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J. Comments
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SGW-52160
Revision 0

Landstreamer and Gimbaled Geophones Phase II-200 Areas: a High-Resolution Seismic Reflection Survey at the Hanford Site

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Contractor for the U.S. Department of Energy
under Contract DE-AC06-08RL14788

CH2MHILL
Plateau Remediation Company
P.O. Box 1600
Richland, Washington 99352

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Landstreamer and Gimbaled Geophones Phase II-200 Areas: a High-Resolution Seismic Reflection Survey at the Hanford Site

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Date Published
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Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Contractor for the U.S. Department of Energy
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CTUIR-44972-00	44972	10	2	01/27/2012

(6) CONTRACTOR: Confederated Tribes of the Umatilla Indian Reservation, Dept of Science & Engineering, 46411 Timine Way, Pendleton, OR 97801

SIGNATURE Ted Repasky DATE: 1/27/2012

(7) TO: PROJECT RECORDS SPECIALIST MSIN: Phone: 509- -

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- C Revise and Resubmit

Busler, Charmaine N

From: Ted Repasky [TedRepasky@ctuir.org]
Sent: Monday, February 06, 2012 9:31 AM
To: Busler, Charmaine N
Subject: RE: CONTRACT 44972 - SUB 010 V2 - Final Results Summary Report ***STATUS: A***

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From: Busler, Charmaine N [mailto:Charmaine_N_Busler@RL.gov]
Sent: Monday, February 06, 2012 8:50 AM
To: Ted Repasky
Cc: Hanson, Katlin M; Miller, Steven F; Thompson, Michael D
Subject: CONTRACT 44972 - SUB 010 V2 - Final Results Summary Report ***STATUS: A***

Ted,

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****STATUS: A****

Sincerely,

Charmaine Busler
Project Document Control
200E/MO2229/R4-29
Office: 509-942-3941

Busler, Charmaine N

From: Miller, Steven F
Sent: Thursday, February 02, 2012 8:12 AM
To: 'Figgins, Miranda R'; ^Project Document Control; Busler, Charmaine N
Subject: A - Conforms: CONTRACT: 44972 - SUB 010 V2 - Land Streamer Final Results Summary***OUT FOR REVIEW***

Busler, Charmaine N

From: Miller, Steven F
Sent: Thursday, February 02, 2012 8:12 AM
To: 'Figgins, Miranda R'; ^Project Document Control; Busler, Charmaine N; Thompson, Michael D
Cc: Hanson, Katlin M; Williams, Bruce A
Subject: RE: CONTRACT: 44972 - SUB 010 V2 - Land Streamer Final Results Summary***OUT FOR REVIEW***

CTUIR has addressed our comments and I approve the revised report.

From: Busler, Charmaine N
Sent: Tuesday, January 31, 2012 1:40 PM
To: Miller, Steven F; Thompson, Michael D
Cc: Hanson, Katlin M; Williams, Bruce A
Subject: CONTRACT: 44972 - SUB 010 V2 - Land Streamer Final Results Summary***OUT FOR REVIEW***
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Cc: Miller, Steven F; Williams, Bruce A
Subject: A - Conforms: CONTRACT: 44972 - SUB 010 V2 - Land Streamer Final Results Summary***OUT FOR REVIEW***

Charmaine and Katlin,

I've read through the report and it meets the submittal criteria…

They've more than adequately addressed my concerns…

Mike.

Landstreamer and Gimbaled Geophones Phase II—200 Areas: A High-Resolution Seismic Reflection Survey at the Hanford Site

D. A. Sunwall, Montana Tech of the University of Montana, Butte, MT
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September, 2011

Prepared under the direction of the Confederated Tribes of the Umatilla Indian Reservation Department of Science and Engineering and Director Stuart Harris for CH2MHill Plateau Remediation Company, Contract No. 44972

Department of Science and Engineering
Confederated Tribes of the Umatilla Indian Reservation
Pendleton, OR 97801

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SUMMARY

The Confederated Tribes of the Umatilla Indian Reservation (CTUIR) was contracted by the CH2M Hill Plateau Remediation Compay (CHPRC) to complete a second phase of geophysical seismic landstreamer surveys conducted on the Hanford nuclear site. From April to May of 2011, CTUIR and Montana Tech collected approximately 12 km of seismic reflection data north of the 200 Areas and in the Gable Gap Area. These data were collected using a landstreamer of gimbaled geophones and primarily an Accelerated Weight Drop (AWD) for a seismic source.

CHPRC is responsible for the remediation of the entire Central Plateau of the Hanford site, and as part of the Central Plateau cleanup, CHPRC is attempting to better understand contaminated groundwater migration between the 200 Areas and Gable Gap. In 2009, CHPRC contracted CTUIR to conduct a seismic reflection survey north of the 200 Areas and map the top surface of the basalt. CHPRC also desired to test the feasibility of using a landstreamer of gimbaled geophones and using an Accelerated Weight Drop (AWD) to collect high-resolution seismic reflection data in this area. Using gimbaled geophones allows seismic data to be collected faster compared to using spike geophones. The successful results of the 2009 landstreamer survey demonstrated the reliability of the landstreamer/AWD method and prompted CHPRC to solicit a second phase of data collection north of the 200 Areas during 2011. The 2011 survey was designed to infill and expand the data coverage from the 2009 survey.

Contaminated groundwater has been observed to be migrating from the 200 East Area toward the Columbia River. The purpose of the 2011 survey is to map the basalt surface and observe features which might control groundwater movement. The survey was conducted in the Gable Gap Area which might provide a groundwater pathway North to the Columbia River. Specifically we have observed erosional features in the basalt which might control the direction of horizontal groundwater flow in the suprabasalt aquifer (the aquifer within the Hanford Formation flood and lake deposits which overly the basalt). We have also observed faults within the basalt which might control the vertical migration of groundwater. Faulting and deformation within the basalt might facilitate the movement of groundwater between the suprabasalt aquifer and intrabasalt aquifers. Identifying these features which control groundwater migration will help CHPRC identify preferred pathways for contaminant migration and may ultimately help prevent contaminates from reaching the Columbia River.

Prestack depth migration results show the interpreted top of the basalt and faulting within the basalt. Uninterpreted poststack time migrations and unmigrated time seismic sections also clearly show the basalt reflector and faults. The 2011 data support the idea that significant deformation and erosional events have contributed to the rough and irregular top surface of the basalt. Sections of the seismic data with fewer erosional features might help distinguish between areas of high erosion and low erosion, which might help delineate paleochannels. Faulting is evident on most of the seismic sections.

ACKNOWLEDGEMENTS

The Confederated Tribes of the Umatilla Indian Reservation (CTUIR) would like to acknowledge CHPRC for providing funding under Contract No. 44972 to collect additional seismic data using the landstreamer system with gimbaled geophones. Special thanks are given to CHPRC employees Gloria Cummins, Chris Wright, Steve Miller, and Mike D. Thompson for their review and support of this contract. The CTUIR coordinated the work and safety schedule with the assistance of Kathleen Thompson.

We thank CTUIR employees Vern Bronson, Richard Bronson, Heather Billy, Audwin Minthorn, Ashleigh Wolf, Janice Jones, Titto Moses, and Beverly Penny for help in data collection and field preparation.

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1.0 INTRODUCTION

1.1 Site Location

Phase II of the seismic geophysical study was conducted on the Hanford Site which is located in the south-central portion of Washington State and north of the city of Richland, Washington. The study area within the Hanford Site is north of the 200 Areas and is approximately 9 km south of the Columbia River (Figure 1.1-1). Most of the seismic data were collected south of Gable Gap which is between Gable Mountain and Gable Butte, and the northern extent of the seismic survey partially crosses Gable Gap (Figure 1.1-2).

1.2 Objective of Investigation

The objectives of the 2011 Phase II study was to map the top of the basalt, identify preferred pathways for contaminated groundwater movement, and evaluate and validate anomalous regions identified in the 2009 interpretation. Specifically, we hope to image features (i.e. paleochannels, erosional features, structural features, etc.) in the top of the basalt which might control the horizontal flow of contaminated groundwater within the suprabasalt formations. Other targets include faults and high-relief erosional features which might cause vertical hydrologic communication between the contaminated suprabasalt aquifers and the intrabasalt aquifers. Although past seismic surveys in the area have not produced good reflections within the suprabasalt section, we hoped to differentiate the Hanford formation from—if they are present—the Ringold formation and Cold Creek unit. The desired final results are unmigrated time seismic sections and both time- and depth-migrated seismic sections, all which were used for our analysis.

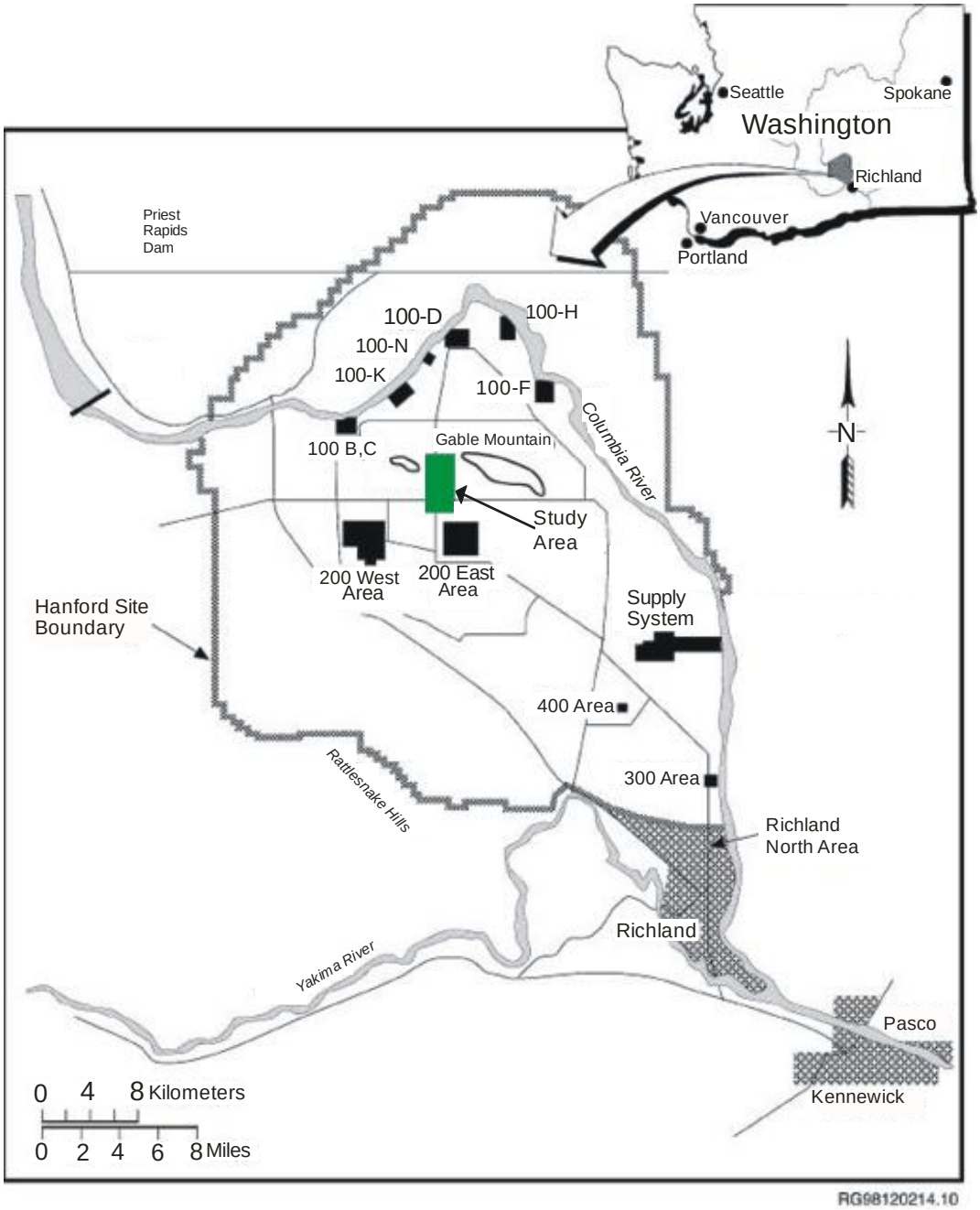


Figure 1.1-1. The Hanford site is located in south central Washington, north of Richland, Washington. Within the Hanford area the Phase II seismic survey was conducted northwest of the 200 East area in the study area shown in green (modified after Barnett et al., 2005).

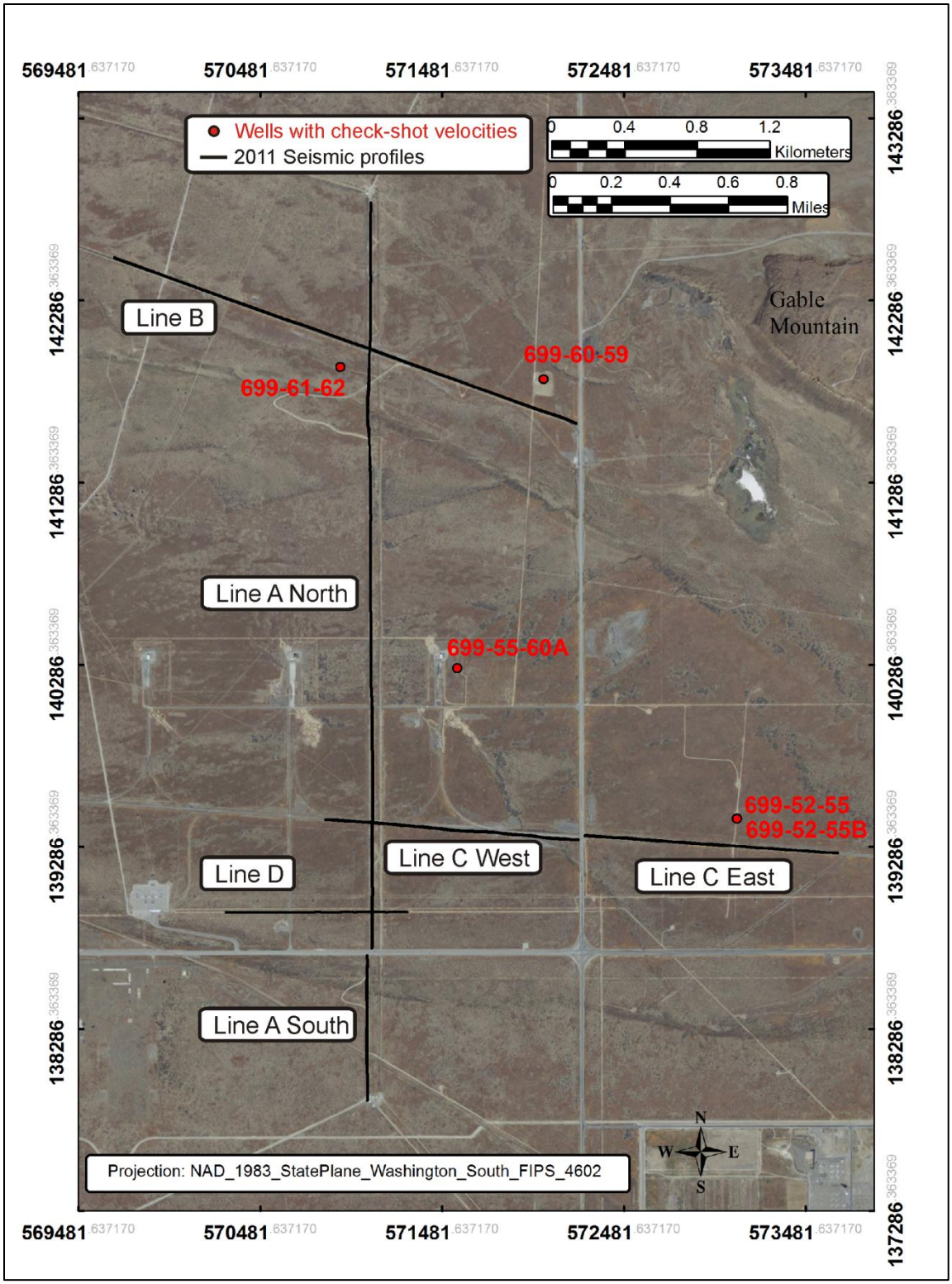


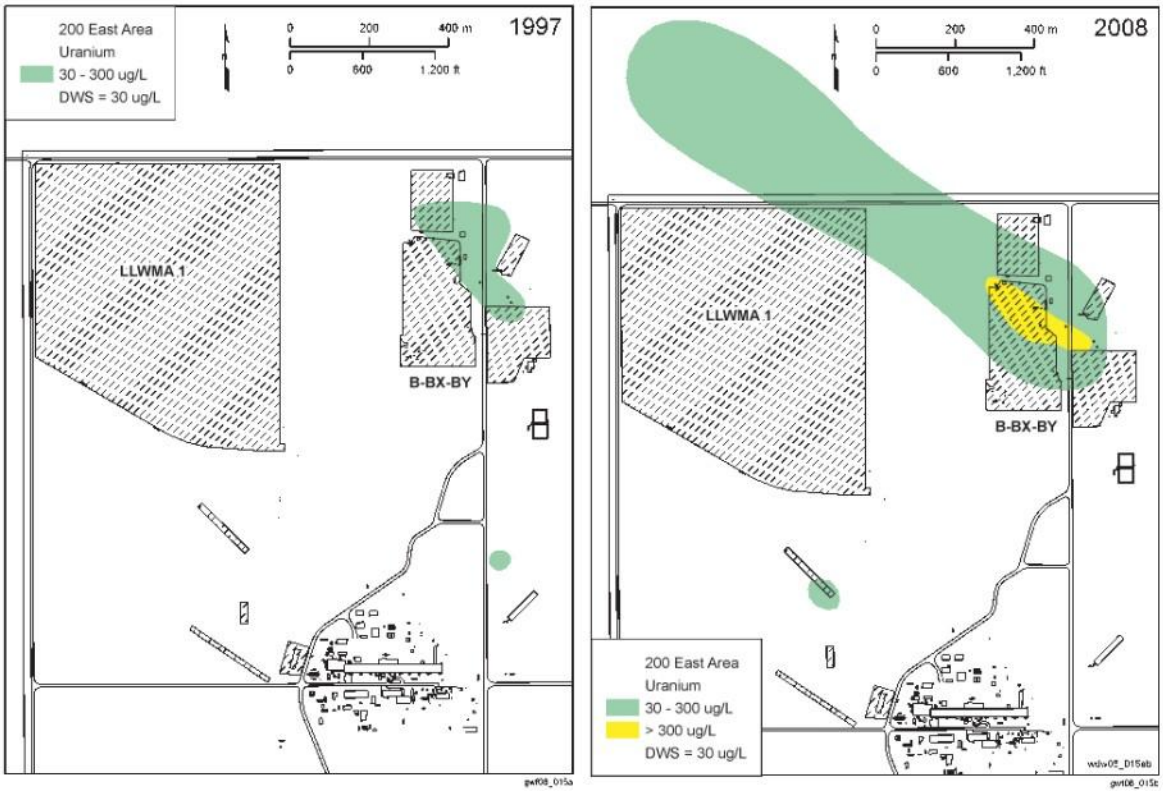
Figure 1.1-2. A base map showing the locations of the six 2D seismic lines and 5 wells which have check-shot velocity information. The six seismic lines comprise about 12.25 km of high-resolution seismic reflection data. The coordinates are displayed in the North American Datum (NAD) of 1983 in the Washington South State Plane Coordinate System. Wells 699-52-55 and 699-52-55B are so close together that their difference in location cannot be distinguished at the map's scale.

2.0 BACKGROUND

2.1 Hanford Site Remediation

From 1944 until the late 1980's, Hanford nuclear reactors and associated processing facilities were used primarily to produce plutonium for atomic weapons. Over this time and as a result of plutonium production, chemical and radionuclide byproducts were discharged into the ground resulting in the contamination of the groundwater. In 1989, the U. S. Department of Energy (DOE), the Washington State Department of Ecology, and the U. S. Environmental Protection Agency joined efforts to remediate the Hanford site. Currently, seven prime contracting agencies, under guidance of the DOE, are involved with the Hanford cleanup effort. These prime contractors are Advanced Technologies and Laboratories International, Inc.; Bechtel National, Inc.; Washington River Protection Solutions, LLC; CSC Hanford Occupational Health Services; CH2M HILL Plateau Remediation Company; Mission Support Alliance; and Washington Closure Hanford. The CH2M HILL Plateau Remediation Company (CHPRC) is prime contractor to the DOE for all aspects of environmental cleanup of Hanford's Central Plateau region, including the remediation of contaminated groundwater. CTUIR was contracted by CHPRC to conduct the 2011 landstreamer survey. Hanford stakeholders include federal/state/local regulatory agencies, environmental groups, regional communities/governments, and the public.

Although groundwater contamination is extensive in the central area of the Hanford site, this study is focused on the contamination pathway north of the 200 East Area. The 200 East Area contains non-reactor facilities, and a uranium plume is observed to be migrating from these disposal facilities in a northwest direction towards the Columbia River (Figure 2.1-1). The plume has migrated towards the area known as Gable Gap where a potential groundwater pathway (between two structural high basalt features—Gable Mountain and Gable Butte) may lead to the Columbia River. Seismic data have the potential to help characterize the subsurface geology, specifically the elevation and nature of the basalt surface, in this study area and help CHPRC to better understand groundwater behavior in the Gable Gap area.



(a) (b)

Figure 2.1-1. Uranium plume in the 200 East Area is shown to be spreading in a north west direction between (a) 1997 and (b) 2008 in the general direction of the Columbia River (Hartman et al., 2009).

2.2 2009 Landstreamer Survey: Phase I

The CTUIR 2011 seismic reflection survey is the second phase seismic landstreamer project conducted north of the 200 Areas. The first phase took place in 2009 when a full scale seismic survey was conducted to test the feasibility of using a gimbaled-geophone landstreamer and an accelerated weight drop to collect high-resolution seismic reflection data (SGW-43746, 2009; Hyde et al., 2011). The 2009 survey successfully mapped the surficial relief of the basalt and possible preferential pathways for horizontal groundwater migration. Interpreted faults and sharp erosional features in the basalt also indicate the possibility of vertical groundwater communication between the deep vadose zone and the aquifers confined within the basalt. The success of the 2009 survey prompted the continuation for another landstreamer seismic survey, and the 2011 survey was conducted to extend and infill the 2009 landstreamer data coverage.

2.3 Site Conditions

The Hanford Site is located in a windy, arid, high desert climate. Seismic data were collected in April and May to avoid hot summer months when vegetation becomes dry and fire danger becomes high enough to stop all off-road activity. At times strong winds and short rain storms during April and May of 2011 created enough noise to stop data collection, but wind and rain noise never stopped production for more than half of a day.

Most portions of seismic lines were collected on or near asphalt, gravel, dirt, or two-track roads. However, on line A North, approximately 500 meters of data were collected off road on a grassy surface. On line C West, approximately 430 meters of data were collected off road on a rocky and grassy surface. A problematic hill on line A North was too steep for the pickup truck and seismic-source trailer, so a sledge hammer was used in place of the accelerated weight drop. The ends of several seismic lines (the north end of line A South, the south end of line A North, the east ends of line B and line C West, and the west end of line C East) were close to busy roads. Traffic noise was higher during mornings and evenings when employees are commuting to and from work. Large trucks hauling waste materials move continually throughout the day and are especially detrimental to data quality. When collecting seismic data next to busy roads, shots were timed to avoid contaminating the shot record with traffic noise, and as a result production slowed. Traffic noise became less severe the farther the geophones were from the busy roads. Normal production speed was resumed when traffic noise was no longer a problem.

2.4 Geology and Hydrogeology

The two primary geologic units in the study area are the Columbia River Basalt Group (CRBG) and the overlying Hanford formation. The CRBG resulted from flood basalts which were emplaced during the Upper to Middle Miocene times (17-5 Ma). Results from the 2009 landstreamer survey (Hyde et al., 2011) indicate that the depths to the top of basalt range from 30 m to 100 m. The CRBG has been faulted and deformed in association with the Yakima Fold Belt, and later eroded by catastrophic Ice Age Floods over the past 2 million years (Bjornstad et al., 2001). The top of the basalt is the lower boundary of the suprabasalt aquifer, and basalt-confined aquifers occur within the epiclastic and volcaniclastic sediments of the Ellensburg Formation or within the vesicular basalt of the lower and upper sections of basalt flows (Barnett et al., 2007, Tolan et al., 2007). In our study area, the Hanford Formation is the primary formation overlying the CRBG and was deposited during the Pleistocene Epoch (Barnett et al., 2007). The Hanford formation consists of unconsolidated gravels, sands, and silts.

Other geologic units can occur in the area such as the Ringold Formation and the Cold Creek unit, but they might have been completely eroded during Ice Age floods (William et al., 2000; Neitzel et al., 2005; Barnett et al., 2007). The 2009 seismic data did not show reflectors in the suprabasalt section, but the lack of reflectors does not necessarily preclude the presence of these geologic units. The Ringold Formation and Cold Creek Unit might be present, but the elastic and inertial property contrasts between the Ringold Formation, the Cold Creek Unit, and the Hanford Formation might not be large enough to produce reflections. More detailed information about the geology and hydrogeology in the study area can be found in a report (SGW-43746, 2009) and in a recent publication (Hyde et al., 2011) detailing the results of the 2009 landsteamer survey. The generalized stratigraphy and hydrostratigraphy is shown in Figure 2.4-1.

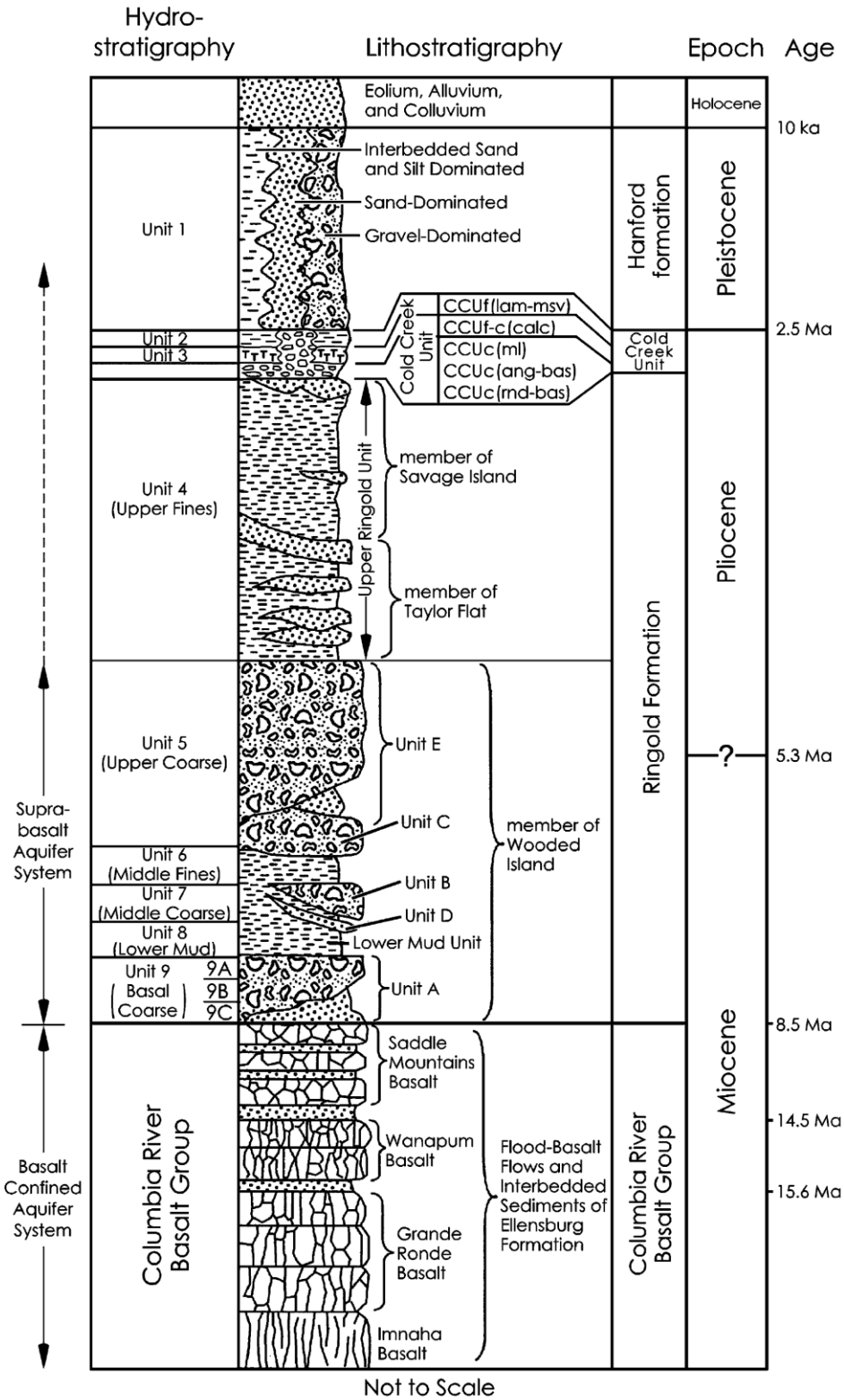


Figure 2.4-1. Generalized stratigraphy of the Hanford Site and the 200 East Area. The Columbia River Basalt Group serves as the bedrock in the study area and is interbedded by sedimentary units of the Ellensburg Formation. Atop the CRBG is the sedimentary Ringold Formation. The overlying Cold Creek Formation and Hanford Formation are also sedimentary deposits (Williams et al., 2000).

3.0 GEOPHYSICAL THEORY

3.1 Introduction

Seismic exploration methods are a non-invasive approach for extracting subsurface geological information from Earth's surface. A controlled man-made seismic source (i.e. an explosion, a sharp impact, etc.), coupled to Earth's surface, is used to generate elastic waves which travel through the subsurface. This man-made seismic signal is also known as a shot, and a shot point is a physical location along the seismic profile where a shot is generated. Variations in subsurface geology generate seismic responses which travel back to the Earth's surface and are recorded by an array of receivers called geophones.

Geophones are velocity (or ground vibration) sensors that generate a voltage proportional to the velocity of the ground-surface motion, and the output voltage from the geophone is recorded by a seismograph. A seismograph records the seismic signal detected by the geophone array, and the final recorded output (from all geophones in the array) is called a shot record. In the field, multiple shot records from a single shot point are stacked together to generate a new, single shot record with an increased signal-to-noise ratio. The signals recorded by the geophones are then processed in order to construct an image which delineates the variations in subsurface rock properties. During processing, seismic traces are sorted and stacked into Common-MidPoint (CMP) gathers in order to enhance (by summing) the signal of traces with common reflection points.

Exploration seismic methods are divided into two major categories: seismic *refraction* methods and seismic *reflection* methods. Refraction methods use seismic energy which is critically refracted at the boundary between adjacent geological units. Reflection methods use seismic energy which is reflected and transmitted at boundaries between adjacent geological units. The 2011 Hanford landstreamer survey implemented the seismic reflection method.

3.2 Seismic Reflection Method

Seismic reflection data record the energy reflected at boundaries between geologic units (Figure 3.2-1). Adjacent geologic units must have a significant contrast in elasticity in order to induce a reflection. Figure 3.2-1 shows a simple two layer earth model where each layer has different elastic properties. For a normal-incident p-wave (compressional wave), the amount of energy reflected back to the geophones depends the p-wave velocity and density in each medium. The reflection coefficient for a normally-incident wave is given by the following equation: *Reflection Coefficient* = $(V_2\rho_2 - V_1\rho_1) / (V_2\rho_2 + V_1\rho_1)$ where V and ρ represent velocity and density respectively. If the overlying and underlying units have the same p-wave velocities and the same densities, then all seismic energy will be transmitted through the boundary and none will be reflected. Fortunately, the geology within our study area is conducive to seismic reflection methods because the CRBG has a high p-wave velocity and density compared to the overlying Hanford formation. Therefore the reflection coefficient is large at the CRBG/Hanford-formation boundary, and strong reflections can be measured from the CRBG/Hanford-formation boundary.

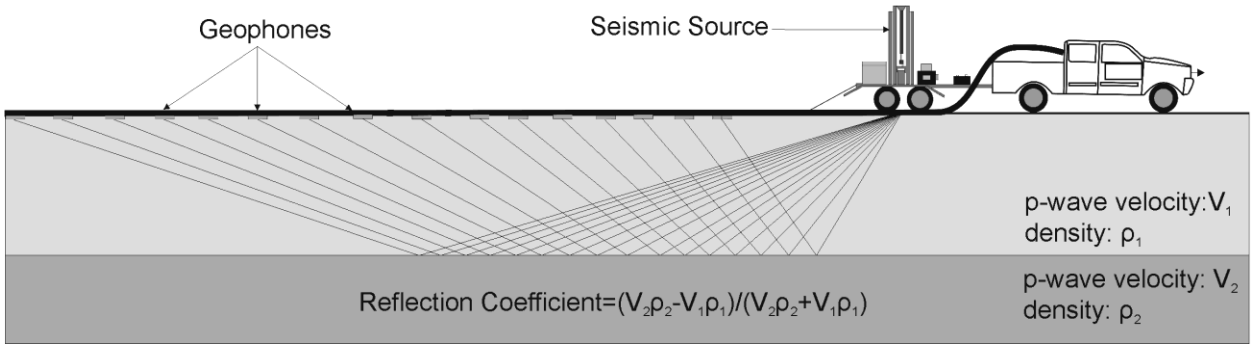


Figure 3.2-1. Schematic demonstrating the basic concept of a seismic reflection survey. At the surface a seismic source is used to generate elastic waves which travel through the subsurface and are reflected at geologic interfaces. The reflected energy is recorded by geophones at the surface. The amount of energy reflected at interfaces depends on the elastic properties of the rock units.

4.0 METHODOLOGY

4.1 General Description

In April and May of 2011, data for six two-dimensional seismic-reflection lines were collected on the Hanford Site (Figure 1.1-2). In terms of common depth point (CDP) coverage approximately 12.25 km of high-resolution seismic data were collected using an Accelerated Weight Drop (AWD) and a landstreamer consisting of gimbaled geophones. The seismic source was a 227 kg (500 lb) AWD mounted on a trailer. The landstreamer cable consisted of 96 gimbaled geophones and was dragged behind the AWD trailer. The AWD trailer was towed by a four-wheel-drive pickup truck and the acquisition equipment was housed in the cab of the pickup.

Prior to seismic data acquistion, pin flags were placed at 2 m intervals to mark station locations. The station flags were used to align the shots and geophone positions. During seismic surveying, observer notes were recorded to properly correlate the shot record files to the station locations. Following seismic data acquisition, GPS equipment was used to locate the stations in x, y, and z.

The seismic observer notes, GPS surveyor notes, and raw seismic data were sent to TRICON Geophysics, Inc. for processing. The final processed results included time-stacked seismic sections (unmigrated), poststack time-migrated seismic sections, prestack time-migrated seismic sections, and prestack depth-migrated seismic sections. The prestack depth-migrations were constrained using check-shot velocities from nearby wells.

Finally, the processed seismic sections were sent back to Montana Tech for interpretation. The top of the basalt and faults (if present) were interpreted on the prestack depth-migrated seismic sections. Also, the check-shot velocity profiles from nearby wells were projected on the prestack depth-migrated seismic sections to ensure proper depth conversion.

4.2 Equipment

4.2.1 Accelerated Weight Drop

The seismic source was an accelerated weight drop installed on a dual-axle trailer (Figure 4.2-1). The 227 kg (500 lb) steel ram was raised by a hydraulically powered arm. The hydraulically powered arm is moved up or down using an electrical switch which controls the hydraulic pump. The hydraulic pump is driven by a small Honda engine. A hook on the end of the hydraulic arm was used to grab and lift the steel ram. As the steel ram lifted, an elastic band wrapped around the top end of the steel ram and attached to the trailer became loaded. When the steel ram is released from the lifting hook, the steel ram is accelerated downward by the elastic band and strikes a steel plate (60 cm × 60 cm) located beneath the trailer and coupled to the ground. Electrical wires from the acquisition equipment were attached to the steel plate and to the steel ram, so when the ram struck the plate, the electrical circuit became closed and triggered the acquisition software to begin recording. Data began recording as soon as the ram struck the plate.

On line A North, a steep hill prevented us from using the truck and AWD trailer. Instead we used a 7 kg (16 lb) sledge hammer as the seismic source. Using a sledge hammer slowed production yet allowed us to record continuous data through the rough terrain.

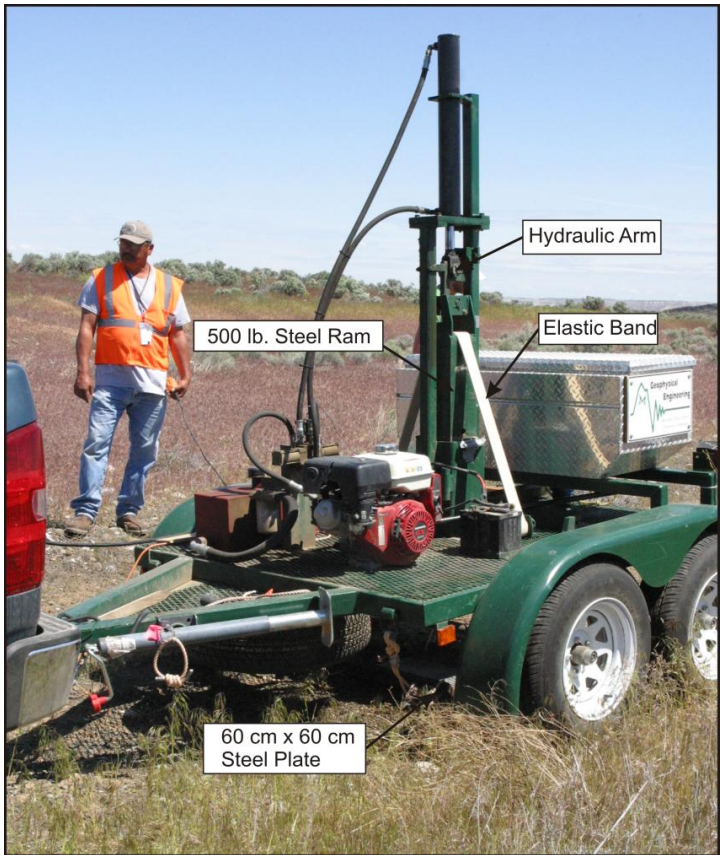


Figure 4.2-1. Photograph of the 227 kg (500 lb) Accelerated Weight Drop (AWD). In this photograph the steel ram is lifted off the steel plate, and the elastic band is loaded. Workers in the pickup truck, who are observing the seismic data, will signal the worker, who controls the seismic source, to release the loaded steel ram. The ram strikes the steel plate causing the acquisition software to begin recording.

4.2.2 Seismic Landstreamer

The seismic landstreamer consisted of a seismic cable, manufactured by HL Technologies, and 96 SM-7 gimbaled geophones manufactured by Input/Output Inc. The gimbaled geophones are 30 Hz velocity sensors that are 360˚ roll gimbaled and have 180˚ pitch tolerance. 30 Hz geophones were selected to enhance higher frequencies and therefore to increase data resolution. The seismic cable connects to four Geometric Geodes seismographs that are between the landstreamer cable and the acquisition computer. Each of the Geodes converts analog data from 24 of the 96 channels to digital data which are recorded in Geometrics Seismodule Controller software. Geophones were at 2 m spacing.

Using the landstreamer is faster than conventional seismic cables with spiked geophones because gimbaled geophones do not need to be planted into the ground (Figure 4.2-2). Gimbaled geophones are housed in 1 kg cylindrical cases which couple well to the ground and can be dragged across the ground's surface. In side-by-side comparisons, data collected with gimbaled geophones are similar in quality and frequency content compared to spike geophones (Miller et al., 2003). Other tests by Van der Veen et al. (1998, 2001) also show good frequency content with gimbaled geophones when the geophones were dragged in a self-generating furrow (Figure 4.2-3). The 2011 survey was conducted mostly on gravel roads, dirt roads, and road shoulders. These surfaces were conducive to creating a furrow during surveying, and because geophones were dragged in a self-generating furrow, the geophones had good coupling with the ground (Figure 4.2-4). The landstreamer was connected to and towed behind the AWD trailer using a chain system (Figure 4.3-4).

Figure 4.2-2. Photograph showing a gimbaled geophone (left) and a traditional spiked geophone (right). The streamer can be pulled to the desired location without having to plant individual geophones (modified after Miller et al., 2003).

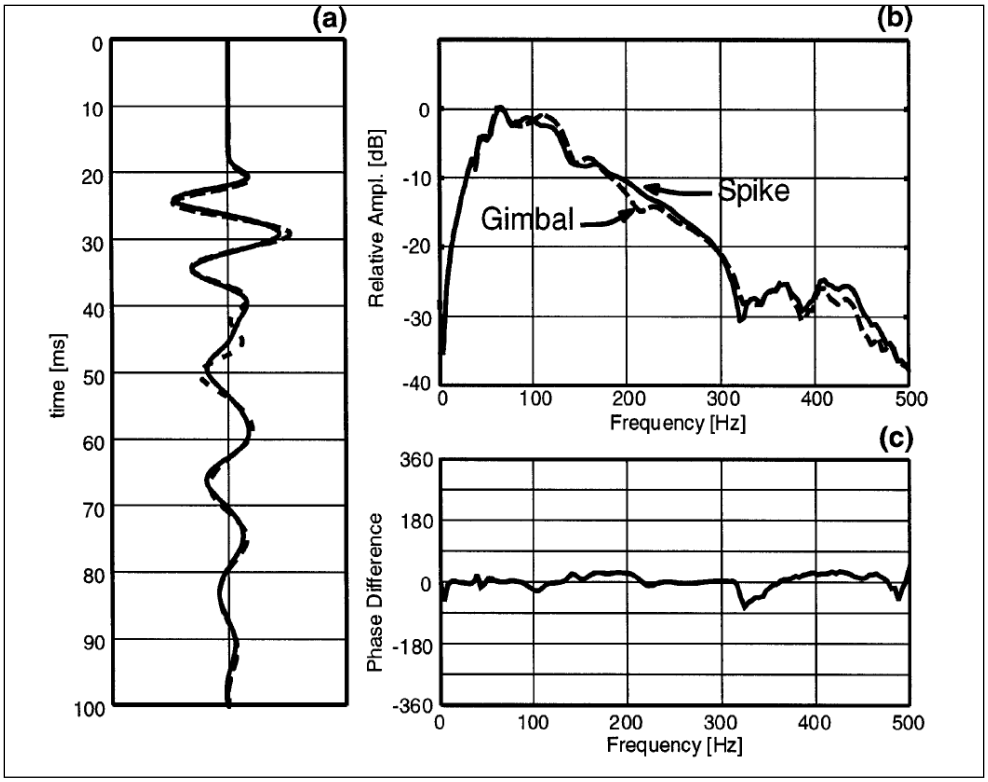


Figure 4.2-3. Comparison of response of a gimbaled and a traditional spiked geophone placed in a shallow furrow on the ground. (a) The seismic trace of the spike (solid line) and the gimbaled (dotted line) from the common seismic source. (b) The amplitude spectrum of both geophones. (c) The phase difference between the spike and gimbaled geophone (Van der Veen et al., 1998).

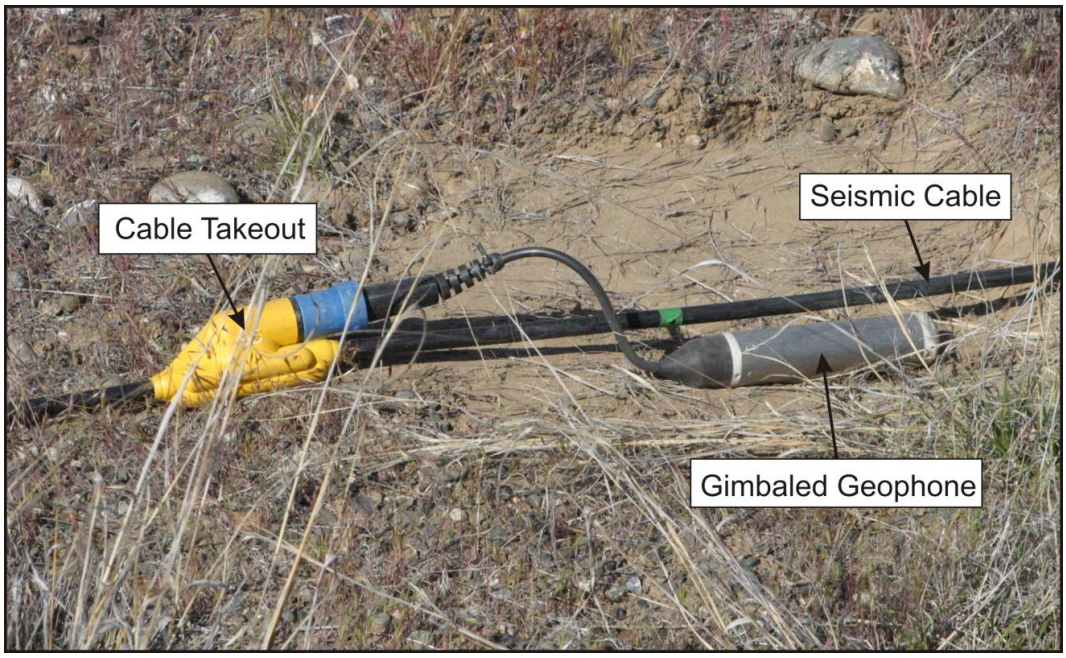


Figure 4.2-4. Photograph from the 2011 Hanford landstreamer survey. A 1 kg cylindrical gimbaled geophone connected to a geophone takeout on the seismic cable.

4.3 Field Procedures

A total of six seismic lines were collected for the 2011 landstreamer seismic survey (Figure 1.1-2) in agreement with accepted standards of ASTM (2005). The surveying procedure can be divided into the three following steps: station surveying with flags, seismic data acquisition, and GPS surveying.

4.3.1 Station Surveying with Flags

Prior to collecting seismic data, stations were positioned using a tape measure and marked using pin flags. Flags were planted at 2 m intervals to guide the placement of the seismic source during seismic data acquisition (Figure 4.3-1). Using a permanent marker, flags were labeled with the station number. The first pin flag for each line was labeled as station one, and station numbers were increased by an increment of one for each consecutive flag. Because shot records were collected at every station, the shot interval (i.e. the shot move-up) is also 2 m. The labeled flags also helped the seismic observer quality control the observer's notes, so station numbers were correctly linked to the shot record's data file. GPS coordinates were collected at each pin flag location.

Figure 4.3-1. Stations were marked and labeled with pin flags. Each station was located using a tape measure, and flags were spaced 2 m apart. The flags were used to guide the placement of the seismic source during data acquisition and helped ensure that the shot move-up was 2 m.

4.3.2 Seismic Data Acquisition

Overview

Three crew members were required to collect seismic data. Two of the workers were in the pickup truck. The driver was responsible for moving the truck, the seismic source, and landstreamer cable to the next source location and to help quality control shot records during

acquisition. The passenger recorded the observer's notes and was the primary quality control for shot records during acquisition. The third crew member walked beside the seismic source during surveying and controlled the release of the AWD when signaled by the truck driver or passenger. When performing a shoot-through, again, only three crew members are necessary; two crew members were assigned to a secondary truck which pulls the AWD while the third crew member records observer notes and quality controls seismic data in a stationary truck (Figure 4.3-2). This approach is a fast method for acquiring seismic reflection data with a relatively small field crew size.

All lines, except line D, began with a shoot-through procedure. Though the beginning of line D did not require a shoot through, the placement of line D was chosen to ensure the continuity of full CMP coverage between the 2009 and 2011 landstreamer data. The landstreamer was laid out so that geophones were aligned with the station flags. During the shoot-through the landstreamer remained stationary, and shot records were recorded at every station along the landstreamer cable. After the shoot-through, the landstreamer was connected to and in line with the AWD in an off-end shooting geometry, and shot records were collected with the source offset 6 m from the near-offset geophone. The shot move up was 2 m for both the shoot-through and off-end shooting procedures. During the shoot-through and during off-end shooting, a total of 5 shots were collected at each station and vertically summed. Vertically stacking shot records in the field helps to increase the data signal-to-noise ratio. Vertical stacking is especially helpful in windy conditions which we experienced during the 2011 Hanford survey. Other survey parameters are listed in Table 4.3-1.

On line A North, a steep hill prevented us from using the pickup truck and AWD trailer. Instead, as the seismic source, we used a 7 kg (16 lb) sledge hammer to strike a smaller aluminum-alloy plate. Using a sledge hammer slowed production yet allowed us to collect continuous data through the steep terrain. When using the sledge hammer 9 shots were stacked together instead of 5 stacks when using the AWD (Table 4.3-1). The number of stacks was increased because the sledge hammer produced less energy, and additional stacks helped increase the signal-to-noise ratio. The sledge hammer was only used for 53 stations on line A North.

Table 4.3-1. List of acquisition parameters used for seismic lines.

Source type	227 kg (500 lb) accelerated weight drop 7 kg (16 lb) sledge hammer
Recording system	24 channel Geometrics Geode 24 bit seismographs
Lateral source offset (shoot through geometry)	source offset perpendicularly 1.5 m from landstreamer
Source near-receiver offset (off-end shooting geometry)	source in-line but offset 6 m from near-offset geophone
Vertical stack	5 stacks→227 kg (500 lb) AWD 9 stacks→7 kg (16 lb) sledge hammer
Receiver interval	2 m
Nominal fold	48
Live channels	96
Sampling rate	0.5 ms
Record length	2.0 s

Shoot-Through Procedure

All seismic lines, except for line D, were started with a procedure called a shoot-through. For a shoot through, the Geodes and acquisition computers are located in a primary truck at the end of the landstreamer. During the shoot-through, the primary truck, landstreamer, and geophones remain stationary while a secondary truck tows the AWD alongside the landstreamer. The AWD is offset approximately 1.5 m perpendicular to the landstreamer. Shot records are recorded at 2 m intervals next to each station which is occupied by a geophone. A long trigger cable was used to connect the AWD to the acquisition computer, and the trigger cable allowed the AWD to communicate the recording start time to the acquisition computer. The seismic observer in the primary truck communicated with the driver in the secondary truck via hand-held radios; using the radios, the seismic observer would give the signal to release the AWD. The shoot-throughs increased the Common Midpoint (CMP) fold coverage at the start of the lines compared to starting with the off-end shooting procedure.

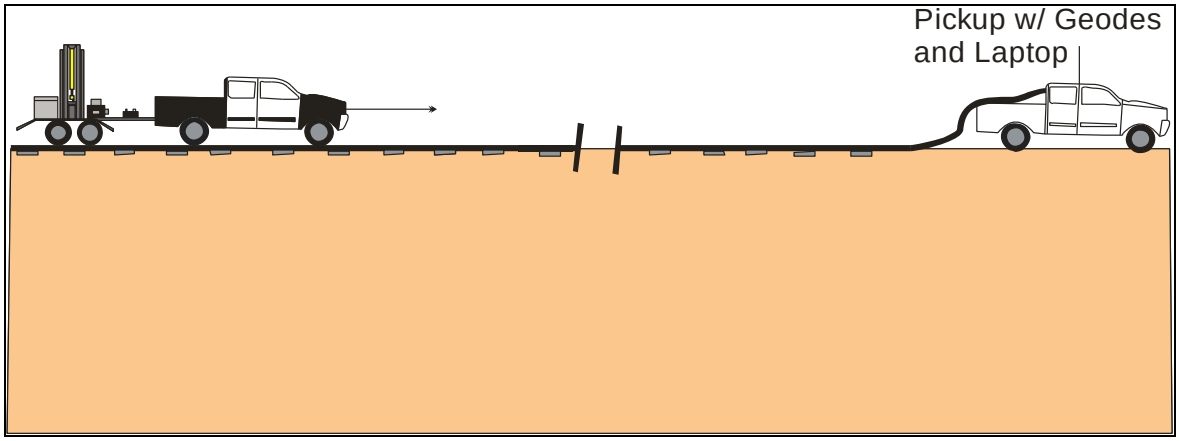


Figure 4.3-2. A schematic demonstrating the shoot-through procedure. At the beginning of each seismic line, the geophones were located at stations 1-96 and remained stationary during the shoot through. The white truck with the Geodes and the acquisition laptop also remained stationary during the shoot-through. A secondary truck (the black truck) towed the AWD trailer alongside the landstreamer and activated the source next to each geophone. Data were collected in the white pickup truck, and a long trigger cable connected the AWD drop to the laptop in the stationary truck (figure after SGW-43746, 2009).

Off-End Shooting Procedure

The off-end shooting procedure was implemented after the shoot-through, except for line D which was collected entirely using the off-end shooting procedure. The majority of the seismic data were collected using an off-end shooting geometry which began as soon as the AWD proceeded 6 m past the near offset geophone (Figure 4.3-3). When the AWD was 6 m past the near-offset geophone, the landstreamer was chained to the back of the AWD trailer. Off-end means the seismic source (i.e. the AWD) is offset from the end of the landstreamer cable and in line with landstreamer cable. During off-end shooting, the AWD trailer and the landstreamer are moved together as a single unit, and the relative geometry between the seismic source and geophone array is kept constant—i.e. both the source and receivers move ahead 2 m. In the 2011 survey, the source and near-receiver offset was 6 m (Figure 4.3-4). When the truck and trailer proceed to the next station, the driver backs up the trailer to relieve tension in the landstreamer. When tension in the landstreamer was not relieved, unwanted cable noise is observed in the data.

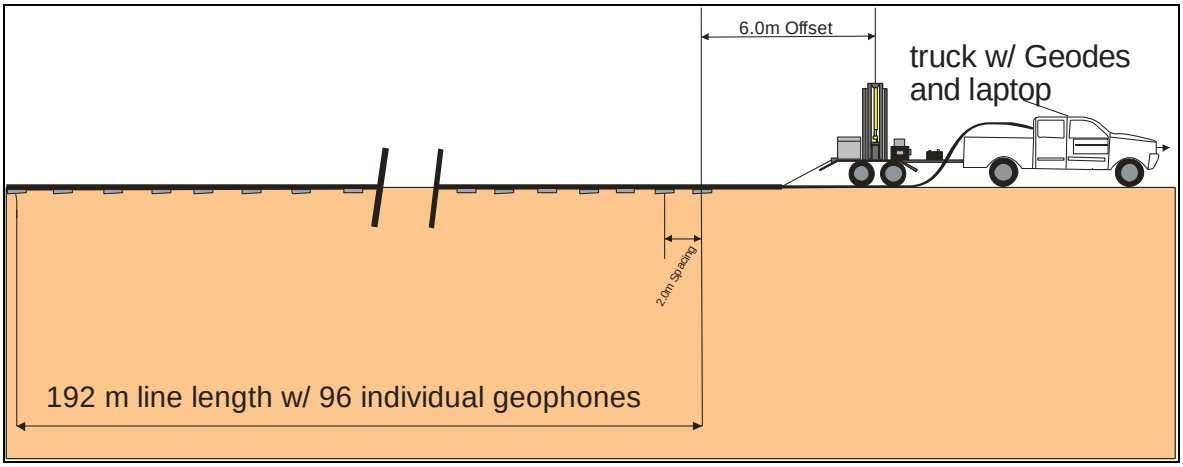


Figure 4.3-3. A schematic demonstrating the off-end shooting procedure where only one truck is required. After the source had shot through the line as demonstrated in Figure 4.3-2, the source was moved in line with the landstreamer cable and offset 6 m from the near-offset geophone. At each station thereafter the source shot at every station (every 2 m), and each time the source moved forward to the next station, the geophone array was also moved forward one station. The process was continued until the seismic line was completed (figure after SGW-43746, 2009).

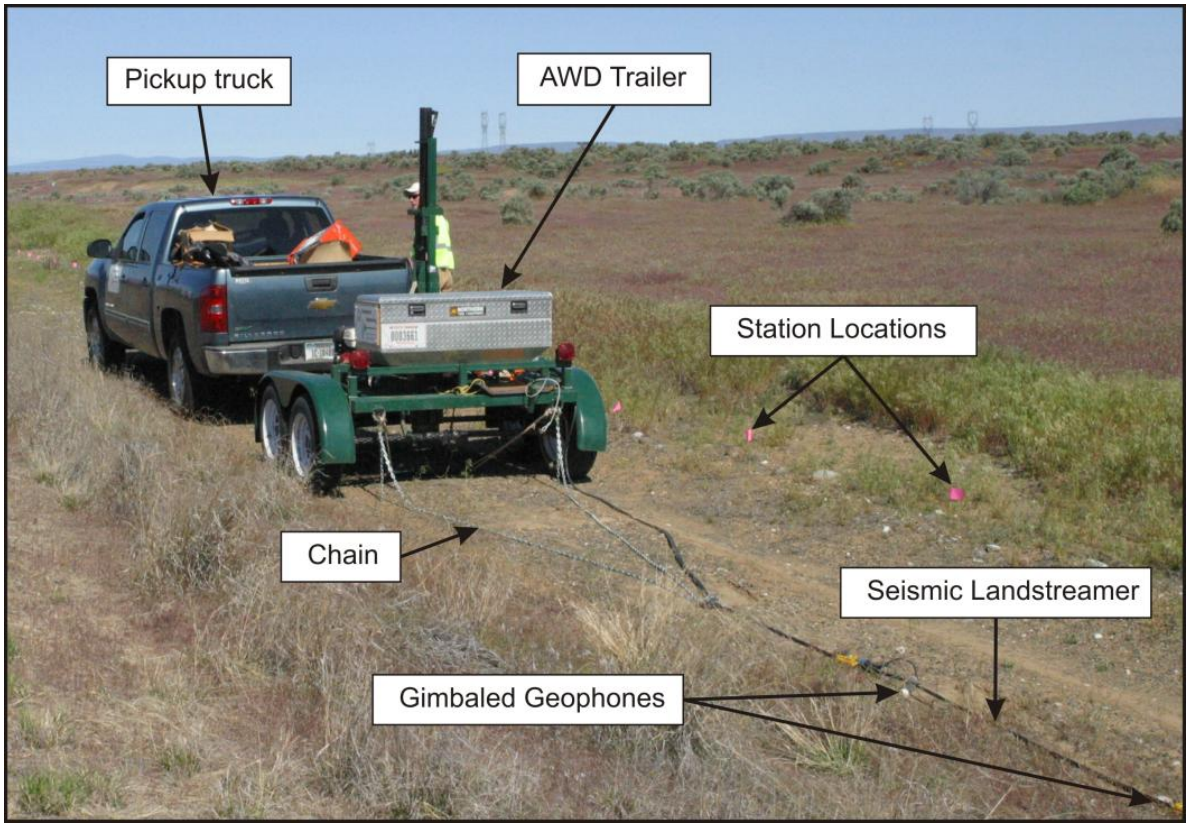


Figure 4.3-4. Photograph of the seismic system during off-end shooting geometry. The truck tows the AWD trailer and the landstreamer is chained to the back of the AWD trailer. During off-end shooting, the move up of the AWD trailer is guided by flagged station locations. The seismic landstreamer is dragged behind the trailer, and gimbaled geophones also reside on station locations. After pulling ahead to the next station, the trailer is backed up to reduce tension in the landstreamer. If tension is not relieved, cable noise will be observed in the data.

4.3.3 GPS Surveying

GPS surveying was conducted after seismic surveying to ensure that the exact shot locations and receiver locations would be marked with the GPS equipment. On line A South and line D, coordinates were recorded at every station, but for all other lines, only every other station was recorded. Collecting GPS data on every other station helped save time in the field. The GPS coordinate data for the missing stations is still needed for seismic data processing, so these missing coordinates were interpolated from measured points. For lines A North , B, C East, and C West, the small topographic relief, in conjunction with a small (2 m) station spacing, justified skipping every other station, and the required interpolation was sufficient for seismic data processing. The GPS data were recorded using a Leica 1200 Global Positioning System by Leica Geosystems (Figure 4.3-5).

GPS coordinates—horizontal and vertical—were recorded on Leica's mobile Rover unit, and raw GPS coordinates are relative to the stationary Base unit. The Rover unit and Base unit communicate by a radio signal, and the two units must be in line-of-sight to ensure connectivity. Because of the study area terrain, a single base station would not have line-of-sight over the entire extent of the survey area, so multiple base station locations were required. A total of eight base station locations were implemented in the GPS survey: line A North and line B had two base stations per line while line A South, line C East, line C West, and line D each one base station.

Because coordinates are recorded relative to the base station's location, each base station reading was corrected to its absolute position using the Online Positioning User Service—OPUS (http://www.ngs.noaa.gov/OPUS/). The survey-grade GPS files (RINEX files which were exported using the LEICA Geo Office program) collected by the base station unit were uploaded and processed to produce highly accurate National Spatial Reference System (NSRS) coordinates. OPUS calculates the base station NSRS coordinates from the National Geodetic Survey network of Continuously Operation Reference Stations. Base station accuracies—including two axes of horizontal and one axis of vertical data—ranged from 0.6 cm to 6.3 cm while most accuracies were below 2 cm.

GPS data were recorded in latitude and longitude on a WGS 1984 ellipsoid, but were converted to NAD 1983, Washington State Plane, South, FIPS 4062. Vertical data were then converted to NAVD 1988 orthometric heights using the GEOID09 model. GPS data processing was done in the LEICA Geo Office program. After converting GPS coordinates, lines with GPS data for only every other station were interpolated. In summary, the final coordinates loaded to the seismic trace headers were NAD-83, Washington State Plane, South, FIPS, 4062 for the horizontal coordinates and NAVD-88 for elevation data. These final GPS data are essential for the seismic data processing sequence and are necessary for georeferencing purposes.

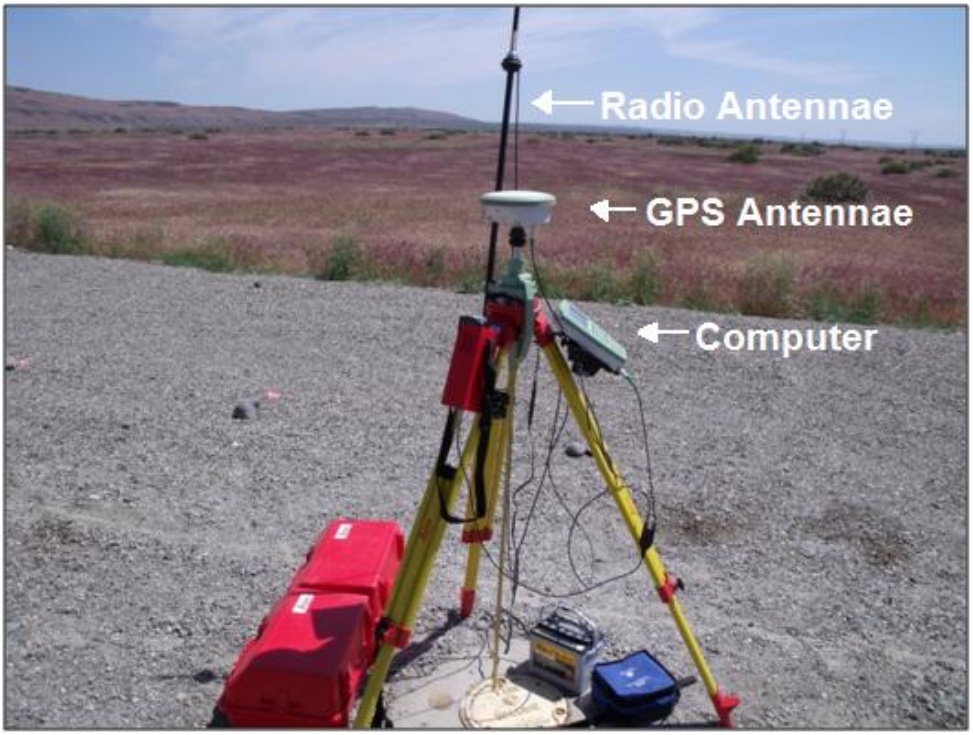


Figure 4.3-5. Photograph of the Leica GPS base station used in the 2011 landstreamer survey. The GPS antennas for both the rover and the base station receive satellite signals which are relayed to handheld computers via Bluetooth connections. Data are communicated between the rover and base station computers through radio signals (figure after SGW-43746, 2009).

4.4 Seismic Data Processing

Seismic data processing was performed by TRICON Geophysics, Inc., Denver, CO. Seismic data were processed according to bid specifications shown in Table 4.4-1. The chosen processing steps are consistent with the 2009 landstreamer processing steps which were proved to accurately define the underlying basalt surface. TRICON Geophysics, Inc. is a fully licensed Focus 3D interactive 64-bit software-processing center and features Paradigm Geodepth 2D Time & Depth software with the curved ray turning wave option. The software used for the 2011 data included: (1) PARADIGM Focus, (2) TRICON Geophysics, (3) Refraction analysis using Hampson-Russell GLI3D, (4) TSUNAMI 2D Kirchhoff PSTM, and (4) PARADIGM GeoDepth 2D Time & Depth. As in 2009, the 2011 processing datum is 200 m and the replacement velocity is 4000 m/s.

For each seismic line, the final results include six different kinds of processed seismic sections (Table 4.4-2). Unmigrated and postack migrated time sections include sections with and without poststack signal enhancement (i.e. FX deconvolution). Unenhanced unmigrated time sections, enhanced unmigrated time sections, unenhanced 90% poststack time-migrated sections, enhanced 90% postack time-migrated sections, and prestack time-migrated sections can be found respectively in appendices A, B, C, D, and E (Table 4.4-2). All time sections are uninterpreted. Interpreted prestack depth-migrated seismic sections can be found in the following section (5.0 RESULTS AND INTERPREATIONS), and uninterpreted prestack depth-migrated seismic sections can be found in appendix F.

Table 4.4-1. Data processing bid specifications used by TRICON Geophysics.

Data Reformatting
Trace Edit
Geometry Assignment
Gain Recovery/Spherical Divergence
Surface Wave Removal (f-k filtering)
Surface Consistent Amplitude Scaling
Trace Balancing
Surface Consistent Gap 12 ms Deconvolution
Spectral Whitening and Balance 20-120 Hz
Refraction Statics
CDP Sort
Interactive First Velocity Analysis
2-D Normal Moveout (NMO) Corrections
Mute
Brute Stack
2-D Surface Consistent Residual Statics (6 ms limit)
Intermediate Stack
2nd Interactive Velocity Analysis
2-D Surface Consistent Residual Statics (3 ms limit)
NMO Analysis and Application
CDP Trim Statics (2 ms limit)
*Pre-Stack Depth Migration (or Pre-Stack Time Migration)
Stack
**Post-Stack Time Migration
Final Filter and Gain Modification: Time variant trace equalization to adjust RMS levels to parity.
***Post Stack Signal Enhancement FX Decon (noise reduction filter applied after stack)
SEGY output of data

*Processing step used for prestack depth or prestack time migrations only
**Processing step used for poststack time migrations only.
***Processing step used for prestack depth migrations, prestack time migrations, enhanced poststack time migrations, and enhanced unmigrated time sections only.

Table 4.4-2 Final seismic sections delivered by TRICON Geophysics Inc and their respective locations in this report.

Unmigrated time sections (without poststack signal enhancement)	Appendix A
Unmigrated time sections (with poststack signal enhancement)	Appendix B
90% Poststack time-migrated sections (without poststack signal enhancement)	Appendix C
90% Poststack time-migrated sections (with poststack signal enhancement)	Appendix D
Prestack time-migrated sections	Appendix E
Interpreted prestack depth-migrated sections	Section 5.0 RESULTS AND INTERPRETATIONS
Uninterpreted prestack depth-migrated sections	Appendix F

5.0 RESULTS AND INTERPRETATIONS

5.1 Line A North

Line A North is a north-south trending line containing approximately 4.3 km of subsurface-CDP data coverage. Figure 5.1-1 shows the interpreted PreStack Depth-Migrated (PSDM) seismic section of line A North. The interpreted top of the basalt is a relatively uneven surface with a large trough or valley between the distances of 2200 m and 3100 m. The total relief of this trough is about 70 m, and the material within this trough which overlies the interpreted top of the basalt appears to be heavily fractured or faulted. Five faults are grouped together on the southern end of this trough at a distance of approximately 2000 m, and one fault was interpreted at the base of the trough at the 2600 m distance mark. A few other faults are scattered throughout this seismic line, and another group of four faults is located at about the 1100 m distance mark. A shallower trough, similar in characteristics to the large trough is located between the 100 m and 900 m distance marks. Plots of check-shot velocities from wells 699-61-62 and 699-55-60A were spliced into the seismic section. Well 699-61-62 is offset perpendicularly 160 m to the West of line A North, and well 699-55-60A is offset perpendicularly 475 m to the East of line A North. Although no basalt was encountered in well 699-55-60A, we note that a sudden increase in velocity (over 3000 m/s) occurs at the same depth where we have interpreted the top of the basalt in line A North. However, because well 699-55-60A is such a far distance (nearly half of a kilometer) from line A North, the similarity in depths between the well's velocity increase and line A North's interpreted basalt surface may be coincidental.

5.2 Line A South

Line A South is a north-south trending line and contains approximately 1 km of subsurface-CDP data coverage. Figure 5.2-1 shows the interpreted PSDM seismic section of line A South. Line A South and line A North are separated by a busy road which is why these two lines were not collected as one seismic line. In line A South, the top of the basalt is relatively smooth and dips towards the south. There are possible faults below 80 m of elevation, but none of these faults extend into the upper portion of the basalt and were, therefore, not interpreted. No wells with check-shot information are available for line A South.

5.3 Line B

Line B trends northwest-southeast and has about 2.9 km of subsurface-CDP data coverage. Figure 5.3-1 shows the interpreted PSDM seismic section of line B. Between distances 1250 m and 1800 m the top of the basalt is jagged and uneven. Some of these jagged features might be associated with two small faults which are located at the 1520 m and 1570 m distance marks. Only one other possible fault was observed at about the 550 m distance mark. A sharp corner in the top of the basalt is located at about the 370 m distance mark. Check-shot velocity profiles from wells 699-61-62 and 699-60-59 were projected onto the PSDM seismic section of line B (Figure 5.3-1). The top of the basalt in both wells are about 12 m below the interpreted top of the basalt in line B, but this is not unreasonable given the sharp variations in the basalts topography and that wells are not located directly on line B. Wells 699-61-62 and 699-60-59 are offset 150 m to the south and 168 m to the north, respectively, of line B. Please note the high velocity range (0 m/s to 7000 m/s) on well 699-60-59 compared to the velocity range (0 m/s to 4000 m/s) of other wells. On well 699-60-59 (and similar to most other wells), basalt is first encountered where the velocity becomes about 3000 m/s and not where the velocity increases sharply to about 6000 m/s. At first glance of well 699-60-59 one might mistake the top of the basalt as the sharp increase to 6000 m/s, when actually basalt was first encountered at the less-drastic increase to 3000 m/s.

The faults interpreted in this line are unusual because they do not appear to extend more than 30 m below the top of the basalt. If these are not faults then these jagged features between the 1250 m and 1800 m distance marks might be attributed to erosion. The sharp corner in the top of the basalt located at 370 m distance mark might also be an erosional feature.

5.4 Line C East

Line C East trends west-east and has about 1.6 km of subsurface-CDP data coverage. Figure 5.4-1 shows the interpreted PSDM seismic section from line C East. The top of the basalt surface is relatively even, or flat, with a small bump located at about 350 m which is a possible block left over from erosion. Two wells, 699-52-55 and 699-52-55B, are only about 3 m apart from each other and both are offset perpendicularly about 152 m to the north of line C East. The check-shot velocity profiles from these two wells were projected onto the PSDM seismic section of line C East. The basalt observed in the wells is about 15 m higher in elevation than the basalt observed on line C East's PSDM seismic section. This discrepancy is not unusual given the rugged characteristic of the top of the basalt and that these wells are about 152 m from the seismic line. Three faults were interpreted at the 220 m, 670 m, and 1070 m distance marks and all are dipping towards the east.

5.5 Line C West

Line C West also trends west-east and recorded about 1.6 km of subsurface-CDP data coverage. Figure 5.5-1 shows the PSDM seismic section from line C West. On line C West, the imaged basalt surface exhibits more localized topographic relief (than line C East) which is attributed to erosional processes, but line C West has a similar remnant block of basalt which is located at 650 m. Again these irregularities in the basalt's top surface were likely caused by catastrophic erosion during the Ice Age floods. Five faults were interpreted at the 200 m, 450 m, 590 m, 1000 m, and 1250 m distance marks. No wells with check-shot information were close enough to correlate to line C West.

5.6 Line D

Line D trends west-east and contains about 0.9 km of subsurface-CDP data coverage. Figure 5.6-1 shows the PSDM seismic section for line D. The surface of the top of the basalt is smooth compared to all other seismic lines from the 2011 survey. Only two faults were interpreted on this seismic line at distances of 230 m and 580 m along the top of the profile. No well information was tied into line D.

5.7 Discussion and Summary

All the final PSDM seismic sections were merged into a fence diagram to show the spatial arrangement of the seismic lines (Figure 5.7-1). The average vertical resolution for all the PSDM seismic sections is about 4.3 m. The vertical resolution was calculated based on the Rayleigh criterion which states that the vertical resolution is equal to one quarter of the data's dominant wavelength. The value for the dominant wavelength, and therefore vertical resolution, was based on the dominant wavenumber (i.e. the inverse of wavelength) of these data. The dominant wavenumber was calculated by performing a Fast Fourier Transformation on a 200 m vertical section of data located directly beneath the ground surface.

These 2011 data are consistent with the CTUIR 2009 data sets and with the geologic model for the area. These seismic data are also consistent with velocity data from wells nearby the seismic lines. Most seismic lines in this data set show variations in the basalt's topography, and lines A North, B, and C West show evidence of erosion. Most noticeably, the large and small troughs identified in line A North might be large paleochannels either from an ancestral version of the Columbia River, or from an ancestral flood channel. The high amplitude response within the fractured and broken material within the large trough suggests the material might be basalt which might have been deposited in a chaotic manner after erosion. All seismic lines, except for A South, show evidence of faulting. Other than material infilling the trough of line A North, no evidence clearly demonstrates the presences of other geologic units, such as the Ringold formation and Cold Creek unit, overlying the CRBG. Linear features in the shallower portion of the seismic sections are source related features which were not removed by muting. These linear source-related features should not be construed as reflections.

Faults within the CRBG could provide potential vertical pathways between the suprabasalt aquifers and the intrabasalt aquifers. Because of these faults, contaminated groundwater plumes overlying the basalt could potentially spread below the top surface of the basalt. Additionally, deep scours such as the large paleochannel in line A North could potentially expose an intrabasalt aquifer to the overlying suprabasalt aquifer. The paleochannel might also provide a path which is conducive for horizontal groundwater migration.

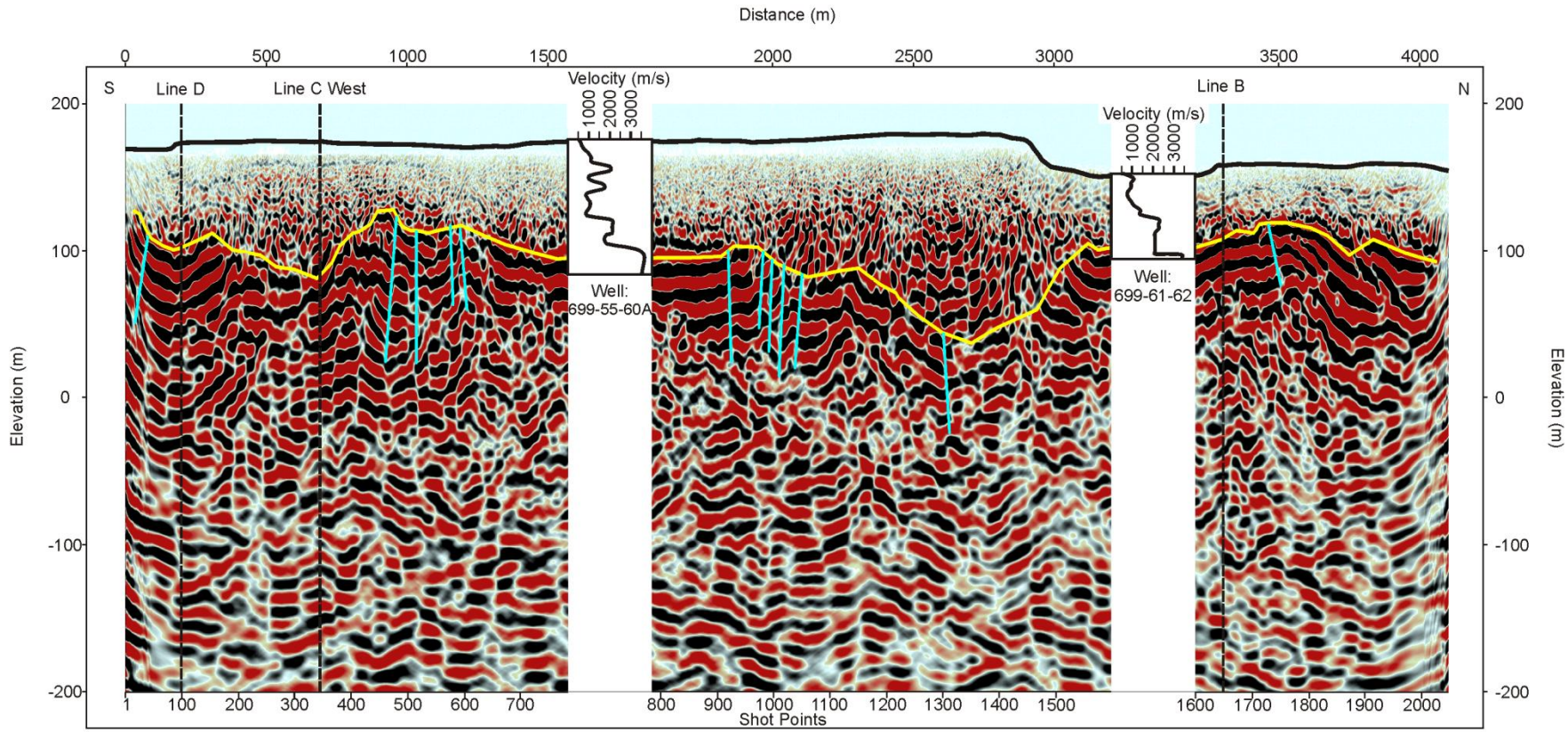


Figure 5.1-1. A prestack depth-migrated seismic section of line A North. The black line represents the ground-surface elevation. The yellow line is the interpreted top of the basalt, and the blue lines are interpreted faults within the basalt. The vertical dashed lines represent the intersection of other seismic lines. The check-shot velocity profiles for wells 699-61-62 and 699-55-60A were projected onto this seismic section at the 900 m and 2530 m distances respectively. The vertical axis is displayed as elevation relative to the North American Vertical Datum (NAVD) of 1988. This seismic section has a vertical exaggeration of 5.3.

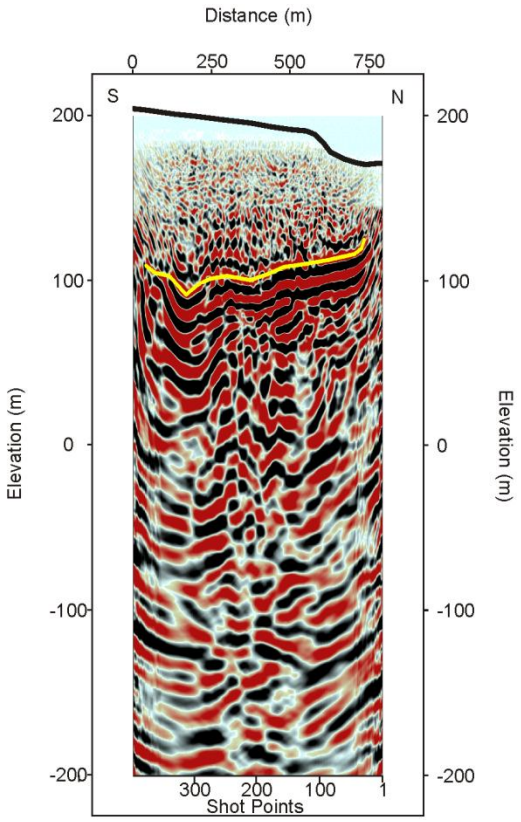


Figure 5.2-1. A prestack depth-migrated seismic section of line A South. The black line represents the ground-surface elevation. The yellow line is the interpreted top of the basalt. The vertical axis is displayed as elevation relative to the North American Vertical Datum (NAVD) of 1988. This seismic section has a vertical exaggeration of 5.3.

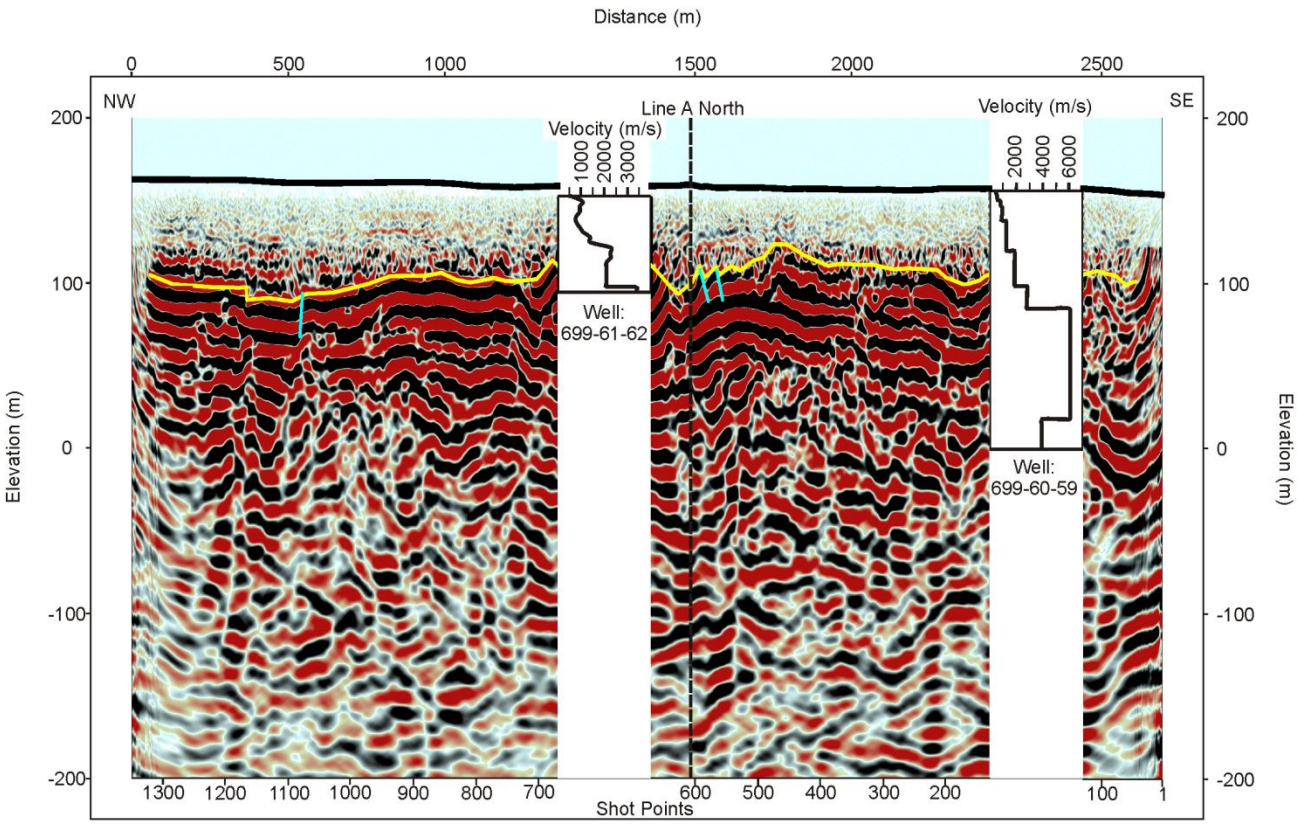


Figure 5.3-1. A prestack depth-migrated seismic section of line B. The black line represents the ground-surface elevation. The yellow line is the interpreted top of the basalt, and the blue lines are interpreted faults within the basalt. The vertical dashed line represents the intersection of another seismic line. The check-shot velocity profiles for wells 699-61-62 and 699-60-59A were projected onto this seismic section at the 1360 m and 2440 m distances respectively. The vertical axis is displayed as elevation relative to the North American Vertical Datum (NAVD) of 1988. Please note the high velocity range (0 m/s to 7000 m/s) on well 699-60-59 compared to the velocity range (0 m/s to 4000 m/s) of other wells. On well 699-60-59 (and similar to most other wells), basalt is first encountered where the velocity becomes about 3000 m/s and not where the velocity increases sharply to about 6000 m/s. At first glance of well 699-60-59 one might mistake the top of the basalt as the sharp increase to 6000 m/s, when actually basalt was first encountered at the less-drastic increase to 3000 m/s. This seismic section has a vertical exaggeration of 5.3.

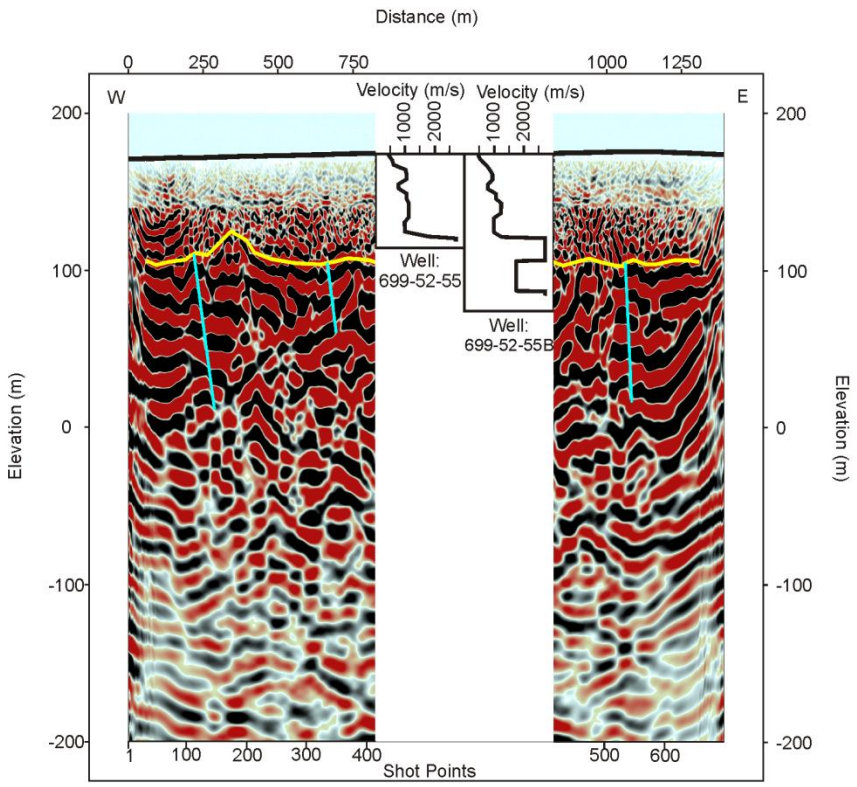


Figure 5.4-1. A prestack depth-migrated seismic section of line C East. The black line represents the ground-surface elevation. The yellow line is the interpreted top of the basalt, and the blue lines are interpreted faults within the basalt. The check-shot velocity profiles for wells 699-52-55 and 699-52-55B were both projected onto this seismic section at the 825 m distance. The vertical axis is displayed as elevation relative to the North American Vertical Datum (NAVD) of 1988. This seismic section has a vertical exaggeration of 5.3.

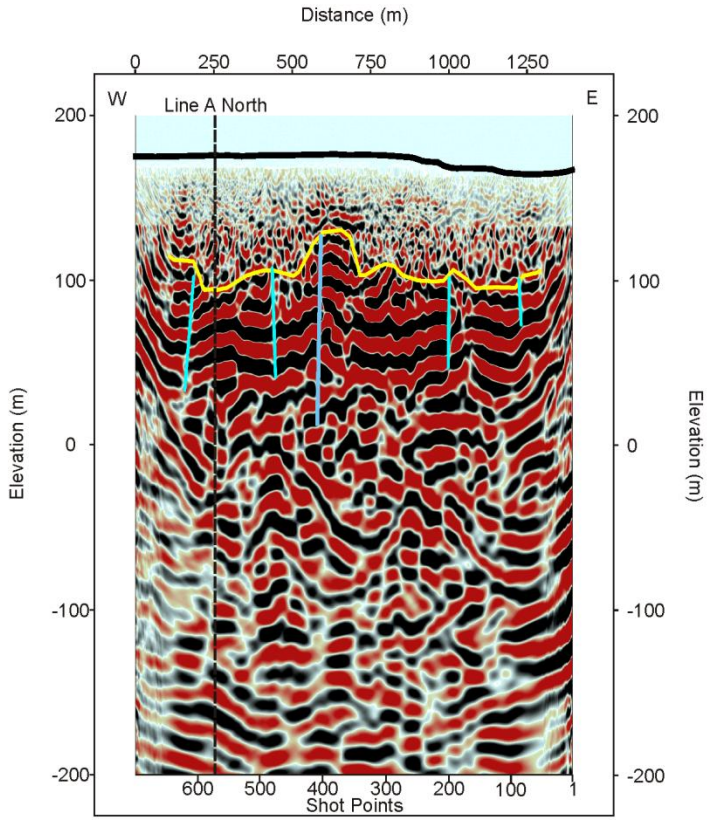


Figure 5.5-1. A prestack depth-migrated seismic section of line C West. The black line represents the ground-surface elevation. The yellow line is the interpreted top of the basalt, and the blue lines are interpreted faults within the basalt. The vertical dashed line represents the intersection of another seismic line. The vertical axis is displayed as elevation relative to the North American Vertical Datum (NAVD) of 1988. This seismic section has a vertical exaggeration of 5.3.

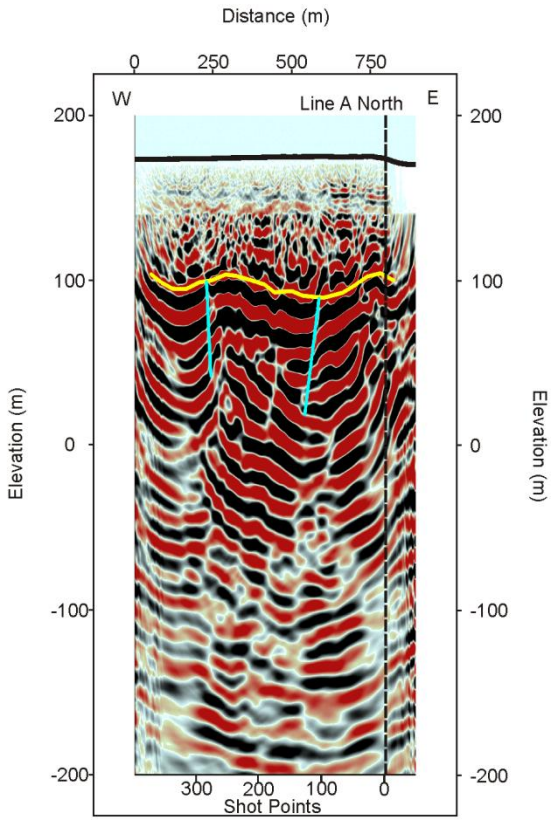


Figure 5.6-1. A prestack depth-migrated seismic section of line D. The black line represents the ground-surface elevation. The yellow line is the interpreted top of the basalt, and the blue lines are interpreted faults within the basalt. The vertical dashed line represents the intersection of another seismic line. The vertical axis is displayed as elevation relative to the North American Vertical Datum (NAVD) of 1988. This seismic section has a vertical exaggeration of 5.3.

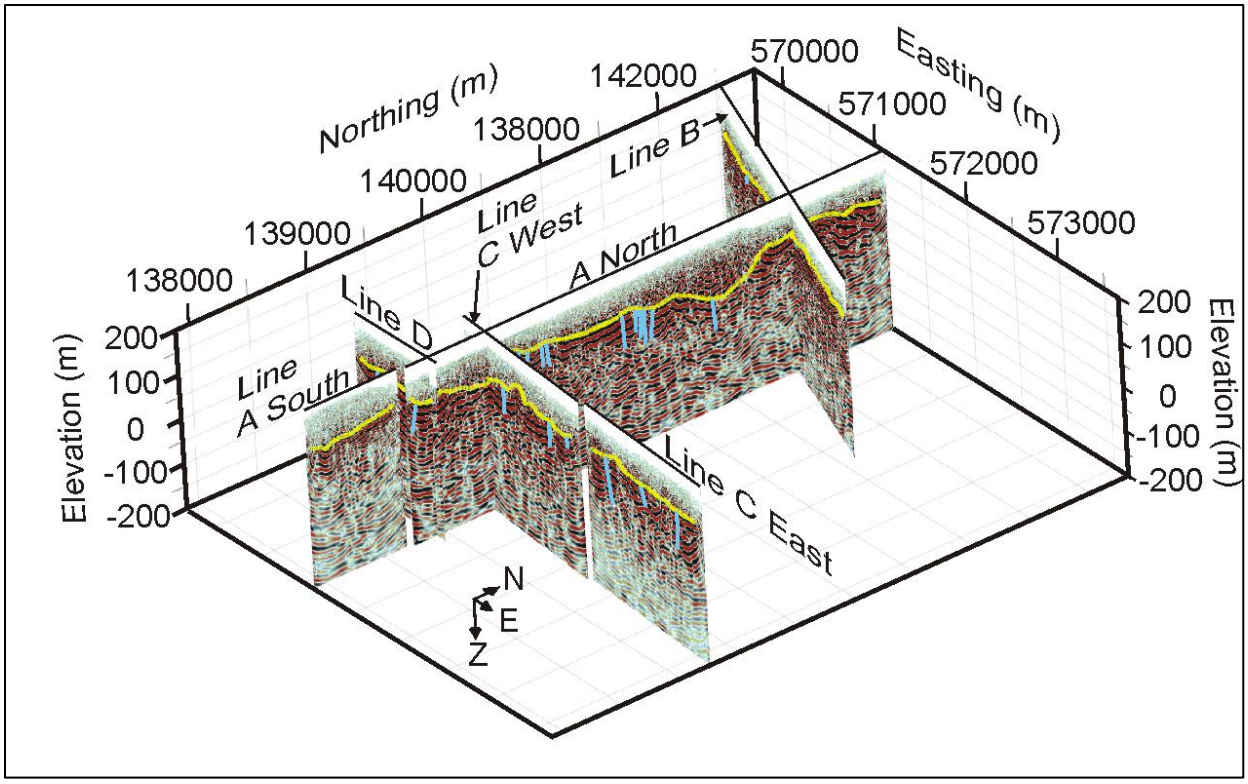


Figure 5.7-1. A Fence diagram of the prestack depth-migrated seismic sections from the 2011 landstreamer survey. The yellow lines represent the interpreted top of the basalt, and the blue lines are interpreted faults within the basalt. The vertical axis is displayed as elevation relative to the North American Vertical Datum (NAVD) of 1988.

6.0 CONCLUSIONS

In April and May of 2011, approximately 12.25 km of high-resolution seismic reflection data were successfully collected on the Central Plateau of the Hanford Nuclear Site using a landstreamer of gimbaled geophones and an accelerated weight drop. Six seismic lines were collected, and all the final processed seismic sections clearly show a strong reflection from the top of the CRBG. Our interpretations (on prestack depth migrations) of the top of the basalt are in agreement with check-shot velocities from nearby wells. According to the Rayleigh criterion these data have a vertical resolution of 4.3 m. Line A North, line B, and line C East show the strongest evidence for erosional features which might have been caused by catastrophic flooding during the Ice Age. Large troughs in the basalt surface on line A North might be interpreted as flood paleochannels. All seismic lines, except for A South show evidence of faulting.

7.0 RECOMMENDATIONS

Because the 2011 survey was conducted in April and May, we encountered more weather related problems than in the 2009 survey. Days of high winds and rain slowed, and sometimes shut down, data collection. We also experienced a slower rate of data collection when data were collected near busy roads. We recommend that future surveys anticipate these weather and cultural related problems. We also recommend bringing a spare power inverter out into the field. The inverter was used to convert the car's DC battery power into an AC power source for the acquisition computer. Even though the power inverter was working in terms of charging the laptop computer's battery, it was also sending electrical signals to the acquisition software and

continuously causing false triggers. After replacing the malfunctioning power inverter with a new power inverter, the acquisition software experienced very few false triggers. We also experienced problems with the AWD's rubber band breaking several times. The rubber bands were prone to breaking especially when the AWD's steel ram dropped lower than the base of the trailer tires. The rubber band broke most often on line B which was collected down the axis of a ditch, causing the trailer tires to be higher than the steel ram's point of impact. When the steel ram dropped too low, the rubber band would strike the edge of the metal support which guides the steel ram. Either the source trailer needs to be redesigned, or future surveys should avoid long stretches of uneven surfaces. Montana Tech might redesign the seismic source so that the steel ram will be accelerated with a nitrogen gas spring rather than with large elastic bands.

8.0 QA/QC AND SOFTWARE USED

As stated in section 6.3.6 in ASTM (2005), every field day the seismic data acquisition system was monitored for quality control purposes. Prior to seismic data collection, the acquisition software, the landstreamer, and every gimbaled geophone were tested. After the acquisition software was turned on, a field worker walked down the line to test every geophone. The real-time noise monitoring featured in Geometrics Seismodule Controller Beta 11 allowed us to monitor each geophone response and allowed us observe possible data acquisition software problems, dead traces, or noisy channels within the landstreamer. After each day of seismic data collection the raw shot records were saved to multiple hard drives and the data were viewed in Parallel Geoscience's Seismic Processing Workshop (SPW) version 2.2.12 to ensure data quality. Data were not collected in high wind, rain, or any other noisy conditions in accordance with standard industry practices stated in 6.3.5.6 in ASTM (2005). On a daily basis, we reviewed shot records in the SPW software to ensure that shot records were properly imaging top of the basalt, which is the geologic target. First break times and timing of reflection events in shot records were carefully observed to ensure proper triggering.

Before sending the GPS and seismic data to TRICON Geophysics Inc. for processing, GPS data were processed using Leica's GeoOffice software. The software used by TRICON for the 2011 data processing included: (1) PARADIGM Focus, (2) TRICON Geophysics, (3) Refraction analysis using Hampson-Russell GLI3D, (4) TSUNAMI 2D Kirchhoff PSTM, and (4) PARADIGM GeoDepth 2D Time & Depth. Final processed seismic sections were exported as SEGY files using TRICON's processing software. Montana Tech preformed minor trace-header manipulation using Landmark's ProMAX processing software in order to properly import seismic sections into the interpretation software. PSDM seismic sections were interpreted in the SMT KINGDOM software, and all seismic sections were displayed and exported as figures using SMT KINGDOM software.

9.0 REFERENCES

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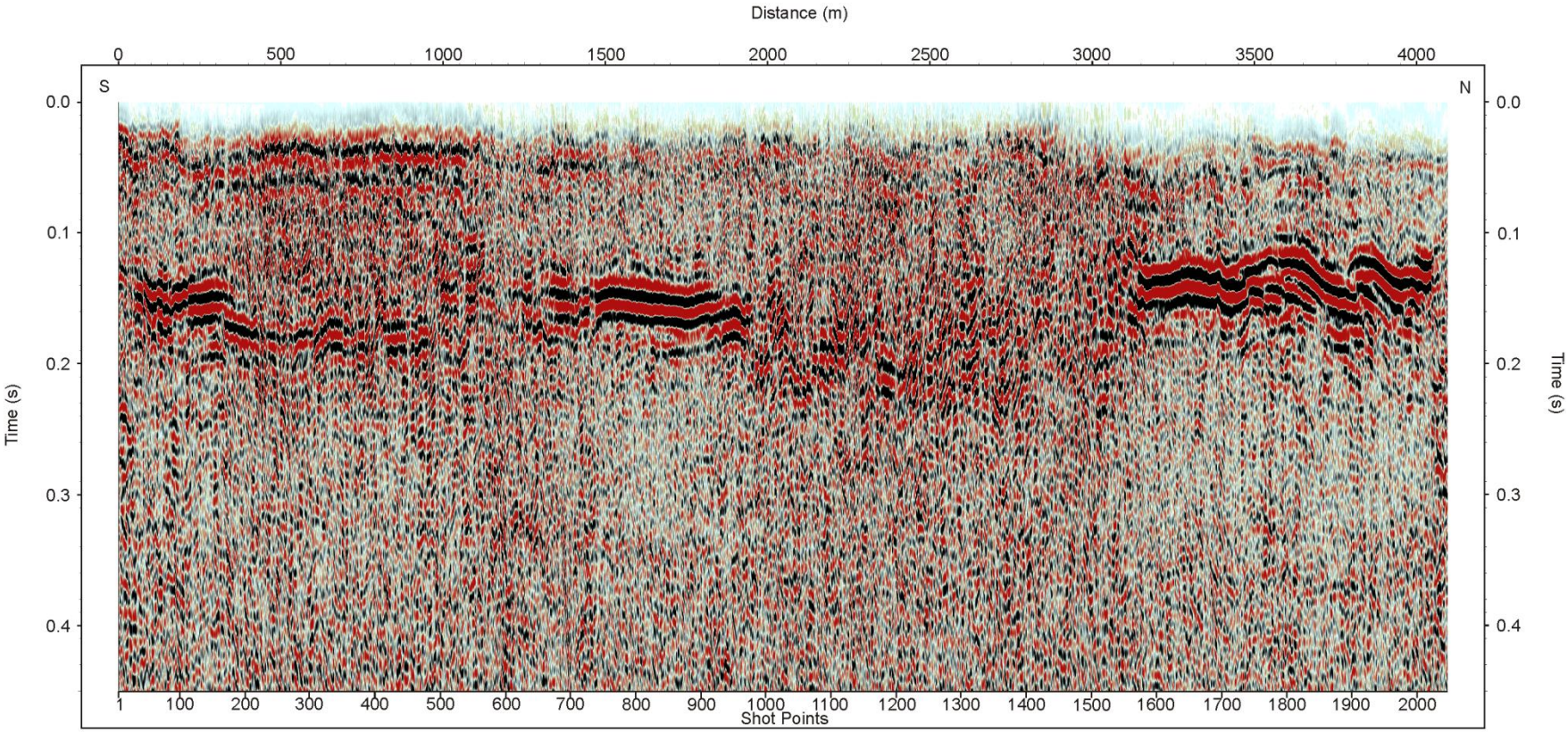
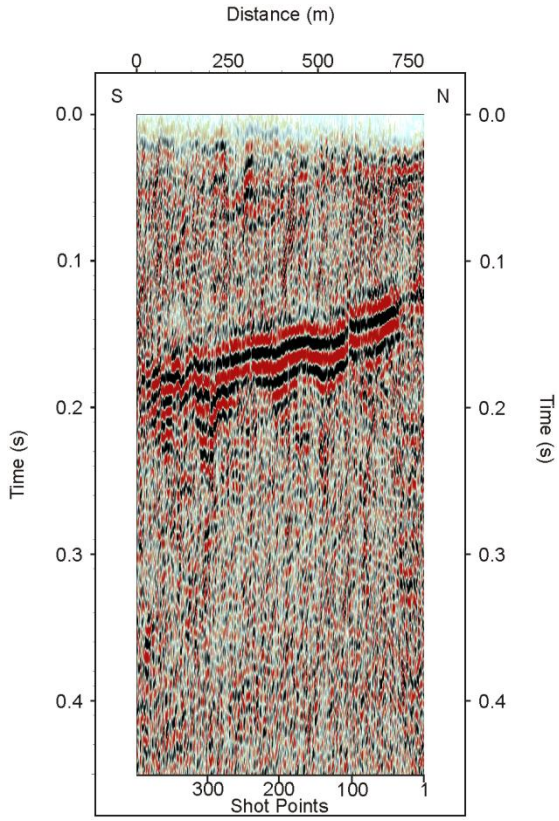
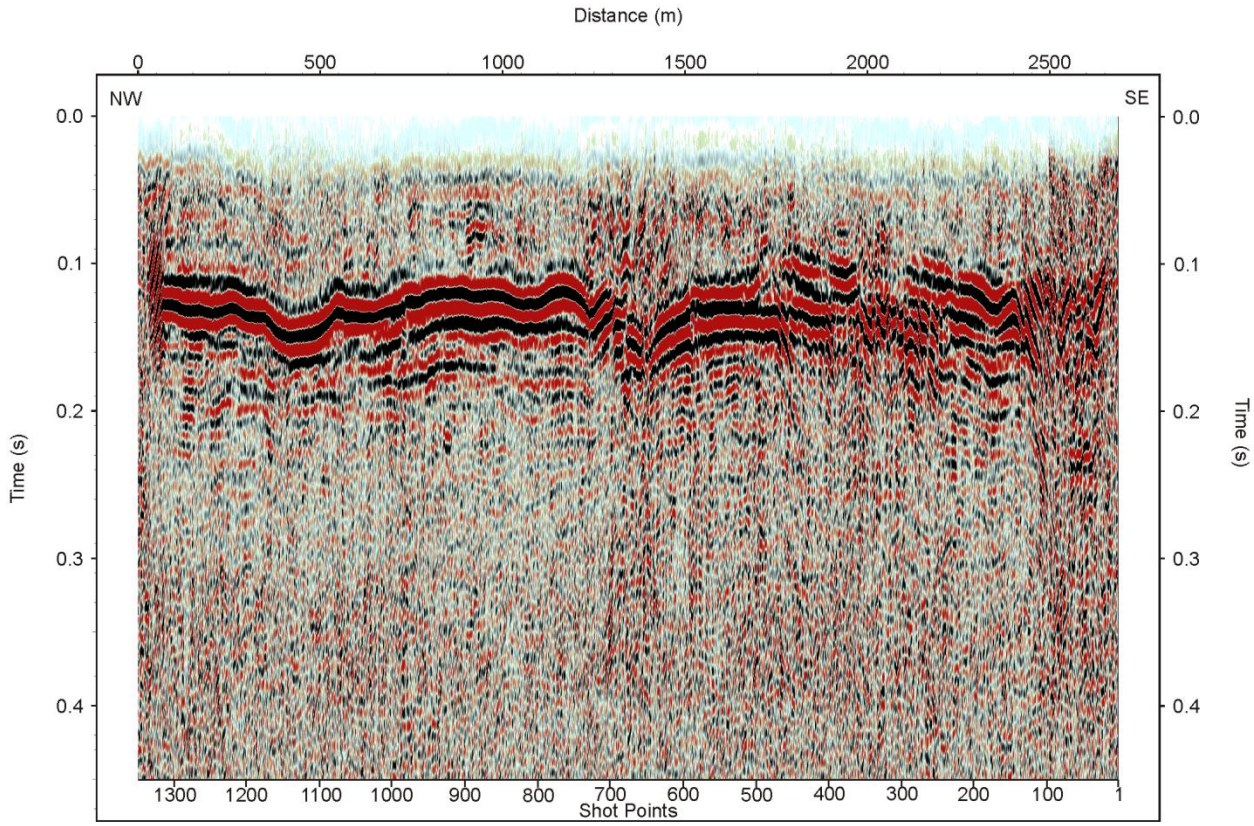
APPENDIX A – Final Time Unmigrated Stacked Seismic Sections



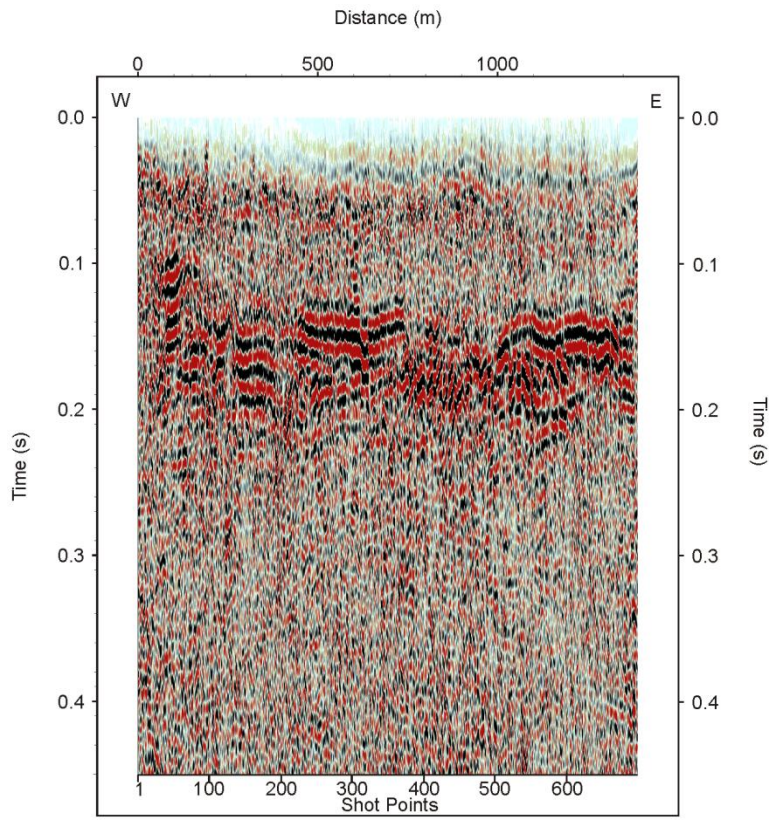
A-1. Final time unmigrated stacked seismic section of line A North.



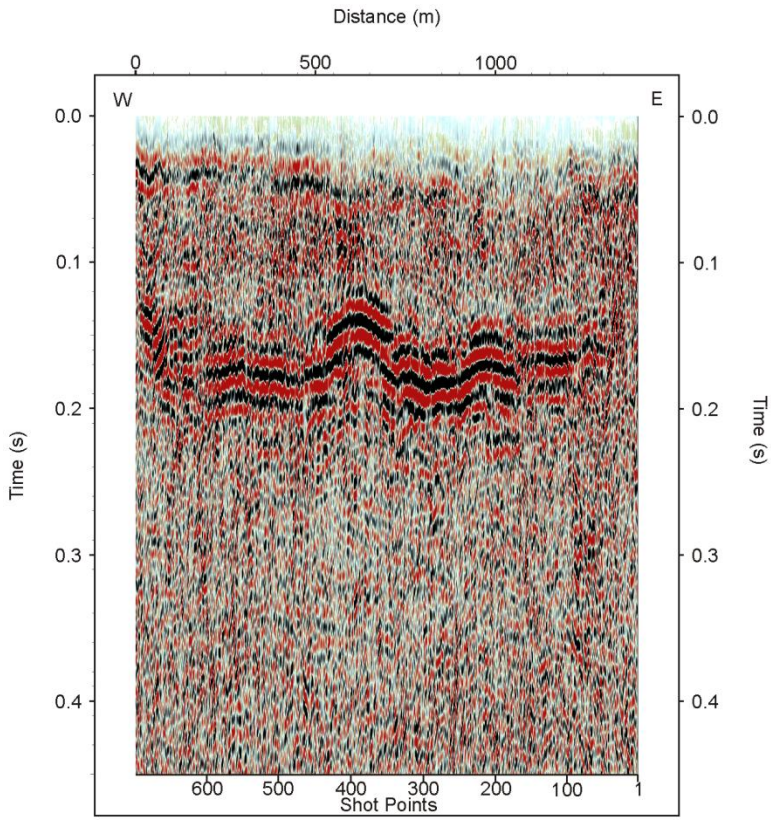
A-2. Final time unmigrated stacked seismic section of line A South.



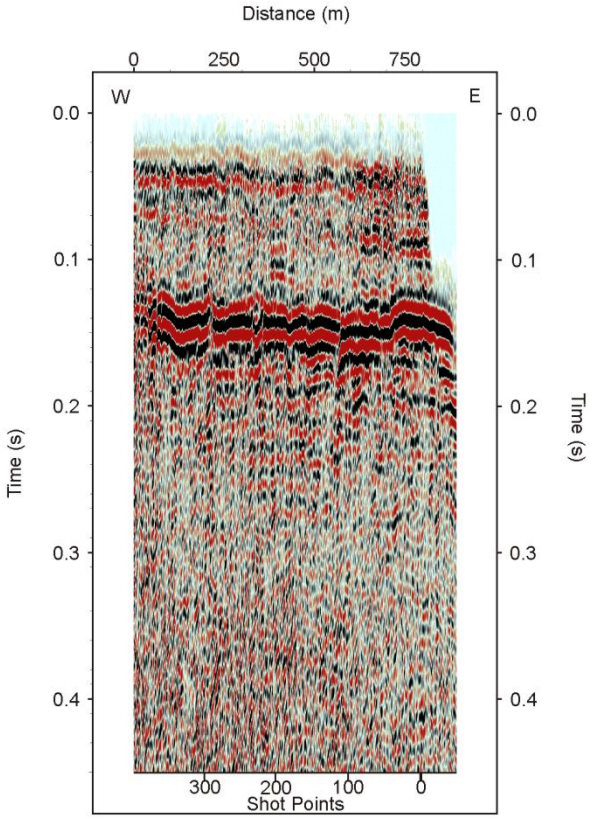
A-3. Final time unmigrated stacked seismic section of line B.



A-4. Final time unmigrated stacked seismic section of line C East.

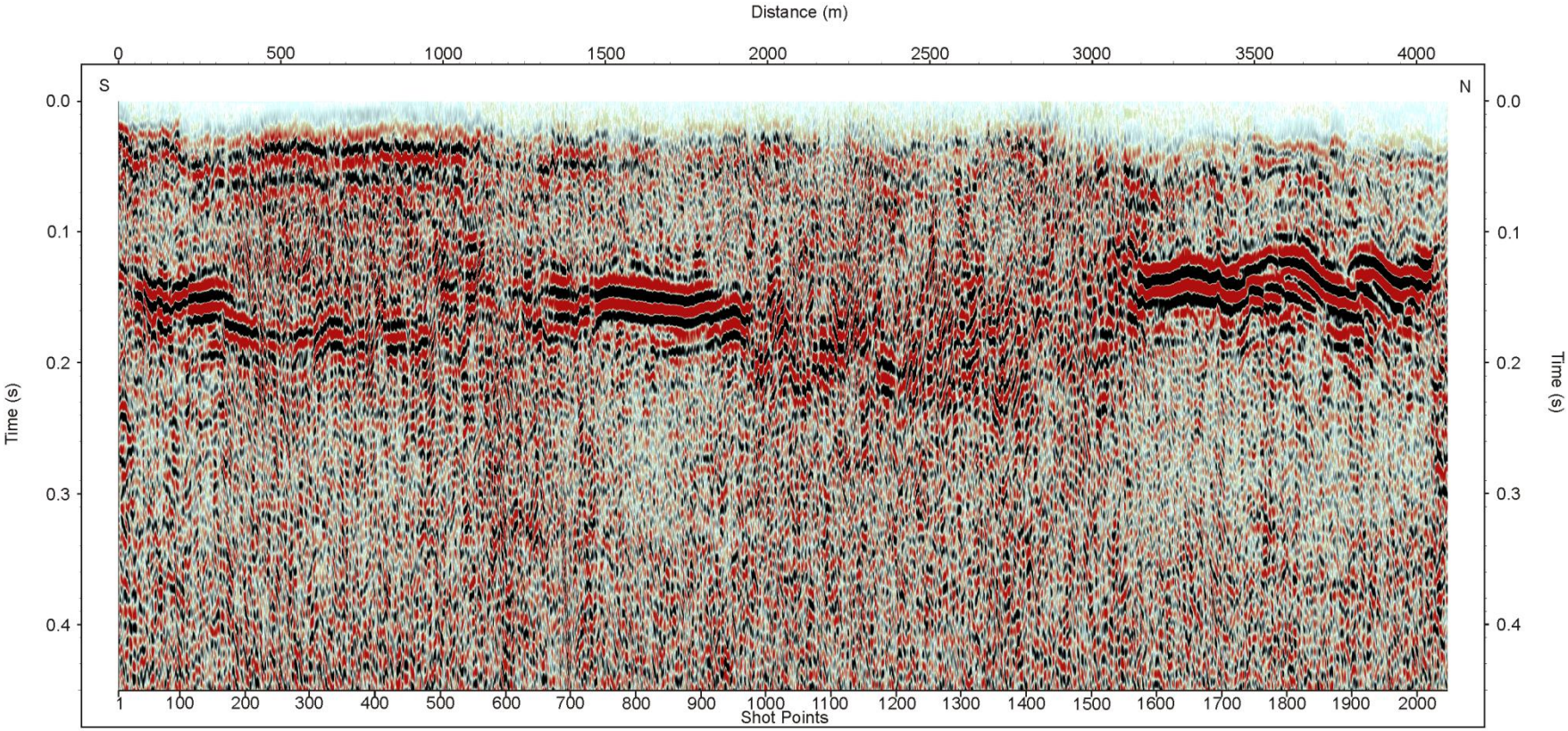


A-5. Final time unmigrated stacked seismic section of line C West.

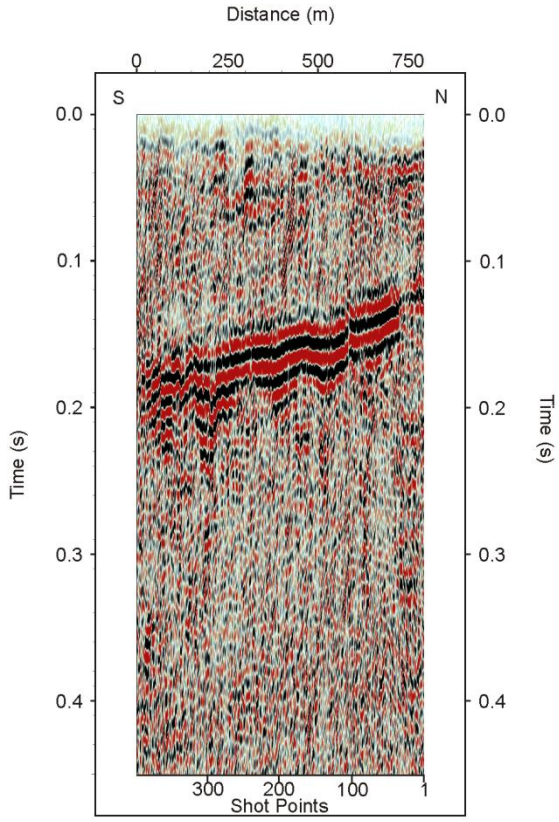


A-6. Final time unmigrated stacked seismic section of line D.

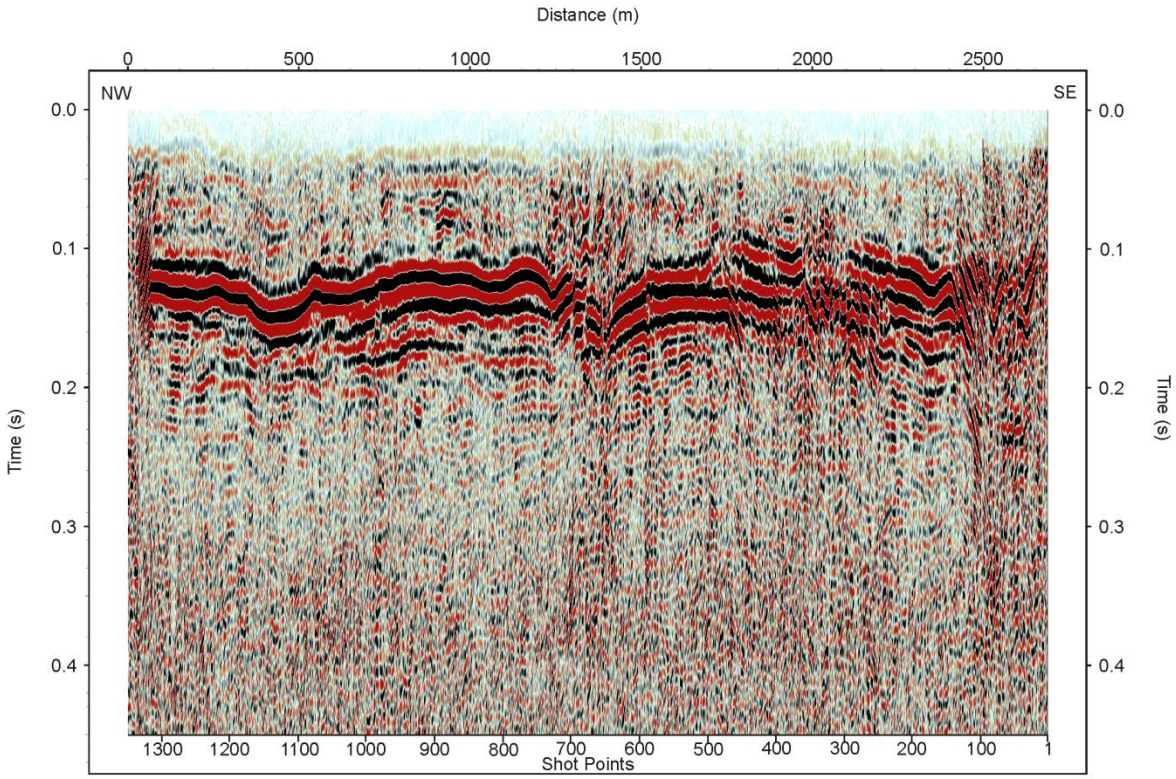
APPENDIX B – Enhanced Final Time Unmigrated Stacked Time Sections



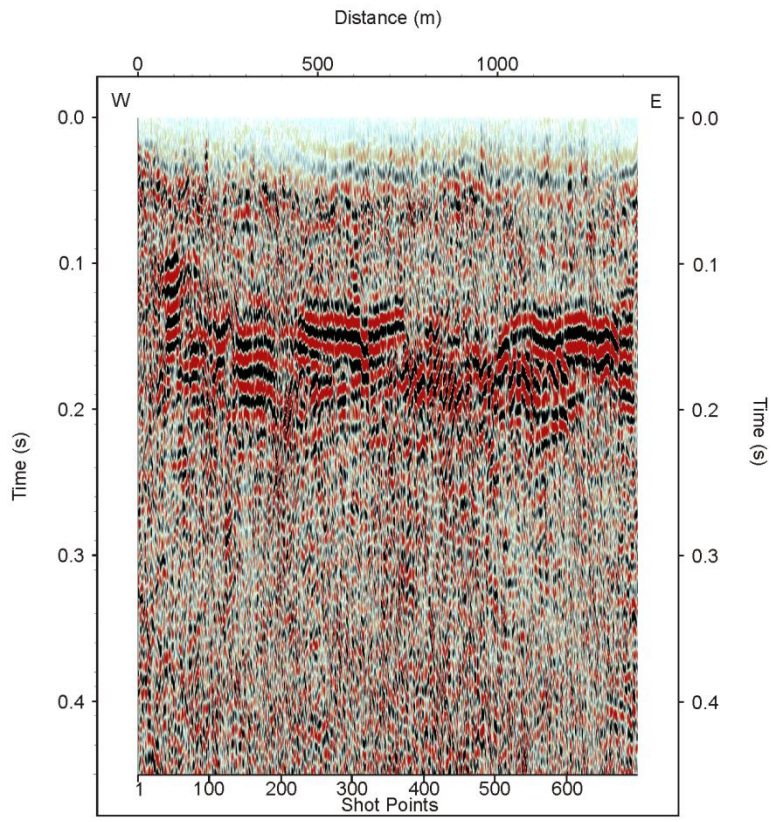
B-1. Enhanced final time unmigrated stacked seismic section of line A North.



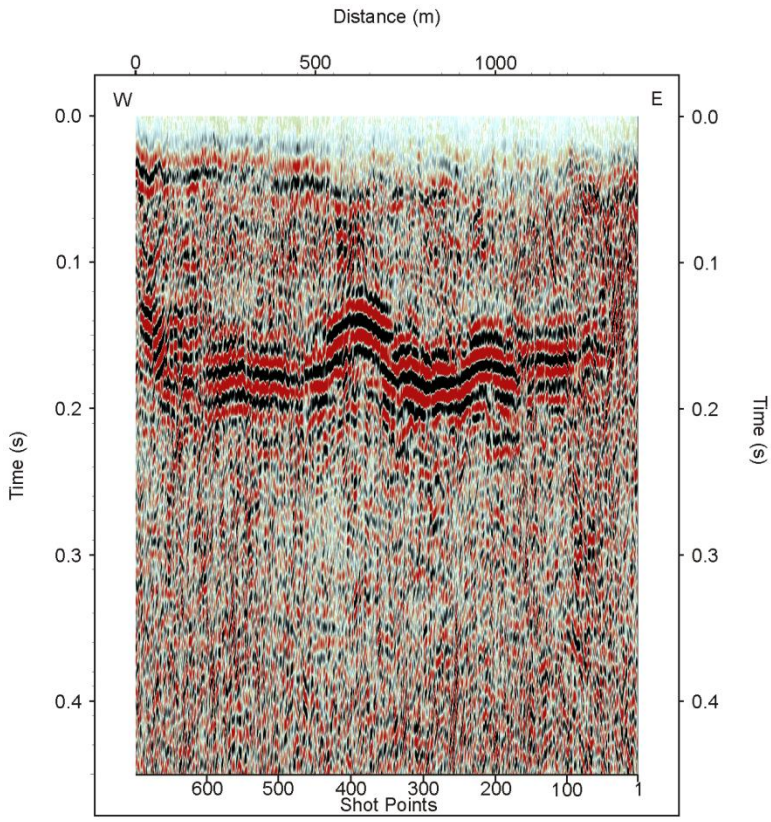
B-2. Enhanced final time unmigrated stacked seismic section of line A South.



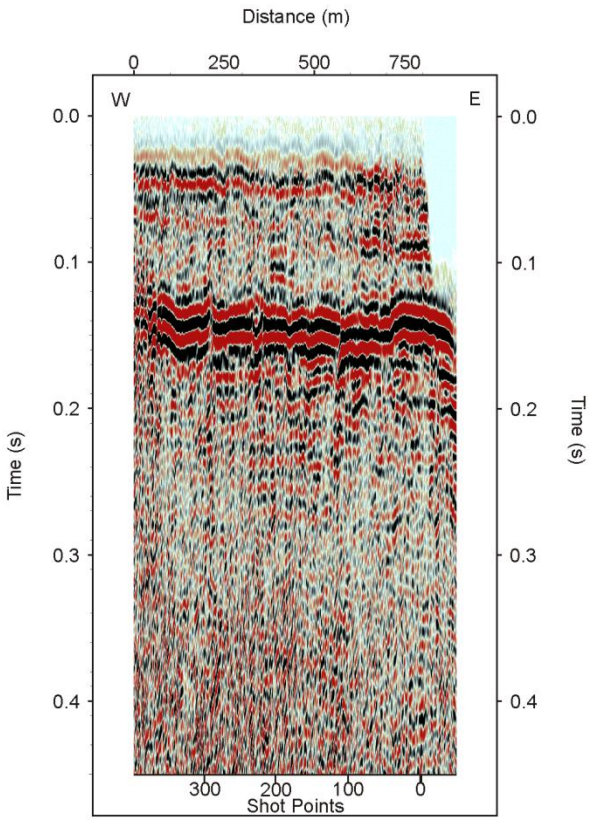
B-3. Enhanced final time unmigrated stacked seismic section of line B.



B-4. Enhanced final time unmigrated stacked seismic section of line C East.

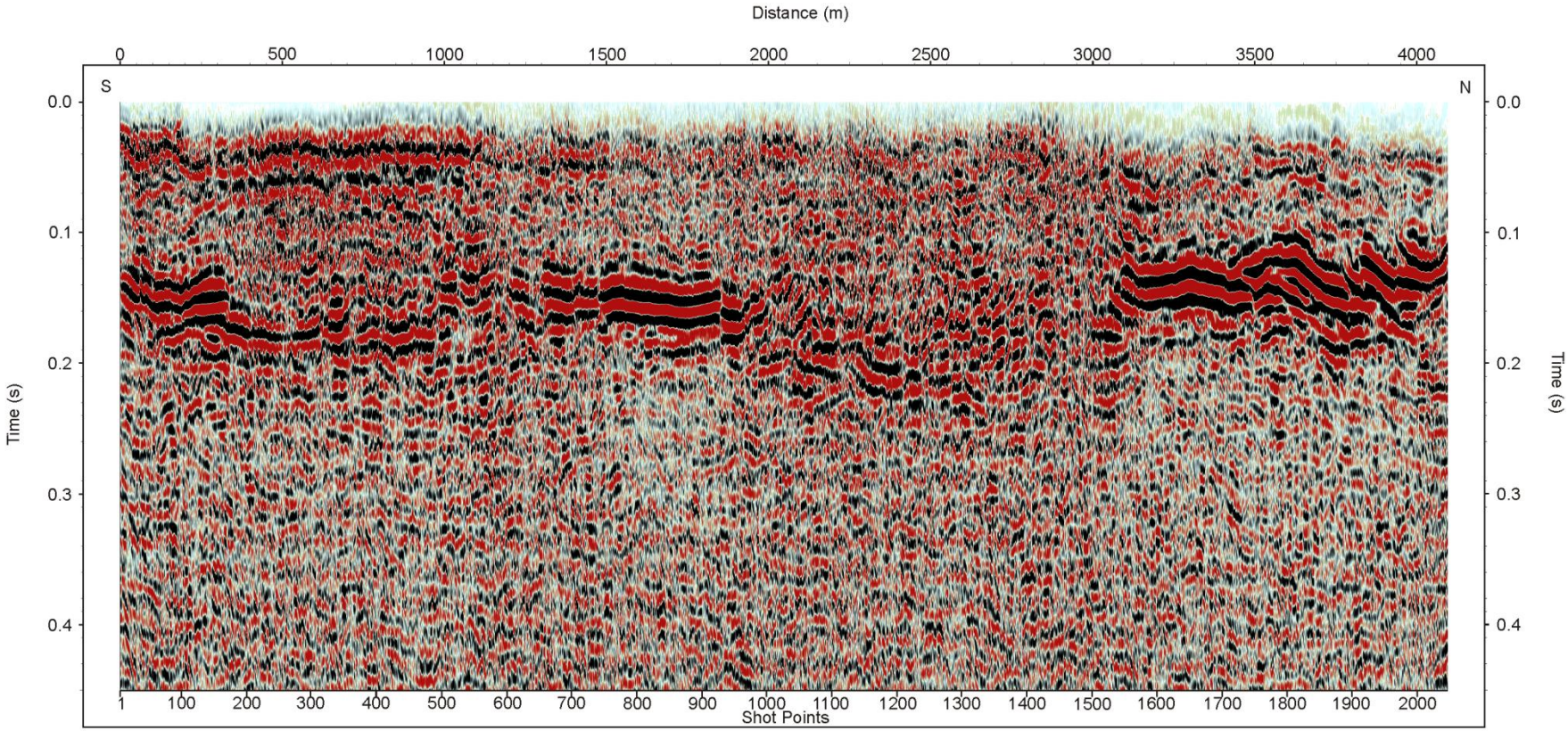


B-5. Enhanced final time unmigrated stacked seismic section of line C West.

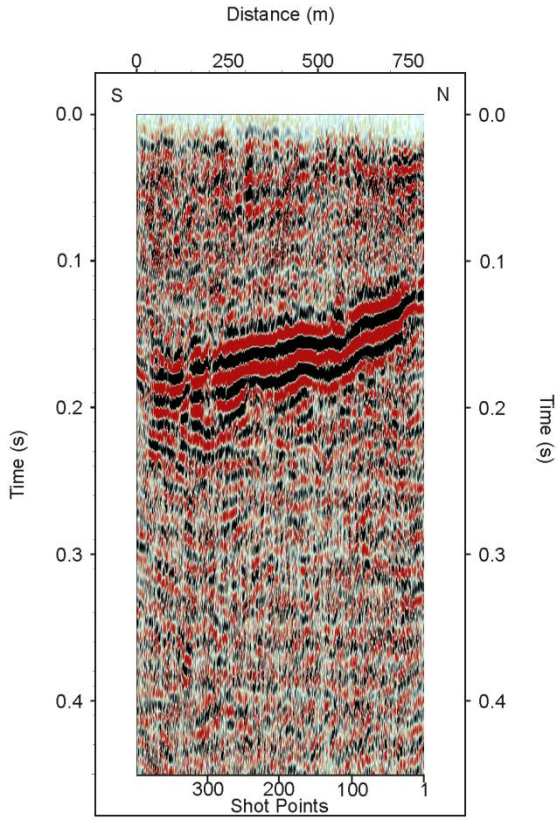


B-6. Enhanced final time unmigrated stacked seismic section of line D.

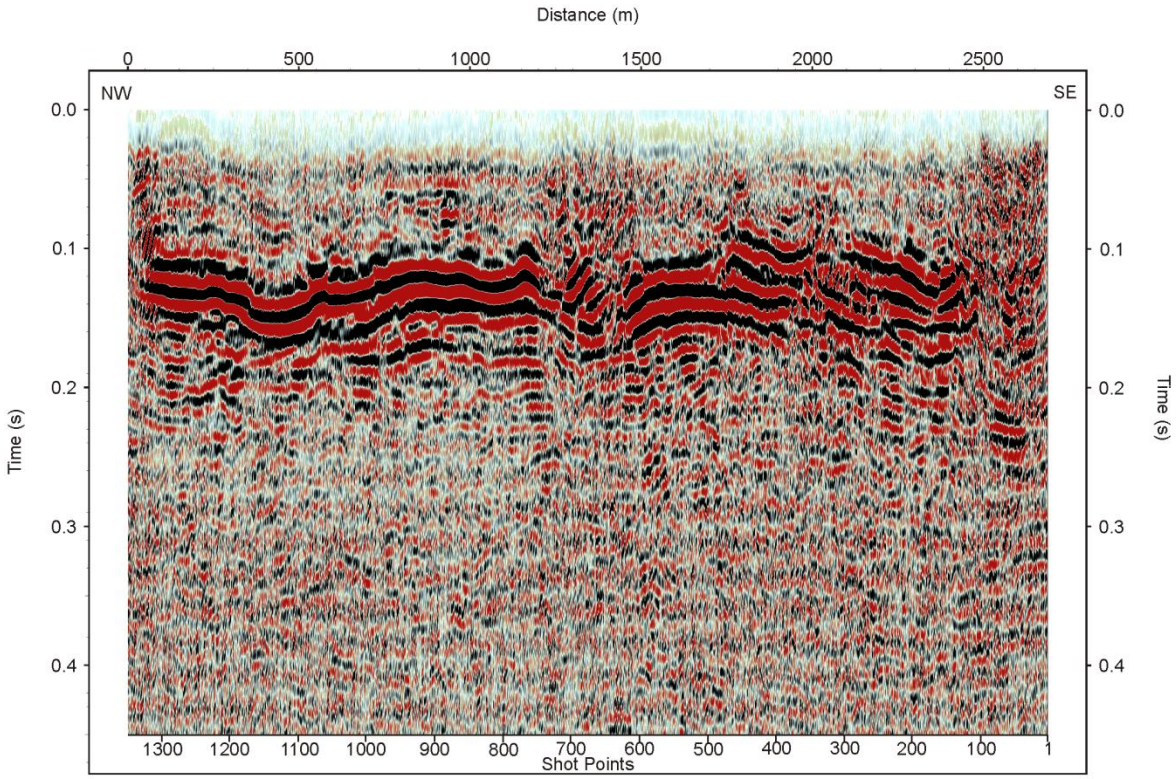
APPENDIX C – 90% Poststack Time Migrated Stacked Sections



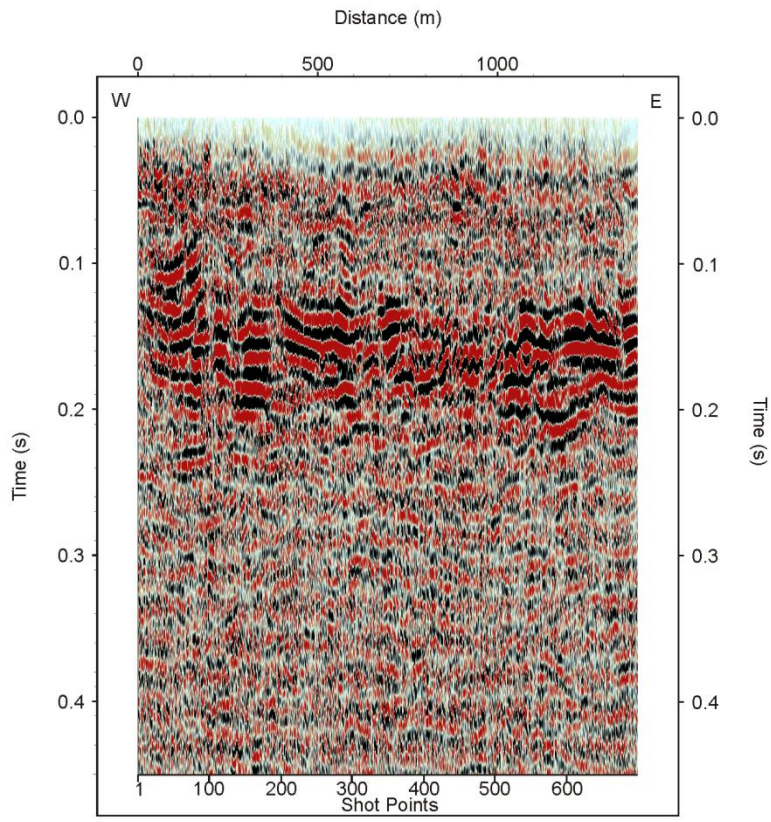
C-1. 90% poststack time migrated stacked seismic section of line A North.



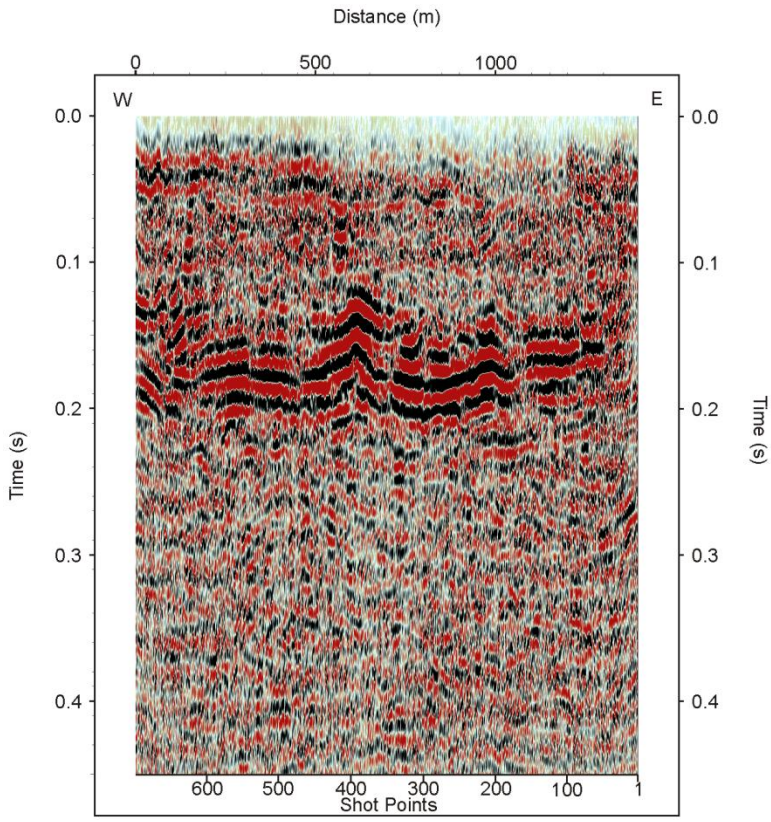
C-2. 90% poststack time migrated stacked seismic section of line A South.



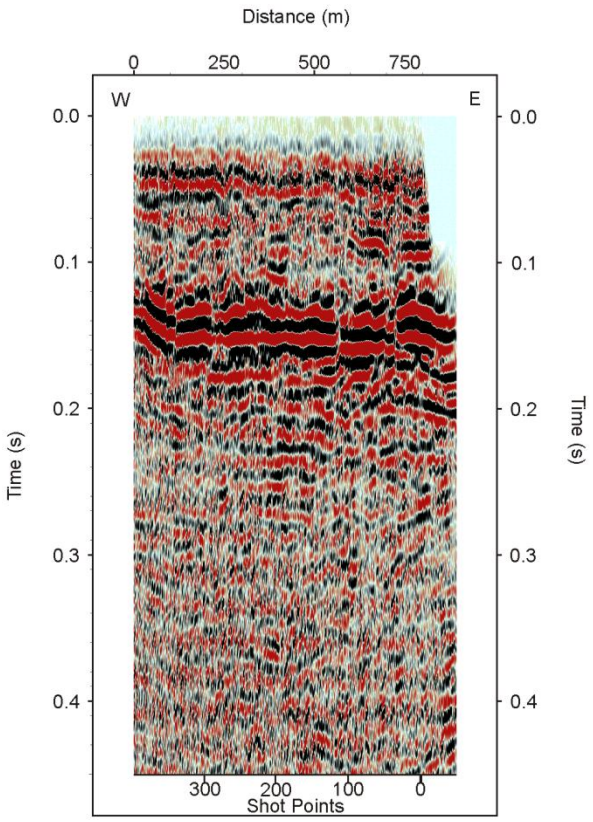
C-3. 90% poststack time migrated stacked seismic section of line B.



C-4. 90% poststack time migrated stacked seismic section of line C East.

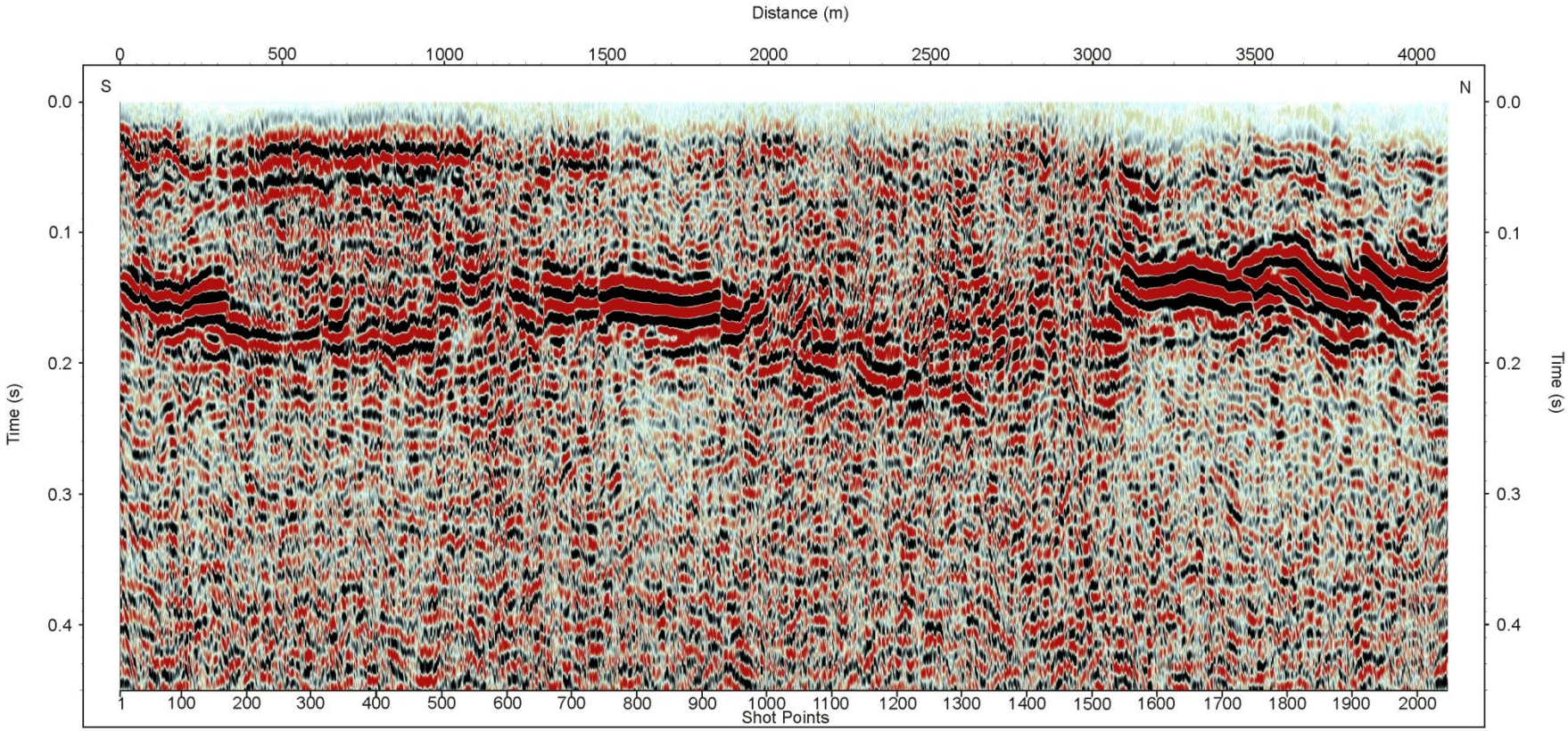


C-5. 90% poststack time migrated stacked seismic section of line C West.

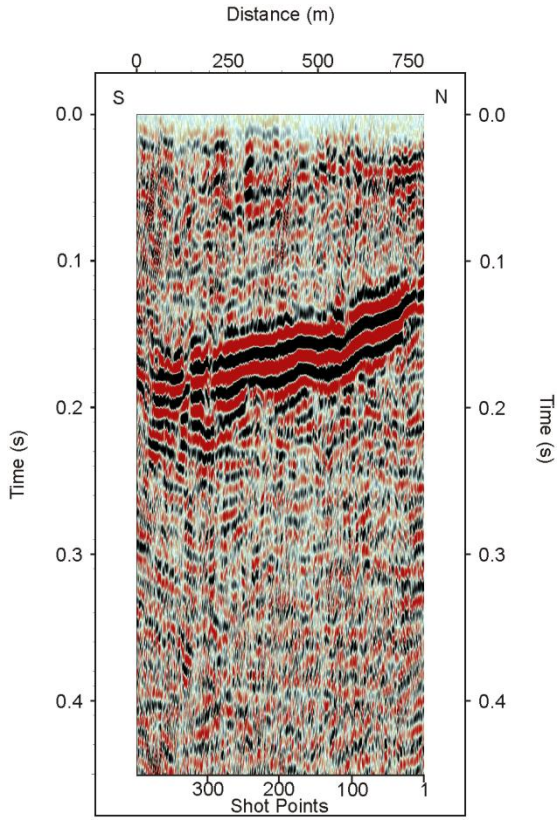


C-6. 90% poststack time migrated stacked seismic section of line D

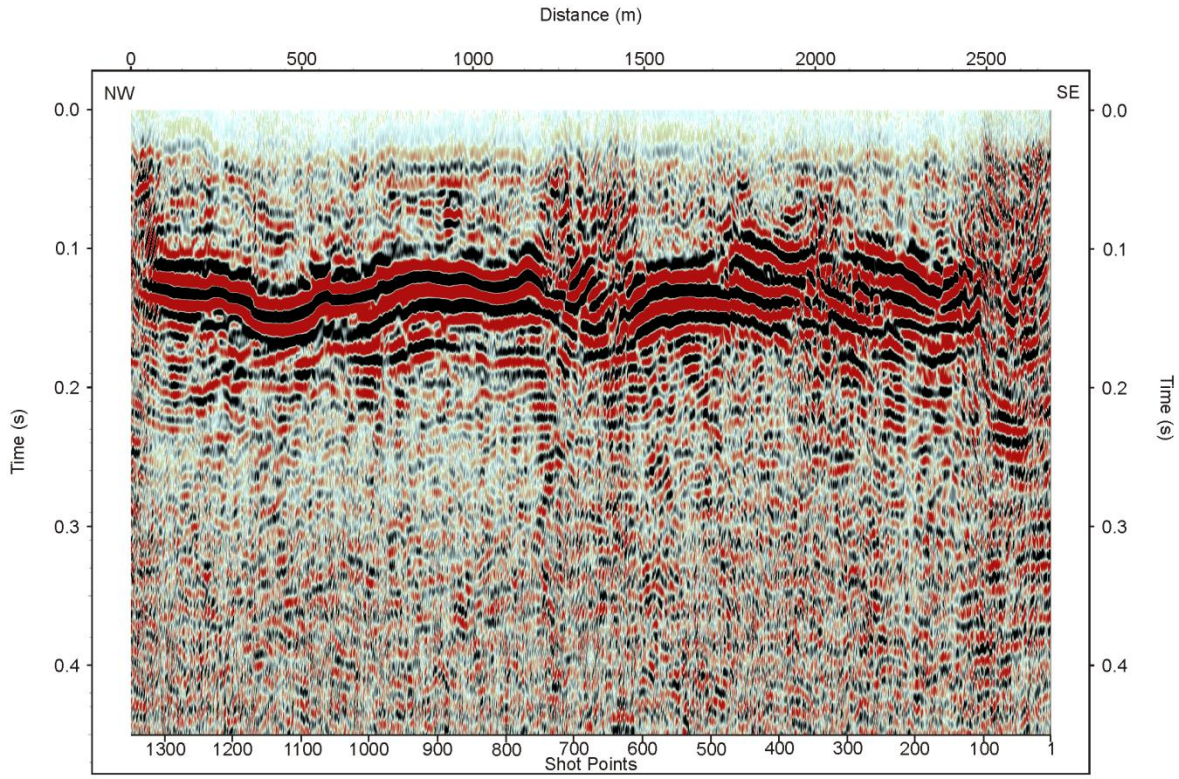
APPENDIX D – 90% Enhanced Poststack Time Migrated Stacked Seismic Section



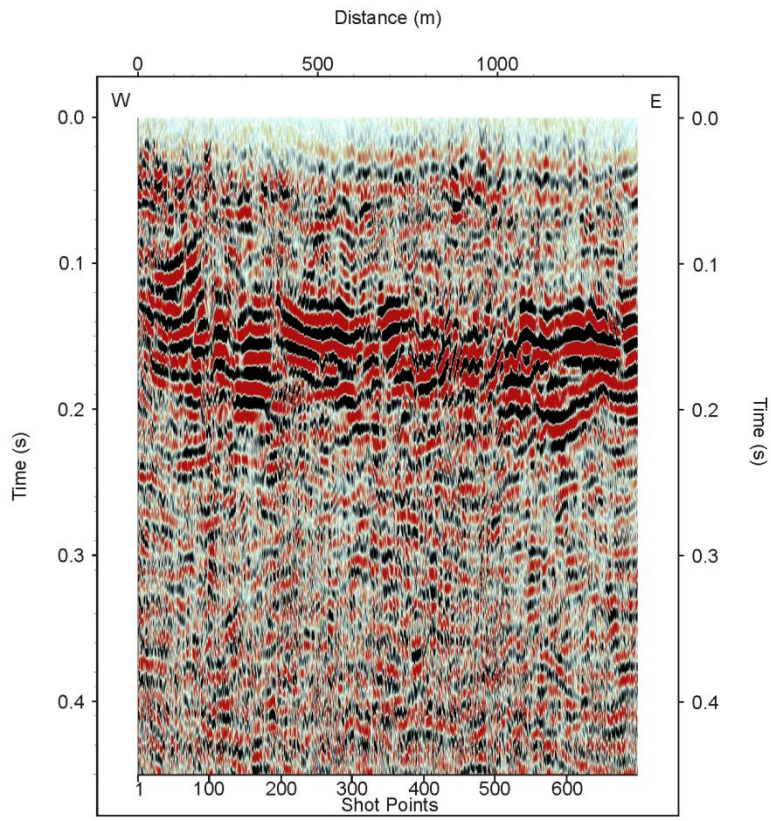
D-1. 90% enhanced poststack time migrated stacked seismic section of line A North.



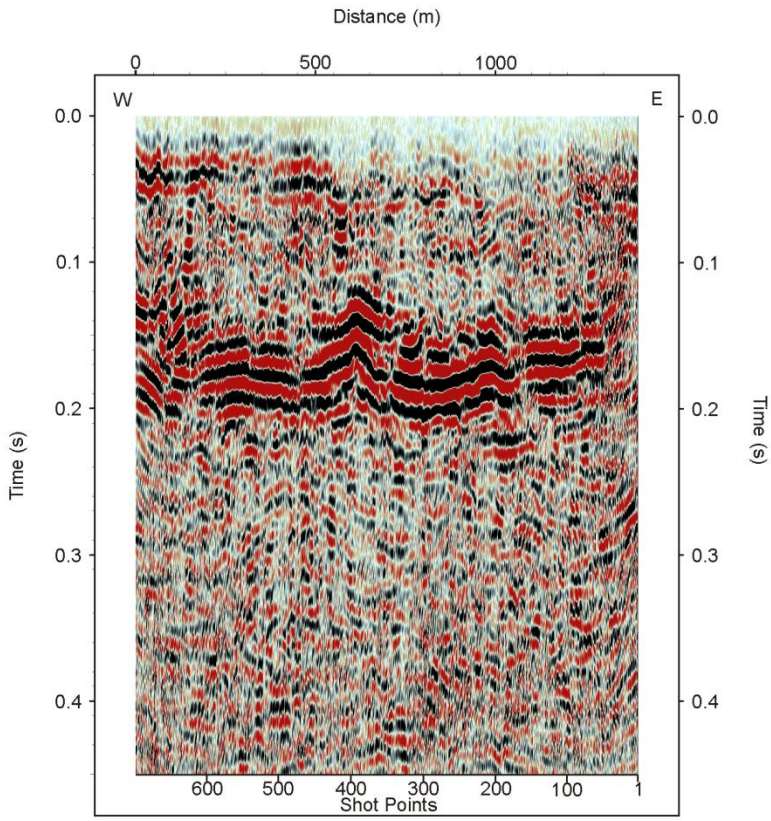
D-2. 90% enhanced time poststack migrated stacked seismic section of line A South.



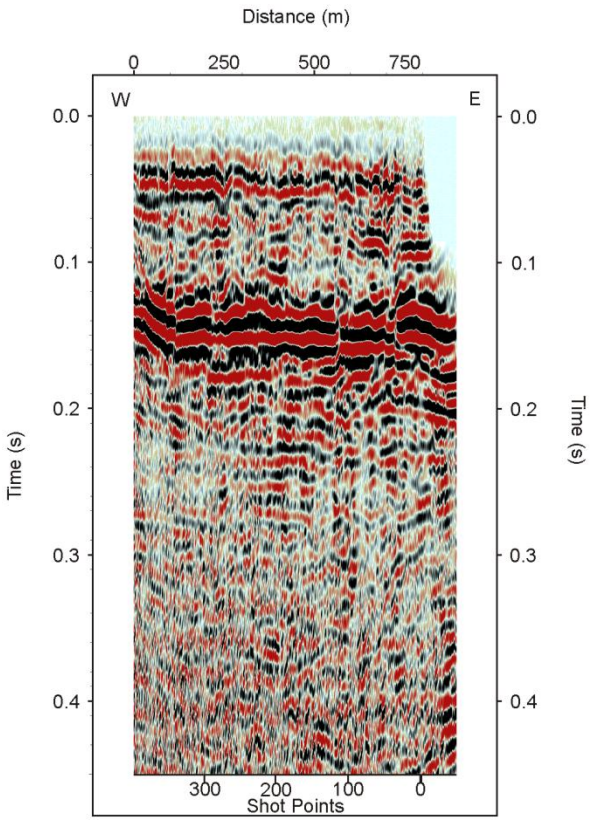
D-3. 90% enhanced poststack time migrated stacked seismic section of line B



D-4. 90% enhanced poststack time migrated stacked seismic section of line C East.

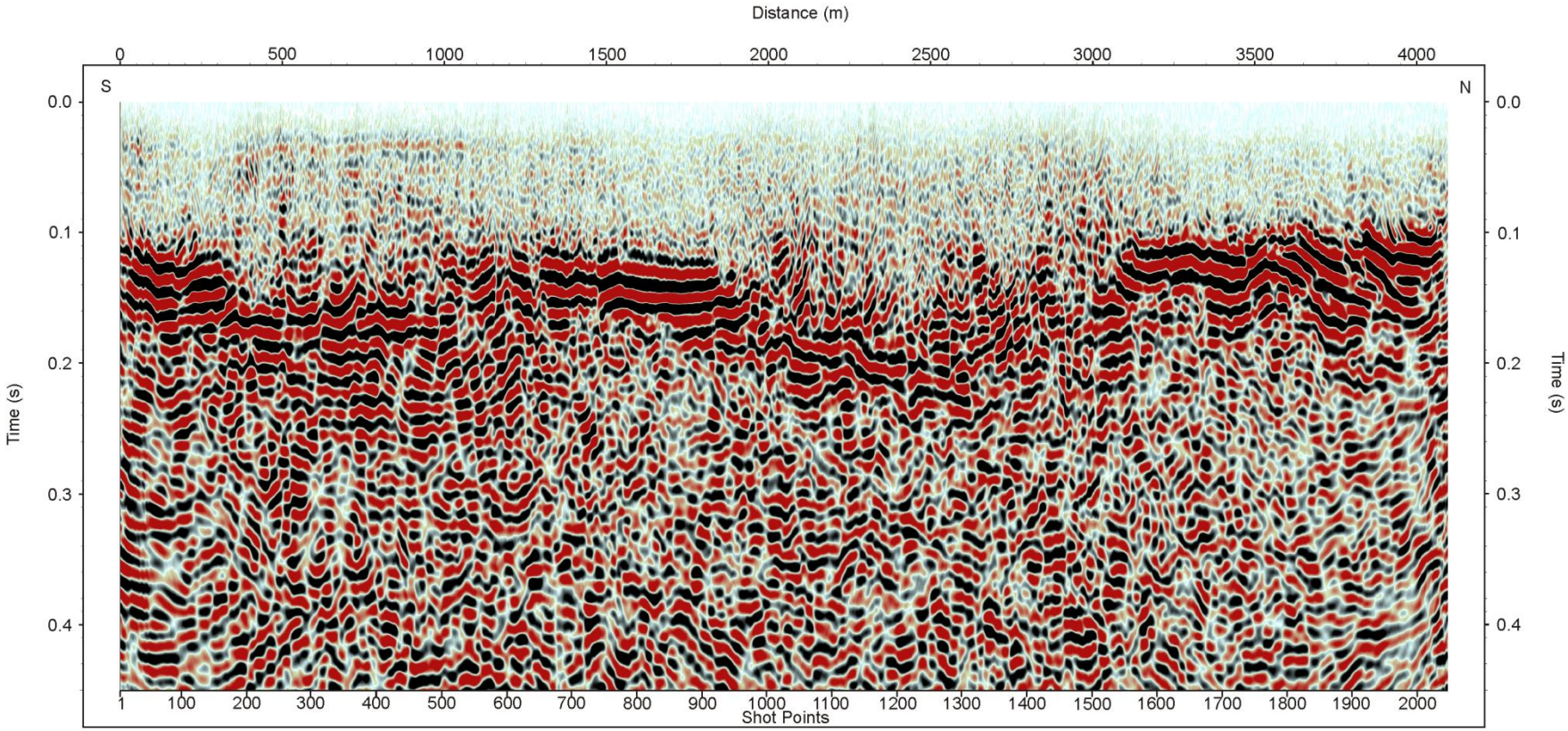


D-5. 90% enhanced poststack time migrated stacked seismic section of line C West.

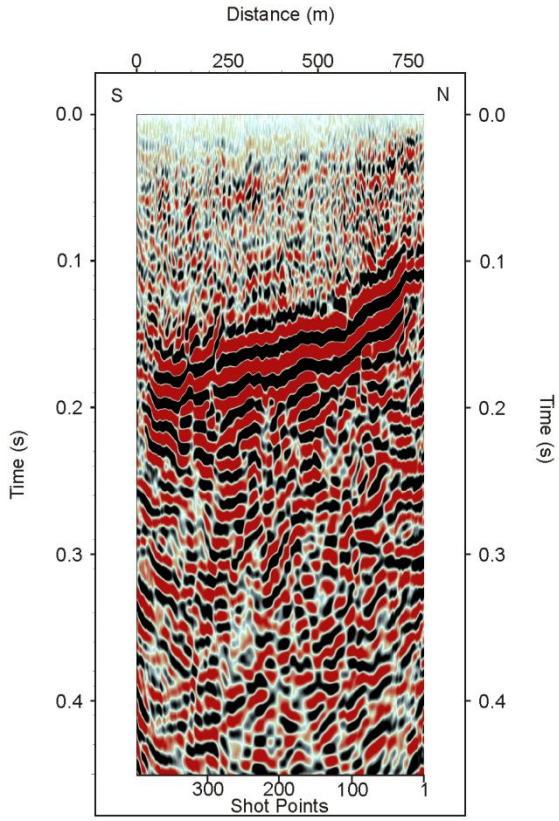


D-6. 90% enhanced poststack time migrated stacked seismic section of line D.

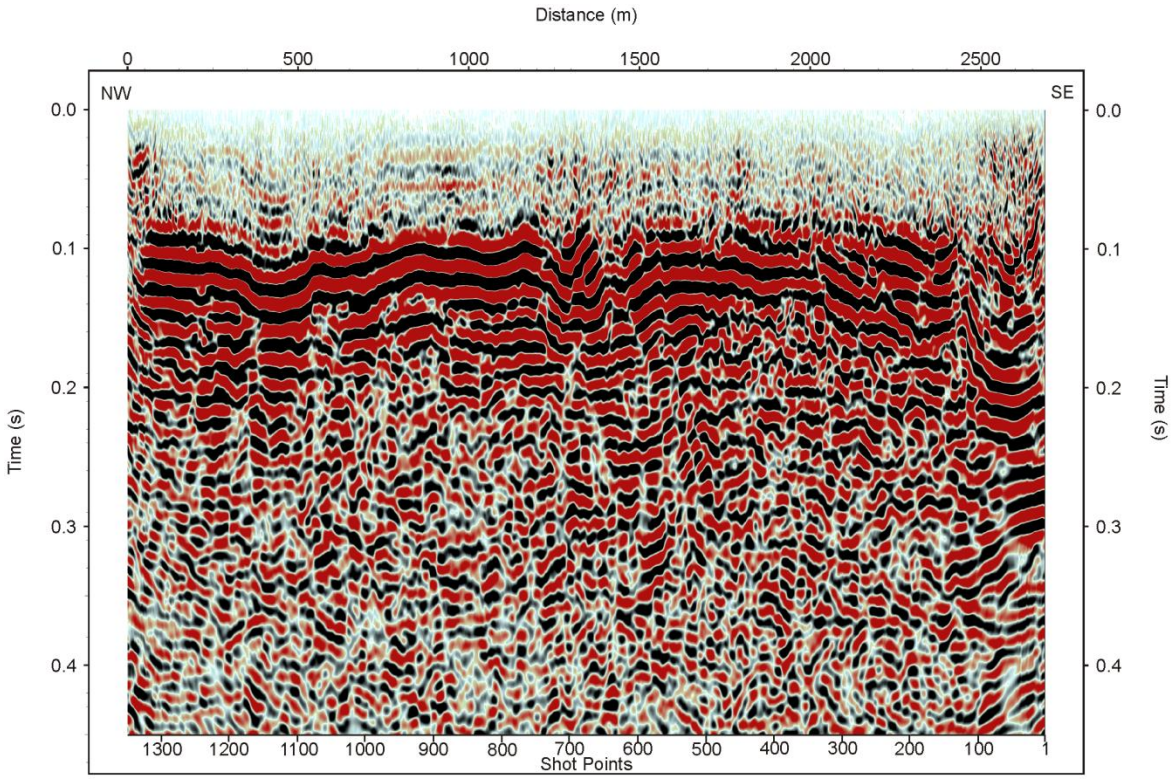
APPENDIX E – Prestack Time Migrated Stacked Seismic Sections



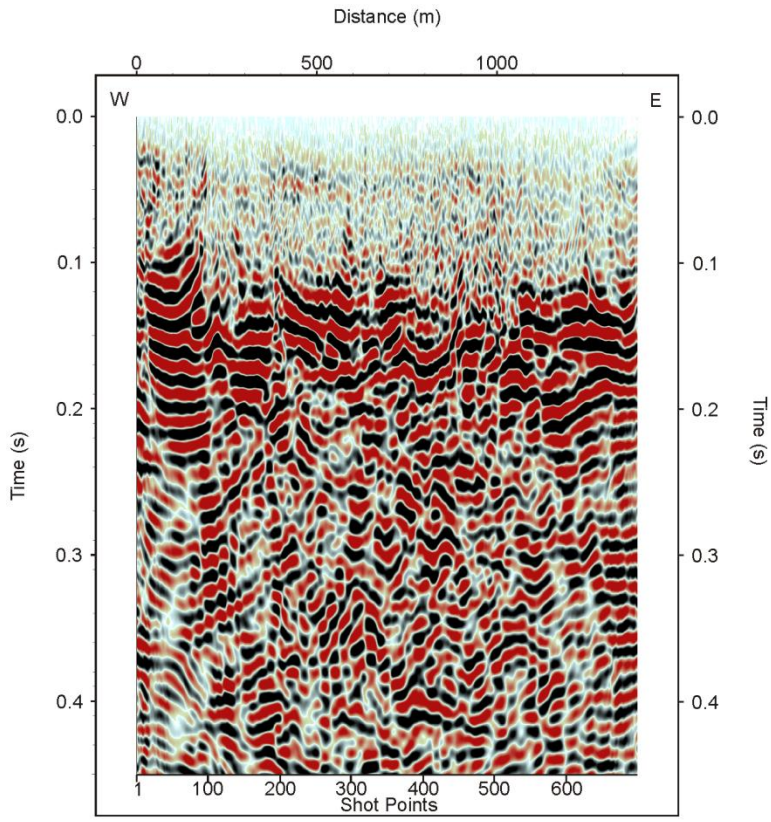
E-1. Prestack time migrated stacked seismic section of line A North.



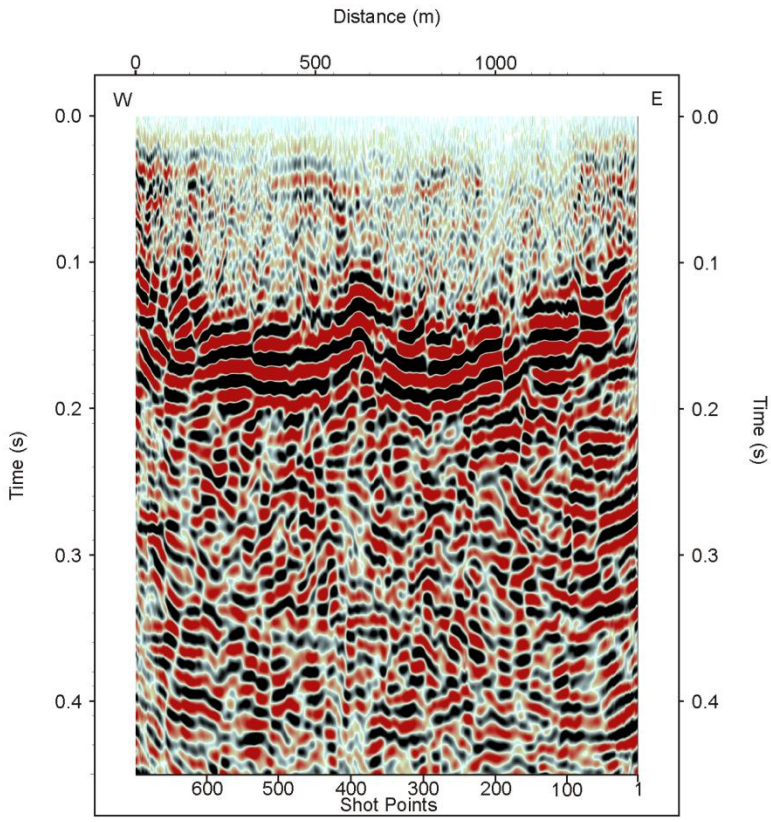
E-2. Prestack time migrated stacked seismic section of line A South.



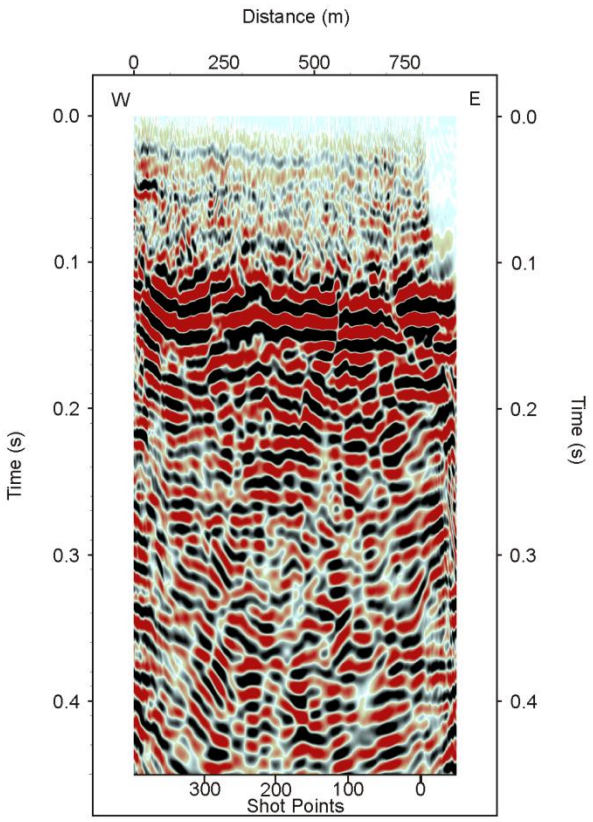
E-3. Prestack time migrated stacked seismic section of line B.



E-4. Prestack time migrated stacked seismic section of line C East.

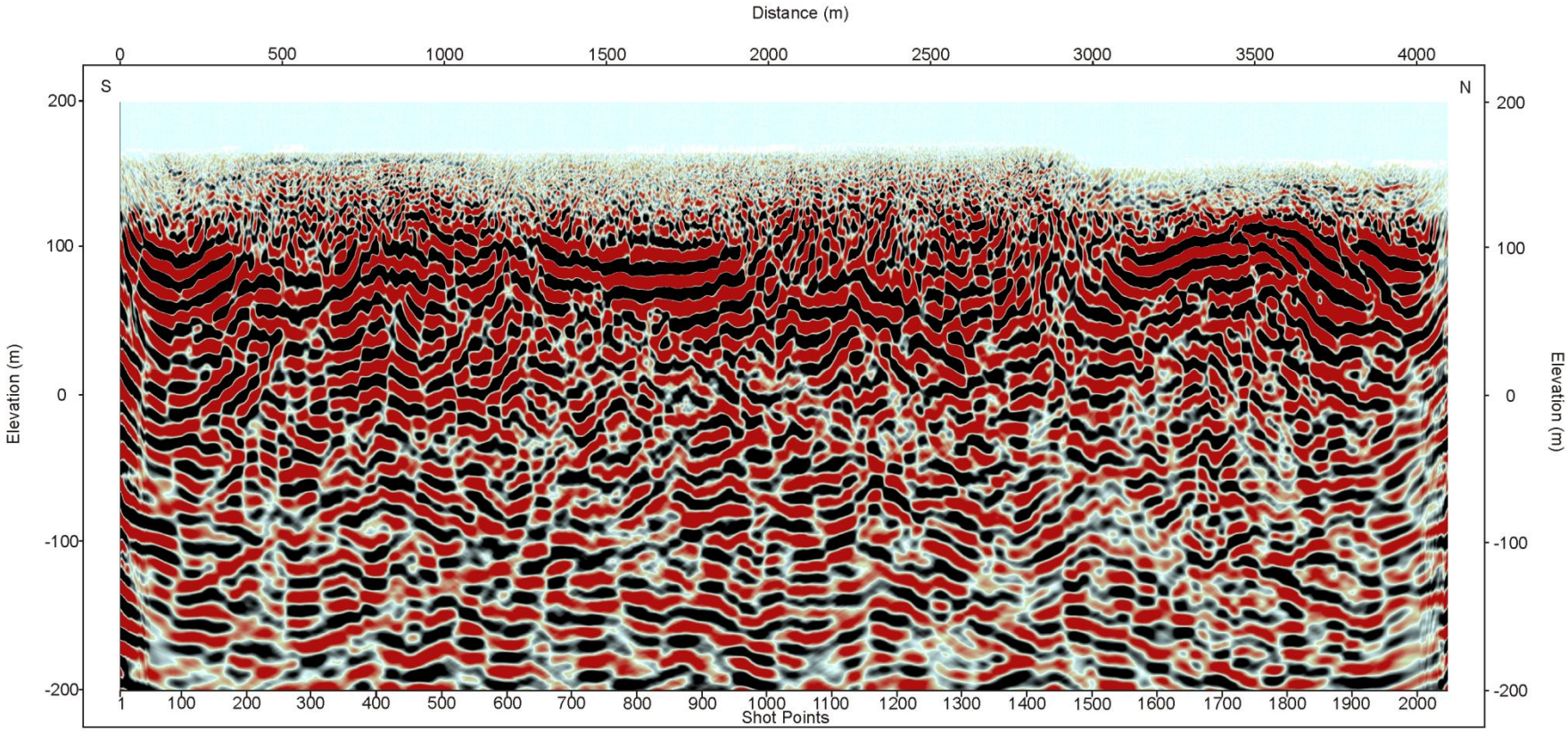


E-5. Prestack time migrated stacked seismic section of line C West.

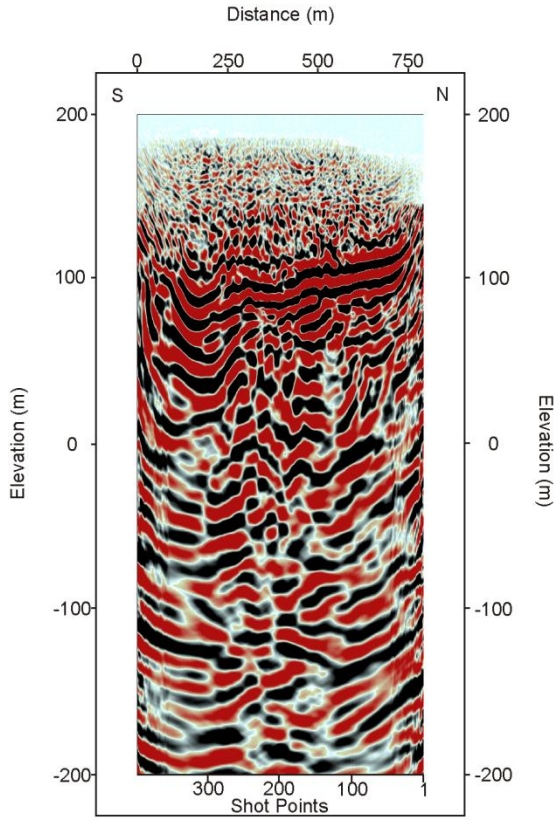


E-6. Prestack time migrated stacked seismic section of line D.

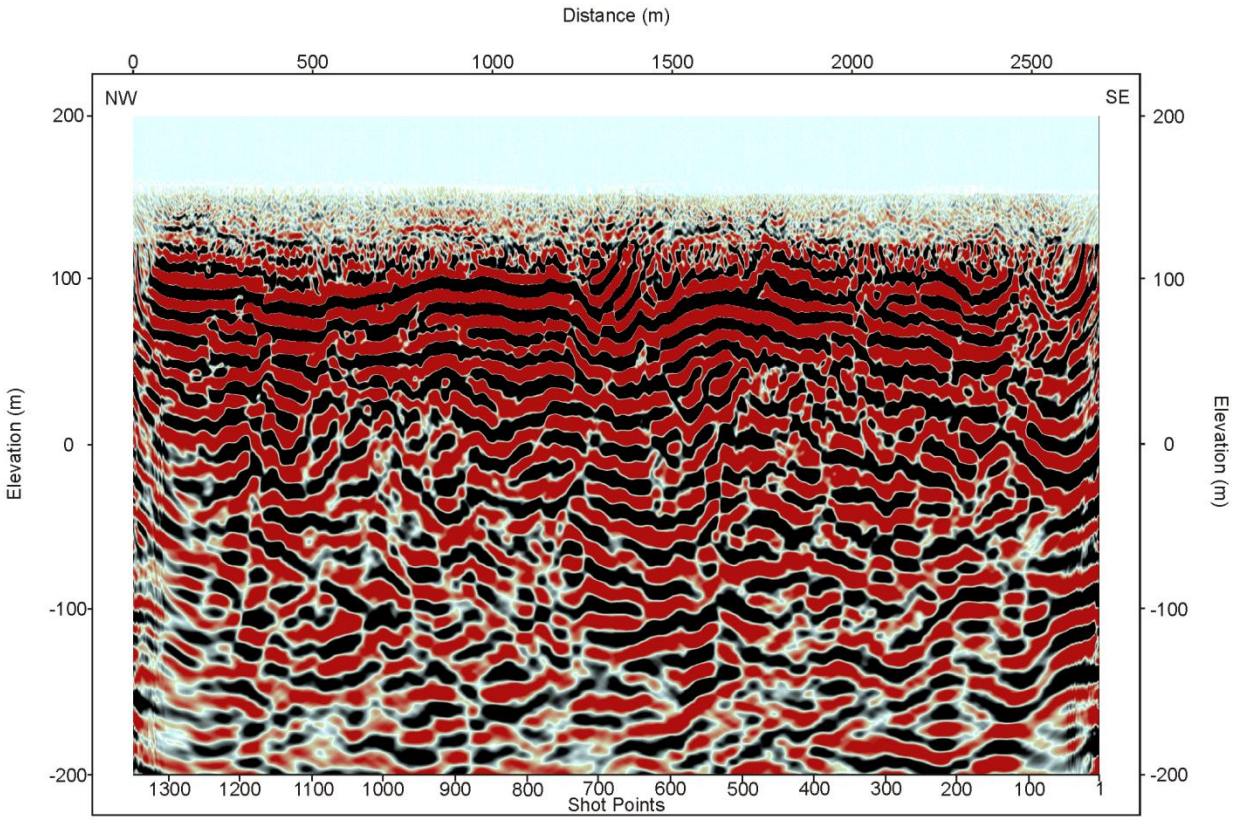
APPENDIX F – Uninterpreted Prestack Depth Migrated Stacked Seismic Sections



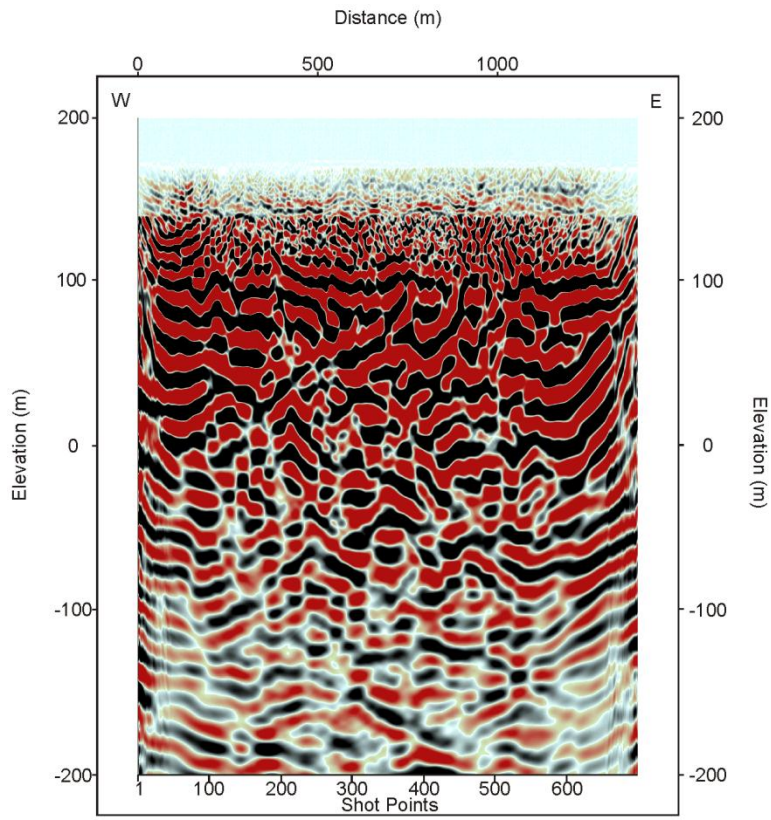
F-1. Uninterpreted prestack depth migrated stacked seismic section of line A North.



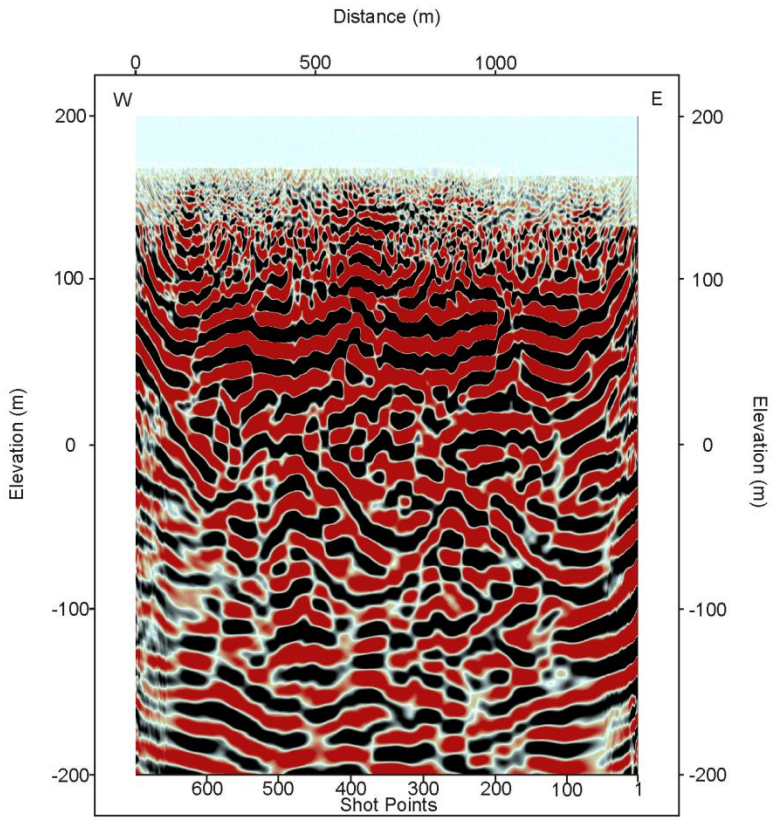
F-2. Uninterpreted prestack depth migrated stacked seismic section of line A South.



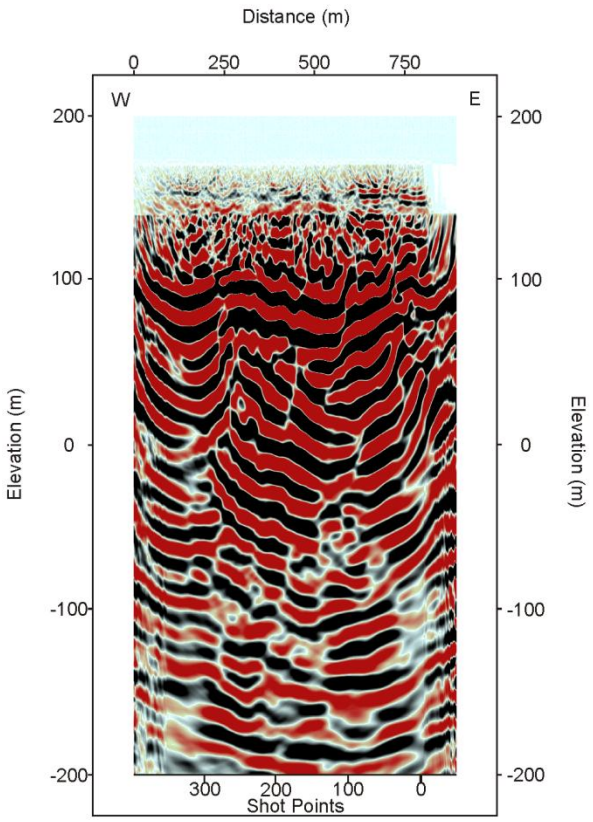
F-3. Uninterpreted prestack depth migrated stacked seismic section of line B.



F-4. Uninterpreted prestack depth migrated stacked seismic section of line C East.



F-5. Uninterpreted prestack depth migrated stacked seismic section of line C West.



F-6. Uninterpreted prestack depth migrated stacked seismic section of line D.