# Development of land streamer technologies for estimating shear wave velocities in an urban environment

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## Abstract

We designed, built, and tested a 48-m multi-component seismic land streamer to simultaneously and rapidly acquire a variety of surface and body wave measurements along urban city streets. In this report, we describe our seismic land streamer construction, field implementation and data processing. We describe 2-component and 3-component seismic data that were obtained by dragging a seismic source and streamer behind a vehicle. Reflection and surface wave data quality from the land streamer is comparable to traditional geophone plant surveys, but data acquisition rates are significantly faster.

Our body wave analysis shows that ray bending from the high velocity asphalt layer requires the use of vertical and radial components to optimally extract high frequency p-wave reflection and refraction information. Our three-component geophone configuration also allows us to analyze mode converted and pure shear wave reflection signals through component rotation and to observe the complete wavefield signals from active and passive seismic recordings. Because the road material provides a constant high velocity surface medium, the emergent body wave ray angle allows us to more confidently distinguish and separate surface and body wave signals when compared to single component data. While the longer wavelength surface waves may be less sensitive to a thin high velocity near surface layer, we utilize radial and vertical component measurements to optimize Rayleigh wave dispersion information for shear wave velocity inversion and to identify the spectral ratio between horizontal and vertical signals. This multi-component land streamer system design allows us to employ multiple techniques to extract subsurface physical properties for earthquake site response and fault mapping studies.

## Introduction

Land streamer technology has gained an increase in interest and use for the past 15 years for shallow seismic applications. 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 (e.g., e.g., Inazaki, 1999; Pugin et al, 2002, Miller et al., 2003; Van der Veen and Green, 2001; Figure 1). Land streamers using 3-component geophones are now being built within the near surface seismic community 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). To date, there has been little use of seismic land streamer for earthquake hazard analyses. Here, we focus on urban hazard mapping along existing city streets with the use of a land streamer. We focus on extracting shear wave velocity information to obtain Vs30 measurements (or deeper) along crossing and parallel profiles, p-wave reflection imaging of the upper 100 m (or deeper) to identify faults, stratigraphic signature, and hard boundary information, and p-wave refraction information to obtain depth to water table or other velocity boundaries to obtain shallow Vp/Vs ratios for liquefaction and physical property estimates for the upper few meters below land surface. We first describe our seismic

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streamer design and integration with a variety of seismic sources. We then present results from a number of field studies where we examine the benefit of radial component inclusion in both surface and body wave analysis for a number of communities within western Idaho. We show that a 2-component approach to both multi-channel surface wave (MASW) and reflection analysis can improve our signal quality and provide an improved confidence in the separation of surface and body waves in near surface data and we can extract additional information to improve earthquake site characterization.

## Approach

### *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. 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.

### *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.

# Seismic land streamer methods

### *Seismic streamer design*

Seismic land streamers borrow on the idea of marine seismic systems. We tow a seismic source and streamer behind a vehicle to obtain seismic velocity, refraction, and reflection information in profile. Although marine streamers are towed continuously and immediately below the water surface to record signals with pressure sensors or hydrophones, our land-based system utilizes motion sensor ground-coupled geophones where the vehicle must stop before obtaining a seismic reading. The seismic land streamer concept allows for faster acquisition of seismic data compared to traditional land-based surveys because geophones are not manually planted, leveled or oriented (shear wave sensors). Field deployment time is only a few minutes and point measurements can occur every few seconds. Additionally, the fixed geometry of the receivers relative to the source allow us to obtain real-time positioning and geometry information via GPS to quickly analyze the data. An added benefit to data acquisition along city streets is the uniform near surface velocity layering from the road foundation and relatively smooth surface that minimize static corrections that can degrade seismic reflection and refraction results. Additionally, this uniformity leads to more consistent source and receiver coupling. Our current streamer design that was constructed at Boise State University consists of 48 geophone-mounted
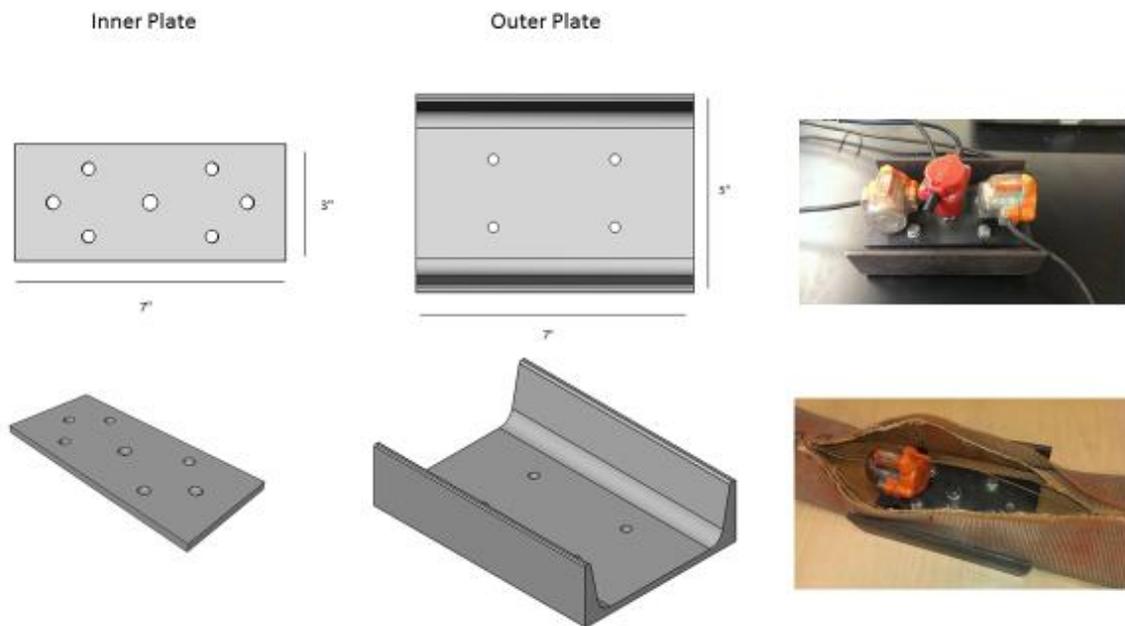


**Figure 1. Boise State multi-component land streamer constructed using recycled fire hose and steel. Channel steel wraps around the fire hose to protect the geophones and the fire hose protects the seismic cables that interface with a recording system housed in the towing vehicle. Our streamer supports up to 3 geophones per shoe to allow for full active or passive seismic wavefield imaging.**

shoes spaced one meter apart (Figure 1). These shoes are interconnected by recycled fire hose that acts as a structural support to house and protect geophone cables. The number of geophones within a land streamer, and the length of the streamer, is generally limited by the practical concerns of operating along urban city streets.

The individual base plates are constructed of four inch wide channel steel that couples geophones to the ground as well as provides a smooth surface for the streamer to slide along a city street (Figure 1). A steel plate that sits inside the fire hose bolts to the channel steel and fixes the geophone shoe to the fire hose. These inner plates are drilled and tapped, allowing for the mounting of up to three individual geophones. Each shoe weighs approximately three pounds, allowing for adequate ground coupling to provide data quality similar to spiked geophones (e.g., Van der Veen and Green, 1998; Inazaki, 2004). We cover each shoe with PVC protect the geophones and their connections from any undue wear and tear. The geophone make and model, and receiver orientation is flexible. Currently, we house three 4.5 Hz geophones with Kooter clips within our streamer (vertical, in-line and cross-line) to utilize both surface and body wave information.

### 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 multi-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 that are permanently mounted and oriented, and a hammer source offers an opportunity to provide a more comprehensive analysis of subsurface properties.

### Multi-component seismic land streamer signal quality

We have tested our land streamer on a number of paved and gravel road surfaces using a variety of seismic sources (Figure 2; Gribler and Liberty, 2014a; Liberty and Gribler, 2014). We

find results similar to previous studies (e.g., Van der Veen and Green, 1998; Inazaki, 2004) showing the signal quality from a land streamer is comparable to geophone planted results. To date, we have focused much of our land streamer work to obtain high quality p-wave refraction, p-wave reflection and surface wave signals (Figure 2).
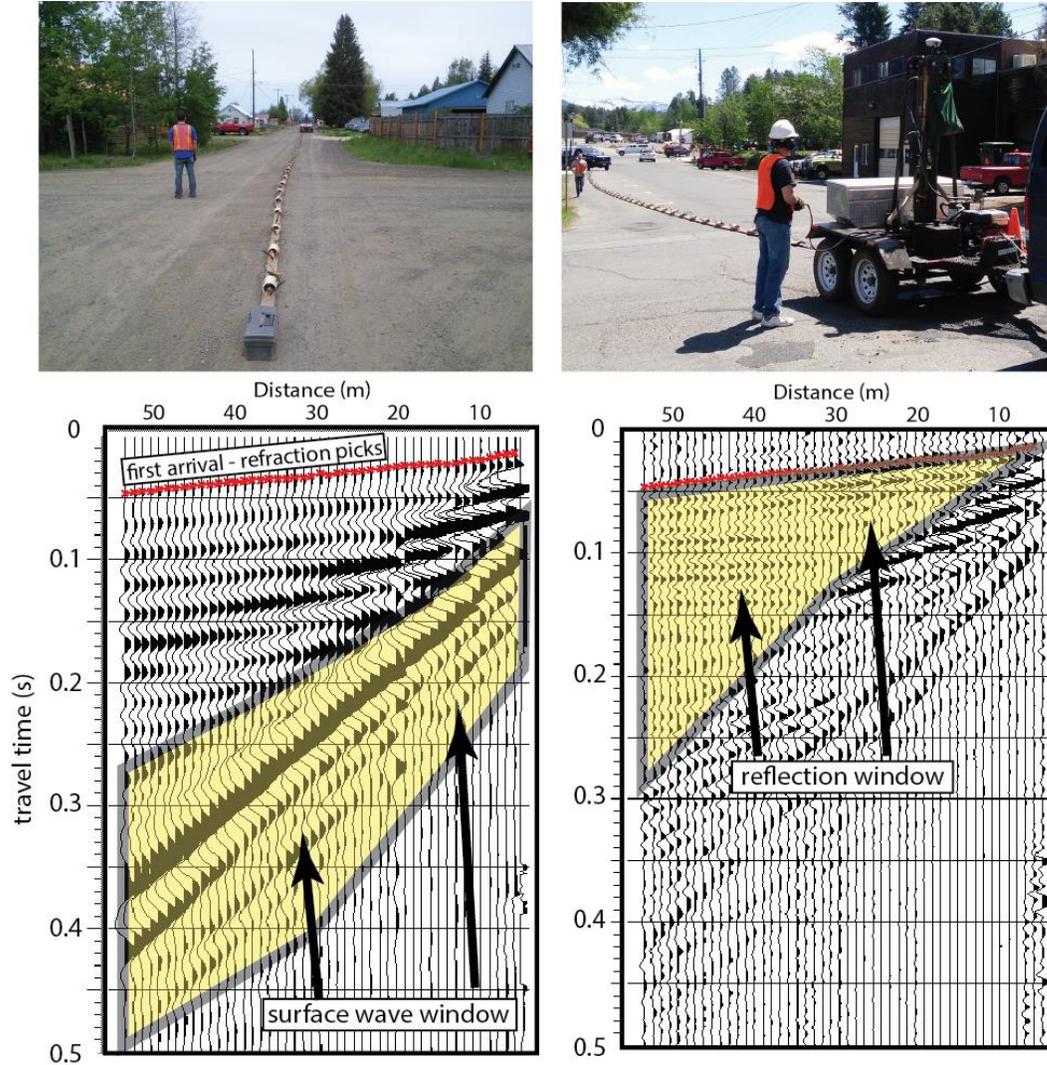


**Figure 2. (top) Seismic land streamer with seismic accelerated weight drop source during acquisition in Donnelly (gravel road) and McCall (paved road), Idaho. (Bottom) Seismic shot gather -unfiltered (left) and high-pass filtered (right) - to emphasize first arrival picks (red stars), p-wave reflections, and surface wave signals.**

Additionally, we have focused on the utilization of both vertical and radial (in-line horizontal) signals to extract additional and more precise subsurface physical property information (Liberty and Gribler, 2014a; b). Figure 3a shows four 48-channel vertical and radial component shot gathers that were acquired along a city street on an asphalt surface. By rotating the seismic wavefield to obtain the maximum signal orientation contained on both the vertical
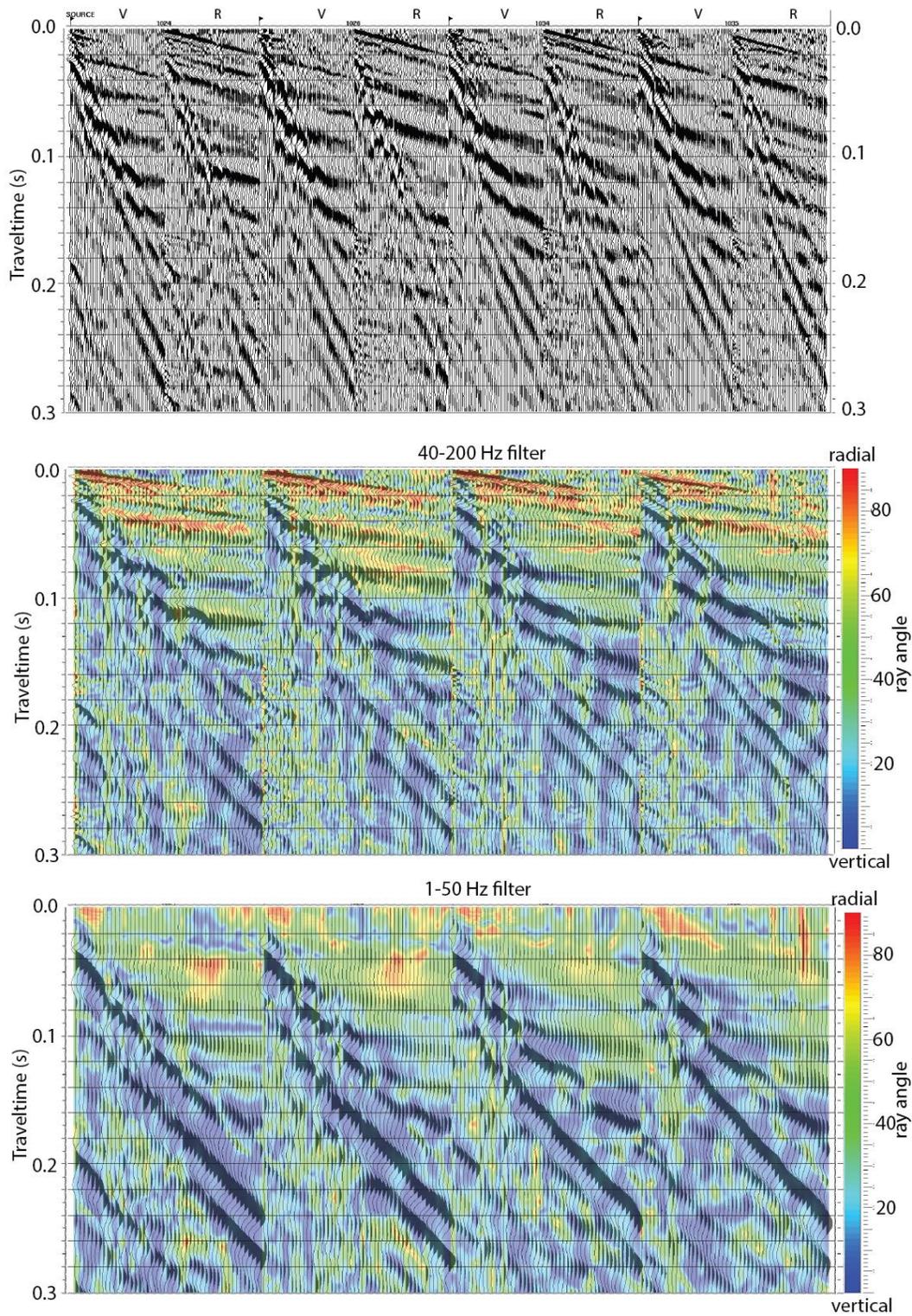
**Figure 3. Top image shows four shot gathers with the vertical (V) and radial (R) components. Middle and bottom images show the rotated shot gathers with the angle of emergence overlaid in color (red all horizontal energy, dark blue is vertical). This is similar to a 2-d hodogram plot.**

and radial components, we capture the maximum energy traveling in line along the profile (Figure 3b) (Thomsen, 2002). Superimposed on these rotated shot gathers, we show the particle motion orientation for each trace in color, comparable to a 2-d hodogram analysis. We perform this analysis for both the high frequency component (Figure 3b) and the low frequency component (Figure 3c). We observe reflected and refracted arrivals (between the surface waves and zero time axis) that include a strong radial component (yellow to red colors) while the lower frequency surface waves (Figure 3c) appear to propagate mostly on the vertical component (blue colors) for these shots. However, Rayleigh wave signals are clearly observed on the radial component (Figure 3a) and can be utilized with our data analysis. For these shots, we measure the p-wave velocity for the asphalt layer at ~2500 m/s. This direct wave is contained mostly on the radial component (red colors on Figure 3b) of the shot gathers due to this high velocity layer overlying slower dry unconsolidated sediments (more coherent first arrivals on the radial component of Figure 3a).  For body waves at wide angles, this high velocity surface layer horizontally bends the p-wave reflections and is captured, in part, on the radial component of the shot gather. This ray-bending phenomenon is frequency dependent since an average city road is only 30-50cm thick, so longer wavelength frequencies are less affected and appear mostly on the vertical component of the seismic wavefield.

With a high velocity asphalt layer at the surface, the higher frequency p-wave refraction and wide-angle reflection signals will typically bend in-line towards the horizontal axis while the low frequency body waves will be mostly unaffected by this thin surface layer. For example, given a 2,500 m/s asphalt surface and 500 m/s unsaturated sediments below the road layer, Snell's law would predict a vertically traveling refraction bent by 79 degrees (orange color first arrival on Figure 3b). This effect is frequency dependent, as the low frequency energy (e.g., 1-50Hz of Figure 3c) is less sensitive to a high velocity thin bed layer when compared to the higher frequency content (e.g., 40-200Hz of Figure 3b) energy. Additionally, by utilizing the emergence angle information, we can more easily separate surface wave and body wave signals that may contain a unique response. For example, note the dominant vertical surface wave signals (blue) compared to more radial signal energy (green to red) for the optimum reflection window on Figure 3b and 3c.

## Surface wave analysis from a land streamer

Using the MASW approach with our land streamer, we can estimate a shear wave velocities for the upper 30-50 meters. The MASW technique utilizes Rayleigh waves to create dispersion curves to measure phase velocity for a range of frequencies (e.g., Park et al., 1999). These phase velocities can be inverted to estimate a shear wave velocity profile (e.g., Xia et al., 1999). Land streamer surface wave work is established within the engineering geophysics community to provide a rapid assessment of shear wave velocities, in profile, for a variety of applications.
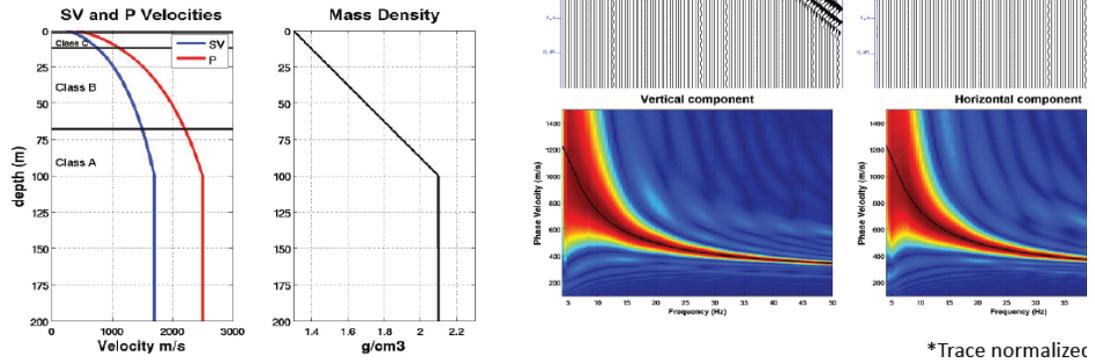
**Figure 4. (right) Synthetic shot gathers and dispersion curves for both vertical and radial signal components for a typical shallow bedrock model (left).**
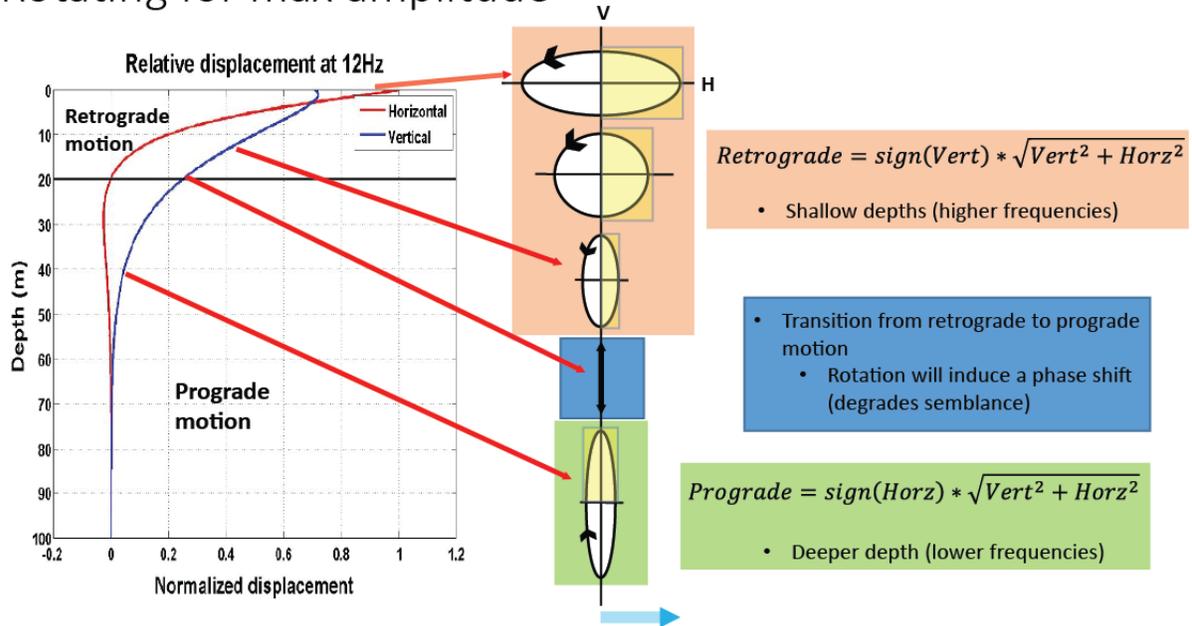
### *Multicomponent Rayleigh wave motion*

For a typical sedimentary basin with a shallow bedrock (Figures 3 and 4), we show a significant Rayleigh wave signal component on the radial (inline) horizontal component (Aki and Richards, 2002). For a vertically oriented source, Rayleigh waves propagate in an elliptical fashion (e.g., Graff, 1975). With two components, one oriented vertically and one in-line horizontal (radial), we are able to capture the entire Rayleigh wave motion from an in-line active source. For a typical near surface velocity distribution, Rayleigh wave motion in the radial direction may represent a significant component of the total signal (Figure 5), especially in the presence of a shallow bedrock layer. By taking advantage of the radial component acquired by our land streamer, we are be able to better constrain our dispersion curve picks which will lead to improved shear wave velocity estimates.

In Figure 6, we extract dispersion curve frequency cross sections for the Figure 4 synthetic model. We show that at higher frequencies (e.g. 15-20 Hz), component rotation of the surface wave signal to account for shallow retrograde (counter clockwise) motion produces larger normalized amplitudes compared to either vertical (green line) or radial (blue line) component signals. Thus, we can improve our dispersion curve pick confidence by utilizing both vertical and radial component signals for these higher frequency (shallow depth) signals (red line). At lower frequencies (e.g. below 10 Hz), it is very difficult to accurately pick the proper phase velocity (black line) from either vertical or radial component signals due to the limited aperture of our receiver spread and the higher velocities with depth (Figure 4). However, by utilizing both the vertical and radial component signals through prograde motion component

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rotation (Figure 5), we improve our low frequency phase velocity picks. Thus, we can improve our shear wave velocity estimates at greater depths with a limited aperture receiver array by assessing the complete Rayleigh wave particle motion.



## Rotating for max amplitude

$$Retrograde = sign(Vert) * \sqrt{Vert^2 + Horz^2}$$

- Shallow depths (higher frequencies)

- Transition from retrograde to prograde motion
  - Rotation will induce a phase shift (degrades semblance)

$$Prograde = sign(Horz) * \sqrt{Vert^2 + Horz^2}$$

- Deeper depth (lower frequencies)

**Figure 5. (left) Fundamental Rayleigh wave particle motion for the vertical (blue) and horizontal (orange) components v. depth for the model shown in Fig. 5. (right) Particle motion shape and direction of motion Note the change from retrograde (counter clockwise) to prograde (clockwise) motion on the radial component at approximately 20 m depth at 12 Hz. Our approach to improving dispersion curve picks is to rotate the signals to retrograde or prograde motion to improve**

# Multicomponent Dispersion
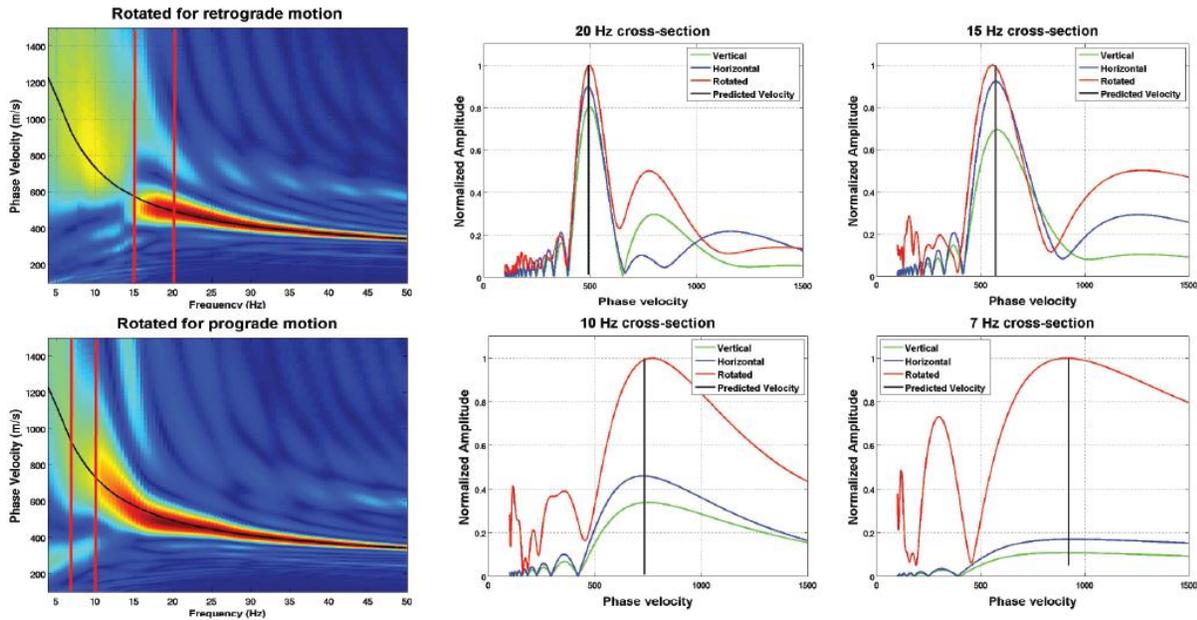


**Figure 6. (left) dispersion curve plots for retrograde (top) and prograde (bottom) motion for the Figure 4 model. Black line represents calculated model dispersion curve and red lines represent cross sections shown at select frequencies. (right) Select cross sections for dispersion curves. Top cross sections are rotated to retrograde (shallow) motion and bottom cross sections are rotated to prograde (deep) motion.**

## *Active Source H/V spectral ratio*

The H/V spectral ratio method was established using strong motion records from ambient noise records (e.g., Nogoshi and Igarashi, 1971). Although this original study did not focus specifically on Rayleigh wave spectral ratios, Rayleigh wave motion within slow velocity shallow sediments propagate with a greater horizontal component of motion compared to faster velocity sediments or bedrock that shows a more circular Rayleigh wave motion (Figure 5). By identifying a peak in the ratio of horizontal (H) to vertical (V) signals, we can estimate the predominant resonant frequency that is related to the average shear wave velocity and sediment thickness. This fundamental site period s a critical measurement for earthquake hazards studies. One down side to the traditional H/V method is that it is unclear from ambient noise records whether the signals represent surface) or body wave energy. By capturing both vertical and radial energy from our active source land streamer data, we can extract the fundamental Rayleigh wave signal and measure the ratio between vertical and horizontal energy to estimate the fundamental site period. The H/V peak will be related to the change in particle motion at the bedrock or other hard boundary interface (Figure 7). Our preliminary results (Gribler and Liberty, 2014b) show great promise in using our seismic land streamer to estimate the site period for shallow bedrock conditions.
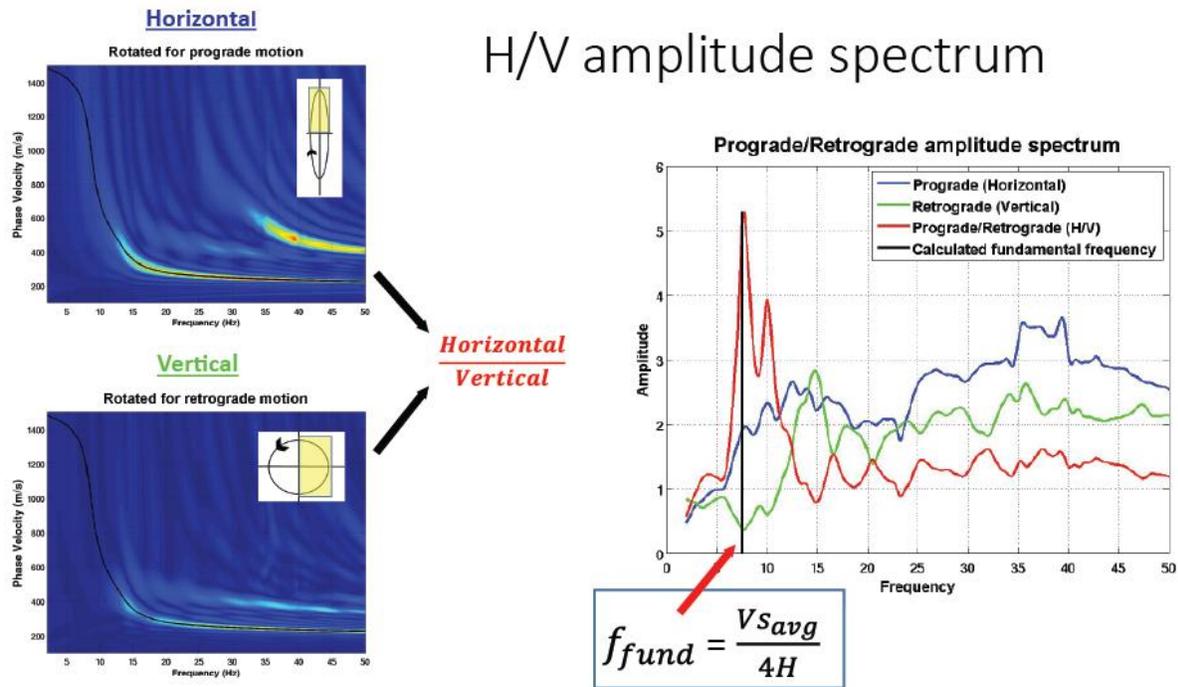
**Figure 7. (left top) prograde signal rotated dispersion curve that emphasizes horizontal energy and (left bottom) retrograde signal rotated dispersion curve that emphasizes vertical energy. (right) The ratio of vertical to horizontal signal showing the greatest peak at the fundamental site period.**

## Land streamer field tests

### *ReMi approach using a seismic land streamer*

We tested a ReMi-style survey (Louie, 2001) using traffic noise to measure surface wave signals to obtain a shear wave velocity profile with depth. The benefit of land streamer ReMi over the traditional approach is the utilization of three component geophones compared to the traditional single sensor deployment to factor source directionality via horizontal component signal rotation. This signal rotation allows for a more accurate phase velocity estimate to improve shear wave velocity values. A second benefit to a land streamer approach to ReMi surveys is the rapid field deployment to acquire many measurements. We can deploy and retrieve the land streamer in a matter of minutes compared to much longer deployment times with a traditionally planted geophone survey with little signal degradation (e.g. Inazaki, 2004). Although we did not perform a robust comparison with established ReMi practices, our initial test results showed great promise in improving ReMi-style data results at greater data collection rates.

### *Hammer p-wave/s-wave/surface wave seismic survey*

We tested a sledge hammer seismic source with our land streamer to examine both surface and body wave signals. This test involved a vertical sledge hammer source to image fluvial and lacustrine deposits of the Western Snake River Plain in Boise, Idaho. Our reflection results are consistent with previous seismic images from the downtown Boise area (Wood, 1994; Liberty, 1998, 2011) and show south-dipping prograding delta sediments below fluvial sands of the Boise River (Figure 8). With a sledge hammer source and our 48-m land streamer, we obtained clear p-wave reflections to 0.15 s or approximately 150 m depth. This survey suggests that the land streamer can adequately reproduce seismic results from planted geophone surveys that focus on shallow depths.

The multi-channel surface wave analysis from this same dataset show shear wave velocities in the upper 30 m that are consistent with stiff soil to soft rock (Vs values between 200-800 m/s; Figure 8). A borehole shear wave survey near the southern portion of this profile (ERB 1110) show similar shear wave velocities compared to our MASW results, consistent with previous method comparisons (e.g., Stephenson et al., 2005). We identify a large shear wave velocity boundary at approximately 18 m depth that is consistent with an increase in shear wave velocities along the MASW profile.

In Figure 8, we integrate the shear wave velocity profile derived from Rayleigh wave inversion with the shear wave reflection profile derived from our multicomponent land streamer. We obtained the reflection image by stacking the component rotated gathers at the shear wave velocities derived from the Rayleigh wave inversion. Shear wave reflections are generated and captured with our land streamer geophones, in part, due to the high velocity asphalt surface bending the shear waves in the same way as our p-wave reflections are bent. We can utilize both the in-line radial and vertical components to capture shear wave reflections. The integrated result can improve the confidence in our site response analysis by including reflecting boundaries into the analysis. In this example, a large amplitude reflector matches the high velocity boundary observed in the ERB 1110 borehole.
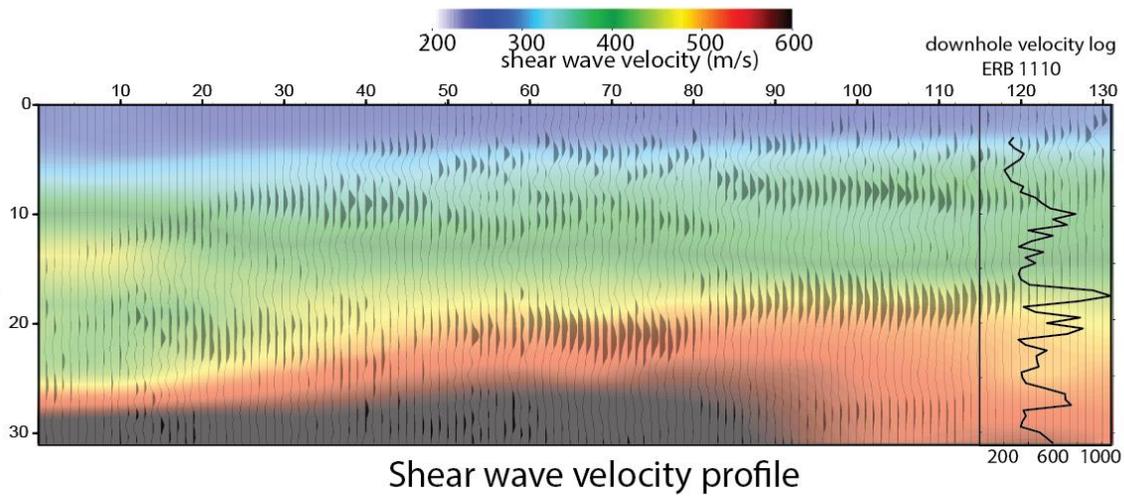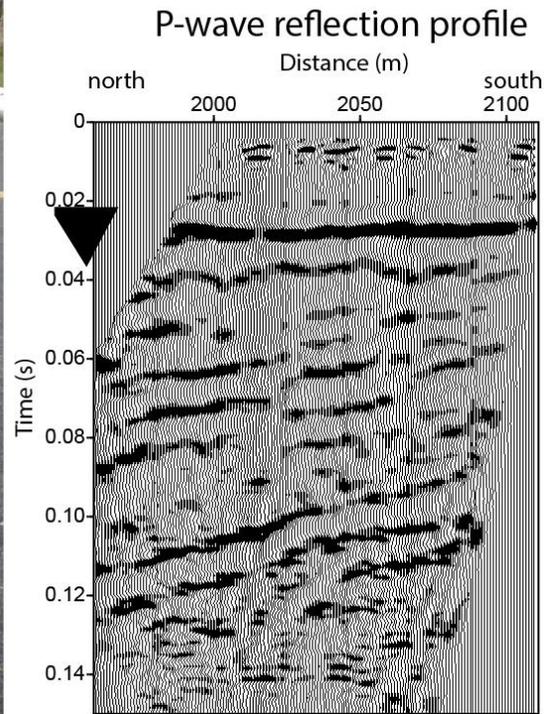
**Figure 8. (top left) Land streamer acquisition within Boise, Idaho. (top right) Reflection profile obtained from the land streamer showing both water table reflector (triangle) and south dipping prograding delta silts and sands from paleolake Idaho (e.g. Wood, 1994). (bottom) Shear wave velocity profile for the upper 30 m derived from Rayleigh wave signals. This figure also shows shear wave reflection results from the land streamer and the shear wave velocities obtained from a nearby borehole (ERB 1110) to compare with our land streamer results.**

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### *Shear wave velocity/p-wave refraction/reflection integration*

To test our land streamer in production mode, we acquired approximately 7 km of land streamer seismic profiling within a series of communities in western Idaho that are prone to earthquake ground shaking (Liberty and Gribler, 2014). For this experiment, we acquired our seismic data using a 200 kg weight drop source (Figure 9) and 48-m two-component land streamer. Seismic data quality were excellent (see Figure 2) using only a single hammer hit along a range of geologic and urban settings. This dataset has allowed us to test our new system and advance our multicomponent surface and body wave land streamer analysis.
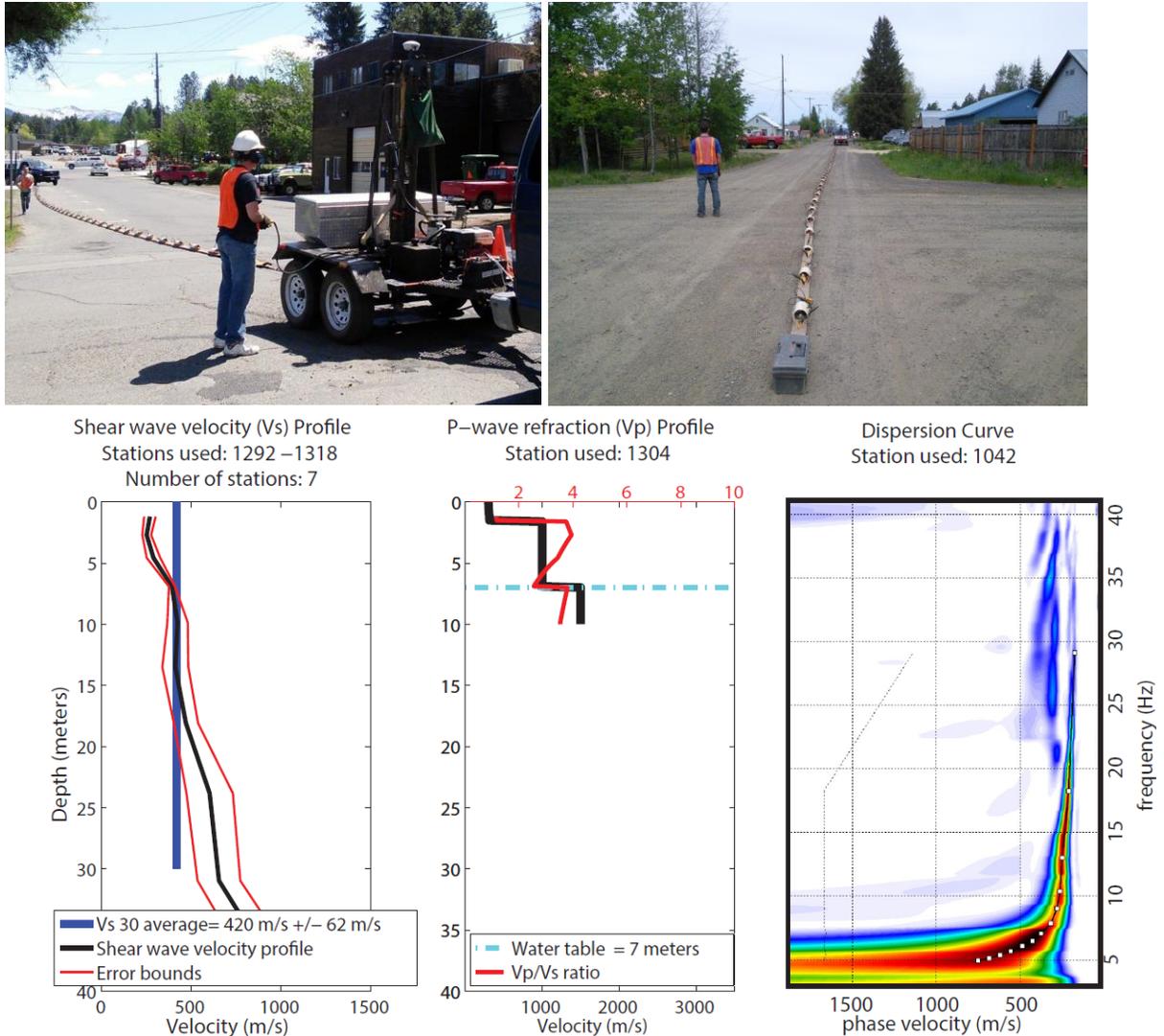


**Figure 9. (top) field photos of land streamer and weight drop source. (bottom) (left) Shear wave velocity profile and average Vs30 calculation for downtown McCall, Idaho. (middle) P-wave, Vp/Vs ratio and water table depth measurement for a portion of the profile. (right) Shot gather derived dispersion curve and phase velocity picks suggesting high confidence results for the upper 40 m.**

We acquired a shot gather every 4 meters along the length of the survey at a production rate upwards of 4 km per day. This dataset produced 6-fold reflection data (0.5 m mid-point spacing), and a refraction and Vs measurement every 4 meters. An increased density of our source spacing would produce higher fold reflection data that may benefit stratigraphic analyses. However, this increased spatial density would result in shorter profile lengths or increased production time. We acquired parallel and perpendicular (crossing) profiles to compare profile information and methodologies. From the surface wave information, we obtained shear wave velocity profiles via MASW methods. We processed the surface wave data with SurfSeis (Kansas Geological Survey) and in-house code for multi-component analysis. Once we calculated shear wave velocities from inversion of Rayleigh wave dispersion curve picks, we converted the velocity information to NEHRP class (Figure 10c) using established shear wave velocity boundaries (BSSC, 2001). We picked first arrival refraction data to identify the cross over distance between slow unsaturated sediments and fast, water sediments to estimate water table depth (Figure 9). We processed the refraction data using in-house refraction software and plotted water table depths on the Vs profile maps (Figure 10b). 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.

The p-wave reflection results helped characterize the stratigraphic framework for each profile. We processed these data using both ProMAX (Landmark Graphics) and Seismic Unix software and integrated these results with the NEHRP class profile images (Figure 10c). Because of the fixed source and receiver geometry, and data collection along a smooth road surface, data processing included filters, top (refraction) and bottom (surface wave) mutes, vertical/radial component rotation to the maximum reflection signal energy, bandpass filter, deconvolution, velocity analysis and post-stack migration.

Example composite velocity and reflection profiles are shown on Figures 10 and 11. Both profiles show strong reflectivity in the upper 50 m that represents fluvial, lacustrine and glacial strata (NEHRP Class C,D,E) that lie above a shallow (40-60 m deep) bedrock (NEHRP Class A) surface.
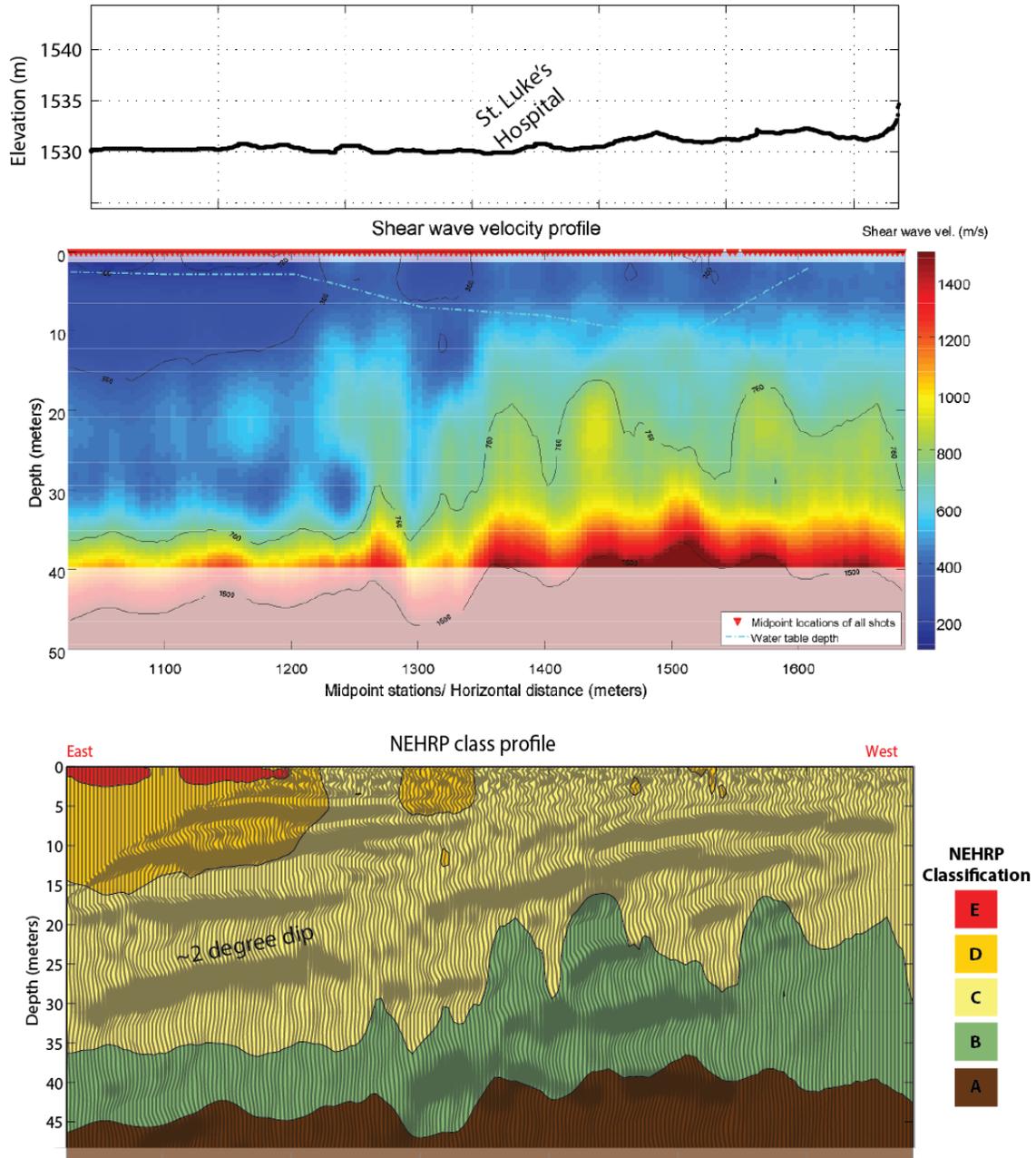
**Figure 10. (top) Elevation profile for the Forest Street profile in McCall, Idaho. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exaggeration ~6:1.**
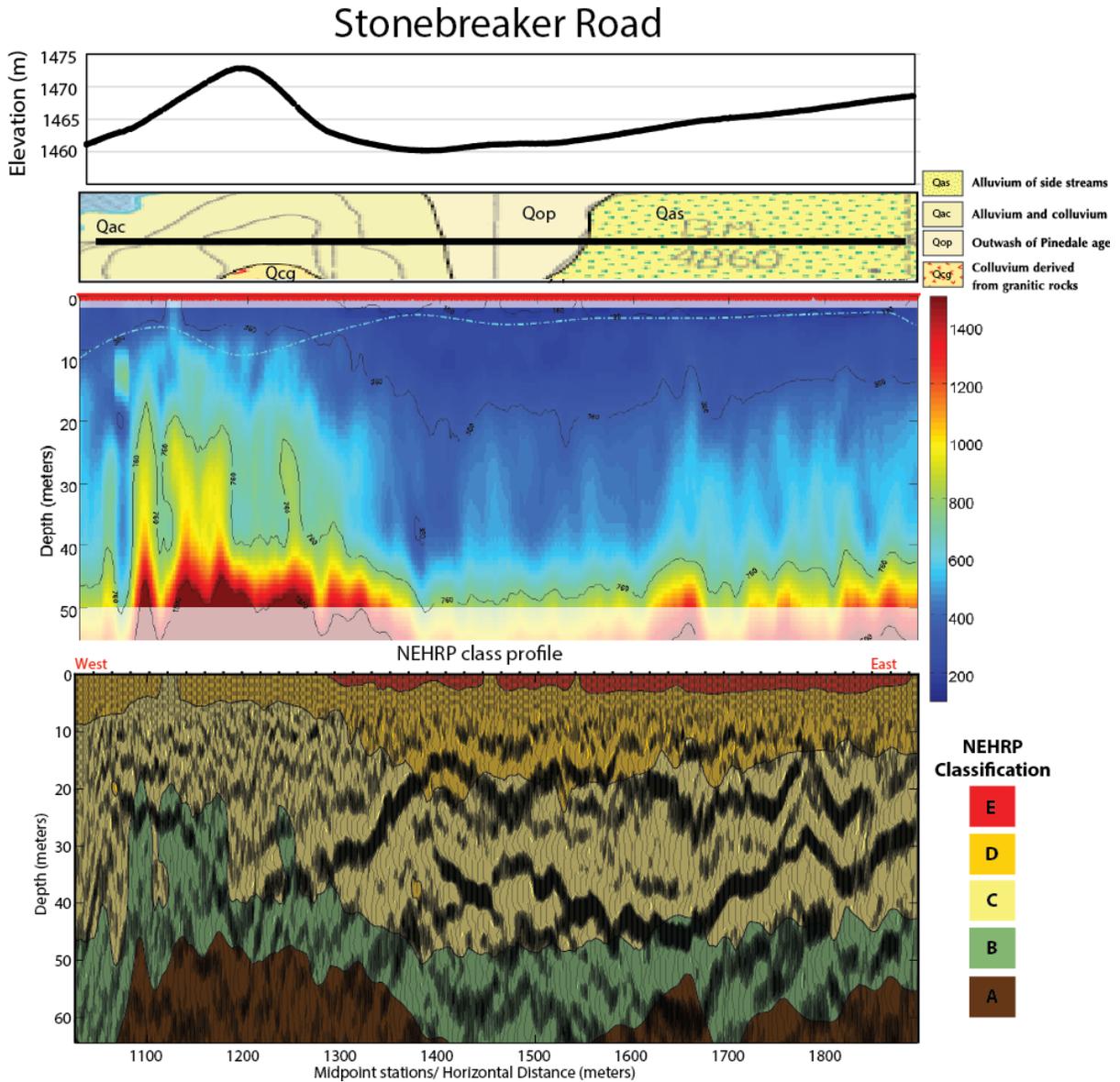
**Figure 1. (top) Elevation profile for the Stonebreaker Road profile near Cascade, Idaho. (middle) Shear wave velocity profile derived from phase velocity picks. Measurement locations are show as red triangles at the top of the plot. Semi-transparent area represents low confidence zones. (bottom) NEHRP class profile with superposition of reflection image. Velocity profile vertical exageration ~5:1.**

## Scientific outcomes, and future land streamer directions

Land streamer results to date include presentations, abstracts, and proceedings papers for SEG and AGU annual 2014 fall meetings (Griber and Liberty, 2014a;b) and 2015 SSA annual meeting abstract is pending. Boise State graduate student (Gribler) is completing his multi-component surface wave thesis and related software for analysis (estimated May 2015 completion). Two manuscripts are currently in-prep from this study. Additionally, we acquired production data sets in numerous western Idaho cities to provide earthquake site response and liquefaction information (Liberty and Gribler, 2014). Collaboration with USGS personnel (W. Stephenson) is planned for FY15 for further testing and land streamer development. Integration with capacitively-coupled resistivity sensors is being explored and USGS NEHRP funding is secured for imaging faults and shear wave velocities along the Wasatch Front. Additionally, we plan to improve upon and build new land streamers for spring deployments.

## Summary

Seismic land streamer methods provide an opportunity to rapidly acquire seismic data along city streets to measure site response, map fault locations and slip histories, and to obtain subsurface boundary conditions for site response constraints. The land streamer with ground-coupled geophone base plates and integrated GPS allows for multi-component data seismic acquisition at a rate many times faster than traditional surveys. For surface wave analysis, while traditional seismic surveys utilize only the vertical component to invert for shear wave velocity information often at a single site, multi-component land streamer data acquisition allows us to capture the complete elliptical Rayleigh wave motion in profile to improve dispersion curve picks both spatially and with depth. Additionally, we can measure spectral ratio information from the fundamental Rayleigh wave mode to improve our estimation of fundamental site period and better constrain shear wave velocity information for the upper 30-50 m depth. The high seismic velocity road surface offers both a challenge and opportunity to measure subsurface seismic body wave properties.

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