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Revision 1

Interpretation and Integration of Seismic Data in the Gable Gap

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

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Revision 1

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Terms

AMSL	Above Mean Sea Level
bgs	below ground surface
BWIP	Basalt Waste Isolation Project
CCU	Cold Creek unit
CSM	conceptual site model
FY	fiscal year
OU	operable unit
TWT	two-way travel time

1

1 Introduction

A refined understanding of groundwater flow in the Gable Gap Area north of the 200 Areas is needed to evaluate contaminant migration (Figure 1). Primary factors influencing contaminant movements in both the vadose zone and the aquifer systems include the geologic stratigraphy, migration pathways of contaminants, recharge (or deep infiltration), groundwater flow rates and direction, and physical/geochemical properties of the sediments. Preliminary conceptual site models (CSMs), developed for the 200-BP-5 Operable Unit (OU), indicated that groundwater flow directions and basalt elevations are needed to support contaminant pathway evaluation.

Seismic reflection data were acquired in the Gable Gap during fiscal years (FY) 2009 and 2011. . Targets of these surveys were to delineate the structure of the basalt surface and, where possible, identify basalt interbed and supra-basalt sediment contacts. FY 2009 seismic reflection surveys were acquired within the Gable Gap Area north of the 200 Areas as a field demonstration testing the feasibility of using a landstreamer system to acquire high-resolution seismic data. These surveys were successfully completed, and preliminary analyses (SGW-43746, *Landstreamer/Gimbaled Geophone Acquisition of High Resolution Seismic Reflection Data North of the 200 Areas, Hanford Site*) identified the likely topography of the basalt surface. FY 2011 surveys using the same landstreamer system were located to reduce data gaps and to improve the model for the underlying basalt surface (SGW-52160, *Landstreamer and Gimbaled Geophones Phase II – 200 Areas: A High-Resolution Seismic Reflection Survey at the Hanford Site*). Other seismic data sets detailing the basalt surface include high-resolution reflection surveys acquired during FY 2008 within the 200 East Area, and during FY 1979 and FY 1980 as part of the Basalt Waste Isolation Project (BWIP) geotechnical investigations.

This report provides a reanalysis of these seismic data and integrates the data with updated geologic information. The revised seismic data set provides additional pertinent information for CSM development by bridging between the sparsely distributed wells, which ultimately will help reduce uncertainties in the evaluation of likely groundwater migration pathways.

1.1 Objectives and Scope

The overall scope of this study was to determine the elevation of the basalt surface from the seismic data and to use this new information to refine CSMs developed for the Gable Gap Area. The following goals are specific to this study:

1. Provide supporting information for CSM development within the Gable Gap Area of the 200-BP-5 Groundwater OU.
2. Integrate existing geologic tops and well information with the seismic reflection.
3. Identify potential groundwater migration pathways.

This work focused on interpreting existing seismic reflection data using available geologic and auxiliary geophysical information. Interpretations were constrained using seismic check shot data (travel time and depth) plus geologic cross-sections.

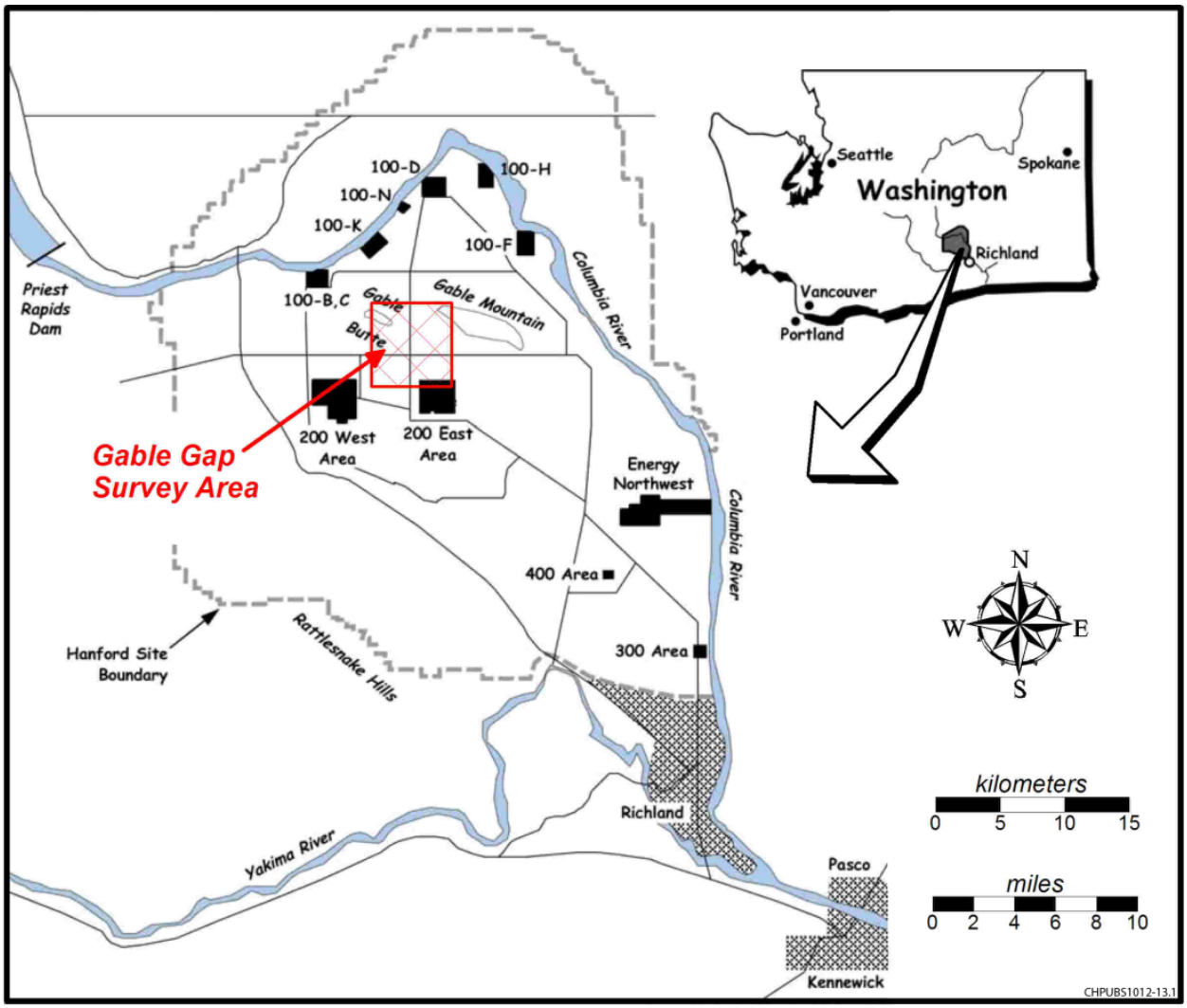

Figure 1. Hanford Site and Location of Seismic Surveys

1.2 Seismic Data Sets

Seismic information available for the Gable Gap portion of 200-BP-5 OU consists of seismic reflection data collected during FY 1979 and FY 1980 under BWIP, in FY 2008 for 200-PO-1 OU investigations in the 200 East Area, and during FY 2009 and FY 2011 in the Gable Gap Area using a seismic landstreamer (Figure 2).

BWIP seismic profiles provide approximately 80 km (50 mi) of seismic reflection coverage throughout the Hanford Site, of which 15 km (9 mi) were used to aid the 200-BP-5 OU investigations. Although BWIP survey objectives were primarily focused on delineating zones within the basalt for waste storage, more recent analyses indicate that the data provide some information about the orientation of Ringold Formation units (SGW-42313, *Geophysical Investigations: 200-PO-1 Groundwater Operable Unit*). Data acquisition and processing information are provided in B067305, *Final Report on Seismic Reflection Survey Conducted in Benton and Grant Counties, Washington, FY-79 Program, Pasco Basin, Hanford Site, Basalt Waste Isolation Program* and B067306, *Final Report on Seismic Reflection Survey Conducted in Benton County, Washington, FY-80 Program, Pasco Basin, Hanford Site, Basalt Waste Isolation Program*. To facilitate modern interpretation methods, hard copy printouts of the BWIP profiles

were scanned and converted into a standard digital seismic format for use with the KINGDOM® seismic interpretation software.

Bay Geophysical, Inc. collected a total of 24 km (15 mi) of seismic reflection surveys during FY 2008 in the 200 East Area. Approximately 7 km (4 mi) lie within the 200-BP-5 OU. The design criteria for these surveys included imaging subsurface acoustic interfaces, between 22 to 300 m (75 to 1,000 ft) below ground surface (bgs), with top-of-basalt as the primary target. Data acquisition details are provided in SGW-39675, *Reflection Seismic Survery Report, 200 East Area, Hanford Site*, and interpreted results are presented in SGW-42313.

Approximately 23 km (14.3 mi) of seismic reflection profiling was conducted during FY 2009 and FY 2011 in the Gable Gap Area and north 200 East Area using a seismic landstreamer. Design criteria were to image top-of-basalt as well as supra-basalt sedimentary interfaces within the upper 150 m (500 ft) bgs. Acquisition details and preliminary results are presented in SGW-43746 and SGW-52160.

Auxiliary information used to tie the seismic data to the underlying geology consisted of check shot seismic velocity surveying, sonic logs, and geologic information from wells adjacent to the profiles (Figure 2). Check shot surveys were conducted during FY 2007 for the Waste Treatment Plant design (PNNL-16559, *Downhole Measurements of Shear- and Compressional-Wave Velocities in Boreholes C4993, C4996, C4997 and C4998 at the Waste Treatment Plant DOE Hanford Site*; PNNL-16652, *Site-Specific Velocity and Density Model for the Waste Treatment Plant, Hanford, Washington*), in FY 2008 to support the 200-PO-1 OU investigations (SGW-39676, *Check Shot Survey Summary Report, 200 East Area, Hanford Site – Fiscal Year 2008*; SGW-42313), in FY 2009 to support both the landstreamer surveys and 200-PO-1 investigation (SGW-42313), in FY 2010 to support site-wide model development (SGW-47535, *Measurement of Compressional-Wave Seismic Velocities in 29 Wells at the Hanford Site*), and in FY 2011 to support the Gable Gap landstreamer surveys. Sonic logs were acquired to support the BWIP investigations, and survey details are reported in *Seismic Velocity Survey, Rockwell Hanford Operations ESG, DC 2, 3, 4, 6, and 7, Benton County, Washington* (B040899); *Report of Borehole Seismic Analysis for Rockwell International RRL-5, -7, -8, -10, and -16, Benton County, Washington, B066327, B066329, B066331, B066333, and B066335* (Dresser Atlas, 1985); and *Seismic Velocity Structure in the BWIP Reference Repository Location from Seismic Refraction and Vertical Seismic Profiling Data* (SD-BWI-TI-359). Fourteen check shot surveys and one sonic log were used for interpreting the seismic data in the Gable Gap Area and north 200 East Area (see Figure 2 for locations).

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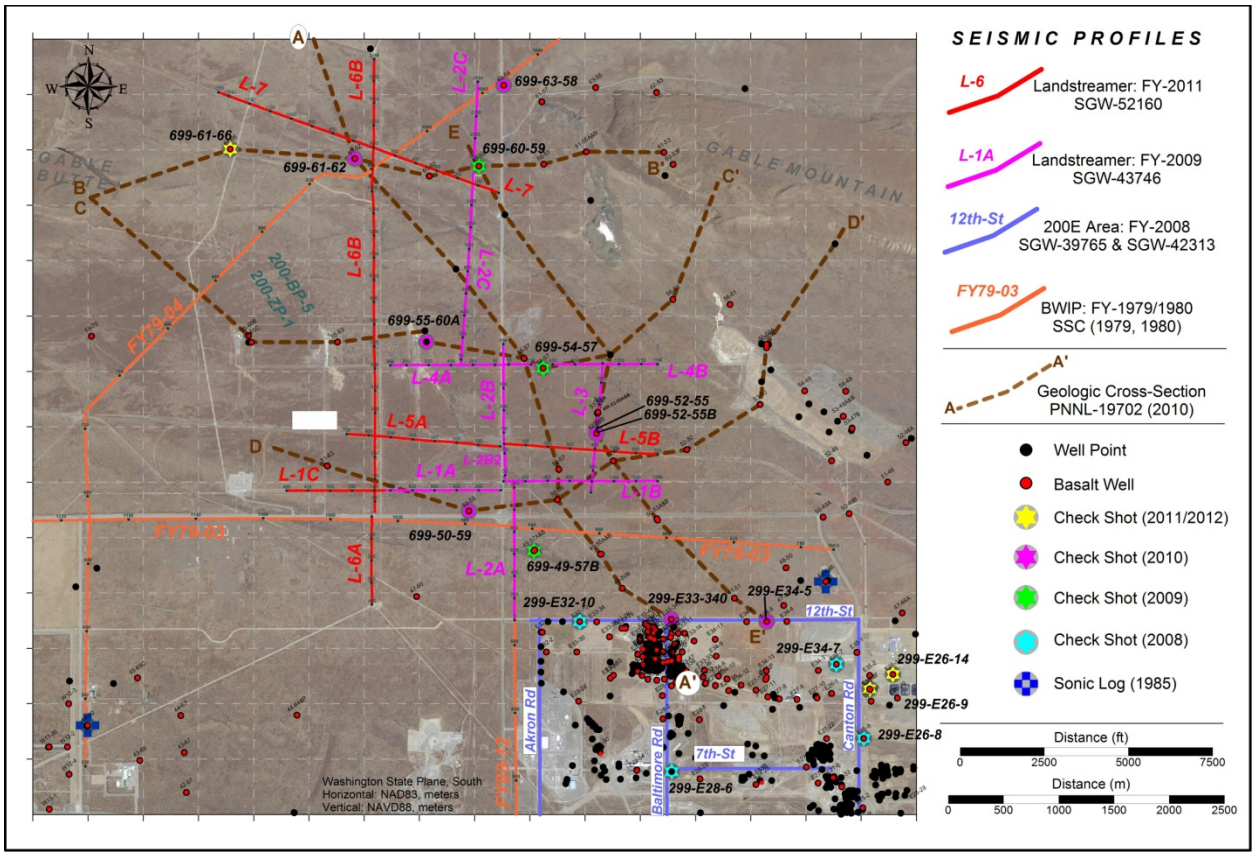

Figure 2. Location of Seismic Profiles and Wells in the Gable Gap Region

2 Interpretation of Seismic Reflection Profiles

Seismic reflection profiling maps changes in acoustic impedance (variations of seismic velocity and material density), and is used to construct a "reflector" image of the subsurface. The resulting seismic reflection section, similar to a geologic cross section, in that it can be used to map the orientation and structure of stratigraphic layers as well as changes in lithology. Both the BWIP and 200 East Area seismic reflection profiles were provided in cross-sectional format with units of distance as the horizontal axis and two-way travel time (TWT) for the vertical axis. The FY 2009 and FY 2011 landstreamer data were provided as both travel time and depth migrated sections. New velocity functions were developed using the existing check shot and well information to convert from travel time to depth (or elevation).

2.1 Correlation with Geologic Units

Geologic control is provided by the Hanford internal geologic tops data set and from recent geologic interpretations in the Gable Gap Area (PNNL-19702, *Hydrogeologic Model for the Gable Gap Area, Hanford Site*). The locations of the geologic cross-sections and wells are shown in Figure 2.

The primary method for correlating seismic data to the geology is to use travel time and depth information derived from check shot surveys conducted in nearby monitoring wells to associate observed seismic reflectors with known geologic information. Check shot surveys are acquired by lowering a borehole geophone (acoustic receiver) into a well and measuring the seismic travel time from the ground surface to various depth points. The travel time and depth information allows computing seismic velocity

for sediment and rock in the vicinity of the well point and provides a direct tie between subsurface geology and reflecting horizons identified on the seismic reflection surveys.

Note that the travel time position of the basalt surface at a well point is dependent on the average velocity measured from ground surface to top of basalt. Check shot surveys (SGW-47535) indicate a substantial variation in sediment velocity arising from changes in sediment type, geologic unit, and/or degree of saturation. Without check shot information, seismic velocity variations can be difficult to resolve because the “seismic” position of the basalt surface may be different for two different wells even though the basalt was encountered at the same elevation in both wells. With check shot information, both the seismic position and the reflector character at that position are used to interpret between wells. When more than one check shot survey has been acquired, the appropriate seismic position of the basalt can be determined by either averaging the check shot data (if position is between check shots) or using multiple check shot information to determine the likely range for the basalt position and rejecting interpretations that fall outside that range.

Figure 3 shows check shot results for Well 699-52-55B, which is located within the Gable Gap Area and adjacent to landstreamer profile L-3 (see Figure 2). The leftmost plot is one-way seismic travel time with depth and, in the rightmost plot, the resulting seismic interval velocities calculated from changes in slope on the time-depth plot. The geologist log, geologic units encountered by the well, and natural gamma log for adjacent Well 699-52-55 are also shown. Check shot information indicates that the top-of-basalt should occur at a one-way travel time of approximately 0.06 seconds, which equates to a TWT of 0.12 seconds. The approximate three-fold increase in seismic velocity across the sediment-basalt interface, from 1,220 m/s (4,000 ft/s) above to over 3,000 m/s (9,843 ft/s) below, should produce a relatively strong reflection signal on the seismic section. Thus, strong reflectors in the vicinity of this TWT are best interpreted as the sediment-basalt geologic contact.

Examples of how specific geologic units are correlated with seismic sections using check shot information are shown in Figure 4 as short segments of FY 2009 and FY 2008 seismic profiles. The resulting velocity-depth curves computed from the check shot survey are shown on each seismic section and, for all three cases, the basalt surface is represented by strong reflectors that correlate with a sharp increase in interval velocity-from 900 to 2,000 m/s (3,000 to 6,500 ft/s) above (sediment) to 3,300 m/s (10,827 ft/s) and greater for the basalt. For the FY 2009 seismic data, strong reflectors correlate with top-of-basalt as indicated by the check shot surveys in wells 699-52-55B and 699-54-47. Top-of-basalt is indicated in the FY 2008 seismic data, and subtle changes in interval velocity within the sedimentary column appear to be loosely correlated with changes in seismic character and tied to Hanford formation sub-units.

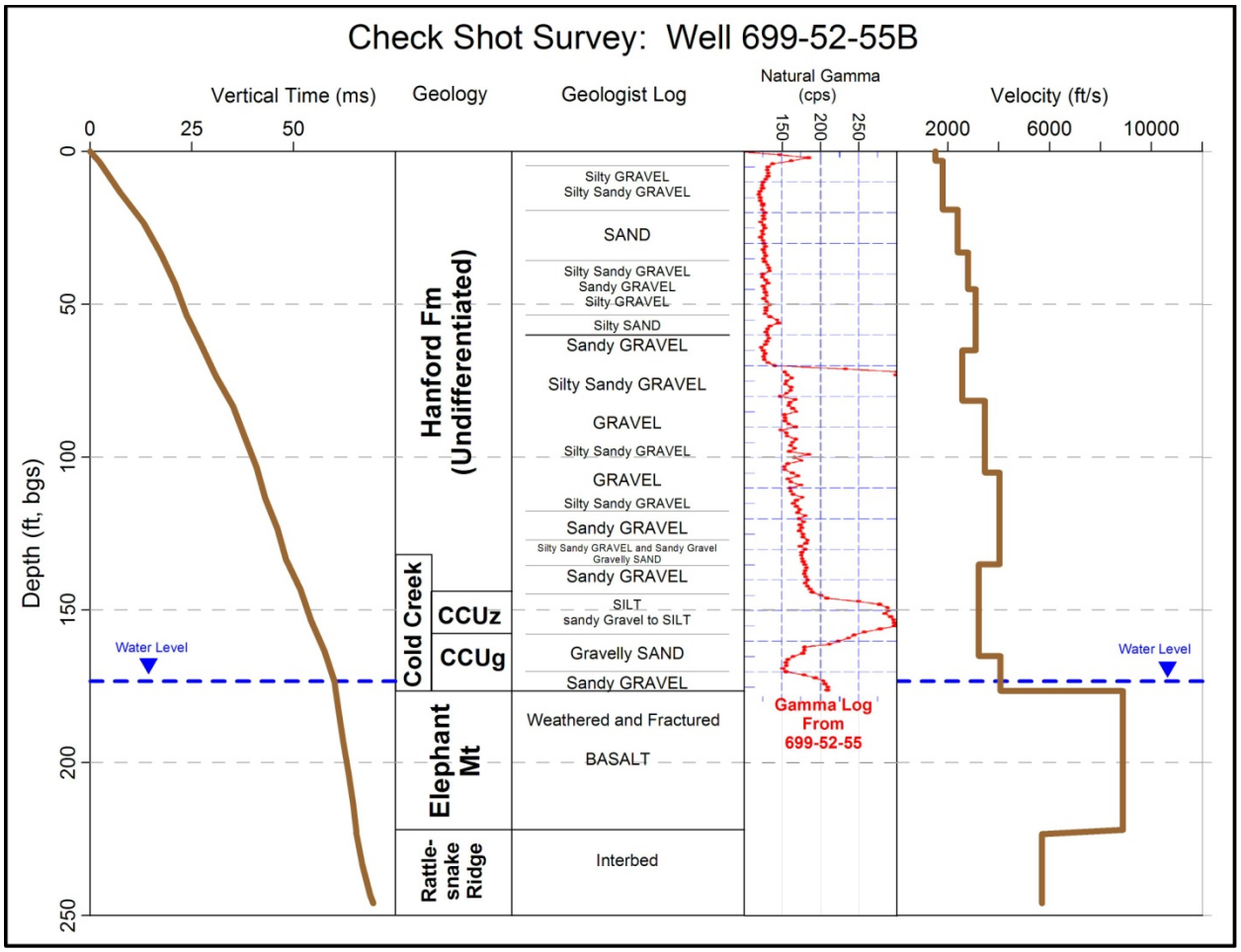

Figure 3. Check Shot Information in Well 699-52-55B

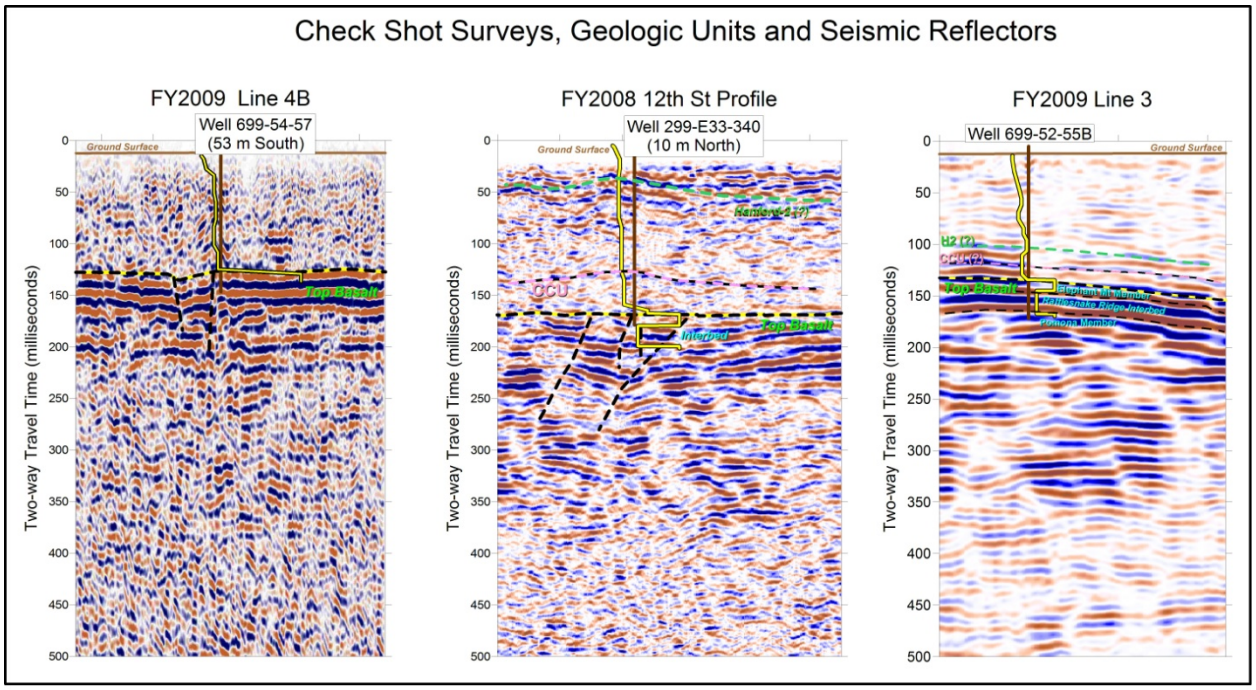

Figure 4. Seismic Reflection – Geology Correlation

2.2 Seismic Reflection Results

Top-of-basalt was interpreted on all of the seismic reflection data based on geologic information from wells located either directly on or in the vicinity of the seismic profile (Figure 2). Recent cross-sectional geologic interpretations (PNNL-19702) were used to augment the interpretation of the seismic data where these geologic cross sections either intersected or came close to the seismic profile. The interpreted basalt surface is represented as a magenta and yellow dashed line on each of the seismic sections. Additional geologic interfaces are indicated by either short horizontal markers (with annotation) or as dashed lines where either seismic character or other information warrants inclusion. Also shown on each seismic section are well points, cross-lines, intersections with the geologic cross-sections and other cultural and geologic features of interest. Interpretations are presented from the oldest (BWIP) to the newest (landstreamer) seismic surveys.

2.2.1 BWIP Profile FY-79-03

Interpreted results for the Gable Gap segment of BWIP profile FY-79-03 are shown in Figure 5. This profile extends east to west along along Route 11A from the Hanford town site (east) to west of the Yakima Barricade (west). The Gable Gap segment discussed in this report extends from the 200 East Area to northeast of the 200 West Area (see Figure 2). A usable copy of the results for the portion of FY-79-03 between the Hanford town site and the 200 East Area was not in any of the Hanford archives.

Several major undulations of the basalt surface are interpreted on profile FY-79-03 (Figure 5), with a broad topographic depression in the basalt surface imaged between seismic Station 1140 and 1080 (at least 30 m [98.4 ft] of elevation change). Another topographic depression in the bedrock surface is interpreted at the eastern end of the seismic section with its position honoring nearby borehole information. Relative highs occur between Stations 980 and 1040, and between Stations 780 and 840. The position of the interpreted basalt surface is consistent with check shot results in Wells 699-49-57B and

699-50-59 (near Stations 930 and 980) and velocity information acquired in Well 699-48-48B (near the east end of profile).

The position of Hanford 2, Cold Creek, and Ringold units are tentatively interpreted on the profile based on the geologic interpretations of cross-sections A-A' and E-E' (PNNL-19702). The top of the Cold Creek is tentatively extended west from the cross-section A-A' intersection along a weak reflector and its vertical position determined from well 699-49-57B. Ringold units were not encountered in either 699-49-57A or 699-49-57B, so the Ringold units are interpreted to pinchout against the basalt surface before reaching the position of the wells. Well 699-50-59 identified a thick gravel zone above basalt that is tentatively traced eastward along a weak reflector. It is unclear at this time whether this gravel zone can be correlated with gravels observed below in 699-49-57A/B. Resolution of these units on the BWIP profile is extremely poor, primarily due to the wide geophone spacing (15.2m) and the relatively low frequency content of the seismic data. It is unclear from the seismic data whether Ringold or Cold Creek units are present in the basalt low beween seismic stations 1080 and 1140.

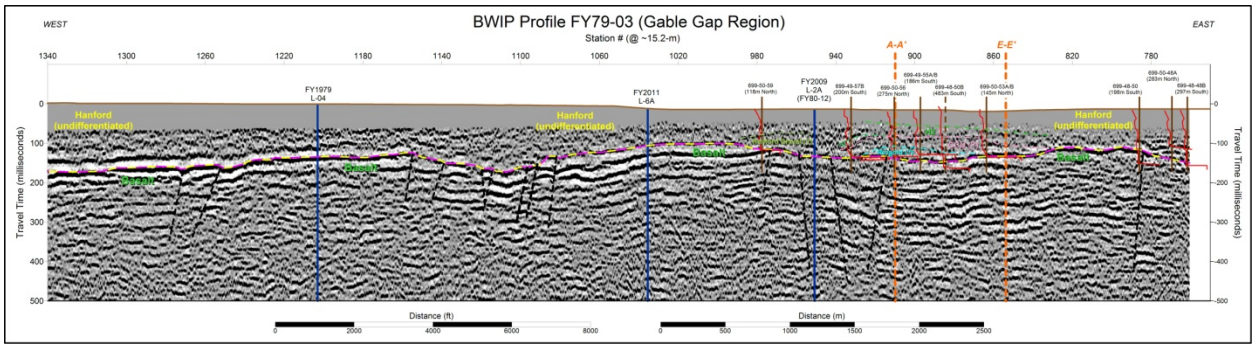

Figure 5. BWIP Profile FY-79-03 (Gable Gap Region)

2.2.2 BWIP Profile FY79-04

Interpretation of BWIP profile FY79-04 in the Gable Gap Area is shown in Figure 6. The profile was originally collected south to north from the Rattlesnake Barricade (south) to northeast of the 200 West Area, and then along a general northeast heading through the Gable Gap and ending near the 100-F area. Check shot information acquired in wells 699-61-62 and 699-63-58 provides the primary tie between the geology and seismic section. Additional control for interpreting the seismic section was obtained by projecting geologic information from wells 699-44-70, 699-55-70 and 699-55-65B using check shot derived velocity information, and by extending the basalt interpretation on cross-lines FY79-03, L-2C, L-6B, and L-7.

Starting at the south end of the profile (Figure 6), the basalt surface rises approximately 51 m (170 ft) northward to where it crosses BWIP profile FY79-03. North and northeast of this point, seismic results indicate a broad topographic depression centered near seismic Station 730 (near the bend in the profile). This depression likely correlates with a similar topographic depression observed towards the southeast on profile FY-79-03 (see Figure 5; FY-79-03, Station 1100). A broad high is tenuously interpreted northeast of the depression between Stations 820 and 900, with the interpretation relying primarily on projecting the sparsely distributed wells onto the profile. This structural high likely corresponds to the buried southeast extension of the Gable Butte structure.

The basalt surface decreases in elevation northeast of the presumed Gable Butte structure in a stair-step fashion. It is likely that the stair-step structure reflects variable erosion into the elevated basalt surface that has exposed diffent basalt formations, otherwise a series of high-angle normal faults would be required to explain the breaks and offsets in reflector continuity. A basalt surface depression is interpreted

between seismic Stations 920 and 960, with Well 699-61-62 located on the northeast flank of this depression. Poor seismic resolution above the basalt surface precludes differentiating supra-basalt sedimentary interfaces within the depression.

A broad topographic high with smaller scale depressions is interpreted for the basalt surface between seismic Stations 960 and 1080. The topographic high likely correlates with a northwest extension of the Gable Mountain structure. Continuing northeast, the basalt surface descends steeply northeast of this broad high into the Wahluke Syncline. High-angle reverse or thrust faulting located on the northeast side of Gable Mountain is the most likely cause for this change in elevation. The fault surface, however, is not imaged by the seismic section. Additional faults are depicted as sub-vertical black lines and are interpreted based on discontinuities in the reflector character.

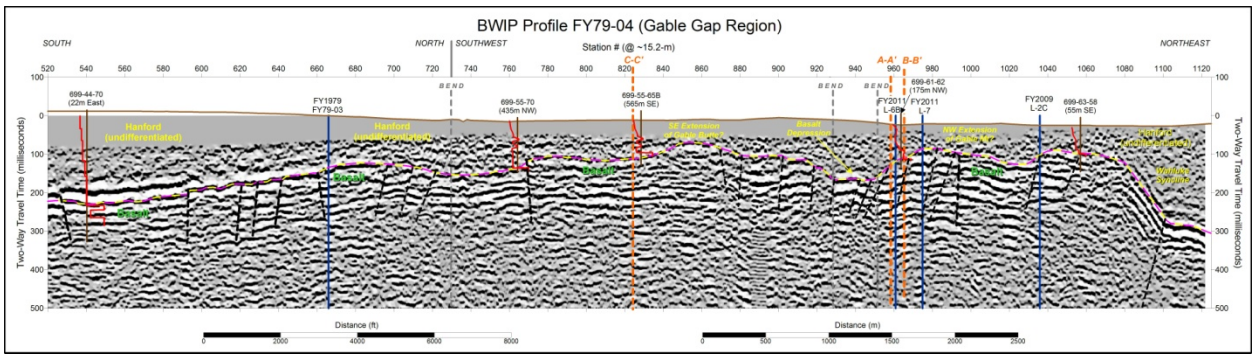

Figure 6. BWIP Profile F79-04 (Gable Gap Region)

2.2.3 12th Street Seismic Profile, 200 East Area

Results for the 12th Street profile acquired in FY2008 are shown in Figure 7. This profile extends east to west along the north end of the 200 East Area (see Figure 2). Check shot information collected in Wells 299-E32-10, 299-E33-340, and 299-E34-5 was used to constrain the basalt surface interpretation and project geologic information obtained for wells near the profile onto the seismic section. From the west end of the profile, the basalt surface is interpreted to rise gently towards Station 450, with minor topographic fluctuations estimated at 2 m (6.6 ft) or less. Total rise from west end to Station 450 is approximately 4-to-5 m (13-to-16 ft). Several discontinuities are imaged within the basalt within a zone north and northwest of the B-Farm Complex. It is not clear whether these discontinuities are true faults, changes in flow-top, weathering effects, or some combination of these factors.

East of the B-Farm Complex, the basalt surface is interpreted to rise approximately 4.5 m (14.8 ft) in elevation, with maximum height occurring near Station 250 (Well 299-E34-4). This west to east increase in elevation is consistent with observed basalt elevations in Wells 299-E33-340 and 299-E34-6. East of Station 250, the basalt surface is tentatively interpreted to form a subtle topographic depression, though poor reflectivity of the basalt surface east of Station 250 precludes a definitive interpretation of the basalt. The cause for loss in reflectivity of the basalt surface east of Station 400 is not well understood at this time, but is probably a result of the acquisition parameters (coarser 4 m geophone spacing) and more heavily fractured or weathered basalt.

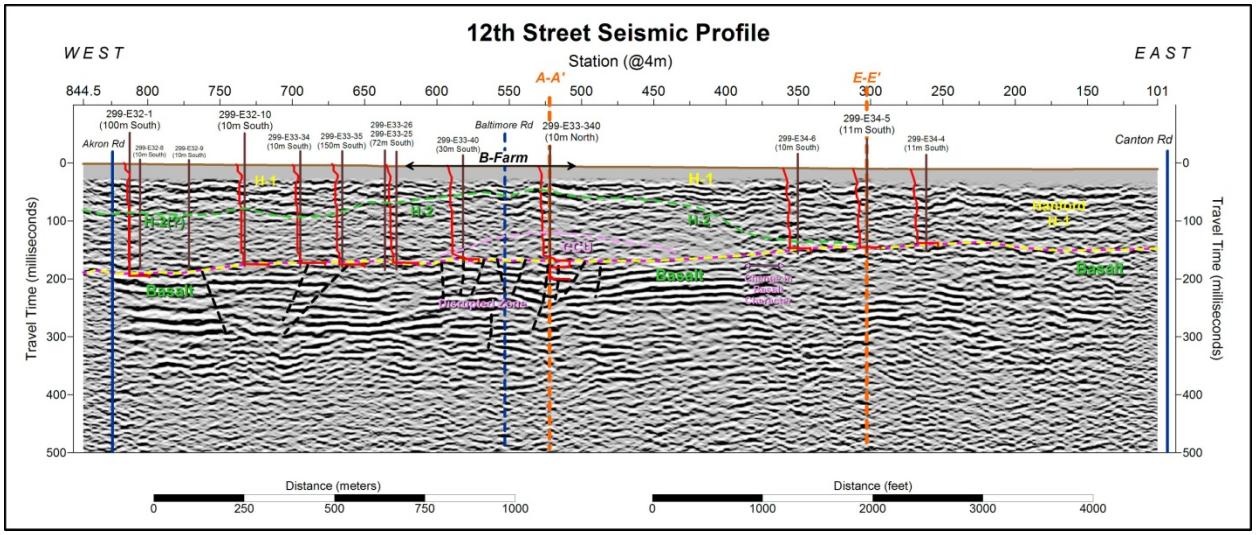

Figure 7. 12th Street Seismic Profile, 200 East Area

2.2.4 Landstreamer Profile L-1

Interpreted results for the seismic profiles acquired with the landstreamer system during FY 2009 (SGW-43746) and FY 2011 (SGW-52160) are shown in Figures 8 through 14. Surveys were collected along existing right-of-ways (roads, railroad tracks and power lines) to reduce the environmental impact. As a result, profiles L-1, L-2 L-4, L-5 and L-6 were constructed from two or more line segments, identified as A, B, and C. Profile locations and survey segments are shown in Figure 2.

Results for west to east profile L-1 is shown in Figure 8. The profile is comprised of 3 survey segments, L-1C (west), L-1A (middle) and L-1B (east). Segments L-1A and L-1B were acquired during FY2009 and Segment L-1C in FY2011. The basalt surface is interpreted along the first strong reflector that is consistent with check shot travel time information obtained for Well 699-50-59, and for projected top-of-basalt using available check shot information for wells 699-51-63, 699-50-56, 699-52-57 and 699-52-54. Geologic information from cross-sections A-A', D-D' and E-E' were also used to constrain the interpretation and top of basalt picks were made consistent with the cross-lines.

Top-of-basalt is interpreted to show an overall west-to-east decrease in elevation of approximately 4 m (13 ft). Localized topgraphic depressions in the basalt surface are observed near Stations 420 (L-1C), 710 and 450 on L-1A and 150 (L-1B), with maximum change in relief of approximately 15 m (49 ft). Comparison with geologic cross-section D-D' (PNNL-19702, Figure 2) indicates that the depressions on Segment A may correlate with the subcrop position of the Rattlesnake Mountain interbed, and thus represent an erosional feature into the less indurated interbed sediments. The basalt surface remains relatively flat to the east and currently is interpreted to dip eastward off the east end of the profile.

The basalt surface is generally overlain by the Hanford H1 sub-unit, though the Hanford H2 sub-unit, and Cold Creek unit (CCU) are projected onto the profile near Stations 500 and 750 (L-1B) based on the geologic cross-section interpretations in PNNL-19702. The H2 interpretation is extended towards the east based on the seismic profile L-3 and Well 699-52-54 and the intersection of cross-section E-E'. The top of the CCU is tentatively extrapolated away from the well point based on a very subtle change in character of the seismic section, and is tentatively interpreted to lie with a basalt topographic depression.

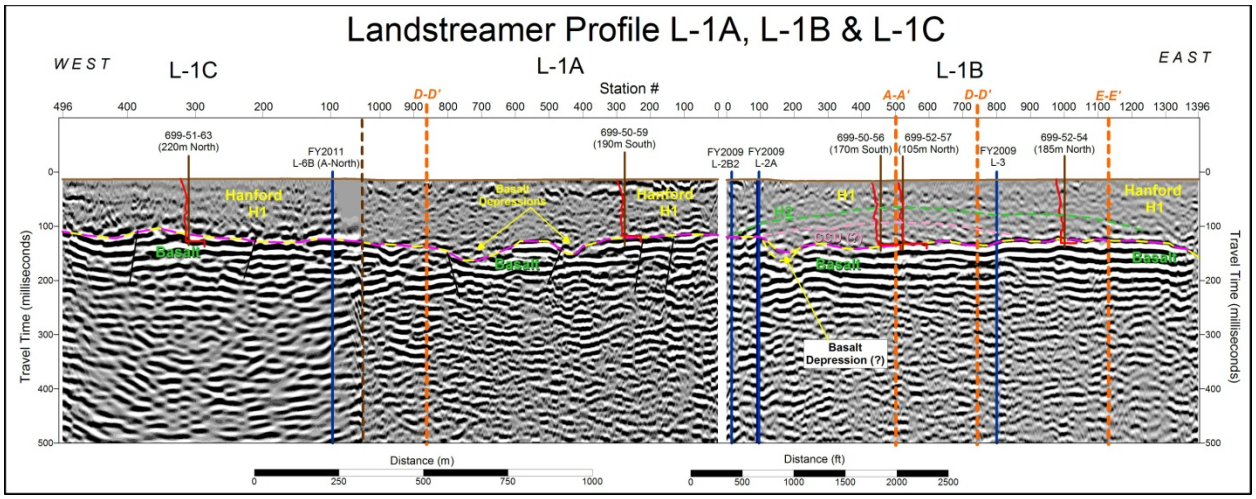

Figure 8. Landstreamer Profile L-1

2.2.5 Landstreamer Profile L-2

Results for the south to north profile L-2 are shown in Figure 9. Also shown are the boundaries for the four segments (L-2A, L-2 B2, L-2B, and L-2C) as indicated by vertical dashed dark-brown lines and changes in station numbering along the top of the seismic section. Check shot information from wells 699-49-57B (east of profile), 699-50-59 (west of profile, traced along L-1A), 699-54-57 (east of profile, traced along L-4B), 699-60-59 (on profile), and 699-63-58 (east of profile) was used to constrain the top-of-basalt interpretation. Additional geologic control is provided by wells 299-E32-1 (south end of profile), 699-50-56, 699-52-57, 699-55-57, 699-55-60B, 699-57-59, 699-59-58, and 699-60-60 were projected on to the seismic section using check shot derived velocities. Wells 699-55-60B, 699-57-59, 699-59-58 did not encounter basalt, but the well TD is used to constrain the maximum possible elevation for the top of basalt on the profile. For these wells, estimates of the basalt elevation were derived from the geologic cross-sections constructed for the Gable Gap region (PNNL-19702), and check shot information used to project the estimated basalt elevation on to the profile. Note too that the position of the basalt at individual well points is dependent on both the depth and seismic velocity used to convert from depth to travel time. For example, seismic velocity to top of basalt measured in well 699-49-57B was slower than for Well 699-50-59, resulting in a greater apparent travel time depth to basalt despite being higher in elevation than 699-50-59 (and 699-50-56).

Starting at the south end of the profile, the basalt surface rises approximately 12.5 m (40 ft) to where it forms a broad platform near the central third of the profile (all of Segments L-2B2 and L-2B). Hanford sub-unit H1 is interpreted to overlie the platform, though interpretation of profile L-4B (Figure 11) suggests that CCU might directly overlie L-2B near the intersection with Segment L-4B. Consequently, the top of the CCU is tentatively placed on a subtle change in reflector character and extended south and north from the L-4B intersection. Further south, neither Hanford sub-unit H2, the CCU, nor the Ringold unit interpreted in Well 699-50-56 could be traced westward onto cross-line L-2 using profile L-1B.

North of the platform (on Segment L-2C), the basalt surface drops approximately 40 m (131 ft) in elevation where it forms a broad depression between stations 400 and 650. Several high-angle vertical faults are interpreted to bound the southern edge of the depression, and a series of faults likely occur along the northern edge. This basalt depression is similar in width and depth to that observed on BWIP profile FY79-04 to the northwest (see Figure 6, Stations 920 through 960) and L-6B to the west (see Figure 13, Stations 950 through 1500).

Strong reflectors within the depression likely correlate with CCU or Ringold units, as based on geologic interpretations of sediments in wells 699-57-59 and 699-59-58. These wells did not extend to basalt, and the basalt depth in their vicinity is estimated from the A-A' and E-E' geologic cross-sections.

The basalt surface rises towards the north and forms another broad platform with several localized basalt depressions. The elevation of this platform is consistent with check shot results in wells 699-60-59 and 699-63-58. Hanford sub-unit H1 are interpreted to overly the basalt in this region.

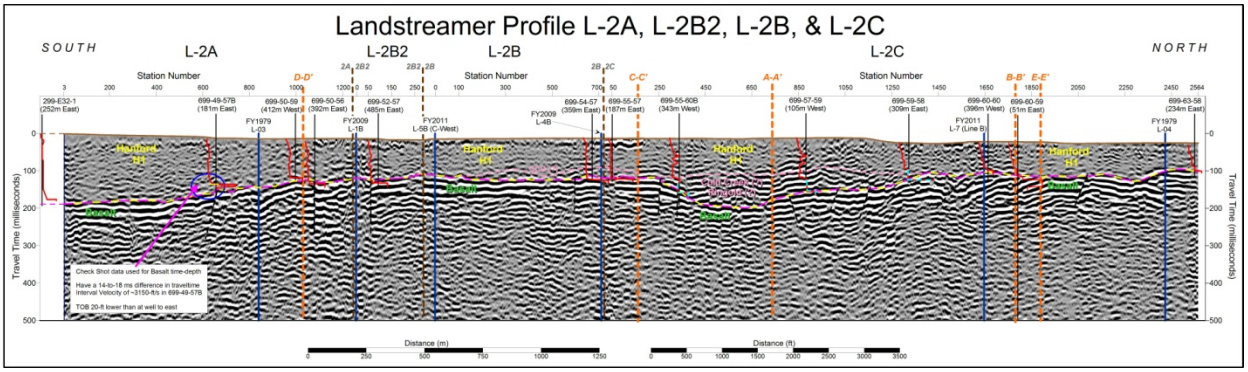

Figure 9. Landstreamer Profile L-2

2.2.6 Landstreamer Profile L-3

Figure 10 shows the interpreted results for profile L-3 along with check shot information provided by Wells 699-52-55 and 699-52-55B, which are located directly on the profile (at this scale the well points plot on top of each other and only 699-52-55B is shown). The basalt pick is traced southward, along the strong reflector that corresponds with the check shot determined travel time, and forms a subtle rise between Stations 100 and 300. The top-of-basalt pick is consistent with travel time estimates to top-of-basalt in wells 699-50-56, 699-52-54 and 699-52-57, and for cross-lines L-1B and L-5B.

North fromWell 699-52-55B, the basalt surface is interpreted to form a depression in the vicinity of well 699-53-55A. For this case, the "interpreted basalt" surface represents the top of the CRBG because the Elephant Mt member has been eroded at Well 699-53-55A resulting in the Rattlesnake Ridge interbed subcropping beneath the overlying Hanford sediments. An erosional structure must exist, though the seismic data, as processed, does not resolve the edges of this feature. A decrease in elevation for the top of the CRBG is approximately 23 m (78 ft). Check shot results for Well 699-52-55A/B allow tracing the top of the Rattlesnake Ridge interbed (light green dashed line) and underlying Pomona Basalt member (purple dashed line) north to 699-53-55A.

Top of basalt is tentatively extended north along a strong reflector that is positioned consistent with the underlying Rattlesnake Ridge interbed and Pomoma basalt using Well 699-53-55A. The travel time of this reflector at the north end of the profile is consistent with the travel time interpreted for the basalt reflector on cross-line profile L-4B. The basalt surface north of Well 699-53-55A forms a broad saddle structure between stations 900 and 1000. The maximum elevation of the basalt here is likely lower than 121 m (397 ft) observed at 699-52-55A/B. Caution is urged, however, for interpreting the true elevation for the saddle structure as cycle skipping (reflection phase picking) and unclear presence or absence of faulting, may have resulted in picking too low of a reflecting horizon. Elevation here could be as much as 14 m (47 ft) higher than currently estimated if a shallower reflecting horizon is used. Also note that either the Elephant Mt or Pomona basalt member likely subcrop at the Line 3 and Line 4B intersection, and L-3 would need to be extended further north to resolve this further (loss of reflector quality due to end of profile issues).

The basalt surface north of profile L-3 (and cross line L-4B) must drop steeply in elevation because Well 699-55-55 (north of profile) did not encounter a basalt member through its total depth of ~95 m (312 ft). The first CRBG member encountered by the well is the Selah interbed at an elevation of approximately 83.4 m (273.8 ft) indicating that both the Elephant Mt and Pomona basalt members have been removed. The steep slope for the CBRG is likely sub-parallel to the west-to-east profile L-4B. Additional evidence for supporting a drop in the basalt surface to the north is found in Well 699-56-53 (not shown, >500 m north of the profile's east end) encountered Elephant Mt basalt at an elevation of approximately 19 m (62 ft) lower than at Well 699-52-55A/B.

Hanford sub-unit H2 and the CCU are interpreted in Well 699-52-55B and Well 699-52-57 towards the southwest. Subtle reflector character is used to trace the H2 sub-unit south, at least to cross-line L-1B. The CCU is also tentatively picked along a subtle change in reflector character. Both horizon picks are consistent with cross line L-1B(see Figure 8).

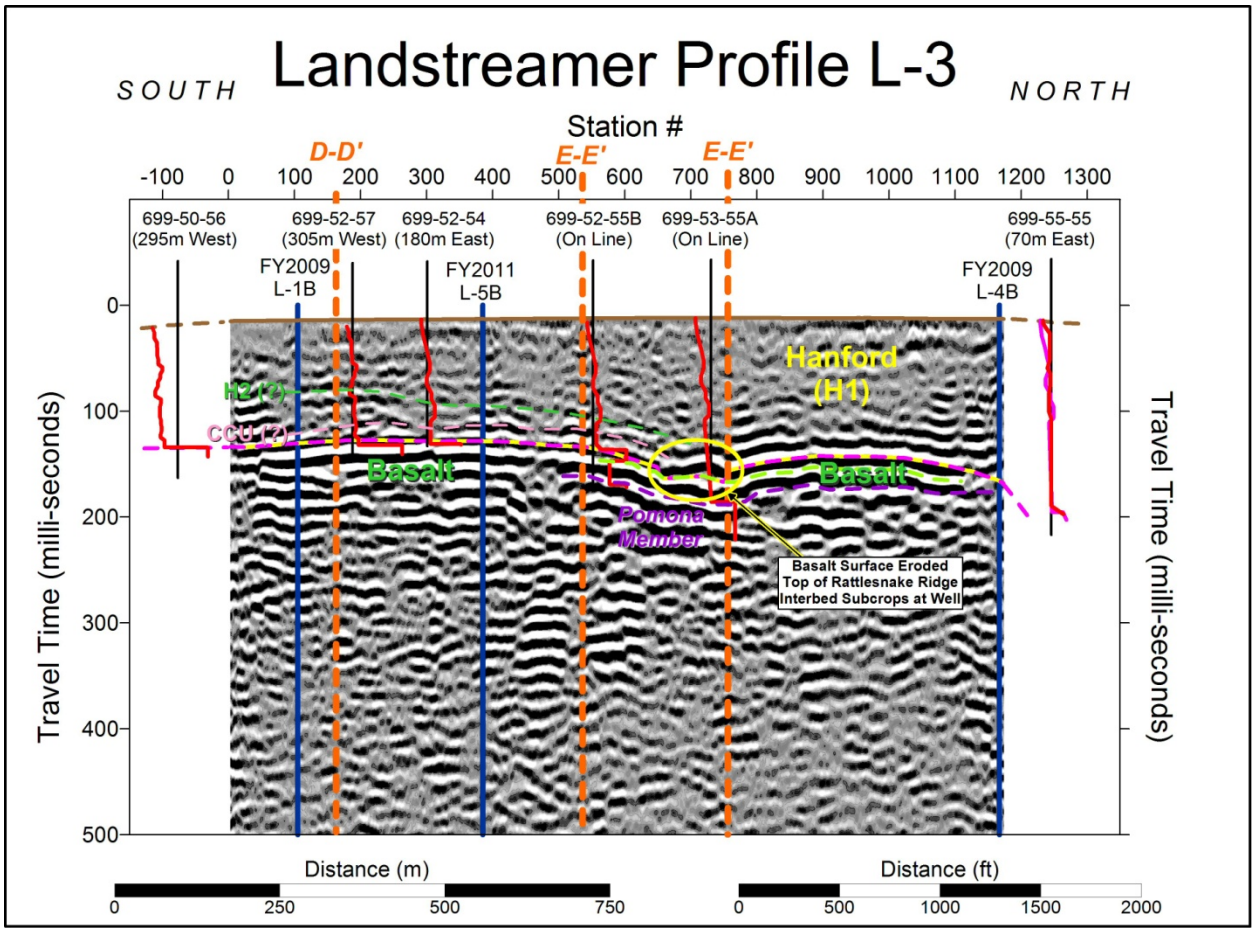

Figure 10. Landstreamer Profile L-3

2.2.7 Landstreamer Profile L-4

Results for seismic profile L-4 are shown in Figure 11. Profile L-4 is constructed from 2 survey segments, L-4A (west) and L-4B (east) acquired duing FY2009. Interpretation of the seismic profile is constrained using check shot information from Wells 699-54-57 and 699-55-60A, projection of geologic information from wells 699-55-57, 699-55-55 and 699-55-60B, geologic interpretations in cross-sections A-A', C-C' and E-E', and crossline interpretations from L-2B, L-2C, L-3 and L-6B (offset ~80m west of L-4A).

Basalt is interpreted along a strong reflector that remains relatively horizontal across Segment L-4A, except under Stations 500 and 200, where topographic depressions of 20 m (65 ft) and 8 m (26 ft) are interpreted, and between stations 50 and 150 where the basalt is estimated to be 3 to 4 m (10 to 13 ft) higher in elevation. The elevation of the basalt depression under station 500 is estimated at approximately 100.6 m (330 ft) AMSL, which is slighty lower than the TD for Well 699-55-60A (104.5 m) [342.7 ft]) and higher for Well 699-55-60B (87.9 m [288.3 ft]) which are located 220 m and 318 m north-northwest of the depression. Neither well encountered basalt or other CRBG members, and thus the basalt must be lower towards the north. Both depressions observed on segement L-4A are most likely erosional features, though the possibility for a fault controlled structure cannot be ruled out.

For Segment L-4B, the basalt surface remains relatively flat between staions 0 and 450 though a subtle depression is indicated between Stations 200 and 400, and east of the C-C' intersection. Breaks in reflector continuity suggest faulting may have controlled the formation of this depression, though the possibility of this being an erosional feature where a different CRBG member subcrops is also possible.. East of Station 500, the basalt surface is interpreted to descend approximately 30 m (100 ft) in elevation forming a broad low between stations 750 and 1250. The decrease in elevation is consistent with geologic cross section C-C' (PNNL-19702). Basalt was not encountered in Well 699-55-55 (70 m north of L-4B) and the basalt surface associated with the nearby L-4B seismic data is estimated to be about 15 m (51 ft) higher in elevation than the bottom of the borehole. Well 699-55-55 encountered the Selah Interbed near the well's TD, and comparing the sequence of reflectors above this point suggest that the basalt surface has to be either the Pomona or Elephant Mt member. This is different than the C-C' geologic section where the Ezquatel basalt member is interpreted to subcrop between wells 699-54-57 (west) and 699-55-55 (east). Profile L-3 (Figure 10) would have needed to be extended 80 to 100 m further north to help resolve this issue.

Breaks in reflector continuity are indicated by sub-vertical dashed lines that possibly correlate with either changes in CRBG member basalts being the first to subcrop (via erosion) or from true offsets along fracture/fault planes. A north-facing erosional surface is required to explain the first encounter with the Selah Interbed in Well 699-55-55 (north of L-4B) and the first encounter of the Rattlesnake Ridge Interbed in Well 699-53-55A (south of profile).

Hanford sub-unit 1 is interpreted to overly the basalt surface across most of the profile, except in the vicinity of stations 0 through 360 of Segment L-4B where geologic cross-section A-A' and C-C' interpret the presence of Cold Creek units. The top of the Cold Creek is tentatively interpreted along a subtle change in reflector character near the intersection with cross-section A-A'. Cold Creek units are interpreted to pinch-out to the west after crossing seismic Profile L-2B, and to the east prior to Well 699-54-57. Both of these pinch-outs are interpreted to occur against a localized rise in the basalt surface.

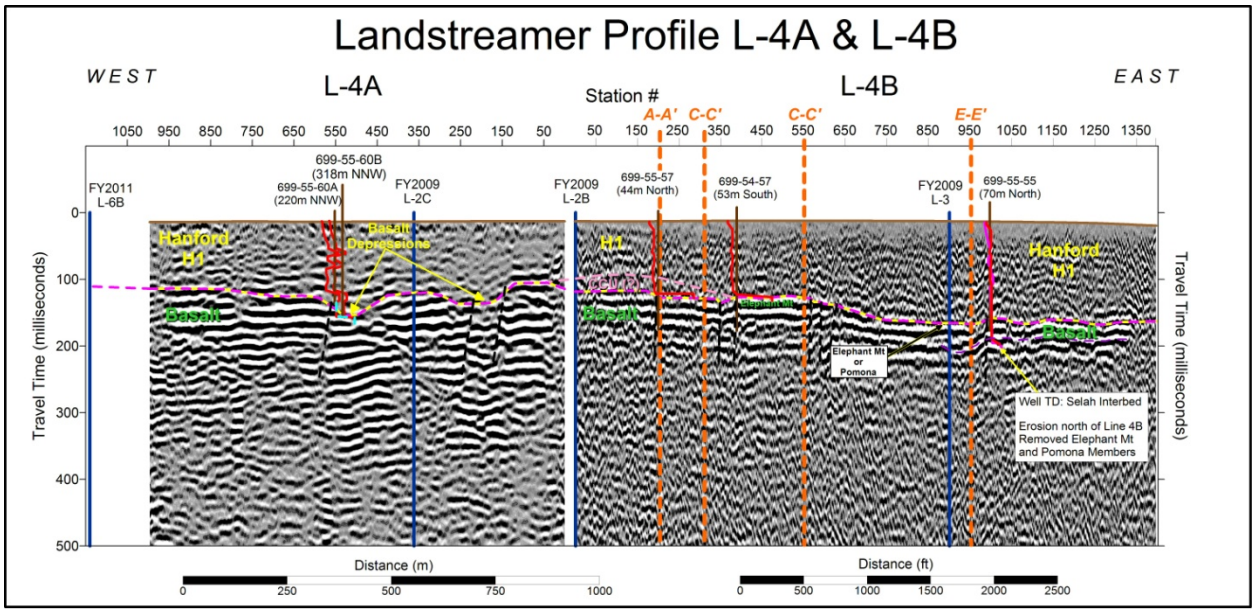

Figure 11. Landstreamer Profile L-4

2.2.8 Landstreamer Profile L-5

Figure 12 shows results for profile L-5, which is comprised of two seismic segments L-5A (west) and L-5B (east) acquired during FY2011. Interpretation of the top-of-basalt is constrained by check shot results in wells 699-50-59 and 699-52-55B, projection of geologic information from wells 699-51-63, 699-52-57, 699-52-54 and 699-52-52 using check shot derived velocities, and on cross-line analyses with seismic profiles L-2B, L-3 and L-6B. Geologic control was also provided by cross-sections A-A', D-D', and E-E'.

The basalt surface is interpreted to form a broad low near the west end of the profile and extending to station 450 of L-5A. Basalt is about 10 m (33 ft) lower in elevation in this low than in Well 699-51-63 (about 150 m west and 295 m south). East of Station 450, the interpreted basalt surface rises steeply about 13 m (44 ft) to where it forms a localized topographic high near station 400 (L-5A). Continuing east, the basalt surface is interpreted to descend 14 m (46 ft) to where it forms a topographic depression near Station 250. Breaks in reflector character are tentatively interpreted as high angle fault surfaces

A relative topographic high is interpreted near the center of the profile, though it is unclear the genesis of the strong reflectors above the interpreted basalt surface between stations 20-70 of L-5B (as indicated by the red question marks). It is likely that these are processing artifacts due either to incorrect stacking velocities or improper muting.

A localized depression in the basalt is imaged near Station 125 of L-5B. Vertical relief is estimated to be a maximum 6 m (20 ft) for this depression. Continuing east, the basalt surface is imaged to form a localized topographic high near the intersection with geologic cross-section A-A', and a depression near station 450 (L-5B). Both of these features are estimated to have a maximum relief of about 3 to 4 m (10 to 12 ft) relative ot the average basalt elevation. A subtle depression is indicated near the east end of Line 5B, though basalt surface is consistent with Well 699-52-52 northwest of the east end of the profile.

Hanford sub-unit 1 is interpreted to overly the basalt surface over most of profile L-5 except where geologic cross-sections A-A' and E-E' argue for Cold Creek and Hanford sub-unit H2. The top of the H2

sub-unit is interpreted along a extremely subtle change in reflector character, and is extended westward until it pinches out agains the basalt high near the center of Profile L-5. The H2 sub-unit is tentatively interpreted to pinchout towards the east against a possible scour filled with H1 sub-units near station 650. The absence of the H2 sub-unit in this area is consistent with the geologic interpretation along this portion of section D-D'.

Top of the Cold Creek is picked along a stronger reflector that occurs within the relative basalt low between stations 200 and 550 on L-5B. The Cold Creek is interpreted to pinchout towards the west against the relative basalt high near geologic section A-A', and towards the east against the potential H1 scour fill, though this interpretation remains extremely tentative.

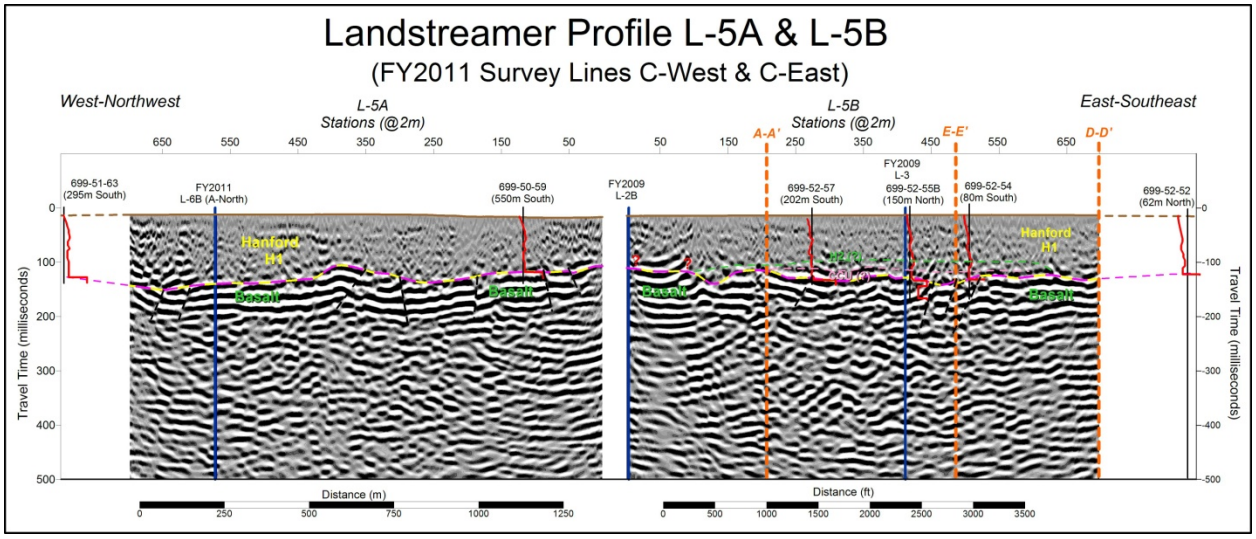

Figure 12. Landstreamer Profile L-5

2.2.9 Landstreamer Profile L-6

Results for seismic profile L-6 are shown in Figure 13. The profile is constructed from 2 survey segments, L-6A (south) and L-6B (north) acquired during FY2011. Interpretation is constrained by check shot 699-61-62, projection of geologic information in wells 699-47-60, 699-51-63, 699-55-63, 699-64-62, cross-line analysis of seismic profiles FY79-03, FY79-04, L-1A, L-5A, and L-7, and geologic interpretations of cross-sections A-A', B-B', C-C' and D-D'.

Top-of-basalt is interpreted to rise 19 m (62 ft) in elevation from south end of L-6A to the intersection with seismic profile FY79-03. Basalt is interpreted along the top of the first strong reflector and its vertical position is consistent with the estimated travel time in Well 699-47-60. North of the FY79-03 intersection, the basalt surface is interpreted to descend approximately 18 m (60 ft) to form a broad depression between stations 200 and 550 on Line 6B). Breaks in seismic character are tentatively interpreted as high-angle faults (sub-vertical, dashed black lines). Reflector offsets towards the north end of Line 6A are suggestive of high angle reverse faulting.

A broad platform region is imaged between stations 550 and 925 on Line 6B. The elevation of the basalt in this area is consistent with the basalt elevation calculated for Well 699-55-63, and with the platform region defined along seismic profile L-2B (Figure 9) towards the east and southeast. The interpreted basalt surface dips gently northward between stations 650 and 900 (Line 6B), and the strong and laterally continuous reflectors suggest more competent and less fractured basalt in this region.

A major topographic depression in the basalt surface is imaged between stations 950 and 1500 of segment L-6B. High-angle faults are interpreted to bound both the north and south flanks of this depression. A maximum relief of about 41 m (135 ft) relative to the broad platform region to the south is estimated near station 1250. The width and depth of this feature is similar to that observed between stations 250 and 1300 of seismic profile Line 2C (Figure 9), and consistent with a basalt surface depression between stations 920 and 960 of profile FY79-04 (Figure 6). Well 699-55-60B (southeast) did not encounter basalt, and the elevation at its maximum drilled depth is approximately 7 m (22 ft) higher than the basalt elevation estimated in the lows for both Line 2C and Line 6B.

Strong reflectors within the basalt depression are tentatively interpreted as Cold Creek. The interpretation is based on similarity with results for seismic profile Line 2C (to the east) and interpretation along geologic cross-section A-A'. The top-of the Cold Creek is interpreted to pinch out along both the north and south flanks of the depression. Hanford 1 sub-units are interpreted overlying the basalt along the rest of the profile.

North of station 1600, the top-of-basalt is interpreted as a broad platform with localized undulations of 2-3 m (6.5-10 ft). The southern edge of the Wahluke Syncline is not observed on this profile, and the position of the basalt surface north of the profile (near Well 699-64-62) is tentatively drawn to maintain the average elevation of the basalt platform as this well did not encounter basalt.

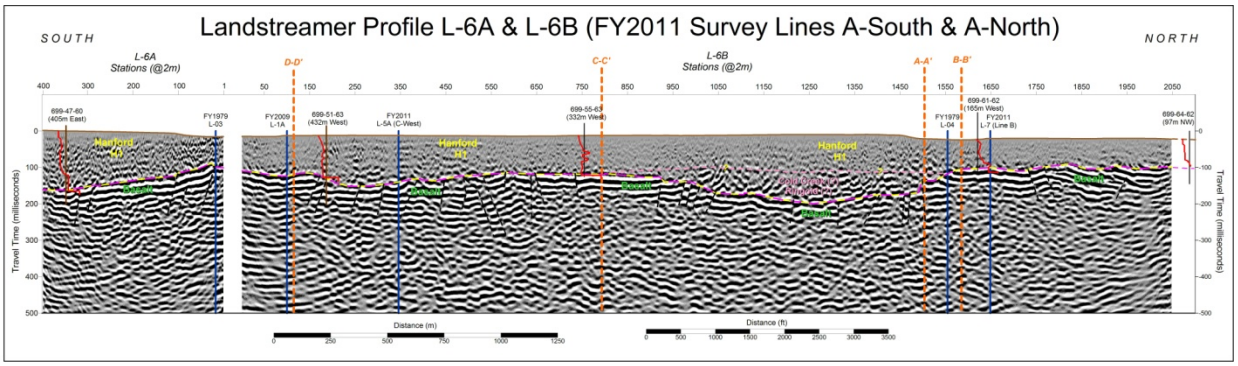

Figure 13. Landstreamer Profile L-6

2.2.10 Landstreamer Profile L-7

Results for seismic profile L-7 (FY2011) are shown in Figure 14. The top-of-basalt interpretation was constrained by check shot information in wells 699-60-59, 699-61-62 and 699-61-66, projection of geologic information in wells 699-60-59, 699-60-60, 699-61-62, 699-61-66, cross-line analysis of seismic profiles FY79-04, L-2C and L-6B, and geologic interpretations of cross-sections A-A', B-B', C-C' and E-E'.

Top of basalt was interpreted along the first strong reflector that is consistent with check shot and cross line interpretations. The interpreted surface maintains a relatively flat orientation with a depression near station 1140 with a maximum relief of about 8 m (25 ft), and at the east-southeast end of the profile where the basalt descends approximately 15 m (50 ft). Smaller depressions 3 to 4 m (10 to 13 ft) are observed to the west of cross line L-6B, and west of cross line FY79-04.

Hanford 1 sub-units are interpreted to overlie the basalt across Line 7. Several high-angle faults are interpreted at offsets in reflector continuity.

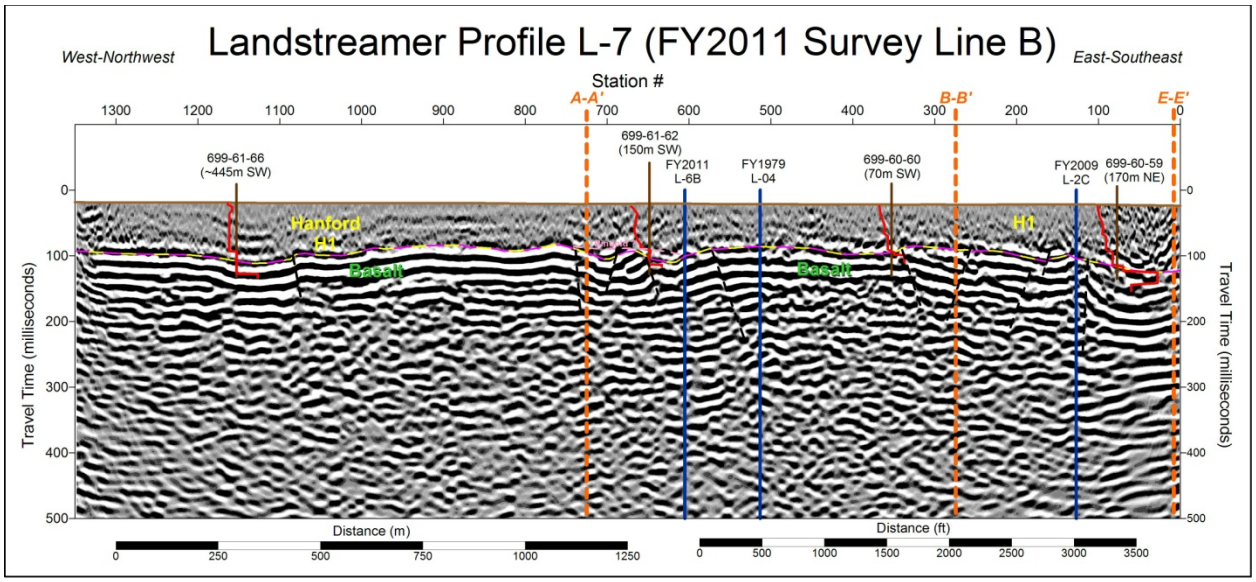

Figure 14. Landstreamer Profile L-7

2.3 Calculation of Basalt Elevations

The basalt surface interpreted in Figures 5 through 14 is based on seismic travel time and needs to be converted to elevation for use in the CSMs. Ideally, a velocity function is developed using information from the processing flow and external velocity estimates to convert the seismic section from travel time to depth (termed depth migration). This was attempted for the FY 2009 landstreamer data, where the Contractor was requested to provide the seismic sections processed into units of elevation. Preliminary analysis of the depth migrated sections indicated a good correlation between seismic and well derived basalt elevations where the basalt surface is relatively constant in elevation. The depth migrated sections, however, appear to have over-estimated the depth to basalt within localized lows which resulted in producing pronounced and geologically unreasonable topographic depressions in the basalt surface. Further analysis revealed that the travel time to depth function used by the Contractor had too fast of a seismic velocity for the material within the basalt depressions.

Figure 15 illustrates what likely is occurring with the depth migration as applied to the landstreamer data. The upper plot is a depth model showing a hypothetical depression in the basalt surface (brown polyline), and the lower plot is a simple representation of the model in seismic travel time. The position of a well point with known seismic velocities for each layer are shown on both plots and, to the right, average velocity curves (depth divided by travel time) are plotted in both depth and travel time space. The blue curve represents the average velocity function at the well point, and the brown curve represents the true velocity function at the center of the basalt surface depression.

The average velocity functions for the two cases are different, with the true average velocity to top-of-basalt within the depression lower than what it would be if measured at the well point (at the same travel time or depth). If the velocity function for the check shot (blue curve) is used to calculate the depth of the depression based on the seismic travel times, then the seismic velocity used is too fast and the resulting depth is greatly exaggerated (dashed blue line in depth model). This is most likely what occurred with the depth migration conducted by the Contractor because all of the supplied check shot points appear to lie outside of observed basalt surface depressions.

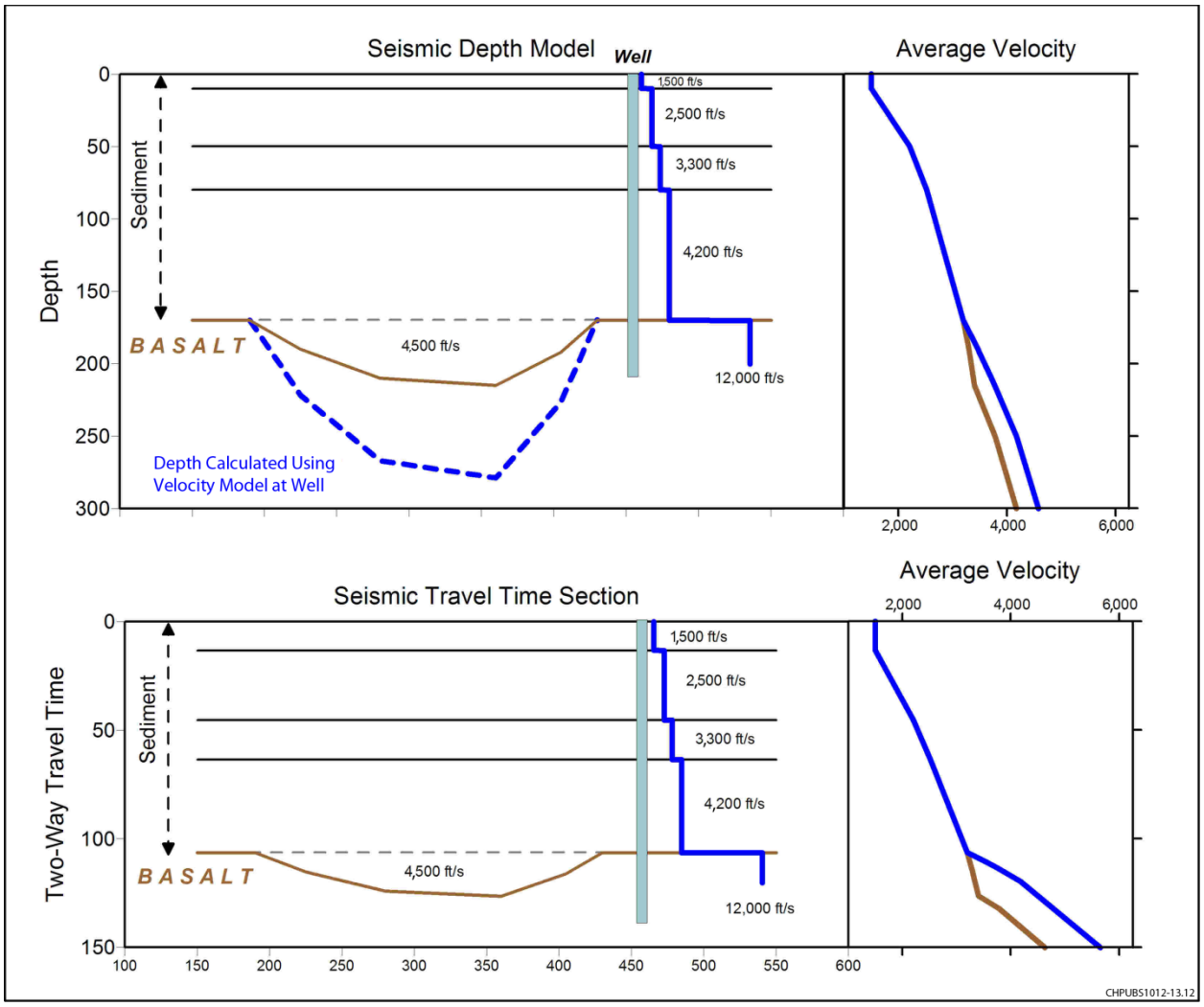

Figure 15. Velocity—Depth Conversion Issues

To minimize the overexaggeration of basalt depth that resulted from the depth migration, an alternate approach employing known velocities and tying the seismic derived surface to known basalt elevations was used. The method essentially drapes the seismically interpreted basalt surface onto the well control, while preserving seismic structure observed between well points. The basic steps are as follows:

- Determine correction velocities along the seismic profile to convert seismic travel time to depth:
  - For basalt elevation (or depth), the correction velocity is equivalent to the average velocity from ground surface to top-of-basalt.
  - For wells with check shot information, directly use the travel time and depth information to determine the average velocity from ground surface to top-of-basalt. Check shot derived velocities remain invariant during the conversion from seismic travel time to elevation.
  - For wells without check shot information, use either the nearest check shot derived velocity or an interpolation/average if between or near more than one check shot survey. Cross-check the interpolation/averaging assumptions by using these velocities to predict where the top-of-basalt

should appear on the seismic section and adjust, as needed, until the predicted and interpreted basalt surfaces are consistent.

  - Determine the location of these wells along the seismic profile. For wells distant from the profile, use known structural trends to project the well point onto the profile.
  - Interpolate the correction velocity between the well points, creating a smoothly varying velocity function that should preserve the general shape of the interpreted basalt surface while placing it at the proper depth (elevation) for the well points.
  - Include the position of intersecting lines to allow for cross-line analysis.

- Determine the seismic travel time from ground surface to top-of-basalt along the seismic profile:
  - Use the profile topographic data, seismic datum, and datum correction velocity used during processing to calculate the ground surface position in travel time on the seismic section.
  - Subtract the corresponding basalt surface travel time from the ground surface travel time and divide by two to get the one-way travel time from ground surface to top-of-basalt.
- Apply the correction velocity to convert from travel time to depth bgs. Subtract the computed depth from the topography to determine the basalt elevations.
- Perform cross-line analysis to ensure that depth (or elevations) are consistent at line intersections. If not consistent, use either an average of the cross-line velocities or other external information to adjust the depth (elevation) at the intersection.
- Catalog the derived basalt elevation data by line number and station to allow further quality assurance/quality control analysis. Adjust the final product as newer velocity or check shot information becomes available.

The method is illustrated in Figure 16. The top panel is the seismic travel time section with the interpreted basalt surface represented by the yellow line and the ground surface by the brown line. The middle panel shows estimates and measurements of the average velocity from ground surface to top-of-basalt along the profile. Red circles are velocities measured using check shot surveys. Green circles are estimates of the average velocity using the seismic travel time and depth to basalt from nearby wells. The dashed magenta line is the corresponding smoothed velocity function. Basalt elevation, shown in the lower panel, is computed with the following equation:

$$B_E = GS_E - V_C\,(B_{twt} - GS_{twt})/2$$

where:

B_E = basalt elevation

GS_E = ground surface elevation

V_C = correction velocity (average velocity)

B_{twt} = TWT to interpreted top-of-basalt

GS_{twt} = TWT to ground surface

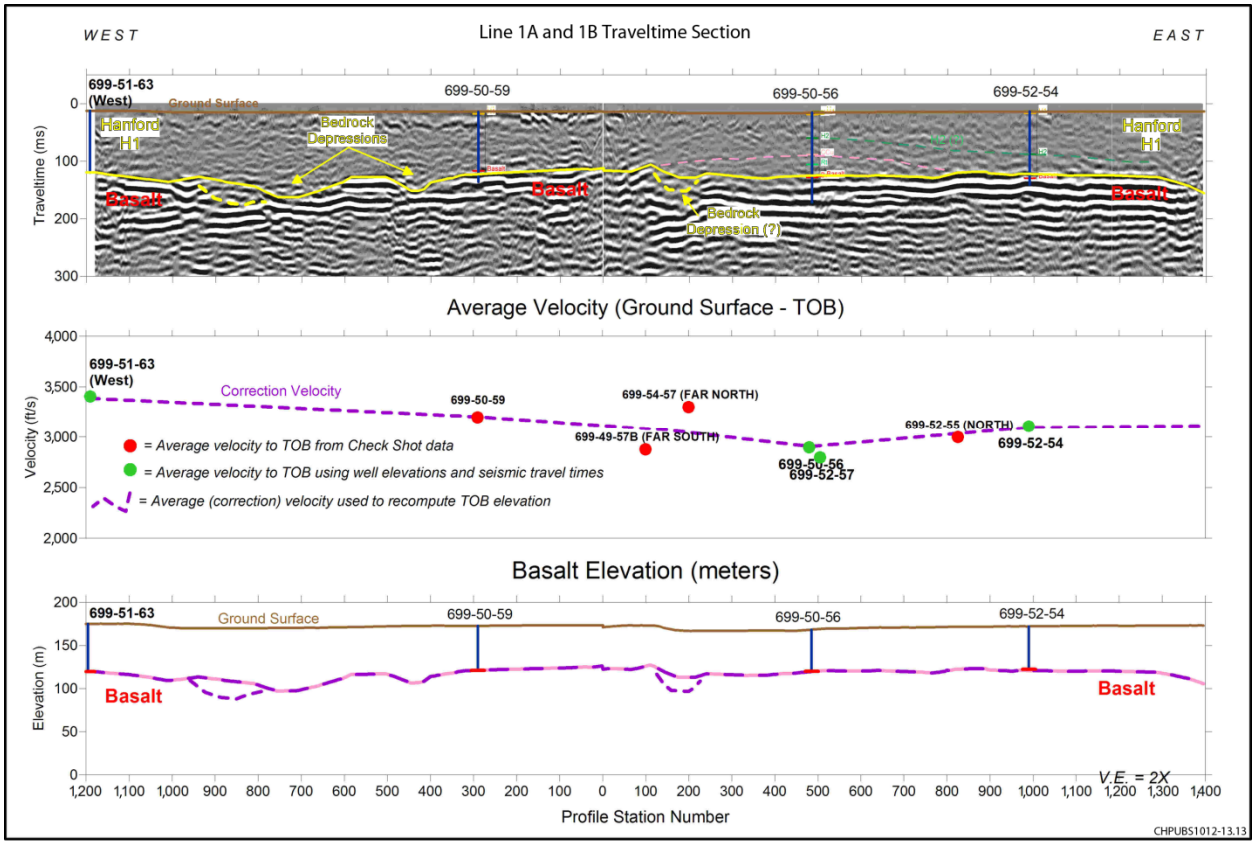

Figure 16. Velocity—Depth Conversion

2.4 Basalt Surface

Basalt elevation data were tabulated by line identification and line station number geographic coordinates and then merged with existing well control data to construct a two-dimensional surface (topographic model) of the basalt elevation. Topography of the basalt surface defined by geologic cross-sections presented in PNNL-19702 were used to provide constraints on the seismic interpretation, though not used in constructing the basalt surface. The basalt topographic surface constructed from the seismic and well control is shown in Figure 17 and plotted with a 20 ft contour interval. Index contours are plotted at 100 ft intervals and given a greater line thickness. Wells that encountered basalt are shown as red dots with both the well name and basalt elevation plotted. Wells that did not encounter basalt are also plotted as light-

blue dots, with both the well name and elevation at the base of the borehole (total drill depth) plotted. Also shown are the positions of the seismic profiles and the geologic cross-sections.

Significant features on Figure 17 are a west-northwest-east-southeast oriented basalt surface depression that extends between the Gable Mountain and Gable Butte structures, and oriented sub-parallel to seismic profile L-7. This topographic low connects wells 699-61-62 and 699-61-66, and is interpreted to merge with a broad depression in the north-central part of the study region.

The basaalt depression can be traced south- and southeastward using profiles BWIP FY79-04 (Figure 6, between stations 920 and 980), L-6B (Figure 13, between stations 950 and 1550), and L-2C (Figure 9, between stations 250 and 1450). The portion of the depression under Line 2C is consistent with the elevation at the drilled depth for Well 699-55-60B, which did not encounter basalt to an elevation of 87.8 m (288 ft). The northern extent of this broad depression likely extends to well 699-59-55 (south of Gable Mt), which also did not encounter basalt. The well'stotal depth yields a maximum possible basalt elevation of about 87.5 m (287 ft). The depression is also interpreted to extend south and east towards Well 699-55-55 which would allow for a maximum basalt elevation of about 78 m (256 ft). This broad and low area is extremely tentative, and conforms with the geologic interpretation along coss-section E-E' (PNNL-19702).

South of the basalt topographic depression, the seismic data image a broad platform with an overall local relief of 3 to 5 m (10 to 16 ft). Localized depressions imaged on seismic profiles L-1A, L-4A and L-6B indicate changes in basalt elevation of 8 to 15 m (25 to 50 ft). The overall pattern of the basalt surface in the vicinity of seismic profiles L-1, L-2, L-3, L-4, L-5 and L-6 is that of pothole geomorphology. The presence of this platform region indicates that the southeastern sub-crop extent of the Gable Butte structure must terminate somewhere between seismic profiles FY79-04 and L-6. The current basalt surface interpretation tentatively calls for a more southerly orientation of the Gable Butte subcrop, connecting with wells 699-55-65B and 699-55-65C and possibly extending as farth south as the intersection of Lines FY79-03 and L-6A/B.

A northwest trending basalt topographic high, extending from the northeast part of 200 East serves as a groundwater boundary. The new basalt surface, however, no longer supports extending a paleo-channel from the basalt depression defined by wells 699-47-50, 699-48-48B, and 699-48-50 northwest towards the central basalt low. Previous interpretations (see PNNL-19702) place this low intersecting the eastern 300 m of profile L-5B. The seismic data argue instead for a relatively flat basalt surface that is near in elevation that observed in well 699-52-54. It is possible, for this low to extend further east (either between profile L-5B and well 699-52-52 or east of 699-52-52). Extension of either L-1B or L-5B approximately 1500 m toward the east would facilitate the determination of the presence or absence of this low.

The top of basalt in the region north-northwest of the 200 East Area is predominantly a broad platform, with longer wavelength swale and saddle features and localized (current interpretation) depressions in the basalt surface. An east-west trending high likely connects with and is probably related to the southeastern subcrop of the Gable Butte structure. The overall sense is for a topographic divide along a SSW to NNE trend.

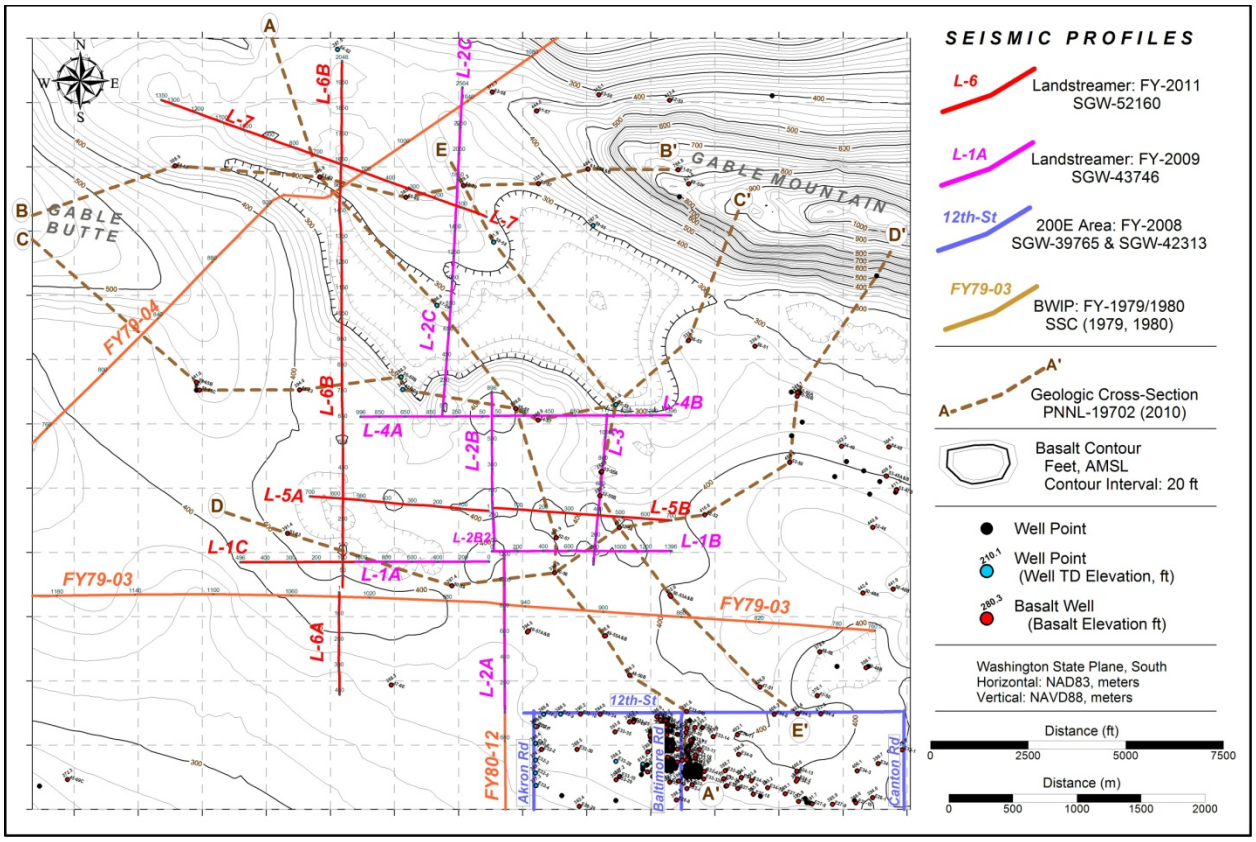

Figure 17. Basalt Topography—Gable Gap Area

3 Summary

Seismic reflection profiles were used to help constrain the basalt surface interpretation within the Gable Gap Area of the Hanford Site. Available seismic data sets consisted of the FY 2009 and FY 2011 landstreamer surveys collected in the Gable Gap north of the 200 Areas, FY 2008 high-resolution reflection acquired in the 200 East Area, and FY 1979 and FY 1980 seismic reflection data conducted as part of the BWIP investigations. The combined seismic data set provides approximately 34 km (21 mi) of profile coverage.

Interpretation of the seismic data suggests that the current state-of-art seismic methods used during the FY 2008, FY 2009 and FY 2011 surveys are capable of resolving interfaces within the vadose section of the supra-basalt sediments. Reflecting horizons observed in the FY 2008 data appear to correlate with Hanford sub-units, whereas CCU and/or Ringold unit are potentially imaged by the FY 2009 and FY 2011 seismic sections. Enhanced reprocessing focusing on the supra-basalt sediments may yield additional information if critical data needs warrant further investigations.

Interpretations and refinements provided in this report were derived from the two-way travel-time sections rather than the depth migrated (and converted to elevation) seismic sections provided by the contractor (SGW-52160). This route was chosen because the contractor depth migrated sections have a lower vertical resolution (4.3 m) than the travel-time sections (~1.5 m), and there are issues with variability in seismic velocity for the supra-basalt sediments and estimates of the depth to basalt described in Section 2.3. The depth migrated sections have over-estimated the depth to basalt within localized lows which resulted in producing pronounced and geologically unreasonable topographic depressions in the basalt surface. Further analysis revealed that the travel time to depth function used by the Contractor had

too fast of a seismic velocity for the material within the basalt depressions The contractor supplied depth sections, however, do provide a first pass interpretation of the basalt surface from which refinements can be made. Horizontal resolution is estimated to be approximately 16 m (55 ft) at 60 m (~200 ft) in depth using a 1st Fresnell Zone approximation.

Seismic derived basalt surface elevations were successfully integrated with existing geologic tops information and used to support both CSM and hydrogeologic model development. Top of basalt was interpreted along a strong, and reasonably easily identifiable reflector, observed on all of the seismic profiles. This interpretation is supported by co-analysis of seismic check shot and geologic information obtained in nearby wells which indicated that the transition from sediment to basalt results in a significant acoustic change (3 to 4 fold increase in seismic velocity) at a seismic travel time position consistent with the observed strong reflector. The impact of the water table on this interpretation appears to be minimal. Where the water table is at or below the elevation of the basalt, the basalt surface reflection will be the dominant seismic feature. This is also the case where the water table is above and near the basalt surface (within about 3 m [~10 ft]) as this.approaches the theoretical vertical resolution limits of the data as processed.

Major refinements from previous interpretations (see for example PNNL-19702) are:

(a) the basalt low in the northern Gable Gap region is now oriented sub-parallel to the strike of the Gable Mt structure (see Figure 17, southwest of L-7)
(b) the Gable Butte structural sub-crop (anticlinal or saddle feature) southeast to Well 699-50-59 is a broader platform area;
(c) a variable basalt topography following a W-NW – to – E-SE trend occurs west of Well 699-50-59 with the elevated basalt surface being higher than the water table and forming a topographic divide for SSW – NNE oriented trends;
(d) derivation of a velocity function based on the geologic tops and check shot information has reduced the exaggerated depth to basalt in localized depressions that were originally identified in the contractor supplied depth-migrated sections (result of too fast a velocity used when transitioning from upland to depression); and
(e) removal of the basalt low (i.e., paleochannel) connecting the central Gable Gap region with wells 699-47-50, 699-48-48B, and 699-48-50 (north of the eastern quarter of 200 East). Previous structure maps placed this low between seismic profile L-1B (FY2009) and well 699-52-52, but results for Profile L-5B (FY2011) make it extremely difficult to maintain the old position. If present, this depression must lie east of Well 699-52-52. Unfortunately, no data exists to support this latter interpretation.

The ability to bridge between the sparsely distributed well points provides further information to reduce uncertainties in both the CSM and evaluations of groundwater migration. Of particular importance is the improved definition of where the basalt surface is above (higher in elevation than) the water table (unconfined aquifer); regions that potentially serve as barriers to groundwater flow through the Gable Gap area. The improved understanding of the basalt surface structure and its relationship to groundwater flow allows for more technically sound decisions regarding groundwater monitoring.

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