MAPPING TOP-OF-BEDROCK AND SOFT-SOIL ZONES BENEATH HIGH-TRAFFIC AREAS USING 2D REMI

Phil Sirles, Zonge Geosciences, Inc., Lakewood Colorado*
JB Shawver, Zonge Geosciences, Inc., Minneapolis Minnesota
Satish Pullammanappallil, Optim, Inc., Reno Nevada
Zoran Batchko, PB Americas, Orange, California

Abstract

Two-dimensional seismic refraction microtremor data were acquired, processed and interpreted for the Honolulu High-Capacity Transit Corridor Project - Waipahu to Aiea - Ewa, Oahu, Hawaii. The objective was to image the *depth-to-bedrock* and determine the lateral and vertical extent of *soft-soil* conditions. Approximately 2.66-line miles (4.28 km) of two-dimensional (2D) refraction microtremor (ReMi) data were acquired along 12 separate lines. Data were acquired along the Farrington and the Kamehameha Highways. Line locations were selected based on a variety of geologic settings and the need for subsurface information between, below and beyond geotechnical borings. Results indicate the seismic and geologic/geotechnical data could be integrated to yield valuable information beneath the area investigated. The 2D seismic survey reveals that basaltic bedrock can be encountered as shallow as 5 feet (1.5 m), to as deep as ~230 feet (70.1 m) beneath the existing highways. Additionally, the seismic survey results provide good information regarding the presence of-, lateral variation of-, and extent of-soft soils.

Introduction

In August 2008, Zonge Geosciences, Inc. (Zonge) conducted a seismic survey under subcontract to Geolabs, Inc. (Geolabs) in the greater Honolulu Hawaii area. Figure 1 outlines the project area, which generally covers from Waipahu on the west end to Aiea on the east end. The seismic investigation was performed under the direction of Robin Lim, Ph.D., P.E., Vice President of Geolabs, as part of the on-going geotechnical investigation.

Objectives of the seismic investigation were two-fold:
1) Determine depth-to-bedrock; and,
2) Determine the lateral variability of the soils deposits.

To meet these two objectives Zonge completed a 2D ReMi survey. Site conditions along this portion of the proposed Honolulu High-Capacity Transit Corridor Project (HHTCP) were very similar where seismic data were acquired in traffic lanes, medians or along sidewalks (*see inset photo*). Line locations were selected depending on crew safety, day of the week, and lane closure/accessibility. Geolabs provided geologic and geotechnical data, in the form of boring logs and shear-wave velocity data, which assisted with the seismic interpretation.

The geologic setting varies considerably over the ~5-mile (8.05 km) survey area. In general, there are overburden soils overlying bedrock. As is case for most of the Honolulu area, boring logs indicate the overburden materials are composed of a complex series of soils that range from coarse-grained, loose to very dense sands and gravels (with cobbles) to fine-grained, very soft to very stiff clays. In addition to this normal range of coarse- and fine-grained soils, interbedded layers of coralline, mudflow or clinker deposits are also present within the overburden. Across the seismic survey area the bedrock is defined as basalt. Outcrops and boring logs indicate that the basaltic bedrock has significant variability in the degree of weathering, the fracture density, and other lithologic characteristics (i.e., vuggy, pillows, etc.). Based on a considerable amount of boring and geotechnical data collected in this area over many years, the depth to bedrock was anticipated to vary drastically across the project site, with no consistent trend (i.e., *a regional 'dip'*).

Figure 1: Project location map showing the area of investigation (red box).

Topographic relief on the bedrock surface is generally attributed to erosional features such as paleo-channels or relief caused at the time the basalt flow was deposited. That is, there can be basalt ridges that exist now because the lava filled an alluvial valley at the time of deposition and the soft materials have eroded away from the lava flow. Subsequently, the subsurface soil/bedrock contact is complex. The water table is typically shallow due to the proximity to the coast, but it can also be quite variable due to the inter-bedded fine-grained soil layers, course-grained (permeable) deposits, and the irregular bedrock surface. Numerous borehole logs identifying soil classification, bedrock lithology, and associated geotechnical properties of the subsurface materials encountered were provided to Zonge for correlation with the seismic data acquired during this investigation.

Purpose and Scope

The primary focus of the seismic survey was to define the soil / bedrock interface (i.e., objective #1); and, to a lesser extent the variability of the near-surface soil deposits. The purpose of the survey was to assess conditions between and below existing geotechnical boreholes. It is intended that results from the geophysical investigation be used in the geotechnical evaluation of the site, and ultimately to aid in the foundation design. The combination of a need for subsurface imaging, the complex geologic setting, and the field conditions of an urban, noisy, heavy traffic site created a unique opportunity to apply a relatively new seismic method. One additional item that relegated the approach proposed is that the seismic method could not be affected by to the presence of shallow groundwater in the soil.

The ReMi field method was selected because it satisfies all the conditions and survey needs described above. ReMi is relatively new, but it is becoming a standard and robust geophysical method for use in urban settings to derive the IBC site classification (Louis, 2001). ReMi is a one-dimensional (1D) '*seismic sounding*' technique that measures passive-surface wave dispersion to determine the shear-wave (S-wave) velocity distribution with depth. The S-wave velocity sounding is obtained below a surface array of standard refraction-type geophones and recording equipment. As will be shown by this paper, the ReMi method is gaining acceptance for other applications beyond the IBC S-wave site classification (i.e., Vs30). In the past two years, Zonge has performed numerous 2D ReMi field programs, which is simply an extension of the 1D field method. The approach has been utilized to image the soil / bedrock interface beneath rivers (i.e., saturated soil conditions where standard P-wave methods do not work) or in urban settings where noisy site conditions prohibit use of refraction, reflection, or active surface-wave (MASW) test methods. Data presented in this paper represents an advanced geophysical technique that has provided substantial value to geotechnical designs for wind energy, power plants, and transportation projects for only the past few years.

Because it was difficult to predict traffic patterns and the need for crew safety was paramount, the location and length of each ReMi line varied. Line lengths were adjusted *on-the-fly* based on access, as dictated by local traffic control, as well as based the need for access to commercial enterprises. Twelve locations were selected for seismic testing, however each line position was not finalized until the field conditions were assessed on a daily basis. Often a line was very short (e.g., Line 9), due to major intersections for example, while other lines were quite long (e.g., Line 4). Approximately 16,800 line feet (5.121 km) of data were acquired split among 12 test locations. Table 1 lists the line number, associated line length, as well as general location.

No line location map was generated because the site covers an area of approximately 5 miles (8.05 km). Independent line maps were generated using Google Earth images which are reasonably accurate; an example is shown on Figure 2. They indicate the general line location and nearby intersections for ease of reference. Geolabs provided these Google Earth images to Zonge for use during this investigation. The images include the ReMi lines and also their geotechnical boring locations are posted. The line numbers generally represent line segments starting at the west end of the survey area, in Waipahu, and continue in a non-continuous fashion to Aiea at the east end near the Honolulu football stadium. Table 1 indicates that in some areas there is nearly continuous line coverage, except maybe a major intersection where safety issues prevented acquiring data. But in most cases, because of the both traffic cones & police control, ReMi lines were able to be pushed continuously through small intersections, turn-outs, turn-arounds, and retail entrances. Note that some of the line segments represent a continuous ‘sounding’ profile. For example, Lines 2, 3, 4 and 5 combine for 5,500 line feet (1.68 km) of continuous 2D soundings. The individual lines were acquired on separate dates that were most appropriate for the specific location. Through the effort of the entire field crew to maintain safety, line coverage varied daily with a minimum line length of 960 feet (293 m), and a maximum line length of 1,960 feet (597.5 m). In general, approximately 1,500 to 1,600 feet (457.2 to 487.7 m) of 2D data were acquired daily.

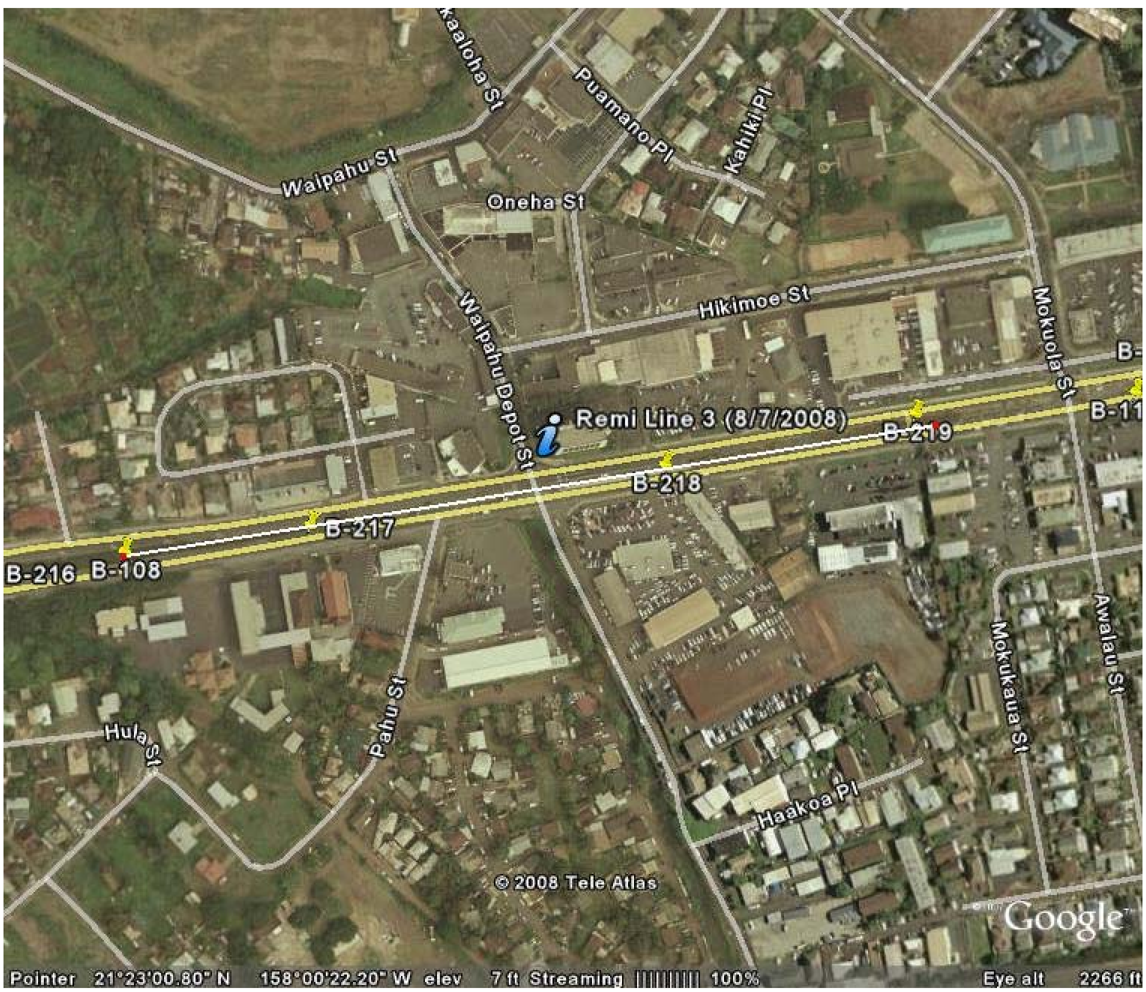

Figure 2: General 2D ReMi line location map - seismic line is white (with date acquired) and Geolabs boreholes (e.g., B-217) shown with yellow markers [*Google Earth background image*].

Table 1: ReMi line numbers, lengths and positions.

LINE #	Date Acquired	Line Footage* (ft)	Start Distance (ft)	Stop Station (ft)	Sounding Length (ft)
1	7/29/2008	990	0	760	760
2	7/29/2008	460	0	240	240
3	8/7/2008	1870	280	1920	1640
4	8/8/2008	2170	1960	3900	1940
5	8/11/2008	1790	3940	5500	1560
6	8/5/2008	1670	0	1440	1440
7	7/30/2008	1190	0	960	960
8	8/10/2008	1190	0	960	960
9	8/6/2008	310	0	80	80
10	8/6/2008	1710	370	1850	1480
11	8/9/2008	1770	1770	3310	1540
12	8/12/2008	1670	0	1440	1440
**Each line is 230' longer than the sounding (profile) length.*					

Instrumentation and Field Method

Seismic ReMi data were acquired along the proposed HHCTCP site using a 24-channel Seismic Source DAQ LinkII seismograph. This system represents a state of the art, 24-bit floating-point seismograph that is connected to a field laptop via ethernet cable. Analog signals from vertically-oriented geophones are collected in the DAQ seismograph where it is anti-alias filtered, converted to a digital signal, transmitted to the laptop computer and then recorded on the hard drive. DAQ modules have a 24-channel capacity, and as such only one module was needed for this seismic investigation. However, 48 receivers were placed on the ground along the survey line at 10 foot intervals for the survey to move along more rapidly in the highway setting. The receivers were all low-frequency 4.5-Hz vertical component, velocity-transducer geophones.

An active ‘seismic’ source was placed off the end of the line, a standard rubber-tired backhoe, in order to acquire quality passive-surface wave energy in-line with the receiver array (which was always oriented parallel to traffic). No timing was used for this backhoe source which thumped, idled and drove around to create surface waves, thus the survey approach is still defined as a passive surface wave technique. Each 1D ReMi sounding was acquired using a 24-channel active array and the backhoe for the ‘in-line’ energy source. The backhoe was typically located about 100 to 200 feet (30.5 to 60.9 m) off the end of the line. Physical positioning of the backhoe was dictated by intersections and coned-off areas. A set of records acquired for each set of 24 geophones produced one 1D ReMi sounding. The 'line' (of 24 geophones) would increment up, or roll-up, by 4 receivers, thus 40 feet (12.2 m), providing a single 1D sounding every 40 feet (12.2 m) along the line. As will be described in the next section, ReMi sounding data are placed at the middle of the receiver array. In this fashion, the ReMi line for this project is 230 feet (70.1 m) longer than the 2D sounding profiles produced for each line. For each line there were 12 geophones (115 feet, 35 m) behind and ahead of the first and last 1D sounding, respectively.

Figure 3 illustrates the '*roll-along*' approach of placing 48 receivers on the ground with two 24-channel cables and actively recording seismic data on only 24 'live' channels. This set up is standard practice for reflection seismic surveys, where it allows the operator to quickly move up the live 24 channels and continue recording data while receivers are picked up behind the live array, and laid out ahead of the array. The upper diagram (A) shows just the initial two cable set up with 48 receivers, while the lower diagram (B) identifies the sounding number and location(s) for a long profile. This diagram illustrates the field set-up used for the HHCTCP investigation. This approach greatly increases field performance for 2D ReMi surveys. It is the lower diagram it's clear that the first 115 feet (35 m) and the last 115 feet (35 m) of seismic line do not produce subsurface coverage (i.e., a ReMi sounding).

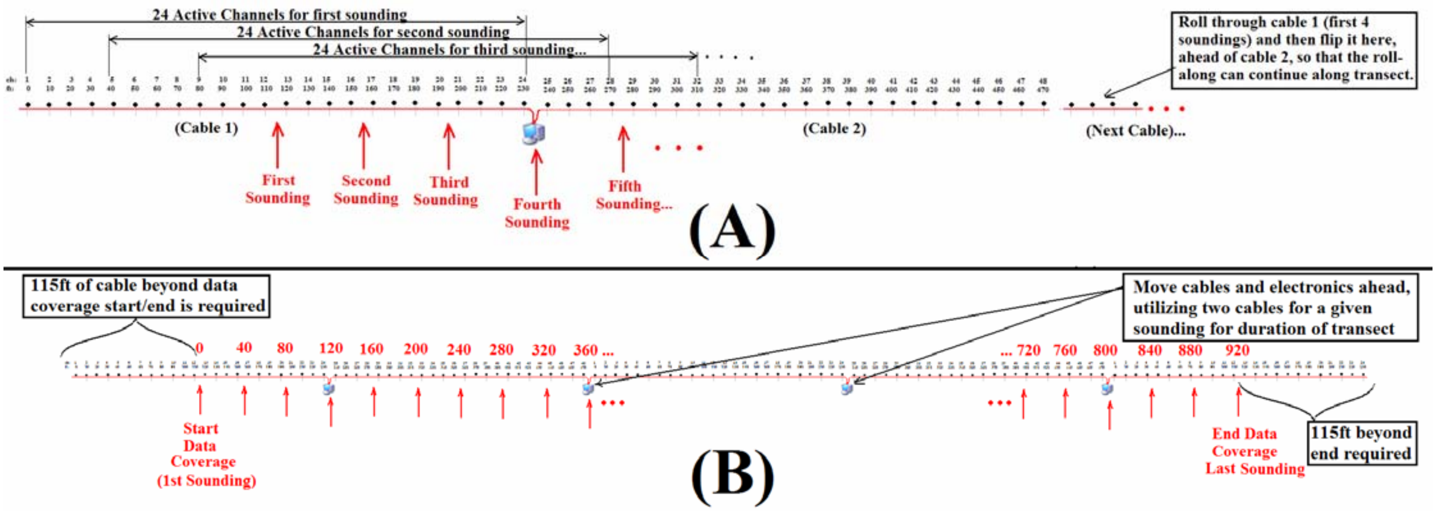

Figure 3. Layout used for the 2D ReMi profiling survey technique. The 1D "*sounding*" spacing is 40 feet – 12.2 m).

Data Processing

The ReMi method uses the same instrumentation and field layout as a standard refraction survey. However, with this seismic method there are no predefined source points or any need for timed or 'triggered' seismic shots. The method is a surface-wave technique that relates the Rayleigh-wave velocity to shear-wave velocity through an empirical relationship. That is, the ReMi method uses ambient noise, or vibrational energy that exists at a site without the use of input energy from hammers or explosives like those used on refraction and reflection surveys, or even multi-channel analysis of surface-wave (MASW) surveys to derive the S-wave velocity.

Ambient energy can be anything from foot traffic to vehicles, construction activities, tidal energy and microtremor earthquakes. The HHCTCP site was rich with all of these noise sources.

Either by active noise, ambient energy and other cultural disturbances, these small-strain vibrations cause surface wave energy to propagate along the receiver line (in both directions). These are the seismic energy that get recorded by the ReMi method. Actual positioning of the active source (i.e., the backhoe) is not relevant for the ReMi data analysis. For nearly all the sounding locations along the project corridor at least ten, unfiltered, 30-second ambient and backhoe vibrational energy records were recorded on the live 24 channel array using a 2 msec sample rate. In order to roll-through busy intersections quickly only five 30-second records were acquired at those locations. These 5 records proved sufficient during data analysis to provide quality soundings beneath these areas; however, 10 records were better. For data quality analysis purposes, ReMi records were collected with and without the backhoe source. This was done to compare the data quality that would be achieved if the backhoe was not used.

1D ReMi: The ReMi method calculates the shear-wave velocity (Vs) of layers and the respective depths to interfaces beneath the refraction line as described by Louie (2001). The ReMi method is primarily used to calculate shear velocity versus depth at a point (1D) in order to differentiate between different soil and rock strata.

Noise records (including backhoe hits) collected at this site were processed using the SeisOpt® ReMi™ software, © Optim Inc., 2005 (Louie, 2001). The ReMi technique is based on two fundamental concepts. The first is that seismic-refraction recording equipment can effectively record surface waves at frequencies as low as 2 Hz with the use of low-frequency geophones. The second idea is that a simple, two-dimensional slowness-frequency (p-f) transform of a microtremor record can separate Rayleigh surface waves from other seismic arrivals. This separation allows recognition of the true phase velocity and discriminates against energy propagating in other modes without dispersion. The advantages of ReMi from a seismic surveying point of view are several, including the following: It requires only standard refraction instrumentation; it requires no triggered source of wave energy; and, it will work best in seismically noisy urban settings.

Four processing steps were used to derive a 2D ReMi Vs profile (see Figures 4a and 4b):

<u>Step 1</u>*:* After acquiring a series of noise records a velocity spectrum or slowness (p) versus frequency (f) curve (i.e., a *p-f plot*) is generated – The distinctive slope of dispersive surface waves is an advantage of the p-f analysis; body waves and airwaves cannot have such a slope. Even if most of the energy in a seismic record is in a phase other than Rayleigh waves, the p-f analysis will identify the dispersion of the surface waves (Pullammanappallil and others, 1993 and 1994).

<u>Step 2</u>*:* Pick the Rayleigh-wave dispersion – Picking is done along a lowest p-f envelope bounding the dispersed energy appearing on the p-f image. The picks thus discriminate against higher apparent velocities present when 'noise' impacts the linear array from off-line or out-of-line directions. Picking a surface-wave dispersion curve along an envelope of the lowest phase velocities at each frequency has a further desirable effect. Because higher-mode Rayleigh waves have phase velocities above those of the fundamental mode, the refraction microtremor technique preferentially yields the fundamental-mode surface wave phase velocities.

<u>Step 3</u>*:* Generate1D shear wave velocity sounding (S) – The ReMi method interactively forward-models the normal-mode dispersion data picked from the p-f images with a code adapted from Saito (1979, 1988) by Yuehua Zeng(1992). This code produces results identical to those of the forward-modeling codes used by Iwata et al. (1998), and by Xia et al. (1999) within their

inversion procedure. The modeling iterates on phase velocity at each period (frequency). The analysis approach and the propagation properties of surface waves allow velocity reversals (low Vs layers at depth) to be modeled successfully.

<u>*Step 4*</u>: Generate 2D shear wave profiles – Once a series of 1D Vs soundings (S) have been modeled, the data are entered into a contouring or smoothing algorithm that produces a 2D smooth-model of a series of 1D inverted Vs models. The 2D profile represents a cross-section of the subsurface with soundings spaced at 40 feet (12.2 m) (*field method dependent*). Initially an 'unsmoothed' profile is generated, which only plots the 1D sounding without any smoothing operation applied, then the smoothing is applied appropriately for the anticipated geologic setting. A concerted effort is taken during Step 4 to ensure that any and all geologic / geotechnical data available are analyzed and integrated with the final processing step. Soil stiffness (e.g., relative density from blow counts) and rock competency (from drill core RQD), and depth that bedrock was encountered are important parameters for modeling (1D – Step 3) and generating 2D smooth ReMi profiles.

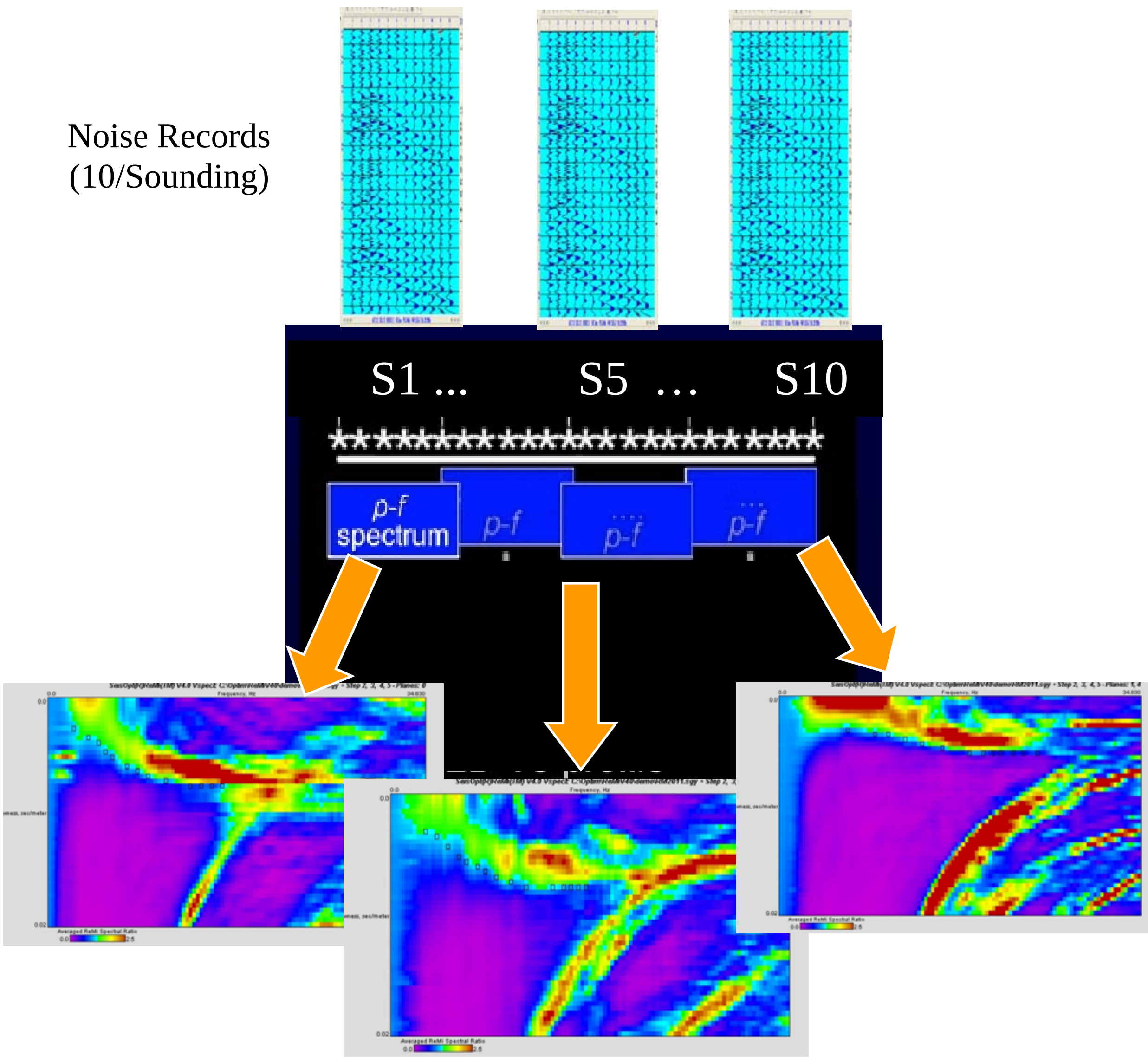

Figure 4a. Schematic showing processing steps 1 and 2.

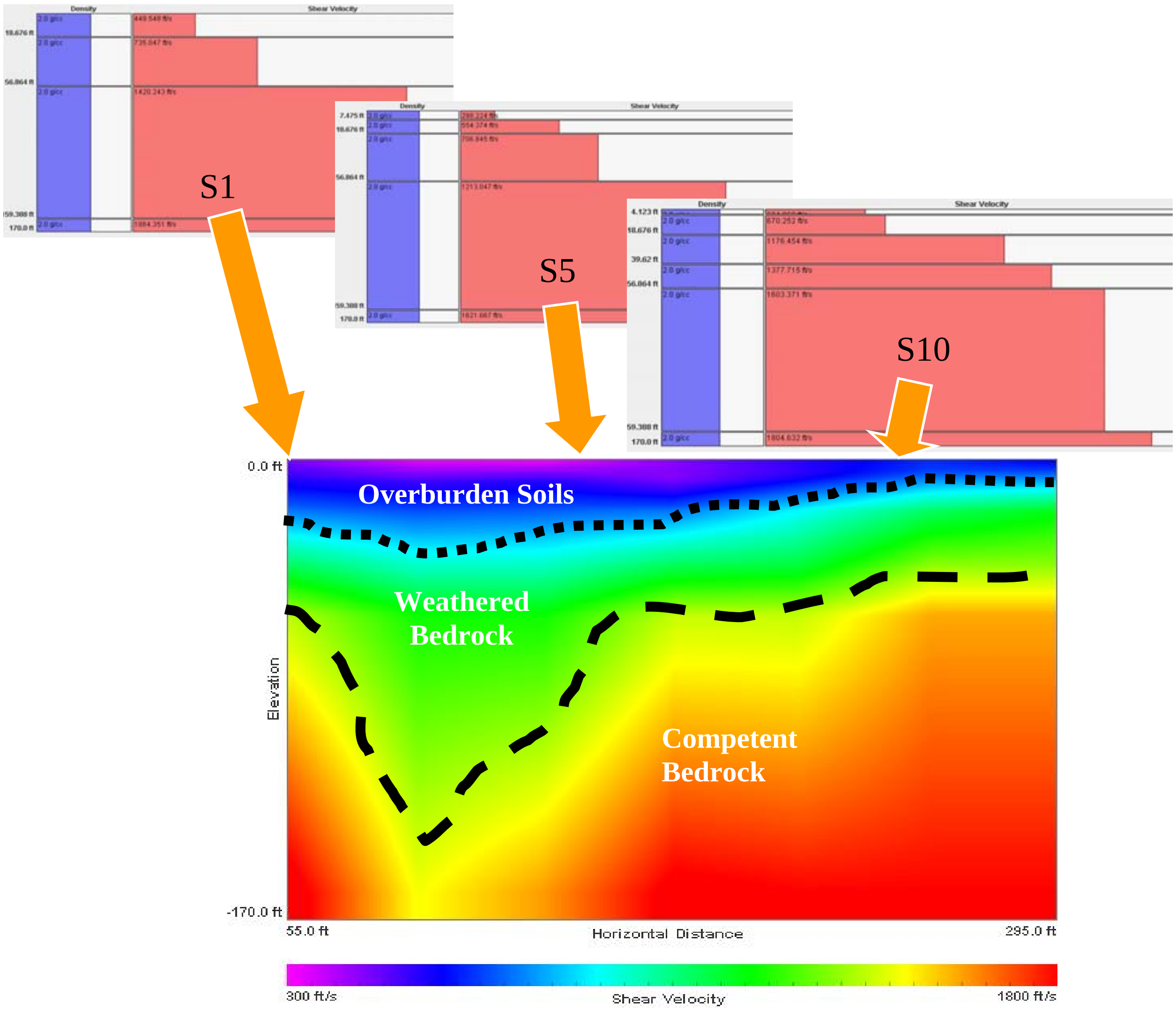

Figure 4b. Schematic showing processing steps 3 and 4.

Results

2D ReMi results from data acquired along Line 3 are presented on Figures 5a and 5b, and results from Line 4 are presented on Figures 6a, 6b, and6c. These data represent a nearly continuous subsurface profile that covers approximately 3,620 feet (1103.4 m) from west to east, with an short interruption at the end of Line 3 due to a large intersection. The figures were created to allow comparison from line to line; that is, each figure uses the same color (Vs velocity) scale, and horizontal to vertical exaggeration. Each figure presents only 760 line feet (231.6 m) of ReMi soundings laterally, therefore the profiles have been split among separate pages to accommodate the line length (labeled a, b and c).

Geotechnical borings and their locations have been posted on the figures for integration of material property data with the S-wave velocity results. A few of the boring locations are approximate as they had not yet been drilled by the time the seismic investigation was concluded. Two velocity contours have been placed on the cross-sections: 1) a 600 feet per second (ft/s) (183 m/s), a contour that represents the interpreted transition from undifferentiated *soft or loose* soil deposits to *stiff or d*ense soil deposits; and, 2) a 2,000 ft/s (610 m/s) contour. Based on all the S-wave velocity data and the depth-to-bedrock from boreholes a 2,000 ft/s (610 m/s) contour best represents the velocity interface between undifferentiated soils and bedrock at this site. The soil/bedrock interface, as described on Geolabs boring logs, shows a wide variation in the degree of weathering (e.g., *slightly- to intensely-weathered*), as well as a significant difference in the fracture density (e.g., *moderately- to highly-fractured*). Close inspection of the boring logs at the associated locations along the ReMi profiles and also downhole S-wave velocity data acquired in the area, actual bedrock shear-wave velocity likely ranges between about 1,800 and 2,400 ft/s (~550 to 730 m/s). Degree of weathering and fracture density significantly decreases the compressional- or shear-wave velocity of rock formations.

As described in this paper the ReMi technique is a seismic method that averages the subsurface bulk properties the receiver line (i.e., a 230-feet, 70.1 m). Each sounding represents that bulk or average shear-wave velocity (*see Figure 4*). Using data acquired beneath over 350 soundings the smooth models shown on Figures 5 and 6 are the best representation of the depth to- and geometry of- the basalt contact between, below and beyond drill hole control. As anticipated at this site, the ReMi data indicate significant variation and relief on the bedrock surface; additionally, there is considerable correlation between boring logs and bedrock depths as interpreted by 2D ReMi profiling.

As indicated on Figures 5a and b, east of boring B-217 along the profile there is a definite deepening of the bedrock surface to greater than 120 feet (36.5 m) beneath distance 1,600 feet (488 m) on Line 3. This trend is confirmed further east along Line 4 (Figure 6a) at approximate distance 2,050 feet (625 m) near borings B-109(SW) and B-110. The correlation of ReMi derived velocities with S-wave velocities measured by Geolabs in B-109(SW) is very good. It shows the soft soil contact at about 45 feet (13.7 m). Similarly, boring B-110 terminated at ~177 feet (54 m) bgs without encountering bedrock which confirms the deepening of bedrock. Along this east end of Line 4 (Figure 4c) the depth to bedrock determined by 2D ReMi imaging is the deepest within the survey area (approximately 230 ft, 70.1 m).

It should be understood that this depth is the absolute maximum resolvable depth with the field set-up and instrumentation used for this project. The absolute depth may not be resolvable in this area, compared with other places along the project, because of the depth-to-bedrock, the wavelengths that could be measured with the 230-foot (70.1m) line length. However, the shape, size and approximate depth of this anomalously deep bedrock are substantiated by the data. As this long continuous profile continues east toward Line 5, bedrock slowly rises to less than 100 feet (30.5 m) and continues to rise till the position of B-221 along Line 5 where the bedrock is within 10 feet (3 m) of the ground surface. Also shown on Figure 6 is a stretch of Line 4 where a considerably thick layer of ‘soft’ soils (<600 ft/s, 183 m/s) was detected.

Conclusions

Acquisition of 2D seismic data along the HHCTCP project provided good imaging of the soil/bedrock contact as well as detecting the presence of soft soils in the undifferentiated overburden deposits. The ReMi method was selected because of its ability to acquire seismic data in *very* noisy environments and to distinguish between soil and bedrock based on shear-wave velocity. The method is not affected by the presence of a shallow water table, which was important as much of the survey area was very near the coast. Correlation with geologic logs for depth to bedrock was good. The seismic data show a wide range of S-wave velocities that could be appropriately interpreted as the soil/basalt contact. There appears to be some deep dense gravel with cobbles and boulders that likely overlap the seismic velocity range interpreted as bedrock. The ReMi data indicate areas of thick soft materials, in excess of 60 feet (18.3 m), interpreted to be soils with less than 600 ft/s (183 m/s) S-wave velocity. Boring logs and ReMi data collectively indicate that the basalt interface may be identified by velocities ranging from about 1,800 ft/s (550 m/s) if intensely weathered and highly fractured, to greater than 2,400 ft/s (730 m/s) in areas with lesser fracture density or little weathering at the soil/bedrock interface. Overall, the geometry of the bedrock surface (its relief and depth) was well defined by this survey technique over long stretches of the proposed HHCTCP site.

The method proved that it can be used when basaltic bedrock is shallow (e.g., 10 feet bgs or 3 m), and when it is quite deep (200+ ft bgs or 60+ m bgs) with a 'standard' refraction seismic set-up using a 230-foot (70.1 m) long spread and 10-foot (3-m) geophone spacing. Using a wider geophone spacing and/or a longer receiver array would yield much deeper imaging due to the large amount of low-frequency energy observed at this site. The use of a backhoe significantly added to the quality of the *p-f* curves and thus the ability to pick the surface-wave dispersion data. Quality of the ReMi data ranged from good to very good, which is directly attributed to the use of the backhoe and the tidal (low-frequency) energy present near the coast. Although the basaltic bedrock velocity clearly varies across the site, additional analysis of geotechnical data (if available) from borings regarding degree of weathering and fracture density would likely narrow the velocity range used to define depth-to-bedrock. The 2,000 ft/s (610 m/s) contour has been used to represent a *normalized* bedrock surface, but it may not be the actual Vs for bedrock from Waipahu in the west to Aiea in the east.

Acknowledgements

Zonge would like to thank Geolabs, Inc. whose support while in the field was invaluable. Additionally, we appreciate the input from the PB World project team. The entire geotechnical design team consisted of many individuals that helped make this project a success.

References

Iwata, T., Kawase, H., Satoh, T., Kakehi, Y., Irikura, K., Louie, J. N., Abbott, R. E., and Anderson, J. G., 1998, Array microtremor measurements at Reno, Nevada, USA (abstract): Eos, Trans. Amer. Geophysical. Union, v. 79, suppl. to no. 45, p. F578.

Louie, J, N., 2001, Faster, Better: Shear-wave velocity to 100 meters depth from refraction microtremor arrays: Bulletin of the Seismological Society of America, v. 91, p. 347.

Pullammanappallil, S.K., and Louie, J.N., 1993, Inversion of seismic reflection travel times using a nonlinear optimization scheme: Geophysics, v. 58, p. 1607-1620.

Pullammanappallil, S.K., and Louie, J.N., 1994, A generalized simulated-annealing optimization for inversion of first arrival times: BSSA, v. 84, p. 1397-1409.

Saito, M., 1979, Computations of reflectivity and surface wave dispersion curves for layered media; I, Sound wave and SH wave: Butsuri-Tanko, v. 32, no. 5, p. 15-26.

Saito, M., 1988, Compound matrix method for the calculation of spheroidal oscillation of the Earth: Seismol. Res. Lett., v. 59, p. 29.

Xia, J., Miller, R. D., and Park, C. B., 1999, Estimation of near-surface shear-wave velocity by inversion of Rayleigh wave: Geophysics, v. 64, p.691-700.

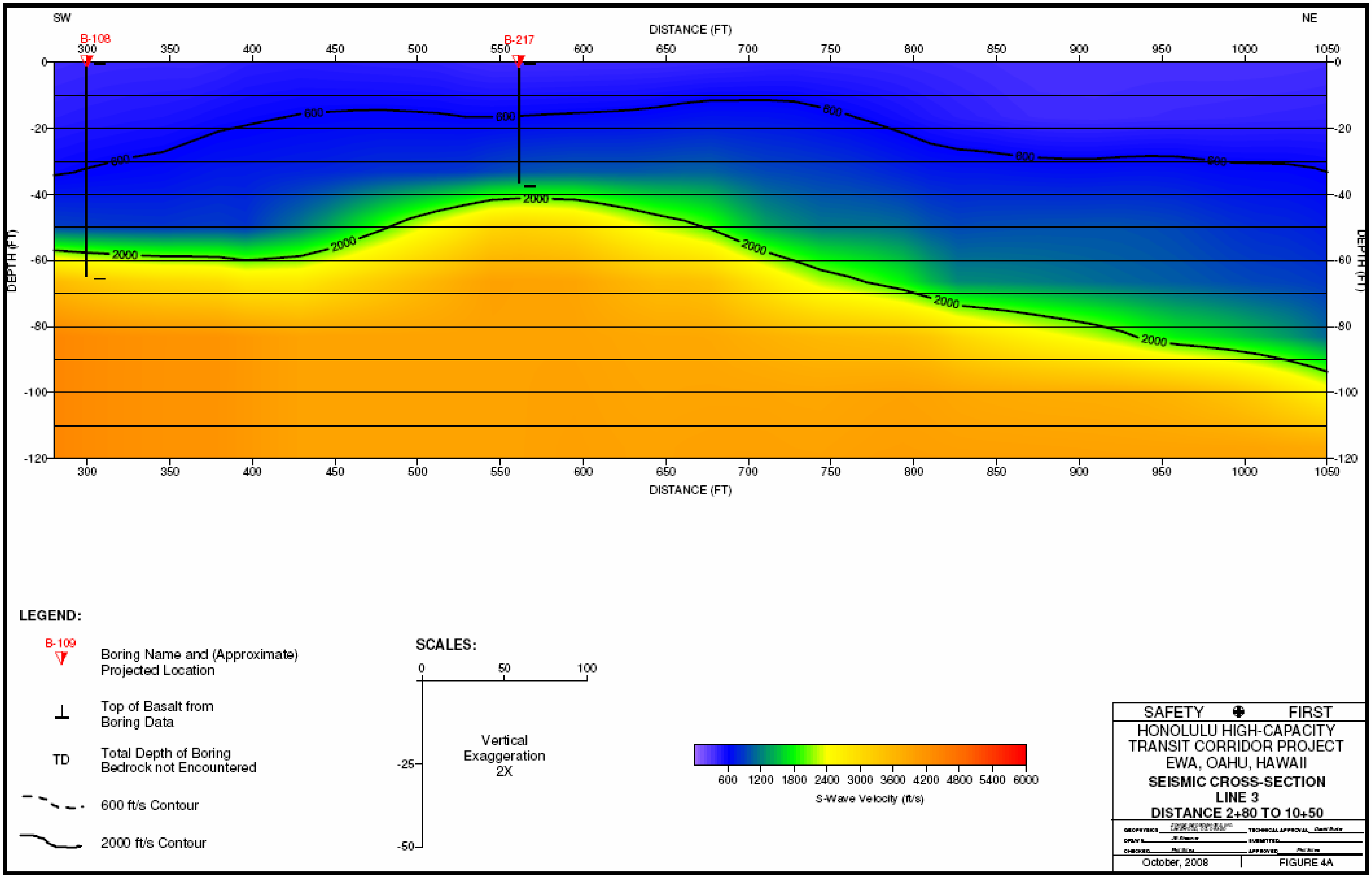

Figure 5a. 2D ReMi results Line 3 (*continued on Figure 5b*).

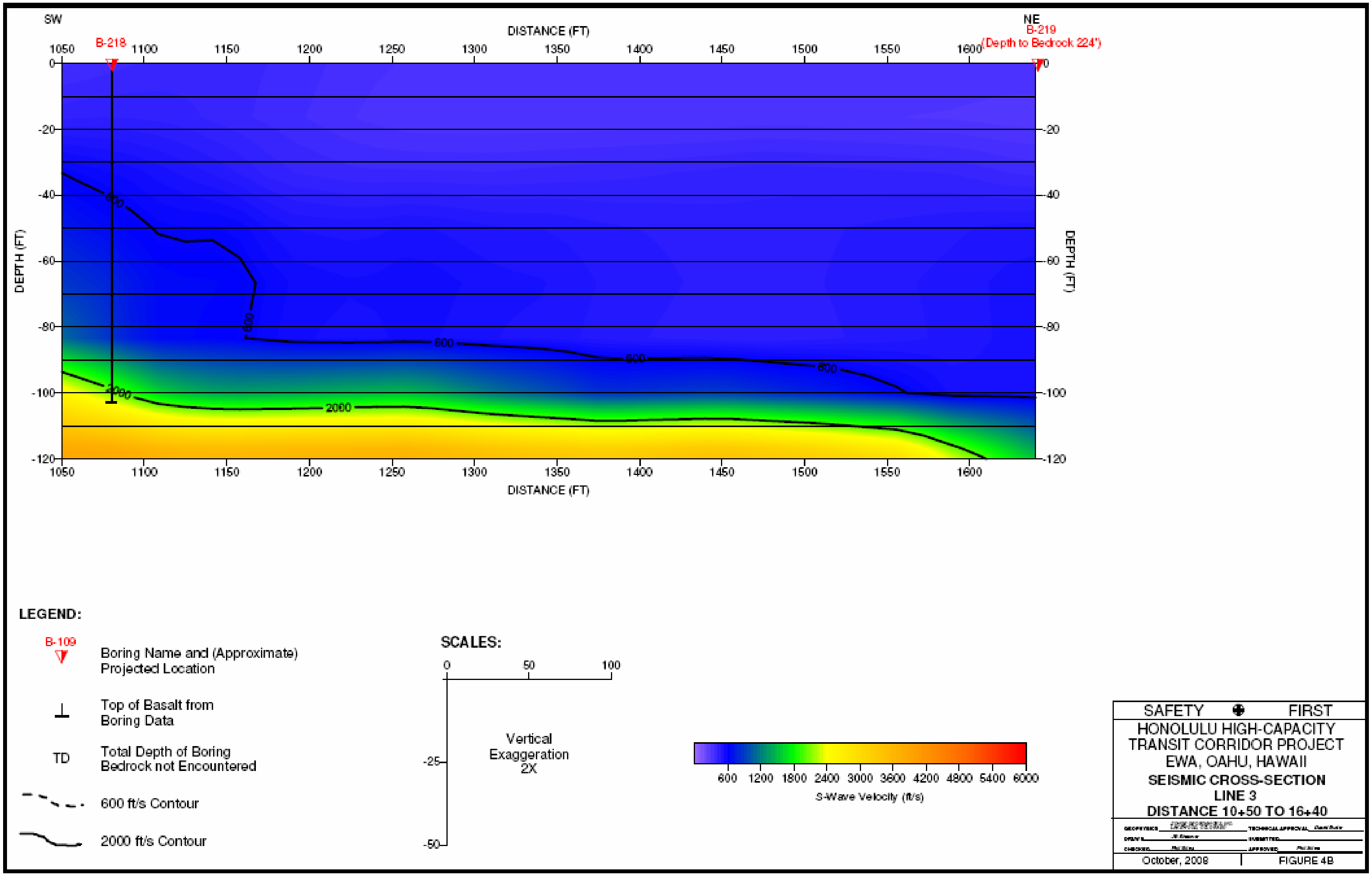

Figure 5b. 2D ReMi results from Line 3 (*continuation from Figure 5a*).

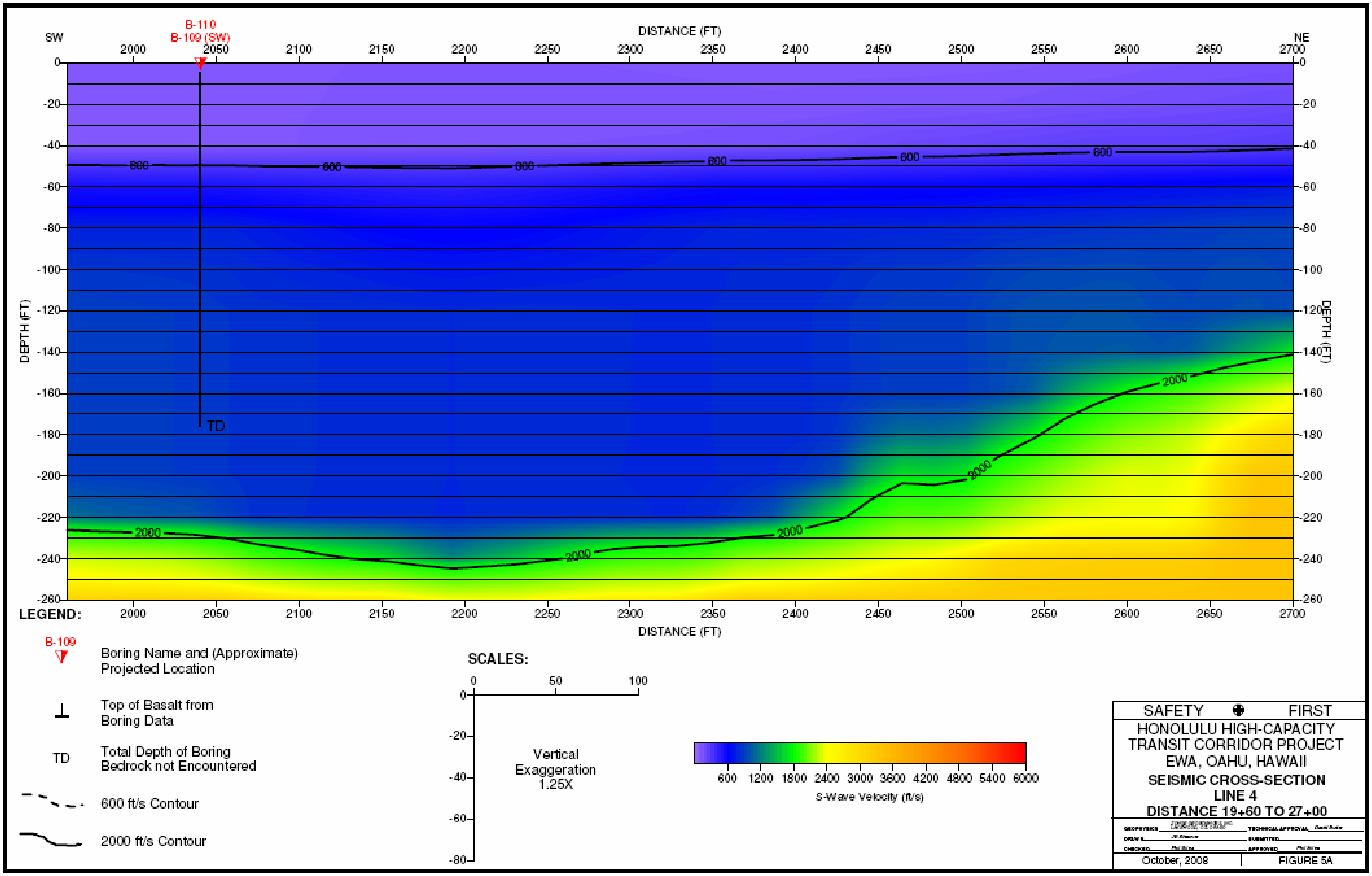

Figure 6a. 2D ReMi results from Line 4 (*continued on Figure 6b*).

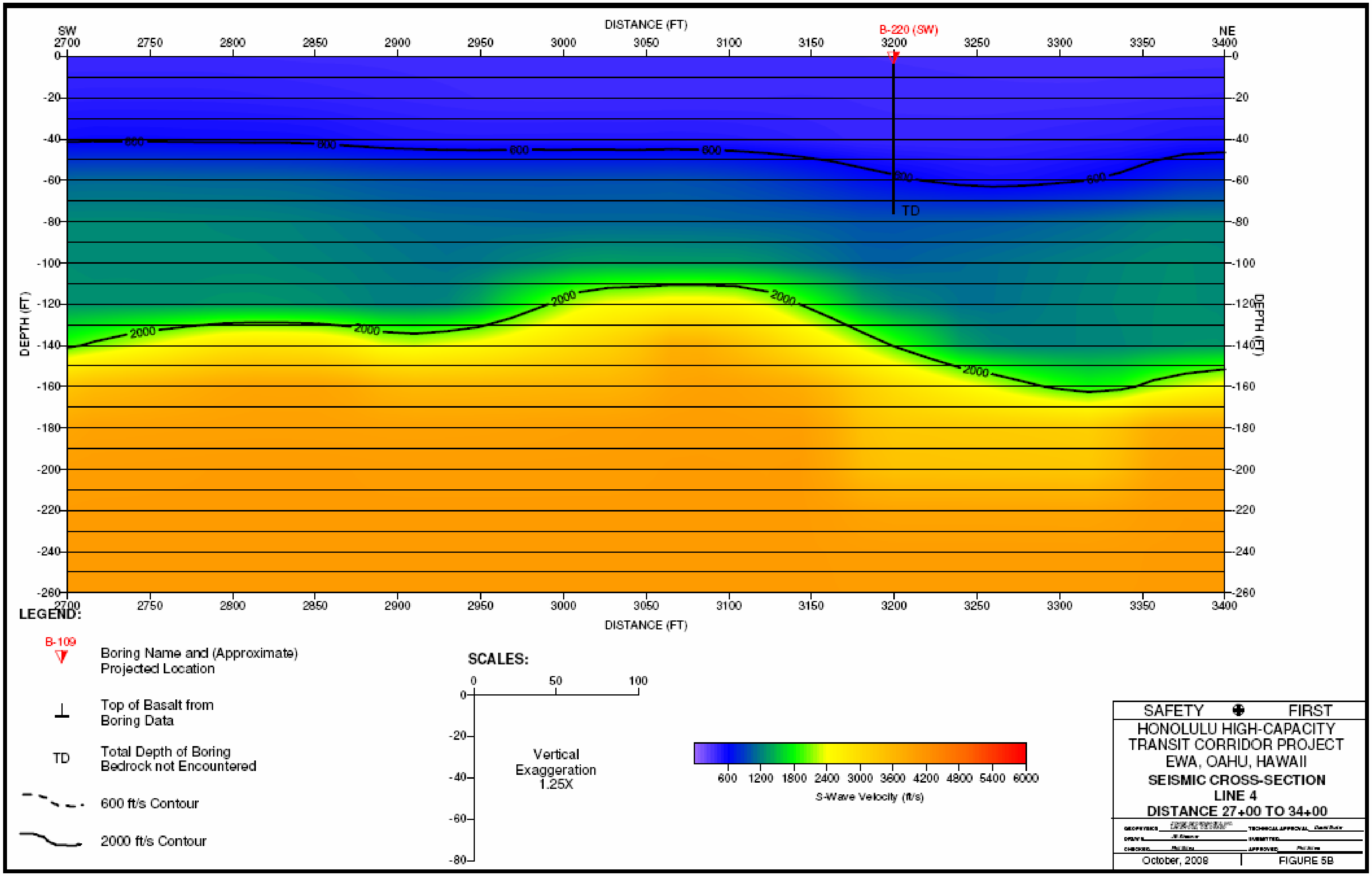

Figure 6b. 2D ReMi results from Line 4 (*continuation from Figure 6a and continued on Figure 6c*).

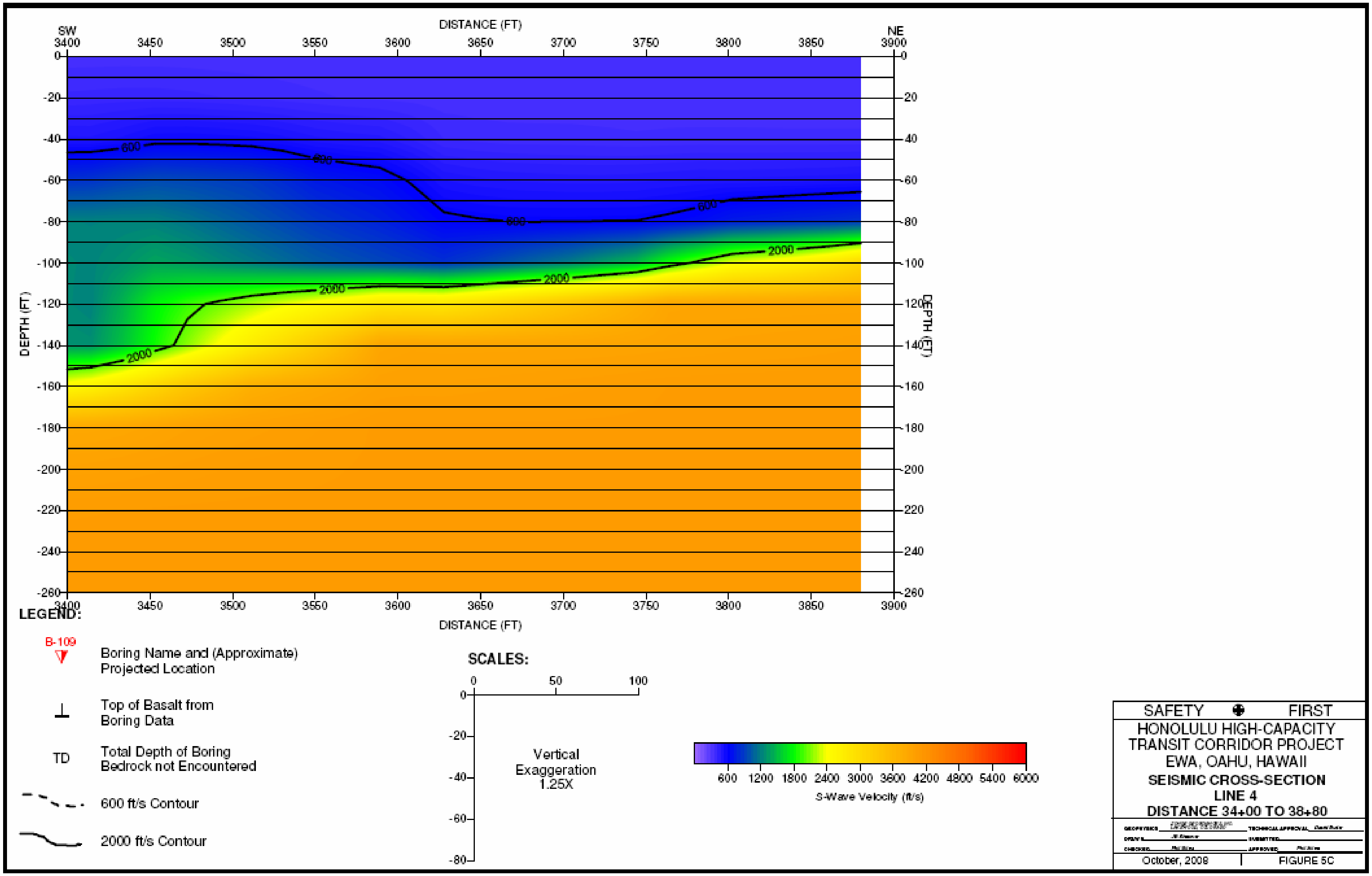

Figure 6c. 2D ReMi results from Line 4 (*continuation from Figure 6).*