**Non-Invasive Determination
of the
Location and Distribution of Free-Phase
Dense Nonaqueous Phase Liquids (DNAPL)
by
Seismic Reflection Techniques**

Semi-Annual Technical Progress Report

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by

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Abstract

The Earth Sciences and Resources Institute, University of South Carolina is conducting a 14 month proof of concept study to determine the location and distribution of subsurface DNAPL (carbon tetrachloride (CCl_4) contamination at the 216-Z-9 crib, 200 West area, DOE Hanford Site, Washington by use of two-dimensional high resolution seismic reflection surveys and borehole geophysical data. The study makes use of recent advances in seismic reflection amplitude versus offset (AVO) technology to directly detect the presence of subsurface DNAPL. The techniques proposed are a noninvasive means of site characterization and direct free-phase DNAPL detection.

This report covers the results of Tasks 1, 2 and a portion of Task 3. Task 1 contains site evaluation and seismic modeling studies. The site evaluation consists of identifying and collecting preexisting geological and geophysical information regarding subsurface structure and the presence and quantity of DNAPL. The seismic modeling studies were undertaken to determine the likelihood that an AVO response exists and its probable manifestation. Task 2 is the design and acquisition of 2-D seismic reflection data designed to image areas of probable high concentration of DNAPL. Task 3 is the processing and interpretation of the 2-D data.

During the commission of these tasks four seismic reflection profiles were collected. Subsurface velocity information was obtained by vertical seismic profile surveys in three existing wells.

Seismic models indicate that the contact between the Hanford Fine and the Plio/Pleistocene should be a high amplitude positive reflection, except where high concentrations of CCl_4 are present. In the later case the positive amplitude should decrease to a negative amplitude (dim-out). At the contact between the Plio/Pleistocene and the caliche the models indicate that the presence of CCl_4 should cause a noticeable positive increase in the seismic amplitude (bright spot).

Based upon the results of Tasks 1, 2 and a portion of Task 3 it appears likely that AVO seismic techniques can be used to detect high concentrations of CCl_4 on the seismic data.

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1.0 Introduction

This semi-annual report is for Tasks 1, 2 and the data processing portion of Task 3 of project DE-AR26-98FT40369. After the success of using high-resolution seismic reflection surveying and applying amplitude versus offset (AVO) analysis to image DNAPL in the subsurface at the DOE Savannah River Site M area, South Carolina, it was proposed that another site with drastically different geologic setting be tested using these techniques. The area adjacent to the 216-Z-9 crib at the 200 West area, DOE Hanford Site, Washington was selected (Figure 1). When this project was conceived assumptions were made as to the availability of certain types of data, e.g. limited amounts of borehole geophysical logs and existing core data. These assumptions were not ill conceived, but were based upon the authors' experience doing similar type of work at other DOE sites. As a contingency, it was proposed that if data were not available, one test hole would be drilled to obtain the data necessary for modeling and seismic acquisition design. However, because of budget constraints and the cost of drilling a well in the 200 West area, a new well could not be drilled.

2.0 Executive Summary

This semi-annual report is for Tasks 1, 2 and part of Task 3 of project DE-AR26-98FT40369. After the success of using high-resolution seismic reflection surveying and applying amplitude versus offset (AVO) analysis to image dense non-aqueous phase liquids (DNAPL) in the subsurface at the DOE Savannah River Site M area, South Carolina it was proposed that another site with different geologic conditions be tested using this technique. The new study area is adjacent to the 216-Z-9 crib at the 200 West area, DOE Hanford Site, Washington. At 200 West area there is a large subsurface plume of highly concentrated carbon tetrachloride (CCl_4). When this project was conceived assumptions were made as to the availability of certain types of data, e.g. limited amounts of borehole geophysical logs and existing core data. Unfortunately, these assumptions were overly optimistic. As a contingency it was proposed that if certain data were not available, one test hole would be drilled to gather data necessary for modeling and seismic acquisition design. However, due to budget constraints and the cost of drilling a well at the 200 West area, a well could not be drilled.

The initial proposed research is a 14 month proof of concept study to determine the location and distribution of subsurface DNAPL (carbon tetrachloride) contamination at the 200 West area at DOE Hanford Site by the use of two and three-dimensional high-resolution seismic reflection data and borehole geophysical surveys. The specific project objectives are:

- Subsurface imaging of geologic sinks where DNAPL can pool.
- Direct detection of DNAPL by use of the seismic reflection amplitude versus offset (AVO) method.

Task 1 consisted of a site visit to familiarize Earth Sciences and Resources Institute personnel with the site geology at the 200 West area and to collect any pertinent geologic and geophysical data. After the site visit, it was necessary to return to the 200 West area and collect compressional (P) and shear (S) wave velocity data and density information from wells in the vicinity of the Z-9 crib.

The velocity and density data were used in Task 2 for design and collection of the 2-D high-resolution seismic reflection data. In Task 2 four seismic lines were acquired using a 120 channel 24 bit seismograph and a high frequency vibrator source. The source and receiver intervals were only one meter (3.05 ft.) to yield dense spatial coverage.

Task 3 dealt with the processing of the four seismic lines and interpretation of the 2-D data. As of the time of this report only the processing of the four Seismic lines have been completed.

Amplitude versus offset (AVO) analysis involves comparing modeled responses with field data to find a deviation from an expected background response. The expected background response is usually assumed to be water saturated rock. In this study the background response is an air saturated aquifer. DNAPL has the same response as liquid hydrocarbons. If DNAPL is present in free-phase and in large enough quantities, then AVO analysis similar to that used in the petroleum industry can be done to determine a response. One important aspect of this project is the modeling to determine the type of seismic AVO response, if any, the presence of CCl_4 would cause. In this report Shuey's (1985) modification of Zoeppritz equations is used to express the angle dependent reflectivity in terms of P wave velocity, bulk density, and Poisson's ratio.

Four different scenarios were modeled: 1) the contact of the Hanford Fine with the Plio/Pleistocene, 2) Hanford Fine saturated with CCl_4 overlying the Plio/Pleistocene, 3) the contact of the Plio/Pleistocene with the caliche, and 4) the Plio/Pleistocene saturated with CCl_4 overlying the caliche. At the contact of the Hanford Fine and the Plio/Pleistocene there is a positive reflection coefficient of approximately 0.7. However, if the Hanford Fine is saturated with CCl_4 the reflection coefficient drops to -0.1. This is referred to as a "dim-out." At the Plio/Pleistocene-caliche contact the reflection coefficient is approximately 0.18. If, however, the Plio/Pleistocene is saturated with CCl_4 the reflection coefficient at the contact increases from approximately 0.18 to 0.38. This is referred to as a "bright spot."

Based on the modeling, the surface seismic data can image areas where seismic amplitude anomalies are associated with high concentrations of carbon tetrachloride. This assumption has to be taken with some caution. The P wave, S wave, and density values for the fluid filled rock were mathematically derived.

3.0 Project Objectives

The research as initially proposed was a 14 month proof of concept study to determine the location and distribution of subsurface DNAPL (carbon tetrachloride) contamination at the 200 West area, DOE Hanford Site by the use of two and three-dimensional high-resolution seismic reflection data and borehole geophysical surveys. The specific objectives of the research were:

- Subsurface imaging of geologic sinks where DNAPL can pool.
- Direct detection of DNAPL by use of the seismic reflection amplitude versus offset (AVO) method.
- All the project objectives would be accomplished in six tasks as outlined in the management plan.

4.0 Project Accomplishments

- Determine which area at Hanford would be suitable for conducting the study. The Z-9 crib at the 200 west area is the site selected for this study.
- Since there are no velocity or density information at or in the vicinity of the 200 west three vertical seismic profiles (VSP) would be conducted in exist wells and one density log ran in one well. (See section of VSP for which wells VSP were conduct in.
- Four seismic lines were located around the crib and the data collected and processed during this reporting period (Figure 1).

5.0 Problems Encountered

For this reporting period there are no problems to report.

Figure 1. Location map of the seismic reflection lines and key wells at the 216-Z-9 crib, 200 West area, DOE Hanford Site.

6.0 Experimental: Amplitude Versus Offset Modeling

6.1 Theory

In the 1960's petroleum companies recognized that in young sediments (Tertiary age) large seismic amplitudes were associated with gas saturated sands. However, it was soon realized that not all large seismic amplitudes represented hydrocarbon saturated sands. The normal incidence (NI) reflectivity (bright spot) techniques involved three different scenarios based upon a water saturated state and a hydrocarbon saturated state (for this discussion a sand/shale or sand/clay interface). The scenarios are classified by changes in NI reflectivity from a water saturated sand to a gas or hydrocarbon bearing sand.

The three scenarios are:

- Dim-spot- a large positive amplitude that is reduced to a smaller positive amplitude,
- Phase reversal- a small positive amplitude that changes to small negative amplitude and
- Bright spot- a negative amplitude increasing to a large negative amplitude.

The dim-spot is generally associated with a large acoustic impedance contrast and is a technique for inferring lithology. Bright spot anomalies are generally used for interpreting lithology and estimating sand thickness. Phase reversal reflections are not generally reliable because geologic features (e.g. faults) can cause the reflections to appear to reverse phase. Thus, a reflection phase reversal does not necessarily indicate a change in lithology (Verm and Hilterman, 1995). The bright spot technique was the first direct hydrocarbon indicator.

In 1984 Ostrander published a article entitled "Plane-wave reflection coefficients for gas sands at non-normal angles of incidence." Ostrander observed that the P wave reflection coefficient at the interface between two media varies with the angle of incidence of the impinging energy. Ostrander also investigated the phenomenon of compressional wave reflection amplitude variation with angle of incidence and changes in Poisson's ratio. Poisson's ratio is defined as the ratio of transverse strain to longitudinal strain and can be expressed in terms of P wave and S wave velocity (Sheriff, 1991):

$$\sigma = \frac{\frac{V_p^2}{V_s^2} - 2}{2 \left(\left[\frac{V_p}{V_s} \right]^2 - 1 \right)} \quad (1)$$

σ = Poisson's ratio

V_p = compressional wave velocity

V_s = shear wave velocity

Much of Ostrander's work was based upon Koefoed's 1955 work on determining the reflection coefficients of plane longitudinal waves reflected at a boundary between two elastic media. Koefoed observed that if there were two elastic media with the top medium having a smaller

Poisson's ratio than the underlying medium there would be an increase in the reflection coefficient with increasing angle of incidence. He also observed that if Poisson's ratio of the lower medium was lower than the overlying medium, the opposite would occur with a decrease in the reflection coefficient with an increase in the angle of incidence. Another observation showed that the relative change in reflection coefficient increases as the velocity contrast between two media decreases. Koefoed also observed that if Poisson's ratio for two media was increased but kept equal, the reflection coefficient at the larger angles of incidence would also increase. Ostrander (1984) observed that changes in Poisson's ratio caused by the presence of hydrocarbons in the pore space has dramatic effect on the P wave reflection coefficients and that these effects can be related to seismic amplitude anomalies.

In order to understand amplitude versus offset (AVO) analysis, one has to understand offset dependent reflectivity. Offset dependent reflectivity is defined as the variation of the reflection and transmission coefficients with Changing of the incident angle (Castagna and Backus, 1993). The offset refers to source to receiver separation. Increasing source to receiver separation results in increasing angle of incidence for raypaths as measured from the normal to a horizontal interface. Coincident source and receiver locations results in what is termed normal incidence, i.e. vertical transmission and reflection from a horizontal interface. The amplitude of the reflected and transmitted waves are described by the reflection and transmission coefficients. The following discussion describes the equations and theory used to determine amplitude for both the reflected and transmitted waves at an acoustic boundary for normal incident energy and non-normal incident energy, i.e. offset dependent reflectivity. Note that this discussion is for a simplistic model of a single interface. The majority of reflections observed on a seismic profile are the superposition of events from multiple layers and has a more complex AVO response.

As implemented in the Petroleum industry, AVO analysis involves comparing modeled AVO responses with field data to find a deviation from an expected background response. The expected background response is usually taken to be a water saturated reservoir; hence, the deviation from the expected response is an indication of hydrocarbon presence but does not indicate quantity. DNAPLs have the same acoustic characteristics as liquid hydrocarbons; therefore, if DNAPL is present in free-phase and in large enough quantities, similar types of analyzes as those performed for the petroleum industry can be applied to directly detect the presence of DNAPL.

An understanding of reflection AVO techniques can be obtained by a review of elastic wave propagation. A P wave incident on a boundary between two linear elastic homogeneous isotropic (LEHI) media generates four types of waves: 1) transmitted P wave, 2) reflected P wave, 3) reflected S wave, 4) a transmitted S wave (Figure 2). The amplitudes of the reflected and transmitted waves at the boundary depend upon the P wave and S wave velocities. The density of the two media, and the angles of incidence and refraction, are as determined from Snell's Law.

Figure 2. Elastic waves generated at a boundary. A P wave incident at a angle θ on a boundary between two linear elastic homogenous isotropic (LEHI) materials generates four wave types: reflected P, reflected S, transmitted P, transmitted S. The angles of reflection and refraction are governed by Snell's law from optics. The material properties of the media are described by the P wave velocity, density, and Poisson's ratio. The S wave velocity can be found from the P wave velocity and Poisson's ratio.

Snell's Law,

$$p = \frac{\sin \Theta_1}{V_{p1}} = \frac{\sin \Theta_2}{V_{p2}} = \frac{\sin \phi_1}{V_{s1}} = \frac{\sin \phi_2}{V_{s2}} \quad (2)$$

V_{p1} = P wave velocity in medium 1,
 V_{p2} = P wave velocity in medium 2,
 V_{s1} = S wave velocity in medium 1,
 V_{s2} = S wave velocity in medium 2,
 Θ_1 = incident P wave angle,
 Θ_2 = transmitted P wave angle,
 ϕ_1 = reflected S wave angle,
 ϕ_2 = transmitted S wave angle, and
 p is the ray parameter.

The reflection coefficient of the P wave as a function of the incident angle, $R_p(\Theta)$, is defined as the ratio of the amplitude of the reflected P wave to that of the incident P wave (Castagna and Backus, 1993). The P wave transmission coefficient, $T_p(\Theta)$, is the ratio of the amplitude of the transmitted P wave to that of the incident P wave (Castagna and Backus, 1993). The P wave reflection coefficient, R_p , at normal incidence is given by the following equation:

$$R_p = \frac{I_{p2} - I_{p1}}{I_{p2} + I_{p1}} = \frac{1}{2} * \frac{\Delta I_p}{I_{pa}} \approx \frac{1}{2} * \ln * \frac{I_l}{I_l} \quad (3)$$

I_{p2} = acoustic impedance of medium 2 = $\rho_2 V_{p2}$
 ρ_2 = density of medium 2
 I_{p1} = acoustic impedance of medium 1 = $\rho_1 V_{p1}$
 ρ_1 = density of medium 1
 I_{pa} = average acoustic impedance across the interface = $(I_{p2} + I_{p1})/2$, and
 $\Delta I_p = I_{p2} - I_{p1}$.

The P-wave transmission coefficient at normal incidence T_p is given by:

$$T_p = 1 - R_p. \quad (4)$$

The variation of the reflection and transmission coefficients with incident angle and source to receiver offset is referred to as offset dependent reflectivity (Castagna and Backus, 1993). The values of the reflection and transmission coefficients for non-normal angles of incidence are given

by the Zoeppritz (1919) equations. The complexity of the Zoeppritz equations has led to numerous approximations to simplify the calculations. Some of the approximations are Bortfield (1961), Aki and Richards (1980), and Shuey 1985. The Aki and Richards (1980) approximation to the Zoeppritz equations is given below:

$$R(\theta) \approx a \left(\frac{\Delta V_P}{V_P} \right) + b \left(\frac{\Delta \rho}{\rho} \right) + c \left(\frac{\Delta V_S}{V_S} \right) \quad (5)$$

$$\begin{aligned} \theta &= \arcsin \left[(V_{p2} / V_{p1}) \sin \theta_{\text{incident}} \right] \\ a &= \frac{1}{2} + \tan^2 \theta \\ b &= 0.5 - [(2V_S^2 / V_P^2) \sin^2 \theta] \\ c &= -(4V_S^2 / V_P^2) \sin^2 \theta \\ V_P &= (V_{p1} + V_{p2}) / 2; & V_P \text{ is P wave velocity} \\ V_S &= (V_{s1} + V_{s2}) / 2; & V_S \text{ is S wave velocity} \\ \rho &= (\rho_1 + \rho_2) / 2; & \rho \text{ is bulk density} \\ \Delta V_P &= V_{p2} - V_{p1} \\ \Delta V_S &= V_{s2} - V_{s1} \\ \Delta \rho &= \rho_2 - \rho_1 \end{aligned}$$

In this equation the reflection amplitude is expressed in three terms containing P wave velocity, S wave velocity, and bulk density.

The Aki and Richards approximation (Equation 5) was rearranged by Shuey (1995) to obtain a more convenient form. The Shuey approximation of the Zoeppritz equations stresses the importance of Poisson's ratio as the primary determinant of the AVO response of a reflection (Allen and Peddy, 1993). In this study we used the Shuey approximation, which expresses angle dependent reflectivity in terms of P wave velocity, bulk density, and Poisson's ratio to compute the AVO models.

The Shuey (1985) formula for the reflection coefficient (amplitude) is:

$$R(\theta) \approx R_0 + (A_0 * R_0 + \frac{\Delta \sigma}{1 - \sigma^2}) * \sin^2 \theta + \frac{1}{2} * \frac{\Delta V_P}{V_P} * \tan^2 \theta - \sin^2 \theta \quad (6)$$

$$\Delta V_P = (V_{p2} - V_{p1}) \quad \theta = (\theta_2 + \theta_1) / 2$$

$$V_P = (V_{p2} + V_{p1}) / 2 \quad \Delta \sigma = (\sigma_2 + \sigma_1)$$

$$\Delta V_S = (V_{s2} - V_{s1}) \quad \sigma = (\sigma_2 + \sigma_1) / 2$$

$$V_s = (V_{s2} + V_{s1}) / 2$$

$$\Delta\rho = (\rho_2 - \rho_1) \quad \rho = (\rho_2 + \rho_1) / 2$$

$$R_o \approx \frac{1}{2} \left(\frac{\Delta V_p}{V_n} + \frac{\Delta \rho}{\rho} \right)$$

$$A = A_0 + \left(\frac{1}{(1 - \sigma)^2} \right) \frac{\Delta \sigma}{R_0}$$

$$A_0 = B - 2 \left(1 + B \right) \left(\frac{1 - 2\sigma}{1 - \sigma} \right)$$

$$B = \frac{\frac{\Delta V_p}{V_p}}{\frac{\Delta V_p}{V_p} + \frac{\Delta \rho}{\rho}}$$

V_{p1} = P wave velocity of layer one V_{p2} = P wave velocity of layer two
 V_{s1} = S wave velocity of layer one V_{s2} = S wave velocity of layer two
 ρ_1 = density of layer one ρ_2 = density of layer two
 σ_1 = Poisson ratio of layer one σ_2 = Poisson ratio of layer two
 θ_1 = incidence and transmission angle layer one.
 θ_2 = incidence and transmission angle layer two.
 R_0 = Normal incidence (NI), i.e. reflection coefficient for zero-offset.
 B = is the AVO gradient.
 A_0 = is the normal incidence amplitude.

The approximation above can be simplified further. If the average Poisson's ratio is assumed to be 1/3 and higher order terms that are insignificant above 30° are dropped, the formula for the angle dependent reflection coefficient becomes:

$$R(\theta) \approx NI + \left(\frac{9}{4} \Delta \sigma - NI \right) \sin^2 \theta \quad (7)$$

$$\approx NI + B \sin^2 \theta \quad (8)$$

$$R(\theta) \approx NI \cos^2 \theta + PR \sin^2 \theta \quad (9)$$

NI and PR are defined as

$$NI = \frac{(V_{p2}\rho_2) - (V_{p1}\rho_1)}{(V_{p2}\rho_2) + (V_{p1}\rho_1)} = \frac{(z_2 - z_1)}{(z_2 + z_1)} \quad \text{z is the acoustic impedance:} \quad (10)$$

$$PR = \frac{\Delta\sigma}{(1 - \sigma_{avg})^2} \quad (11)$$

(Verm and Hiltermann, 1995). Reflection AVO can be thought of a combination of normal incidence reflectivity and a far offset reflectivity, or “Poisson reflectivity,” that arises primarily as a result of changes in the Poisson’s ratio between media.

To implement AVO analysis, the NI and PR coefficients are extracted from a common depth point (CDP) gather. Initially the CDP gather is transformed from a function of offset to incident angle. This transformation requires knowledge of the root mean square (RMS) velocity, which is ideally obtained from borehole sonic logs. In the absence of sonic logs a rough estimate of the RMS velocity can be obtained from the normal moveout (NMO) stacking velocities. Next, the NI and PR coefficients are found by fitting either Equation (8) or (9) to the amplitudes.

6.2 Modeling

The most important aspect of this study is the AVO modeling. The modeling determines the type of AVO response, e.g. dim-out, bright spot, or phase reversal that might be expected to occur because of the presence of DNAPL. Models were generated using Shuey’s approximation to the Zoeppritz equations (Equation 6). One set of models consisted of the Hanford Fine overlying the Plio/Pleistocene and the Hanford Fine overlying the Plio/Pleistocene with the Plio/Pleistocene saturated with CCl_4 . The second set of models consisted of the Plio/Pleistocene overlying the caliche layer and the Plio/Pleistocene overlying the caliche with the caliche saturated with CCl_4 . These scenarios were chosen because it appears from well data that the CCl_4 is concentrating along the Hanford Fine - Plio/Pleistocene contact and along the Plio/Pleistocene-caliche contact. The models were constructed using the information shown in Table 1.

In Table 1 the P wave and S wave velocities of the units without CCl_4 were determined from vertical seismic profiles (VSPs) in wells 299-W15-32 and 299-W15-217 (Figure 1). The densities of these same units were obtained from values published by Rohay and others (1994). Published values for density were used rather than the geophysical log collected in well 299-W15-32 because the borehole

density log values were low compared to the laboratory measurements. The low density of the caliche as compared to calcium carbonate suggests that it might have vuggy porosity. If this is so, then CCl_4 might concentrate within this unit.

Table 1. AVO Modeling Parameters

Lithology	V_p m/s	V_s m/s	Density g/cc
Hanford Fine	620	394	1.56
Hanford Fine w/ CCl_4	1270	327	2.26
Plio/Pleistocene	1351	679	1.79
Plio/Pleistocene w/ CCl_4	1671	596	2.32
Caliche	2103	679	1.49
Caliche w/ CCl_4	1966	447	2.58

To determine the AVO response that might arise from CCl_4 saturated sediments it is necessary to have the corresponding velocity and density values for the CCl_4 saturated sediments. The ideal method to obtain these values is to flood representative cores with various concentrations and saturations of

CCl_4 and measure the change in velocity and density that occurs. Unfortunately, no core material is available to conduct a core flood study. In lieu of actual core measurements, the velocities and densities of the units saturated with CCl_4 were mathematically derived. The Gassmann theory of fluid saturated rocks (e.g. White, 1983) was used to find the velocity of the CCl_4 saturated sediments. The bulk density of the saturated sediments is a simple weighted average governed by the porosity. The porosity of the units was assumed to be 35-40 percent, which is common for loosely consolidated sediments.

Gassmann theory assumes that motion of pore fluid is negligible compared to the motion of the fluid filled rock itself, i.e. the fluid and rock move together. In addition, it is assumed that the seismic frequencies are low, less than a megahertz. Because the shear modulus, μ , is not affected by fluid saturation, the formulation by Gassmann is for the bulk modulus, k , of the fluid filled rock. Once this value is obtained, the P wave velocity is found by following formula:

$$V_p = \left(\frac{K + \frac{4}{3}\mu}{\rho} \right)^{\frac{1}{2}} \quad (12)$$

The S wave velocity is moderately depressed by the introduction of fluids because it cannot propagate in fluids and is influenced only by density. The formula for S wave velocity is:

$$V_s = \left(\frac{\mu}{\rho} \right)^{\frac{1}{2}} \quad (13)$$

Note that the density, ρ , is the bulk density, which combines both the rock density and fluid density.

Gassmann's equation for the bulk modulus of a fluid filled rock is as follows:

$$K_w = K_{dry} + \frac{(1 - \frac{K_{dry}}{K_{ma}})^2}{\frac{\phi}{K_{fl}} + (1 - \frac{\phi}{K_{ma}}) - \frac{K_{dry}}{K_{ma}}} \quad (14)$$

- K_w = Bulk modulus of the fluid filled rock
- K_{dry} = Bulk modulus of the rock skeleton
(aggregate of grains)
- K_{ma} = Bulk modulus of matrix (individual grains)
- K_{fl} = Bulk modulus of the pore fluid
- μ_w = Shear modulus of the fluid filled rock
- μ_d = Shear modulus of the rock skeleton
- $\mu_w = \mu_d$

In calculating the bulk modulus of the geologic units saturated with CCl_4 (Table 1), the following assumptions were made:

- K_{dry} is equal to the bulk modulus calculated from the measured P wave and S wave velocity from the VSP and the density reported by Rohay and others (1994). It is also assumed that the pore space is filled with air.
- K_{ma} is the weighted average of bulk moduli of the framework grains (percent quartz, rock fragments, feldspar, and clay (kaolinite)) calculated from modal analyses published by Wright, Conca, and Chen (1994).
- K_f is the bulk modulus of the fluid mixture using Wood's equation (15):

$$K_f = \frac{K_{CCl_4} * K_{air}}{K_{air} * S_{CCl_4} + K_{CCl_4} * S_{air}} \quad (15)$$

K_{CCl_4} = bulk modulus of CCl_4
 K_{air} = bulk modulus of air
 S_{CCl_4} = fractional CCl_4 saturation
 S_{air} = fractional air saturation

The density values for each of the units filled with CCl_4 and air were calculated using the following equation:

$$\rho_b = (1 - \sigma)\rho_{ma} + S_{CCl_4} * \sigma * \rho_{CCl_4} + S_{air} * \sigma * \rho_{air} \quad (16)$$

ρ_{ma} = density of matrix grains
 ρ_{CCl_4} = density of CCl_4
 ρ_{air} = density of air
 S_{CCl_4} = fractional CCl_4 saturation
 S_{air} = fractional air saturation
 σ = fractional percent porosity

In the 216-Z-9 trench area the highest concentration of CCl_4 is found at the contact of the Hanford Fine with the Plio/Pleistocene units in well 299-W15-217 (Figure 1) (Rohay et al, 1994; Rohay personal communication, 1999). In wells 299-W15-219, 218, and 223 high concentrations of CCl_4 were encountered in the Pliocene/Pleistocene at or near the contact with the caliche layer (Figure 1). In order to determine the effect, if any, of CCl_4 on the reflection coefficient as a function of incident angle, a series of seismic models were generated 1) without CCl_4 in the pore spaces and 2) with 100% CCl_4 saturation. The reflection interfaces studied were the contact of the Hanford Fine

with the Plio/Pleistocene (Model 1) and the contact of the Plio/Pleistocene with the caliche layer (Model 2).

Model 1A represents the contact of the Hanford Fine with the Plio/Pleistocene with out CCl_4 in the pore spaces (Figure 3). The modeled response indicates a strong positive reflection coefficient, which on the seismic sections would be displayed as a positive amplitude. If CCl_4 is introduced the reflection coefficient becomes slightly negative (Model 1B)(Figure 4). Therefore, high concentrations of CCl_4 along the contact of the Hanford Fine with the Plio/Pleistocene would be displayed as a low amplitude negative reflection or as a dim-out. A seismic profile that crosses a high concentration of CCl_4 in the Hanford Fine shows a strong positive amplitude becoming weaker in amplitude and then reversing to a slight negative amplitude over the contaminant.

Model 2A is the Plio/Pleistocene overlying the caliche layer saturated with 100% air. The reflection coefficient is positive and increases with increasing offset (Figure 5). Model 2B (Figure 6) is the same model with the caliche layer saturated with 100% CCl_4 . The introduction of CCl_4 causes the reflection coefficient to more than double in magnitude. On a seismic section this phenomenon is known as a bright spot. In this case, a seismic profile that crosses a high concentration of CCl_4 in the Plio/Pleistocene shows a strong positive amplitude becoming somewhat stronger in amplitude as the contaminant is crossed.

The model study suggests that at the 200 West area the introduction of CCl_4 into pore spaces causes significant changes in the P wave reflection coefficient as a function of offset for the interfaces studied. Furthermore, these changes should be visible on zero-offset stacked seismic sections. It must be noted that these models represent only single interfaces. The seismic section represents the superposition of many responses from each interface in the subsurface positioned in time according to the subsurface velocity field. If the overlying and underlying units at an interface are thin compared to the wavelength of the seismic data, the observed response is a composite caused by interference of the superposed waveforms. For this reason a primary goal of seismic recording is to record the highest frequency signals possible in order to resolve closely spaced interfaces.

Model 1A

Figure 3. Graph of reflection coefficient versus angle of incidence for air saturated Hanford Fine overlying air saturated Plio/Pleistocene.

Model 1B

Figure 4. Graph of the reflection coefficient versus the angle of incidence for CCl_4 saturated Hanford Fine overlying the Plio/Pleistocene.

Model 2A

Figure 5. Graph of the reflection coefficient versus angle of incidence for air saturated Plio/Pleistocene overlying air saturated caliche.

Model 2B

Figure 6. Graph of the reflection coefficient versus the angle of incidence for CCl_4 saturated Plio/Pleistocene overlying the caliche.

7.0 Results and Discussion: Seismic Reflection Data Acquisition and Processing

In January 1999 ESRI-USC collected vertical seismic profiles in three wells in the vicinity of the Z-9 Crib in the 200 West area. This was followed by recording four 2-D seismic profiles around the crib in March 1999 (Figure 1).

7.1 Vertical Seismic Profiles

7.1.1 Vertical Seismic Profile Acquisition

Compressional wave (P) and shear wave (S) vertical seismic profiles (VSPs) were collected in wells 299-W15-32, 299-W15-82, and 299-W15-217. The VSPs were collected to obtain data on the P and S wave velocity field of the geologic layers at, above, and below the known DNAPL contamination. The velocity data were used to construct seismic models to determine the probable amplitude versus offset (AVO) response that would be recorded by the surface seismic survey. In addition, subsurface velocity information was needed to perform high-fidelity ties between the surface seismic profiles and the well lithology picks. Using the well for seismic ties to construct the velocity versus depth curves obtained from the VSPs, the interpretations made on the seismic data were converted to depth.

Seismic recordings were made at one meter (3.05 ft.) increments from the bottom of the well to approximately one meter (3.05 ft.) below land surface using a three geophone (1 vertical, 2 horizontal) Geostuff sonde and a 7.3 kg (16 lb.) sledge hammer source. A Geometrics Strataview seismograph recorded the output from the geophones and stored 1024 milliseconds (ms) of data digitized at 0.125 ms intervals. For P-wave acquisition a vertical steel cylinder was placed on the ground and struck six times. Each hit was vertically summed to the preceding hits in the seismograph and written to disk as a single record for each level. For S-wave acquisition strike plates were mounted on the ends of a 2.4 m (8 ft.) horizontal plank and a truck was driven on the plank to couple the plank to the ground. Each end of the plank was struck six times, first from one side of the vehicle and then the other. The summed records for each source orientation were written to disk separately for each level.

The VSP data were noisy and little reflected signal was apparent in the raw records (Figure 7). Well construction reports indicate that the annular space between the casing and the borehole is filled with bentonite. The resulting poor coupling of the casing to the formation probably accounts for the poor VSP record quality. Considerable experimentation was necessary to optimally record the data. Tests were done by varying the offset of the source from the well and by varying the number of source hits. Because of the uncertain data quality, well 299-W15-32 was logged twice for P waves to ensure that usable data were recorded. The recording parameters for each VSP are summarized in Table 2.

VSP Field

Records

Figure 7. Raw VSP data from well 299-W15-32. P wave VSP (left) and S wave VSP (right). Bandpass filter: 30-150 Hz.

Table 2. Summary of VSP recording parameters.

	299-W15-32	299-W15-82	299-W15-217
Recorded depth P wave (m from TOC)	1-71, 2-71	1-22	2-36
Recorded depth S wave (m from TOC)	2-71	1-22	2-36
Source offset P wave (m)	6, 10.03	5.55	6.0
Source offset S wave (m)	10	6.0	6.06
No. of hits P-wave, S-wave	6, 6, (6,6)	6, (6,6)	6, (6,6)
Depth increment (m)	1	1	1
Sample rate (ms)	0.125	0.125	0.125
Record length (ms)	1024	1024	1024

7.1.3 VSP Data Processing

The generalized data processing flow for the VSP data appears in Figure 10. In the field some rudimentary data processing was performed for QA/QC purposes using the Seismic Image Software, Ltd. VISTA seismic processing software. The infield QA/QC proved to be invaluable given the low signal-to-noise ratio of the data.

First arrival times were picked on the P-wave records and the better of the two channels on the S wave records. These times were corrected for source offset from the borehole to true vertical travel time (TVT), or zero-offset time, using a straight raypath assumption. No correction for reflection normal moveout was made.

The velocity profile, average velocity and interval velocity, for each borehole was computed (Figs. 9-17, Tables 3-8). The average velocity (total depth divided by total time) from the surface to the recording depth is used to convert recording time to depth. The interval velocity, or velocity of the material between recording levels, is an approximate indicator of lithologic changes in the borehole. The VSP records were heavily edited and the computed interval velocities smoothed. Generally, the S wave VSP records were better quality than that the P wave records. Despite the poor quality of the field records, useful velocity information was obtained from the boreholes. This is confirmed by the consistency of the interval velocity curves among the wells.

For correlation to the surface seismic data, displays of the up-going wavefield data were shifted to two-way reflection time (twice TVT) and narrow (3-10 trace) front corridor stacks were produced (Figure 18). Because the time-depth relationship for the front corridor stack is known, the depth to the reflectors in the subsurface can be determined.

Generalized Vertical Seismic Profile Data Processing Flow

Figure 8. Vertical seismic profile (VSP) data processing flow.

Table 3. P wave velocity table from well 299-W15-32.

Well 299-W15-32

P-Wave Vertical Seismic Profile

GL = 202.627 m TOC = 203.487 m

(Offset = 10.03 m)

Seq.	Depth (TOC)	Pick Time	Depth (GL)	True Vertical Time	Average Velocity	Interval Velocity	Two-way Time
No.	(m)	(ms)	(m)	(ms)	(m/s)	(m/s)	(ms)
70	2	30.50	1.14	3.44	331	331	6.89
69	3	29.40	2.14	6.13	349	372	12.27
68	4	27.50	3.14	8.22	382	480	16.43
67	5	25.63	4.14	9.78	423	640	19.56
66	6	25.00	5.14	11.40	451	616	22.80
65	7	25.38	6.14	13.25	463	541	26.50
64	8	28.25	7.14	16.38	436	319	32.77
63	9	31.00	8.14	19.53	417	317	39.07
62	10	32.25	9.14	21.72	421	457	43.44
61	11	33.63	10.14	23.91	424	457	47.82
60	12	32.25	11.14	23.97	.	.	.
59	13	32.25	12.14	24.86	488	2099	49.72
58	14	32.25	13.14	25.64	513	1294	51.27
57	15	32.88	14.14	26.82	527	845	53.64
56	16	33.75	15.14	28.14	538	759	56.27
55	17	35.00	16.14	29.73	543	628	59.45
54	18	36.25	17.14	31.29	548	641	62.57
53	19	37.75	18.14	33.04	549	572	66.07
52	20	38.25	19.14	33.88	565	1185	67.76
51	21	40.00	20.14	35.81	562	519	71.61
50	22	41.13	21.14	37.16	569	738	74.32
49	23	42.13	22.14	38.38	577	822	76.75
48	24	43.63	23.14	40.03	578	604	80.06
47	25	44.75	24.14	41.32	584	773	82.65

46	26	46.13	25.14	42.85	587	657	85.69
45	27	47.38	26.14	44.24	591	720	88.47
44	28	48.38	27.14	45.38	598	874	90.76
43	29	49.63	28.14	46.75	602	730	93.50
42	30	51.13	29.14	48.35	603	626	96.69
41	31	53.38	30.14	50.66	595	434	101.30
40	32	54.63	31.14	51.00	599	741	104.00
39	33	56.00	32.14	53.46	601	686	106.91
38	34	56.25	33.14	53.84	616	2626	107.68
37	35	56.88	34.14	54.57	.	.	.
36	36	56.50	35.14	54.33	.	.	.
35	37	57.13	36.14	55.05	657	2477	110.10
34	38	57.88	37.14	55.88	665	1206	111.76
33	39	58.38	38.14	56.46	676	1718	112.92
32	40	59.88	39.14	58.01	675	647	116.01
31	41	60.88	40.14	59.06	680	945	118.13
30	42	61.88	41.14	60.12	684	948	120.24
29	43	63.38	42.14	61.66	683	650	123.32
28	44	69.00	43.14	67.21	.	.	.
27	45	67.30	44.14	65.63	.	.	.
26	46	69.00	45.14	67.36	670	526	134.71
25	47	70.00	46.14	68.40	675	957	136.80
24	48	70.50	47.14	68.96	684	1805	137.91
23	49	73.00	48.14	71.47	.	.	.
22	50	72.00	49.14	70.55	697	1259	141.09
21	51	72.00	50.14	70.60	.	.	.
20	52	74.50	51.14	73.11	.	.	.
19	53	74.50	52.14	73.16	713	1148	146.32
18	54	75.13	53.14	73.83	720	1497	147.65
17	55	75.38	54.14	74.12	.	.	.
16	56	75.88	55.14	74.66	739	2414	149.31
15	57	76.50	56.14	75.31	745	1532	150.62
14	58	77.38	57.14	76.21	750	1102	152.43
13	59	77.38	58.14	76.25	.	.	.
12	60	76.50	59.14	75.42	.	.	.
11	61	79.63	60.14	78.55	766	1287	157.09
10	62	77.50	61.14	76.48	.	.	.
9	63	80.38	62.14	79.35	783	2476	158.71
8	64	80.88	63.14	79.88	790	1903	159.76
7	65	81.50	64.14	80.52	797	1555	161.04
6	66	82.88	65.14	81.91	.	.	.

5	67	81.38	66.14	80.46	.	.	.
4	68	83.13	67.14	82.22	817	1769	164.44
3	69	83.88	68.14	82.99	.	.	.
2	70	84.00	69.14	83.13	832	2192	166.26
1	71	84.25	70.14	83.40	841	3680	166.80

Figure 9. Graph of P wave interval velocity, smoothed interval velocity, and average velocity versus depth in well 299-W15-32.

Figure 10. P wave time-depth curve for well 299-W15-32.

Table 4. S wave velocity table from well 299-W15-32.

Well 299-W15-32

S-Wave Vertical Seismic Profile

GL = 202.627 m TOC = 203.487 m

(Offset = 10.0 m)

Seq.	Depth (TOC)	Pick Time	Depth (GL)	True Vertical Time	Average Velocity	Interval Velocity	Two-way Time
No.	(m)	(ms)	(m)	(ms)	(m/s)	(m/s)	(ms)
70	2.0	51.25	1.14	5.80	196	196	11.61
69	3.0	50.88	2.14	10.65	201	207	21.29
68	4.0	47.13	3.14	14.12	222	288	28.24
67	5.0	44.25	4.14	16.93	245	356	33.85
66	6.0	41.25	5.14	18.86	273	518	37.71
65	7.0	42.00	6.14	21.98	279	321	43.95
64	8.0	43.63	7.14	25.35	282	296	50.71
63	9.0	48.25	8.14	30.46	267	196	60.92
62	10.0	51.13	9.14	34.50	265	248	68.99
61	11.0	53.50	10.14	38.09	266	278	76.18
60	12.0	53.50	11.14	39.81	.	.	.
59	13.0	54.88	12.14	42.36	287	469	84.72
58	14.0	54.25	13.14	43.17	304	1233	86.34
57	15.0	54.50	14.14	44.50	318	754	88.99
56	16.0	55.88	15.14	46.63	325	469	93.25
55	17.0	57.13	16.14	48.56	332	516	97.13
54	18.0	58.88	17.14	50.86	337	436	101.71
53	19.0	61.00	18.14	53.42	340	390	106.84
52	20.0	62.75	19.14	55.62	344	455	111.23
51	21.0	64.88	20.14	58.11	347	401	116.22
50	22.0	66.38	21.14	60.01	352	528	120.01
49	23.0	68.38	22.14	62.32	355	432	124.64
48	24.0	70.13	23.14	64.38	359	486	128.75
47	25.0	72.50	24.14	66.98	360	384	133.96

46	26.0	74.13	25.14	68.88	365	526	137.76
45	27.0	78.13	26.14	72.97	.	.	.
44	28.0	78.13	27.14	73.31	370	451	146.62
43	29.0	80.75	28.14	76.09	370	360	152.18
42	30.0	82.88	29.14	78.39	372	434	156.78
41	31.0	85.50	30.14	81.15	371	363	162.30
40	32.0	87.63	31.14	83.43	373	438	166.87
39	33.0	90.13	32.14	86.06	373	381	172.12
38	34.0	90.75	33.14	86.88	381	1219	173.76
37	35.0	92.13	34.14	88.42	386	652	176.83
36	36.0	93.63	35.14	90.05	390	610	180.11
35	37.0	95.50	36.14	92.04	393	503	184.08
34	38.0	97.25	37.14	93.91	396	536	187.81
33	39.0	96.63	38.14	93.47	.	.	.
32	40.0	98.75	39.14	95.68	409	1129	191.35
31	41.0	99.50	40.14	96.55	416	1146	193.10
30	42.0	99.75	41.14	96.93	.	.	.
29	43.0	104.75	42.14	101.92	.	.	.
28	44.0	104.75	43.14	102.04	423	546	204.09
27	45.0	106.63	44.14	103.99	424	513	207.99
26	46.0	109.25	45.14	106.66	.	.	.
25	47.0	109.00	46.14	106.53	433	790	213.05
24	48.0	110.50	47.14	108.09	.	.	.
23	49.0	110.25	48.14	107.95	446	1410	215.89
22	50.0	111.38	49.14	109.14	450	835	218.29
21	51.0	111.75	50.14	109.59	458	2229	219.18
20	52.0	113.50	51.14	111.39	459	556	222.78
19	53.0	113.88	52.14	111.84	466	2216	223.68
18	54.0	116.88	53.14	114.86	.	.	.
17	55.0	116.63	54.14	114.69	472	702	229.38
16	56.0	118.50	55.14	116.60	473	524	233.20
15	57.0	118.00	56.14	116.17	.	.	.
14	58.0	119.38	57.14	117.59	486	2011	235.19
13	59.0	121.88	58.14	120.12	484	396	240.23
12	60.0	123.25	59.14	121.53	487	710	243.05
11	61.0	123.88	60.14	122.20	492	1477	244.40
10	62.0	124.50	61.14	122.87	498	1503	245.73
9	63.0	124.38	62.14	122.80	.	.	.
8	64.0	125.50	63.14	123.96	509	1839	247.91
7	65.0	126.88	64.14	125.37	512	709	250.73
6	66.0	126.38	65.14	124.92	.	.	.

5	67.0	126.75	66.14	125.33	.	.	.
4	68.0	126.75	67.14	125.37	.	.	.
3	69.0	129.88	68.14	128.50	530	1275	257.01
2	70.0	132.00	69.14	130.64	529	468	261.28
1	71.0	132.63	70.14	131.30	534	1511	262.60

Figure 11. Graph of S wave interval velocity, smoothed interval velocity, and average velocity versus depth in well 299-W15-32.

Table 5. P wave velocity table from well 299-W15-82.

Well 299-W15-82

P-Wave Vertical Seismic Profile

GL = 201.195 m TOC = 201.918 m

(Offset = 5.55 m)

Seq.	Depth (TOC)	Pick Time	Depth (GL)	True Vertical Time	Average Velocity	Interval Velocity	Two-way Time
No,	(m)	(ms)	(m)	(ms)	(m/s)	(m/s)	(ms)
22	1	23.38	0.3	1.18	236	236	2.36
21	2	22.00	1.3	4.98	257	263	9.96
20	3	22.38	2.3	8.56	266	279	17.13
19	4	22.88	3.3	11.71	280	317	23.43
18	5	23.38	4.3	14.35	298	379	28.71
17	6	21.75	5.3	15.06	350	1418	30.12
16	7	21.75	6.3	16.36	384	769	32.72
15	8	24.00	7.3	19.15	380	359	38.29
14	9	26.63	8.3	22.18	373	330	44.36
13	10	27.63	9.3	23.77	390	630	47.53
12	11	27.50	10.3	24.25	424	2088	48.49
11	12	28.25	11.3	25.39	444	873	50.78
10	13	28.13	12.3	25.67	478	3565	51.34
9	14	29.00	13.3	26.79	496	892	53.58
8	15	29.88	14.3	27.88	512	917	55.77
7	16	31.25	15.3	29.40	520	658	58.81
6	17	32.38	16.3	30.68	531	785	61.35
5	18	34.38	17.3	32.76	.	.	.
4	19	34.25	18.3	32.78	557	943	65.59
3	20	34.75	19.3	33.42	.	.	.
2	21	34.75	20.3	33.54	605	2699	67.08

Figure 12. Graph of P wave interval velocity, smoothed interval velocity, and average velocity versus depth in well 299-W15-82.

Figure 13. P wave time-depth curve for well 299-W15-82.

Table 6. S wave velocity table from well 299-W15-82.

Well 299-W15-82

S-Wave Vertical Seismic Profile

GL = 201.195 m TOC = 201.918 m

(Offset = 6.0 m)

Seq.	Depth (TOC)	Pick Time	Depth (GL)	True Vertical Time	Average Velocity	Interval Velocity	Two-way Time
No,	(m)	(ms)	(m)	(ms)	(m/s)	(m/s)	(ms)
22	1	33.50	0.3	1.55	179	179	3.10
21	2	34.75	1.3	7.24	177	176	14.47
20	3	33.63	2.3	11.94	191	213	23.87
19	4	36.40	3.3	17.45	188	181	34.90
18	5	37.00	4.3	21.48	199	248	42.96
17	6	35.13	5.3	23.20	227	580	46.40
16	7	35.63	6.3	25.76	244	391	51.51
15	8	35.25	7.3	27.20	268	694	54.40
14	9	35.75	8.3	28.95	286	572	57.89
13	10	34.13	9.3	28.66	.	.	.
12	11	43.88	10.3	37.90	.	.	.
11	12	48.63	11.3	42.93	.	.	.
10	13	43.88	12.3	39.42	311	382	78.85
9	14	45.88	13.3	41.81	318	419	83.62
8	15	47.75	14.3	44.02	324	452	88.04
7	16	49.00	15.3	45.61	335	630	91.22
6	17	52.63	16.3	49.38	330	265	98.76
5	18	53.50	17.3	50.54	342	864	101.08
4	19	58.13	18.3	55.23	331	213	110.46
3	20	60.25	19.3	57.53	335	435	115.06
2	21	58.88	20.3	56.46	.	.	.
1	22	67.88	21.3	65.33	326	256	130.66

Figure 14. Graph of S wave interval velocity, smoothed interval velocity, and average velocity versus depth in well 299-W15-82. The picks for this well were heavily edited.

Table 7. P wave velocity table from well 299-W15-217.

Well 299-W15-217

P-Wave Vertical Seismic Profile

GL = 203.82 m TOC = 204.82 m

(Offset = 6.0 m)

Seq.	Depth (TOC)	Pick Time	Depth (GL)	True Vertical Time	Average Velocity	Interval Velocity	Two-way Time
No.	(m)	(ms)	(m)	(ms)	(m/s)	(m/s)	(ms)
35	2	23.70	1.0	3.87	259	259	7.74
34	3	24.38	2.0	7.65	262	264	15.30
33	4	23.00	3.0	10.21	294	390	20.42
32	5	23.00	4.0	12.68	316	406	25.35
31	6	23.38	5.0	14.88	336	453	29.77
30	7	23.88	6.0	16.81	357	521	33.61
29	8	25.00	7.0	18.90	370	476	37.81
28	9	26.50	8.0	21.13	379	450	42.25
27	10	26.50	9.0	21.98	410	1167	43.97
26	11	27.25	10.0	23.31	429	756	46.61
25	12	29.00	11.0	25.40	433	477	50.80
24	13	29.38	12.0	26.23	458	1212	52.45
23	14	29.63	13.0	26.86	484	1588	53.71
22	15	30.38	14.0	27.88	502	976	55.76
21	16	30.50	15.0	28.28	531	2506	56.56
20	17	30.88	16.0	28.88	554	1671	57.76
19	18	31.63	17.0	29.79	571	1092	59.59
18	19	33.50	18.0	31.75	567	511	63.50
17	20	34.75	19.0	33.11	574	736	66.21
16	21	36.00	20.0	34.45	581	743	68.91
15	22	37.00	21.0	35.55	591	912	71.10
14	23	38.60	22.0	37.21	591	601	74.43
13	24	40.50	23.0	.	.	.	.
12	25	40.63	24.0	39.39	609	918	78.79

11	26	42.38	25.0	41.19	607	558	82.38
10	27	44.25	26.0	43.10	603	524	86.19
9	28	44.75	27.0	43.66	618	1758	87.33
8	29	46.25	28.0	45.20	619	649	90.41
7	30	47.63	29.0	46.62	622	704	93.25
6	31	49.25	30.0	48.28	622	605	96.55
5	32	50.38	31.0	49.44	627	855	98.89
4	33	51.50	32.0	50.60	632	865	101.20
3	34	54.30	33.0	53.41	618	356	106.81
2	35	55.38	34.0	54.52	624	898	109.04

Figure 15. Graph of P wave interval velocity, smoothed interval velocity, and average velocity versus depth in well 299-W15-217.

Figure 16. P wave time-depth curve for well 299-W15-217.

Table 8. S wave velocity table from borehole 299-W15-217.

Well 299-W15-217

S-Wave Vertical Seismic Profile

GL = 203.82 m TOC = 204.82 m

(Offset = 6.06 m)

Seq.	Depth (TOC)	Pick Time	Depth (GL)	True Vertical Time	Average Velocity	Interval Velocity	Two-way Time
No.	(m)	(ms)	(m)	(ms)	(m/s)	(m/s)	(ms)
35	2	28.63	1.0	4.67	215	215	9.35
34	3	29.63	2.0	9.30	215	216	18.60
33	4	30.88	3.0	13.71	219	227	27.42
32	5	33.63	4.0	18.54	216	207	37.07
31	6	36.38	5.0	23.16	216	216	46.32
30	7	36.13	6.0	25.43	236	441	50.85
29	8	36.75	7.0	27.79	252	423	55.58
28	9	38.50	8.0	30.69	261	344	61.39
27	10	42.13	9.0	34.95	258	235	69.90
26	11	43.13	10.0	36.89	271	516	73.78
25	12	48.00	11.0	42.04	.	.	.
24	13	46.40	12.0	41.42	290	441	82.84
23	14	48.10	13.0	43.60	298	459	87.20
22	15	49.13	14.0	45.09	311	671	90.18
21	16	49.38	15.0	45.79	328	1434	91.57
20	17	51.40	16.0	48.07	333	438	96.14
19	18	52.13	17.0	49.10	346	966	98.21
18	19	53.63	18.0	50.83	354	580	101.66
17	20	55.75	19.0	53.11	358	437	106.23
16	21	59.88	20.0	57.31	.	.	.
15	22	58.80	21.0	56.50	372	592	112.99
14	23	64.38	22.0	62.07	.	.	.
13	24	64.00	23.0	61.89	372	371	123.78
12	25	67.50	24.0	65.45	.	.	.

11	26	67.63	25.0	65.73	380	521	131.45
10	27	69.38	26.0	67.57	385	543	135.14
9	28	71.75	27.0	70.01	386	410	140.02
8	29	73.63	28.0	71.96	389	511	143.93
7	30	75.88	29.0	74.28	390	433	148.55
6	31	77.63	30.0	76.09	394	550	152.19
5	32	81.75	31.0	80.23	386	242	160.46
4	33	83.25	32.0	81.80	391	639	163.59
3	34	85.40	33.0	84.00	393	455	167.99
2	35	88.13	34.0	86.76	392	361	173.53
1	36	88.88	35.0	87.58	400	1228	175.15

Figure 17. Graph of S wave interval velocity, smoothed interval velocity, and average velocity versus depth in well 299-W15-217.

Front Corridor

Stacks

Figure 18. Front corridor stacks from wells 299-W15-32 and 299-W15-217. To find the depth of a reflector on stacked seismic section, the front corridor stack is matched against the seismic section at the well tie point. Because the depth of any reflection (to TD) on the front corridor stack is known from the time-depth tables, interpretations made on the surface seismic data can be reliably converted to depth. Passband 60-300 Hz.

7.2 Seismic Reflection Profiles Acquisition: Results and discussions

7.2.1 Seismic Reflection Acquisition

Four seismic reflection profiles were collected to encompass the Z-9 Crib (Figure 1). These profiles are designated lines Z-9-1, Z-9-2, Z-9-3, and Z-9-4. A single vibrator seismic source and a 120 channel Geometrics Strataview seismograph were used to record the data. Because the caliche layer at the top of the Ringold Formation is a strong acoustic boundary and is near the DNAPL contaminated layers, the seismic acquisition parameters were chosen to optimally image this interval. Other considerations included having adequate temporal and spatial sampling necessary for high-resolution recording and to attenuate acoustic noise. The parameters used to record the 2-D seismic profiles are listed in Table 9.

Test records indicated that ground roll is a severe problem in this area and is present throughout the recording band. The requirement to do high-resolution recording, however, prohibited the use of source and receiver arrays used normally to attenuate ground roll. Consequently, data processing techniques and a lowering of the vibrator drive level helped to attenuate ground roll.

The receiver group spacing and shot interval were set at one meter (3.05 ft) and three geophones were bunched at each recording station. This arrangement resulted in 60 CMP fold data nominally. Shorter group and shot intervals were impractical because the footprint of the vibrator pad was approximately one meter (3.05 ft). To reduce the effect of wind noise each geophone was buried approximately 15 cm (6 inches) deep. The spread was designed to have equal numbers of positive and negative offsets after NMO muting on the caliche layer; however, because of the low velocity of the overburden the fold of the target reflector is only about 30. An asymmetric split spread recording geometry was used because a symmetric split-spread would yield little velocity information on the deeper layers.

After extensive field testing the vibrator sweep was set at 30-300 Hz for six seconds and six sweeps were summed per VP. The test program indicated that higher frequencies were not returned from the target horizon. The low frequencies were needed to image deeper layers and to stabilize residual statics computations and deconvolution operators. The 300 Hz high-end of the sweep, if returned from the subsurface, results in approximately one meter vertical resolution at the level of the Plio/Pleistocene-Hanford Fine contact. The Vibroseis data were recorded uncorrelated. This allowed the flexibility to correlate the data with a synthetic sweep and for more data processing options.

Table 9. Summary of seismic reflection profile recording parameters.

Type of survey	P wave seismic reflection
Station interval	1 meter
Source	Industrial Vehicles International (IVI) MiniVib high-frequency vibrator 12000 lb. peak force.
Source interval	1 meter on half stations
Type of sweep	Linear
Sweep frequencies	30 to 300 Hz
Sweep length	6 seconds
Source Offset (Pad)	1.5 m nominal
Record Length	7 seconds
Listen time	1 second (7 s RL – 6 s sweep)
Recording instrument	Geometrics RX 24 bit A/D resolution
Number of channels	120
Instrument Gain	48 dB fixed
Field Correlator	None
Sample interval	0.5 millisecond
Data format	SEG-2
Data redundancy	60 Fold
Geophones	Geospace 40 Hz vertical 3 per station
Near offset	0.5 m (inline), 1.58 m (straight line)
Far offset	40.5 m, 78.5 m
Cable Geometry (m)	40.5'--0.5'--VP--0.5'--78.5'

7.2.2 Seismic Reflection Data Processing Discussion and Results

During seismic acquisition data were processed to brute stack sections daily for QA/QC purposes. The term “brute stack” is used to mean a stack section with no field or residual statics and with only a few velocity analyses performed. These sections were essential to ensure that survey objectives were being met and that the data quality was consistent throughout the survey. The platform used to process the data in the field was a 333 MHz, 128 MB RAM Dell laptop computer with 15 GB of internal and external disk space operating under Microsoft Windows NT. The computer was equipped with the Seismic Image Software, Ltd. VISTA seismic processing package and the Seismic Micro-Technology Kingdom seismic interpretation software

After completion of the field survey extensive detailed seismic data processing was performed at ESRI-USC’s Environmental Geophysics Laboratory on the campus of the University of South Carolina. To process the data the Landmark Graphics Corp. state-of-the-art ProMAX software operational on a Sun Microsystems Ultra-60 workstation was used. The generalized flow used to process the data is shown in Figure 19.

The data processing effort was directed towards imaging the subsurface from the middle of the Hanford Fine Formation where DNAPL contamination is known to exist to the caliche layer at the top of the Ringold Formation. The processing parameters determined in the field were used as a starting point for the laboratory processing. Data processing began with the raw uncorrelated field data because of the greater stability of the ProMAX algorithms compared to the PC software. Differences between the infield data processing and the laboratory data processing effort include: greater numbers of velocity analysis locations, surface consistent amplitude scaling, surface consistent deconvolution, refraction statics, surface consistent automatic residual statics, spectral whitening, and FX deconvolution.

The field data processing revealed that a major problem existed with surface wave energy in this area to the extent that no reflections are visible in the raw correlated field records (Figure 22). Only after deconvolution, spectral whitening, and low-cut bandpass filtering are reflections visible (Figure 20). Experiments with F-K and Tau-p two-dimensional filtering techniques to attenuate surface energy were only partly successful and resulted in significantly lower frequency content. The only two-dimensional filtering technique to yield acceptable results was a simple center weighted 3 trace by 3 sample mix. This intrashot mix was applied to all the shots.

Refraction statics were computed and applied to three of the lines. Refractions could be picked for only about half the shots on line Z-9-4. On this line the loss of refraction energy is probably caused by a near surface velocity inversion. The application of automatic residual statics proved to be critical to the quality of the stack sections. Because of the low signal-to-noise ratio of the data, the maximum stack power technique was used and the maximum allowable static shift was set at 3 ms. The optimum residual statics computation gate was found to be 160 ms centered on the caliche layer and the pilot trace was an 11 trace sum.

To enhance the continuity of the stacked data, a 3 pt trace mix and FX deconvolution were applied. The data were migrated using a finite difference technique and filtered to a 60-280 Hz passband in the area of the interest. For interpretation purposes the sections are displayed at a datum

of 205 m (672.6 ft.) using a datum correction velocity of 1000 m/s (3281 ft/s).

Seismic Data Processing Flow

Figure 19. Diagram showing the data processing sequence followed to produce seismic sections for structural/stratigraphic interpretation.

Raw and Processed Field Record

Figure 20. Raw and processed field record from line Z-9-1. Top figure is a raw field file. Note the strong ground roll and hint of a reflection at 50 ms. Bottom figure is top figure after preprocessing was applied. After preprocessing ground roll is attenuated and reflection events are clearer. AGC 200 ms.

8.0 Conclusions

During this reporting period the Z-9 crib at the 200 west area at DOE Hanford was selected for this study. After the site visit and evaluation of existing data at the 200 west area, vertical seismic profiles were conducted in three wells to obtain p-wave and s-wave velocities and a neutron density log was also run in one well for density information which was used in the AVO modeling. Base upon the P-wave and S-wave velocities as well the density information if carbon tetrachloride replaces air in the pore spaces there is an effect of the seismic amplitude. The amplitude changes are not true AVO anomalies but rather a amplitude decrease (Hanford fine-Plio-Pleistocene) or amplitude increase (Plio-Pleistocene- caliche) when carbon tetrachloride is introduce into the pore spaces.

The process data seismic has numerous reflectors and during the interpretation part the project will calibrated the reflectors to the different geologic contacts.

9.0 References

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