 ms
		Scalar:	Mean
Depth migration	2-D poststack	Method:	Explicit finite-difference
		Maximum dip:	50
		Interval velocity:	0-250/15-1400 m-m/s

The flow included top muting, amplitude recovery, bandpass filtering, ground roll removal, deconvolution, elevation static correction, NMO correction and stacking. The data were sorted in CMP gathers and the time zero delay present in the seismic records was corrected with a static bulk shift of -250 ms applied to the traces (**Figure 4.20a**). Amplitude variations with offset and time in the gathers were recovered using a trace equalization that was computed on a mean basis in a 500 ms window, and an AGC computed in a 75 ms window (**Figure 4.20b**). The direct and refracted waves were muted out by means of a top mute with a ramp of 10 ms (**Figure 4.20c**).

After evaluating the frequency content of the seismic records by means of both power spectra and frequency filter panels (**Figure 4.21**), the data were bandpass filtered using a minimum-phase Butterworth filter from 100 to 400 Hz. The slope on either side of the pass band was set to 12 db/octave (**Figure 4.22a**).

The ground roll, still present on the gathers after bandpass filtering even though significantly reduced, was removed by means of coherent noise attenuation (**Figure 4.22b**). After testing, the values of 10-400 Hz for the frequency, and 160-260 m/s for the velocity, were used. In order to apply the coherent noise attenuation tool, the data were sorted in shot gathers, and then back to CMP gathers.

Because the geophone-related reverberations appear only in the horizontal plane (see **Appendix C**), a typical predictive deconvolution was adequate to remove the unwanted reverberations from the seismic traces (**Figure 4.22c**). Both autocorrelation and deconvolved data were used to determine the final parameters of 8 ms for the prediction lag, 40 ms for the filter length, and 0-160 ms for the filter design time gate. A bandpass filter with the same parameters previously used was reapplied to the seismic records.

Figure 4.20: Example of CMP gathers from the P-vertical data, (a) before processing, (b) after amplitude recovery, and (c) after top mute.

Figure 4.21: Test for the frequency filter on CMP gathers from the P vertical dataset, performed by trying (left) different low-cut and (right) different high-cut filters. Most of the coherent signal is encompassed in the 100–400 Hz frequency range. Ground roll is predominant at frequencies below 120 Hz.

Figure 4.22: Example of CMP gathers from the P-vertical data, (a) after AGC, top mute and frequency filtering, (b) after coherent noise attenuation, and (c) after predictive deconvolution.

Elevation static corrections were computed and applied to the seismic records mainly to reference the 2-D lines to the datum of 1431 m a.s.l., and to account for any topographic variations along the acquisition lines. In fact, because a constant velocity of 300 m/s, based on direct arrivals, was used as replacement velocity, the resulting static shifts equal 1/2 those determined for the SH-transverse data (see **Figure 4.15**). In particular, the maximum relative time-shift between stations is limited to ~0.8 ms (~2 samples) in the NS profile, and ~1.6 ms (~3 samples) in the EW profile. Such static correction have a minimal impact on the seismic records, even considering the higher dominant frequency compared to the S-wave data. No residual static correction was applied to the CMP gathers.

Fitting hyperbolas directly to the reflection of interest on processed CMP gathers provided the basis for the velocity analysis (**Figure 4.23**). NMO corrected CMPs were then analyzed and the velocity readjusted. Because of a lateral variability in the velocity picks greater than that of comparable shear-wave data, lateral smoothing was necessary to reduce large NMO velocity gradients. The velocity model was smoothed by a five-point-running average (1 m).

Stacking of P-vertical data

Lastly, the processed and NMO corrected CMP gathers were stacked. A 10% stretch mute was applied during the NMO correction process (**Figure 4.24**). The stack images are dominated with the reflection associated to the aquiclude-alluvium interface. The geometry and converted depth of the buried-channel are similar to the SH-transverse images, suggesting that high reflectivity is originating from a lithological variation, and

not from a zone of water saturation of the sediments. In contrast to the S-wave images, possible shallower reflections appearing in the common-midpoint gathers have been muted and are not present in the final stacked section. The mute function tended to be quite conservative to ensure that the amplitude variations at shallow depths did not dominate the stack.

Figure 4.23: Example of velocity analysis performed by fitting hyperbolas directly on the reflector of interest in CMP gathers of (a) line EW and (b) line NS.

Depth migration of P-vertical stacks

The P-vertical stack sections were depth migrated using an interval velocity model varying vertically from 250 m/s at surface to 1400 m/s at 15 m of depth.

Figure 4.24: Final P-wave data stack sections along (a) the EW profile and (b) the NS profile. The number of traces in each stacked CMP is plotted beneath each seismic section.

The depth migrated P-wave sections (**Figure 4.25**) appear particularly noisy and difficult to interpret without the support of the well data. This is particularly true for the EW line, where coherent arrivals are repeated in depth, but also applies to the NS profile, where only a portion of the sub-horizontal bottom of the channel is correctly imaged. The comparison between the final time sections and the depth migrated sections displayed at equivalent scales, highlights the poor result of migration, in particular for the EW line (**Figure 4.26**). The coherent noise trains present on the stack sections makes the corresponding migrated sections difficult to interpret.

TIME SECTIONS COMPARISON AND INTERPRETATION

The overall quality and interpretability of the final stack sections along the two seismic lines is surprisingly good, considering the low S/N ratio of the data and the shallow depth of the target (**Figure 4.27** and **Figure 4.28**). The main reflector, interpreted as the interface between the unconsolidated surficial sediments of the Provo alluvium and the underlain Alpine clay (aquiclude), appears coherent and continuous in both intersecting profiles. In addition, the images obtained using compressional-wave and shear-wave data match, save for the different time scale. It follows that the reflectivity on the P-vertical seismic sections is related to a change in lithology, and not to the water content of the sediments. Moreover, the accuracy of the final results is corroborated by corresponding images obtained processing two independent datasets.

Some significant differences in the reflection character between SH-transverse and P-vertical stacks are noticeable.

P-VERTICAL DATA

Figure 4.25: Depth-migrated stack sections (a) along the EW line and (b) along the NS line. The dashed yellow line marks the depth of the clay layer as inferred from the borehole logs. The semi-transparent panels indicate low-fold zone (<10 traces/CMP).

Figure 4.26: P-vertical images: comparison between (top) stack section and (bottom) depth migrated image along (a) the EW line and (b) the NS line. The scale of the images is comparable.

The S-wave stacks exhibit a relatively weak reflectivity, partially because of the two-way propagation path through a highly attenuative and heterogeneous near surface, and partially because of the intrinsic inefficiency of the S-wave source, which had a tendency to slip.

SH Transverse Data

P Vertical Data

Figure 4.27: Comparison between (a) the SH-transverse and (b) P-vertical time sections across the buried paleochannel (EW line). The red line is interpreted as the top of the clay layer. The vertical scale of the S-wave image is twice the one of the P-wave image.

However, the main reflection appears more continuous, and the sections overall less noisy, than the corresponding P-wave profiles. Also, the stacks show deeper coherent events, potentially related to lithological variations within the clay.

SH Transverse Data

P Vertical Data

Figure 4.28: Comparison between (a) the SH-transverse and (b) P-vertical time sections along the buried paleochannel (NS line). The red line is interpreted as the top of the clay layer. The vertical scale of the S-wave image is twice the one of the P-wave image.

However, the profiles appear noisy and the source pulse appears as a doublet. In addition, possible deeper events are disguised by the strongest impedance contrast.

An approximate estimate of the average V_p/V_s ratio of the alluvium can be achieved by comparing the TWT of the target reflector in the corresponding time sections. A vertical scale of the SH-transverse images two times the P-vertical images, results in an almost isochron main reflector, and suggests an approximate value of V_p/V_s ratio equal to 2.

TRAVELTIME INVERSION

In order to derive 2-D P-wave and S-wave velocity models of the near surface along the two seismic profiles, the traveltimes of first arrival seismic energy were inverted. The inversion was performed using the First Arrival Seismic Tomography (FAST) program package, based on a regularized and smoothed tomographic inversion technique (Zelt and Barton, 1998). This is the same method used by Zelt et al. (2006) applied to 3-D refraction data acquire at OU-2 in 2000. First arrival traveltimes were picked directly from individual shot gathers and plotted versus offset (**Figure 4.29**). Although the source energy was generally sufficient to reach the far offsets, low S/N ratio and strongly attenuated signals made it sometimes difficult to confidently discriminate the first breaks in the shots, especially for the larger offsets of the S-wave source gathers. Therefore, in order to reduce the time uncertainty in the picks, these were iteratively selected and then readjusted on increasingly higher frequency seismic records. The accuracy of the picks was verified on common-receiver and common-offset gathers.

Due to the limited offset of the data and low velocity of body waves in the near surface, it is important to distinguish the different phases in the seismic record.

Figure 4.29: Example of (a) P-wave, vertical component and (b) S-wave, transverse component shot gathers, and picking of the first arrival traveltimes (red dashes). A 10 ms time delay is applied to the traces. The vertical scales are one twice the other.

On the P-wave data (**Figure 4.30**), surface waves are characterized by a combination of P and SV waves (Rayleigh waves). The horizontal (radial) and vertical components of ground motion are out of phase in a characteristic retrograde elliptic fashion (Stein and Wysession, 2003). Similarly, refracted arrivals are polarized in the X-Z plane, at a degree dependent on the incident angle, but lack elliptical motion.

In contrast, surface waves generated by S-wave sources in a layer and half space and resulting from SH waves trapped near the surface (Love waves), appear on the transverse component (Y) only (**Figure 4.31**). Likewise, refracted arrivals are polarized on the horizontal plane and in the direction transverse to the receiver line. However, the velocity of surface waves is lower, although only marginally, than that of S-waves, and most importantly the attenuation of surface waves is significantly less.

The detailed examination of the seismic records gives confidence that the picked first arrivals are indeed direct and refracted events, although a higher uncertainty applies to the nearest offsets (< 2 m).

Arrival time-differences between reciprocal source-receiver pairs can be used to determine the error/uncertainty in the picking (**Figure 4.32**). The iterative inversion method, in fact, attempts to generate a model so that predicted and observed traveltimes eventually match within a tolerance determined by the picking errors. Ideally, the reciprocal times should agree. However, considerable variations are possible, especially at large offsets, because of the noise present in the data. Because on average only about 58% of the reciprocal source-receiver pairs are within 1 ms while about 85% of them are within 2 ms, the assigned picking error for each of the four datasets was 2 ms.

Figure 4.30: (a) Vertical-component P-wave shot gather on the EW profile, and relative hodogram of (b) first arrival region and (c) ground roll region. A 200 Hz low-pass filter is applied.

Figure 4.31: (a) Transverse-component S-wave shot gather on the EW profile, and relative hodogram of (b) first arrival region and (c) ground roll region (c). A 100 Hz low-pass filter is applied.

The results of the tomography of both P-wave and SH-wave dataset along the two 2-D profiles (**Figure 4.33** and **Figure 4.34**), show that in general VP increases from ~ 250 m/s to ~ 1500 m/s in about 12 m depth (a factor of 6), and Vs increases from ~ 150 m/s to ~ 400 m/s in about 8 m (a factor of 2.7).

Although the depth of penetration is limited, especially for the Vs models, due to a combination of short offset available and velocity gradient with depth, some features can be recognized and are consistent on the velocities fields.

Figure 4.32: First-breaks arrival time along the EW profile for (top) the P-vertical dataset and (bottom) the SH-transverse dataset. The bar plots display the distribution of the time difference between reciprocal arrivals.

Figure 4.33: Velocity model and ray coverage for (a) the P-wave first arrival traveltimes and (b) the S-wave first arrival traveltimes, acquired along the EW profile.

Figure 4.34: Velocity model and ray coverage for (a) the P-wave first arrival traveltimes and (b) the S-wave first arrival traveltimes, acquired along the NS profile.

The 1-D velocity profiles at the crossing point of the lines were used to check the agreement between the velocity models V_P (**Figure 4.35a**) and V_S (**Figure 4.35b**) obtained from the first arrival traveltimes tomography inversion. The relative difference in velocity between the profiles is always smaller than 10% at the crossing point, at any depth, both for P-waves and S-waves.

V_P starts to increase in a marked manner above the water table, where it reaches a maximum value consistent with the velocity of P-waves in water saturated clay near the surface. In the shallow subsurface, V_P presents a consistent step at about 2.5-3.0 m of depth. The S-wave velocity model presents a knee at about the same depth of 3.0 m. No other structure is evident in the V_S profile.

Using the average 1-D velocity curve at the crossing point for compressional and shear-waves, it was possible to calculate the 1-D curve with depth for the V_P/V_S ratio (**Figure 4.35c**) and for the equivalent Poisson's ratio (**Figure 4.35d**).

Although the measurement is limited to one point, where the two profiles cross each other, these depth-profiles can potentially be related to lithology changes in the subsurface. The values obtained are plausible for the materials at shallow conditions. Low V_P/V_S - Poisson's ratios are generally associated with sands, while high V_P/V_S - Poisson's ratios are indicative of clays. The interpretation of the curves suggests the existence of a superficial thin layer characterized by a relatively high V_P/V_S (Poisson's) ratio, overlaying less compacted, coarser sediments, possibly related to the superficial thin layer of caliche, highly cemented, overlaying the unconsolidated mixture of clay, sand and gravel. This interpretation is consistent with an exceedingly shallow reflection

detectable on the CMP gathers, but muted and therefore not present in the final stacked sections.

P-wave and S-wave tomographic velocity profiles were used to build 2-D maps of V_P/V_S ratio and equivalent Poisson's ratio along the acquisition lines (**Figure 4.36** and **Figure 4.37**). Although a quantitative interpretation is not possible, because of the lack of any borehole information for the calibration of the data, areas with different sand-clay content can be observed on the 2-D sections. In particular, the superficial thin layer characterized by a relatively high V_P/V_S (Poisson's) ratio, overlaying coarser sediments, can be spatially extrapolated along both the profiles. On the EW line, the easternmost part of the section shows a thick area with low V_P/V_S ratio, in good accordance with the map of the clean sand interpolated from borehole logs (**Figure 2.9b**), showing clean sand at very shallow depth in the approximate same position. The westernmost part of the profile exhibits a higher V_P/V_S ratio, suggesting more clayey sediments. In addition, patches of clay are present in the northernmost and southernmost portion of the NS line, at shallow depth. Finally, both profiles present an increased value of V_P/V_S ratio in the deepest part of the imaged sections, possibly indicating more fine sediments filling the channel. Although qualitative, the differentiation of lithologies in the subsurface helps to develop an accurate groundwater flow model, essential to any remediation effort, in particular when technologies such as chemical flooding and water flooding are used to mobilize and remove residual and pooled DNAPLs.

Figure 4.35: 1-D velocity profiles at the crossing point between the EW and NS lines for both (a) V_P and (b) V_S velocity models obtained from the inversion. The difference between the profiles is always smaller than 10% (bar plots). The average 1-D velocity models are used to determine (c) V_P/V_S ratio and (d) equivalent Poisson's ratio with depth at the crossing point.

Figure 4.36: 2-D map of the V_P/V_S ratio along (top) the NS line and (bottom) the EW line.

Figure 4.37: 2-D map of the Poisson's ratio along (top) the NS line and (bottom) the EW line.

CHAPTER V

Discussion and Conclusions

The purpose of this study was to investigate the potential of seismic methods for studying surficial sediments in the context of groundwater contamination and remediation, and to develop high-resolution seismic methods for identifying structural/stratigraphic traps for contaminants. Understanding the surficial geology is particularly important in order to predict possible groundwater flow paths, and design effective and cost-efficient remediation strategies. When dense non-aqueous phase liquids (DNAPLs) are involved, a comprehensive knowledge of the geometry of the subsurface is essential to predict the migration and accumulation of the dense contaminant beneath the water table. In fact, upon release DNAPLs sink until an impermeable layer (aquiclude) is reached, at which point pooling and lateral spreading may occur. Seismic techniques can provide spatially continuous information regarding shallow subsurface structures, avoiding the problems associated with the invasive nature of direct testing, such as the inherent lateral limitations and the potential to spread contaminants, of particular concern in characterizing contaminated regions.

For these reasons, a set of elastic-wave seismic investigations was conducted at Hill Air Force Base (HAFB), Operable Unit 2 (OU-2), in an area of about 36 x 92 m. This study takes into consideration 3-D P-wave reflection data acquired in 2000, and elastic-wave 2-D seismic profiles (two lines) acquired in 2005. Processing of the records was carried out using Landmark's ProMAX[®] seismic processing software for the reflection data and

FAST for the refraction data. The specific target of the surveys at HAFB was the bottom of a paleochannel eroded in a clay layer at a depth of 10-15 m from the topography and filled with a mix of sands, clays, and gravels with different compaction and water saturation. Because the buried channel acts as contaminant trap for polluting DNAPLs, a detailed map of its geometry, lateral boundaries and depth is crucial to the remediation effort.

OU-2 proved to be an exceptionally complex site, magnifying the challenges omnipresent in the world of experimental geophysics (Danbom, 2005). The extremely shallow target (10-15 m from topography) in addition to the highly heterogeneous medium in terms of velocity, compaction and water saturation, resulted in a low S/N seismic response. Moreover, the extremely hard soil, the remediation equipment on the ground, and the aircraft activity at the Base posed additional problems.

3-D post-stack depth migration of the 3-D survey data was a critical step in correctly imaging the geometry of the paleochannel, but required high S/N ratio and a correct velocity model. Thus, the processing flow had to be carefully designed to remove the noise from the seismic record and highlight the coherent signal. Although the whole process produced a satisfying final result, two steps appeared particularly effective in enhancing the quality of the data: flexi-binning and coherent noise attenuation. The first resulted in higher and more uniformly distributed fold, and the second substantially reduced the strong ground roll present on the seismic records. Lastly, the available waveform tomography velocity field (Gao et al., 2006) provided the necessary accurate

interval velocity model required by migration. The successful result confirmed the ability of inverse methods to build a velocity model that is not only interpretable on its own, but also suitable as the migration velocity model, with the advantage of eliminating a number of velocity analysis processing steps difficult to perform in poor signal resolution datasets.

The final depth-migrated volume of the seismic data represents a three-dimensional image of the subsurface that can be directly interpreted. The agreement with available well logs is satisfactory along the bottom, gentle dipping channel in geometry and depth. In contrast, the accuracy of the seismic image degrades where the degree of dip is higher. The smoothed geometry and depth inaccuracy on the sides of the paleochannel are possibly related to the inherent limitation of post-stack migration to resolve steep dips. However, uncertainties in the borehole logs map are also likely.

By picking the reflector assumed to be the top of the clay layer on each of the depth-migrated 527 inlines, it was possible to reconstruct the topography of the buried paleochannel as imaged by the reflection seismic data (**Figure 3.27**). The resulting contour map of the channel can be directly used to plan injection/extraction well placements in the ongoing groundwater remediation program. The elevations of the top of the clay layer obtained with seismic were compared to the one inferred from available borehole logs. The absolute difference between the two datasets shows that the accuracy of the seismic image is limited to the central, deepest part of the paleochannel, below ~12 m of depth. However, because the contaminant is assumed to be concentrated on the

bottom of the buried channel, this is the most important element for the remediation effort, while the shallow part of the channel is not as critical. This observation is supported by the fact that the monitoring wells are concentrated in the central part of the channel, while the rest of the area has very few data points.

Vertical and lateral resolutions can be estimated using conventional definitions of $\frac{1}{4}$ of the wavelength and 1st Fresnel zone, respectively (Sheriff and Geldart, 1995).

Considering a velocity of 1400 m/s for the saturated sediments at the bottom of the paleochannel (14 m depth) and a 250 Hz dominant frequency, the resulting vertical resolution is ~1.4 m, and the lateral resolution is ~6.3 m.

This study took advantage of having depth of the clay layer borehole data available for a cross-validation of the final 3-D image and for depth control. Well data must therefore be considered an important asset to corroborate the seismic results, even for shallow investigations. However, the final map of the paleochannel obtained from seismic data can be directly used, eliminating the need for many wells.

In the fall of 2005, additional 2-D seismic data were acquired at the same site, employing both compressional-wave and shear-wave sources. The data were recorded using three-components receiver groups, along two perpendicular profiles across and along the buried paleochannel. After preliminary processing involving the rotation of the components from a Gal'perin to Cartesian coordinate system, the SH-transverse data and the P-vertical data were extracted and processed separately.

Although kept to a minimal number of steps, processing of the shallow reflection seismic records was challenging and time consuming. More specifically, the SH-transverse data were severely contaminated by coherent noise, not evident in common-shot gathers. These unwanted vibrations are likely the response of the Gal'perin receiver groups, coupled with the extra hard ground present at the site, to the source energy. Effectively removing such ringing required a predictive deconvolution customized on common-receiver gathers. In addition, separating ground roll from coherent signal on the P-vertical data turned out to be a difficult task, due to the particularly short offsets and low velocity of the medium.

Nonetheless, the processing effort resulted in overall good quality stack sections along both seismic lines, especially considering the low S/N ratio of the data and the depth of the target. The main reflector, interpreted as the interface between the unconsolidated surficial sediments of the Provo alluvium and the underlain Alpine clay (aquiclude), is coherent and continuous in both intersecting profiles. In addition, the mis-tie at the crossing point is small. Furthermore, there is a good match between comparable images obtained using compressional-wave and shear-wave data, save for the different time scale (**Figure 4.27** and **Figure 4.28**).

The TWT comparison of the target reflector in corresponding P-wave and S-wave time sections indicates an average V_P/V_S ratio of about 2 for the alluvium.

In the S-wave images, the vertical resolution is ~ 1.5 m, and the lateral resolution is ~ 6.5 m, considering a target depth of 14 m, a dominant frequency of 75 Hz and a velocity of 450 m/s. In the P-wave images vertical and lateral resolution are slightly lower because

of the lower dominant frequency in the seismic records. Considering a 220 Hz signal, the resulting vertical resolution is ~ 1.6 m, and the lateral resolution is ~ 6.7 m.

The depth-migrated sections reflect the different quality of the stack sections. In particular, the SH-wave images appear superior to the P-wave images, in terms of noise and continuity of the main reflector. Moreover, in the SH profiles the geometry and depth of the clay layer determined from the seismic data are more similar to the one derived by using well data, although the bottom of the paleochannel is shifted west about 3 m in the EW profile.

The first arrival travel-times of both P-wave and S-wave shot gathers were inverted, in order to obtain 2-D compressional and shear-wave tomographic velocity models along the crossing lines. The velocity difference at the crossing point of the two lines is always smaller than 10% at any depth, for both V_P and V_S , corroborating the results of the inversion. Although the depth of penetration is limited, especially for the V_S models, some features can be recognized on the velocity profiles. Specifically, at the crossing point both V_P and V_S profiles exhibit a step at approximately 2-3 meters of depth. In addition, the V_P profile shows a significant increase between ~ 8 and ~ 10 m of depth, suggesting that the water table is not a sharp boundary, but a fringe with increasing water saturation. This observation is in agreement with that observed in the P-wave seismic data.

Using the P-wave and S-wave velocity profiles it was possible to construct 2-D profiles of VP/Vs ratio and equivalent Poisson's ratio along the two acquisition lines. These profiles can be related to lithology changes in the subsurface. In fact, low VP/Vs (Poisson) ratios are generally associated to sands, while high VP/Vs (Poisson) ratios are indicative of shales (**Figure 4.36** and **Figure 4.37**). At the crossing point, the VP/Vs ratio has an average value of about 2 for the alluvium, in good agreement with the value inferred comparing the final SH-transverse and P-vertical time sections. Moreover, areas with different sand-shale content can be observed on the 2-D sections. In particular, a superficial thin layer characterized by a relatively high VP/Vs (Poisson) ratio, overlaying less compacted, coarser sediments, possibly related to the superficial thin layer of caliche, highly cemented, overlaying the unconsolidated mixture of clay, sand and gravel. This interpretation is consistent with an exceedingly shallow reflection detectable on the CMP gathers, but muted and therefore not present in the final stacked sections.

Our study at HAFB shows that, although challenging, it was possible to image and delineate the geometry of the buried paleochannel with sufficient resolution and accuracy using reflection seismic data. The images made using the different seismic methods are in good accordance with each other and the available well data, and allow a cross-validation of the final results. Moreover, similar S-wave and P-wave images suggest that the high reflectivity interpreted as target reflector (aquiclude) is originating from a lithological variation, and not from a zone of water saturation of the sediments.

Lastly, tomographic inversion of the first arrival traveltimes of compressional-wave and shear-wave data allowed reconstructing VP and Vs models of the near surface. These two

important elastic properties of the medium provided the basis for a simple characterization of the shallow subsurface.

The improving efficiency and diminishing cost of shallow seismic acquisition and processing make this method a valid alternative, in areas where the target depth or the soil and/or hydrologic conditions preclude an effective use of other more cost-efficient geophysical methods, such as GPR.

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APPENDIX A

Ground Roll Attenuation

Strong, source-generated coherent noise is often dominant in shallow reflection seismic data. Such kind of noise has the double effect of both obscuring possible reflectors when present, and generating non-reflective coherent events on the final sections, often misinterpreted as true reflections. Therefore, it is of primary importance to remove coherent noise trains from the seismic record. In the attempt to eliminate or at least attenuate the strong ground roll from the shot-gathers, different methods were evaluated.

f-k filtering

Frequency-wave number filtering is a way of attenuating noise that has a different spatial relationship (slope) than reflections, performed in the f-k domain (**Figure A.1**).

Filtering in the f-k domain was carried out on preprocessed and bandpass-filtered shot-gathers. After transformation, a polygon was design in the f-k panels, separating the region containing the signal to pass, from the region containing the ground roll to filter. The data transformed back into space-time domain show how a sufficiently robust filter successfully attenuated the ground roll from the shot-gathers. However, while increasing the coherency of the reflections, f-k filtering generated artifacts and enhanced aliased phases, when present in the data. Moreover, a good control of the f-k filtering parameters requires a S/N ratio for the reflections of interest and a separation of phases in the f-k domain, not always applicable to the present dataset.

Figure A.1: Single receiver line of shot-gather and relative f - k spectrum (a) before f - k filtering, (b) after a conservative f - k filtering, and (c) after a more robust f - k filtering. Ground roll is highlighted in the unfiltered data. The polygon in the f - k panel represents the “passed” area.

Trace mixing

Trace mixing computes mixes of traces in a specified spatial window. By steering the trace mix along a velocity dip equal to the velocity of a particular linear noise such as ground roll, it is possible to reconstruct the noise itself (Haldorsen et al., 1989). The resulting mixed sample can then be subtracted from the input sample and the coherent noise removed, or attenuated, from the seismic record (**Figure A.2**). The critical parameter is the number of traces (spatial window) to mix. In fact, a number of traces too small is not effective in removing the ground roll, while a large number of traces smoothens the reflections laterally and creates artificial coherent events in the shot-gathers. Furthermore, because the spatial window is necessarily an odd integer number, a fine-tuning to the peculiar dataset is often problematic.

Tau-P transformation

The intercept time - ray parameter domain is a very important seismic representation from the geophysical point of view. It can be used to separate different seismic signals since they are located in distinct zones of the Tau-P plane. Thus, there is the possibility to separate ground roll from useful seismic data (Stoffa et al., 1981).

Filtering in the Tau-P domain was done on preprocessed and bandpass-filtered shot-gathers, single receiver lines and offset sides (**Figure A.3**).

The seismic data were transformed from x-t domain to Tau-P domain including the entire range of ray parameters present in the data. The data were then reverse transformed limiting the range of ray parameters, in order to filter out the slowness associated with ground roll.

Figure A.2: Comparison between single receiver line of shot-gather (a) after coherent noise attenuation, (b) after 5 traces mixing and subtraction, and (c) after 7 trace mixing and subtraction.

Figure A.3: Part of pre-processed and bandpass filtered shot gather (a) in X-T domain and (b) in Tau-P domain. The groundroll (G) and the main reflection (R) are indicated by arrows. The same data after inverse transform limited to (c) 6 ms/m, (d) 4.5 ms/m, and (e) 3 ms/m of slowness, respectively. For comparison, the same shot gather (f) after coherent noise attenuation is shown.

The results are comparable to the ones obtained applying coherent noise attenuation, and the ground roll is effectively removed from the seismic record. However, Tau-P transformation and filtering require considerable manpower for a correct application. Because of the 3-D configuration, the shot gathers have to be split into separate receiver lines, and each receiver line into positive and negative offsets. Moreover, as in any bidimensional operation, the transformation of seismic data into tau-P domain is very sensitive to spatial aliasing phenomena.

Wave-equation datuming

Wave-equation datuming is the name given to upward or downward continuation of seismic time data aimed to redefine the reference surface on which the sources and receivers appear to be located (Berryhill, 1979). An interesting application of this technique is the possibility to remove surface-waves from the seismic record (**Figure A.4**). The single receiver lines of test shot-gathers were downward continued to a horizontal datum at 1425 m of elevation using a constant velocity of 180 m/s (i.e. the approximate velocity of ground roll). After downward continuation the slower surface-wave phase are pushed upward into negative times and muted. Then, the receivers were upward continued back to the final datum of 1431 m, using the same constant velocity of 180 m/s. As a result, the ground roll was effectively filtered out of the seismic record, although with some artifacts on the shot-gathers. In particular, high-amplitude and low-velocity events were generated in the deepest part of the gathers.

Figure A.4: *Single receiver line of shot gather (a) before and after wave equation datuming at (b) 1430 m, and (c) 1425 m and back to 1430 m, respectively. Note the artifacts generated by the process.*

Each of the techniques tested presents advantages and drawbacks. After evaluation on a sample of shot-gathers from different parts of the survey area and with various S/N content, coherent noise attenuation was considered the best tool for removing the ground roll. The preference was based not only on the effectiveness in removing the ground roll, but also on the manpower required for the application, the sensitivity of the parameters, and the capability to preserve the true events.

APPENDIX B

Vector Rotation

In the Gal'perin configuration, named for the Russian geophysicist who developed it as a tool for three-component borehole studies, three identical, single-component geophones are mounted at an angle of 35.3° to the horizontal and at 120° relative to each other (**Figure B.1-a**). This configuration ensures that each of the three geophones will respond equally to the effects of gravity. Phase and amplitude characteristics between the sensors should therefore be matched. Records obtained with Gal'perin mounted geophones must, however, be rotated into an earth-referenced coordinate system (X, Y, Z) in order to be interpreted (**Figure B.1-b**). If one of the three geophones in the Gal'perin cluster is oriented parallel to the line of acquisition, the following represents the trigonometric transformation to an XYZ coordinate system:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos \alpha & -\cos \alpha \sin \beta & -\cos \alpha \sin \beta \\ 0 & \cos \alpha \cos \beta & \cos \alpha \cos \beta \\ \sin \alpha & \sin \alpha & \sin \alpha \end{bmatrix} \cdot \begin{bmatrix} G_1 \\ G_2 \\ G_3 \end{bmatrix}$$

where $\alpha = 35.3^\circ$ and $\beta = 30^\circ$. G_1 is the geophone oriented parallel to the line of acquisition, while G_2 and G_3 follow G_1 in a clockwise direction.

While the vertical component (Z) is only dependent on the receiver orientation with respect to the vertical, the radial and transverse components (X and Y) are dependent on geophone orientations with respect to both, the vertical and the horizontal. Consequently,

the 3-C unit must be placed vertically, and oriented horizontally at a consistent and known angle. An improperly connected or noisy geophone within a 3-C Gal'perin group, results in the degradation of both the radial and transverse components of ground motion.

Figure B.1: (a) Gal'perin mount configuration and (b) vector rotation from Gal'perin to Cartesian coordinate system.

APPENDIX C

Group-Related Reverberations

Preliminary analysis of the 2-D seismic dataset shows that almost all the records are severely contaminated by coherent noise. Similar ringing is not uncommon on shallow seismic surveys, and it is typically source-generated. However, in this case the noise is incoherent and only perceptible on common-shot gathers, whereas it becomes marked and well organized when the traces are sorted in common-receiver gathers. Moreover, the coherent noise is consistently present on each component of the original (i.e. Gal'perin) data. It affects both P-wave and S-wave source records indifferently, as well as both the profiles, line EW and line NS (**Figure C.1**, **Figure C.2**, **Figure C.3** and **Figure C.4**).

Therefore, the possibility of seismograph malfunction, coherent ambient-noise, or incorrect vector rotation of the components, can be ruled out.

Thus, the noise is likely to be receiver-related, and possibly representing the response of the geophones, in this case Gal'perin receivers groups, to the source energization. The frequency of the ringing is typically 70-80 Hz, consistent in the same receiver, but varying from receiver to receiver, and therefore disguised in the common-source gathers. After vector rotation from Gal'perin to Cartesian coordinate system, the reverberations are visible exclusively on the X and Y components, and not affecting the Z component (**Figure C.5** and **Figure C.6**). Polarization analysis of the direction of particle motion, performed in a trace-time window containing the reverberations, confirmed that the ringing is solely polarized in the horizontal plane, independently from the energization source (**Figure C.7** and **Figure C.8**). As a result, such coherent noise, while seriously

affecting the SH-transverse data, does not represent a problem for the P-vertical seismic record.

A possible explanation for these reverberations is that for the extra hard ground present at the site we had to pre-drill for the geophone shafts, which made each of the Gal'perin receivers groups an inverted pendulum with its own natural frequency of unwanted vibrations. The response of an inverted pendulum to rapid-frequency, small-amplitude oscillations is in fact a harmonic motion around the vertical position. If this were the case, frequency differences of the ringing between different receivers would be related to unequal deviations from the vertical of the bubble-leveled Gal'perin groups.

Regardless of the cause, a common-receiver sorting scheme allowed it not only to be recognized, but also to suppress the reverberations, by tailoring a predictive deconvolution to the receiver gathers.

S-WAVE source - Common-source gather

Line EW

S-WAVE source - Common-receiver gather

Line EW

Figure C.1: Original (Gal'perin) seismic data and relative autocorrelation of the traces (top) in common-source and (bottom) common-receiver domain. The data refer to the S-wave source, and were acquired along the EW profile.

P-WAVE source - Common-source gather

Line EW

P-WAVE source - Common-receiver gather

Line EW

Figure C.2: Original (Gal'perin) seismic data and relative autocorrelation of the traces (top) in common-source and (bottom) common-receiver domain. The data refer to the P-wave source, and were acquired along the EW profile.

S-WAVE source - Common-source gather

Line NS

S-WAVE source - Common-receiver gather

Line NS

Figure C.3: *Original (Gal'perin) seismic data and relative autocorrelation of the traces in (top) common-source and (bottom) common-receiver domain. The data refer to the S-wave source, and were acquired along the NS profile.*

P-WAVE source - Common-source gather

Line NS

P-WAVE source - Common-receiver gather

Line NS

Figure C.4: *Original (Gal'perin) seismic data and relative autocorrelation of the traces in (top) common-source and (bottom) common-receiver domain. The data refer to the P-wave source, and were acquired along the NS profile.*

Figure C.5: Example of rotated (XYZ) common-receiver gather and relative autocorrelation of the traces acquired in the same position on the EW line (top) using P-wave and (bottom) S-wave sources.

Figure C.6: Example of rotated (XYZ) common-receiver gather and relative autocorrelation of the traces acquired in the same position on the NS line using (top) P-wave and (bottom) S-wave sources.

Figure C.7: (a) Common-receiver gather in the XYZ domain and (b) hodogram of one station (source 31) showing the particle motion. Only one of the components (Y) is displayed in the gather. The data were acquired along the EW line using the S-wave source.

Figure C.8: (a) Common-receiver gather in the XYZ domain and (b) hodogram of one station (source 31) showing the particle motion. Only one of the components (Y) is displayed in the gather. The data were acquired along the EW line using the P-wave source.