**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 Dense Nonaqueous Phase Liquid (DNAPL) carbon tetrachloride (CCl_4) contamination at the 216-Z-9 crib, 200 West area, Department of Energy (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 towards site characterization and direct free-phase DNAPL detection.

This report covers the results of Task 3 and change of scope of Tasks 4-6. 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. Task 4, 5, and 6 were designing, acquiring, processing, and interpretation of a three dimensional seismic survey (3D) at the Z-9 crib area at 200 west area, Hanford.

During the commission of Tasks 1 and 2, four seismic reflection profiles were collected and processed. Task 3, the interpretation of these data, is in two parts. Part one is the construction and interpretation of structure contour maps of the contact between the Hanford Fine unit and the underlying Plio/Pleistocene unit and of the contact between the Plio/Pleistocene unit and the underlying caliche layer. These two contacts were determined to be the most likely surfaces to contain the highest concentration CCl_4 . Part two of the interpretation used the results of the AVO modeling to locate any seismic amplitude anomalies that might be associated with the presence of high concentrations of CCl_4 .

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). This situation is borne out by field observations. In areas where extraction wells have high concentrations of CCl_4 a corresponding dim-out is noted on the 2-D seismic data. 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). On the 2-D seismic data the amplitude along the Plio/Pleistocene-caliche contact increases in areas where well control indicates high concentrations of CCl_4 occur.

Based upon the results of Task 3, it appears likely that AVO seismic techniques can be used to detect high concentrations of CCl_4 . However, this conclusion is predicated upon the assumption that the seismic models are correct. As a cautionary note, some of the model parameters were, by necessity, based upon mathematically derived results. It became clear after the 2D survey that the 3D seismic survey could not be completed, because the area of high concentration of carbon tetrachloride was under numerous buildings, therefore it was decided to rescope the project. The new scope of work was to drill and core a new well and use the samples for a core flood study to verify the AVO modeling. To verify the models the velocity and density values used from the CCl_4

saturated material.

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1.0 Introduction

This report is for Task 3, data interpretation, project DE-AR26-98FT40369 and the rescoping of Tasks 4-6. After the success of using high-resolution seismic reflection surveying and applying amplitude versus offset (AVO) analysis to image Dense Nonaqueous Phase Liquids (DNAPL) in the subsurface at the Department of Energy (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 the cost of drilling a well in the 200 West area and budget constraints, a new well could not be drilled.

It became clear after the 2D survey that the three dimensional (3D) seismic survey could not be completed in the area of high concentration of carbon tetrachloride due to the numerous buildings, it was decided to rescope the project. The new scope of work included drilling and coring a new well and using the samples for a core flood study to verify the AVO modeling study (see Appendix A). To verify the models, the velocity and density values were to be gathered from CCl_4 saturated material obtained from the core flooding study. After four months it was determined that the cost of new well was prohibitive in addition obtaining free release of any samples for offsite analysis could not be granted. Therefore the discussions with DOE it was decided the project team would have to locate a new site. It was decided to rescope Tasks 4-6 so that a new site could be investigated (see Appendix B).

2.0 Executive Summary

This report is for Task 3, data interpretation and the rescoping of Tasks 4-6 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 3 dealt with the processing of the four seismic lines and interpretation of the 2-D data. This report contains the interpretation portion of Task 3. The quality of the seismic data was good and two principal horizons were mapped on the seismic lines. The first horizon is the contact between the Hanford Fine and the Plio/Pleistocene. The second horizon is contact between the Plio/Pleistocene and the caliche layer. Existing well data indicates that these two layers are located where the highest concentrations of CCl_4 are found.

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. 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 results of the Hanford Fine and the Plio/Pleistocene contact, there should be a high amplitude reflection (positive reflection coefficient) at the contact except where there is no CCl_4 saturating the Hanford Fine. However, if the Hanford Fine is saturated with CCl_4 , the seismic amplitude should decrease to a negative reflection coefficient. On the seismic line Z-9-1 a south to north line located on the west side of the crib at well 299-W15-217 there is "dim-out" along the contact of the Hanford Fine with the Plio/Pleistocene. At well 299-W15-217 the highest concentrations of CCl_4 at the Hanford Fine and Plio/Pleistocene contact have been reported. At the Plio/Pleistocene-caliche contact the highest CCl_4 concentrations are in wells 299-W15-32, 299-W15-218 and 299-W15-219. These wells are located on seismic line Z-9-2 an east to west line located on the north side of the Z-9 crib. In the vicinity of line Z-9-2 at the Plio/Pleistocene-caliche contact there are areas where there is a substantial increase in seismic amplitude (positive reflection coefficient) which correspond to areas of high concentrations of CCl_4 . On seismic lines Z-9-3 a

south to north line located on the east side of the crib and line Z-9-4 a west to east line located south of the Z-9 crib, there appears to be an absence of seismic anomalies associated with the presence of high concentrations of CCl_4 . There are also no reported areas of high concentrations at either the Hanford Fine-Plio/Pleistocene contact or at the Plio/Pleistocene-caliche contact along these two seismic lines.

Based on the modeling, the surface seismic data imaged 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. It is recommended that either a new well be drilled or an existing well deepened so that core samples from the Hanford Fine unit, Plio/Pleistocene unit, and caliche layer can be taken. The core samples can be flooded with differing saturations and concentrations of CCl_4 and the P wave velocity, S wave velocity, and densities will be measured after each flood. Once that has been completed, the new values will be used to model the data. If the models remain the same, it can be concluded that this seismic technique can be used to image high concentrations of CCl_4 .

It became clear after the 2D survey, the 3D survey could not be completed, because the area of high concentration of carbon tetrachloride was located under numerous buildings. Therefore it was decided to rescope the project. The new scope of work was to drill and core a well and use the samples for a core flood study to verify the AVO modeling. To verify the models the velocity and density values used for CCl_4 saturated material would be obtained from core flooding studies. After four months it was determined that the cost of new well was prohibitive and that the project team would have to locate a new site. It was decided to rescope Tasks 4-6 so that a new site could be investigated.

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.

4.0 Project Accomplishments

- Task 3 was completed. The seismic data was able to map the contact between the Hanford fine and the Plio-Pleistocene and the lower contact between the Plio-Pleistocene and the caliche layer. Base upon the modeling results and exiting data on carbon tetrachloride concentrations, the contact between the Hanford fine and the Plio-Pleistocene show have a decrease in seismic amplitudes and the seismic data indicates a decrease or dimming of the seismic amplitudes in the area reported to have the highest concentrations. The contact of the Plio-Pleistocene and caliche layer the modeling indicated a dramatic increase in seismic amplitudes in the zones of highest concentrations

of carbon tetrachloride and the seismic data indicates a increase in amplitudes in the area reported to have the highest concentrations of carbon tetrachloride.

- Rescope Tasks 4-6 for the core flood study (see Appendix A).
- Rescope Tasks 4-6 to investigate a new site which is the DOE Paducah Site in Paducah, Kentucky.

5.0 Problems

It has now become apparent that the revised scope of work for the core study will not occur. This is because we have been unable to obtain free release of core samples to a lab outside of the Hanford complex boundaries. We were informed that because the samples were coming from an area suspected to be contaminated with radionuclides, we would have to send the samples to a certified lab for analysis. We located a such a lab at the Lawrence Livermore National Laboratory. We notified Hanford that we had located a certified lab, but was then informed that the samples could not leave the Hanford site; thus, the lab would have to relocate to Hanford. At this point, and after conversations with Tom Hicks (SUBCON) and Richard Bush at NETL, we again changed the project scope. The revised project scope is in Appendix B. It must be noted that the project was on hold for 4 months waiting on a decision.

6.0 Experimental

Not applicable to this report.

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

7.0 Results and Discussion: Seismic Interpretation

Phase one of the interpretation was to determine which reflectors correspond to the Plio/Pleistocene boundary and the caliche zone. The significance of these reflectors is that the DNAPL tends to accumulate in the vicinity of these two levels in the subsurface. A VSP was acquired in well 299-W15-32 (Figure 2) to establish a tie between the geologic units and the seismic events present in the survey data. The seismic lines were planned to tie wells in the vicinity of the crib (Figure 1) that have high concentrations of CCl_4 .

7.1 *Stratigraphic and Structural Interpretation*

7.1.1 *Seismic Line Z-9-1*

Seismic Line Z-9-1 was shot from south-southeast to north-northwest along the west side of the crib (Enclosure 1). Two events were interpreted on the line. The green event at approximately 0.120 s corresponds to the top of the Plio/ Pleistocene boundary (Base of the Hanford Fine). The event is somewhat discontinuous, but mappable. Average depth to this unit is approximately 37 meters (121 ft.). The data indicates incisement of this event by the overlying Pleistocene Hanford Fine unit. The Hanford Fine interval on line Z-9-1 has a channel incised into the Plio-Pleistocene from shot point (SP) 183 to SP 241. The depth of incisement is approximately 16 ms (3-4 meters (10-13 ft.)).

The blue event is the top of caliche marker. It roughly corresponds to the Pliocene aged Ringold Formation and based on interpretation of the geologic data is most likely the surface upon which the DNAPL is resting. It is a high amplitude event that is mappable over the entire survey. Amplitude intensity drops in the vicinity of the channel from SP 166-196. Downcutting by the overlying Plio/Pleistocene appears to have occurred from SP 163 to the end of the line making the south end of the line structurally higher. However, the overall dip direction is from north to south.

The Plio/Pleistocene interval displays a rather uniform parallel reflection pattern indicative of deposition in a lower energy environment. This unit more than likely was a fill unit consisting of silts and clays deposited during a low energy fluvial cycle. The Upper boundary displays erosional truncation being truncated by the overlying Pleistocene Hanford Fine. Downlap occurs on to the top surface of the Plio/Pleistocene.

7.1.2 *Seismic Line Z-9-2*

Seismic line Z-9-2 was shot from east to west along the northern boundary of the crib area and intersects lines Z-9-1 and Z-9-3 (Figure 1). The green marker (Enclosure 2) is the top of the top of the Plio/ Pleistocene boundary. The event on this line is more continuous than on line Z-9-1. Average depth to this unit is 36 meters (118 ft.). A channel is incised into the Plio/ Pleistocene boundary from SP 109-165. The horizon is generally flat across the line. Interval characteristics of the Plio/Pleistocene are similar to line Z-9-1 displaying flat lying concordant internal events. The

Top of Caliche (Blue event, Enclosure 2) is a high amplitude event and continuous across the section.

Figure 2. VSP correlation from well 299-W15-32 with seismic line Z-9-2 at shot point 208.

7.1.3 Seismic Line Z-9-3

Seismic Line Z-9-3 is a north-south trending profile east of the crib and intersects Z-9-2 and Z-9-3. The green event is the Plio/Pleistocene (Enclosure 3). The event is discontinuous, but mappable along the line. Average depth to the Plio/Pleistocene is approximately 34-35 meters (112-115 ft.). A significant channel is present down cutting into the Plio/Pleistocene from SP 236-SP 406. The channel has a maximum thickness of 21 ms (approx. 33 meters (108 ft.)). From SP 279-311 the channel has removed almost the entire Plio/Pleistocene section nearly erodes through the caliche zone into the Ringold Formation (Enclosure 3). The green event has an overall dip direction from south to north of approximately 3 meters (10 ft.). The Blue event is the top of caliche. The event is continuous and has high amplitudes across the section. Approximately 3-4 meters (10-13 ft.) of dip from north to south occurs along the line.

7.1.4 Seismic Line Z-9-4

Seismic Line Z-9-4 is an east-west trending line south of the crib and intersects lines Z-9-1 and Z-9-3. The green event (Enclosure 4) is the top of the Plio/Pleistocene and dips from east to west approximately 10 meters (33 ft.). The event is very discontinuous, but still mappable along the line. A channel is incised beginning at SP 252 and continues west to the end of the line. The maximum thickness of the channel is 34ms (11 meters (36 ft.)) and occurs near the end of the line at SP 113. The Blue event (Enclosure 4) is the top of the caliche. This horizon dips from east to west very gently. The amplitude of the event is high and is mappable the entire length of the line. The Pleistocene channel has almost completely removed the overlying Plio/ Pleistocene unit which nearly wedges out at the west end of the line.

7.2 Structural Interpretation

Structure contour maps were generated on two horizons, the Plio/ Pleistocene (green event, and the top of Caliche (blue event). The channel downcutting into the Plio/Pleistocene surface is readily apparent on the structure contour map on top of the Plio/Pleistocene(Figure 3). A structural high is located on line Z-9-1 at SP 340. The surface dips off to the north and northeast from this high (Figure 3). A structural high also exists on the southern end of Line Z-9-3. Most of the relief on this surface is caused by the erosion at the channel in the overlying unit that bisects the map area. The movement of DNAPL in the subsurface is more dependent on structure than groundwater flow. Given the location of the source of entry for the solvents into the ground, the most likely flow direction for DNAPL would be to the north and northeast of the Plio/Pleistocene high present on line Z-9-1 (Figure 3).

A similar structural picture is observed on the Top of caliche map (Figure 4). A structural high exists on line Z-9-1 near the tie with line Z-9-2. The geologic characteristics of this surface would indicate that this would be the most likely place for the DNAPL to collect. Any DNAPL

flowing along this surface, assuming that crib is the source, would be by gravity flow to the north and northeast.

Figure 3. Structure contour map in time on top of Plio/Pleistocene.

Figure 4. Structure contour map in time, top of caliche.

7.3 *Direct Detection of DNAPL*

At the 200 W area the DNAPL present consists of carbon tetrachloride (CCl_4). The solvent is present both in the vadose zone as well as in the water table. Carbon tetrachloride is found throughout the 65 meter (213 ft.) thick vadose zone (Rohay et al., 1994). Rohay and others (1994) states that the highest concentrations of CCl_4 are associated with the Hanford Fine and the Plio-Pleistocene units located approximately 35-40 meters (115-131 ft.) below ground surface.

Based upon the modeling presented in this report an amplitude anomaly should be present along the Plio/Pleistocene and top of caliche horizons where DNAPL is present. Differences in the amplitude values do exist, however. The amplitudes along the Plio/Pleistocene event decrease due to the presence of CCl_4 . The top of caliche event in contrast, displays a significant increase in amplitude when CCl_4 is present. Each line was taken through a standard processing scheme to generate the sections used for structural interpretation. To enhance the amplitude increase due to the presence of DNAPL along the top of caliche an additional processing step was taken. Each line was processed to enhance amplitude increases. Taking each trace and replacing each sample amplitude value by 10 raised to the power of the amplitude of the sample accomplished this. In effect this step had the effect of boosting the high amplitude data exponentially while suppressing the low amplitude values. This enhancement suppressed the amplitude of the events where no DNAPL was present and increased the amplitude of the reflecting horizon where CCl_4 is present.

The interpretation of the Plio/Pleistocene event was made on the standard processed sections. No enhancement was necessary to identify the decrease in amplitude (dim-out) along this event.

7.3.1 *Plio/Pleistocene*

Amplitude maps were created on two horizons, the Plio/Pleistocene and the top of caliche reflectors. Amplitude values along these surfaces were picked and contoured to allow interpretation of the data for DNAPL distribution.

Figure 4 is a contour map of the amplitudes at the top of the Plio/Pleistocene horizon. Modeling of this horizon shows that in the presence of CCl_4 , the amplitude along this event should be reduced, i.e. a dim-out. Areas of dim-out are represented by the green and blue colored areas.

A significant dim-out along the Plio/Pleistocene event exists from shot point 345-398 (Enclosure 1, Figure 4) on Z-9-1. A secondary anomaly exists from SP 200-220 northeast of well 299-W15-36. Line Z-9-2 (Enclosure 2, Figure 4) displays low amplitude values from SP 155-190. Line Z-9-3 (Enclosure 3, Figure 4) displays low amplitude from SP 250-320. Line Z-9-4 (Enclosure 4, Figure 4) has no dim-outs present the length of the line.

In general, these areas are located under the crib, to the east of the crib and west of the crib. These reduced amplitude zones are located in structural lows along the surface of the Plio/Pleistocene (Figure 3).

7.4 *Top of Caliche*

7.4.1 *Z-9-1 Enhanced Amplitude Stack*

Enclosure 5 is the enhanced amplitude stack for Z-9-1. Significant amplitude anomalies exist on line Z-9-1 along the Top of caliche event. An anomaly exists from SP 379-426 at 121 ms, from SP 346-360 at 123 ms and from SP 270 –306 at 125 ms. A minor anomaly exists from SP 128-164 at 123 ms. Amplitude increases are seen in the interval between the Plio/Pleistocene (green event) and the caliche (blue event) boundaries.

According to Rohay and others (1994) well 299-W15-217 had the highest measured CCl₄ concentrations present in the subsurface of the area (37,817 ppb) at a depth of 34.7 meters (114 ft.), the Plio/Pleistocene event (green). This corresponds to one of the significant amplitude anomalies present on line Z-9-1 from SP 346-360 at approximately 120 ms (Enclosure 5).

7.4.2 *Z-9-2 Enhanced Amplitude Stack*

Enclosure 6 is the enhanced amplitude stack for Z-9-2. Significant amplitude increases exist on Z-9-2 from SP 114-152, SP 154-219 and SP 226-261 at approximately 127 ms. This corresponds to near the top of caliche reflector. Amplitudes in general are significantly higher along this profile and are vertically more extensive than on Z-9-1. These amplitudes along with the areal extent suggest that significant DNAPL is present along this surface.

Well 299-W15-218 projects into an amplitude anomaly on Line Z-9-2 at SP 209 and well 299-W15-219 projects into the end of an anomaly on Z-9-2 at SP 260. Wells 299-W15-218 and 299-W15-219 yielded CCl₄ concentrations of 15,794 ppb at 33.5 m and 11,688 ppb at 34.9 m (114.5 ft.) respectively. These depths are in good agreement with line Z-9-2 for the interval between the Plio/Pleistocene and the top of caliche reflectors.

7.4.3 *Z-9-3 Enhanced Amplitude Stack*

Enclosure 7 is the enhanced amplitude stack for Z-9-3. Z-9-3 is located east of the crib area. A major increase in amplitude exists on Z-9-3 from SP 351-400 along the top of caliche reflector. To the south along the line an amplitude increase exists from SP 114-204 within the Ringold Formation, but above the water table. The significance of this amplitude anomaly is not known at this time.

7.4.4 *Z-9-4 Enhanced Amplitude Stack*

Enclosure 8 is the enhanced amplitude stack for Z-9-4. The line is located to the south of the crib area. Z-9-4 displays no amplitude anomalies along the line at any horizon. This would indicate that there is no DNAPL present along the profile.

Figure 5. Contour map of amplitude values Plio/Pleistocene.

7.5 *Integrated Interpretation*

Figure 5 is the amplitude map on the top of the caliche reflector. Based on the modeling, a high amplitude event at the top of the caliche is associated with the presence of DNAPL. Amplitude values on the caliche surface represented by the red and yellow are the highest along line Z-9-2 and are projected to run to the north of the area. A large area represented by the area colored green also displays an increase in amplitude over background. Under assumption that an increase in amplitude indicates DNAPL, CCl_4 in free-phase has collected along the top of caliche in this location. No evidence exists for the presence of DNAPL south and east of the crib in the area colored blue at this horizon.

Figure 6 is a contour map of the average concentration of CCl_4 in the Plio/Pleistocene-caliche interval in the crib area. Information from five wells, 299-W15-216, 299-W15-217, 299-W15-218, 299-W15-219, and 299-W15-220 were collected and averaged over the interval represented by the Plio/Pleistocene and gridded. Figure 28 displays the result of the gridding and contouring. Areas of high concentration of CCl_4 in the interval are represented by red values. Areas of low concentration are in shades of blue. The northwest area of the map (the area encompassing wells 299-W15-217, 299-W15-218, 299-W15-219) falls within the zone of high concentration. This agrees well with the amplitude anomaly maps of the top of Plio/Pleistocene (Figure 4) and top of caliche (Figure 5). The area directly under well 299-W15-218 is an overlay on all maps.

The seismic data showing the position of free-phase CCl_4 in the subsurface agrees well with the known concentrations based on well data. Modeling results indicate that a dim-out in amplitudes should be present along the top of Plio/Pleistocene event where CCl_4 with an increase in amplitude along the top of caliche surface.

Based on the close agreement of the seismic and the well data, a prediction of the location of free-phase CCl_4 can be made with reasonable confidence at the caliche event. The event when enhanced yields a distinctive anomaly that can be mapped with high confidence.

Figure 6. Contour map of the amplitude values top of caliche surface.

Figure 7. Carbon tetrachloride isoconcentration map.

8.0 Conclusions

- The results from Tasks 1, 2, and 3 appear to be promising insofar as accomplishing the task objectives.
- The data quality from the high-resolution reflective P wave seismic surveys provides continuous subsurface data between existing wells for the mapping of possible potential preferential pathways for carbon tetrachloride migration.
- The seismic data provides continuous data about the structural and stratigraphic features of the contacts between Hanford Fine and the Plio/Pleistocene and Plio/Pleistocene and caliche. However, it must be noted that seismic data has to be calibrated with well data either with VSP or a sonic log that can be converted into a synthetic seismogram.
- Based upon the models of reflection coefficient versus angle of incidence it appears that the seismic amplitudes are responding to the presence of high concentration of carbon tetrachloride. Based upon the modeling results along the contact of the Hanford Fine and the Plio/Pleistocene, where there is high concentration of CCl_4 the seismic amplitudes decrease i.e., a dim-out occurs. This is clearly evident on the contour map of the top of the Plio/Pleistocene reflection amplitudes. The models generated for the Plio/Pleistocene-caliche contact with the Plio/Pleistocene saturated with CCl_4 indicated that along the contact the seismic amplitudes show a noticeable increase. The amplitude map for the top of caliche indicates very high amplitudes in the area where there is high concentration of CCl_4 on top of the caliche.
- Assuming the models are correct and the seismic data appear to correlate where there is the indication of high concentration of CCl_4 and where there are not high concentration of CCl_4 . This assumption may not be correct. The velocities and densities for a fluid filled rock were mathematically derived using Gassmann's equations.
- In order to validate the model, core samples from the Hanford Fine, Plio/Pleistocene, and the caliche layer should be used in a core flood study. The study would involve flooding the cores with various saturations and concentrations of CCl_4 . At each different saturation, the changes in the P wave and S wave velocities and densities can be measured. These values are then used to compute new AVO curves. If the curves are the same, then this technique can be used at the Hanford site as well as other DOE sites where there is a significant DNAPL problem.
- Due to the problems with obtaining free release of any core for offset analysis another site with different geologic conditions is selected. The new site is DOE Paducah, Paducah, Kentucky.

9.0 References

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Appendix A

Scope of Work

The University of South Carolina completed a surface geophysics survey using seismic reflection in March of 1999 at the 200-ZP-2 carbon tetrachloride site. The purpose of the survey was to use seismic technology to aid in the identification of dense non-aqueous phase liquid (DNAPL) (carbon tetrachloride) in the subsurface. Evaluation of the seismic data has identified high amplitude responses that may indicate DNAPL. To refine the seismic interpretation and to help confirm the detection of DNAPL, USC requests the collection of continuous split spoon samples near the 216-Z-9 Crib and administrative and field support for geophysical logging in a vadose zone well. These activities should be performed near the 216-Z-9 Crib because of the previous seismic work done in this area (providing correlation between the seismic, sediment and geophysical data) and the high probability of DNAPL in the subsurface (this was the major CCl₄ disposal site).

Description of Work

Initial field activities consist of taking continuous split spoon samples from the Hanford Fine to below the Plio-Pleistocene unit. The planned location of sample collection is at existing well 299-W15-84 situated on the west side of the 216-Z-9 Crib (Figure 1). This well is perforated in the Hanford Fine. A seismic line was situated in close proximity to this well, so these samples can be used to confirm site stratigraphy and geophysical characteristics of these sediments interpreted in the seismic data.

The second phase of field work consists of conducting borehole geophysics measurements across the continuously sampled interval. Geophysical tools measuring S and P wave velocities and a neutron density log will be run inside the water-filled casing. Potable water will be used inside the casing.

Well 299-W15-84 has 8-in carbon steel casing perforated from 75 to 90 feet below ground surface (Figure 1). The split spoon samples will be collected by deepening this well to 120 feet below ground surface. Because this well may also be used to support a vadose zone partitioning inter-well tracer test at a later date, the well may be reconfigured after completion of this work in anticipation of the tracer test. An as-built of the reconfigured well, after sampling and logging, is shown in Figure 3. The general procedure for collecting the samples and performing the downhole geophysics measurements will be as follows:

Perforate the 8-inch casing from 104 ft to 110 ft in well 299-W15-84. The bottom of the casing is at 110 ft.

Set a packer above this interval and pressure grout (cement with 6% bentonite) the perforated interval. The cement will isolate the upper perforated interval (75 to 90 ft) from the lower drilled section of borehole. Remove the packer.

Advance a 6 5/8-inch casing inside the 8-inch casing to within 5 ft of the water table. The casing will be driven after each split spoon sample is collected or after split spoons are collected at predetermined depths. The objective is to minimize the open area outside the 6 5/8-inch casing,

which will provide a better geophysical response.

At the target depth, backpull the casing 5 ft and squeeze cement from the bottom of the well to 5 ft inside the casing (10 ft overall). This should make the casing watertight at the bottom, so that the casing can be filled with water for the geophysical logging.

Borehole geophysical surveys will then be run in a water-filled borehole to measure formation S and P wave velocities. A compensated neutron-density log will also be used. An off-site contractor will perform this activity. USC personnel will set up the geophysics contract and arrange to have the contractor on site at the specified time for logging. USC personnel will work with BHI personnel to arrange for contractor access to the Hanford Site.

Upon completion of this phase of testing, water from the casing will be bailed from the well following ERC disposal procedures. An additional set of perforations may be placed at this time below the Plio-Pleistocene unit in preparation for the later vadose zone gas tracer test. The final configuration will then provide access to the upper part of the vadose zone in the annulus between the 8- and 6-inch casings, and the lower vadose zone inside the 6-inch casing. A spot of bentonite can be tremied between the two casings if deemed necessary to seal the bottom of the 8-inch casing.

Alternate Work Approach. If technical limitations and risks associated with the above work activities are not acceptable, and additional money is available, then a new well may be installed and completed instead of using well 299-W15-84. This well will be located near the 216-Z-9 Crib with the final location and well completion details agreed upon by both BHI and USC personnel, but assumed to be equivalent to the reconfiguration described above for well 299-W15-84.

A drilling contract will be setup by BHI for installation of the new well. The same continuous sampling procedure will be followed from above the contact between the Hanford fines and the Hanford sands, to below the Plio-Pleistocene unit near the water table. This well will be completed initially with a leak free casing, so that borehole geophysics can be conducted in water filled casing. After removing water from the casing, the well will be reconfigured for other purposes such as the tracer test. Formation samples may also be collected during installation of the new well for laboratory tests to support later tracer tests.

Description of Laboratory Work

Analysis of the continuous split spoon samples will require free-release of the samples to an offsite laboratory for testing. USC personnel at the drill site will determine which sample portions will be shipped to the laboratory for testing. It is assumed that by sampling and testing the top and bottom portions of the sample for radionuclides, the central portion of the sample is non-radioactive and can be sent to an offsite non-rad licensed laboratory (e.g., Houston, Texas). Laboratory tests will consist of flooding the samples with fluid (water-contaminant) saturations of 10, 20, 30, 40, 50 and 100% of the pore space. The fluid will consist of water with dissolved carbon tetrachloride at concentrations at 10, 100, 500 mg/L, and a pure solution. After each saturation flood, the density, P-wave, S-wave, velocities of the samples will be measured under 10 bars of confining pressure.

Potential Risks and Limitations

State approval for a temporary well completion that does not meet WAC standards, and for adding water to the well casing, will have to be obtained. There is a possibility that some of the potable water could be lost to the vadose zone. If this occurs, movement of contaminants is possible.

Any loss of water is not expected to affect movement of residual DNAPL, which does not migrate under a small-unsaturated hydraulic head, though some dissolved carbon tetrachloride may move. Even if contaminated water were to reach the aquifer, it would be captured by extraction well 299-W15-32 located to the northeast.

Shipment of the samples off-site will require a free-release for the samples because of potential radiological contamination. Subsurface samples in this area have the potential for containing radionuclides of at least plutonium and americium, which were disposed to the 216-Z-9 Crib. In order to obtain a free-release, the integrity of the samples may be compromised on the ends. By using 5-ft split spoons and at least two 6-inch liners, an internal radiation count can be conducted on the two end sections. If clean, it would be assumed that the intermediate portion of the sample is also clean and could be shipped to the laboratory.

Appendix B

Statement of Work

There are two objectives for this research effort. The first objective is to further demonstrate the feasibility of detecting DNAPL plumes in the subsurface with a minimum of disturbance to the site. Under this part of the contract (proof of concept), the DOE Paducah, Kentucky site is to be investigated for suitability of the seismic reflection technique. The work will be conducted at Paducah via a series of three tasks. Task 1 will consist of a site investigation. Tasks 2 will consist of acquisition of approximately 1200 feet or 1200 shots of 2D seismic reflection data designed to image areas of probable high concentration of DNAPL. Task 3 will comprise processing and interpretation of the seismic data acquired under Task 2.

The second objective is to test the feasibility of using AVO techniques as a monitoring tool on a dynamic underground stripping (steam flood) project at the Savannah River Site, South Carolina M-Area solvent tanks. This part of the project will consist of the acquisition of approximately 480 feet of seismic data across a known DNAPL plume prior to the steam flood. Once the steam flood is complete, we will reoccupy the same location and gather a second set of data to compare to the original pre-steam flood data. If the AVO anomaly is reduced in size or has disappeared as a result of the steam flood, this would indicate that seismic reflection methods can be utilized to monitor the efficiency of dynamic underground stripping to mobilize DNAPL. If additional monies become available, intermediate monitoring will be done during the steam flood. This part of the project will only involve Tasks 2 and 3.

Task 1.0: Site Evaluation

Project personnel will visit the site to be investigated and collect all required subsurface information pertaining to DNAPL location and distribution. This will also include collection of any existing P wave and S wave velocity information. If the P wave and S wave velocity data do not exist, then it will be necessary to collect the velocity data needed for the modeling and design of the 2D seismic survey. Logging of boreholes for velocity data will be done by project personnel (if a vertical seismic profile, VSP, is undertaken) or via a subcontractor.

From the gathered subsurface velocity information one-dimensional seismic modeling studies will be undertaken to determine whether or not a seismic reflection AVO anomaly can be detected. Products from completion of Task 1 include a report on suitability of site for seismic AVO investigations, the seismic model study, copies of any geophysical field data and logs collected in digital format, VSP observers notes, and raw and processed field files.

TECHNICAL APPROACH: Project personnel will visit the Paducah facilities, collect background characterization data and information, and inspect possible survey locations. This information will include the following for the DNAPL contaminated areas: 1) data on the quantity and concentration of DNAPL, 2) borehole geophysical logs, 3) geophysical measurements especially seismic reflection

data, 4) hydrological information, 5) geologic interpretations, i.e. log cross-sections, geologic cross-sections, and structure contour maps.

Subsurface velocity information, both P wave and S wave, and density data are necessary to construct the seismic models. If detailed subsurface velocity information is not available, existing boreholes will be logged to obtain velocity data. The velocity logging will be done via vertical seismic profiles (VSP).

Vertical seismic profiles can be conducted in either cased or uncased boreholes. This survey involves lowering a sensor down the borehole to predetermined depths, clamping it to the borehole wall, and recording the arrival time of elastic waves generated by a surface source. The seismic source will be a hammer. For P wave acquisition the hammer is used to strike a metal plate embedded vertically in the ground. For S wave acquisition the hammer is struck against the ends of a plank set horizontally on the ground. To cancel extraneous P wave noise, a set number of hits are taken at each end of the plank. The records from one of the source orientations is reversed and summed with records from the other source orientation.

Critical recording parameters for VSP acquisition include the depth interval of sensor readings, the size of the seismic source, and the number of repetitions of the source per depth interval. The depth interval of the sensor readings is determined by the sampling rule of at least two measurements per spatial wavelength. The spatial wavelength is based upon the bed thickness needed to be resolved. The frequency of the seismic source determines the vertical resolution of the data, that is, whether the tops and bottoms of geologic layers can be distinguished. For most environmental applications these requirements translate into depth intervals of 1.0 ft - 3.0 ft and seismic frequencies greater than 100 Hz. The size of the seismic source and the number of repetitions per depth interval are determined by field tests. For all seismic recording acoustically quiet conditions must be observed. This criterion might necessitate conducting the surveys at night, on weekends, or require restricted access by vehicles to the area where the survey is being conducted.

Analysis of VSP data is well established in the geophysical literature. A typical data processing sequence would include: vertical summing of records on levels, bandpass filter, picking of first break arrival times, correction for source offset, scaling, upgoing-downgoing wave field separation, true amplitude recovery, deconvolution of upgoing waves, shifting of upgoing waves to two-way vertical reflection time, front corridor muting, and front corridor stack. In addition, from the first break pick time the velocity versus depth profile is generated. This information is used to define the velocities needed for seismic modeling studies and to convert the seismic data from time to depth.

One-dimensional and two-dimensional seismic AVO model responses will be calculated for various geologic scenarios and DNAPL concentrations. The goal of the model study is to determine whether at a given site a seismic AVO response is possible from the DNAPL contaminated sediments and to determine the minimum concentrations of DNAPL that have to be present to elicit an AVO response given typical seismic source frequencies, recording geometries, and resolution limits.

The one-dimensional model will utilize an algorithm based on the standard approximations of the Zoeppritz equations used for elastic wave models. The input parameters include the

subsurface velocities, Poisson's ratio, and density profiles. The models to be tested include an uncontaminated horizon and contaminated horizon with varying amounts of contaminant and thickness of contaminated layer. The model results are displayed as graphs of reflection amplitude versus angle of incidence (offset) and as synthetic common depth point gathers. Key to this modeling is the minimum thickness of DNAPL contamination that can be detected for a given frequency of seismic wavelet.

A two-dimensional model is constructed to determine the field acquisition parameters required to resolve spatially any DNAPL AVO anomaly. Using the results from the one-dimensional model study, an offset ray trace model is created using source points and receiver locations at intervals typical for a seismic survey. The depth and horizontal extent of the DNAPL anomaly is varied. The model results are processed using a standard CDP processing flow to obtain a stacked seismic section. The model stacked section is representative of what would be the zero-offset seismic response due to the presence of DNAPL. Analysis of the CDP gathers and offset range stack sections demonstrate what the expected AVO seismic response from DNAPL contaminated sediments would be. These results can be compared to actual field records.

DELIVERABLES: Deliverables from completion of this work element is a report on the suitability of the site for seismic AVO investigations. This report will include: The seismic model study and copies of any geophysical field data collected including VSP observers notes and raw and processed VSP field files.

Vertical seismic profile (VSP) data will be presented as: 1) raw field record, 2) table of depth, first arrival pick times corrected to vertical first arrival pick times, average velocity, interval velocity, and two-way reflection travel time, 3) upgoing wavefield flattened to two-way vertical time, and 4) front corridor stack. The raw and processed VSP files will be written to magnetic media in Society of Exploration Geophysicists SEG-Y format.

The seismic model study will consist of one and two-dimensional seismic models. The one-dimensional seismic model will be a synthetic amplitude versus offset display of common depth point gathers obtained over a typical DNAPL contamination. The two-dimensional model will be synthetic seismic sections collected over a typical DNAPL contamination.

The report will contain a recommendation whether or not there is likelihood that a seismic response from DNAPL is detectable. If it is determined that an AVO response is detectable, Task 2 and Task 3 will be undertaken.

PARTICIPANTS: Michael G. Waddell (Principal Investigator), William J. Domoracki (Co-Principal Investigator), Tom J. Temples, and Logistics Coordinator.

Task 2.0: 2-D Seismic Reflection Design and Acquisition

Design of the 2-D seismic reflection survey will be guided by the location of areas of high concentration of dissolved phase DNAPL (100's ppm), likelihood of intersecting geologic sinks

where can pool, ease of site access, and lack of acoustic interference. Evaluation of preexisting seismic reflection data, if available, and the modeling results from Task 1 will be done to determine the specific acquisition parameters. Variables such as minimum and maximum offsets, source and receiver spacing, CDP fold, and type of source (hammer or a vibrator source) will be determined in order to collect optimum P wave seismic data. If the budget allows, and geologic conditions are favorable, S wave reflection data will be collected in conjunction with the P wave reflection data. If no preexisting seismic reflection data are available, mobilization of a seismic recording crew will be required to conduct noise tests (walkaways) prior to acquisition of the seismic data. The noise tests will determine the optimum source to receiver spacing and geophone spacing (within the constraints of the AVO modeling) needed to reduce both coherent and random noise.

The 2-D seismic reflection survey will be done subsequent to the field analysis of the noise test. The survey will consist of one or more CDP seismic line profiles with an aggregate length of no more than 1200 feet at the Paducah site and 480 feet at Savannah River Site. Field crews will follow established safety protocols. Daily tests of the recording apparatus will be done to ensure that the instrument operates within the manufacturer's specifications. Source and receiver locations will be surveyed for horizontal and vertical control. Products from completion of this task include copies of observer's logs, surveyor's notes, and raw field files in SEG-Y format.

TECHNICAL APPROACH: The location of the 2-D seismic reflection survey will be guided by the likelihood of intersecting DNAPL concentrations established from Task 1, imaging geologic sinks where DNAPL can pool, ease of site access, and lack of acoustic interference. The seismic recording parameters will be determined from a noise spread and evaluation of any preexisting seismic reflection data and the model study. For all seismic recording acoustically quiet conditions must be observed. This criterion might necessitate conducting the survey at night, on weekends, or require restricted access by vehicles to the area where the survey is being conducted. The limit of acoustic noise that can be tolerated is established from examination of source point files in the field. This will include visual examination, filter band tests, and amplitude spectra analysis.

It is anticipated that seismic recording will involve a minimum of 1200 feet of seismic line consisting of one or more profiles at the Paducah Site. Task 2 will also be performed at Savannah River Site. It is anticipated that approximately 480 feet of seismic data will be collected to monitor the steam flood. The nominal CDP fold is expected to be between 30 and 72. The nominal CDP fold at Savannah River Site is expected to be 60.

Specific acquisition design attributes to be addressed include:

- Source and receiver spacing
- CDP fold (30 fold nominal)
- Type of source (hammer (SRS) or vibrator (Paducah))
- Number of source repetitions, source array
- Minimum and maximum source to receiver offsets
- Sample rate and record length
- Frequency output of the source (vibrator acquisition only)

The noise test will involve: 1) test of various sweep frequencies, sweep length, drive level (source strength) and 2) analysis of coherent and random noise. Source and receiver spacings are determined by spatial sampling protocols and the limits of the recording apparatus. In general, receiver spacings are such that at least four traces sample the diameter of the first Fresnel zone at the target depth. In addition, the maximum source to receiver offset has to be large enough so that any AVO effect, which occurs as the critical angle is approached, is recorded. These parameters are determined from the model study.

The CDP fold, source type, and number of source repetitions are largely functions of the need to cancel random noise and can only be determined empirically. The source output frequency governs the temporal (vertical) resolution of the data. Thus, the highest possible frequency seismic waves need to be generated. The sample rate and record length are determined by the frequencies of the seismic waves to be recorded and depth of the target. The time sampling theorem requires at least two samples per wavelength to ensure adequate representation of the analog waveform.

Field crews will follow established safety protocols. Daily tests of the recording apparatus will be done to ensure that the instrument operates within the manufacturer's specifications. Source and receiver locations will be surveyed for horizontal (to 1.0 ft.) and vertical (to 0.1 ft.) control.

DELIVERABLES: Report on the results of the field test and the 2-D seismic program. The report will include copies of the field observers logs, surveyors notes, and a location map. The raw seismic field files will be presented on magnetic media in SEG-Y format.

PARTICIPANTS: Michael G. Waddell (Principal Investigator), William J. Domoracki (Co-Principal Investigator), Tom J. Temples, and Logistics Coordinator.

Task 3.0: 2-D Seismic Reflection Processing, Interpretation and Validation

The 2-D seismic data will be processed to obtain the optimum image of the subsurface in the DNAPL contaminated areas. Data processing will follow a shallow high-resolution CDP and AVO processing flow designed to preserve the amplitude characteristics of the data and to ensure detection of possible AVO anomalies. Specialized data processing for AVO attributes will include offset range limited CDP stacks and fluid factor stacks.

Seismic data interpretation will comprise correlation of synthetic seismograms or VSP to the seismic data, construction of time-structure maps and structural contour maps (from seismic data), and correlation of seismic attributes to aquifer characteristics, if possible. Products from completion of Task 3 include copies of the processed data in hardcopy and SEG-Y digital format, description of the data processing parameters, copies of all maps and interpretations generated as described above.

Interpretation, integration and validation of the seismic data will entail correlation of synthetic seismograms to seismic data and construction of time-structure and structural contour

maps. Lithological aquifer characteristics and AVO data will be integrated to map sedimentary facies and delineate potential DNAPL anomalies and delineate preferential pathways for subsurface contaminant transport.

TECHNICAL APPROACH: The 2-D seismic data will be processed to obtain the best possible image of the subsurface in DNAPL contaminated areas. Data processing will follow a conventional CDP processing flow designed to preserve the amplitude characteristics of the data to ensure detection of possible AVO anomalies. Specialized data processing for AVO attributes will include offset range limited CDP stacks, fluid factor stacks, and analysis of AVO gradients.

Two-dimensional seismic reflection data processing will follow a conventional CDP data processing flow that includes:

- Gain recovery
- Amplitude balancing (surface consistent)
- Trace edits
- Geometry definition
- Deconvolution (statistical or deterministic)
- Coherent noise reduction (F-K, K-L, or Tau-p filtering)
- CDP sort
- Datum static correction
- Velocity analysis
- Residual statics (surface consistent, iterative application with velocity analysis)
- NMO correction, mute
- CDP stack
- Poststack enhancement (F-X deconvolution, and/or poststack mix when necessary)
- Migration

Specialized data processing for AVO attributes and interpretation includes:

- Generation of near, middle, and far offset stack sections
- Creation of Smith-Gidlow fluid factor sections
- Analysis of AVO gradients

All the seismic reflection data collected will be integrated with existing borehole, hydrological, and AVO information. From these interpretations AVO anomalies that appear to be caused by DNAPL will be targeted for detailed investigation. Existing boreholes might need to be logged to provide the information needed to calibrate the seismic data. The logging program, if necessary, will consist of conducting a VSP to obtain P wave and S wave velocities.

The results from existing borehole geophysical logs, VSP, any additional borehole geophysical logs, and available geologic and hydrologic data will be used to calibrate the seismic

reflection data as to the presence and concentration of DNAPL. Crossplots will be constructed among various seismic attributes (e.g., amplitude, polarity, instantaneous frequency, and instantaneous phase) versus borehole log attributes to determine if any statistical relationships exist. If any statistical relationship exists among the crossplotted attributes, the seismic data can be calibrated for the attribute and mapped.

DELIVERABLES: Deliverables from completion of this task include copies of the processed data in hardcopy and SEG-Y digital format, description of the data processing parameters, and copies of all the different types of stack seismic sections. Also included will be the maps and models described above and a site summary report of the results obtained from this task and the preceding tasks.

PARTICIPANTS: Michael G. Waddell (Principal Investigator), William J. Domoracki (Co-Principal Investigator), Tom J. Temples, and Logistics Coordinator.

Enclosures

Enclosure 1. Seismic line Figure Z-9-1. Green horizon is top of Plio/Pleistocene. Blue horizon is top of caliche.

Enclosure 2. Seismic line Z-9-2. Green horizon is top of Plio/Pleistocene. Blue horizon is top of caliche.

Enclosure 3. Seismic Line Z-9-3. Green horizon is top of Plio/Pleistocene. Blue horizon is top of Caliche.

Enclosure 4. Seismic line Z-9-4. Green horizon is top of Plio/Pleistocene. Blue horizon is top of caliche.

Enclosure 5. Enhanced amplitude plot of line Z-9-1. Areas in black are positive amplitudes, areas in red are negative amplitudes. Green Horizon is top of Plio/Pleistocene.

Enclosure 6. Enhanced amplitude plot of line Z-9-2. Areas in black are positive amplitudes, areas in red are negative amplitudes. Green Horizon is top of Plio/Pleistocene.

Enclosure 7. Enhanced amplitude plot of line Z-9-3. Areas in black are positive amplitudes, areas in red are negative amplitudes. Green Horizon is top of Plio/Pleistocene.

Enclosure 8. Enhanced amplitude plot of Line Z-9-4. Areas in black are positive amplitudes, areas in red are negative amplitudes. Green Horizon is top of Plio/Pleistocene.