Thickness and shear-velocity mapping of Holocene-Pleistocene sediments by array studies of microtremors

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INVESTIGATIONS UNDERTAKEN

There are four phases of work incorporated in this project:

- Acquire a cross-section of ten sites of SPAC observations across the Santa Clara Valley, using a triangular "pyramid" array designed for SPAC observations in urban areas. Stitch the site interpretations into a 2D or 3D velocity model of the upper 500 m of the sediments, in a form suitable for computation of strong-motion site responses.
- Develop an automatic de-spiking algorithm for removing the signature of occasional vehicle traffic passing adjacent to any station of a SPAC array.
- Develop an operational inversion program for interpretation of SPAC data, fitting model and field data in coherency space.
- Prepare public relations material for residents of streets where urban arrays are to be sited.

SITES

Observations were conducted at seven sites as shown in Figure 1, supplementing the five sites previously surveyed in 2004. Whereas sites in 2004 were selected where possible to be in public parks, this year the method was extended to the more generally-available site type of suburban streets.

RESEARCH OBJECTIVES

Characterization of the thickness and softness of geologically-young river and Bay-area sediments is a necessary part of earthquake hazard zonation. This project uses measurement of natural earth vibrations called microtremors, caused by urban road traffic and machinery. By using seismic arrays of typically seven seismometers placed for a few hours on suburban streets, a profile of sediment softness (shear-velocity) vs depth is obtained. The project applies the method at a series of sites across the Evergreen Basin (east Santa Clara valley).

APPROACH

- Collaborate with USGS and other personnel in synthesis and publication of the various “blind” trials of active and passive seismic methods at deep drill-holes in the Santa Clara Valley.
- Demonstrate viability of seismic arrays placed in residential streets for acquisition of sufficient data for non-intrusive measurement of Vs30 and Vs300. Acquire a profile from sites across the Evergreen basin, and compare with existing shear-velocity models.
- Develop a prototype inversion software for SPAC data operating on coherency spectra (as distinct from the conventional approach of inverting phase-velocity dispersion curves).

ACCOMPLISHMENTS

The array geometry developed in previous years was applied to a set of sites across the Evergreen basin and provides accurate Vs30 information, including detection of low-velocity layers of silts within the top 20 m. The method provides Vs data to depths of at least 300 m with approximately half a day of field operations, without requiring drilling, disruption to road traffic, or access to private property borehole drilling and logging.

Figure 1 shows locations of the seven microtremor arrays used in 2004 (red, for water boreholes) and in 2005 (purple).

Coordinates of the centers of the arrays are shown in Table 1. Triangular arrays with side lengths from 33 m to 300 m were used at each site in order to resolve layers from about 3 m depth to order 500 m depth.

TABLE 1

MICROTREMOR OBSERVATIONS SANTA CLARA VALLEY
ARRAY BASELINE CENTERS

FeatureName	FeatureNumber	PointNa	PointNu	GPS_time	GPS_Sta	Y (Degrees La	X (Degrees Lon	Height (m)
IMap Version 3.4.0 (build 9) by Sokkia Inc.. Projection: U.S.A. (NGS) UTM NAD 1983 10 126 W - 120 W Coord: Degrees Lat/Lon (W								
12thSt	cnr Jackson St	g	9	8/08/1999 4:22	2	37.3522993	-121.8868992	20.833
19thSt	cnr Jackson St	g	9	8/07/1999 5:35	2	37.3553168	-121.8805508	20.867
LasPlumas	cnr Lenfest Ave	gg	10	8/08/1999 9:03	2	37.3628896	-121.8694279	26.213
Pacheco	cnr Webster Dr	g	7	8/11/1999 6:35	2	37.3718091	-121.8562708	34.377
FoxRidge	cnr PT CR Dr	g	11	8/11/1999 9:51	2	37.3838515	-121.8489805	50.691
SanMardo	cnr Gridley St	ggg	8	8/10/1999 9:47	2	37.3893562	-121.8369097	62.681
WillowRiverside Dr	cnr Coe Ave	gg2	7	8/09/1999 5:40	2	37.3157667	-121.9023952	31.45
IMap Version 3.4.0 (	by Sokkia	Inc.. Pr	UTM	NAD 1983	10 126 \	Coord: Degrees Lat/Lon (WG		Distance: N

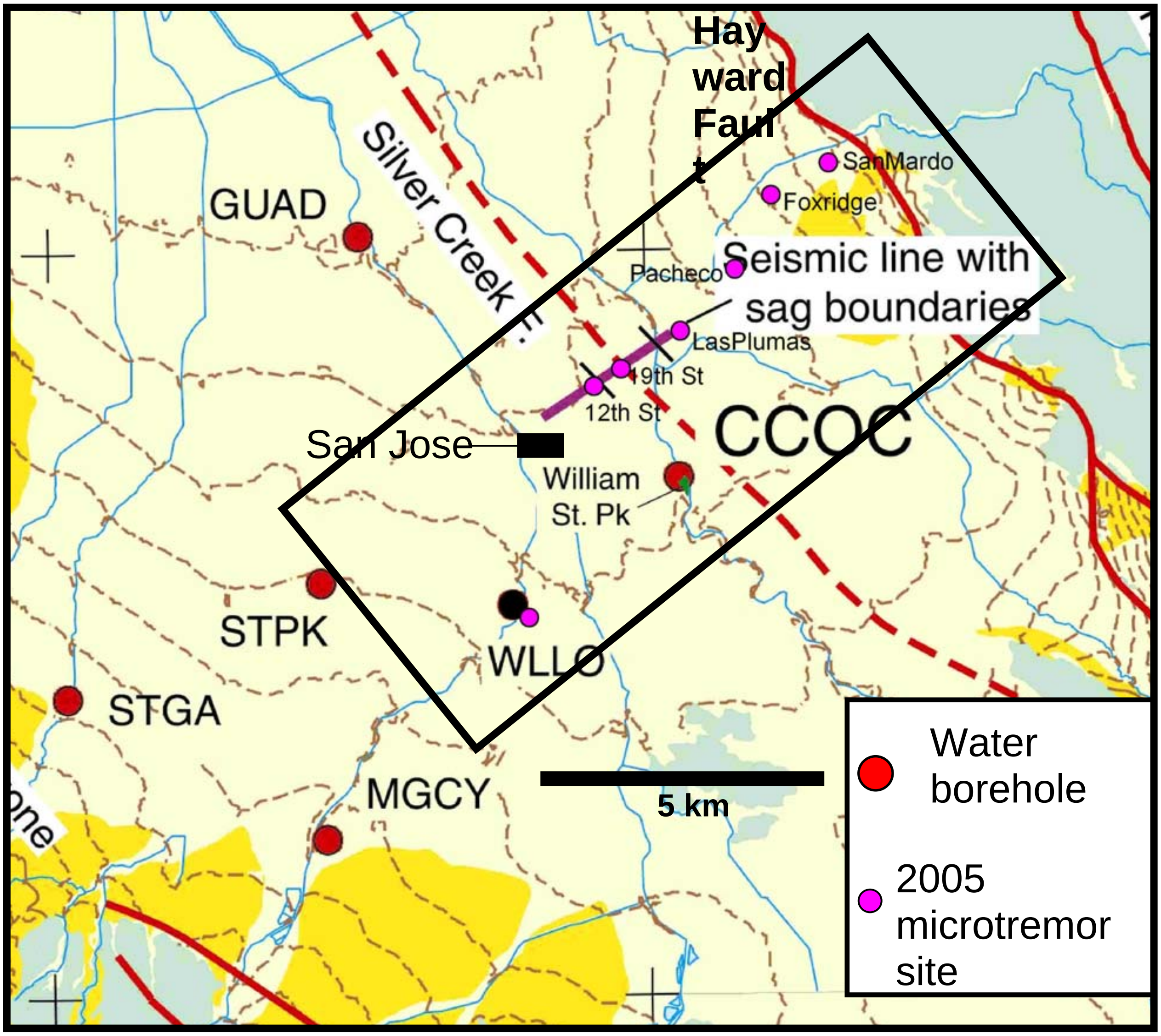

Fig. 1. Location of microtremor array sites at selected water boreholes, and for a traverse across the Evergreen basin, north-west of San Jose, between the Silver Creek and Hayward faults. (Geologic map supplied by C. Wentworth).

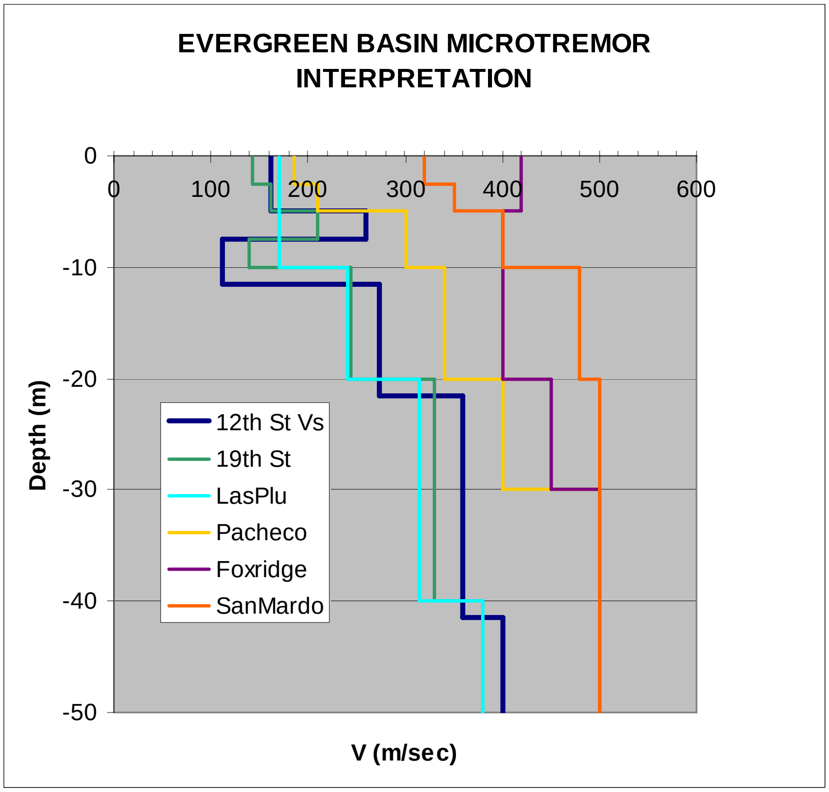

Fig. 2. Shear-velocity Vs profiles at six sites across the Evergreen basin, measured using microtremor array methods. The sites lie along a SE-NW profile, with 12th St being at the western edge of the basin, above (or a few hundred meters west of) the Silver Creek fault. Pacheco is near the center of the basin. San Mardo is at the eastern edge of the basin.

Fig. 2 shows interpreted vertical profiles of Vs with depth for the upper 50 m of sediments, at three sites representing the west edge, center, and east edge of the Evergreen basin (a total cross-section distance of about 5 km). The shear velocity Vs in the upper 50 m increases from the west margin towards the east by more than a factor of two. Figure 3 shows a comparison of these results with previous data based on active seismic measurements (Hartzell et al, 2003). The ability of the microtremor method to identify the very soft near-surface layer at the western margin has implications for site hazard assessment.

The set of layered-earth interpreted models down to basement are included as Appendix A.

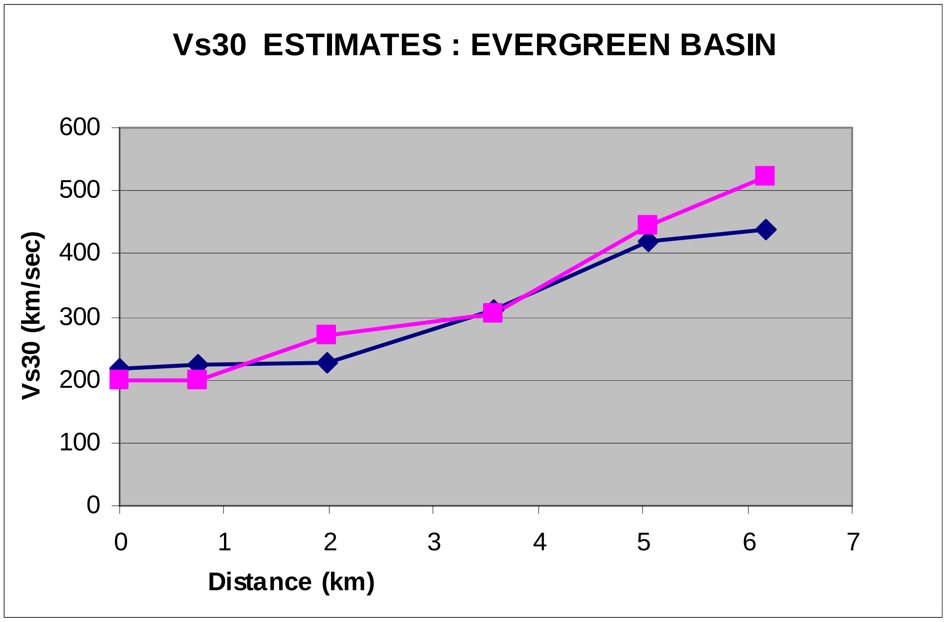

Fig. 3. Vs30 estimates, Evergreen Basin in locality of the San Jose strong motion seismic array.
Blue: Estimates from microtremor methods.
Pink: Estimates interpolated from map based on active seismic measurements by Hartzell et al 2003 (Hartzell, S., Carver, D., Williams, R.A., Harmsen, S. and Zerva, A., 2003, Site response, shallow shear-wave velocity, and wave propagation at the San Jose, California, dense seismic array: Bulletin of the Seismological Society of America, Vol. 93, No. 1, pp. 443–464).

The results are discussed in greater detail in papers delivered at the N. California Earthquake Hazard Workshops, and SSA Meetings, 2005 and 2006. Copies are available online as noted in the Publications list below.

SIGNIFICANCE OF FINDINGS

The tools developed allow non-invasive measurement of the shear-velocity profile to depths of at least 300 m, typically 500-1000 m, in urban areas. The cost is of order $2000 compared with $16000-$30000 for a borehole with geophysical logs. The microtremor method is a cost effective tool for earthquake hazard site classification, and for construction of 3D shear-velocity models of urban sedimentary basins.

PUBLICATIONS (FYO5)

(all publications other than journal publications are available from the website www.geosci.monash.edu.au/research/CEGAS).

Asten, M.W., and Boore, D.M., 2005, Comparison of shear-velocity profiles of unconsolidated sediments near the Coyote borehole (CCOC) measured with fourteen invasive and non-invasive methods: USGS OFR 2005-1169.

Asten, M.W., 2005, Method for site hazard zonation, Santa Clara valley: Thickness and shear-velocity mapping of Holocene-Pleistocene sediments by array studies of microtremors: USGS OFR 2005-1169.

Asten, M.W., 2005, Thickness and shear-velocity mapping of Holocene-Pleistocene sediments by array studies of microtremors: Paper presented at the USGS 2nd Annual Workshop on Earthquake Hazards, Menlo Park, 17-18 January 2005. (Slides available)

Asten, M.W., and Boore, D.M., 2005, Microtremor methods applied to hazard site zonation in the Santa Clara Valley: Paper presented at the Annual Meeting, Seismological Society of America, Lake Tahoe, April 2005. (Poster available).

Asten , M.W., Stephenson, W.R., and Davenport, P., 2005, Shear-wave velocity profile for Holocene sediments measured from microtremor array studies, SCPT, and seismic refraction: Journal of Engineering and Environmental Geophysics: v. 10, no 3, pages 235-242.

Asten MW, Lam N.T.K., Srikanth, V., Rutter, H. and Wilson, J.L. (2005) The importance of shear wave velocity Information of a soil site. Earthquake Engineering in Australia, Proceedings of a conference of the Australian Earthquake Engineering Soc., Albury NSW, Paper 36.

Asten, M.W., 2005, On bias and noise in passive seismic data from finite circular array data processed using SPAC methods: Geophysics, submitted.Lam, N.T.K., Venkatesan, S, Wilson, J.L., Asten, M.W., Roberts, J., Chandler, A.M., & Tsang, H.H., (2005) Generic Approach for Modelling Earthquake Hazard, Journal of Advanced Structural Engineering, in press.

Asten, M.W., 2006, Shear-velocity profile across the Evergreen Basin using microtremor array studies: Paper presented at the USGS 3rd Annual Workshop on Earthquake Hazards, Menlo Park, 18-19 January 2006. (Slides available).

Asten, M.W., and Boore, D.M., 2006, Shear-velocity profile across the Evergreen Basin using microtremor array studies: Paper presented at the Annual Meeting, Seismological Society of America, San Francisco, April 2006. (Poster available).

Sorensen,C, and Asten, M. (2005) Comparison of shear wave velocity profiles of Quaternary sediments in the Newcastle area estimated from SCPT, microtremor spectral ratios and array studies, and drilling. Earthquake Engineering in Australia, Proceedings of a conference of the Australian Earthquake Engineering Soc., Albury NSW., Paper 9.

Roberts, J., and Asten, M.W., 2005, Estimating the shear velocity profile of Quaternary silts using microtremor array (SPAC) measurements: Exploration Geophysics, v.36, 34-40.

Tsang H.H., Roberts J., Asten M.W., Chandler, A.M., Lam N.T.K., and Chan, L.S. (2005) Modelling Shear Wave Velocity Profiles in Rock using the Microtremor Spatial Auto-Correlation Technique: the Hong Kong Case Study. Earthquake Engineering in Australia, Proceedings of a conference of the Australian Earthquake Engineering Soc., Albury NSW, Paper 32.

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NON-TECHNICAL SUMMARY

Characterization of the thickness and softness of geologically-young river and Bay-area sediments is a necessary part of earthquake hazard zonation. The techniques under development in this project measure natural earth vibrations called microtremors, caused by urban road traffic and machinery. By using arrays of seismometers placed for a few hours on suburban streets, sufficient data can be gained to interpret a softness versus depth profile to depths of up to 1 km, without using expensive drilling (typically $16,000 per hole) or active seismic surveys. Measurements at sites in the Santa Clara valley having detailed independent data provided by the San Jose strong motion Array and active seismic investigations, proves the microtremor method to be effective.

APPENDIX

Layered earth models interpreted for all 2004 and 2005 sites used in the Santa Clara Valley

CCOC

We have two models of interest:
CoyPkDec2 is the best truly blind result which honors the array data but not the HVSR data. It gives a depth to basement closest to the independent estimate from Williams et al seismic line.

PkDec2.dat

H	VP	VS	RHO	
10.	360	180	1.78	
10	1700	230.	1.78	
50	1700	340.	1.78	
60	1700	440.	1.78	
100	1800	750	2.0	
190	1800	750	2.0	
3000	2380	1200	2.0	Total depth to Franciscan 420 m
1000.	2940	1700	2.39	
0.	6040	3490	2.8	

The later model PkApr04e is not truly blind (was done after talks with Bill Stephenson) but it honors both the array and HVSR data. Unfortunately it has a poorer correlation (but still believable) with Williams depth to Fransciscan.

This model is probably the better reference since the learning process which produced the dual fit of array and HVSR data was then used for subsequent sites.

PkApr04e.dat

H	VP	VS	RHO	
3.	360	144	1.78	
7.	360	180	1.78	
10	1700	230.	1.78	
20	1700	340.	1.78	
35	1700	340.	1.78	
55	1700	440.	1.78	
140	1800	750	2.0	
250	1800	750	2.0	
500	2380	1200	2.39	Total Depth to Franciscan 520 m
3000	2380	1700	2.39	
1000.	2940	1700	2.39	
0.	6040	3490	2.8	

GUAD

Guad7e is best result for large array

H	VP	VS	RHO	
5.	360	190	1.78	
5.	1700	190	2.	
20	1700	244.	2.	
25	1700	330	2.	
65	1700	380	2.	
100	1800	580	2.1	
155	1800	580	2.1	
500	2980	1200	2.39	Total Depth to Franciscan 375 m
3000	2980	1700	2.39	
1000.	2940	1700	2.39	
0.	6040	3490	2.8	

STGA Saratoga general area

Stga5 is the best model which fits array data although some conflict with HVSR data which seems require deeper basement, but a deeper basement violates array data fit.

H	VP	VS	RHO	
5.	560	330	1.78	
5	1700	330.	2.	
10	1700	400.	2.	
25	1700	440.	2.	
50	1700	530.	2.	
100	1800	760	2.1	
490	1800	760	2.1	
500	2380	1200	2.39	Total Depth to Franciscan 685 m
3000	2940	1700	2.39	
1000.	2940	1700	2.39	
0.	6040	3490	2.8	

SNPK Santana Pk

Snpk9 is the best model; fits array data and god fit with HVSR data

H	VP	VS	RHO	
5.	560	240	1.78	
10	1700	270.	2.	
6	1700	200.	2.	
15	1700	400.	2.	
50	1700	450.	2.	
50	1700	670.	2.	
100	1800	850	2.1	
290	1800	850	2.1	
500	2380	1200	2.1	Total Depth to Franciscan 526 m
3000	2940	1700	2.39	
1000.	2940	1700	2.39	
0.	6040	3490	2.8	

MCGY

Mcgy8 is best fit of poor data; large array is noisy at this site and depth to Franciscan is not reliably resolved in array data.

However HVSR data does provide a constraint using a station reasonably free of cultural noise. This is still open – I am reinterpreting using lessons from the data east of the Silver Ck fault. Best estimate from HVSR thus far is

Mcgy8

H	VP	VS	RHO	
2.	560	315	1.78	
8	1700	315	2.	0
25	1700	480.	2.	
45	1700	640.	2.	
70	1800	900	2.0	
290	1800	900	2.0	
500	2380	950	2.1	
3000	2940	1700	2.39	Total Depth to Franciscan 940 m
1000.	2940	1700	2.39	
0.	6040	3490	2.8	

WLLO

Preferred model matches array data, and v good fit to HVSR data

Wllo3a

H	VP	VS	RHO	
5	360	165	1.78	
5.	1700	210	2.	
10	1700	260.	2.	
20	1700	330	2.	
40	1700	440	2.	
140	1700	660	2.	
1000	2800	1500	2.2	Total Depth to Franciscan 220 m (preferred result)
.3000	3300	1700	2.3	
0.	6040	3490	2.8	

Alternative – NOT preferred model
Wllo5.dat is best fit for array data alone, but poor for HVSR

H	VP	VS	RHO	
5	360	165	1.78	
5.	1700	210	2.	
10	1700	260.	2.	
20	1800	340	2.	
40	1800	420	2.	
60	2100	600	2.1	
30	2200	730	2.1	
500	3700	2000	2.4	Total Depth to Franciscan 170 m
2500	3700	2000	2.4	
0.	6040	3490	2.8	

12th St
By analogy with CCOC and GUAD we may interpret Franciscan basement when Vs is 1200 m/sec

12thSt7 is best model

H	VP	VS	RHO	
5	360	162	1.78	
2.5	1700	260	2.	
4	1700	111	2.	
10	1700	274.	2.	
20	1700	360	2.	
40	1700	400	2.	
80	1700	430	2.	
140	2200	830	2.1	
250	2200	830	2.1	
300	2800	1200	2.2	Total Depth to Franciscan 551 m
3000	3300	1700	2.3	
1000.	3300	1700	2.3	
0.	6040	3490	2.8	

19thSt

By analogy with CCOC and GUAD we may interpret Franciscan basement when Vs is 1200 m/sec
19thSt8 is best model

H	VP	VS	RHO	
2.5	360	142	1.78	
2.5	360	162	1.78	
2.5	1700	210	2.	
2.5	1700	140	2.	
10	1700	244.	2.	
20	1700	330	2.	
40	1700	380	2.	
80	1700	490	2.	
100	2200	830	2.1	
155	2200	830	2.1	
500	2800	1200	2.2	Total Depth to Franciscan 415 m
3000	3300	1700	2.3	
1000.	3300	1700	2.3	
0.	6040	3490	2.8	

LasPlumas

By analogy with CCOC and GUAD we may interpret Franciscan basement when Vs is >=1200 m/sec, but Wentworths geological sketch may not support Franciscan here
The model as controlled by HVSR frequency maximum interpretation suggests a depth of 1660 to an interface similar to Franciscan, however the shape of the HVSR curve indicates the layered model is more complex and probably more gradational than the model below.

LasPlumas2_gradbase.dat

H	VP	VS	RHO	
10.	1700	170	2.	
10	1700	240.	2.	
20	1700	315	2.	
40	1700	380	2.	
80	1700	520	2.	
1500	2300	830	2.1	
1500	3200	1600	2.3	Total Depth to ?Franciscan? or similar 1660 m
1500	4000	2300	2.5	
.3000	4100	2800	2.5	
0.	6040	3490	2.7	

Pacheco

The model as controlled by HVSR frequency maximum interpretation suggests a depth of 1630 to an interface similar to Franciscan, however the shape of the HVSR curve indicates the layered model is more complex and probably more gradational than the model below.
Pacheco_gradbase5.dat

H	VP	VS	RHO	
2.5	400	185	1.78	
2.5	400	210	1.78	
2.5	1700	300	2.	
2.5	1700	300	2.	
5	1700	340.	2.	
5	1700	340.	2.	
10	1700	400.	2.	
20	2000	500	2.	
40	2000	500	2.0	
40	2100	550	2.1	
1500	2300	830	2.1	
1500	3200	1600	2.3	Total Depth to ?Franciscan? or similar 1630 m
1500	4000	2300	2.5	
.2000	4000	2300	2.5	
0.	6040	3490	2.7	

FoxRidge

Foxridge8.dat

H	VP	VS	RHO	
2.5	600	420	1.78	
2.5	600	420	1.78	
2.5	1700	400	2.	
2.5	1700	400	2.	
5	1700	400.	2.	
5	1700	400.	2.	
10	1700	450.	2.	
20	2000	500	2.	
40	2000	500	2.0	
250	2100	600	2.1	
200	2300	830	2.1	
1500	3500	1800	2.5	Total Depth to ?Franciscan? or similar 520 m
1500	3500	1800	2.5	
1500	3500	1800	2.5	
0.	6040	3490	2.8	

SanMardo

SanMardo5.dat

H	VP	VS	RHO	
2.5	600	320	1.78	
2.5	600	350	1.78	
2.5	1700	400	2.	
2.5	1700	400	2.	
5	1700	480.	2.	0.
5	1700	480.	2.	0
10	1700	500.	2.	
20	2000	500	2.	
60	2000	500	2.0	
230	2100	700	2.1	
400	2300	930	2.1	
1500	3500	1800	2.5	Total Depth to ?Franciscan? or similar 740 m
1500	3500	1800	2.5	
1500	3500	1800	2.5	
0.	6040	3490	2.8	