Shear wave seismic velocity profiling and depth to water table – earthquake site response measurements for Valley County, Idaho

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Contents

Summary

We present earthquake site response and liquefaction susceptibility results from a seismic land streamer and large weight drop system for the urbanized corridors of Valley County, Idaho. We acquired approximately seven km of new seismic data along a grid of city streets in McCall, Donnelly, and Cascade, Idaho where we derived shear wave velocity (Vs) profiles to a depth of 30-50 m by incorporating vertical and radial geophone signals to capture the complete elliptical Rayleigh wave motion that largely controls earthquake ground motion. Additionally, we incorporate results from remote Valley County site surveys that were conducted as part of this project and from past geophysical surveys. In addition to shear wave velocity measurements from our new survey, we also present p-wave reflection and refraction results that provide seismic boundary information that is useful for earthquake hazard assessments. By integrating the derived shear wave velocity profiles with p-wave reflection results, we include depositional and tectonic boundaries from the upper hundred meters into our analysis to assess whether ground motions may be amplified by shallow bedrock. By including p-wave refraction information into the analysis, we can identify zones of high liquefaction potential by comparing p-wave and shear wave velocity (Vp/Vs) measurements relative to refraction-derived water table depth estimates. In addition to providing the established Vs30 site values that provide a reasonable estimate of short- and mid-period amplification factors, we also provide a NEHRP class cross section for each seismic profile and a summary table of Vs measurements for a range of depths for each community. These measurements are useful when a constant shear wave velocity gradient model for the upper 30 m does not adequately capture the subsurface geologic conditions (e.g. shallow bedrock or thick deposits of loose soil).

Results from McCall suggest Vs30 measurements range from NEHRP Class D1 (soil) to C1 (dense soil). We typically observe rock (NEHRP Class A/B) at 30-50 m depth and many of the profiles contain a few meters of NEHRP Class E (soft soil). The depth to water saturated sediments is typically within the upper few meters, consistent with Payette River and lake levels. The community of Donnelly, on average, contains slower Vs30 values (NEHRP Class D1-D2) when compared to McCall or Cascade. These slower velocities reflect a few meters of Class E soft soils along each profile and greater depth to hard rock (Class A), consistent with a past gravity survey that suggests the Donnelly area is close to the deepest portion of the Long Valley sedimentary basin. Our results from Cascade show Vs30 measurements that range from NEHRP Class D1 (soil) to C1 (dense soil) and we measure rock (NEHRP Class B) velocities in the upper 20-30 m along many of the profiles. The shallow depth to bedrock-derived colluvium in the downtown area increase the average Vs30 values when compared to sites that lie outside the city. Typically, the slowest velocities throughout the county were measured at sites located along the Payette River where unconsolidated overbank or flood deposits are common.

Estimating subsurface properties for earthquake hazards assessments

Local amplification of strong ground motion by shallow soils, referred to here as site amplification (Joyner and Boore 1988), is generally recognized as a significant seismic hazard. We have designed a new seismic acquisition system that provides an estimate of p-wave and shear wave velocities for the upper 30-50 m beneath a road surface to assess local site amplification effects for Valley County, Idaho. From the acquired data, we map the subsurface distribution of geological materials, measure the depth to saturated sediments, and approximate the depth to hard boundaries (e.g. bedrock). From these measurements, we can estimate earthquake ground-motion amplification and site response for the communities and neighborhoods of Idaho. Additionally, we can identify areas that may be susceptible to liquefaction by identifying where a shallow water table may coincide with NEHRP Class E loose soils.

Summary of land streamer seismic technologies

Land streamer seismic technologies have gained an increase in interest and use for the past 10-15 years to characterize near surface physical properties. Van der Veen and Green (1998) and van der Veen et al. (2001) constructed and tested the first land streamers with gimbaled geophones. Their interest was in rapid p-wave seismic reflection acquisition, but recognized the potential to integrate a variety of seismic source and receivers into this technology. In the past decade other land streamer designs have been developed and used with shear wave source and receivers, hammer, weight drop, and vibroseis sources. The Boise State land streamer using 48x3-component geophones with integrated kinematic GPS was recently constructed to not only record p-wave, shear wave and surface wave signals, but to also analyze vertically polarized shear waves and to rotate signals in line with actual ground motion (e.g., Pugin et al., 2009). Additionally, passive recording via ReMi (Louie, 2001), or utilizing traffic noise as a seismic signal, has been successfully tested with our land streamer design.

The Boise State land streamer (Figure 1) is a fast and economical approach to acquire seismic data for earthquake hazards studies. The streamer was developed specifically for urban seismic hazards assessments. Field deployments require fewer personnel and production speeds can significantly increase over traditional geophone planted surveys. Additionally, our approach captures heterogeneities along street-based profiling compared to more traditional point-based measurements; and when data are collected along a grid of city streets, we capture geologic and geotechnical information in three dimensions. Although receiver coupling can be compromised with land streamer use, new streamer designs have produced excellent results with surface wave, refraction and reflection methods (e.g., Inazaki, 1999; Miller et al., 2002; Pugin et al, 2002, Van der Veen and Green, 2001; Figure 1). A requirement for such surveys includes relatively straight roads and good coupling to the ground surface (e.g., paved or gravel road).

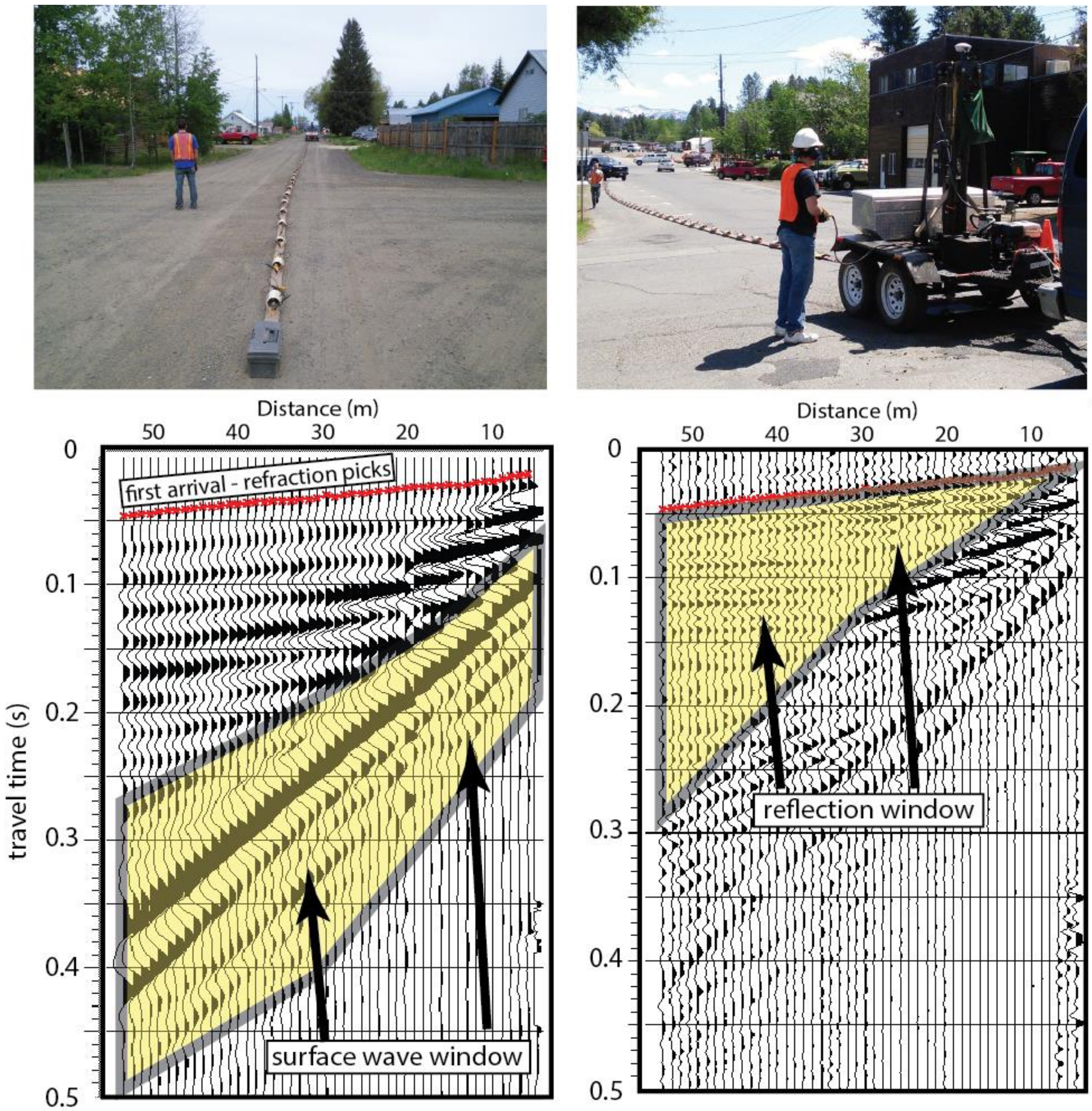

Figure 1. (top) Seismic land streamer with seismic accelerated weight drop source during acquisition in Donnelly and McCall. (Bottom) Seismic shot gather unfiltered (left) and filtered (right) to emphasize first arrival picks (red stars), reflections, and surface waves.

Summary of MASW methods

Multichannel analysis of surface waves (MASW) method estimates subsurface elastic (stiffness) conditions using surface wave measurements with an impulsive (hammer) or swept (vibroseis) source and array of p-wave seismic sensors (e.g. Park et al., 1999). Analysis of dispersion curves from seismic shot gathers (we show a dispersion curve plot for each site in this report) for provides a direct estimate of Rayleigh-wave phase velocity values (Figure 1). By inverting dispersion curves for shots distributed along a string of geophones, a shear wave velocity profile can be produced to identify and characterize lateral subsurface variability. Generally, a sledge hammer source can produce an MASW profile for the upper 20 m while accelerated weight drop sources or vibroseis sources can image considerably deeper (e.g., Stephenson et al, 2005; Liberty, 2011). Stephenson et al. (2005) showed that a 250 kg accelerated hammer was capable of Vs measurements to 100 m depth (at 4 Hz) and results comparable to ReMi and downhole seismic results. By combining MASW methods with a land streamer and a large accelerated hammer source owned by Boise State University, shear wave velocity (Vs) measurements can be collected at a rate of hundreds of measurements per day.

For the Valley County survey, we acquired all seismic data at a four meter source spacing and a one meter receiver spacing. The MASW data were processed using Seismic Unix (http://www.cwp.mines.edu/cwpcodes/) for component rotation and trace organization, in-house computer code for format conversions a data viewing and display, and with SurfSeis (http://www.kgs.ku.edu/software/surfseis/) for Rayleigh wave windowing, dispersion curve picks and data inversion, consistent with a standard surface wave processing approach (e.g., Park, et al. 1999).

Summary of seismic refraction/reflection methods

Shallow refraction and reflection measurements with hammer sources have been utilized for engineering and environmental applications for the past decade and more (see a summary in Pelton, 2005). Typically, hammer seismic surveys can successfully image the upper tens of meters while larger weight drops can image to hundreds of meters depth. A large change in refraction velocity at the water table makes p-wave refraction imaging ideal for providing constraints to liquefaction susceptibility. Incorporation of body wave information can be very important for site response and liquefaction studies, also. In particular for earthquake site response, surface wave dispersion methods (both active and passive source) often do not accurately resolve large velocity contrasts (e.g., where bedrock is shallow), whereas a shear and p-wave refraction profile can easily characterize shallow bedrock velocity (e.g., Pugin et al., 2002; Stephenson et al, 2009). While reflection images provide a measure of lateral variability of strata, refraction data will identify key boundaries including depth to water table. Although reverse coverage is needed to accurately model refraction data where dip is present, the water table typically varies over scales larger than our geophone spread and therefore can accurately estimate depth to saturated sediments.

For the Valley County project, the seismic survey design was optimized for surface wave processing and not for reflection imaging. With the acquisition geometry, we obtained six-fold reflection data. This low fold provides poor p-wave velocity control and therefore depth estimates for reflected arrivals were obtained by utilizing refraction results for the upper 10 m and assuming a stacking velocity gradient below water table depths. We processed all seismic reflection data using Seisspace ProMAX software (https://www.landmarksoftware.com/Pages/SeisSpaceProMAX.aspx) and Seismic Unix (http://www.cwp.mines.edu/cwpcodes/) processing packages using a standard processing approach outlined by Yilmaz (2001).

Summary of accelerated weight drop sources

Accelerated weight drop sources are commercially available and are relatively easy to build. Boise State University has built a number of accelerated weight drop sources at a variety of scales. These sources operate on city streets with no surface damage, can rapidly strike the ground, and are scalable to image to depths (with reflection methods) that exceed one km (e.g., Liberty and Pratt, 2008; Liberty, 2011). Production rates of 1-2 km per day are typical using an accelerated weight drop source and planted geophones (120 channels at 5 m spacing). Integration of a land streamer methods result in significantly higher production rates and lower personnel costs (deployment occurs one time per street, independent of the profile length). MASW and refraction/reflection measurements have resulted in production rates of a few km per day. Therefore, MASW and shear wave seismic imaging for the Valley County project was completed in a few days of acquisition.

Multi-component acquisition

Multi-component seismic data analysis is generally underutilized in the engineering seismology community, but is now firmly established in the oil/gas sector (e.g., Hardage et al. 2011). Estimation of soil/rock properties, improving seismic facies character, and the presence of fluids/fractures can all be obtained from multicomponent data. Additionally, mode conversions and ray path angles can be assessed by examination of full-waveform data (e.g. Pugin et al., 2009). Whereas one site may yield high quality p-wave (reflected) signals, another site may produce higher resolution shear wave or surface wave results. This change in data quality may be strongly influenced by large velocity contrasts at the water table (e.g. high Vp/Vs ratio) or other near-surface high velocity layers (e.g., shallow volcanic layers, caliche, etc). By routinely acquiring 3-component data, the full waveform is available for analysis. Although more seismic channels and larger data volumes are acquired with 3-component methods, reduced cost per seismic channel, along with modern computing methods and inexpensive disk storage, makes this a smaller concern than in past years.

To estimate shear wave properties, most engineering seismologists prefer not to deploy shear-wave sensors due to the difficulty in leveling and orienting geophones. Hence, vertical sensor MASW methods are the preferred data collection method to more easily acquire seismic data. However, MASW results may be insensitive to discrete high velocity boundaries. Land streamer data using 3-component geophones and a hammer source offers an opportunity to acquire 3-C seismic data to provide a more comprehensive analysis of subsurface properties.

NEHRP classifications

The NEHRP site classification for estimating the capability of shallow soil and rock to locally amplify strong ground motion is widely used throughout the engineering community and has been incorporated into many US building codes. Shear wave velocity boundaries were first published in 1994 and these boundaries have since been refined over the past 15 years (Table 1; BSSC, 2001). The approach is based on shear-wave velocity measurements to a depth of 30 m (Vs30). Velocity profiles may be measured directly or inferred from correlations of shear wave velocity profiles. For the seismic design of a structure, the Vs30 beneath the building determines the appropriate short- and mid-period amplification factors. We have added to this standard approach by providing incremental Vs measurements for the upper 5 m to our greatest imaging depth, and by providing reflection images that can better define seismic boundary information. Additionally, we identify locations where more than 3 m of type E class soils are present. These low velocity soils may be derived from artificial fill or poorly consolidated overbank river deposits from the Payette River. Where a shallow water table coincides with these deposits, liquefaction during strong ground shaking may result. In addition to providing shear wave velocity boundaries for NEHRP classes, Table 1 also shows an equivalent p-wave velocity for unsaturated sediments (assuming a constant Vp/Vs ratio of 2.5). We obtain the Vp measurements by picking first arrival p-wave direct and refracted wave arrivals.

Table 1. NEHRP Modified Site Classification criteria based on shear wave velocity (FEMA, 1994; International Code Council, (2009). Equivalent p-wave velocities (Vp) are estimated using a Vp/Vs ratio or 2.5.

NEHRP Class		Vs Range (m/sec)	Vp unsaturated (est @2.5x Vs) (m/sec)	Vp saturated (est) (m/sec)	Sediment Type
E		< 180	<450	1500	Soft soil
	D1	180 - 240	600		
D	D2	240 - 300	750	1600	Stiff soil
	D3	300 - 360	900		
	C1	360 - 490	1225		
C	C2	490 - 620	1550	2000	Very dense soil/soft rock
	C3	620 - 760	1900		
B		> 760	>1900	>3000	Rock
A		>1500	>3750	>3000	Hard Rock

Valley County geologic, tectonic, and earthquake overview

The modern tectonic framework for Valley County, Idaho is best described as Basin and Range style extension. The largest sedimentary basin, Long Valley basin or graben, has formed from extensional deformation related to the western Idaho shear zone (e.g., Giorgis et al., 2008; Figure 2). The Long Valley fault zone, located along the western margin of the Long Valley basin, is the controlling tectonic structure within Valley County (Figure 2) and is divided into a northern and southern segment (Personius and Lewis, 2010). To the west, Long Valley is bound by tilted Columbia River basalt and metamorphic and granitic rocks of West Mountains. To the east lies the Salmon River Mountains of the Idaho Batholith. The western Idaho shear zone displays two orientations of steep faults: one set of normal faults strikes north-south and the other set strikes east-west and accommodates components of both normal and strike-slip movement (Giorgis et al., 2006; 2008). Gravity data suggests that the north end of Long Valley is an asymmetric basin about one kilometer deep, with the depocenter located approximately 5 km northwest of Donnelly (Giorgis et al., 2006).

The Long Valley graben contains two subbasins (Figure 2) that are comprised of late Quaternary lacustrine, fluvial and glacial sediments (Breckenridge and Othberg, 2006). Near the largest city of McCall, the Payette Lakes are dammed behind a sequence of Pleistocene end moraines. Glacial outwash forms the valley floor from McCall south to the town of Cascade. The sediments that underlie these communities will likely result in a greater degree of earthquake ground shaking when compared to the more mountainous areas of Valley County. Therefore, understanding the distribution of sediments near population centers is critical to estimating local site amplification effects.

Over the past few decades, small magnitude (M<4) earthquakes have appeared throughout Valley County. The most notable earthquake sequence or swarm occurred in 2005 when thousands of small earthquakes were recorded near Alpha, approximately 15 km south of Cascade, Idaho near the convergence of Long Valley and Cascade Valley (Figure 2). These earthquakes were located at relatively shallow depths (<6 km depth), and five earthquakes with magnitudes as high as 4 were recorded (Sprenke et al. 2007). Although little damage was reported, the events were widely felt throughout the County. The larger earthquakes suggest a northwest-directed compression and a component of strike-slip on an unknown fault. This fault may be associated with the Alpha escarpment which separates Long Valley to the north and Round Valley to the south. If this swarm was located along this blind fault, it suggests that no motion occurred on the Long Valley normal fault, the longest and most prominent fault in the county. While this earthquake swarm did not produce any damage, these earthquakes may point to an active fault that is capable of producing larger, more damaging earthquakes.

The northern segment of the Long Valley fault is characterized by the U.S. Geological Survey as 46 km long fault with latest motion less than 130,000 years old (Personius and Lewis, 2010). The poorly constrained slip rate is estimated between 0.2-1 mm/yr. If the entire length of this fault were to rupture, the fault could be capable of supporting a M6.8 earthquake (Wells and

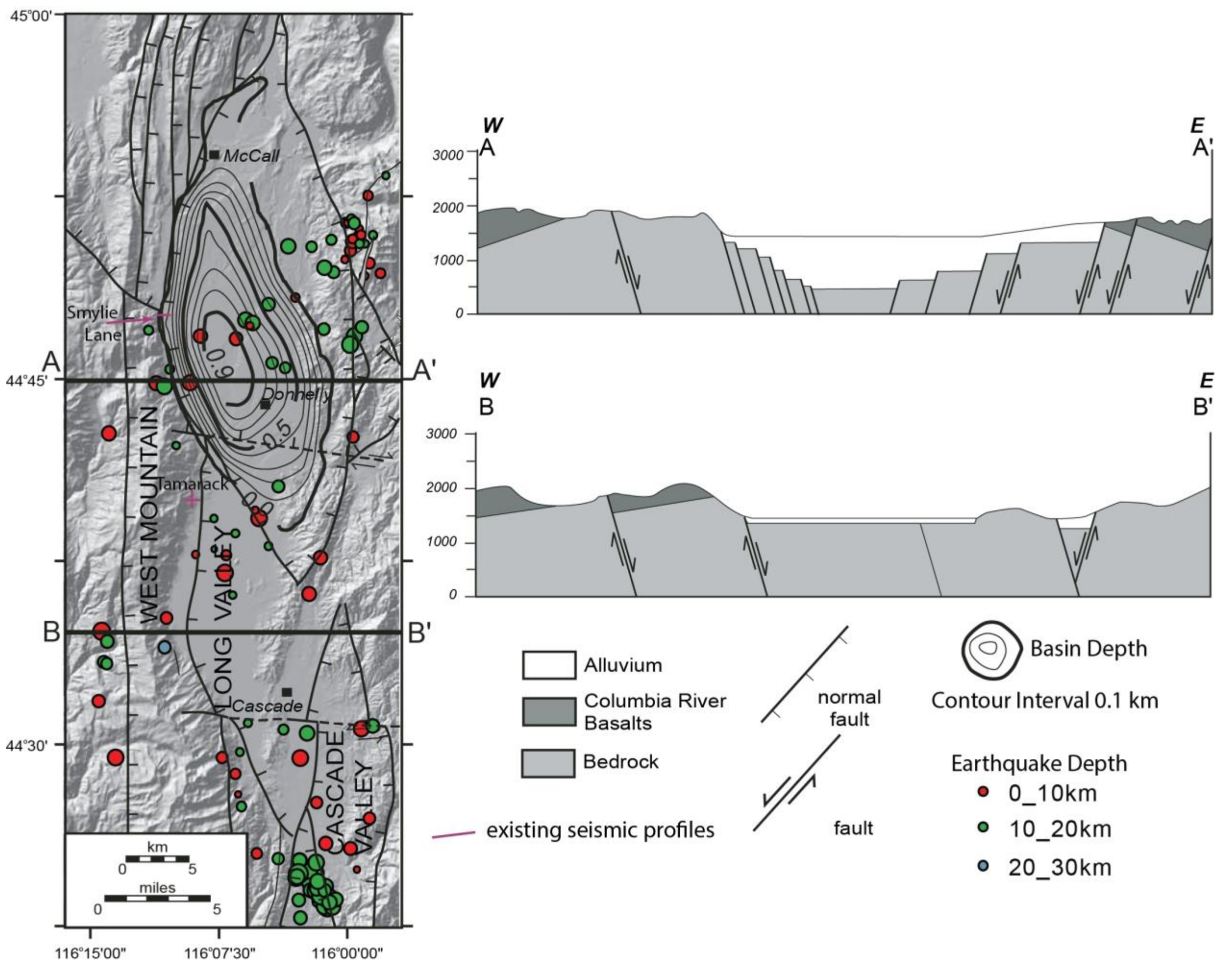

Figure 2. (left) Topographic map for the Valley County, Idaho area with mapped normal faults (Giorgis et al., 2006), earthquake epicenter locations from 1990-2013 (NEIC database – neic.usgs.gov), and gravity-derived basin depth for Long Valley (Giorgis et al., 2006). (right) Two tectonic cross sections (simplified from Georgis et al., 2006) showing normal fault geometries and basin depth. Bedrock consists of Cretaceous batholith rocks and equivalent.

Coppersmith, 1994). An earthquake of this magnitude could produce significant damage to Valley County communities. The southern segment of the Long Valley fault is characterized by the U.S. Geological Survey as 19 km long fault with a slip rate of less than 0.2 mm/yr. One additional fault worth noting is the Cascade fault that forms the western margin of Cascade Valley just east of Long Valley. This 11 km long fault is mapped south from the town of Cascade to the town of Alpha with an estimated slip rate of less than 0.2 mm/yr. Site amplification measurements are key to help mitigate the risks from earthquake ground shaking.

McCall Site response measurements

We acquired 11 seismic profiles in McCall to estimate shear wave velocities, water table depths, and depths to key depositional and structural boundaries. We focused most of the profiles within the urban corridor that is bound by Main Street, Payette Lake and the Payette River (Figure 3).

Table 2 provides a summary table of the McCall seismic results. Based on average Vs30 measurements along the profiles, we define two sites (Forest Street and Thula Street) as Class C (very dense soils/soft rock). The other 9 sites are defined as Class D (stiff soil). The slowest shear wave velocities were measured at a site we term the RV Park access road. This access road to the river is located immediately south of the RV Park along the Payette River where loose sands dominate the near surface layers. The fastest average Vs30 shear wave velocities were located beneath the glacial till of downtown McCall. Class E loose soils were found in the upper 2-3 meters of a few of the profiles with the Mill Road profile showing the greatest thickness of this low velocity material. Here, upwards of 5 m of Class E soils were likely derived from lake sands deposited when Payette Lake had a higher level, and/or artificial fill associated with sawmill operation at this site. A shallow water table at this site (essentially at lake level) may make this area susceptible to liquefaction during strong ground motion.

Table. 2. Shear wave velocity summary table for McCall. Details are described in each profile description summary below. Asterisk represents an extrapolated value based on the approach of Boore (2004).

McCall	Forest Street	Park Street	First Street	Lenora Street	Idaho Street	Thula Street	Sewage Road South	Second Street	Mill Street	Samson Trail	RV Park Access Road
Reference Station	1304	2122	3142	4118	5126	6078	7126	8042	9114	9530	10026
Vs 5	279	237	223	201	202	278	259	209	163	280	189
Vs 10	322	264	244	234	234	320	303	246	226	303	204
Vs 20	359	308	289	284	291	368	288	264	283	305	222
Vs 30	432	318	340	298	323	432	305	*297	310	348	233
Vs 40	491		370		351	463	378		342	393	
Vs 30 NEHRP Class	C1	D3	D3	D2	D3	C1	D3	D2	D3	D3	D1
Average water table depth (meters)	7	3	2.7	7	3.5	10.5	8.5	2.8	3.2	4	3.8
Depth to shear wave velocity confidence (meters)	39	31	44	34	51	46	40	22	43	60	31

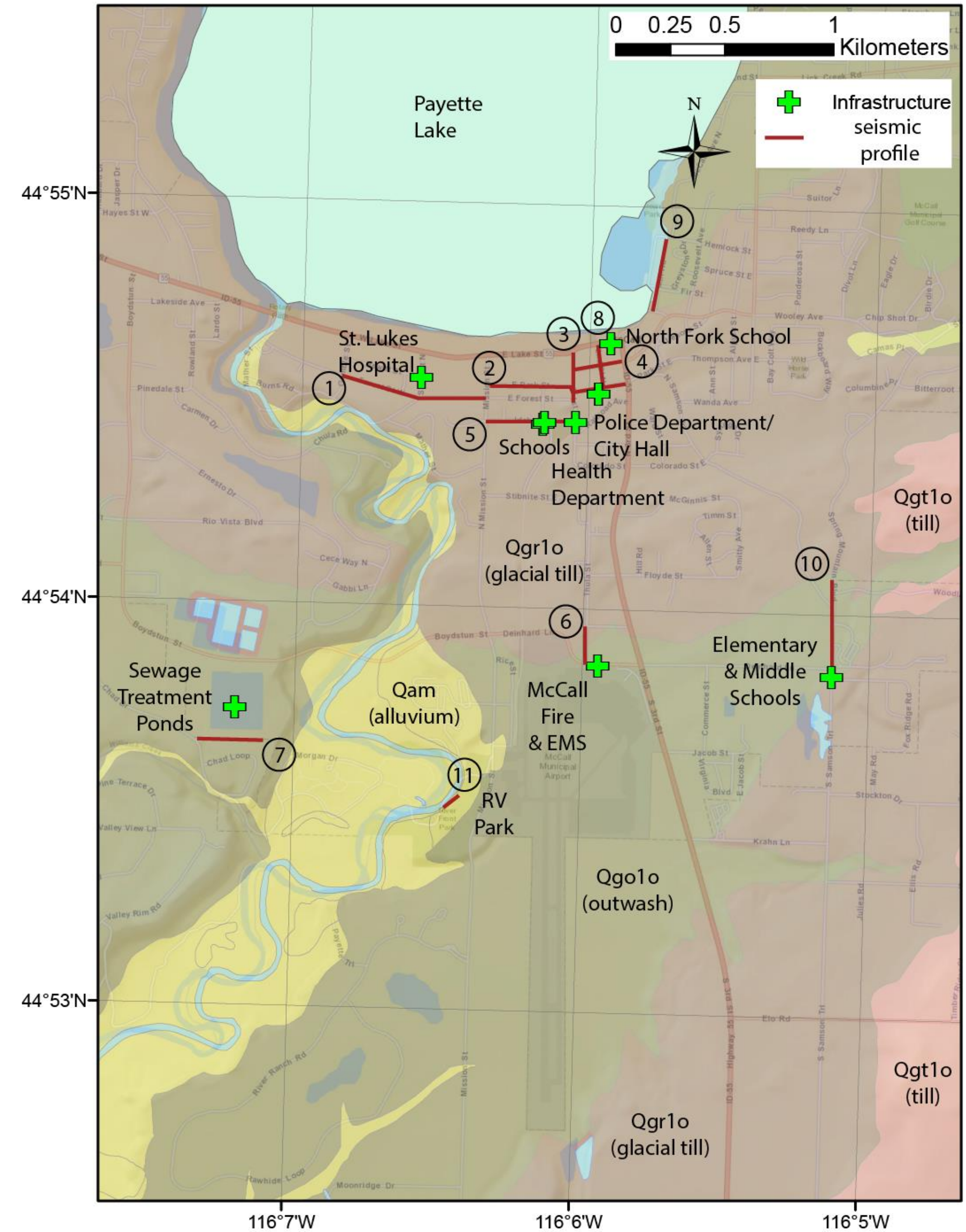

Figure 3. Seismic profile locations (red lines) for the McCall, Idaho area. The profile locations focused on critical infrastructure located within city limits. The circled numbers represent profile locations that are described below. Surficial geology from Breckenridge and Othberg (2006).

Figure 4. Downtown McCall aerial photo with seismic profile locations.

1) Forest Street (east-west)

North Mission Street to Gamble Road (664 m length, 166 shots)

The Forest Street profile begins at North Mission Street, crosses St. Luke's Hospital near the profile midpoint (positions 1310-1350), and Cross Road at position 1300 (Figure 3). This east to west 664 m long profile sits upon mapped Quaternary glacial till beneath road asphalt. The profile parallels East Lake Street (Hwy 55) with an increase in surface elevation from east to west of approximately 2 m. The profile is located 7-9 m above Payette Lake levels. Shear wave velocities were derived from Rayleigh wave dispersion picks from 163 weight drop seismic shot gathers.

High quality land streamer seismic data along Forest Street resulted in clear first arrivals for first break p-wave refraction picks to 10-15 m depth, confident surface wave dispersion curve picks to 40 m depth, and reflection profiling to 100 m depth (Figures 5 and 6). P-wave seismic velocities for the upper few meters range from 300-470 m/s, consistent with dry unconsolidated sediment. The depth to water saturated velocities (>1,500 m/s) is highly variable along the profile, ranging from 2-10 m depth. Shear wave velocities for the same depths range from 150-600 m/s (mostly NEHRP class C/D) with an increase in shallow shear wave velocities from east to west. Along the eastern 1/4 of the profile, very shallow shear wave velocities (upper 1-2 meter depth) are consistent with soft soil (NEHRP Class E), but we estimate NEHRP Class D stiff soils appear at the surface for the majority of the profile. Between ~15-35 m depth, shear wave velocities are consistent with soft rock (NEHRP Class C). Shear wave velocities below 35 m are >760 m/s, consistent with rock velocities. The western 2/3 of the profile shows higher velocities than areas to the east. Very dense soil/soft rock deposits (NEHRP Class C) dominate the upper 15-20 m depth and we measure rock velocities (NEHRP Class B) below approximately 20 m depth. The p-wave seismic reflection image shows mostly east-dipping coherent arrivals in the upper 50 m that are consistent with increasing NEHRP class depths from west to east. Within the NEHRP Class C layer, reflectors dip approximately 2 degrees to the east, perhaps related to depositional patterns related to paleo-lake Payette deposits.

We extracted average shear wave and p-wave velocity values for the St. Luke's Hospital area where we calculate an average Vs30 velocity of 420 m/s (NEHRP class C1 or Very dense soil/soft rock). We estimate the water table at a depth of 7 m at this location and a Vp/Vs ratio that ranges from approximately 2-4. We observe higher Vp/Vs ratios near the eastern portion of the profile where slower shear wave velocities and a shallow water table are present.

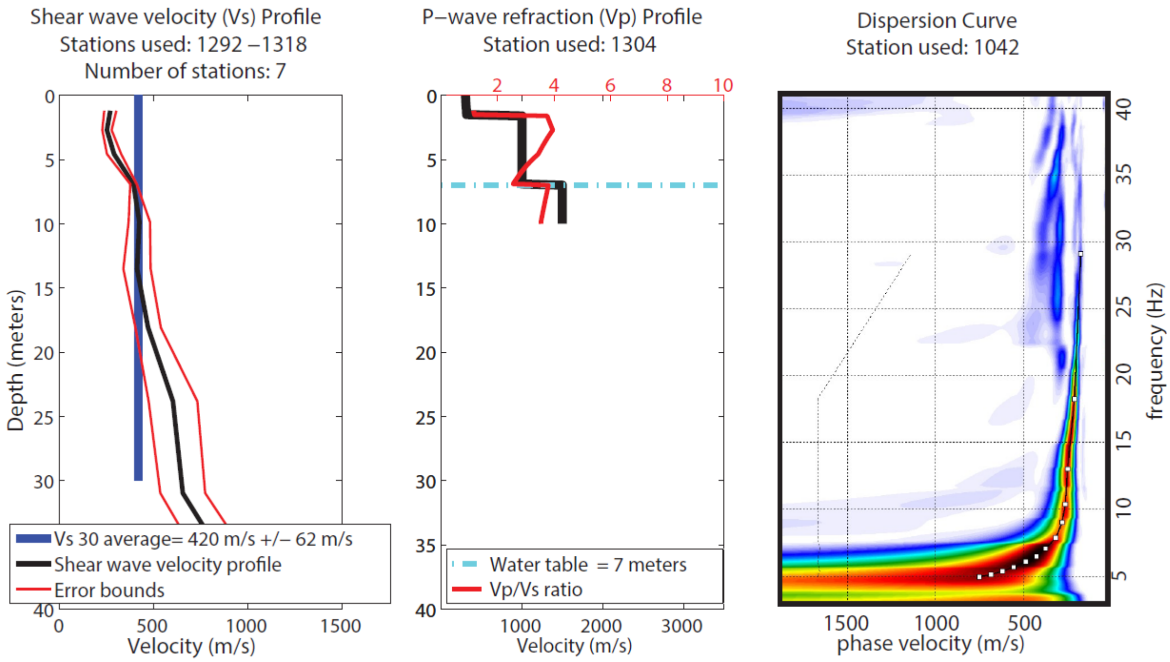

Figure 5. (left) Shear wave velocity profile and average Vs30 calculation for the central portion of the Forest Road profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 40 m.

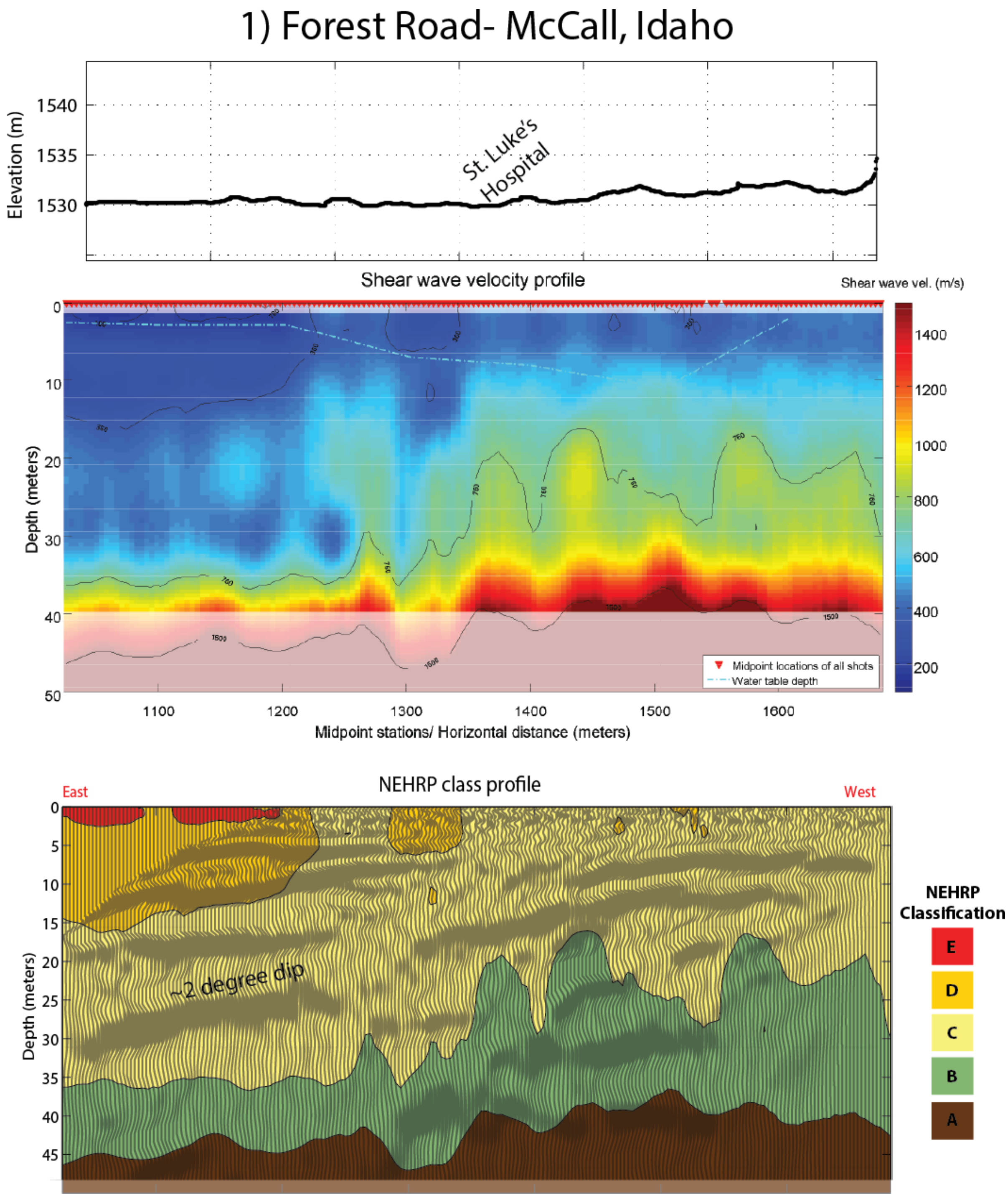

Figure 6. (top) Elevation profile for the Forest Street profile. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~6:1.

2) Park Street (east - west)

Third Street to North Mission Street (468 m length, 117 shots)

The Park Street profile crosses McCall City Hall and Police Department near position 2050, crosses Second Street (profile 8) at position 2050, and crosses First Street (profile 3) at position 2200 (Figure 3). This east to west 468 m long profile sits upon Quaternary glacial till beneath road asphalt between First and Third Street and dirt (asphalt surface was removed for repaving) between First Street and North Mission Street. The profile parallels East Lake Street (Hwy 55) with a change in elevation (down to the west) along profile of approximately 4 m. Shear wave velocities were derived from Rayleigh wave dispersion picks from 117 weight drop seismic shot gathers.

Land streamer seismic data along Park Street resulted in clear first arrivals for first break p-wave refraction picks to 10-15 m depth and confident surface wave dispersion curve picks to 32 m depth (Figures 7 and 8). P-wave seismic velocities for the upper few meters range from 300-470 m/s, consistent with dry unconsolidated sediment. The depth to water saturated velocities (>1,500 m/s) ranged from 2.7-5 m depth. Shear wave velocities for the same depths range from 150-360 m/s (NEHRP class D/E). The upper 25 m of the eastern portion of the profile contains NEHRP Class D soils while Class D soils extend to a depth of approximately 10 m between positions 2100-2450. We identify Class E soils below where the asphalt was removed, perhaps reflecting the repaving process. Very dense soil/soft rock deposits (Class C) dominate the 10-30 m depth range and we measure rock velocities (Class B) below approximately 35-40 m depth. The only clear reflector along the profile is located at the Class D/C boundary, suggesting a sharp break between soil and soft rock. This reflector changes character at the transition from paved road to dirt, suggesting that the asphalt surface provides improved conditions for reflection imaging.

We extracted average shear wave and p-wave velocity values for the downtown corridor between stations 2110-2135 where we calculate an average Vs30 velocity of 318 m/s (Class D3 or stiff soil). We estimate the water table at a depth of approximately 3 m at this location and a Vp/Vs ratio that ranges from approximately 1.5-7. We observe higher Vp/Vs ratios near the western portion of the profile where we map slower shear wave velocities.

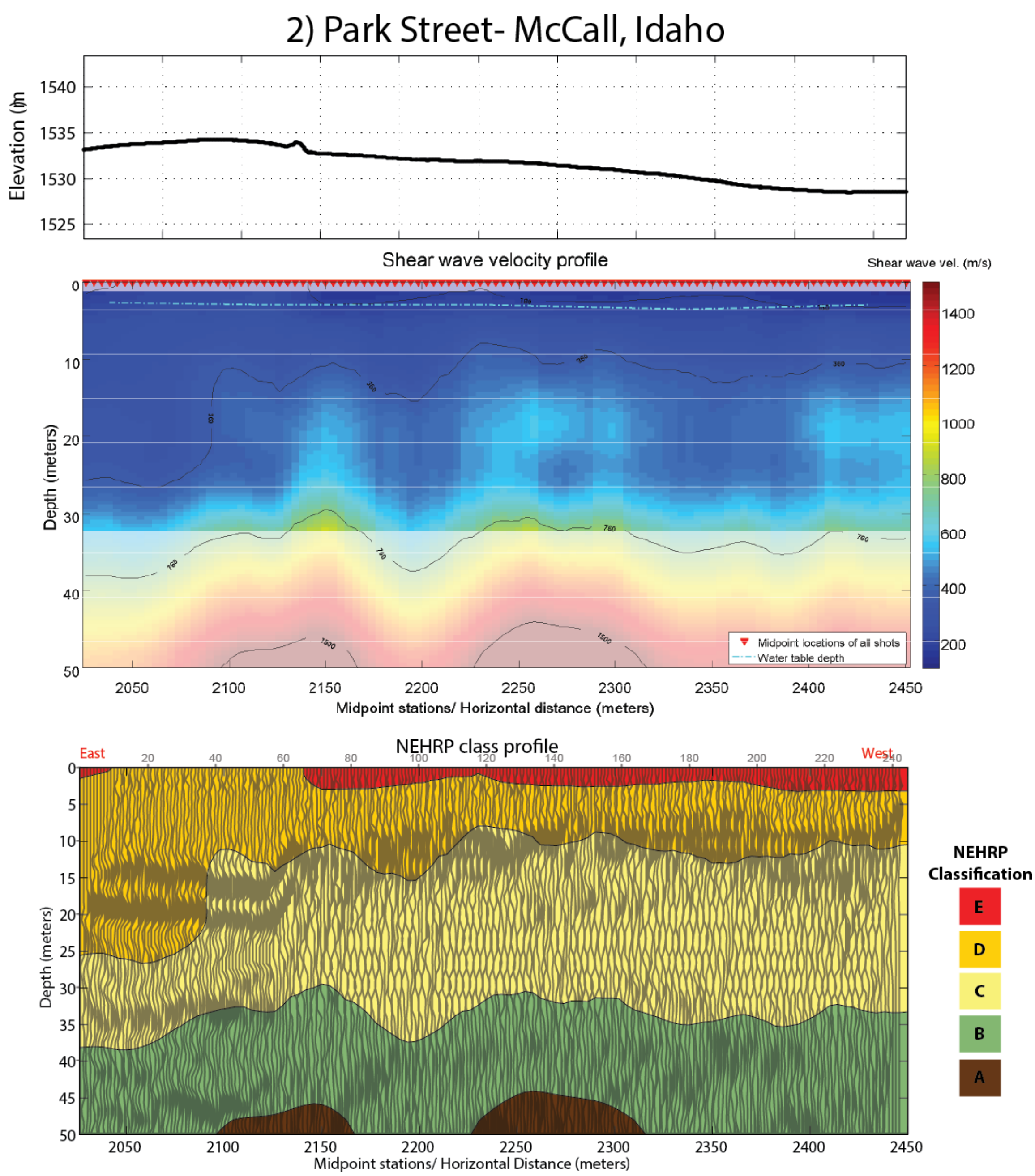

Figure 7. (top) Elevation profile for the Park Street profile. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~4:1.

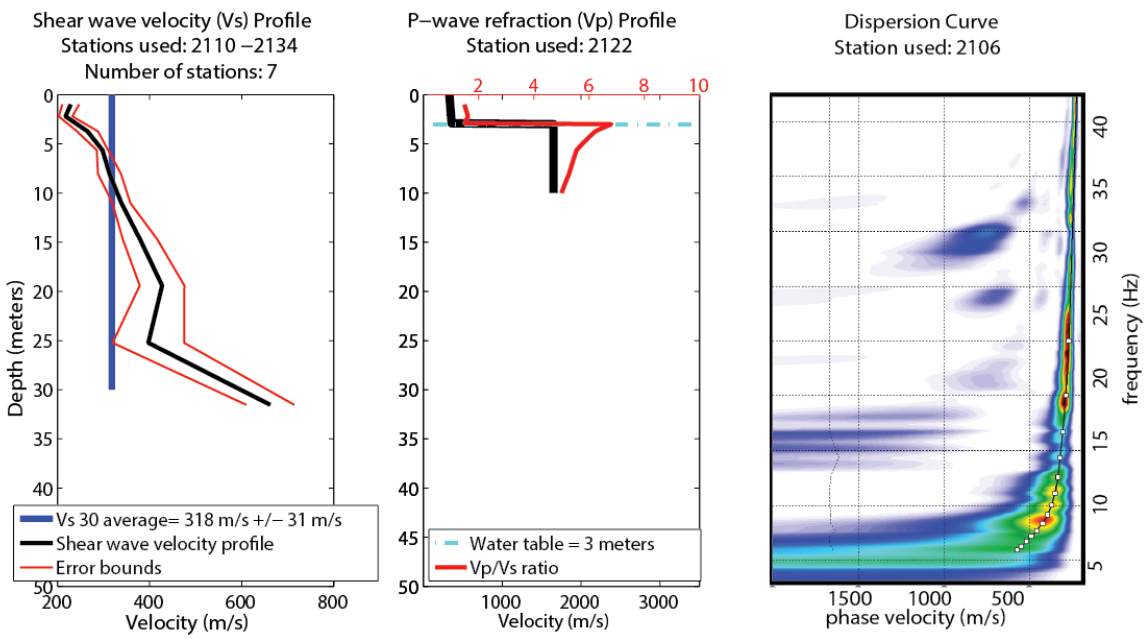

Figure 8. Shear wave velocity profile and average Vs30 calculation for the central portion of the Park Street profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 32 m.

3) First Street (north-south)

East Lake Street (Hwy 55) to Park Street (150 m length, 33 shots)

The First Street profile crosses Lenora Street (profile 4) at position 3050 m and crosses Park Street (profile 2) at position 3120 m (Figure 2). This north to south 150 m long profile sits upon Quaternary glacial till beneath road asphalt, and parallels Third Street (Hwy 55) with a steady increase in elevation along profile of approximately 5 m. The northern start of the profile lies approximately 8 m above Payette Lake levels while the southern limit of the profile lies approximately 13 m above lake level. Shear wave velocities were derived from Rayleigh wave dispersion picks from 33 weight drop seismic shot gathers.

Land streamer seismic data along First Street resulted in clear first arrivals for first break p-wave refraction picks to approximately 10 m depth and confident surface wave dispersion curve picks to 45 m depth (Figures 9 and 10). P-wave seismic velocities for the upper few meters range from 350-400 m/s, consistent with dry unconsolidated sediment. The depth to water saturated velocities (>1,500 m/s) ranged from 1.5-2.5 m depth. Shear wave velocities for the upper few meters range from 170-200 m/s (NEHRP class D/E). We map a thin layer (less than 2 m) of low velocity (NEHRP Class E) soil along much of the profile while NEHRP Class D still soils are mapped to 8-10 m depth. We estimate the depth to a topographically flat (after removal of surface topography) Class B rock surface at 45-50 m. P-wave reflection data show a continuous reflector at 8-15 m depth that mimics the shear wave velocity model transition from NEHRP

Class C to D that suggests that the lithological change at the 360 m/s shear wave velocity contour likely represents the transition from dense soil to soft rock.

We extracted average shear wave and p-wave velocity values between stations 3134-3154 (immediately north of Park St intersection) where we calculate an average Vs30 velocity of 340 m/s (NEHRP Class D3 or stiff soil). We estimate the water table at a depth of approximately 2.7 m at this location and a Vp/Vs ratio that ranges from approximately 2-7.

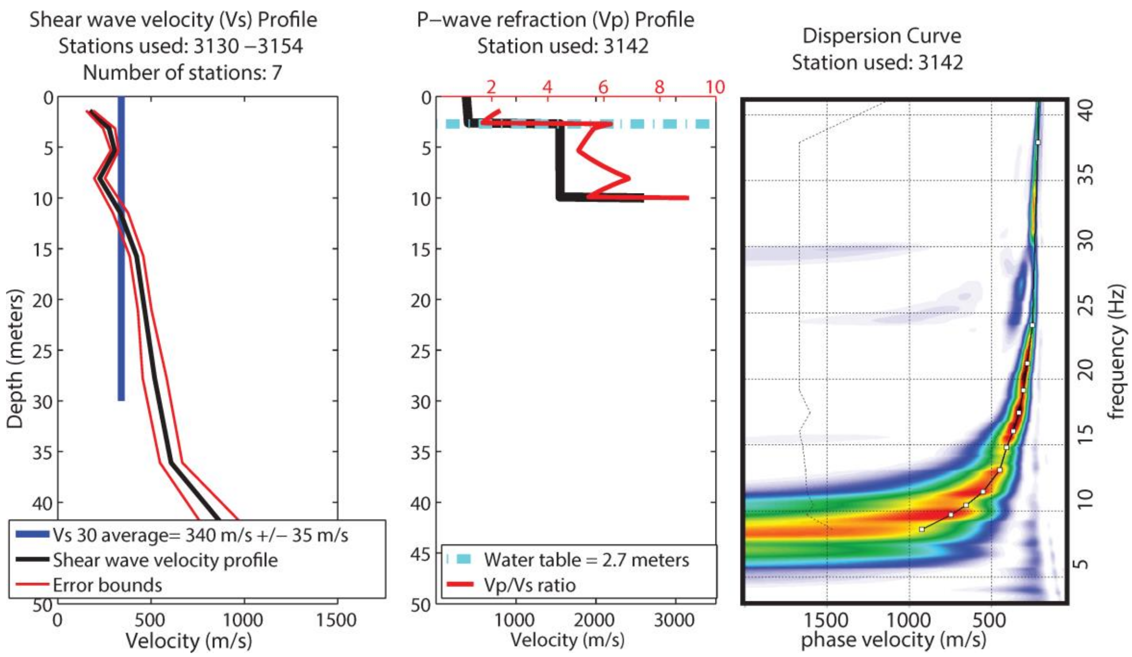

Figure 9. (left) Shear wave velocity profile and average Vs30 calculation for the central portion of the First Street profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 45 m.

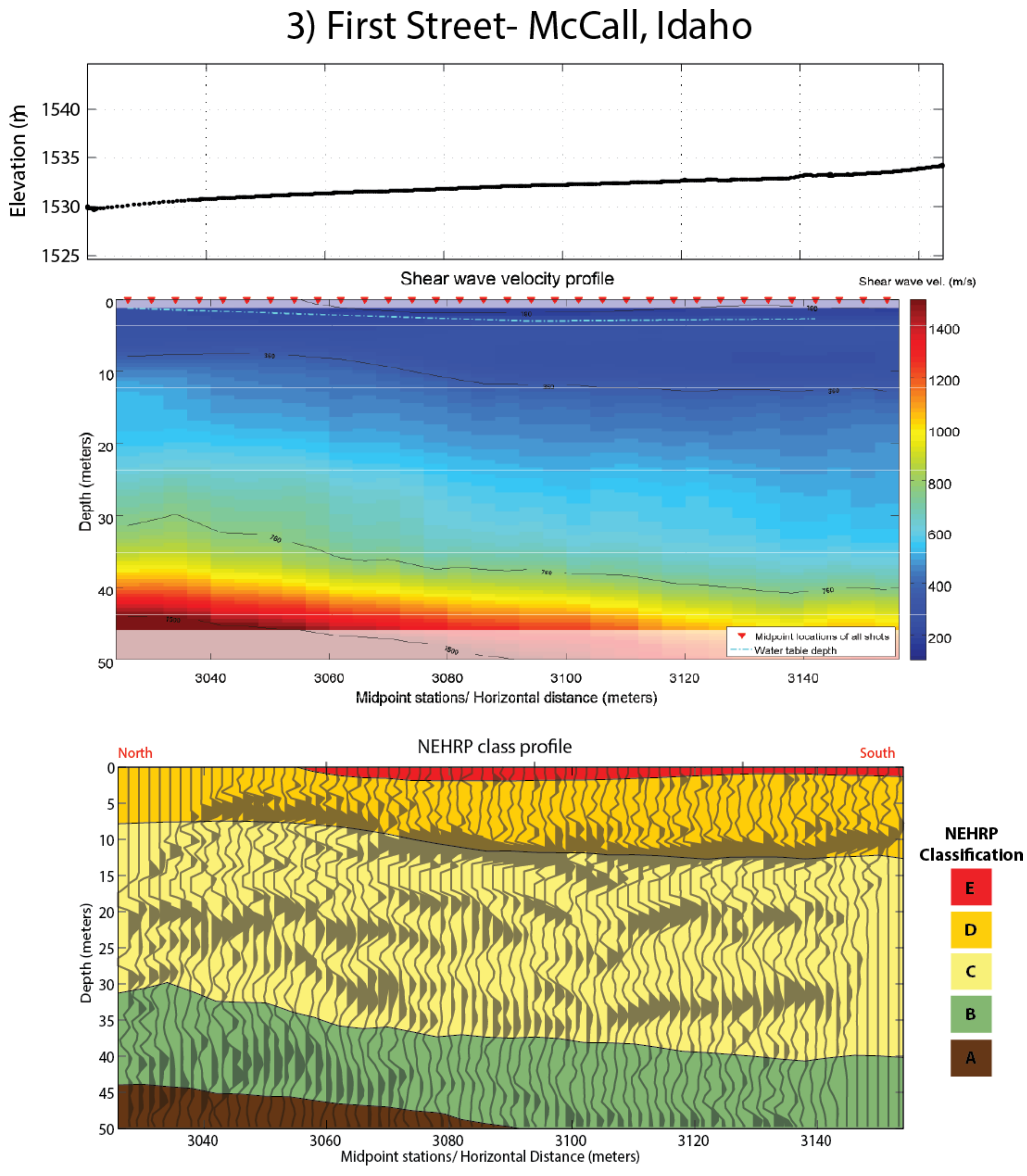

Figure 10. (top) Elevation profile for the First Street profile. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~1:1.

4) Lenora Street (east - west)

Third Street to First Street (160 m length, 34 shots)

The Lenora Street profile crosses Second Street (profile 8) at position 4030 m (Figure 2). This east to west 160 m long profile sits upon Quaternary glacial till beneath road asphalt, and parallels East Lake Street (Hwy 55) with a change in elevation along profile of less than 1 m. The average elevation of Lenora Street lies approximately 10 m above Payette Lake water level. Shear wave velocities were derived from Rayleigh wave dispersion picks from 34 weight drop seismic shot gathers.

Land streamer seismic data along Lenora Street resulted in clear first arrivals for first break p-wave refraction picks to approximately 15 m depth and confident surface wave dispersion curve picks to 35 m depth (Figures 11 and 12). P-wave seismic velocities for the upper few meters were calculated at approximately 1100 m/s, consistent with NEHRP Class C/D unconsolidated sediment. We estimate the depth to water saturated velocities (>1,500 m/s) at 7 m depth. Shear wave velocities for the upper few meters range from 250-300 m/s (NEHRP class D). The depth to NEHRP Class C dense soil/soft rock is estimated at approximately 15 m. We did not measure Class B rock along this profile within the upper 30 m depth, consistent with measurements along the crossing First Street profile that showed Class B depths at more than 30 m depth. A set of discontinuous reflections near the boundary between Class B/C is consistent with Park and First Street profiles.

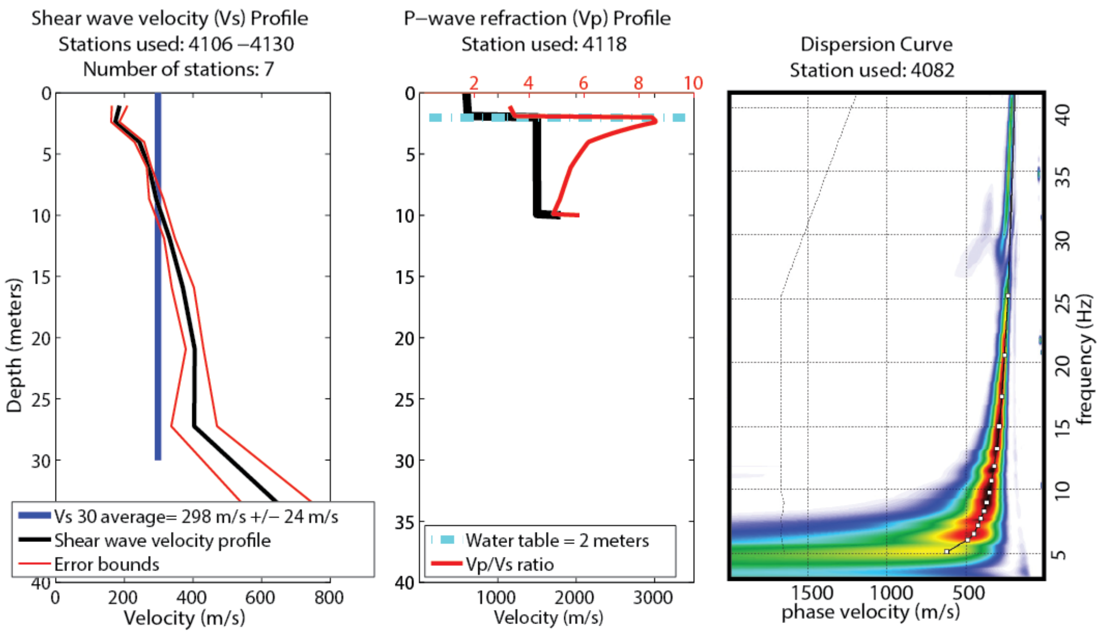

Figure 11. (left) Shear wave velocity profile and average Vs30 calculation for the central portion of the Lenora Street profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 35 m.

We extracted average shear wave and p-wave velocity values between stations 4108-4136 (near the profile midpoint) where we calculate an average Vs30 velocity of 298 m/s (NEHRP Class D2 or stiff soil). We estimate the water table at a depth of approximately 2 m at this location and a Vp/Vs ratio that ranges from approximately 2-8.

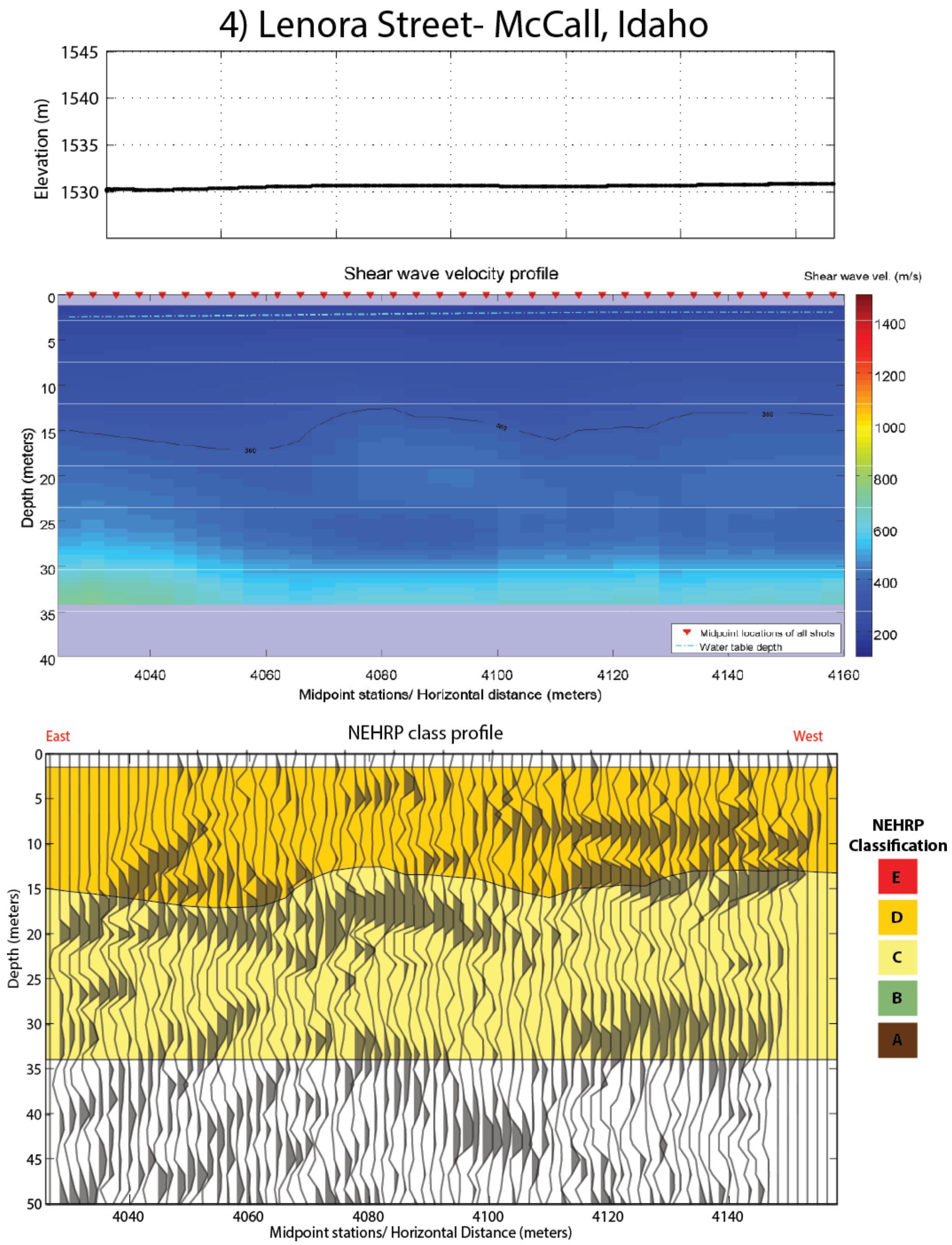

Figure 12. (top) Elevation profile for the Lenora Street profile. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~1:1.

5) Idaho Street (east-west)

First Street to North Mission Street (350 m length, 79 shots)

The Idaho Street profile begins at the Central District Health building at First Street and crosses McCall elementary school at position 5100 m (Figure 2). This east to west 350 m long profile sits upon Quaternary glacial till beneath road asphalt, with a change in elevation along profile of approximately 3 m. Shear wave velocities were derived from Rayleigh wave dispersion picks from 79 weight drop seismic shot gathers.

Land streamer seismic data along Idaho Street resulted in clear first arrivals for first break p-wave refraction picks to approximately 15 m depth and confident surface wave dispersion curve picks to more than 50 m depth (Figures 13 and 14). P-wave seismic velocities for the upper few meters were calculated at approximately 400-800 m/s, consistent with NEHRP Class D/E unconsolidated soil. We estimate the depth to water saturated velocities (>1,500 m/s) at 3-6.5 m depth. Shear wave velocities for the upper few meters range from 160-200 m/s (NEHRP class D/E) and we estimate the presence of NEHRP Class E soils within the upper few meters along much of the profile. We estimate the depth to NEHRP Class C dense soil/soft rock ranges from 11-13 m and we estimate Class B rock at 40-45 m depth. Our reflection results suggest the boundary to soft rock is a few meters deeper, perhaps suggesting that this boundary is represented by slightly faster velocities than the established Class C/D (360 m/s) boundary.

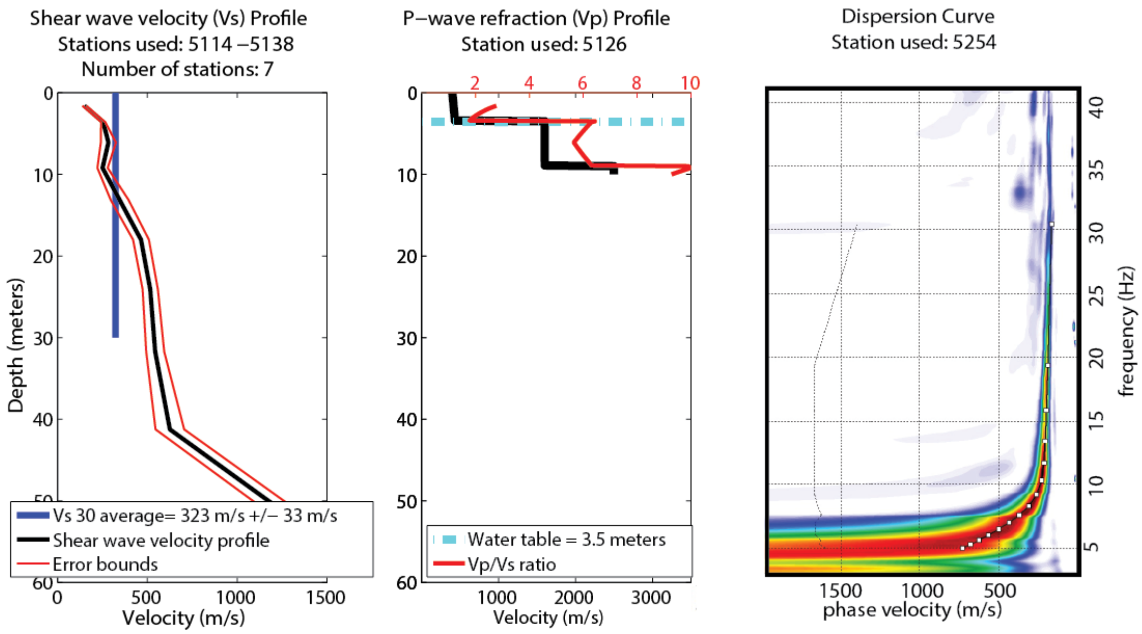

Figure 13. (left) Shear wave velocity profile and average VS30 calculation for the central portion of the Idaho Street profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 52 m.

We extracted average shear wave and p-wave velocity values between stations 5114-5138 (adjacent to the elementary school) where we calculate an average Vs30 velocity of 323 m/s (NEHRP Class D3 or stiff soil). We estimate the water table at a depth of approximately 3.5 m at this location and a Vp/Vs ratio that ranges from approximately 2-7.

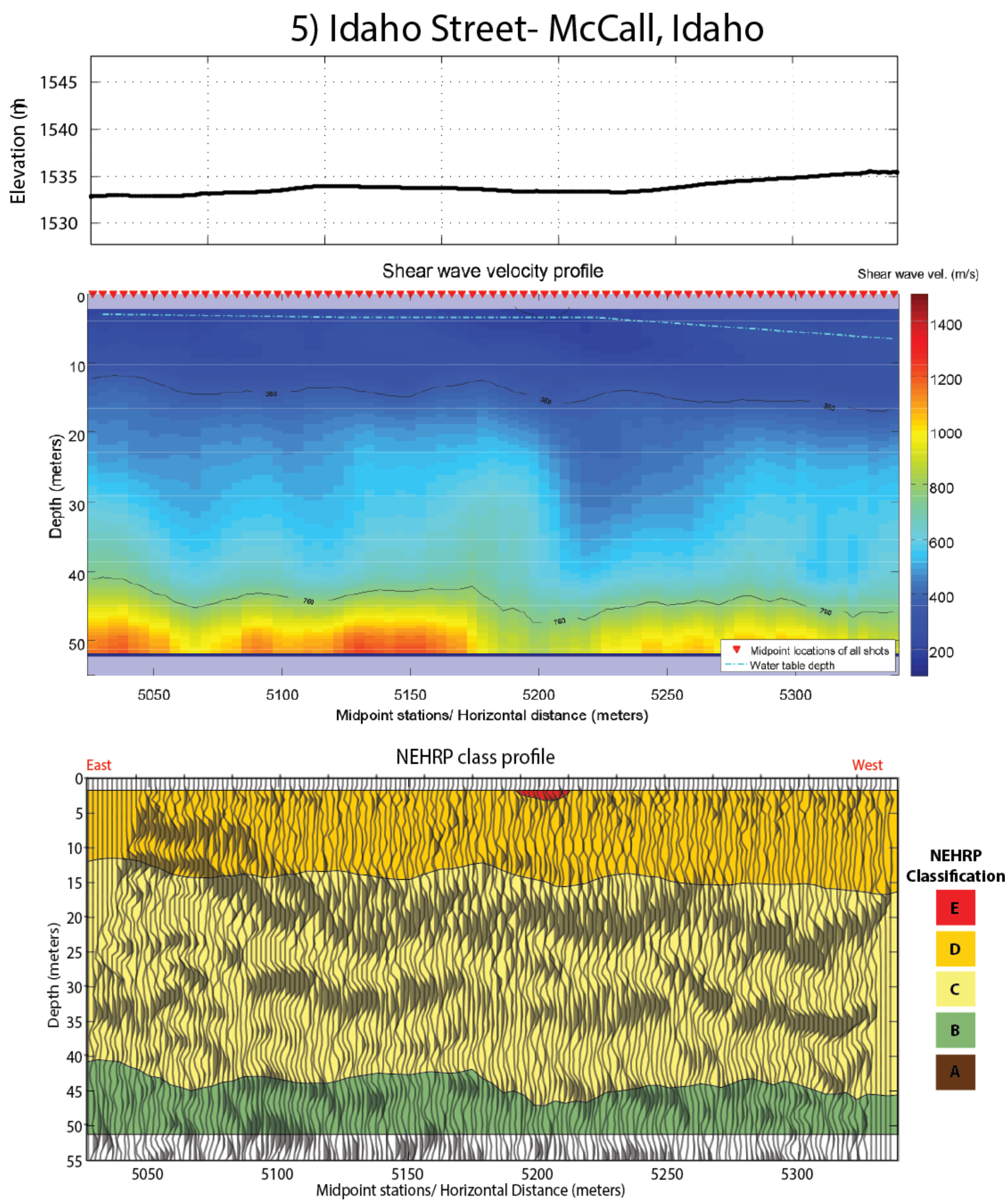

Figure 14. (top) Elevation profile for the Idaho Street profile. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~3:1.

6) Thula Street (north-south)

McBride Street to Deinhard Lane (210 m length, 53 shots)

The Thula Street profile crosses McCall Fire and EMS building between positions 180-250 m (Figure 2). This north to south 210 m long profile sits upon Quaternary glacial till beneath road asphalt along the northern portion of the profile and upon Quaternary glacial outwash along the southern portion of the profile. The profile contains a change in elevation of approximately 6 m. Surface wave arrivals along this profile were contaminated by air wave signals that bounced off the nearby firestation and also possibly from sub-asphalt infrastructure (e.g. sewage line). Therefore, we interpreted results from the best 9 shot gathers to obtain a shear wave velocity profile.

Land streamer seismic data along Thula Street resulted in clear first arrivals for first break p-wave refraction picks to approximately 11 m depth and confident surface wave dispersion curve picks to 45 m depth (Figures 15 and 16). P-wave seismic velocities for the upper few meters were calculated at approximately 650-850 m/s, consistent with NEHRP Class D/E unconsolidated soil. We estimate the depth to water saturated velocities (>1,500 m/s) at 10.5-12.5 m depth. Shear wave velocities for the upper few meters range from 300-320 m/s (NEHRP class D) and we estimate the presence of NEHRP Class D soils across the length of the profile. We estimate the depth to NEHRP Class C dense soil/soft rock ranges from 5-6 m that is approximately 30 m thick. We estimate Class B rock below 35 m depth.

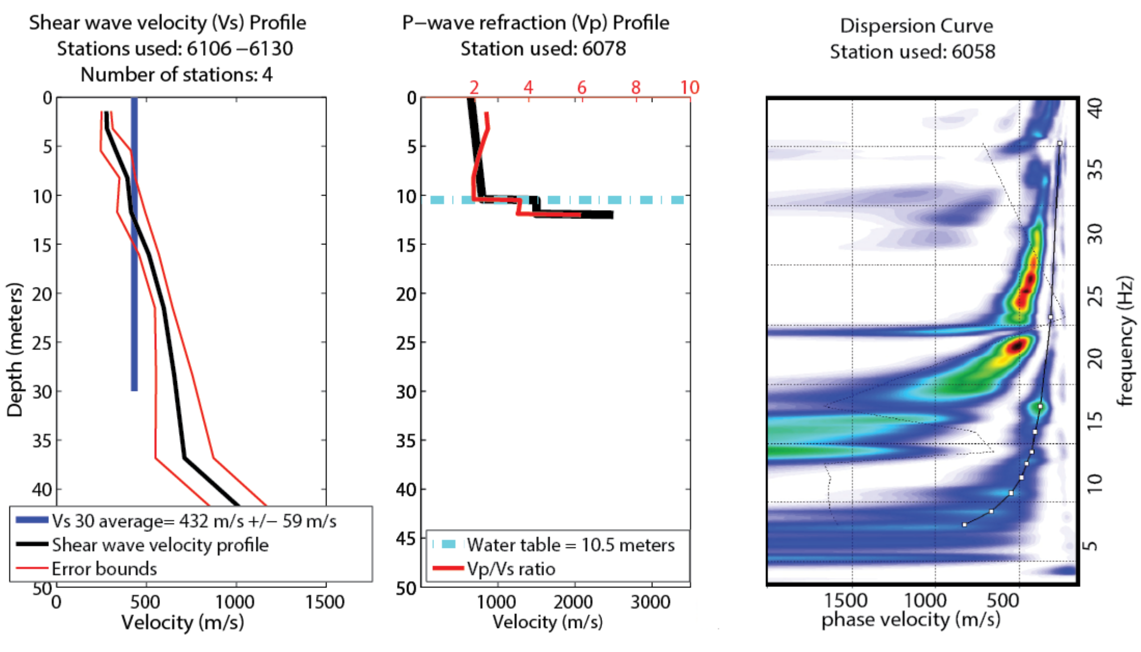

Figure 15 (left) Shear wave velocity profile and average VS30 calculation for the central portion of the Thula Street profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 32 m.

We extracted average shear wave and p-wave velocity values between stations 6106-6130 (adjacent to the fire station) where we calculate an average Vs30 velocity of 432 m/s (NEHRP Class C1 or dense soil). We estimate the water table at a depth of approximately 10 m at this location and a Vp/Vs ratio that ranges from approximately 2-6.

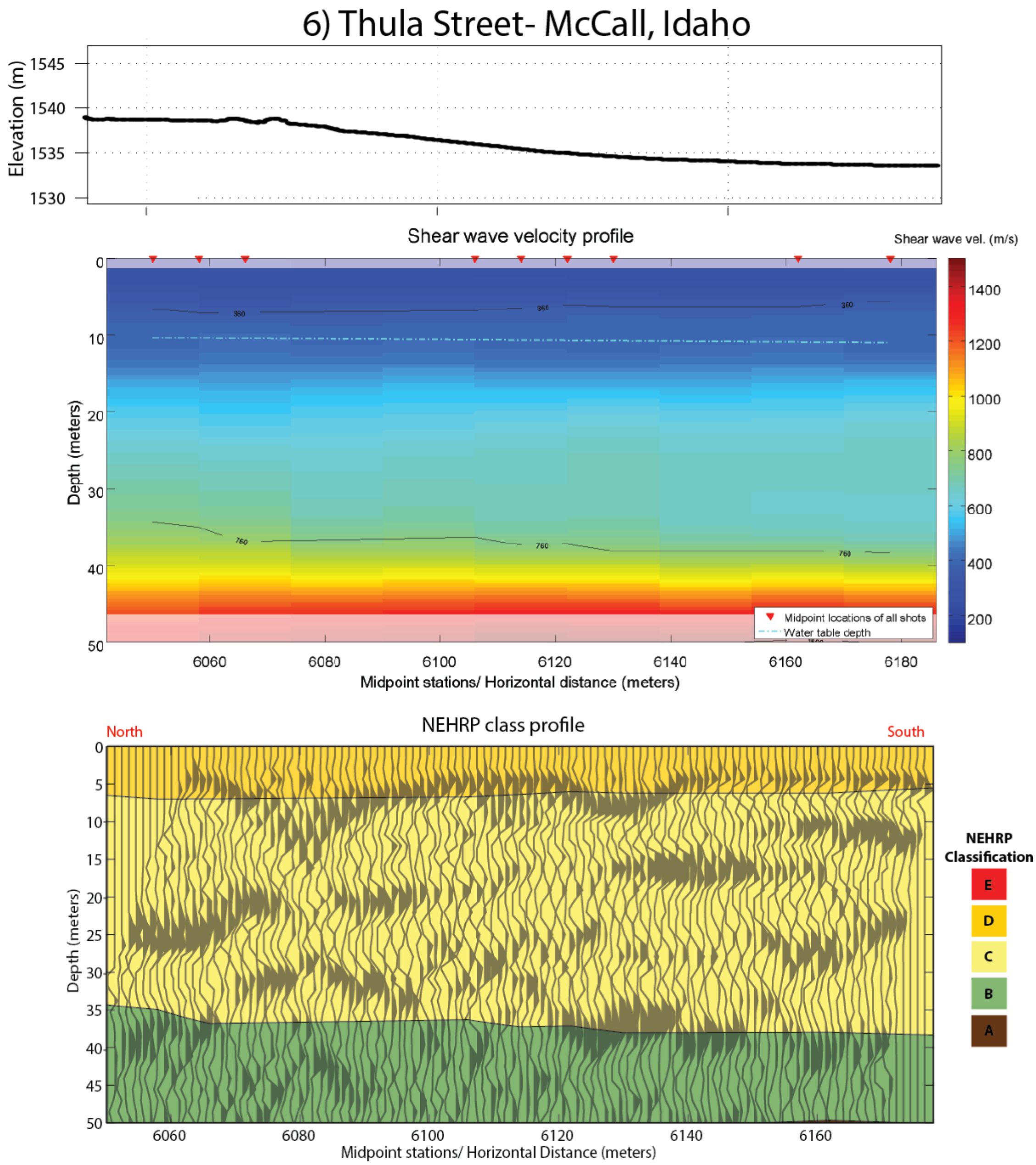

Figure 16. (top) Elevation profile for the Thula Street profile. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~1:1.

7) Sewage site (east-west)

dirt road south of ponds to Chad Drive (250 m length, 58 shots)

The McCall Sewage Treatment Pond traverses an access road along the southern side of the main treatment pond (Figure 2). This east to west 250 m long profile sits upon Quaternary glacial outwash beneath a dirt road surface, with a change in elevation along profile (down to the west) of approximately 4 m. The sewage pond sits on a glacially derived hill that lies only a few hundred meters and approximately 25 m above the fluvial deposits of the Payette River. Shear wave velocities were derived from Rayleigh wave dispersion picks from 57 weight drop seismic shot gathers.

Land streamer seismic data along Sewage access road resulted in clear first arrivals for first break p-wave refraction picks to approximately 10 m depth and confident surface wave dispersion curve picks to approximately 40 m depth (Figures 17 and 18). P-**wave** seismic velocities for the upper few meters were calculated at approximately 400-500 m/s, consistent with NEHRP Class D unconsolidated soil. We estimate the depth to water saturated velocities (>1,500 m/s) at 2-3 m depth. Shear wave velocities for the upper few meters range from 280-320 m/s (NEHRP class D). We observe a 2-4 m thick lens of higher velocity NEHRP Class C soils at 5-10 m depth, then a velocity inversion and slower Class D soils between 10-20 m depth. We measure Class C dense soils/soft rock again from 20-40 m depth and rock below 40 m depth.

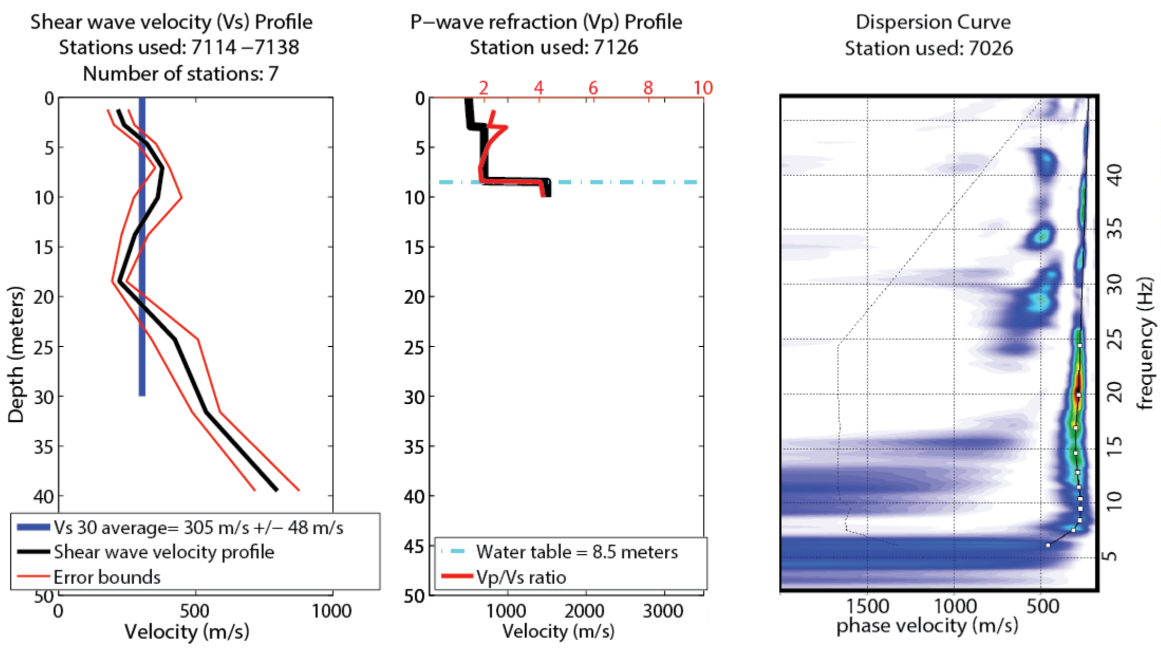

Figure 17. (left) Shear wave velocity profile and average VS30 calculation for the central portion of the Sewage Pond profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 40 m.

We extracted average shear wave and p-wave velocity values between stations 7114-7138 (midpoint location) where we calculate an average Vs30 velocity of 305 m/s (NEHRP Class D3 or stiff soil). We estimate the water table at a depth of approximately 3 m at this location and a Vp/Vs ratio that ranges from approximately 2-4.

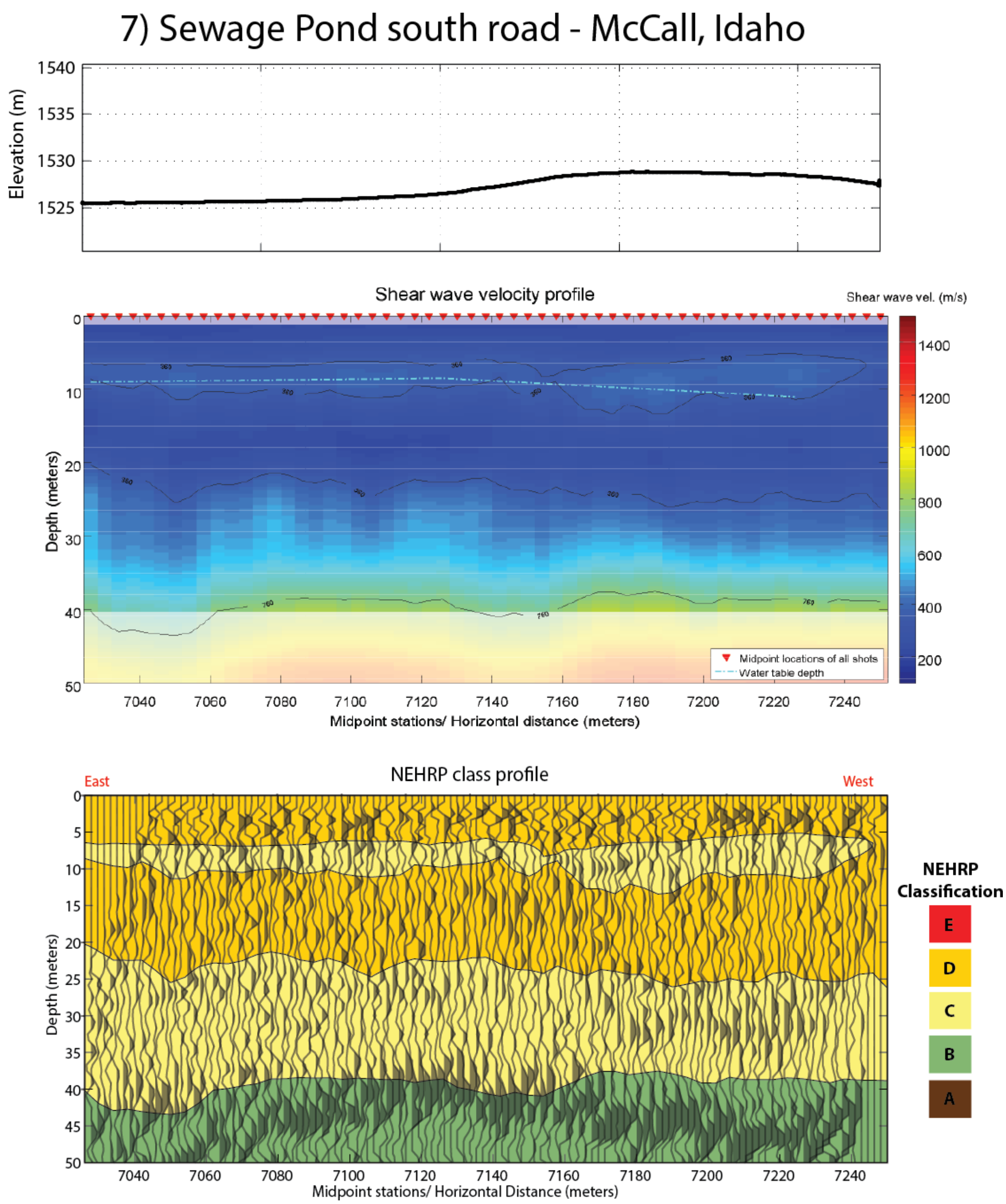

Figure 18. (top) Elevation profile for the Sewage Ponds profile. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~2:1.

8) Second Street (north-south)

East Lake Street (Hwy 55) to Park Street (150 m length, 35 shots)

The Second Street profile begins near the North Fork School in downtown McCall (Figure 2), crosses Lenora Street (profile 4) at position 50 m and terminates near the McCall city hall and police station. This north to south 150 m long profile sits upon Quaternary glacial till beneath road asphalt. The profile contains a change in elevation of approximately 4 m that slopes upward to the south. Shear wave velocities were derived from Rayleigh wave dispersion picks from 32 weight drop seismic shot gathers.

Land streamer seismic data along Second Street resulted in clear first arrivals for first break p-wave refraction picks to approximately 7 m depth and confident surface wave dispersion curve picks to approximately 20-25 m depth (Figures 19 and 20). P-**wave** seismic velocities for the upper few meters were calculated at approximately 400-450 m/s, consistent with NEHRP Class D unconsolidated soil. We estimate the depth to water saturated velocities (>1,500 m/s) at 2.8-3.2 m depth. Shear wave velocities for the upper few meters range from 280-320 m/s (NEHRP class D). We measure Class C dense soils/soft rock from 20-25 m depth and rock (Class B) below 25 m depth. However, signal quality provides a low confidence in this deeper bedrock surface.

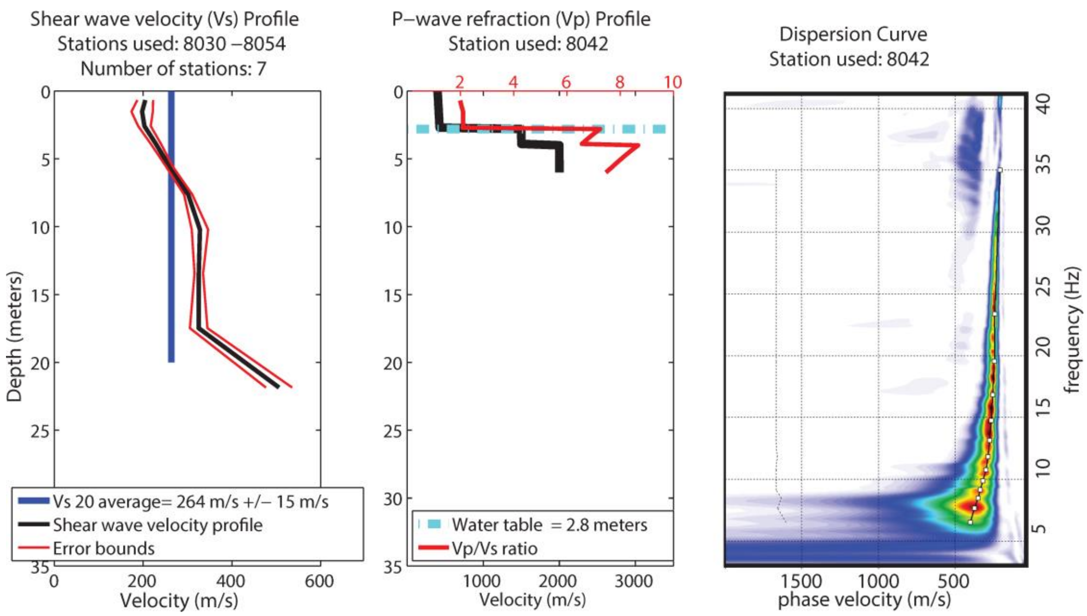

Figure 19. (left) Shear wave velocity profile and average VS30 calculation for the central portion of the Second Street profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 25 m.

We extracted average shear wave and p-wave velocity values between stations 8026-8060 (within the downtown corridor) where we calculate an average Vs30 velocity of 264 m/s

(NEHRP Class D2 or stiff soil). We estimate the water table at a depth of approximately 3 m at this location and a Vp/Vs ratio that ranges from approximately 2.5-7.

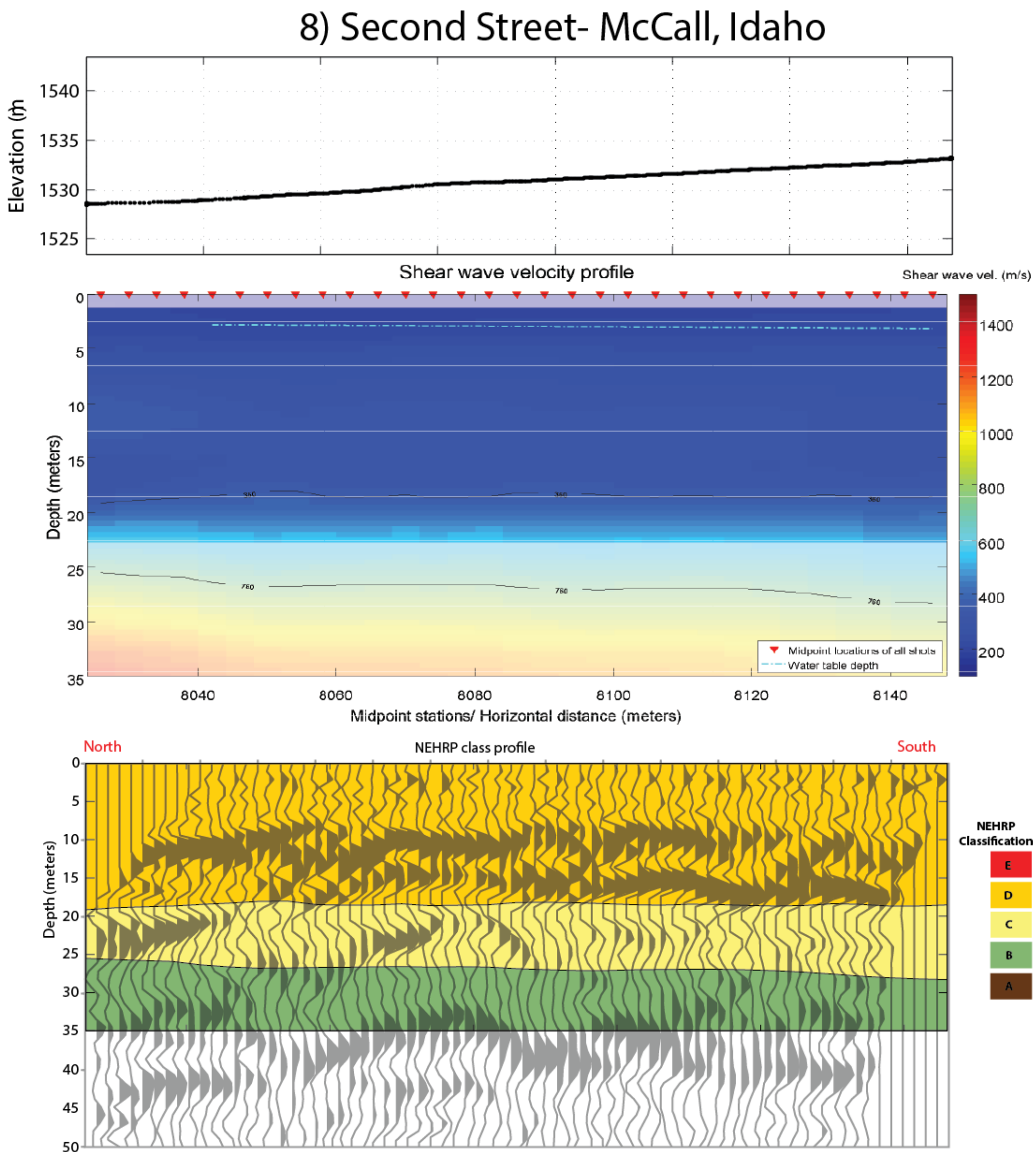

Figure 20. (top) Elevation profile for the Second Street profile. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~1:1.

9) Mill Road (south-north)

Pine Street to Hemlock Street (300 m length, 69 shots)

The Mill Road profile begins at the intersection of Pine Street, crosses Fir Street at position 9080 m and terminates at the intersection of Hemlock Street (Figure 2). This south to north 300 m long profile sits upon Quaternary glacial outwash, glacial till, and possibly artificial fill material beneath road asphalt. The profile contains a change in elevation of approximately 1 m and lies approximately 7 m above Payette Lake water level. Shear wave velocities were derived from Rayleigh wave dispersion picks from 57 weight drop seismic shot gathers.

Land streamer seismic data along Mill Road resulted in clear first arrivals for first break p-wave refraction picks to approximately 10 m depth and confident surface wave dispersion curve picks to approximately 40-45 m depth (Figures 21 and 22). P-**wave** seismic velocities for the upper few meters were calculated at approximately 350-800 m/s, consistent with NEHRP Class D/E unconsolidated soil. We estimate the depth to water saturated velocities (>1,500 m/s) at 2.5-3.2 m depth. Shear wave velocities for the upper 1-3 m range from 160-180 m/s (NEHRP class E). We measure Class D stiff soil from 1-3 m depth with a thickness of 10-20 m. Class C soft rock is estimated at a range of depths from 10-20 m below land surface. We estimate rock (Class B) below 40-45 m depth.

We extracted average shear wave and p-wave velocity values between stations 9104-9132 (near commercial buildings) where we calculate an average Vs30 velocity of 310 m/s (NEHRP Class D3 or stiff soil). We estimate the water table at a depth of approximately 3 m at this location and a Vp/Vs ratio that ranges from approximately 5-7. The high Vp/Vs ratio is due to very slow shear wave velocities at water table depths.

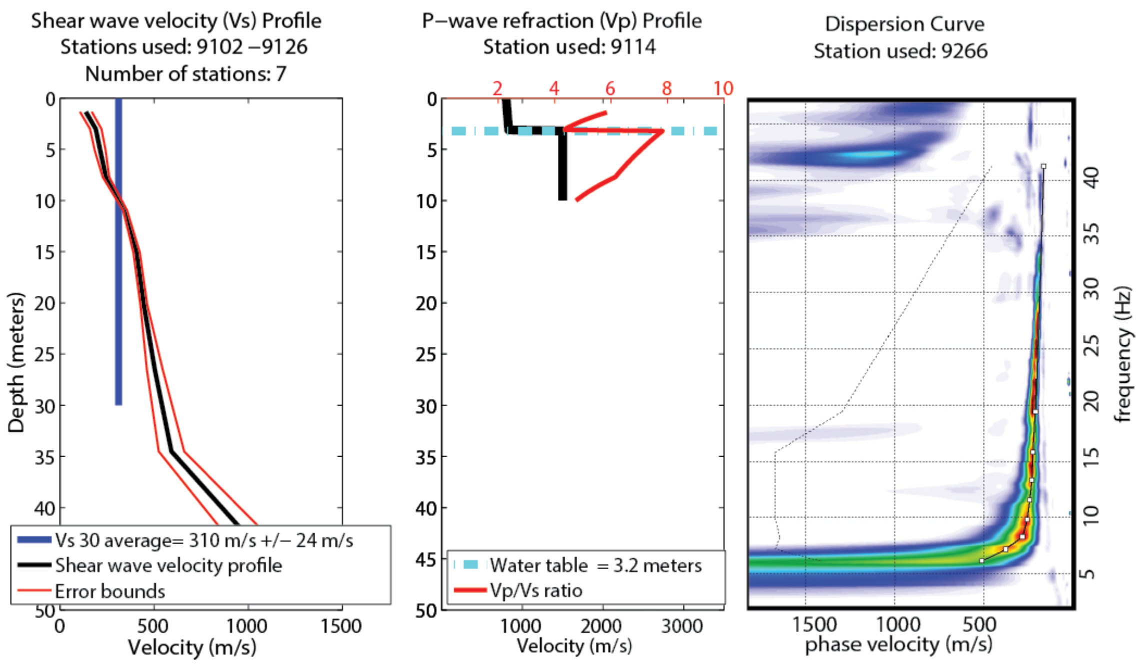

Figure 21. (left) Shear wave velocity profile and average VS30 calculation for the central portion of the Mill Road profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 42 m.

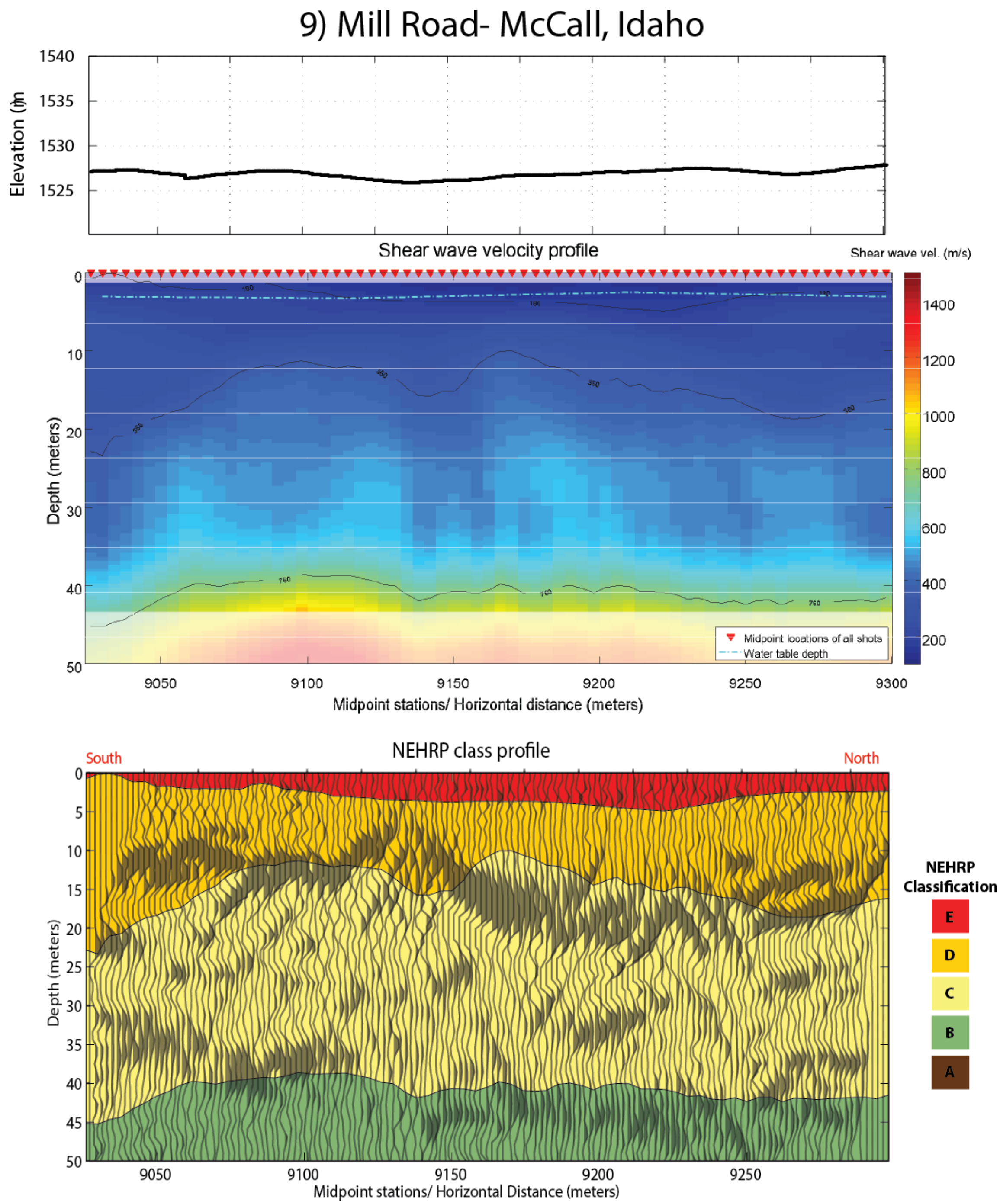

Figure 22. (top) Elevation profile for the Mill Street profile. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~2.5:1.

10) Samson Trail Road (north-south)

Woodlands Drive to Deinhard Lane (272 m length, 68 shots)

The South Samson Trail profile begins near the intersection of Woodlands Drive, crosses the north entrance road to Barbara Morgan School at 170 m, and terminates at the intersection of Deinhard Lane (Figure 2). This 370 m long north to south profile sits upon Quaternary glacial outwash beneath road asphalt. The profile contains a change in elevation of approximately 3 m. Surface wave arrivals along this profile were poor quality, possibly from sub-asphalt infrastructure (e.g. sewage line) or from geological conditions that were present. Therefore, we interpreted results from the only 11 shot gathers to obtain a shear wave velocity profile.

Land streamer seismic data along Samson Trail Road resulted in clear first arrivals for first break p-wave refraction picks to approximately 10 m depth and confident surface wave dispersion curve picks to nearly 60 m depth (Figures 23 and 24). P-**wave** seismic velocities for the upper few meters were calculated at approximately 300-800 m/s, consistent with NEHRP Class D/E unconsolidated soil. We estimate the depth to water saturated velocities (>1,500 m/s) at 2.9-4 m depth. Shear wave velocities for the upper 1-3 m range from 180-200 m/s (NEHRP class D). We measure Class D stiff soil to approximately 22 m depth. Class C soft rock is estimated at a range of depths from 22-50 m below land surface. We estimate rock (Class B) below 50 m depth.

We extracted average shear wave and p-wave velocity values between stations 9750-9774 (near Barbara Morgan School) where we calculate an average Vs30 velocity of 348 m/s (NEHRP Class D3 or stiff soil). We estimate the water table at a depth of approximately 4 m at this

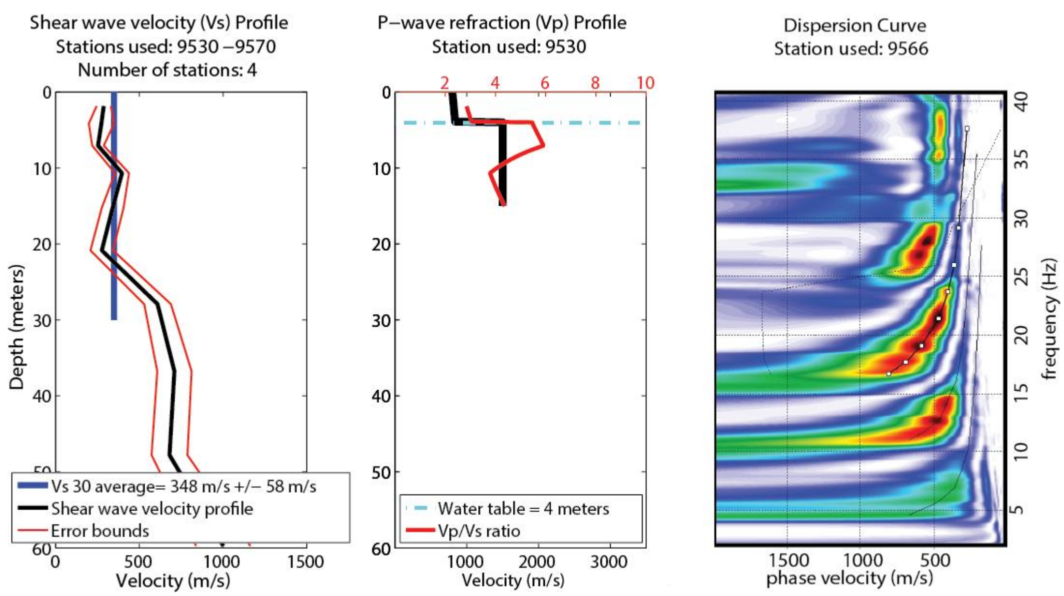

Figure 23. (left) Shear wave velocity profile and average Vs30 calculation for the central portion of the South Samson Trail Road profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 60 m.

location and a Vp/Vs ratio that ranges from approximately 2-8.

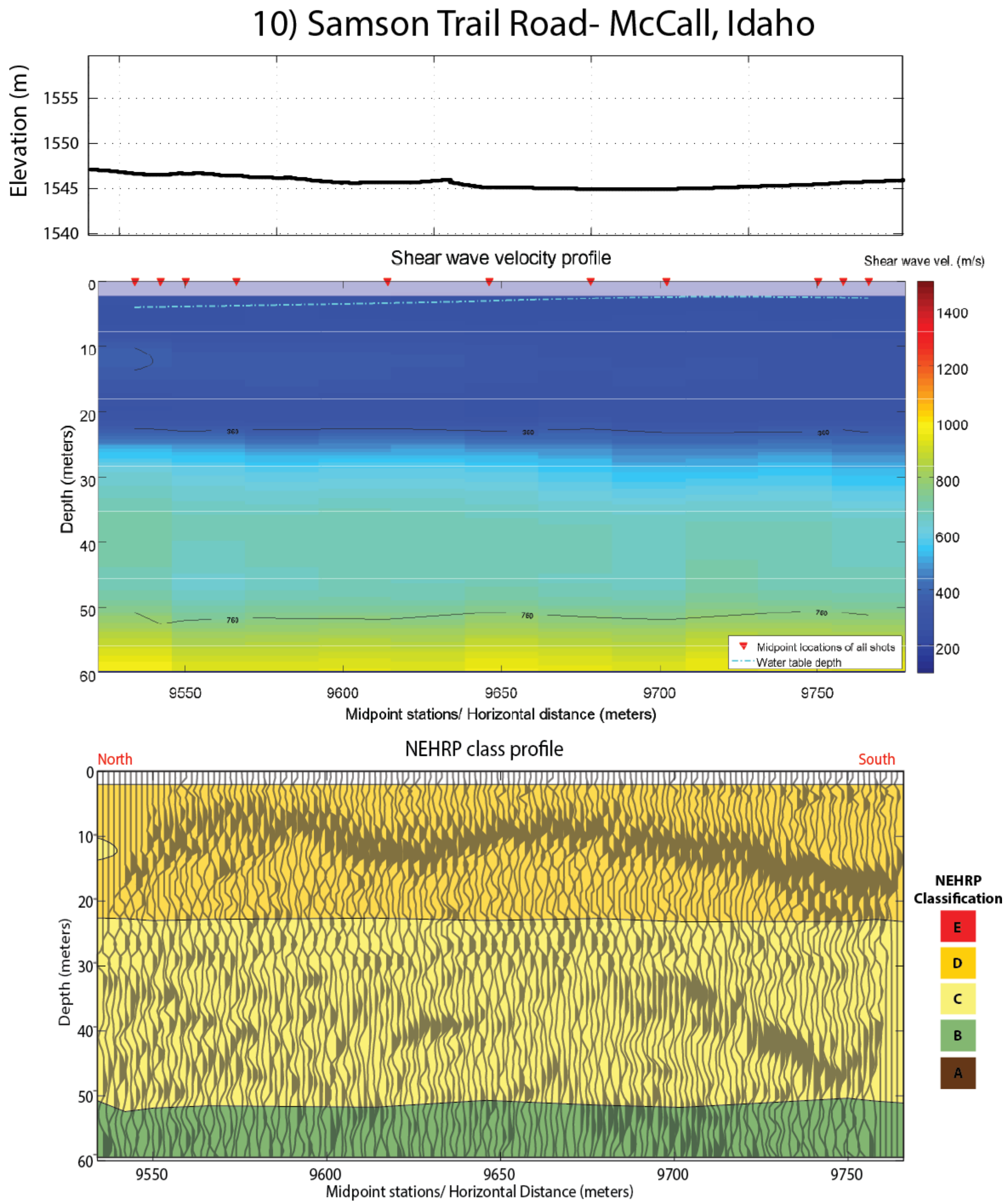

Figure 24. (top) Elevation profile for the Samson Trail profile. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~2:1.

11) RV Park river access road (southwest-northeast)

Dirt road to Payette River footbridge (200 m length, 46 shots)

The RV Park river access road lies adjacent to the McCall municipal airport and Mission Street. The profile begins near a footbridge that crosses the Payette River (Figure 2). This south to north 200 m long profile sits upon Quaternary alluvium along a gravel road surface. The profile contains a change in elevation of approximately 3 m that rises to the north and lies 10-12 m above Payette River levels. Shear wave velocities were derived from Rayleigh wave dispersion picks from 44 weight drop seismic shot gathers.

Land streamer seismic data along RV Park Road resulted in clear first arrivals for first break p-wave refraction picks to approximately 10 m depth and confident surface wave dispersion curve picks to approximately 30-35 m depth (Figures 25 and 26). P-**wave** seismic velocities for the upper few meters were calculated at approximately 240-360 m/s, consistent with NEHRP Class D/E unconsolidated soil. We estimate the depth to water saturated velocities (>1,500 m/s) at 3.8-4.0 m depth. Shear wave velocities for the upper 1-3 m range from 170-200 m/s (NEHRP class D/E). We measure less than 2 m of Class E soft soil near the start and end of the profile and Class D stiff soil for most of the upper 20-25 m depth. We estimate ~ 10 m of Class C soft rock at 20-25 m depth and rock (Class B) at approximately 35 m depth, close to the maximum shear wave imaging depths.

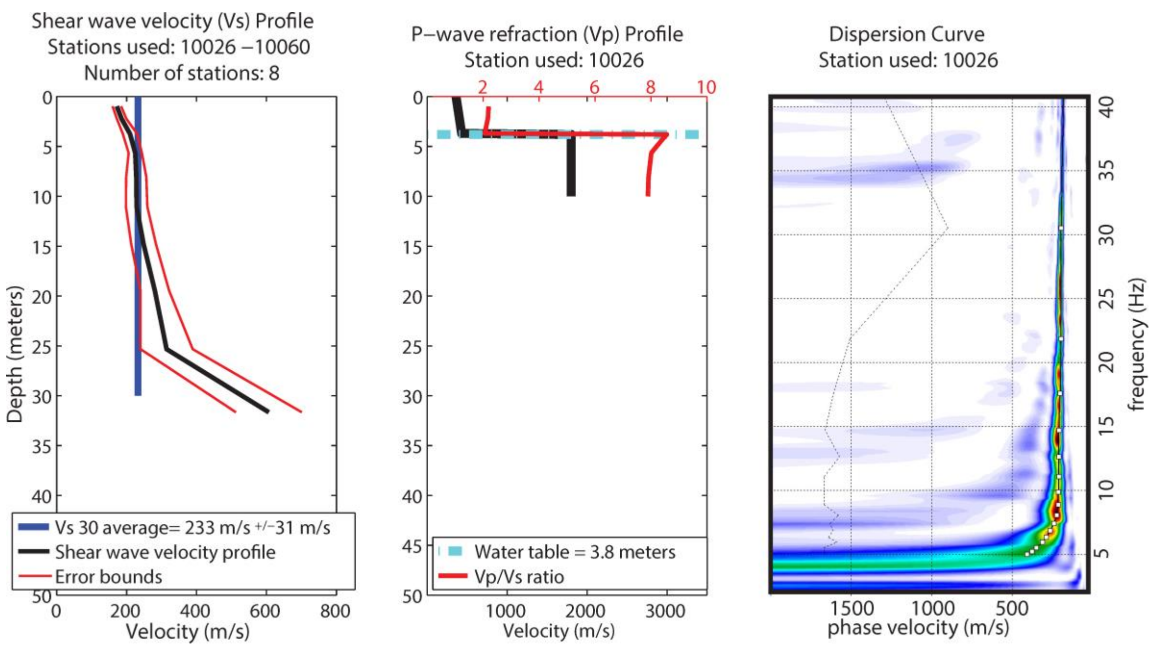

Figure 25. (left) Shear wave velocity profile and average VS30 calculation for the central portion of the RV Park acess road profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 32 m.

We extracted average shear wave and p-wave velocity values between stations 10026-10060 (near the profile start) where we calculate an average Vs30 velocity of 233 m/s (NEHRP Class D1 or stiff soil). We estimate the water table at a depth of approximately 4 m at this location and a Vp/Vs ratio that ranges from approximately 3-8.

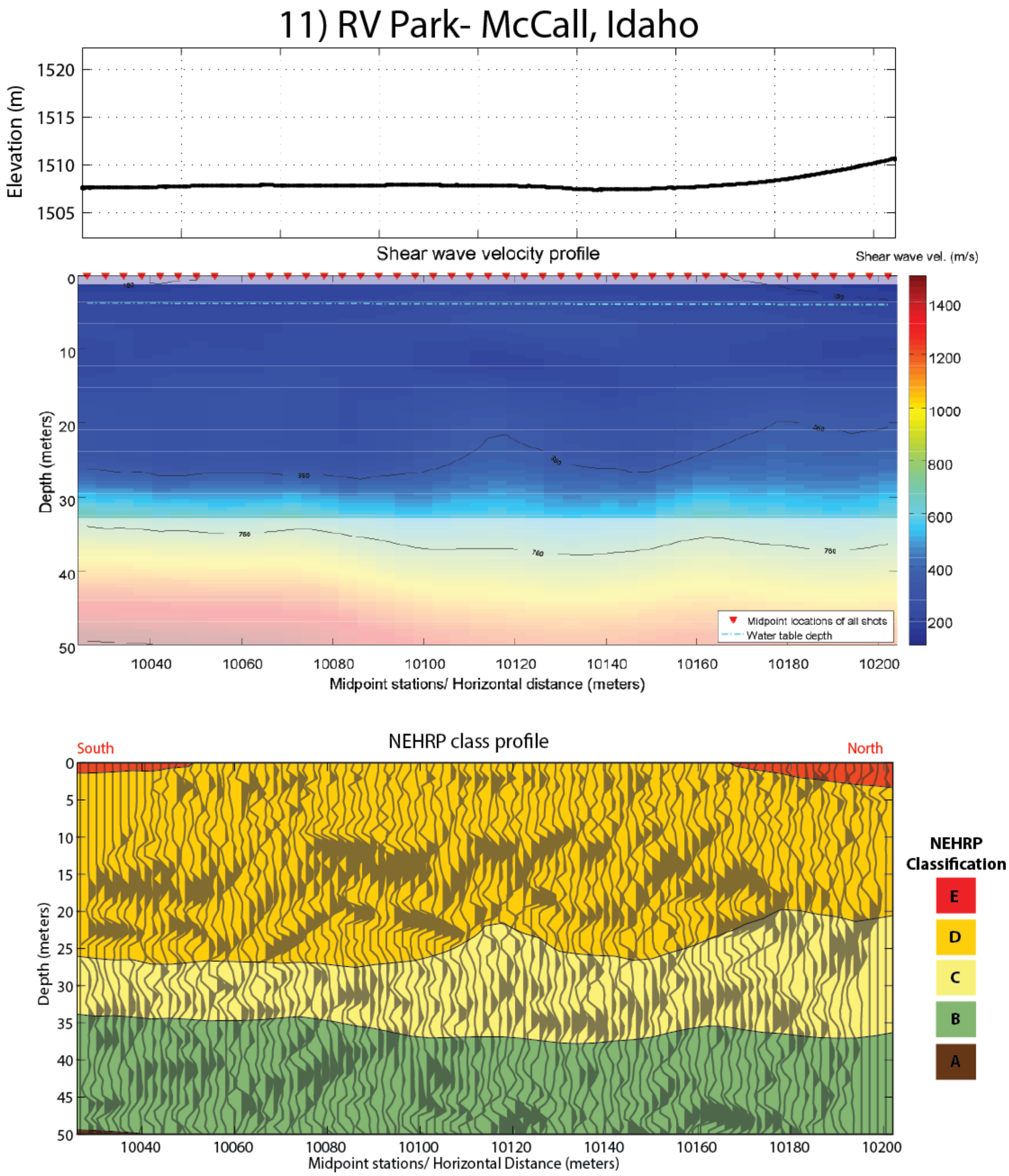

Figure 26. (top) Elevation profile for the RV Park access road profile. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~1.5:1.

Donnelly site response

We acquired 4 seismic profiles in Donnelly to estimate shear wave velocities, water table depths, and depths to key depositional and structural boundaries. We focused three of the profiles within the urban corridor, within one city block of Hwy 55. One additional site was acquired adjacent to the sewage treatment ponds on Eld Lane where we measure Vs30 NEHRP Class D2 stiff soil. Based on Vs30 measurements, we define all locations within downtown Donnelly as NEHRP Class D1. All profiles contained a few meters of Class E soils and rock (Class B) did not appear within the upper 40 m along any profile. Reflection seismic data (Figure 27) show reflectivity in the upper 100 m that is consistent with soft rock derived from lake deposits; thus slower seismic velocities present a higher hazard condition when compared to McCall and Cascade sites. A shallow water table (3 m or less) at all sites makes the Donnelly area more susceptible to liquefaction during strong ground motion when compared to other regions within Valley County.

Table 3. Shear wave velocity summary table for the Donnelly profiles. Details are described in each profile description summary below.

Donnelly	Front Street	Gestrin Street	Halferty Street	Eld Road Sewage access road
Reference Station	11158	12118	12230	130230
Vs 5	163	169	199	131
Vs 10	191	178	216	164
Vs 20	213	215	223	224
Vs 30	226	235	236	265
Vs 40	242	312	296	297
Vs 30 NEHRP class	D1	D1	D1	D2
Average profile water table depth (meters)	3.4	3.5	2.8	3.8
Max depth of shear wave velocity confidence (meters)	56	41	41	47

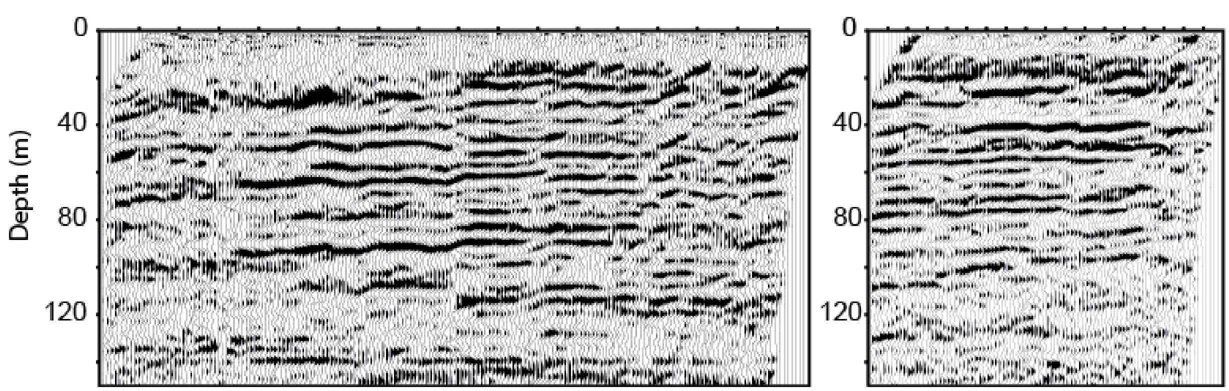

Figure 27. Donnelly reflection profiles from Front Street & Gestrin/Halferty Roads derived from the seismic land streamer. High quality reflection data result from sedimentary layers.

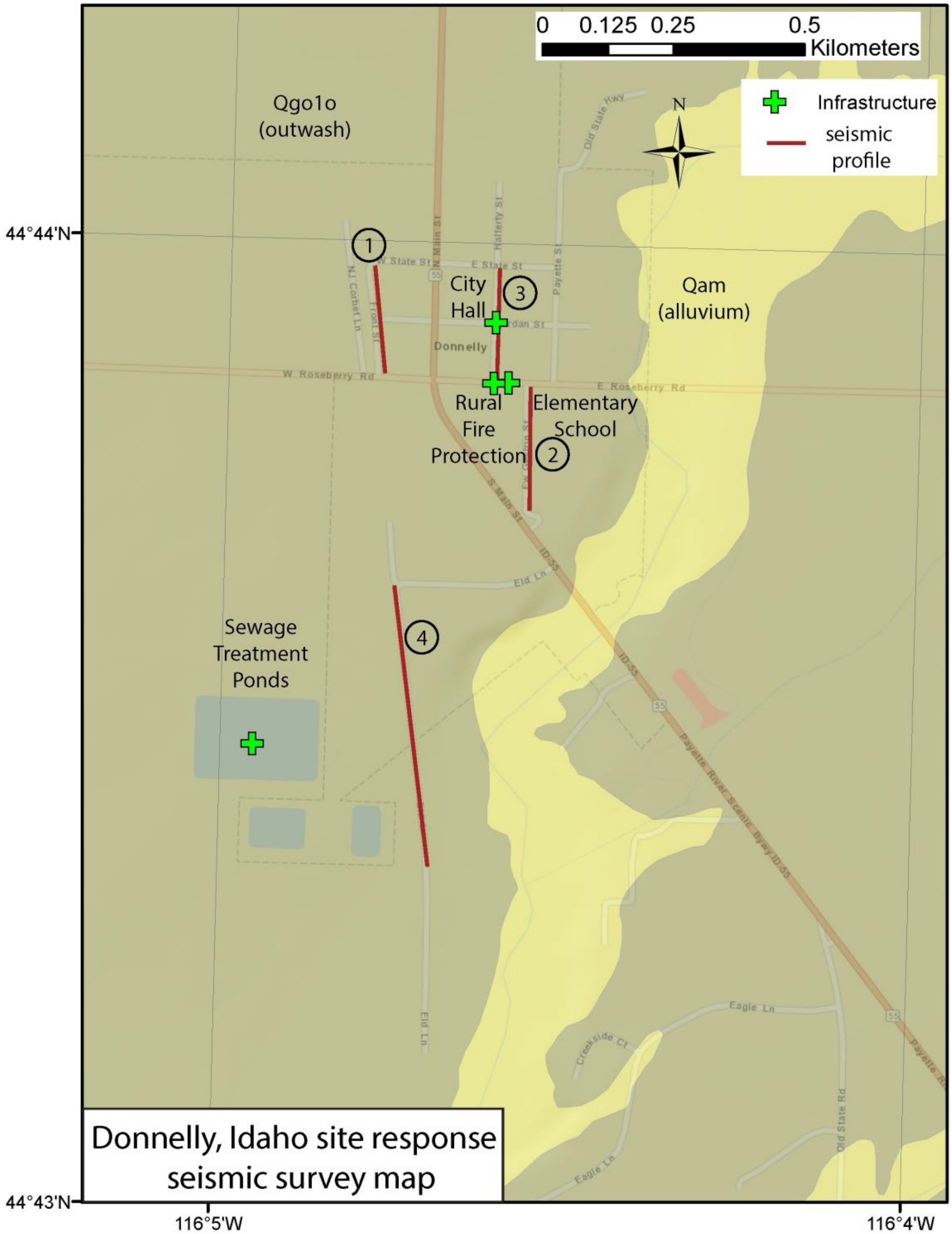

Figure 28. Seismic profile locations (red lines) for the Donnelly, Idaho area. The profile locations focused on critical infrastructure located within city limits. The circled numbers represent profile locations that are described below. Surficial geology from Breckenridge and Othberg (2006).

12) Front Street (south-north)

East Roseberry Road to State Street (170 m length, 39 shots)

The Front Street profile begins at the East Roseberry intersection and extends north to State Street. This south to north 170 m gravel road profile is located one block west of Hwy 55 and sits upon Quaternary glacial outwash (Figure 28). There is no elevation change along this profile. Shear wave velocities were derived from Rayleigh wave dispersion picks from 38 weight drop seismic shot gathers.

Land streamer seismic data along Front Street in Donnelly resulted in clear first arrivals for first break p-wave refraction picks to approximately 15 m depth and confident surface wave dispersion curve picks to 55 m depth (Figures 29 and 30). P-**wave** seismic velocities for the upper few meters were calculated at approximately 450-950 m/s, consistent with NEHRP Class D/E unconsolidated stiff soil. We estimate the depth to water saturated velocities (>1,500 m/s) at 2.5-6 m depth. Shear wave velocities for the upper 1-3 m range from 170-200 m/s (NEHRP class D/E). We measure Class E soft soil within the upper few meters and Class D stiff soil for most of the upper 25-30 m depth. We estimate approximately 30 m of Class C soft rock starting at 30-40 m depth and rock (Class B) at the limits of our shear wave imaging capabilities.

We extracted average shear wave and p-wave velocity values between stations 11146-11170 (near the profile end) where we calculate an average Vs30 velocity of 226 m/s (NEHRP Class

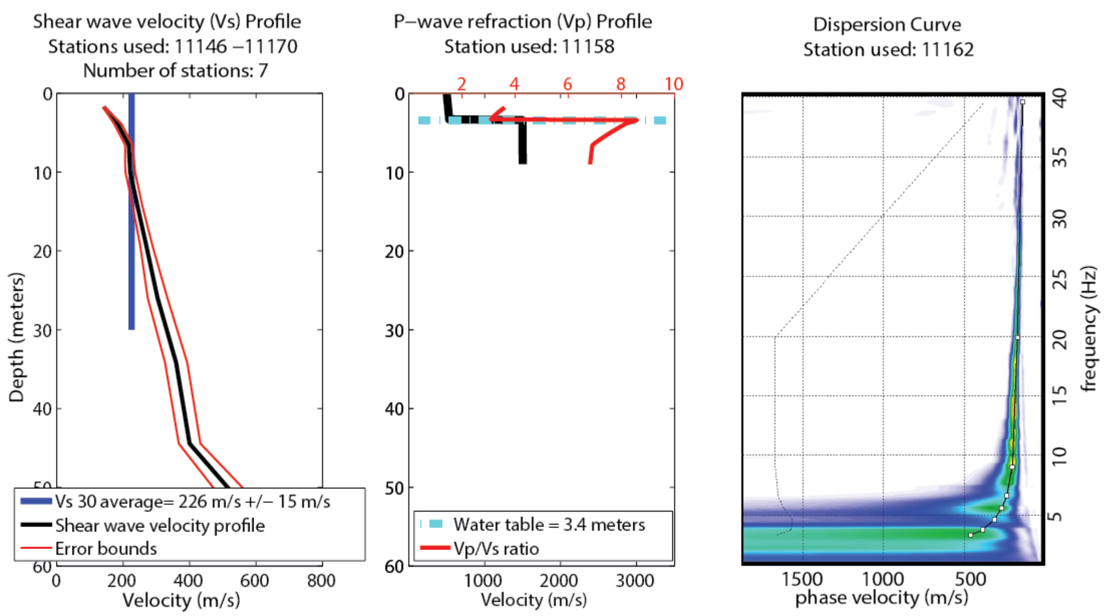

Figure 29. (left) Shear wave velocity profile and average VS30 calculation for the central portion of the Front Street profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 58 m.

D1). We estimate the water table at a depth of 3.4 m at this location and a Vp/Vs ratio that ranges from approximately 3-8.

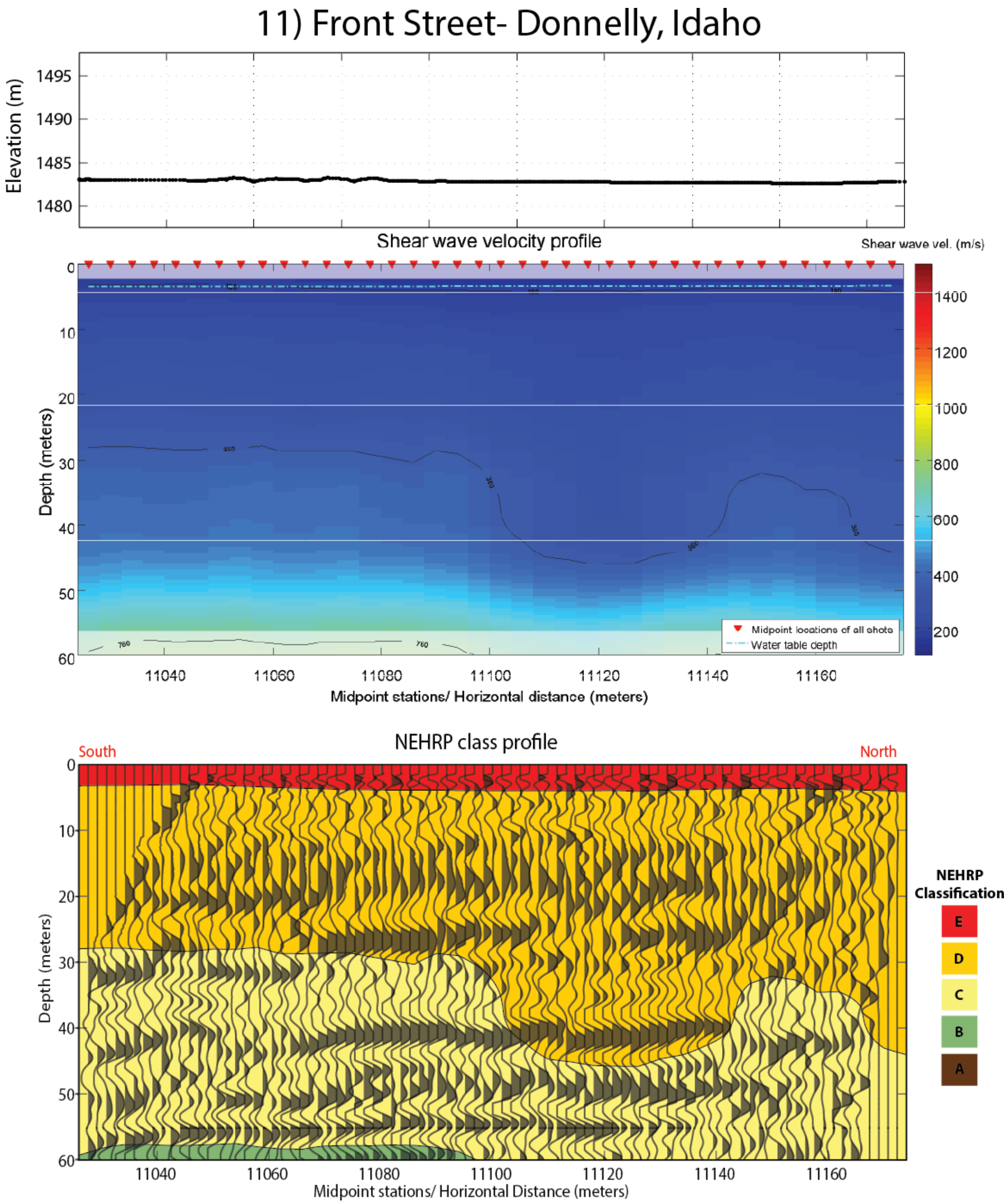

Figure 30. (top) Elevation profile for the Front Street profile. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~1:1.

13) Gestrin Street (south-north)

Hwy 55 to East Roseberry Road (160 m length, 41 shots)

The Gestrin Street profile begins at the tennis courts south of the Donnelly Elementary School and east of Hwy 55 (Figure 28). The south to north 350 m long profile terminates at the East Roseberry intersection, immediately west of the Donnelly elementary school. The profile sits upon Quaternary glacial outwash on a dirt/gravel road that transitions to asphalt pavement near position 120 m. The elevation gain along the road is less than 1 m. Shear wave velocities were derived from Rayleigh wave dispersion picks from 40 weight drop seismic shot gathers.

Land streamer seismic data along Gestrin Street in Donnelly resulted in clear first arrivals for first break p-wave refraction picks to approximately 12 m depth and confident surface wave dispersion curve picks to 42 m depth (Figure 31 and left half of Figure 32). P-**wave** seismic velocities for the upper few meters were calculated at approximately 350 m/s, consistent with NEHRP Class E unconsolidated soft soil. We estimate the depth to water saturated velocities (>1,500 m/s) at 2.8-4 m depth. Shear wave velocities for the upper 1-3 m range from 170-200 m/s (NEHRP class D/E). We measure Class E soft soil within the upper few meters for much of the profile and Class D stiff soil for most of the upper 20-30 m depth. We estimate approximately 20 m of Class C soft rock starting at 20-30 m depth and rock (Class B) below 40

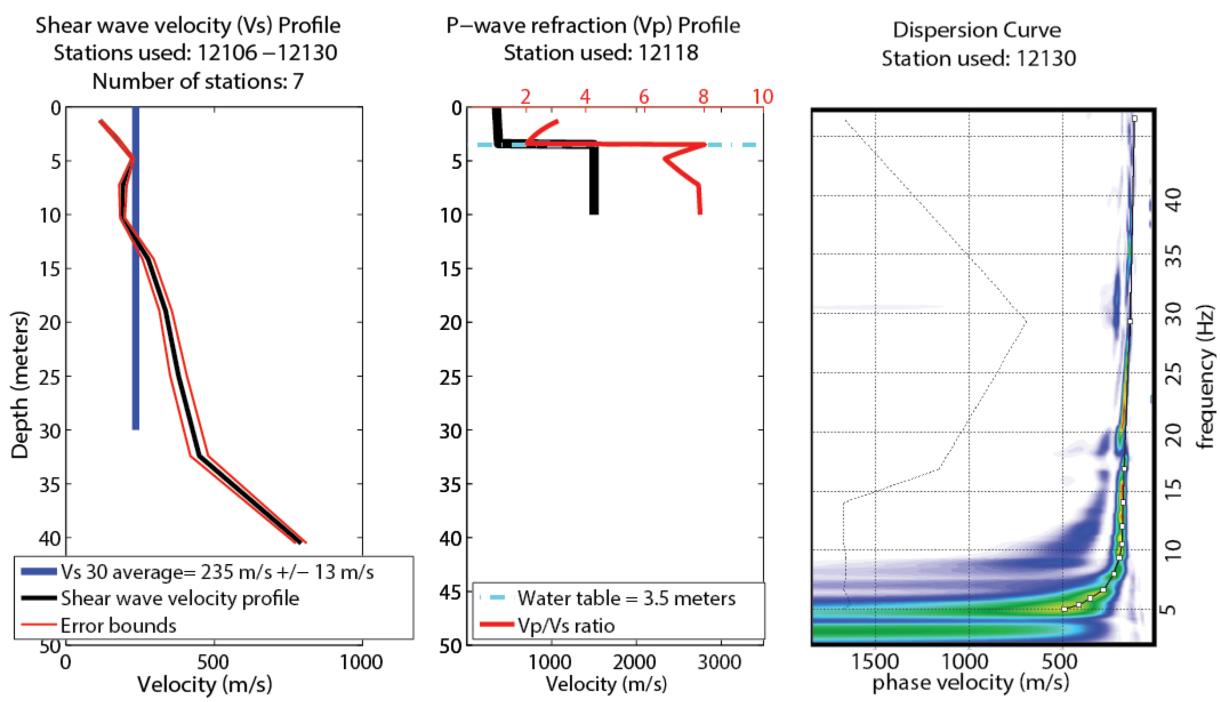

Figure 31. (left) Shear wave velocity profile and average VS30 calculation for the central portion of the Gestrin Street profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 32 m.

m and at the limits of our shear wave imaging capabilities. The left half of Figure 32 represents the Gestrin Street data.

We extracted average shear wave and p-wave velocity values between stations 12104-12132 (near the center of the profile) where we calculate an average Vs30 velocity of 235 m/s (NEHRP Class D1). We estimate the water table at a depth of 3.5 m at this location and a Vp/Vs ratio that ranges from approximately 3-8.

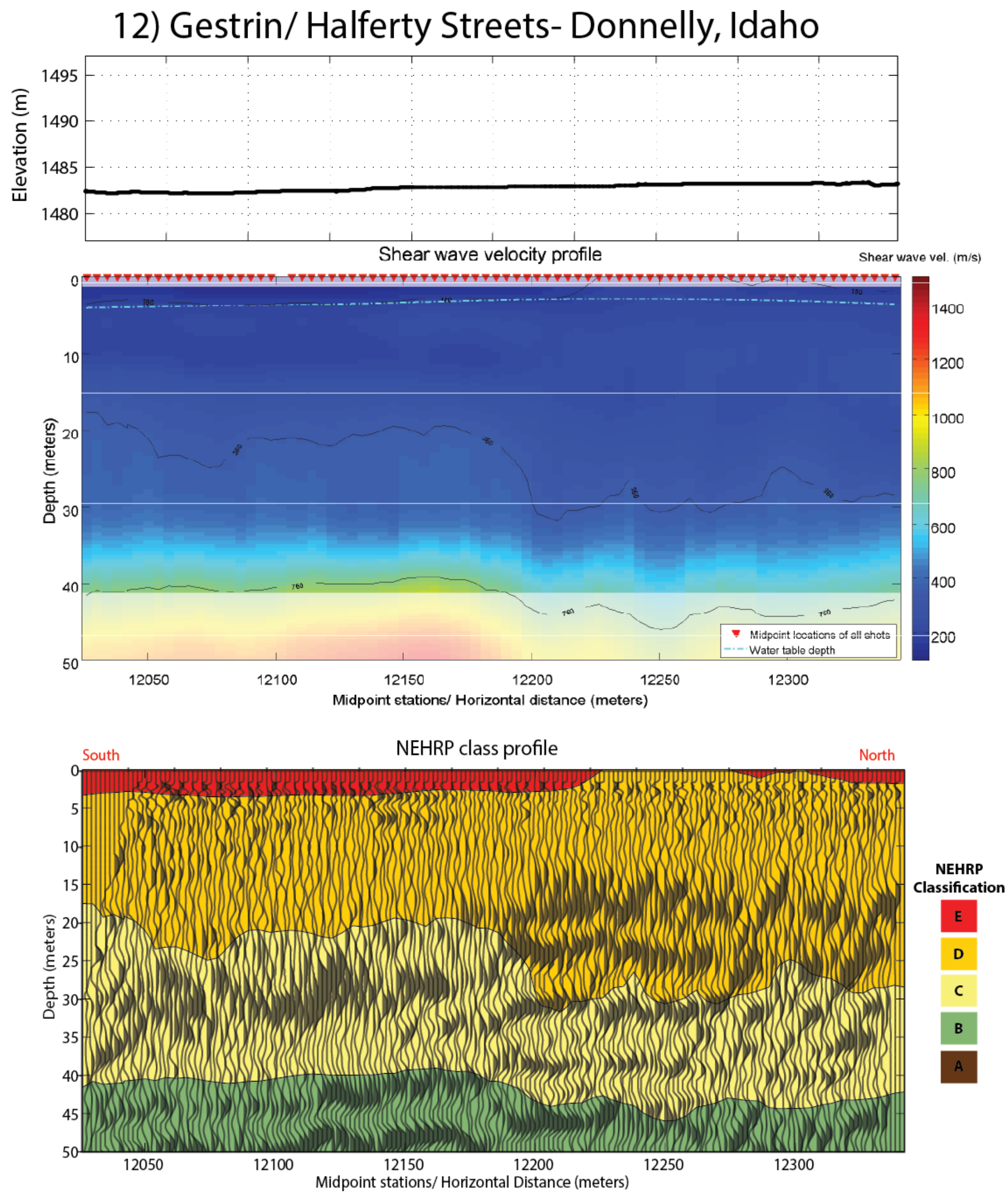

Figure 32. (top) Elevation profile for Halferty/Gestrin Street profile. (middle) Shear wave profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~3:1.

12) Halferty Street (south-north)

Hwy 55 to East Roseberry Road to State Street (160 m length, 42 shots)

The Halferty Street profile begins in Donnelly at the East Roseberry intersection and extends north to State Street (Figure 28). This south to north 200 m long profile sits upon Quaternary glacial outwash and is the northern extension of the Gestrin Street profile and is one block west of Hwy 55. The gravel road profile crosses Jordan Street at position 12300 m and city hall near position 12250 m. The elevation gain along the road is less than 1 m. Shear wave velocities were derived from Rayleigh wave dispersion picks from 40 weight drop seismic shot gathers.

Land streamer seismic data along Halferty Street in Donnelly resulted in clear first arrivals for first break p-wave refraction picks to approximately 10 m depth and confident surface wave dispersion curve picks to 42 m depth (right half of Figure 32 and Figure 33). P-**wave** seismic velocities for the upper few meters were calculated at approximately 350 m/s, consistent with NEHRP Class E unconsolidated soft soil. We estimate the depth to water saturated velocities (>1,500 m/s) at 2.8-4 m depth. Shear wave velocities for the upper 1-3 m range from 170-200 m/s (NEHRP class D/E). We measure Class E soft soil within the upper few meters for much of the profile and Class D stiff soil for most of the upper 20-30 m depth. We estimate approximately 20 m of Class C soft rock starting at 20-30 m depth and rock (Class B) below 40 m and at the limits of our shear wave imaging capabilities.

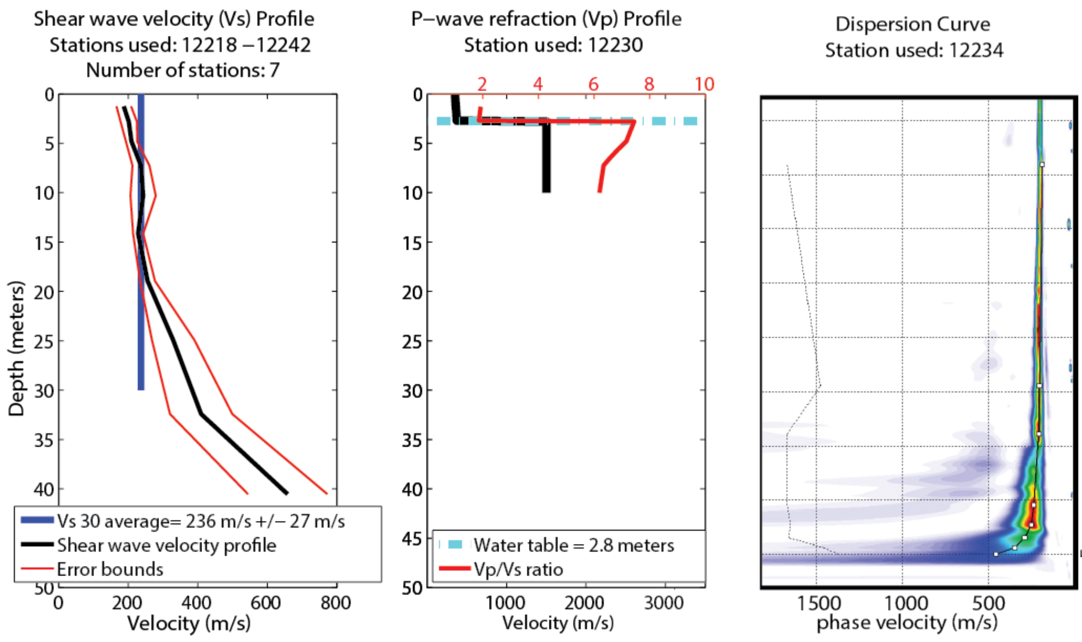

Figure 33. (left) Shear wave velocity profile and average VS30 calculation for the central portion of the Halferty Street profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 40 m.

We extracted average shear wave and p-wave velocity values between stations 12216-12244 (near City Hall) where we calculate an average Vs30 velocity of 236 m/s (NEHRP Class D1). We estimate the water table at a depth of 2.8 m at this location and a Vp/Vs ratio that ranges from approximately 3-8.

14) Eld Lane (south-north)

From pond access road to bend in Eld Lane (400 m length, 97 shots)

The Eld Lane profile lies adjacent to the Donnelly sewage treatment ponds and approximately 0.5 km west of Hwy 55 (Figure 28). This south to north 400 m long profile sits upon Quaternary glacial outwash on a gravel road surface and has a change in elevation of approximately 3 m. Shear wave velocities were derived from Rayleigh wave dispersion picks from 96 weight drop seismic shot gathers.

Land streamer seismic data along Eld Street in Donnelly resulted in clear first arrivals for first break p-wave refraction picks to approximately 10 m depth and confident surface wave dispersion curve picks to 47 m depth (Figures 34 and 35). P-**wave** seismic velocities for the upper few meters range from 350-550 m/s, consistent with NEHRP Class E unconsolidated soft soil. We estimate the depth to water saturated velocities (>1,500 m/s) at 2-5.5 m depth. Shear wave velocities for the upper 1-3 m range from 160-200 m/s (NEHRP class D/E). We measure Class E soft soil within the upper few meters for much of the profile and Class D stiff soil for

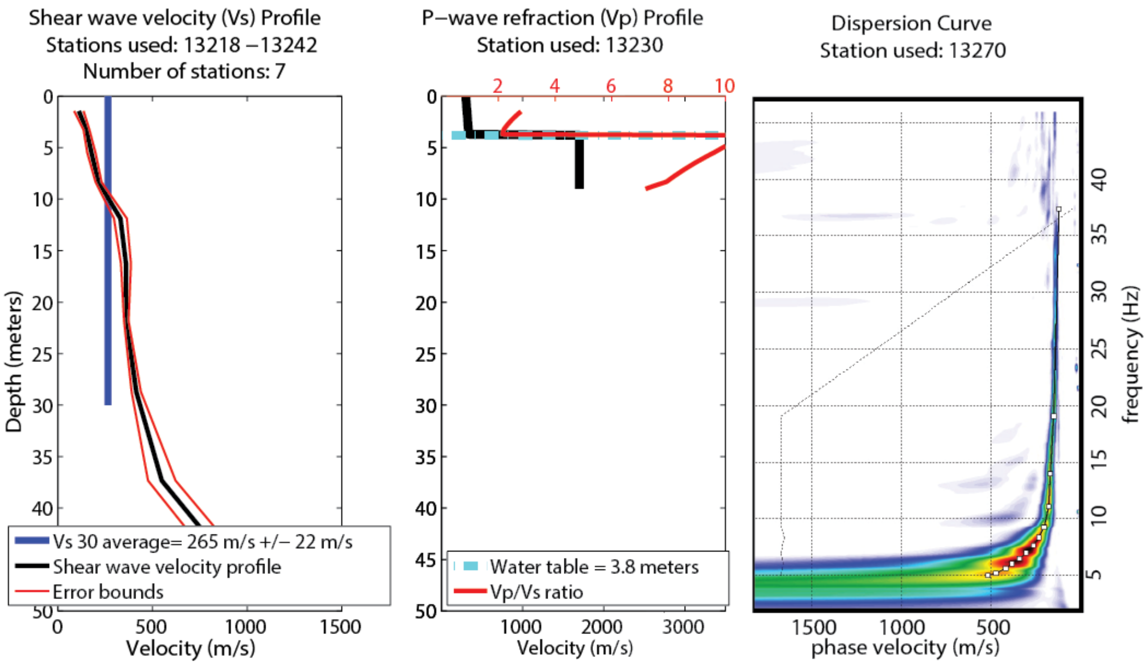

Figure 34. (left) Shear wave velocity profile and average VS30 calculation for the central portion of the Eld Street profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 48 m.

most of the upper 20 m depth. We estimate approximately 20 m of Class C soft rock starting at approximately 20 m depth and rock (Class B) below 45 m depth.

We extracted average shear wave and p-wave velocity values between stations 13216-13244 (near profile center) where we calculate an average Vs30 velocity of 265 m/s (NEHRP Class D2). We estimate the water table at a depth of 4 m at this location and a Vp/Vs ratio that ranges from approximately 3-10.

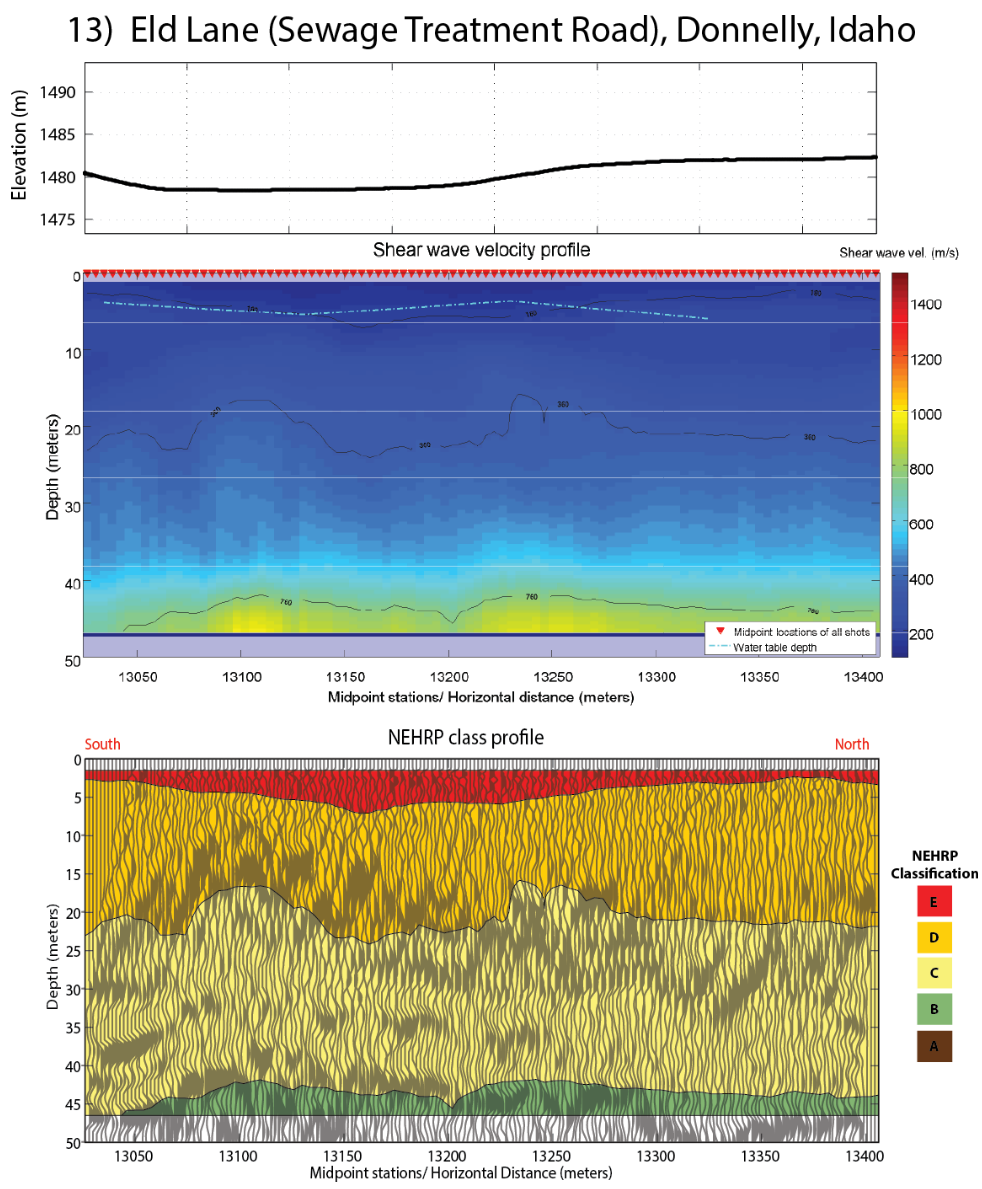

Figure 35. (top) Elevation profile for the Eld Street profile, sewage pond access road. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~3:1.

Cascade site response (Figure 3)

We acquired 6 seismic profiles in Cascade to estimate shear wave velocities, water table depths, and depths to key depositional and structural boundaries. We focused most of the profiles within the urban corridor that is bound by Cascade Reservoir and the Payette River (Figure 36 and 37). Table 3 provides a summary table of the Cascade seismic results. Based on Vs30 measurements, we define two lines on Front St and Idaho St as Class C (very stiff soil/soft rock). The remaining four lines are defined as Class D (stiff soil). The slowest shear wave velocities were measured at a site near the Alzar School and the Eld Street profiles, both lie adjacent to the Payette River and south of town. This school access road river is located immediately adjacent to the Cascade airport and along the Payette River where loose sands dominate the near surface layers. The fastest average Vs30 shear wave velocities were located beneath downtown Cascade along the two roads that parallel Main Street and Hwy 55 (Idaho and Front Streets) where relatively fast Class B rock appears at depths as shallow as 20 m. Class E loose soils are present within the upper few m along a few of the profiles, with the site adjacent to the sewage treatment ponds containing upward of 5 m of loose river deposits or artificial fill. A shallow water table at this site (essentially at lake level) makes this area susceptible to liquefaction during strong ground motion.

Table 3. Summary shear wave velocities for the Cascade area. Asterisk represents 25 m average. Asterisk represents an extrapolated value based on the approach of Boore (2004).

Cascade	Idaho Street	Spring Street	Medical Center	Front Street	Sewage Access Road	Alzar School Entrance
Reference Station	1238	2110	3026	4326	5026	6094
Vs 5	193	208	179	335	143	178
Vs 10	286	267	212	379	182	193
Vs 20	382	321	249	444	210	216
Vs 30	485	254	303	489	256	*267
Vs 40	547	487	332	555		
Vs 30 NEHRP class	C1	D2	D3	C1	D2	D2
Average profile water table depth (meters)	3	5	9	2	2.8	4
Max depth of shear wave velocity confidence (meters)	50	39	49	37	29	25

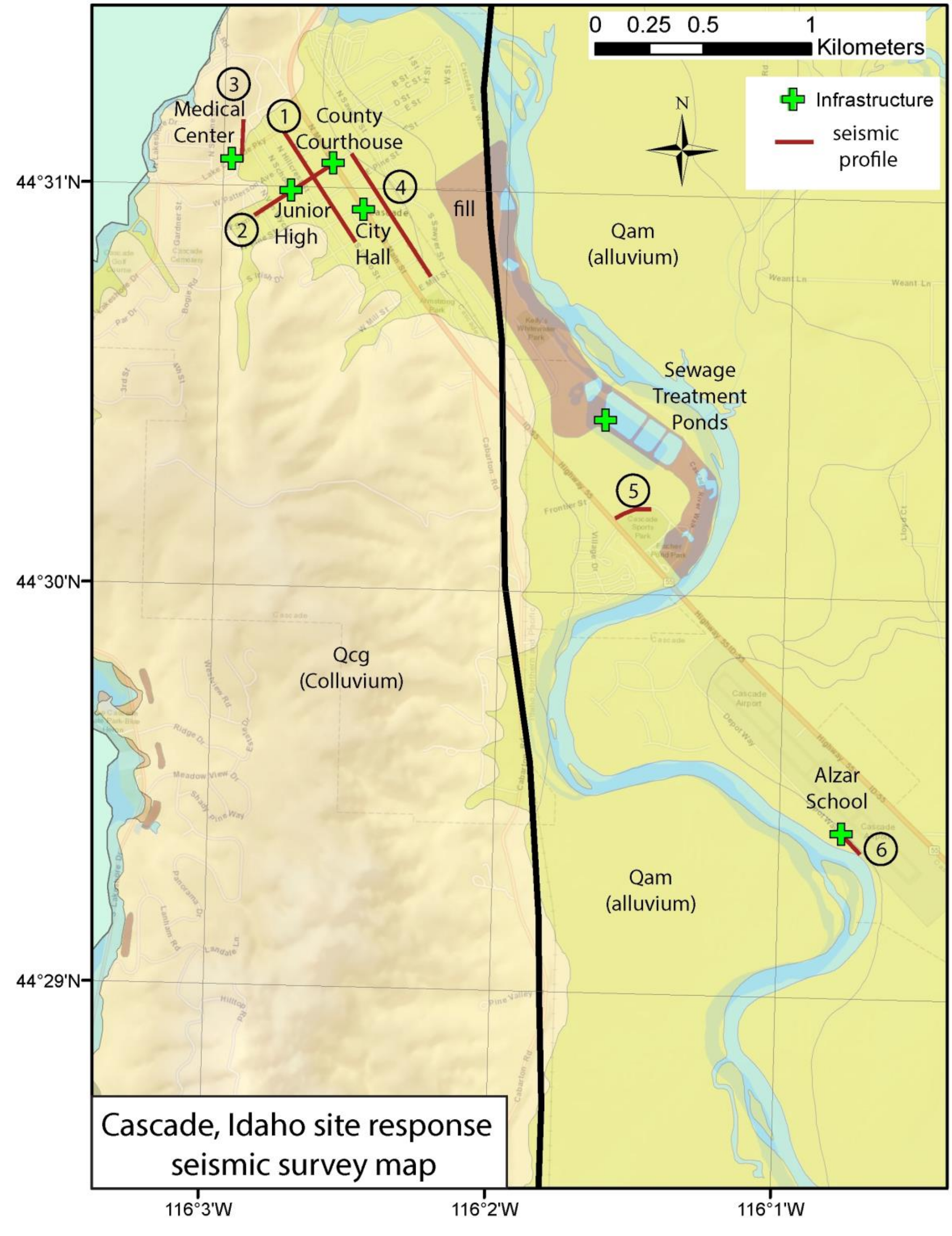

Figure 36. Seismic profile locations (red lines) for the McCall, Idaho area. The profile locations focused on critical infrastructure located within city limits. The circled numbers represent profile locations that are described below. Surficial geology from Breckenridge and Othberg (2006).

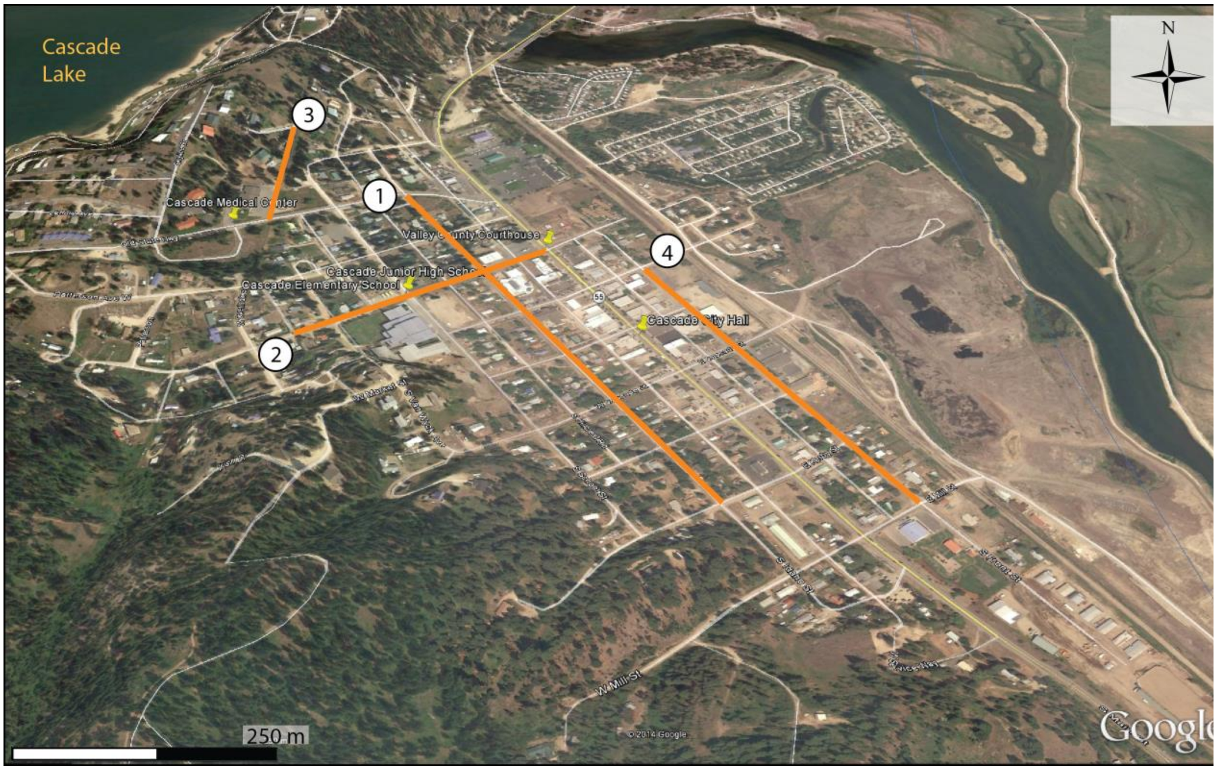

Figure 37. Aerial photo of downtown Cascade, Idaho showing profile locations.

1) Idaho Street (northwest-southeast)

Old State Hwy to Kerby Street (740 m length, 185 shots)

The Idaho Street profile is located approximately 100 m west of Hwy 55 (Main Street) in Cascade (Figure 36). This north to south profile begins at Old State Highway, passes within a city block of the county courthouse (position 1250), city hall, and junior high school (position 1300). This 740 m gravel road profile sits upon Quaternary alluvium with an elevation change of approximately 5 m. The profile crosses Spring Street (Line 2) at position 1220. Shear wave velocities were derived from Rayleigh wave dispersion picks from 94 weight drop seismic shot gathers.

Land streamer seismic data along Idaho Street in Cascade resulted in clear first arrivals for first break p-wave refraction picks to approximately 10 m depth and confident surface wave dispersion curve picks to 50 m depth (Figures 38 and 39). P-**wave** seismic velocities for the upper few meters range from 350-580 m/s, consistent with NEHRP Class D/E unconsolidated soil. We estimate the depth to water saturated velocities (>1,500 m/s) at 2.7-3.5 m depth. Shear wave velocities for the upper 1-3 m range from 160-190 m/s (NEHRP class D/E). We measure Class E soft soil within the upper few meters for much of the profile and Class D stiff soil for most of the upper 10 m depth. We estimate 15-20 m of Class C soft rock starting at 10 m depth, rock (Class B) below 25-30 m depth, and hard rock below 50 m depth.

We extracted average shear wave and p-wave velocity values between stations 1226-1250 (near the County Courthouse) where we calculate an average Vs30 velocity of 485 m/s (NEHRP Class C1). We estimate the water table at a depth of 3 m at this location and a Vp/Vs ratio that ranges from approximately 4-9.

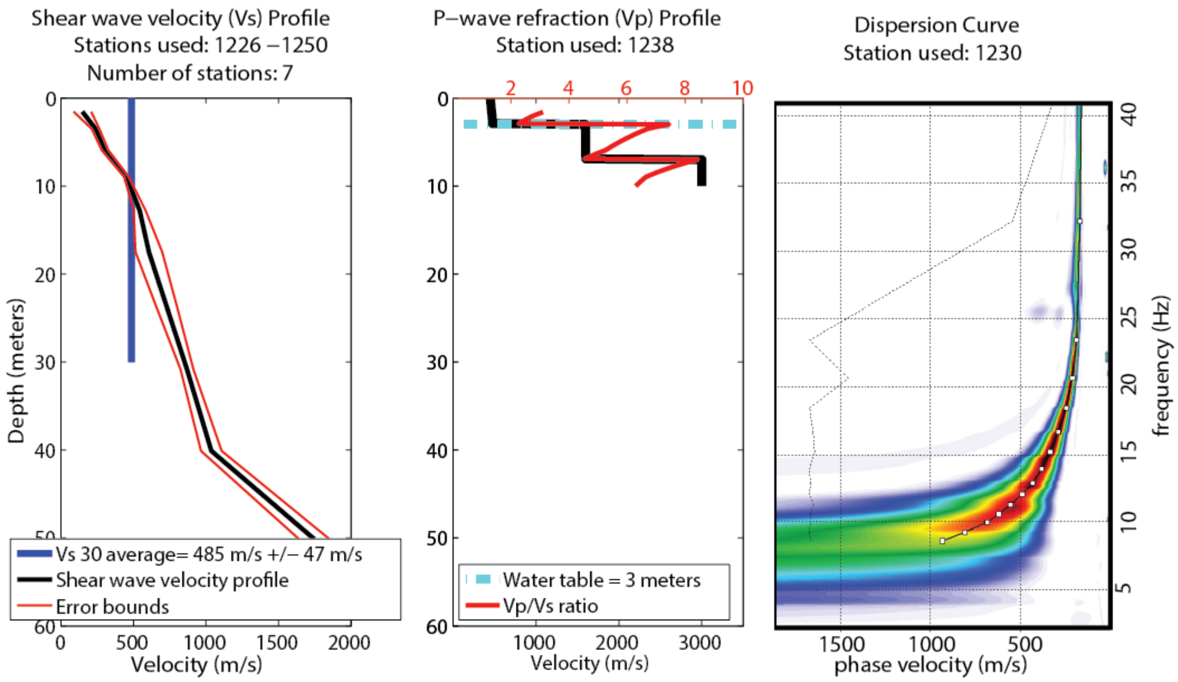

Figure 38. (left) Shear wave velocity profile and average VS30 calculation for the central portion of the Idaho Street profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 50 m.

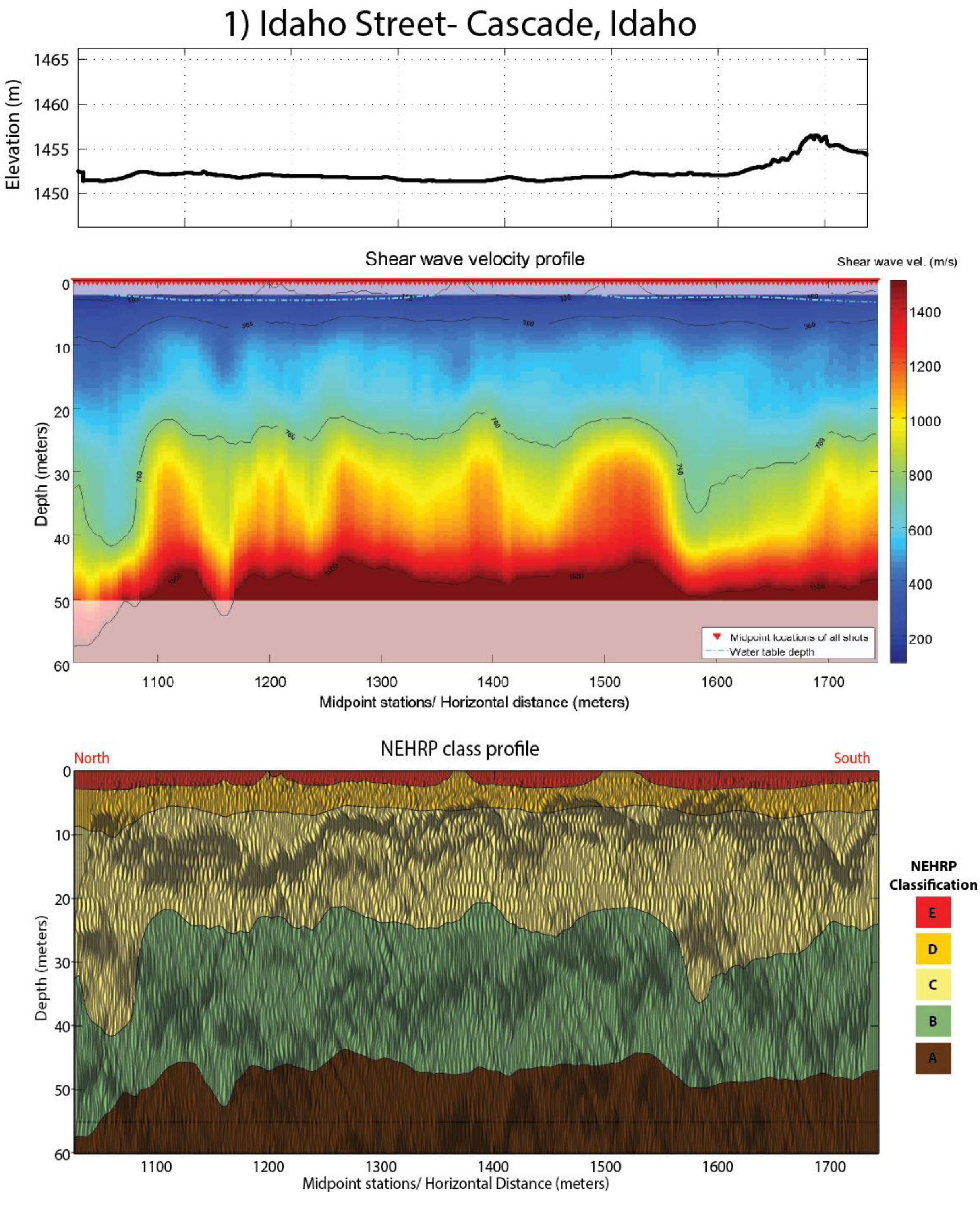

Figure 39. (top) Elevation profile for the Idaho Street profile. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~4:1.

2) Spring Street (southwest-northeast)

Overlook Street to N. Main Street (400 m length, 94 shots)

The Spring Street profile passes the Junior High (position 2200) and the County courthouse (position 2400 m). This southwest to northeast 400 m gravel road profile transitions from Quaternary colluvium to Quaternary alluvium near the southwest edge of the profile and crosses Idaho Street (Line 1) at position 2350 (Figure 36). The profile shows a decrease in elevation along profile to the northeast by approximately 10 m. Shear wave velocities were derived from Rayleigh wave dispersion picks from 94 weight drop seismic shot gathers.

Land streamer seismic data along Spring Street in Cascade resulted in clear first arrivals for first break p-wave refraction picks to approximately 8 m depth and confident surface wave dispersion curve picks to 40 m depth (Figures 40 and 41). P-**wave** seismic velocities for the upper few meters range from 600-750 m/s, consistent with NEHRP Class D unconsolidated soil. We estimate the depth to water saturated velocities (>1,500 m/s) at 2.8-6 m depth. Shear wave velocities for the upper 1-3 m range from 160-200 m/s (NEHRP class D/E). We measure Class E soft soil within the upper few meters for much of the profile and Class D stiff soil for most of the upper 10-15 m depth. We estimate 20 m of Class C soft rock starting at 10-15 m depth, rock (Class B) below 35 m depth, and hard rock below 45 m depth.

We extracted average shear wave and p-wave velocity values between stations 2098-2122 (near the County Courthouse) where we calculate an average Vs30 velocity of 354 m/s (NEHRP Class

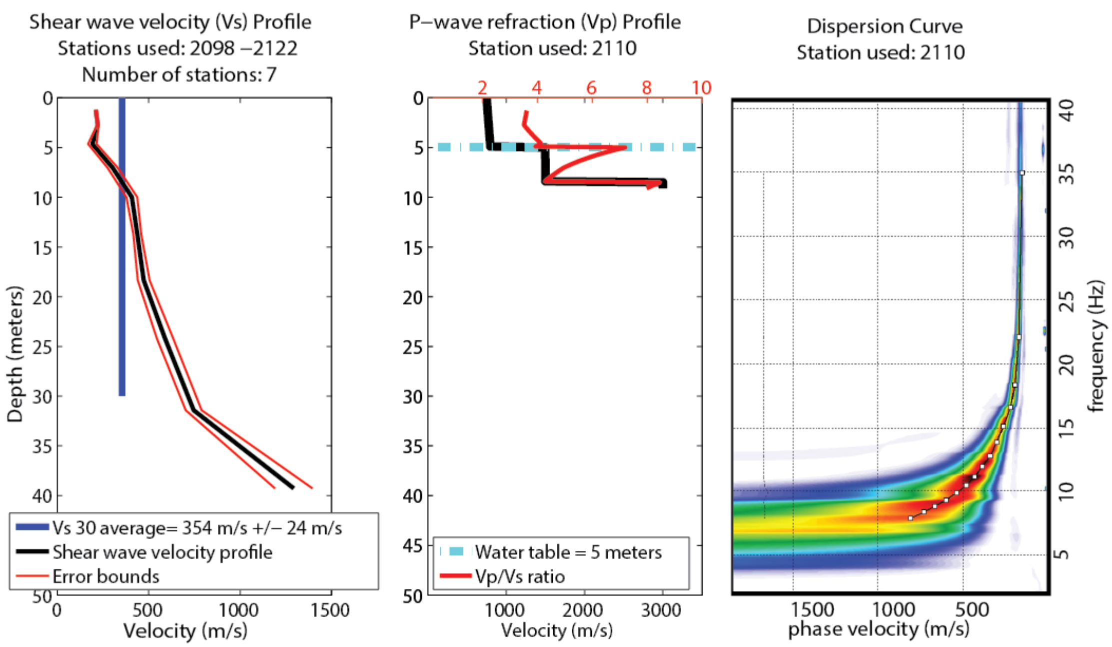

Figure 40. (left) Shear wave velocity profile and average VS30 calculation for the central portion of the Spring Street profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 39 m.

C1). We estimate the water table at a depth of 5 m at this location and a Vp/Vs ratio that ranges from approximately 4-8.

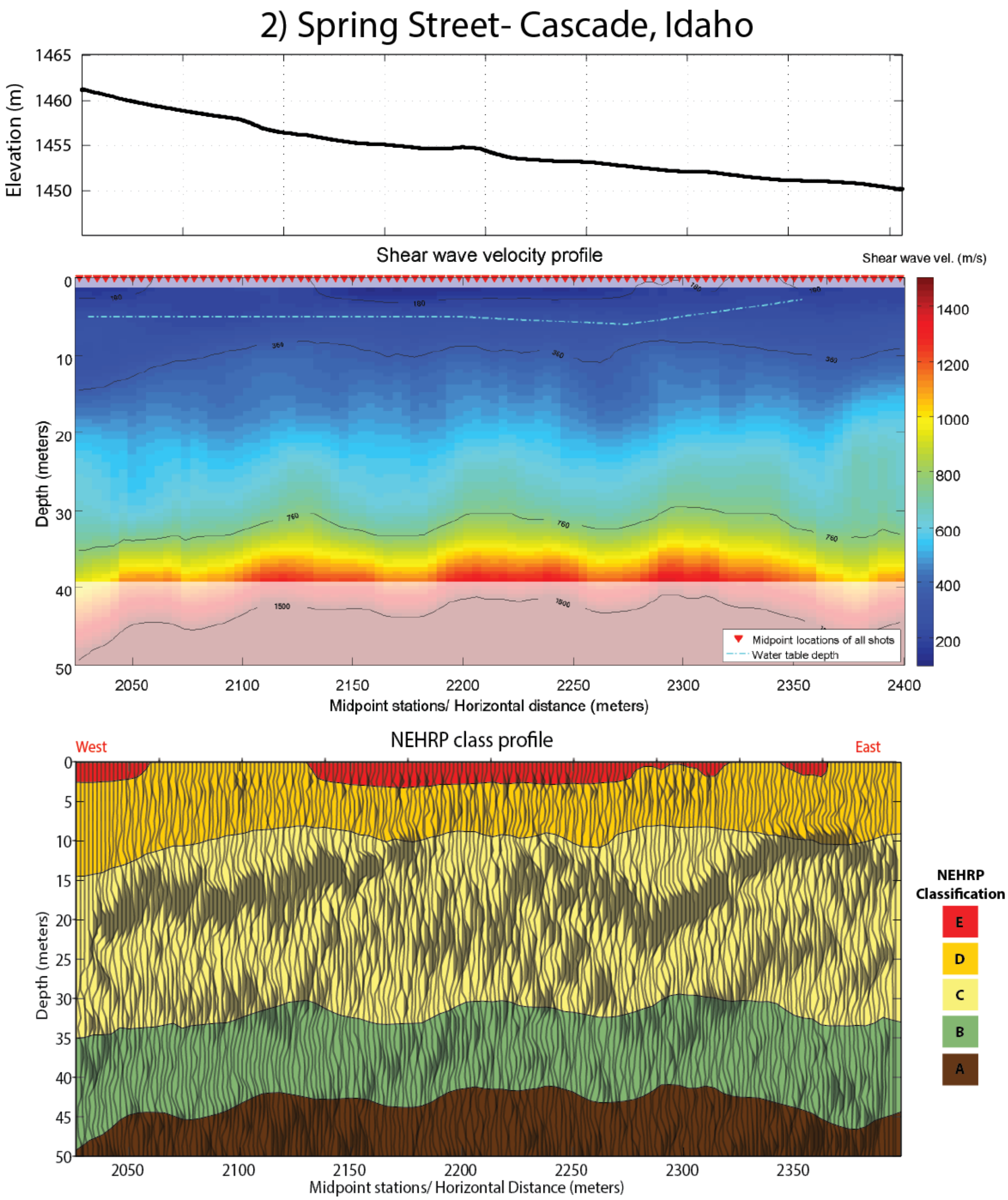

Figure 41. (top) Elevation profile for the Spring Street profile. (middle) Shear wave velocity profile erved from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~3:1.

3) Lefever Drive (Medical Center) (south-north)

Old State Hwy north to residence (76 m length, 19 shots)

The Lefever Drive profile begins at the intersection of Old State Highway, proceeds north passed the Medical Center (position 3020-3050 m) and extends up a gravel road residential hill (Figure 36). The first source location was at the gravel road transition at the north end of the Medical Center parking lot. The profile sits upon Quaternary alluvium at the very south end of the profile and Quaternary colluvium (Qcg) beneath the remainder of the profile. The gravel road increases in elevation by 6 m from the south end to north end of the profile. Shear wave velocities were derived from Rayleigh wave dispersion picks from 19 weight drop seismic shot gathers.

Land streamer seismic data along Lefever Drive in Cascade resulted in clear first arrivals for first break p-wave refraction picks to approximately 10 m depth and confident surface wave dispersion curve picks to 50 m depth (Figures 42 and 43). P-**wave** seismic velocities for the upper few meters range from 400-450 m/s, consistent with NEHRP Class D/E unconsolidated soil. We estimate the depth to water saturated velocities (>1,500 m/s) at 8-9 m depth. Shear wave velocities for the upper 1-3 m range from 170-210 m/s (NEHRP class D/E). We measure Class E soft soil within the upper few meters for the southern end of the profile and Class D stiff soil for most of the upper 10-18 m depth. We estimate 20 m of Class C soft rock starting at 20 m depth along the southern portions of the profile and at 5 m depth along the northern portions of the profile. Rock (Class B) is measured below 40-45 m depth and we estimate the presence of hard rock below 50 m depth along the northern portion of the profile. The prominent reflector shown

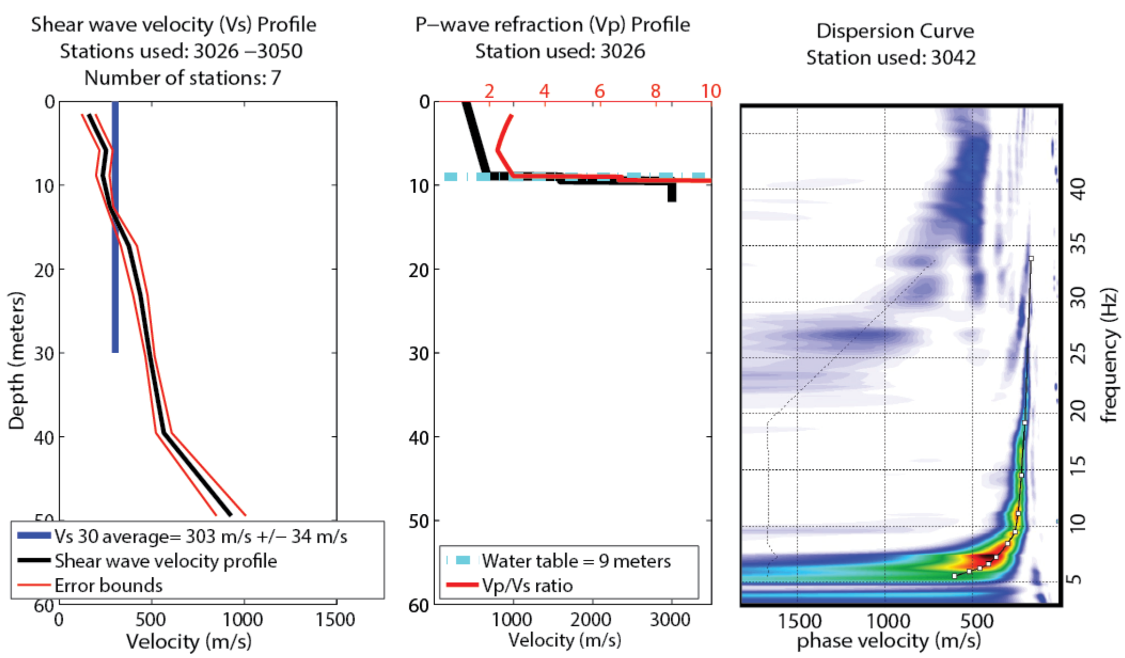

Figure 42. (left) Shear wave velocity profile and average VS30 calculation for the Lefever Drive (Medical Center) profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 49 m.

on figure 43 suggests a slightly steeper dip to the bedrock surface. This discrepancy is likely related to low sensitivity surface wave picks and the bedrock reflection surface may be more accurate.

We extracted average shear wave and p-wave velocity values between stations 3026-3042 (near the Medical Center) where we calculate an average Vs30 velocity of 303 m/s (NEHRP Class D2). We estimate the water table at a depth of 8 m at this location and a Vp/Vs ratio that ranges from approximately 4-10.

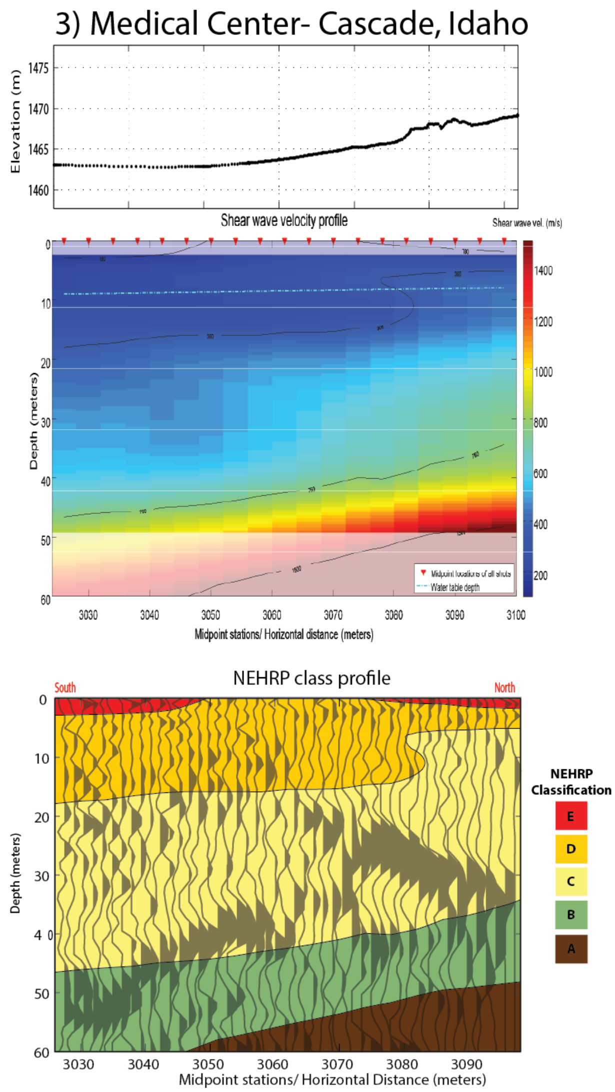

Figure 43. (top) Elevation profile for Lefever Drive (Medical Center) profile. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zone. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~2:1.

4) Front Street (southeast-northwest)

Mill Street to Spring Street (630 m length, 156 shots)

The Front Street profile is located approximately 90 m east of Hwy 55 (North Main Street) in Cascade. This southeast-northwest profile begins at the intersection of West Mill Street, crosses Kirby Street (position 4100 m), Payette Street (position 4210 m), Cascade Street (4320 m), Market Street (position 4430 m) Pine Street (4540 m), and terminates at the intersection of Spring Street. This 630 m gravel road profile transitions to an asphalt surface at position 280 m and sits upon Quaternary alluvium. The profile changes in elevation by less than 1 m. Shear wave velocities were derived from Rayleigh wave dispersion picks from 155 weight drop seismic shot gathers.

Land streamer seismic data along Front Street in Cascade resulted in clear first arrivals for first break p-wave refraction picks to approximately 6 m depth and confident surface wave dispersion curve picks to 37 m depth (Figures 44 and 45). P-**wave** seismic velocities for the upper few meters range from 500-950 m/s, consistent with NEHRP Class D unconsolidated soil. We estimate the depth to water saturated velocities (>1,500 m/s) at 2.5-6 m depth. Shear wave velocities for the upper 1-3 m range from 300-400 m/s (NEHRP class C/D). We measure Class D stiff soil along much of the profile and Class C soft rock for most of the upper 20-30 m depth. Rock (Class B) is measured below 20-30 m depth and we estimate the presence of hard rock below 40 m depth along the length of the profile. The rugged bedrock topography may have

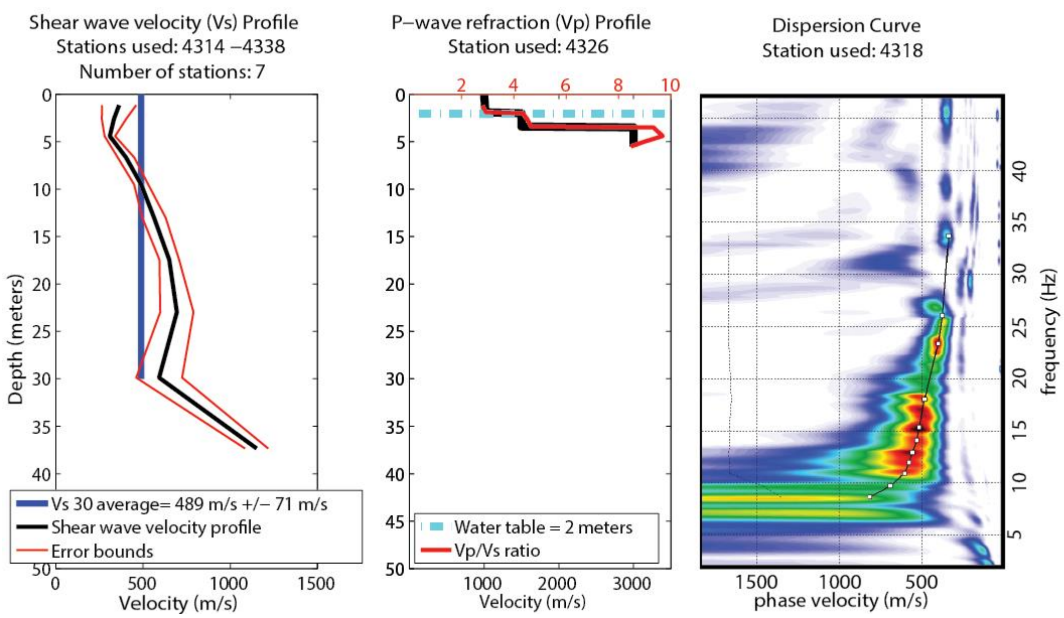

Figure 44. (left) Shear wave velocity profile and average VS30 calculation for the central portion of the Front Street profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 38 m.

resulted from erosion of the bedrock surface. However, this surface approaches our low confidence depth zone that resulted from from poor velocity control at very low frequencies.

We extracted average shear wave and p-wave velocity values between stations 4310-4340 (near the profile center) where we calculate a Vs30 velocity of 489 m/s (NEHRP Class C1). We estimate the water table at a depth of 3 m at this location and a Vp/Vs ratio that ranges from approximately 4-10.

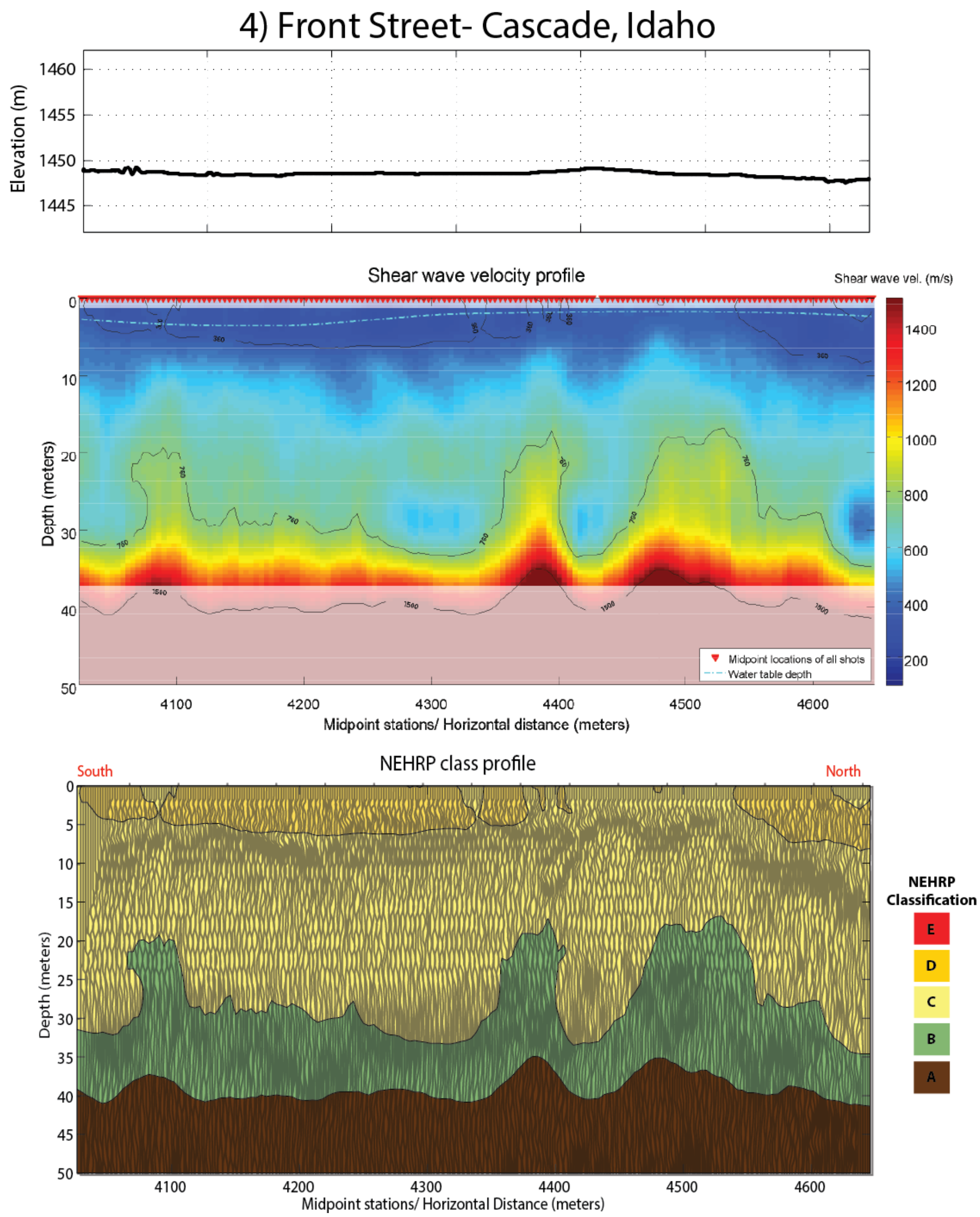

Figure 45. (top) Elevation profile for the Forest Street profile. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~5:1.

5) Sewage Ponds (northwest-southeast)

Park gravel road adjacent to baseball diamond (150 m length, 31 shots)

The Sewage Pond profile is a short gravel road profile located west of the Cascade sewage treatment ponds along an access road to a city park and baseball diamond. The east to west profile terminates at Hwy 55 (North Main Street sits upon Quaternary alluvium. The profile changes in elevation by less than 1 m. Shear wave velocities were derived from Rayleigh wave dispersion picks from 31 weight drop seismic shot gathers.

Land streamer seismic data along Sewage Pond profile in Cascade resulted in clear first arrivals for first break p-wave refraction picks to approximately 7 m depth and confident surface wave dispersion curve picks to 29 m depth (Figures 46 and 47). P-**wave** seismic velocities for the upper few meters range from 300-400 m/s, consistent with NEHRP Class E unconsolidated soil. We estimate the depth to water saturated velocities (>1,500 m/s) at 2.8 m depth. Shear wave velocities for the upper 1-3 m range from 160-180 m/s (NEHRP class E). We measure Class D stiff soil below 5 m depth down to 20-25 m depth. We estimate 5-10 m of Class C soft rock below 20 m depth. The high velocity knob at position 5105 is likely related to velocity insensitivity at a depth that approaches our low confidence region. Rock (Class B) is measured below 35 m depth and we map hard rock below 45 m depth, estimated with low confidence data.

We extracted average shear wave and p-wave velocity values between stations 5026-5050 (near the sewage ponds) where we calculate an average Vs30 velocity of 256 m/s (NEHRP Class D2).

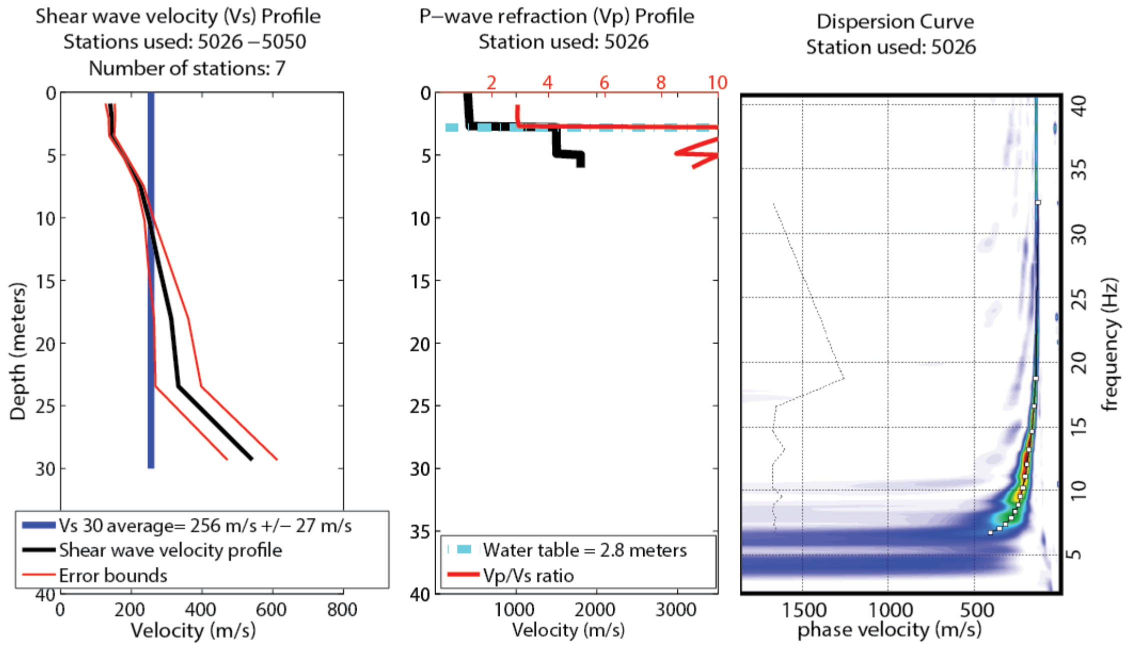

Figure 46. (left) Shear wave velocity profile and average VS30 calculation for the Sewage (city Park) profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 30 m.

We estimate the water table at a depth of 3 m at this location and a Vp/Vs ratio that ranges from approximately 4-10.

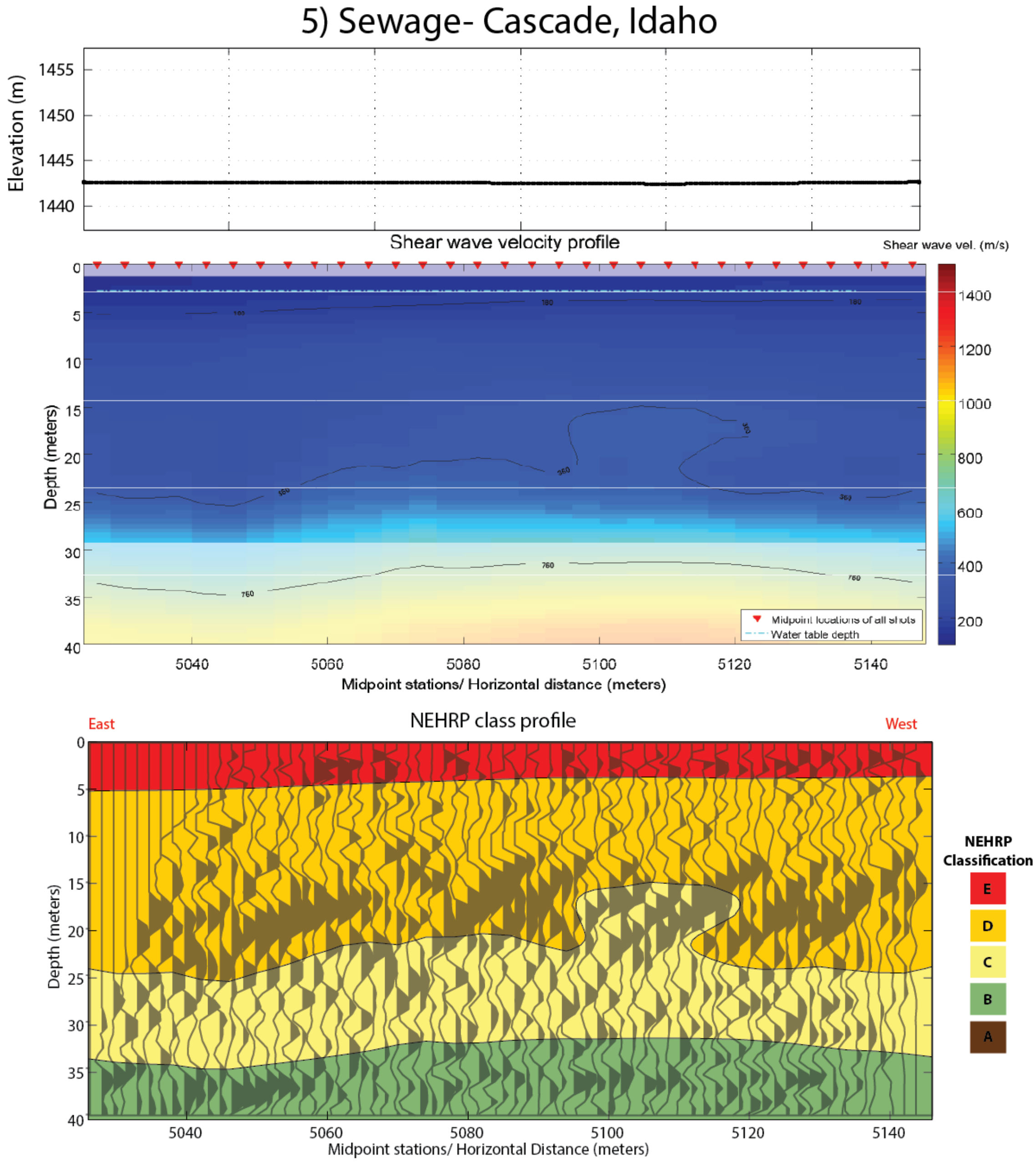

Figure 47. (top) Elevation profile for the Sewage pond access road profile. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~1:1.

6) Alzar School (southeast-northwest)

school entrance (140 m length, 35 shots)

The Alzar School profile begins at the Alzar school entrance gate along a gravel road and proceeds 140 m to the north. This south to north profile lies immediately west of the Cascade airport and immediately east of the Payette River upon Quaternary alluvium. The profile changes in elevation by less than 1 m and lies 3-4 m above Payette River level. The profile changes in elevation by less than 1 m. Shear wave velocities were derived from Rayleigh wave dispersion picks from 35 weight drop seismic shot gathers.

Land streamer seismic data along Alzar School profile in Cascade resulted in clear first arrivals for first break p-wave refraction picks to approximately 7 m depth and confident surface wave dispersion curve picks to 25 m depth (Figures 48 and 49). P-**wave** seismic velocities for the upper few meters range from 400-600 m/s, consistent with NEHRP Class D/E unconsolidated soil. We estimate the depth to water saturated velocities (>1,500 m/s) at 4 m depth. Shear wave velocities for the upper 1-3 m range from 160-180 m/s (NEHRP class E). We measure Class D stiff soil below 3 m depth down to 23-25 m depth. We estimate approximately 10 m of Class C soft rock below 20 m depth. Rock (Class B) is estimated below 35 m depth, estimated with low confidence data.

We extracted average shear wave and p-wave velocity values between stations 6082-6106 (near the profile center) where we calculate an average Vs30 velocity of 237 m/s (NEHRP Class D1).

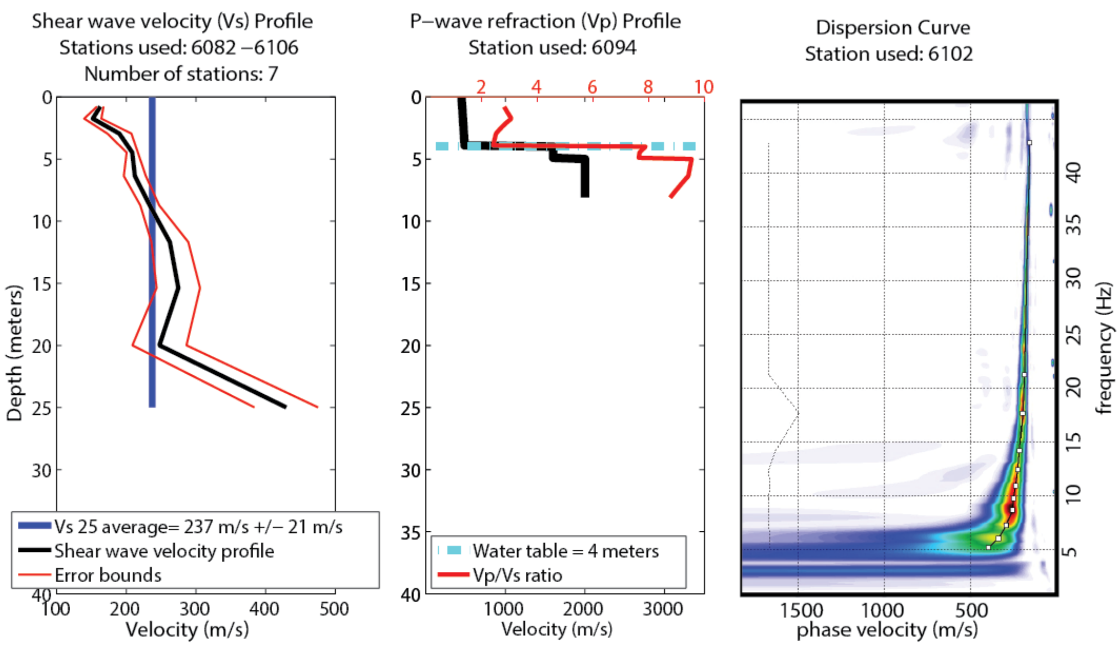

Figure 48. (left) Shear wave velocity profile and average VS30 calculation for the central portion of the Alzar profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 25 m.

We estimate the water table at a depth of 4 m at this location and a Vp/Vs ratio that ranges from approximately 4-10.

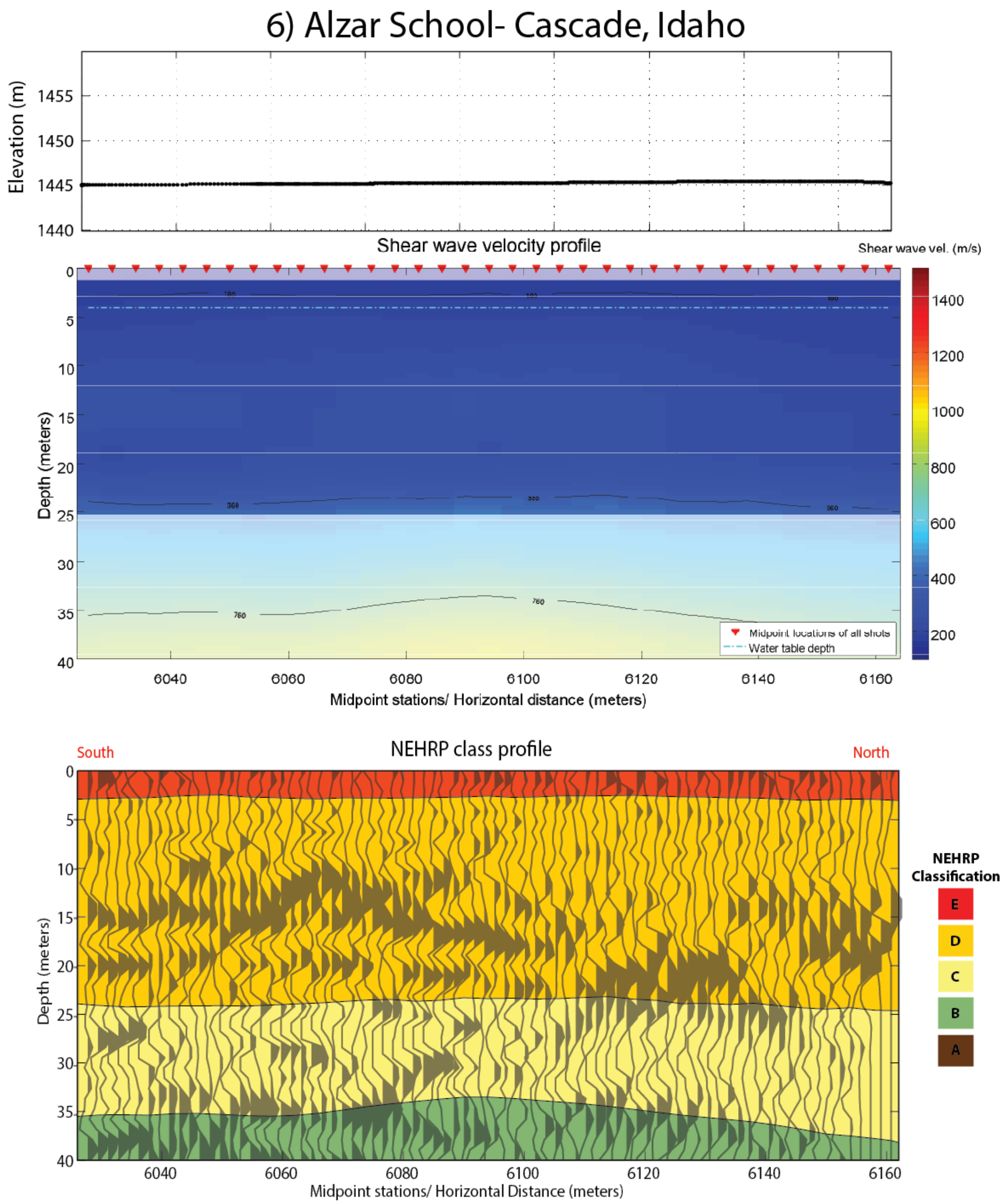

Figure 49. (top) Elevation profile for the Alzar Street profile. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~1.5:1.

Remote Valley County site response

1) Stonebreaker Road (W-E) – (850 m length)

The Stonebreaker Road profile is located on a rural road north of Cascade and immediately east of Cascade Reservoir. Granitic bedrock exposures related to the Idaho Batholith are exposed to the south and east of this profile and this profile location lies at the very southern end of the Long Valley graben (Figure 2). The profile begins immediately east of the reservoir and terminates at Hwy 55. The profile sits upon Holocene and Pleistocene alluvium and colluvium with an along profile elevation change of approximately 12 m (Figure 51).

Land streamer seismic data along the Stonebreaker profile resulted in clear first arrivals for first break p-wave refraction picks to approximately 12 m depth and confident surface wave dispersion curve picks to 50 m depth (Figures 50 and 51). P-**wave** seismic velocities for the upper few meters range from 400-700 m/s, consistent with NEHRP Class D/E unconsolidated soil. We estimate the depth to water saturated velocities (>1,500 m/s) at 3-9 m depth with the greatest water table depth beneath the high topography region near the western portion of the profile. Shear wave velocities for the upper 1-3 m range from 170-200 m/s (NEHRP class D/E). We measure Class D stiff soil below 2 m depth down to 10-20 m depth. We estimate approximately 30 m of Class C soft rock below 10-20 m depth. Rock (Class B) is estimated below 20-40 m depth, with a shallower depth to Class B rock beneath the high topography area.

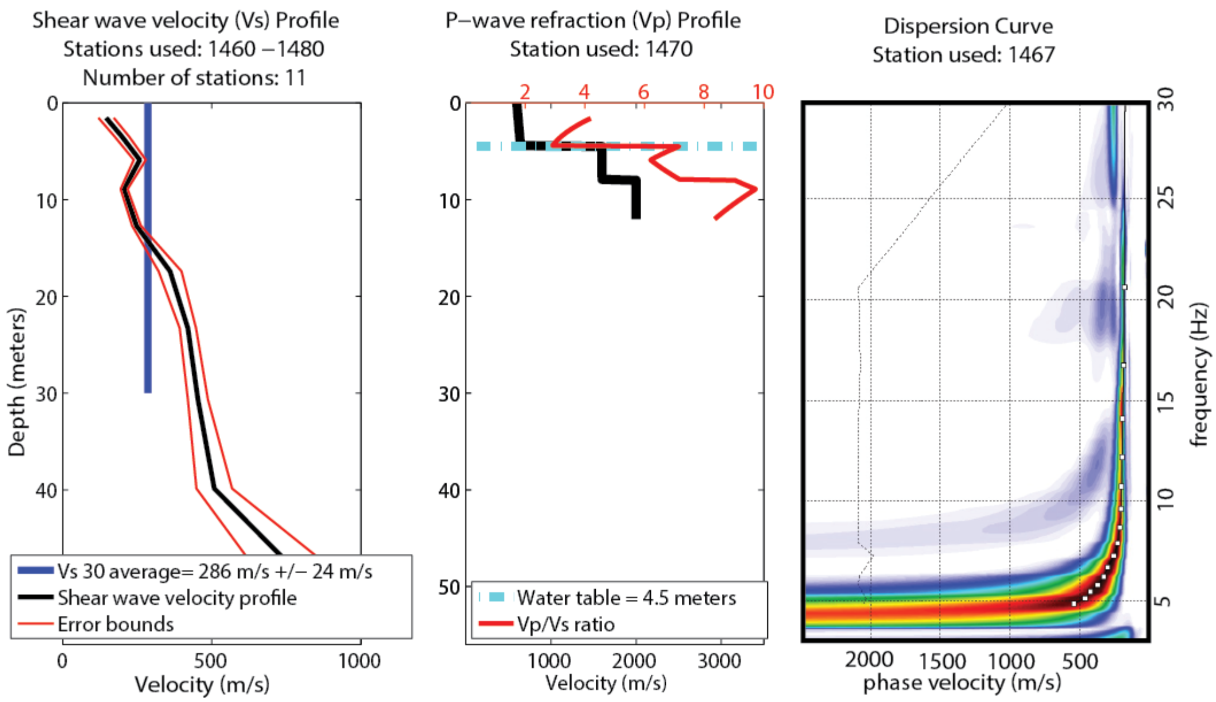

Figure 50. (left) Shear wave velocity profile and average VS30 calculation for the central portion of the Stonebreaker profile. (middle) P-wave, Vp/Vs ratio and water table depth measurement for the central portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 25 m.

We extracted average shear wave and p-wave velocity values between stations 1460-1480 (near the profile center) where we calculate an average Vs30 velocity of 286 m/s (NEHRP Class D1). We estimate the water table at a depth of 4.5 m at this location and a Vp/Vs ratio that ranges from approximately 3-10 (Figure 50).

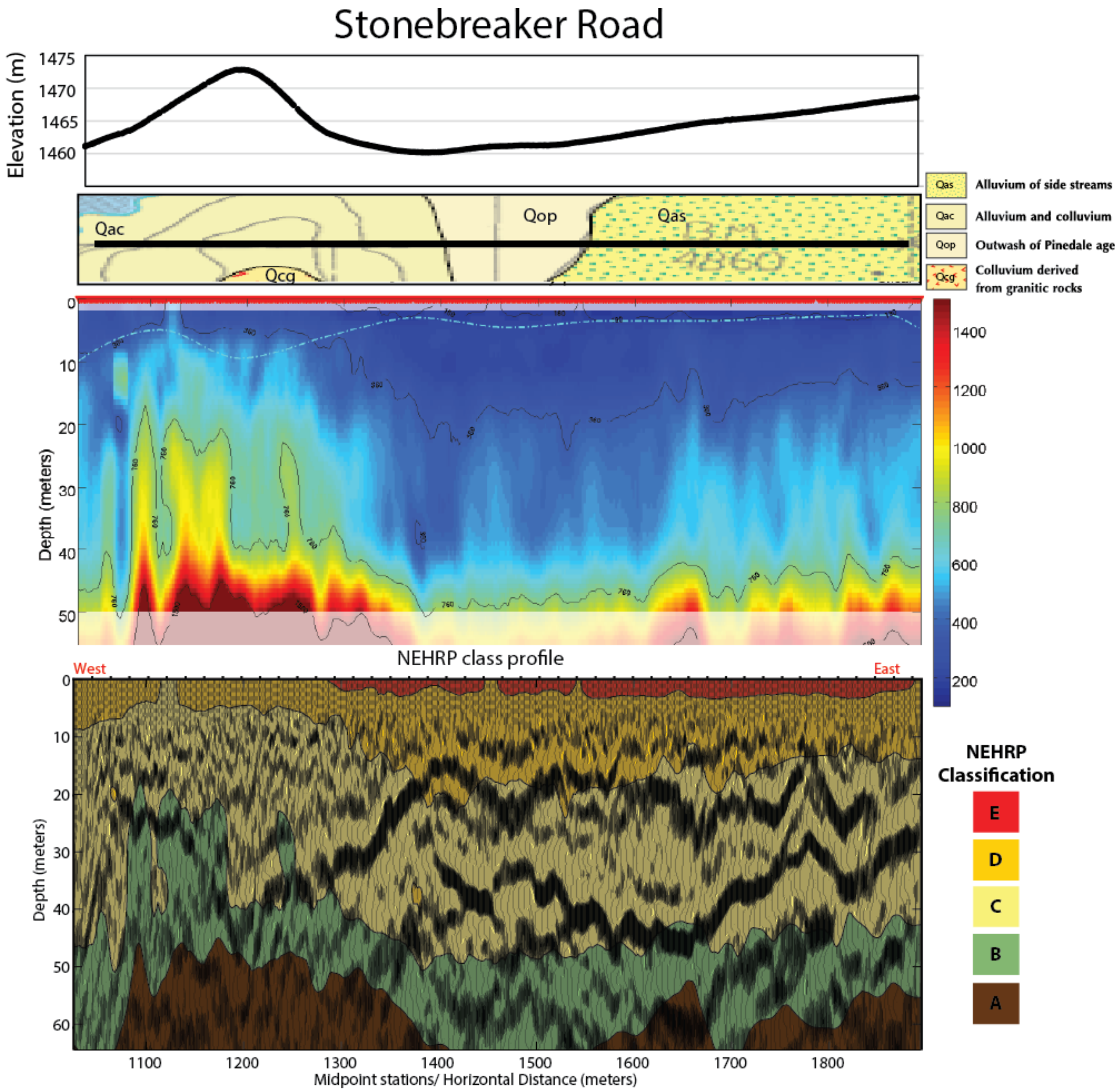

Figure 51. (top) Elevation profile for the Stonebreaker Road profile. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~5:1.

We identify two prominent reflectors from the reflection data (Figure 51). The upper reflector likely represents the transition from stiff soil to soft rock (Class D/C boundary) and is consistent with the shear wave velocity boundary along the eastern portions of the profile. The deeper reflector, between 30-50 m depth, likely represents depth to competent bedrock. Although this reflector is shallower than the interpreted bedrock transition derived from shear wave velocities, this bedrock shallowing to the east is consistent with bedrock-derived colluvium that appears immediately east of Hwy 55 (Breckenridge and Othberg, 2006). This deeper reflector shallows to approximately 20 m depth below the topographic high near the western limits of the profile, consistent with a shallowing of bedrock-derived colluvium that is mapped along this same hill a few hundred meters to the south.

2) Smylie Lane (W-E) – (1060 m length)

In 2003, a Boise State team acquired a one km long seismic reflection profile along Smylie Lane, northwest of Donnelly, Idaho to place an exploratory geothermal well (Liberty and Squires, 2003). This west to east profile extended from bedrock exposures of West Mountain, across the projected location of the Long Valley fault, to the Payette River (Figure 2; Figure 52). Although surface wave data are not viable for shear wave analysis due to the acquisition geometry, the shape of depth of bedrock and overlying stratigraphy is clearly visible from the reflection image.

The Smylie Lane seismic profile begins near exposures of granite-derived colluvium (Qcg) (Figure 52) that we interpret as NEHRP Class A/B rock. A reflector associated with this contact surfaces at the very western edge of our seismic profile and shows a near constant 32 degree dip to the east. This bedrock surface transitions to a flat-lying reflector to the east of West Mountain Road at the presumed location of the Long Valley fault. Above the bedrock surface, we interpret the near flat-lying strata below 100 m depth as Class C soft rock related to paleo lake deposition (often described as blue clay in well logs). This pattern of flat lying reflectors suggests the bedrock surface was shaped prior to sediment deposition (likely Quaternary strata). Although this is a disruption of sediment reflectors in the upper few hundred meters below land surface, no significant reflector offsets suggests that the Long Valley fault that separates flat lying from dipping bedrock has shown little late Quaternary motion. It is possible that a parallel strand of this fault appears to the east of our profile, but no surface fault expression is evident to the east of Payette River.

Because this seismic survey was focused on basin-scale targets, we did not obtain a clear image of shallow stratigraphy from the upper 100 m. We presume that the surface geologic map reflects the shallow stratigraphy where alluvium (Qamo) derived from the Payette River (NEHRP class D/E) occupy the eastern portions of this profile. Given the shallow water table identified from nearby wells (Idaho Department of Water Resources database), we presume that the region near the Payette River may experience local ground amplification and possible liquefaction during a large earthquake.

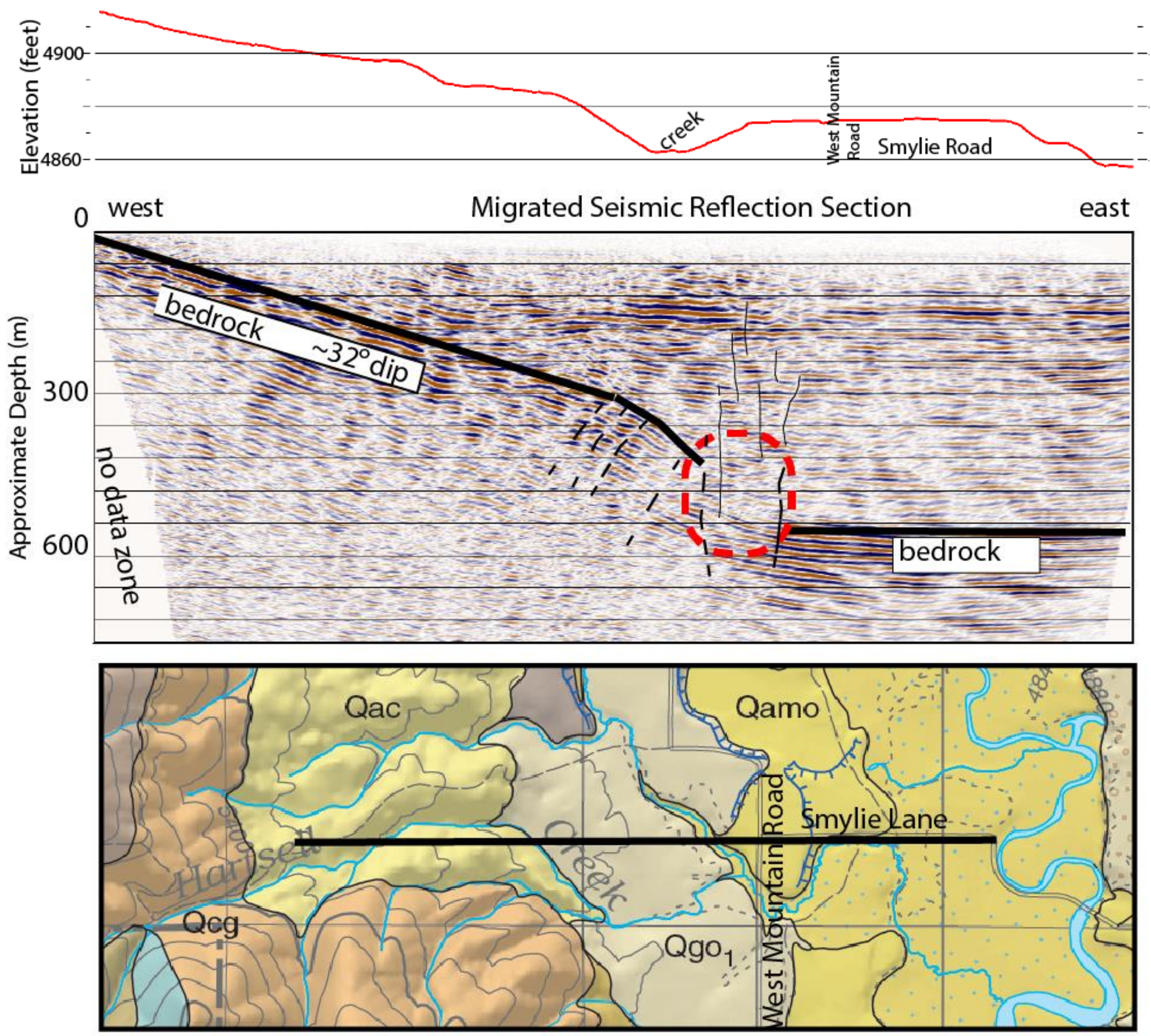

Figure 52. Smylie Road seismic reflection profile, elevation profile, and geologic map (from Breckenridge and Othberg, 2006). The profile location is shown on Figure 2 and our analysis shows a transition from a steeply dipping bedrock surface to a flat surface. The depth to bedrock is approximately 600 m along the eastern portion of the profile. Seismic profile vertical exageration ~2:1.

3) Tamarack Resort (S-N) – (140 m length)

In 2004, a Boise State team acquired seven km of seismic reflection data along four profiles on and adjacent to Tamarack Resort property in Valley County, Idaho (Bradford et al., 2004; Figure 2; Figure 53). The primary objective of the survey was to map the contact between sediments and the underlying granitic bedrock and to identify faults that may be conduits for cold or warm water flow. We identified a well-defined, continuous horizon that we interpret as the sediment/bedrock contact. We found that generally the sediment/bedrock interface forms an approximately planar surface that dips ~10° - 11° degrees in the rangeward direction and ~ 2° - 3° toward the north. The greatest granitic bedrock depth (NEHRP Class A) was found just north and west of the current Tamarack Resort facilities. At this location, the bedrock reflector appears to be truncated against the primary range front fault termed the southern segment of the Long Valley fault (Personious and Lewis, 2010). The west dipping bedrock surface contradicts the modeled results from gravity data (Giorgis et al., 2006; Figure 2). This discrepancy is largely related to the sparse gravity measurements in the vicinity of Tamarack. We presume that a local Tamarack basin depocenter is controlled by a range-bounding southern segment of the Long Valley fault system and that a horst block is located beneath Cascade Reservoir. This interpretation is consistent with the shallow bedrock interpreted on the Stonebreaker profile that is located east of the reservoir and approximately 8 km southeast of Tamarack Resort. This

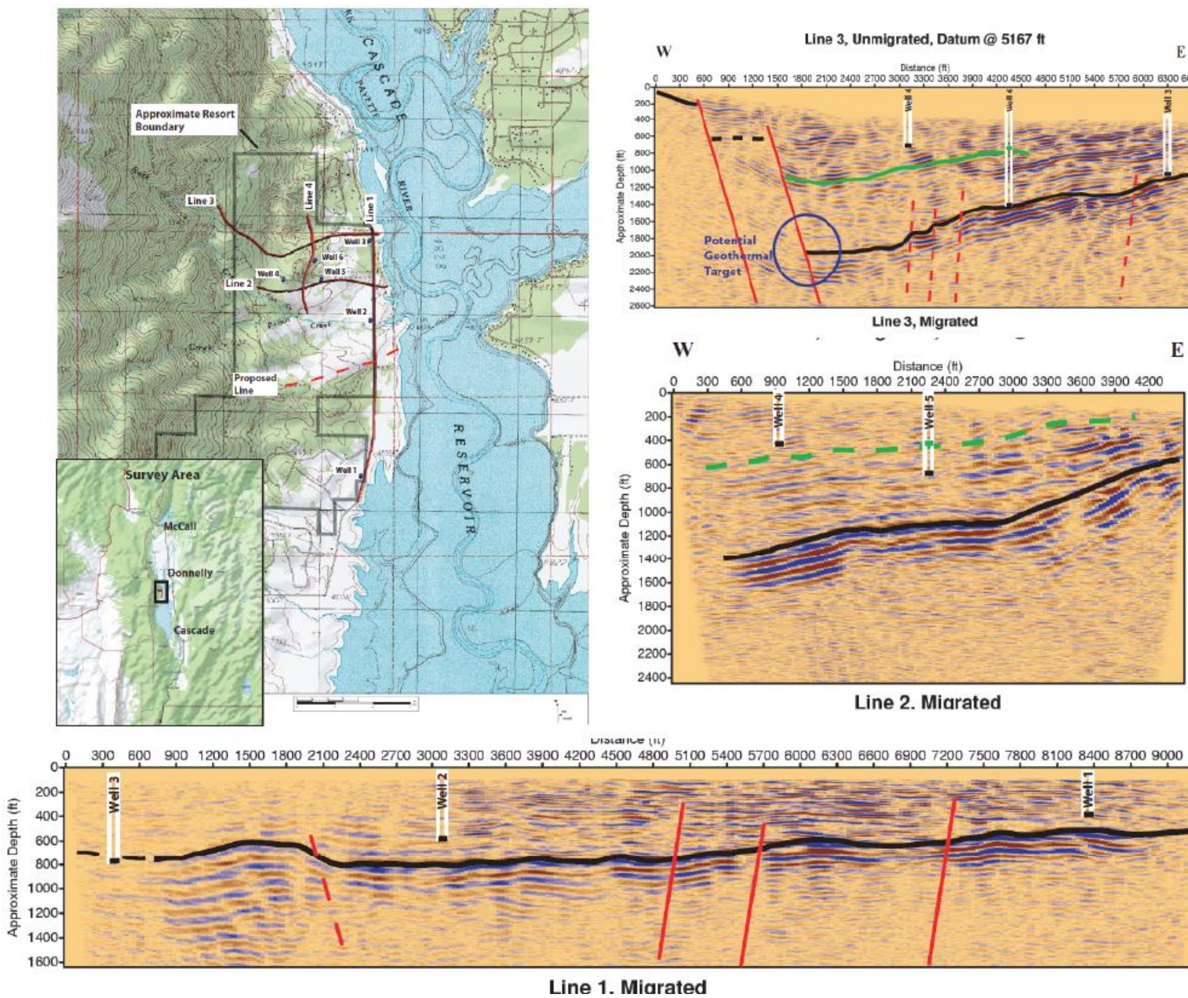

Figure 53. Seismic images and map for the 2004 Tamarack seismic project (Bradford et al., 2004). Our results show a west-dipping bedrock surface that is truncated by the southern segment of the Long Valley fault (Personious and Lewis, 2010). The north to south Line 1 profile (bottom) suggests that bedrock deepens to the north and that west-east faults may segment Long Valley. Seismic profile vertical exageration ~1:1.

interpretation is also consistent with the gravity model shown on Figure 2 where the northern segment of the Long Valley fault system bisects long Valley immediately north of Tamarack.

We presume that the reflectors overlying the bedrock surface consist of NEHRP Class C soft rock related to Quaternary paleo-lake deposits (contemporaneous with the reflectors observed on the Smylie Lane profile). These reflectors are truncated by the Long Valley fault, suggesting late Quaternary fault motion. These truncated reflectors were not seen on the Smylie Lane profile, suggesting more recent fault activity along this segment of the Long Valley fault. As with the Smylie Lane profile, the seismic acquisition geometry precluded a detailed surface wave analysis to estimate near surface lithology. However, drillers logs from the area document sand, clay and rock in the upper 100 m, consistent with Class B/C lithologies.

Conclusions

This report summarizes new and existing active source seismic measurements for Valley County, Idaho. We obtained approximately seven km of new seismic data to map the shear wave velocity distribution down to 30-50 m depth. These shear wave velocity values relate to soil and rock type and this lithologic distribution can be used to estimate local earthquake site response. Additionally, we provide estimates of depth to saturated sediments along each profile via a seismic refraction approach. The p-wave refraction measurements provide a key component to liquefaction susceptibility during ground shaking. Lastly, we present reflection profiling that show the character of the underlying stratigraphy. Our results show that the Valley County areas that lie along the Payette River contain the slowest average shear wave seismic velocities to a depth of 30 m (Vs30). Much of McCall and Cascade that is located away from the Payette River flood plain (as mapped by Breckenridge and Othberg, 2006) contains faster Vs30 seismic velocities when compared to the profiles adjacent to the river. These faster seismic velocities are due to shallow bedrock and colluvium derived from the Idaho Batholith granite.

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References

Bradford, J.H., Liberty, L.M. and Squires, E. (2004). Imaging shallow stratigraphy and bedrock at Tamarack Resort using shallow seismic reflection, 21 p., http://cgiss.boisestate.edu/Techreports/CGISS_04_01.pdf

Boore, D. M. (2004). Estimating Vs (30)(or NEHRP site classes) from shallow velocity models (depths< 30 m). *Bulletin of the Seismological Society of America*, 94(2), 591-597.

Breckenridge, R.M. and Othberg, K.L., Surficial geologic map of Long Valley, Valley County, Idaho, 1:50,000, 1 sheet, 2006.

Building Seismic Safety Council (BSSC) (2001). NEHRP recommended provisions for seismic regulations for new buildings and other structures, 2000 Edition, Part 1: Provisions, prepared by the Building Seismic Safety Council for the Federal Emergency Management Agency (Report FEMA 368), Washington, D.C.

FEMA 222A (1994). NEHRP recommended provisions for the development of seismic regulations for new buildings, 1994 edition, Part 1 – provisions, Federal Emergency Management Agency, 290 pp.

Giorgis, S., McClelland, W., Fayon, A., Singer, B. S., & Tikoff, B. (2008). Timing of deformation and exhumation in the western Idaho shear zone, McCall, Idaho. *Geological Society of America Bulletin*, 120(9-10), 1119-1133.

Giorgis, S., Tikoff, B., Kelso, P., & Markley, M. (2006). The role of material anisotropy in the neotectonic extension of the western Idaho shear zone, McCall, Idaho. *Geological Society of America Bulletin*, 118(3-4), 259-273.

Hardage, B. A., DeAngelo, M.V., Murray, P.E., and Sava, D. (2011). Multicomponent seismic technology, *Society of Exploration Geophysicists*, Geophysical References Series 18, Tulsa, OK, DOI: 10.1190/1.9781560802891, 336 p.

Inazaki, T. (1999). Land Streamer: a new system for high-resolution s-wave shallow reflection surveys: Ann. Symp. Environ. Engin. Geophys. Soc. (SAGEEP) Expanded Abstracts.

International Code Council (2009). The 2009 International Building Code, equation 16-40, page 342, International Code Council.

Joyner, W. B., and Boore, D. M. (1988). Measurement, characterization, and prediction of strong ground motion, Recent Advances in Ground-Motion Evaluation, edited by J. L. Von Thun, American Society of Civil Engineers, New York, pp. 43–102.

Liberty, L.M. (2011). Hammer seismic reflection imaging in an urban environment, *The Leading Edge*, v. 30, no. 2, doi:10.1190/1.3555324.

Liberty, L.M. and Pratt, T.L., Structure of the eastern Seattle fault zone - New insights from seismic reflection data, *Bulletin of the Seismological Society of America,* v. 98, no. 4, 2008.

Liberty, L.M. and Squires, E. (2003). Seismic Reflection Imaging Across the Johnson Ranch, Valley County, Idaho, CGISS Technical Report 03-04, 9, http://cgiss.boisestate.edu/Techreports/CGISS_03_04.pdf

Louie, J. (2001). Faster, better: shear-wave velocity to 100 meters depth from refraction microtremor arrays, *Bulletin of the Seismological Society of America*, 91, 2, pp. 347–364.

Miller, R.D., C.B. Park, K. Park, and R.F. Ballard (2003). A 2-C towed geophone spread for variable surface conditions: Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP 2003), San Antonio, Texas, April 6-10.

Park, C.B., Miller, R.D., and Xia, J. (1999). Multichannel analysis of surface waves, *Geophysics*, 64, 800–808.

Pelton, J. R. (2005). Near-surface seismology: Surface-based methods. Near-Surface Geophysics: Investigations in Geophysics: Tulsa, Oklahoma, Society of Exploration Geophysicists, 219-263.

Personius, S.F., and Lewis, R.S., compilers, 2010, Fault number 628b, Long Valley fault zone, southern section, in Quaternary fault and fold database of the United States: U.S. Geological Survey website, http://earthquakes.usgs.gov/hazards/qfaults

Pugin, A., Larson, T. and Phillips, A. (2002). Shallow high-resolution shear-wave seismic reflection acquisition using a land-streamer in the Mississippi River floodplain: potential for engineering and hydrogeologic applications, *Symposium on the Application of Geophysics to Engineering and Environmental Problems* (SAGEEP) proceedings.

Pugin, A., Pullan, S.A., and Hunter, J.A. (2009). Multicomponent high-resolution seismic reflection profiling, *The Leading Edge*, v. 28, pp. 1248-1261.

Sprenke, K. F., Stickney, M. C., & Peterson, J. L. (2007). The 2005 Alpha Earthquake Swarm, Valley County, Idaho. Idaho Geological Survey.

Stephenson, W.J., Louie, J.N., Pullammanappallil, S., Williams, R.A., and Odum, J.K., 2005, Blind shear-wave velocity comparison of ReMi, and MASW results with boreholes to 200 m in the Santa Clara Valley: Implications for Earthquake Ground Motion Assessment, *Bulletin Seismological Society of America*, v. 95, n. 6, p. 2506-2516.

Stephenson, W.J., Hartzell, S., Frankel, A.D., Asten, M., Carver, D.L. and Kim, W.Y. (2009). Site characterization for urban seismic hazards in lower Manhattan, New York City, from microtremor array analysis, *Geophysical Research Letters*, 36, L03301, doi:10.1029/2008GL036444.

Van der Veen, M. and Green, A.G., 1998. Land streamer for shallow data acquisition: evaluation of gimbal-mounted geophones. *Geophysics*, 63, 1408-1413.

Van der Veen, M. Spitzer, R., Green, A.G., and Wild, P., 2001. Design and application of a towed land-streamer for cost-effective 2D and pseudo-3D shallow seismic data acquisition. *Geophysics*, 66, 482-500.

Wells, D. L., & Coppersmith, K. J. (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bulletin of the Seismological Society of America*, 84(4), 974-1002.

Yilmaz, O. (2001). Seismic Data Analysis: Processing, Inversion, and Interpretation of Seismic Data, Society of Exploration Geophysicists, Tulsa, Oklahoma, 2027 pp.