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Shallow Shear-Wave Velocities Based on Refraction Microtremor Measurements in Areas Damaged by the 2008 M_w 6.0 Wells, Nevada Earthquake

by

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ABSTRACT

Shear-wave velocity (V_s) measurements were made using the Refraction Microtremor (ReMi) technique from ambient noise sources in areas that were damaged by the 2008 M_w 6.0 Wells earthquake. ReMi data were collected at six sites and were analyzed following the ReMi methodology. Multiple shear-wave velocity-profile models were developed for each site, and estimates of the average shear-wave velocity (V_s) for the upper 100 ft (30 m) were made (V_s100 ft; V_s30 m). The V_s100-ft (V_s30-m) range from 879 to 1,174 ft/s (268 to 358 m/s), classifying them all as an International Building Code/NEHRP Site Class D. The preferred V_s100-ft (V_s30-m) estimates ranged from 919 to 1,174 ft/s (280 to 358 m/s). This non-uniqueness of models did not have a large effect on the estimates of the V_s100-ft (V_s30-m), but it does illustrate that there were several different velocity-depth profiles possible at each site that fit the data. The impact of model non-uniqueness on the average shear-wave velocity estimate was 1% to 4% about the preferred value, with most values being within 1% to 2%. At two sites (Lines 1 and 3), the range of models considered all included velocity inversions in the profile, making this a more robust feature in the profile supported by the data and modeling, but other sites could be modeled with or without a velocity inversion, making this feature less certain at these sites.

ReMi Lines 2 and 3 were in the Wells historical district, were perpendicular to each other, and intersected each other. The preferred V_s100-ft (V_s30 m) estimates from Lines 2 and 3 differed by only 21 ft/s (6 m/s) and are within 2% of each other. Also a fairly similar preferred velocity-depth profile was chosen for these sites which included a velocity inversion that is a robust feature of the data for Line 3. These measurements confirm that the ReMi method is repeatable and demonstrate that perpendicular measurement lines at the same site are redundant for estimating V_s100-ft (V_s30-m), but may be useful for gaining more constraints on the velocity-depth profile.

The six V_s100-ft (V_s30 m) measurements made show a rough correlation with damage, despite the limited dataset. The lowest velocity estimate (Line 1: 919 ft/s; 280 m/s) was on the youngest geologic unit sampled, the edge of active medial stream deposits; nearby houses had chimney damage that can be considered indicative of Modified Mercalli Intensity VII. ReMi Lines 2, 3, and 4 were in the Wells historical district and at the high school where damage can be described as Modified Mercalli Intensity VII to VIII. The preferred V_s100-ft (V_s30 m) estimates of ReMi Lines 2, 3, and 4 are remarkably similar, 973 ft/s (297 m/s), 994 ft/s (303 m/s), and 983 ft/s (300 m/s), respectively, suggesting a potential relationship between intensity VII to VIII damage to unreinforced masonry buildings and velocities in the range of 973 to 994 ft/s (297 to 303 m/s), or less. Lines 5 and 6 had the highest V_s100-ft (V_s30 m) measured in Wells, 1,174 ft/s (358 m/s) and 1,047 ft/s (319 m/s), respectively; these sites had limited but serious damage to buildings that would correlate with Modified Mercalli Intensity VII. Lines 2–6 were located on Quaternary alluvial fan deposits. The most general statement that can be made is that significant earthquake damage occurred to unreinforced masonry buildings in areas that are IBC/NEHRP Site Class D.

INTRODUCTION

The February 21, 2008 Wells M_w 6.0 earthquake heavily damaged parts of Wells, Nevada (figures 1–4). Understanding the ultimate causes of this damage requires shallow (100-foot depth; 30-m) shear-wave velocity measurements, which have been found to have a major influence on potential ground motion from earthquakes (e.g., Borcherdt and Glassmoyer, 1992; Anderson and others, 1996). Little was known of the soil properties in Wells, creating a gap in our understanding of the earthquake damage that occurred and in estimating future seismic hazard potential.

Shallow shear-wave velocity (V_s) surveys were conducted in Wells, in areas which exhibited heavy damage from the earthquake. Conventional wisdom would lead one to expect that the areas with low V_s would shake more than areas of higher V_s during an earthquake. The Wells event provides an opportunity for us to investigate these shaking characteristics by running shallow velocity surveys in areas of damage. The International Building Code (IBC) Soils Site Classification chart (table 1) relates shear-wave velocity and Rock/Soil type to a National Earthquake Hazard Reduction Program (NEHRP) Site Class. Basins in Nevada typically have shallow shear-wave velocities that correlate with NEHRP Site Class C (1,200–2,500 ft/s or 366–762 m/s) or Site Class D (600–1,200 ft/s or 183–366 m/s), whereas the surrounding mountain ranges with hard or more competent rock commonly fall into Site Class B (2,500–5,000 ft/s or 762–1,524 m/s). The site classification values are given in English units in the United States; this paper follows that standard, with metric units given in parentheses.

A Refraction Microtremor (ReMi) survey is the easiest and most cost-effective method to obtain repeatable, shallow V_s measurements. The goal of these surveys was to characterize the site conditions beneath the areas with earthquake damage, allowing an opportunity to constrain the contributing factors to that damage, namely the shallow shear-wave velocity and the velocity-depth profile. The Refraction Microtremor (ReMi) method used in this survey was developed and discussed by Louie (2001). Commonly, a ReMi survey line is set up with a linear array of 24 geophones spaced between 10 and 25 ft apart (3 to 7m) giving a total line length of 230 ft (70 m) to 575 ft (175 m), respectively. The IBC code requires measuring the average V_s to a depth of 100 ft (30 m). The geophone spacing determines the resolution for layer depth and thickness, while the line length determines the maximum depth. ReMi is able to resolve deeper in higher V_s material than lower V_s soils due to the attenuation.

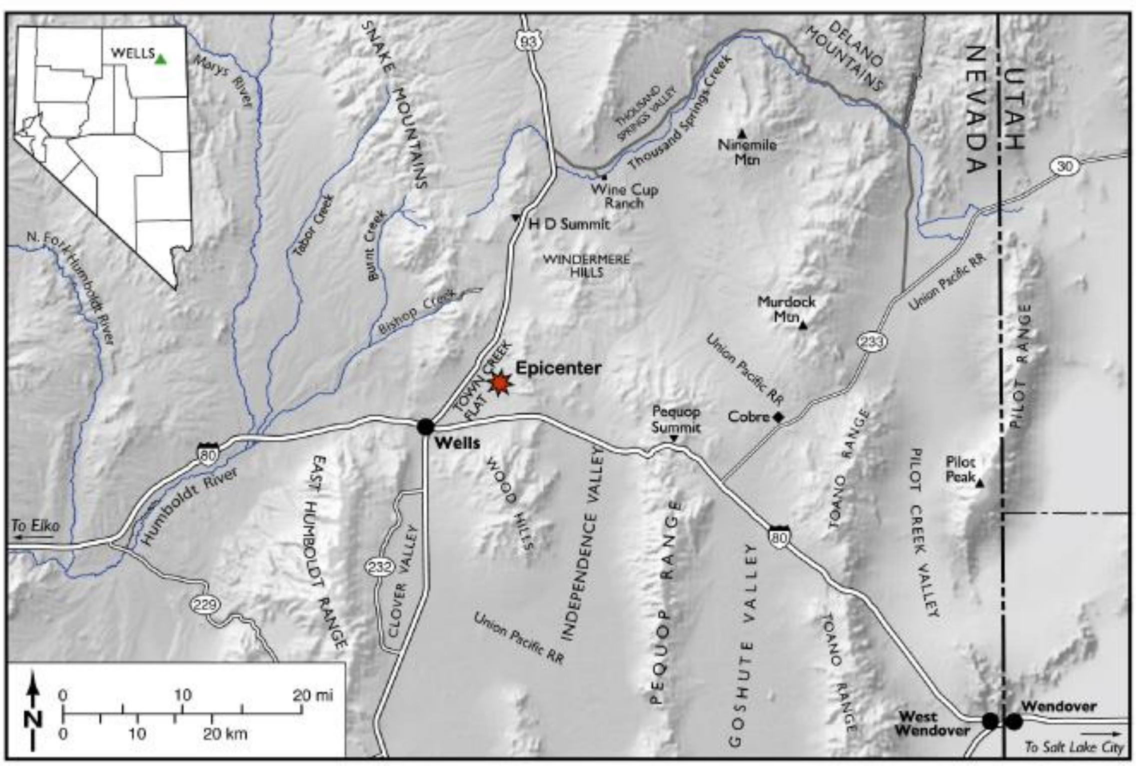


Figure 1. Location map of Wells showing the epicenter of the Wells earthquake.

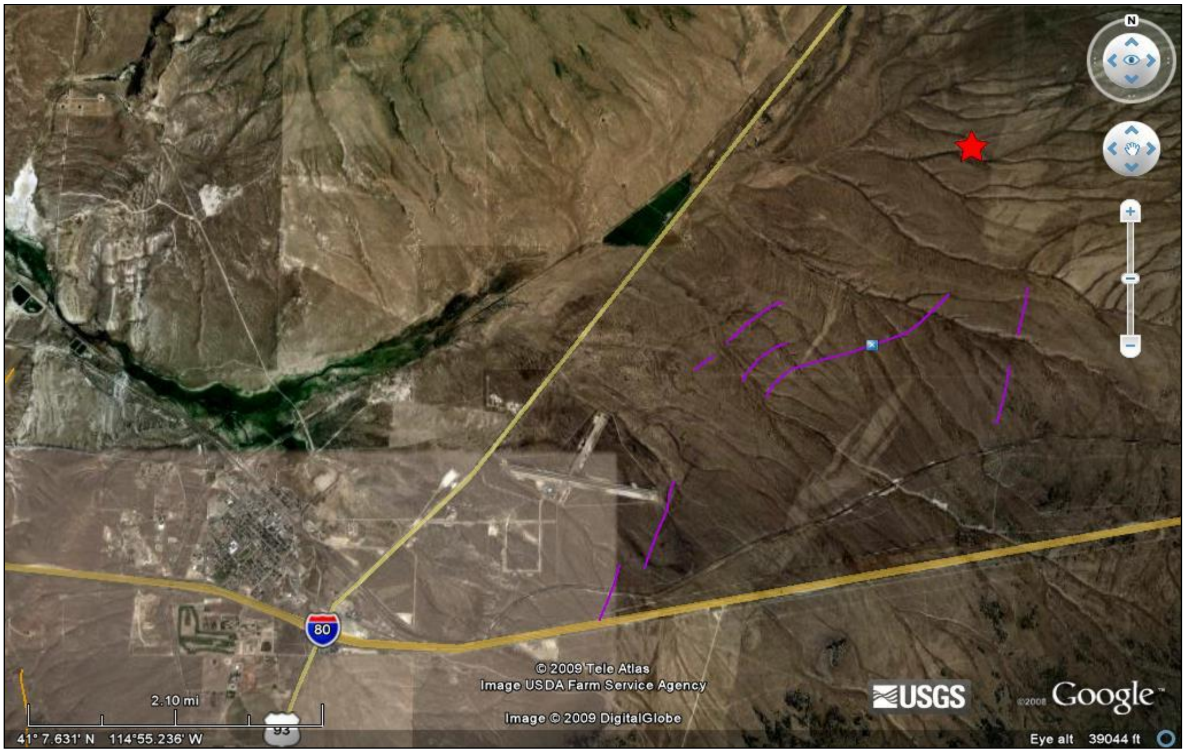


Figure 2. GoogleEarth image with U.S. Geological Survey Fault and Fold Database faults (purple lines). The red star is the epicenter of the M 6.0, 2008 Wells event. Wells is in the lower left part of the image. The green area to the north and northeast of Wells is Town Creek, where the youngest alluvium is, and where potentially lower shallow shear-wave velocities likely exist. Wells appears to be on the southern side of this younger alluvium, but very close to it; the historical district is in the northern part of town.

Figure 3. Collapsed, two-story San Marin Hotel, viewed from the back. The western wall (left side) has collapsed bringing down the second story floor and the roof; only the lower corners remain of the western wall. Wells ReMi Line 2 was laid out on the street in front of this building. *Photograph by C.M. dePolo.*

Figure 4. Western side of the Bullshead Bar. The balcony has been smashed to the ground abruptly breaking the column connections and leaving the columns still standing. Wells ReMi Line 3 was laid out along the avenue this balcony was along. *Photograph by C.M. dePolo*.

Table 1. International Building Code Soils Site Classification (Building Seismic Safety Council)

Site Class	Site Profile Name	Soil Shear Wave Velocity, v_s(ft/sec)	Standard Penetration Resistance, $\bar{N}$ or Nch	Undrained Shear Strength, $\bar{S}_u$ (psf)
A	Hard rock	$\bar{v}_s > 5{,}000$	NA	NA
B	Rock	$2{,}500 < \bar{v}_s \leq 5{,}000$	NA	NA
C	Very dense soil and soft rock	$1{,}200 < \bar{v}_s \leq 2{,}500$	> 50	> 2,000 psf
D	Stiff soil	$600 < \bar{v}_s \leq 1{,}200$	15 to 20	1,000 to 2,000 psf
E	Soft clay soil	$\bar{v}_s \leq 600$	<15	<1,000psf
		Any profile with more than 10 ft of soil having the following characteristics: • Plasticity index PI > 20 • Moisture content $w \geq 40\%$, and • Undrained shear strength $S_u < 500$ psf		
F	Soil requires site response analysis	Liquefiable soils, peat, high plasticity clay		

Wells is located in the south-central part of a small valley, known as Town Creek Flat. The geologic map produced for the Wells earthquake volume shows that most of Wells is built on Quaternary alluvial fan deposits (Henry and Thorman, this volume; figure 5). Wells is just southwest of where the trunk stream exits the flat and is immediately south of where tributary streams coalesce; these are mapped as active medial and tributary stream deposits by Henry and Thorman (this volume). The southern branch of the active medial stream deposits is shown as going around the eastern side of Wells. This branch has a stretch just north of Wells where an inferred southern contact is parallel to the railroad tracks and the main streets of Wells, likely indicating there was fill dirt pushed out into and over the active stream deposits to support building around the transcontinental railroad tracks. The original southern margin of the active stream deposits may have been closer to, although still slightly north of, the railroad tracks near the historical district. The younger, saturated to partly saturated, less consolidated active stream deposits would be anticipated to have the lowest shear-wave velocities, versus the older fan deposits that most of Wells is built on. It should be noted that the deposits that most of Wells is on are distal fan deposits and are generally relatively fine grained (sands and silts with few gravels). Wells ReMi Line 1 was measured on the active stream alluvial deposits, albeit on the edge of these deposits, and the rest of the survey lines were on Quaternary alluvial fan deposits.

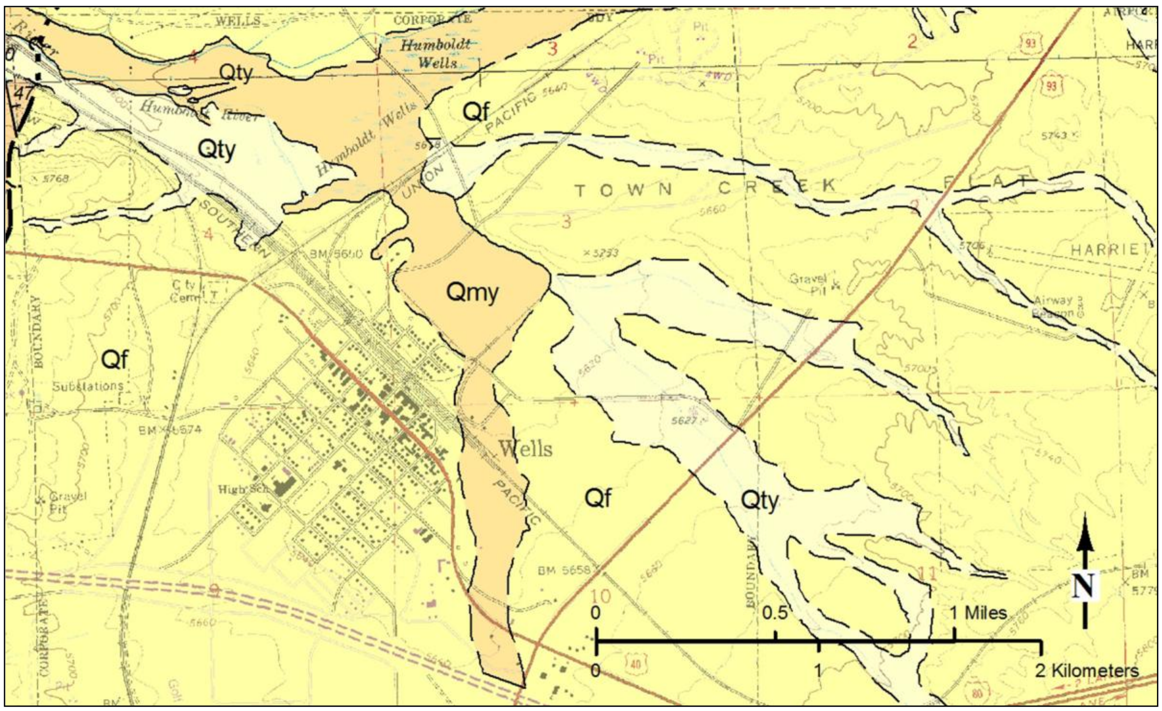


Figure 5. Portion of the geologic map by Henry and Thorman (this volume) near Wells. Qf are Quaternary fan deposits (yellow), Qty are active tributary stream deposits (very light yellow), and Qmy are active medial stream deposits (peach color). The map was originally released at a scale of 1:48,000 and was enlarged about 2x to show the Wells area more clearly. Solid lines are certain geology contacts and dashed lines are inferred contacts.

WELLS REMI SURFACE-WAVE VELOCITY SURVEYS

Six ReMi surveys were conducted in Wells on June 7th and 8th, 2009. The locations of the historical district and the downtown surveys are shown in figure 6 and the GPS locations of the six survey sites are listed in table 2. The goal was to document the shallow surface-wave velocity in areas that had visible or internal building damage from the Wells earthquake. The data was collected with two DaqLink II seismographs from the Seismic Source Company, utilizing their data-acquisition software, Vibroscope version 2.3.36.

In Wells, we used 48 vertical geophones (4.5 Hz) at 10-ft (3-m) spacing to ensure that we met the 100-ft (30-m) depth requirement and obtained the best resolution. Experienced refraction-microtremor data-acquisition technicians can deploy ReMi arrays, record ambient noise, and collect acquisition equipment within 20 minutes. It took approximately 2 hours to run a ReMi line, and 30 data records were taken at each site, using 30-second records, sampled every 2 milliseconds (0.002s).

The seismic source for ReMi surveys consists of ambient seismic "noise", or micro-tremors, which are constantly being generated by cultural/urban and natural sources. At Wells, the source was primarily from traffic on Highway 80 in the southern part of town, and train traffic on the railroad tracks that run through the northeast and western parts of town.

Figure 6. Google Earth image of downtown Wells and the historical district ReMi survey Lines 2, 3, 4 and 5. The red lines show the array alignments. The main transcontinental railroad tracks are in the upper right corner of the figure and Interstate 80 passes a little off the lower left corner; these were major sources of ambient seismic waves for the ReMi surveys.

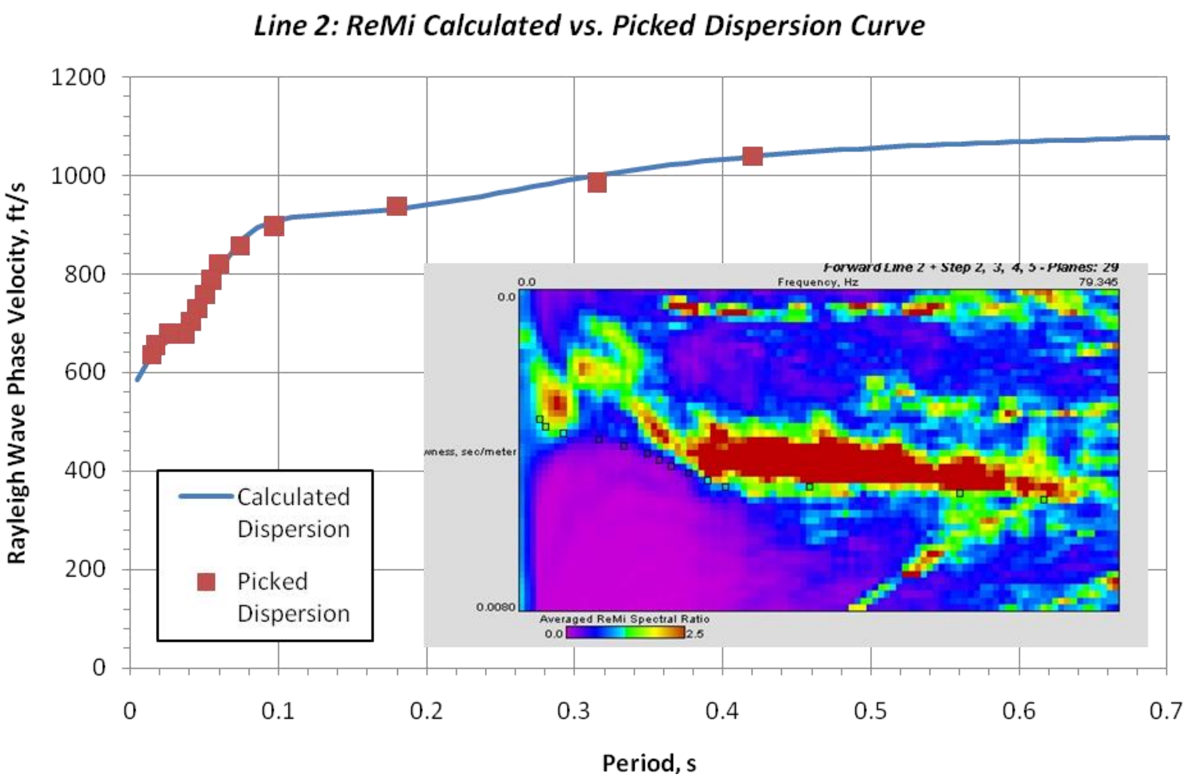
Table 2. Locations of the ReMi Surveys in Wells

ReMi Line	Locations	Local Street	No. of Geophones Used	Layout of Geophones	Survey Length ft (m)
1	41° 6.7564’ 114° 57.5161’	10th St.	44	1 (NW) to 44 (SE)	430 (131)
2	41° 6.7144’ 114° 57.7952’	7th St. (Historic Site)	48	1 (NW) to 48 (SE)	470 (143)
3	41° 6.7300’ 114° 57.8497’	Lake Ave. (Historic Site)	48	1 (SW) to 48 (NE)	470 (143)
4	41° 6.4899’ 114° 58.1914’	Wells HS - Lake Ave	43	1 (NE) to 43 (SW)	420 (128)
5	41° 6.4775’ 114° 58.0524’	City Hall- Clover Ave	48	1 (NE) to 48 (SW)	470 (143)
6	41° 6.1587’ 114° 57.3210’	Resident Inn Parking Lot/ 4-Way Casino Café	48	1 (SW) to 48 (NE)	470 (143)

REFRACTION MICROTREMOR ANALYSIS

The Refraction Microtremor (ReMi) analysis was performed using SeisOpt ReMiVspect V4.0 and ReMiDisper V4.0 from Optim Software. The ReMi process, developed by Louie (2001), is widely used to determine shear-wave velocity profiles using ambient noise recordings. Data processing was performed following the Optim Software guide-lines: Rayleigh waves are separated from other wave arrivals using a two-dimensional slowness-frequency (p-f) transform of the 30-second ambient noise records. The fundamental-mode phase-velocity Rayleigh wave dispersion curve is picked along the minimum-velocity of the envelope of the energy within the slowness-frequency spectral images. The spectrum is normalized as the ratio of the power spectrum at a particular frequency and slowness (1/velocity) over the average value for all slowness values at that frequency. It is not generally necessary to set out two-dimensional arrays to measure the dispersion curve of Rayleigh waves because the minimum phase velocity is correlated with waves traveling parallel to the array. Louie (2001) demonstrated that picking along the minimum edge of contours on slowness-frequency plots, where the slope is steepest, is the best procedure for picking the dispersion curve to obtain the best estimate of the true phase velocity. These Rayleigh wave dispersion curve picks are then interactively modeled using trial-and-error adjustments to obtain a 1-D shear-wave velocity versus depth profile. Modeling was done using the program SeisOpt® ReMi™ (© Optim, 2010). Because forward modeling is used for analyzing data from the test site rather than an inverse method, we are able to test the necessity and sensitivity of the data to both layer thickness and layer velocity. The non-uniqueness of the velocity-depth modeling, with the velocity-depth trade-offs, result in a suite of models that can reasonably fit the dispersion curve data.

An example of the ReMi analysis is shown in figure 7 for Line 2 (7th Street); this example includes the colored slowness-frequency diagram with the picks along the minimum edge of the contours, the Rayleigh wave dispersion plot showing the picks and the preferred model calculated dispersion curve, and the preferred velocity-depth model; note the velocity inversion in the depth profile. Shear-wave velocities were modeled down to at least 130 ft (40 m). Velocity-depth profiles obtained for each of the six lines are shown in figures 8 and 9. Figure 8 shows the range of possible velocity-depth models able to reasonably fit the data, and figure 9 shows the preferred model for each of the six lines.



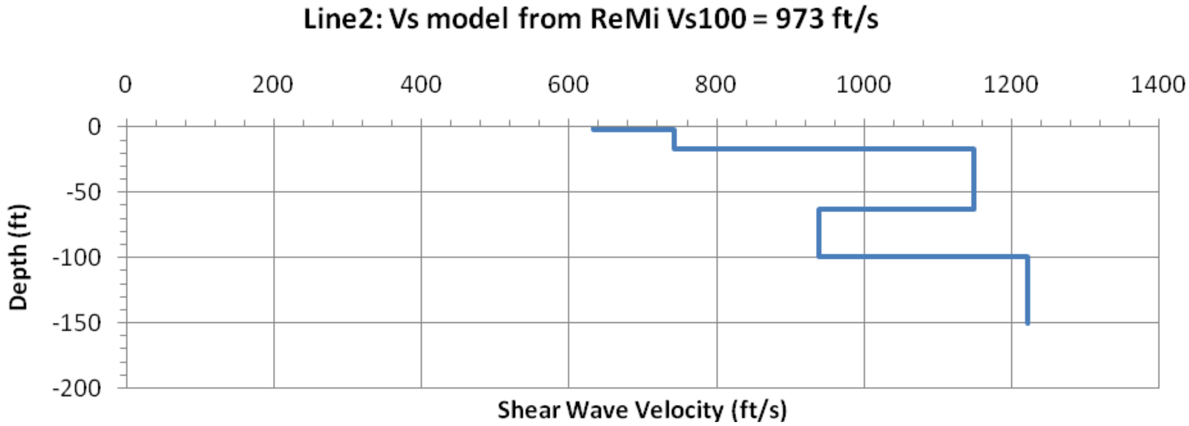


Figure 7. Example of the slowness-frequency diagram (inset colorful graph) with the minimum edge picks (hollow squares) that are shown in upper Rayleigh Wave Dispersion Curve graph (red squares). The lower graph is the shear-wave velocity model with depth that is used to calculate the dispersion curve in the upper figure (the solid blue line). Different velocity structures can be produced that fit the minimum edge picks equally well yielding different possible models that fit the data (see figure 8).

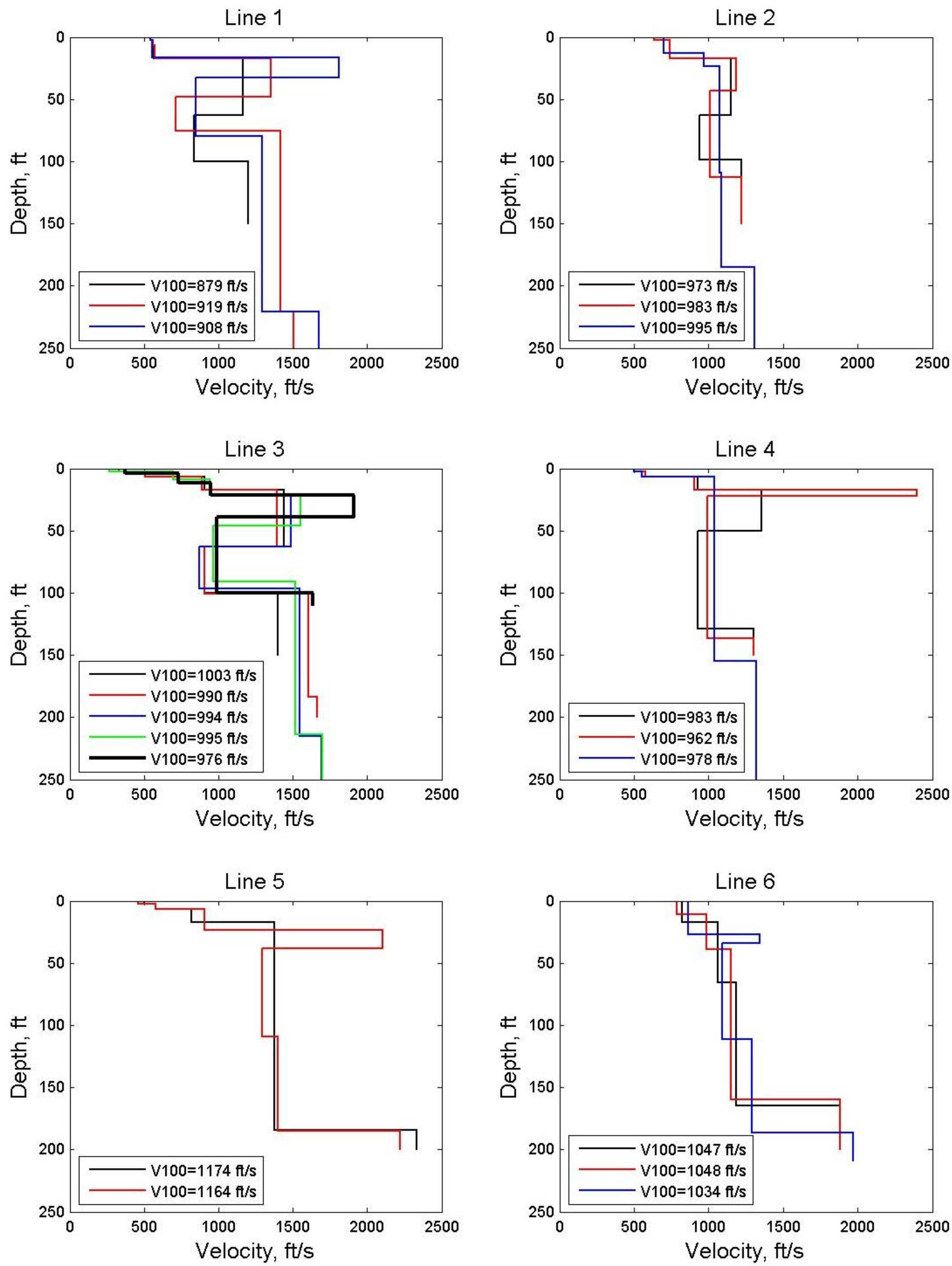


Figure 8. Range of models for each line that can reasonably fit the Rayleigh wave dispersion data. They are picked to show possible significant variations in velocity structure such as illustrating velocity reversals with depth and ranges in velocity structure.

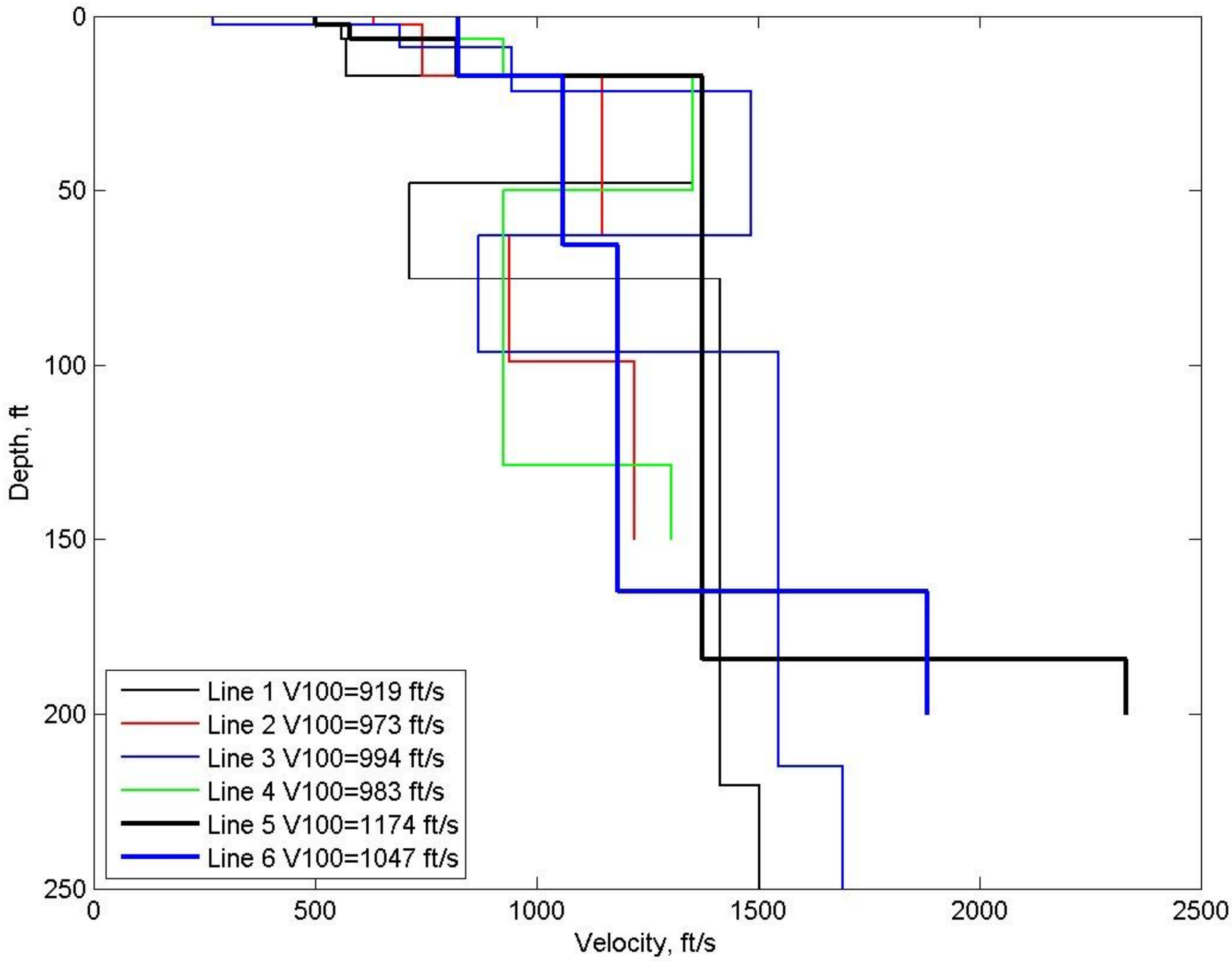


Figure 9. Preferred shear-wave velocity profiles for Wells ReMi Lines 1–6.

REFRACTION MICROTREMOR SURVEY RESULTS

Average shear-wave velocities of the upper 100 ft (30 m) were modeled for the six Wells ReMi lines and range from 879 to 1,174 ft/s (268 to 358 m/s), classifying them all as an IBC/NEHRP Site Class D (Building Seismic Safety Council, 1997).

The variable modeling for each site shows that the thicknesses, velocities, and potential velocity-inversion structure of a vertical profile are non-unique (figure 8). In some instances the models are very similar to each other, but in most there are some differences. Even so, the average V_s100-ft (V_s30-m) remains comparable. Many of the models shown in figure 8 have velocity inversions (a reduction in velocity deeper in the profile). Conventional refraction surveys often have difficulty with detecting velocity inversions but the ReMi method does not. In ReMi Lines 1 and 3, all models show a velocity inversion with depth, making this a robust feature at these sites. Lines 2, 4, 5, and 6, however, can be modeled equally well with or without a velocity inversion (figure 8). Both the thickness and the velocities of these high velocity layers above the velocity reduction are unconstrained. For example, the high velocity layer present in the models for Line 3 can either be modeled as a thin high velocity layer (1,908 to 1,551 ft/s; 582 to 473 m/s) or a thicker layer with lower shear-wave velocity (1,487 to 1,395 ft/s; 453 to 425 m/s). Higher velocity layers can trap seismic waves in overlying lower velocity layers enhancing horizontal seismic waves to resonate (Stephenson and others, 2009) and increasing the damage potential. Variation in the velocity-depth profiles due to non-uniqueness allows quantification of the model uncertainty which ranges from 10 to 40 ft/s (3 to 12 m/s; table 3). The largest model variation difference from the preferred model is relatively small, and ranges from 1% to 4%, with most values in the 1% to 2% range. Thus the model uncertainty does not greatly influence the average velocity estimate over 100 ft (30 m), but does influence the interpretation of the specific velocity structure beneath each of the sites.

The individual Wells ReMi survey lines and analysis are discussed below. Alternative models for each line are shown in figure 8, and the preferred models are shown together in figure 9 and individually in figures that accompany each discussion.

Table 3. Wells Refraction Microtremor (ReMi) Survey Shear Wave Velocity Results (ft/s)

ReMi Line	Preferred Value	Range of Values[1]	% Range from Pref.
Line 1	919	879-919	4%
Line 2	973	973-995	2%
Line 3	994	976-1,003	2%
Line 4	983	962-983	2%
Line 5	1,174	1,164-1,174	1%
Line 6	1,047	1,034-1,048	1%

[1]Variations due to different velocity-depth models that still reasonably fit the data.

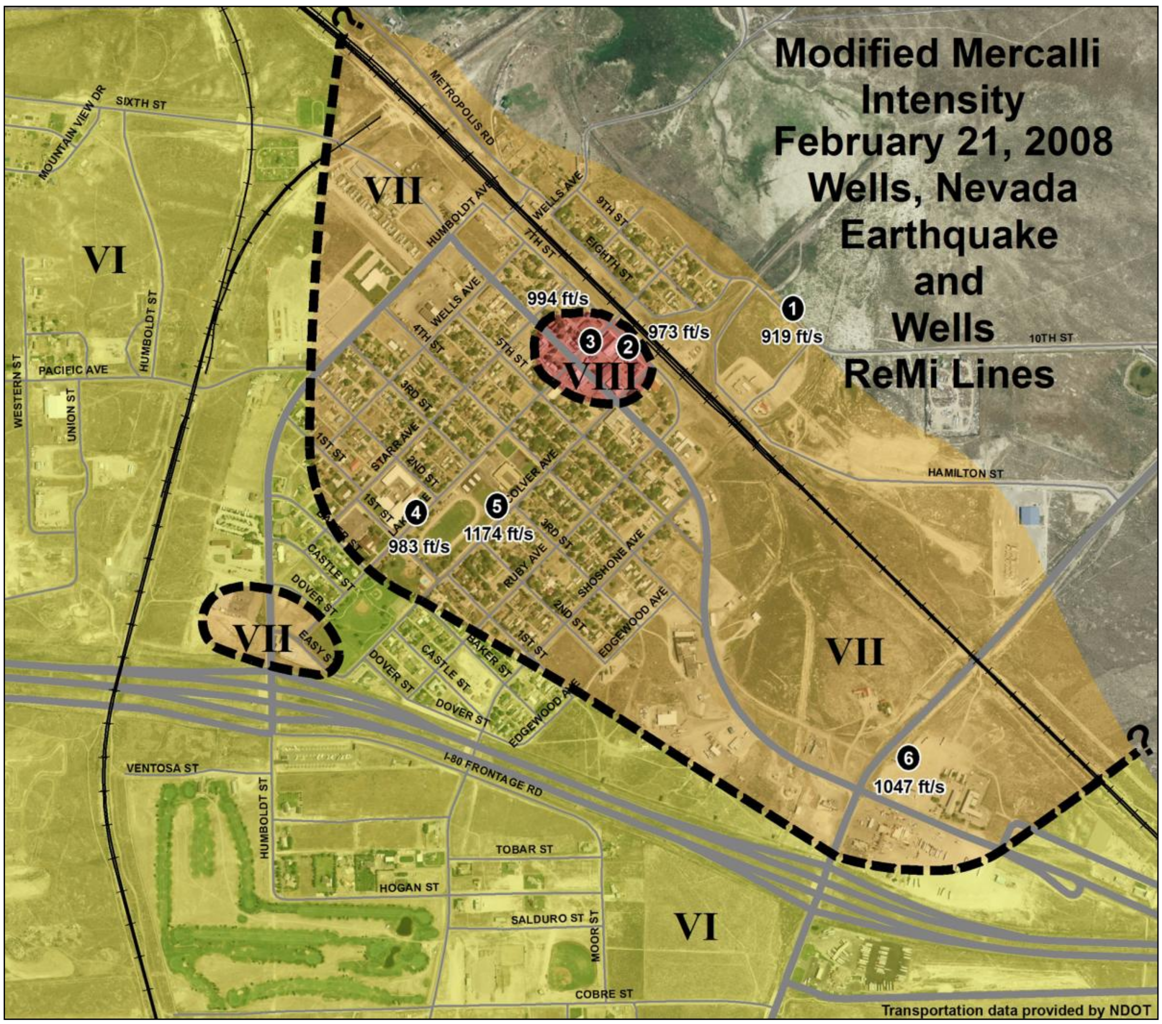


Figure 10. Wells Refraction Microtremor Lines and preferred V_s100-ft; shear-wave velocity results in ft/s. The base map is the intensity map of Wells from dePolo and Pecoraro (this volume).

WELLS REMI LINE 1

Line 1 was located in the northern part of Wells along 10th Street, just east of the old railroad tracks. This location is the closest to Town Creek and the central part of the valley, and had the youngest sediments of the all sites surveyed; it was near the margin of the active medial stream alluvium. This location was chosen because town residents pointed out the area was wet with the water table close to the surface. Damage to nearby houses consisted of broken brick chimneys and some separation between add-on portions of houses and the core structure.

Modeling of the ReMi data from Line 1 indicates NEHRP Site Class D with an average V_s100-ft (V_s30-m) of 879 to 919 ft/s, with a preferred velocity of 919 ft/s. The preferred model (figures 9 and 15) has a lower V_s layer at the near surface with between 555 and 572 ft/s, below which is a high-velocity layer which ranges in velocity and thickness from 1,167 to 1,808 ft/s (356 to 551 m/s) between 17 and 63 ft (5 and 19 m). The preferred model has this higher-velocity layer at 1,354 ft/s (413 m/s) between 17 and 32 ft (5 and 10 m). Beneath this layer there is a velocity inversion, where V_s goes from higher to lower value; an inversion was included in all the velocity models that were reasonable matches to the Rayleigh wave dispersion curve, indicating a velocity inversion with depth at this site is real. The preferred shear-wave velocity results from this site are the lowest measured in the Wells survey, consistent with the location being on the youngest deposits on which measurements were made.

Figure 11. View of 10th Street where ReMi Line 1 was laid out.

WELLS REMI LINES 2 AND 3

Lines 2 and 3 were next to the main area of damage in the Wells historical district. The lines were perpendicular to each other, with Line 2 laid out NW-SE along 7th Street (Front Street) and Line 3 laid out NE-SW along Lake Avenue; the lines intersect at the street corner. Damage in this block included collapsed and partially collapsed unreinforced masonry buildings, and numerous parapet, crowning bond beam, and wall failures (figures 3, 4, and 12). Figures 13 and 14 show parts of the deployed seismic arrays used. The site is located on distal Quaternary alluvial fan deposits (Henry and Thorman, this volume), not far from where it discharged into the medial stream channels.

Figure 12. Damage along 7th Street from the Wells earthquake. Line 2 was laid out along the edge of the street in front of these damaged buildings. The Bullshead Bar is on the corner of the street, near the intersection of Lines 2 and 3. *Photograph by C.M. dePolo.*

Figures 13. View of Wells ReMi Line 2 measured in the historical district where there was collapse and partial collapse of unreinforced masonry buildings.

Figure 14. View of Wells ReMi Line 2.

Models indicate NEHRP Site Class D with an average V_s100-ft (V_s30-m) of 973 and 994 ft/s (297 and 303 m/s), respectively, based on the preferred velocity-profile models. The full range of possible average shear-wave velocities were from 973 to 995 ft/s (297 to 303 m/s) for Line 2 and from 976 to 1,003 ft/s (297 to 306 m/s) for Line 3. Alternative velocity-profile models for both lines are shown in figure 8; the preferred model for Line 2 is shown in figures 7 and 9, and preferred model for Line 3 is shown in figures 9 and 16. These lines can be modeled to be similar with a velocity inversion between about 65 and about 100 ft (20 and 30 m) depth (see figures 7, 8, and 16). The feature that exacerbates this inversion is the relatively higher velocity layer between about 20 and about 65 ft (6 and 20 m) depth. The different velocity models for Line 3 all have a velocity inversion above about 100 ft (30 m) depth making this a robust feature at this site; thus, this velocity inversion should be considered in the evaluation of damaging ground motion in the historical district from the Wells earthquake.

The preferred V_s100-ft (V_s30-m) estimates from the adjacent Lines 2 and 3 differed by only 21 ft/s (6 m/s) and are within 2% of each other, which is an example of the repeatability of the ReMi technique.

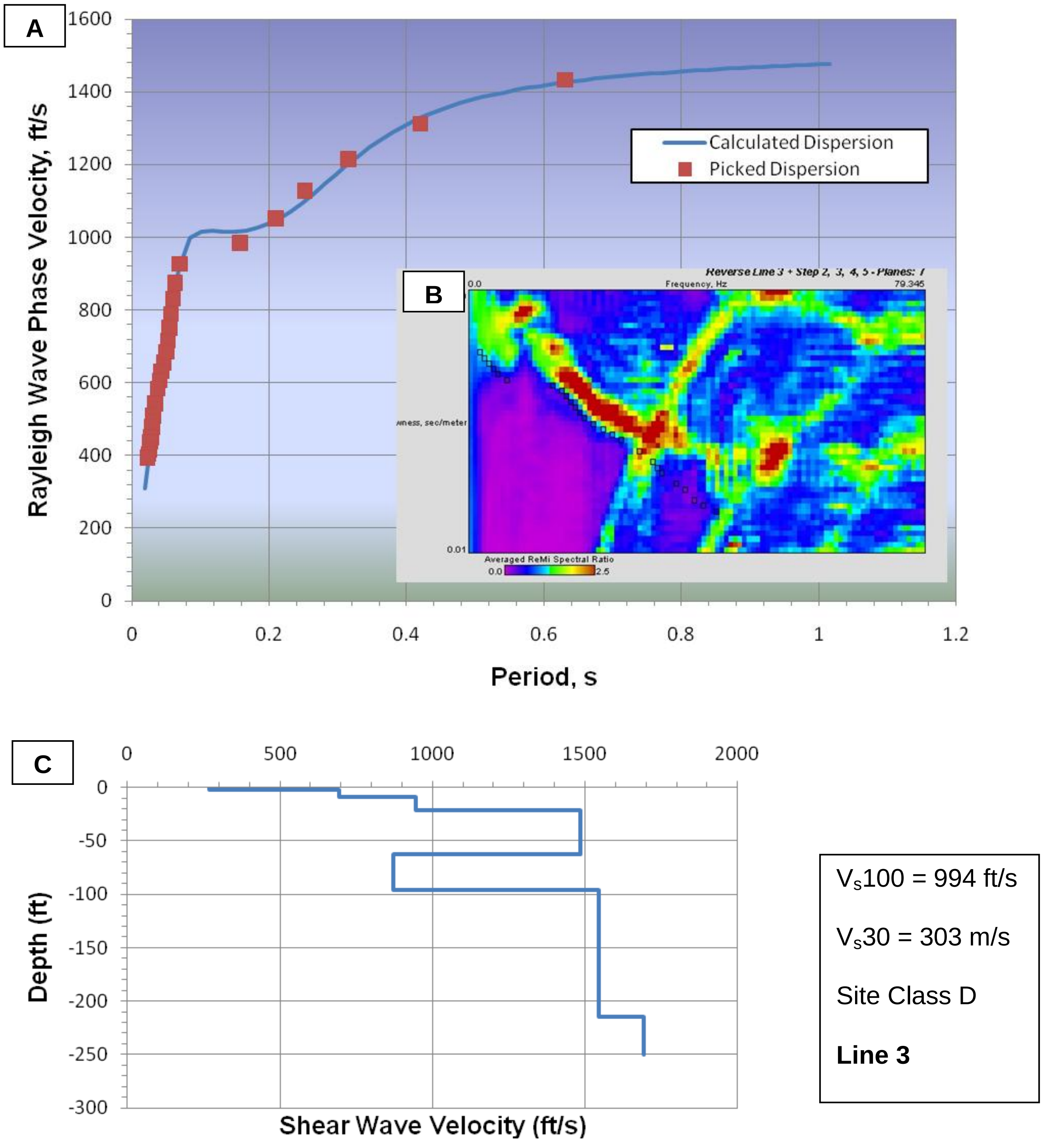


Figure 16. Results from Wells ReMi Line 3. Recorded microtremor data are first transformed into the frequency-slowness domain **(B)** and the minimum edge of the slowness contours are picked. The picked dispersion curve values are displayed on a Rayleigh wave dispersion graph **(A)** and are modeled to obtain a 1D shear-wave velocity profile **(C)**. The model shown is the preferred model; alternative models are shown in figure 8.

WELLS REMI LINE 4

Remi Line 4 was along Lake Avenue in front of the Wells High School gymnasium and auditorium which were damaged from the earthquake (figures 17 and 18) and cost about $2.5 million to repair (see Trabert, this volume). The site is on Quaternary alluvial fan deposits (Henry and Thorman, this volume).

Figure 17. Interior damage to ceiling beam in the Wells High School. *Photograph by C.M. dePolo*.

Figure 18. Interior damage in hallway at the high school. *Photograph by C.M. dePolo*.

Figure 19. ReMi Line 4 survey site with the high school behind. Jim O'Donnell for scale.

Models indicate a NEHRP Site Class D for the Line 4 site with an average V_s100-ft (V_s30-m) of 962 to 983 ft/s (293 to 300 m/s); the preferred velocity is 983 ft/s (300 m/s). Alternative velocity profile models for Line 4 are shown in figure 8 and the preferred model is shown in figures 9 and 20. The data from ReMi Line 4 can be modeled with a velocity inversion or with an increasing velocity with depth. The preferred model has a velocity inversion with a decrease of about 420 ft/s (128 m/s). The lowest average velocity model (figure 8) includes a thin, shallow higher velocity layer (2,400 ft/s; 732 m/s) below which is a velocity inversion illustrating that some very detailed structure can exist and still be a reasonable model fit.

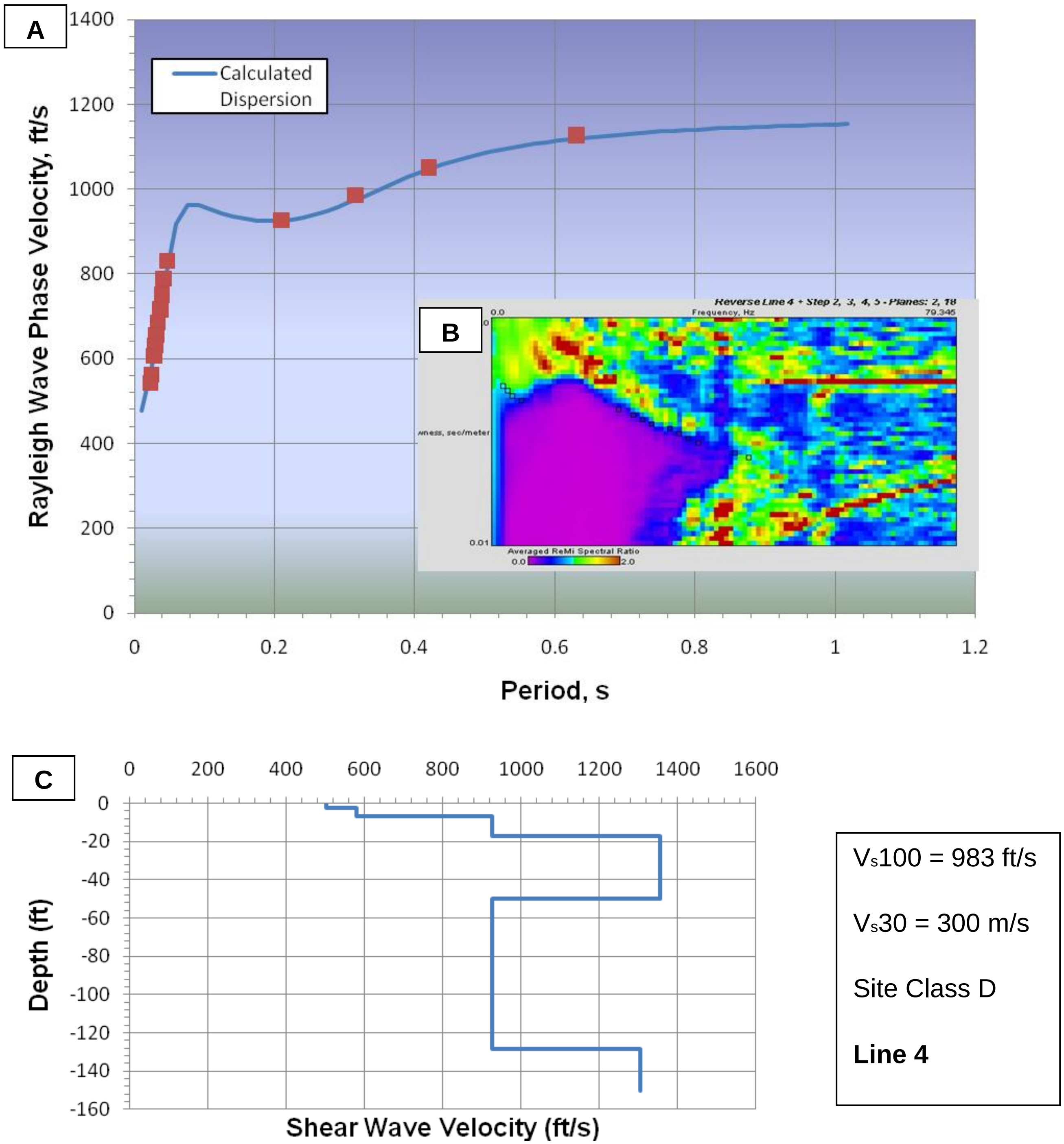


Figure 20. Results from Wells ReMi Line 4. Recorded microtremor data are first transformed into the frequency-slowness domain **(B)** and the minimum edge of the slowness contours are picked. The picked dispersion curve values are displayed on a Rayleigh wave dispersion graph **(A)** and are modeled to obtain a 1D shear-wave velocity profile **(C)**. The model shown is the preferred model; alternative models are shown in figure 8.

WELLS REMI LINE 5

ReMi Line 5 is located near City Hall and the City Shop (figure 21), which had moderate earthquake damage (Modified Mercalli Intensity VII); the line was along the western sidewalk along Clover Avenue. Line 5 is also located within 800 ft (250 m) of the high school, and ReMi Line 4. Figure 22 shows the ReMi Line 6 seismic array. The site is located on Quaternary alluvial fan deposits (Henry and Thorman, this volume).

Figure 21. Damage to the City Shop wall.

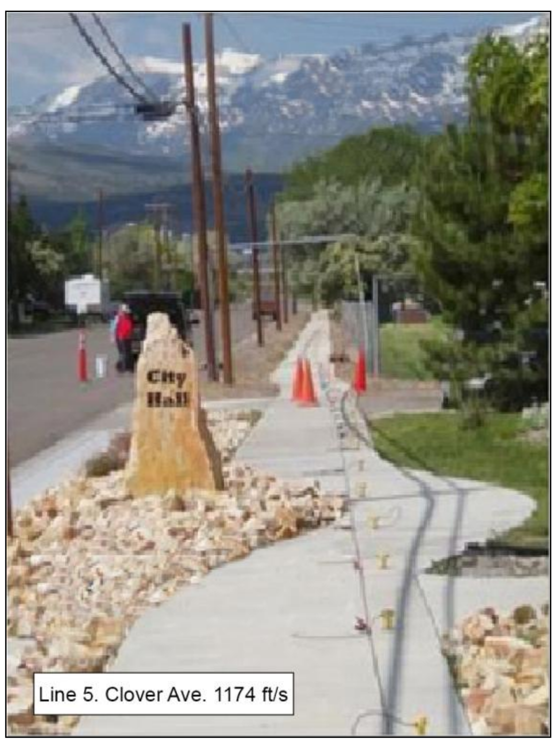


Figure 20. Seismometer array down the sidewalk in front of the City Hall. *Photograph by C.M. dePolo*.

Modeling indicates NEHRP Site Class D for the Line 5 site with an average V_s100-ft (V_s30-m) of 1,164 to 1,174 ft/s (356 to 358 m/s), and a preferred velocity of 1,174 ft/s (358 m/s). Alternative velocity profile models for Line 5 are shown in figure 8, and the preferred model is shown in figures 9 and 23. The data can be modeled to include a velocity inversion with a high velocity layer at 2,106 ft/s (642 m/s) between 23.5 and 38 ft (7 and 12 m), as seen in figure 8. The preferred model, however, does not include a velocity inversion, and has some shallow, lower velocity layers over an approximately 1,400 ft/s layer between depths of 17 and 184 ft (5 and 56 m). The preferred model has a large velocity step at about 180 ft (55 m) depth from about 1,400 ft/s (427 m/s) up to about 2,350 ft/s (716 m/s).

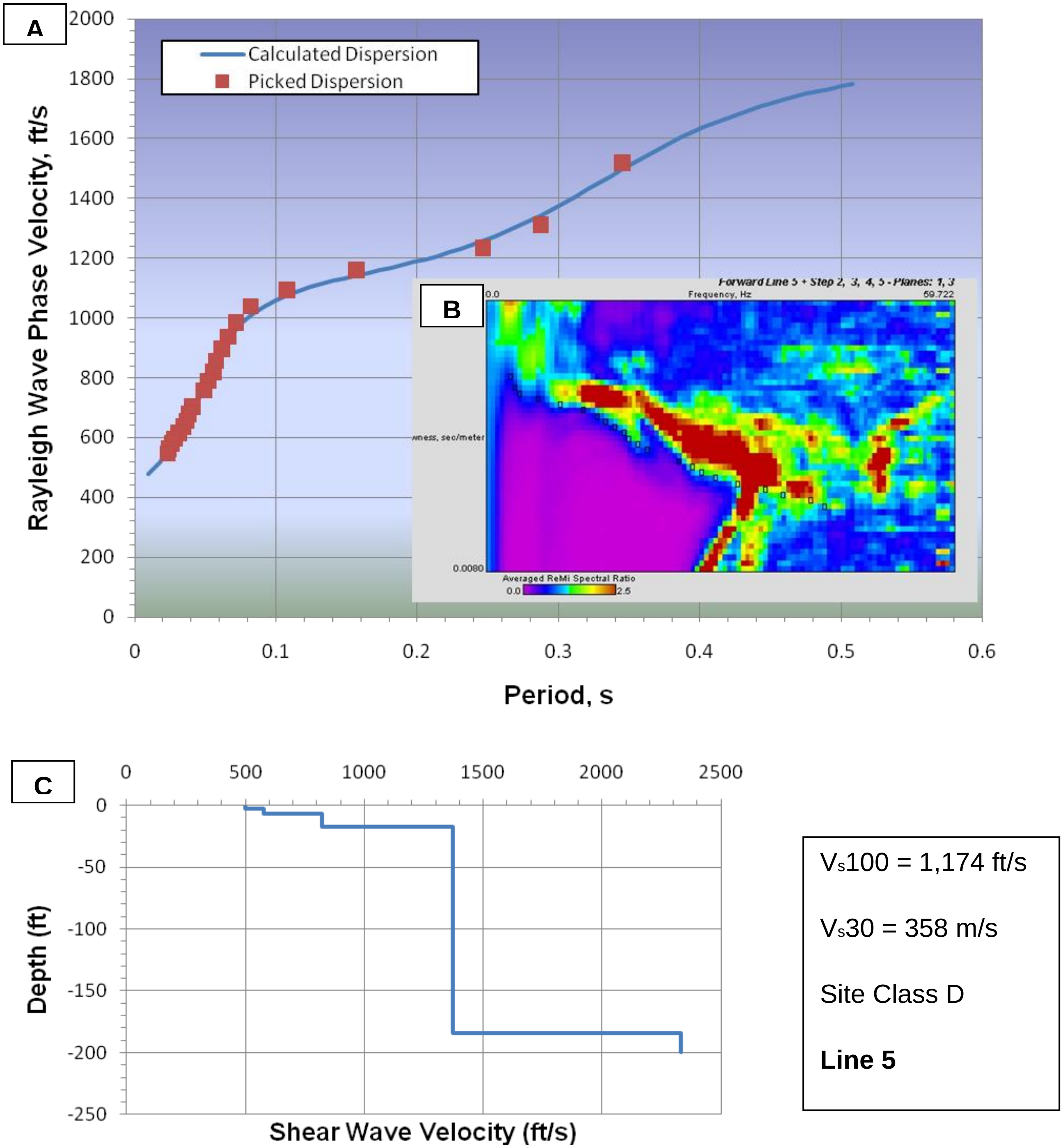


Figure 23. Results from Wells ReMi Line 5. Recorded microtremor data are first transformed into the frequency-slowness domain **(B)** and the minimum edge of the slowness contours are picked. The picked dispersion curve values are displayed on a Rayleigh wave dispersion graph **(A)** and are modeled to obtain a 1D shear-wave velocity profile **(C)**. The model shown is the preferred model; alternative models are shown in figure 8.

WELLS REMI LINE 6

The site is located about 0.6 mile (1 km) east of City Hall, in the southeastern part of town, just southeast of the 4-way intersection between Highway 93 and the old highway that preceded Interstate 80. The location had moderate, Modified Mercalli Intensity VI to VII damage from the earthquake, the most severe being structural damage to an interior wall at the 4-Way Casino (figure 24). Figure 26 is a photograph of the site. The 4-Way location is on Quaternary alluvial fan deposits (Henry and Thorman, this volume).

Figure 24. Earthquake damage at the 4-Way Casino, Nevada. Interior cracking near a column and beam. *Photograph by 4-Way employee*.

Figure 25. Nonstructural content damage. *Photograph by 4-Way employee*.

Figure 26. Seismic array used for Line 6 in the 4-Way parking lot.

Modeling indicates a Site Class D for Line 6 with an average V_s100-ft (V_s30-m) of 1,034 to 1,048 ft/s (315 to 320 m/s) and a preferred velocity of 1,047 ft/s (320 m/s). Alternative velocity profile models for Line 6 are shown in figure 8, and the preferred model is shown in figures 9 and 27. As shown in figure 8, the data can be modeled to include a very insignificant, high-velocity layer at a depth of 27 to 34 ft (8 to 10 m), below which is a velocity reversal. The preferred model, however, shows a simple stepping increase in shear-wave velocity from about 820 ft/s (250 m/s) near the surface to 1,200 ft/s (366 m/s) at 100 ft (30 m) depth.

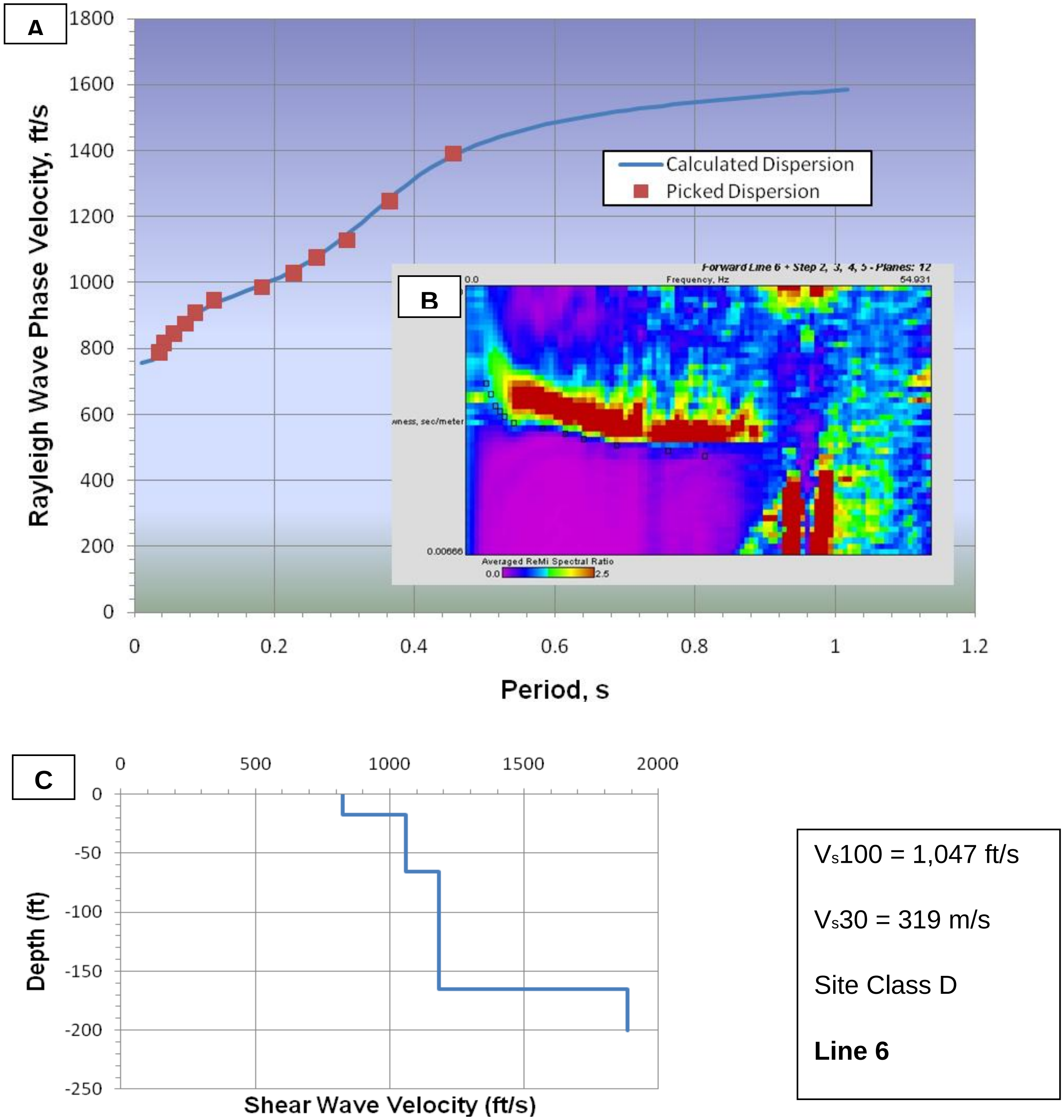


Figure 27. Results from Wells ReMi Line 6. Recorded microtremor data are first transformed into the frequency-slowness domain **(B)** and the minimum edge of the slowness contours are picked. The picked dispersion curve values are displayed on a Rayleigh wave dispersion graph **(A)** and are modeled to obtain a 1D shear-wave velocity profile **(C)**. The model shown is the preferred model; alternative models are shown in figure 8.

DISCUSSION

The ReMi models developed are typical of velocity models seen in basins within Nevada and the Basin and Range Province. Many show a velocity inversion with some variation and a more competent rock type at depths greater than 150 ft (46 m). All the V_s models are between 1,500 and 2,400 ft/s (650 and 910 m/s) below about 220 ft (67 m); this is probably not basement rock but more likely a cemented sandstone or conglomerate deposit. All preferred velocity models have a shallow (20 ft; 6 m depth) low velocity surface layer (<1,000 ft/s; < 305 m/s) underlain by a layer of higher velocity. Lines 2 and 3 from the Wells historical district, where the damage was quite severe, show the large increases from lower to higher velocities at this interface; this could be a source of enhancing horizontal seismic waves to resonate in the shallow layers.

ReMi models are non-unique, which means we can fit many different models to the field data and still obtain reasonable fits. It is always best to constrain the models with borehole logs or other geophysical methods like seismic reflection/refraction, resistivity, or gravity and magnetic surveys. Our velocity models can be changed by modifying the shear-wave velocity layer values, but correspondingly, we also need to change layer thicknesses and depths appropriately to maintain a valid model. It is important to note that ReMi model velocities are the averages along our lines of approximately 470 ft (143 m), and it is likely some variation about this average exists along these lines. On the other hand, the non-unique models had only a small effect on the V_s100-ft (V_s30-m) values, causing a variation of only 1% to 4% in velocity values, with most values being within 1% to 2%.

RECOMMENDATIONS FOR FUTURE STUDIES

Data collection could be improved by including hammer shots to enhance high frequency data content of the dispersion curve. These high frequency data would help further define the shallow velocity structure and therefore add constraint to the depth and velocity of any observed high-velocity layers above velocity inversions. Additional geological and geophysical data from well logs in the region would also help constrain the models. Well log data may provide an understanding as to what is causing the velocity increases and velocity inversions, at what depth ranges the velocity changes are present, and most importantly will be used to help determine the velocity range of the higher-velocity layers. Although refraction surveys are unable to effectively resolve velocity inversions, P-wave refraction surveys obtained in the same location as the ReMi surveys would help constrain velocities of the surrounding material, providing additional constraint to the velocity-depth modeling.

The aim of the project was to correlate the average V_s100-ft (V_s30-m) with observed surface damage from the Wells earthquake. The goal was not to obtain specific velocity-depth profiles, although we produced and displayed models of profiles. Thus, it was not necessary to perform perpendicular arrays, but the arrangement of ReMi Lines 2 and 3 as such was a useful experiment. The preferred models for Lines 2 and 3 (figure 8), which are perpendicular in orientation and intersect, show little difference (21 ft/s; 6 m/s or about 2%) in the average shear-wave velocity to 100 ft (30 m) depth. The preferred models for these lines are also similar in overall structure and include a velocity inversion at about 65 ft (20 m) depth. The recording of Love waves using horizontal geophones is also not necessary if the goal is to determine average V_s30 values, but may provide a useful constraint of the velocity-depth structure. Presently no seismic application warrants such finely detailed velocity-depth structure for engineering purposes. However, for understanding finer details of ground motion for future applications, velocity profiles on this small scale may be useful.

Recording of the horizontal component of motion, which requires using horizontal geophones, along with the vertical component would allow calculation of the Horizontal (H) to Vertical (V) Spectra Ratio (HVSR) method (Nakamura, 1989). Nakamura proposes that the site response can be estimated from the spectral ratio of horizontal versus vertical components of microtremor noise recorded at the site, based on the assumption that only shear-waves are influenced by the soil structure. As both the horizontal and vertical motions retain source and path spectral characteristics, the vertical motion can be used to remove these effects from the horizontal motion to obtain the influence of local geological site conditions on ground motion. This technique may help identify amplification and resonance of horizontal seismic waves trapped in a near-surface, low-velocity layer underlain by a very high velocity layer (Stephenson and others, 2009). As shown in figure 8, each of the ReMi lines can be modeled to include a high velocity layer below which there is a velocity reversal. These high-velocity layers may impede seismic wave propagation, trapping them in the low-velocity, near-surface layers.

A follow-up study should be considered that would add more ReMi measurement sites in Wells, including some sites where damage was limited, and would include some shallow drilling in the Wells historical district, and potentially elsewhere, to measure shear-wave velocities directly, develop detailed velocity profiles for comparison with ReMi results, and to identify rock types and material properties of the shallow soils. Further studies could correlate recorded ground motion of the Wells earthquake with V_s100-ft (V_s30-m) measurements obtained at the seismic station locations. Site response functions relative to a rock site can be derived from recordings of the Wells earthquake to determine relative amplification. Comparison of soil-to-rock spectral amplification has indicated a strong correlation for the Reno area

(Pancha, 2007). These response functions can be compared with those HVSR at the site obtained from the ambient noise recordings to further enhance our understanding of the recorded ground motions.

CONCLUSIONS

Refraction Microtremor (ReMi) data were collected at six sites that sustained damage from the 2008 M_w 6.0 Wells earthquake. Forty-eight vertical geophones with 10-ft (3-m) spacing were used in approximately 470-ft (143-m) lines, assuring that measurements could be modeled for penetration to at least 100 ft (30 m) in depth with good resolution. The data were analyzed following the ReMi methodology, multiple shear-wave velocity-profile models were developed for each site, and estimates of the average shear-wave velocity (V_s) for the upper 100 ft (30 m) were made (V_s100-ft; V_s30-m). Estimates were made of the preferred velocity-profile model and the range of models that could reasonably fit the data and interpretations, and these were promulgated into the average velocity estimates.

Average shear-wave velocities of the upper 100 ft (30 m) were modeled for the six Wells ReMi lines and range from 879 to 1,174 ft/s (268 to 358 m/s), classifying them all as an IBC/NEHRP Site Class D. The preferred V_s100-ft (V_s30-m) estimates ranged from 919 to 1,174 ft/s (280 to 358 m/s).

The range of models that could reasonably fit the analysis of the slowness-frequency diagram data was explored. The velocity-depth modeling is non-unique and different velocity-profiles could reasonably explain the data. This non-uniqueness of models did not have a large effect on the estimates of the V_s100-ft (V_s30-m), but it does illustrate that there were several different velocity-depth profiles possible at each site that fit the data. The impact of model non-uniqueness on the average shear-wave velocity estimate was 1% to 4% about the preferred value, with most values being within 1% to 2%. At two sites, the range in models considered all had velocity inversions in the profile, making this a more robust feature in the profile supported by the data and analysis. The other four lines could be modeled with or without a velocity inversion, making this feature less certain at those sites. Additional information is needed to constrain the velocity-depth profile, which can have an important influence on strong-ground motion.

ReMi Lines 2 and 3 were in the Wells historical district, were perpendicular to each other, and intersected each other. The preferred V_s100-ft; V_s30-m estimates from Lines 2 and 3 differed by only 21 ft/s (6 m/s) and are within 2% of each other. Also a fairly similar velocity-depth profile was chosen for these sites, one which could be modeled with a robust velocity inversion with depth. The measurements confirm that the ReMi method is repeatable and demonstrate that multiple measurement lines at the same site are redundant for estimating V_s100-ft (V_s30-m), but may be useful for gaining more constraints on the velocity-depth profile.

The six measurements made are important for the initial characterization of the V_s100-ft (V_s30-m) in Wells, and do show a rough correlation with damage, but this limited dataset has to be kept in mind when generalizing on the relationships between V_s100-ft (V_s30-m), which might be considered to be only "suggestive" in nature. The lowest velocity estimate (Line 1–919 ft/s; 280 m/s) correlated with the youngest geologic unit sampled, the edge of active medial stream deposits. Fortunately building is limited on these deposits, but some nearby houses had chimney damage that can be considered Modified Mercalli Intensity VII. ReMi Lines 2, 3, and 4 were in areas with severe damage, such as out-of-plane upper wall failures, that correlated with Modified Mercalli Intensity VII to VIII. The preferred V_s100-ft (V_s30-m) estimates of Lines 2, 3, and 4 are remarkably similar, 973 ft/s (297 m/s), 994 ft/s (303 m/s), and 983 ft/s (300 m/s), respectively, suggesting a potential correlation between intensity VII to VIII damage to unreinforced masonry buildings and velocities in the range of 973 to 994 ft/s (297 to 303 m/s), or less. Lines 5 and 6 had the highest V_s100-ft (V_s30-m) measured in Wells, 1,174 ft/s (358 m/s) and 1,047 ft/s (319 m/s), respectively; these sites had limited but serious damage to buildings that would correlate with Modified Mercalli Intensity VII. Wells ReMi Lines 2–6 were located on Quaternary alluvial fan deposits. The most general statement that can be made is that significant earthquake damage occurred to unreinforced masonry buildings in areas that are IBC/NEHRP Site Class D.

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