SHEAR-WAVE VELOCITY COMPILATION FOR NORTHRIDGE STRONG-MOTION RECORDING SITES

Roger D. Borcherdt and Thomas E. Fumal

U.S. Geological Survey Report
Open-File Report Number 2002-107

March 7, 2002

Shear-Wave Velocity Compilation for Northridge Strong-Motion Recording Sites

Roger D. Borcherdt and Thomas E. Fumal

ABSTRACT

Borehole and other geotechnical information collected at the strong-motion recording sites of the Northridge earthquake of January 17,1994 provide an important new basis for the characterization of local site conditions. These geotechnical data, when combined with analysis of strong-motion recordings, provide an empirical basis to evaluate site coefficients used in current versions of US building codes. Shear-wave-velocity estimates to a depth of 30 meters are derived for 176 strong-motion recording sites. The estimates are based on borehole shear-velocity logs, physical property logs, correlations with physical properties and digital geologic maps. Surface-wave velocity measurements and standard penetration data are compiled as additional constraints. These data as compiled from a variety of databases are presented via GIS maps and corresponding tables to facilitate use by other investigators.

INTRODUCTION

Ground shaking generated by the Northridge earthquake of January 17,1994 was recorded by strong-motion instruments at more than 200 sites located out to distances of 250 km. Horizontal ground acceleration at the surface exceeded 0.9 g at seven of these sites within 22 km of the epicenter and 0.4 g at 31 sites within 40 km of the epicenter. As the largest near-source, strong-motion data set yet collected in the US, these recordings provide an important basis for empirical estimates of site-specific amplification factors F_a and F_v as specified in current US building codes at input ground motion levels greater than 0.1g (Borcherdt, 2002a and 2002b).

Detailed geotechnical data collected over a period of several years both before and since the Northridge earthquake provides the necessary basis to characterize the local site conditions quantitatively at the recording sites. These data are needed to quantify the site conditions using shear velocity to 30 m depth and in turn classify the sites according to site-class definitions used in present versions of building codes. This report provides a compilation of shear-wave velocity estimates to a depth of 30 m for 176 strong-motion sites. Estimates are derived from borehole seismic and physical property logs, correlations with physical properties, digital geologic maps as displayed using a GIS, and additional information as guidelines.

Site characterizations herein are based on information assembled from databases kindly provided by a number of investigators (Boore, pers. commun. 1995; Silva, pers. commun. 1995; Vucetic, pers. commun. 1996, Wills and Silva, pers. commun. 1998; Nigbor, and Bardet; ROSRINE, 1999; Gibbs et al., 1999; King, pers. commun. 1995). These data compiled in GIS as reviewed with site visits by Fumal are used to provide a relatively complete and up-to-date list of shear-velocity estimates to 30 m for the recording sites.

STRONG-MOTION SITE CHARACTERIZATION IN TERMS OF $V_{S_{30}}$

Borehole logging efforts to compile shear-wave velocity logs and corresponding physical property logs to depths of at least of 30 m provide the desired database for characterizing the strong-motion sites. The major borehole data sets as collected both before and after the Northridge earthquake by Gibbs et al. (1980; 1996), Fumal et al., (1981; 1982a; 1982b; 1984), and Nigbor et al., (1998) are tabulated in databases of Boore et al. (1995, pers. commun.), Bardet, et al. (1998, http://rccg03.usc.edu/rosrine/), Silva, (1998, pers. commun.), Wills and Silva (1998), and Vucetic, et al. (1996, pers. commun.). Many of the boreholes are near the strong-motion instrument sites and hence, provide a measurement that can be used as an accurate estimate of $v_{s_{30}}$. In other cases the boreholes are not near the recording site and some type of extrapolation is needed.

Towards developing estimates of the shear-wave velocity at sites for which no borehole measurements were nearby, geotechnical information was compiled from digital files of mapped surface geology and site-specific digital databases. Surface geology as compiled digitally from Tinsley and Fumal (1985), Yerkes (pers. commun, 1994), and Jennings, et al., (1977) were used to compile data in a geographic information system (GIS). Digital databases compiled by Boore, (pers. commun. 1996), Silva, (pers. commun, 1998), and Vucetic and Doroudian, (1995) with modifications by King (pers. commun. 1996) were compiled in GIS to provide additional site-specific information. The various geologic maps were displayed using GIS at large scales with superimposed locations labeled with estimates of v_s to 30 m as derived from boreholes and surface wave measurements. Working versions of these maps were used to infer the spatial relationships of the various data sets and derive estimates of $v_{s_{30}}$ for the strong-motion recording sites. v_s measurements as inferred from borehole and surface wave measurements are shown in Figure 1 superimposed on the digital geologic database of Tinsley-Fumal (1985) and in Figure 2 as superimposed on the digital geologic database of Jennings, et al., (1977). (Similar maps are available on request using the site condition map of Wills et al. (2001) as a base.)

Shear-wave velocity estimates for the strong-motion recording sites are tabulated in Table 1. Five types of estimates are indicated. “Type 1” estimates are those derived from borehole measurements within 300 m of the location of the strong-motion recording by the USGS (Gibbs, et al., 1980, 1996, 1999, 2000) or Agbabian and associates (Nigbor, 1998) as part of the ROSRINE program. These data are available in databases developed by Boore (1995, pers. commun.), Bardet et al. (1998), Silva (pers. commun. 1998), and Vucetic and Doroudian (1995). “Type 1b” estimates are derived from borehole measurements within 300 m of the site by CDMG, NUREG, or Crandall and Associates as compiled in the databases of Silva and Vucetic. “Type 2” estimates were derived from borehole measurements from one of the sources identified as “Type 1 or 1b”, but up to distances of 1500 m from the site. “Type 3” identifies those estimates derived from averages computed from measurements in other boreholes in materials with similar physical properties (Fumal, 1978; Fumal and Tinsley, 1985). Sites used to derive the Type 3 estimates are tabulated. “Type 4” identifies those estimates derived from average velocity estimates derived herein for the corresponding geologic unit. Standard deviations for the samples used to Type 4 estimates are tabulated. “Type 5” refers to measurements inferred using surface wave techniques as summarized in the databases of Silva and Vucetic. Type 1 or 2 estimates are available for nearly all of the sites with base accelerations exceeding 0.3 g near or within the projected rupture surface.

Surface geology classifications are provided for each of the sites in Table 1. Sites were classified using physical property logs if available for Type 1 and 1b sites, onsite inspections, for sites visited, and detailed geologic digital maps if other information was not available. Site class designation was assigned to each site based on the estimate of $v_{s_{30}}$.

A histogram showing the distribution of shear-wave velocity estimates for the strong-motion recording sites is shown in Figure 3a. The corresponding histogram for only sites with borehole measurements (type 1 and 1b sites) is shown in Figure 3b. The histogram for all sites suggests a tri-modal distribution with local maximum at 337 m/s, 437 m/s and 862 m/s. This tri-modal distribution is consistent with the site class definitions used in present building code provisions. The histograms (Figures 3a and 3b) indicate gradual transitions in material characteristics at site class boundaries. They show that materials in site classes B, C, and D underlie the strong-motion recording sites with shear-wave velocities ranging between 200 and 1300 m/s.

COMPARISON OF BOREHOLE $V_{S_{30}}$ AND SURFACE-WAVE ESTIMATES

Shear-wave velocity measurements inferred using noninvasive surface-wave techniques are less expensive and generally easier to obtain than borehole measurements. However, uncertainties introduced by the need to infer material characteristics at depth using a variety of models and model assumptions have tended to discourage their use. Comparisons of shear velocity estimates derived from surface wave information and those derived from borehole measurements are shown in Figures 4a and 4b. Comparisons are provided for sites with type 1 borehole data as well as those with types 1, 2, 3, and 4 data. Best fitting least squares lines and correlation coefficients are shown for each comparison together with a theoretical line with unity slope and exact correlation.

The comparisons (Figures 4a and 4b) indicate significant variation in some of the surface wave inferences. The correlation between surface wave measurements and those derived from borehole data is better for Type 1 borehole estimates as opposed to all of the Type 1, 2, 3, and 4 data. However, the Type 1 sample with surface wave data is also significantly smaller. With the exception of site RPV for which the surface wave measurement appears quite anomalous and has been eliminated from the plot, the comparisons indicate that the surface wave measurements show a well-defined correlation with those inferred from borehole information. This comparison suggests that the relationships such as those indicated in Figures 4a and 4b together with surface wave measurements would indeed be useful for characterizing site conditions at sites for which borehole measurements are not feasible.

ACKNOWLEDGMENTS

Site condition data compiled by a number of investigators and assembled in various databases were critical for this study. Databases compiled by Dave Boore, Walt Silva, and M. Vucetic with modifications by Stephanie King and Chris Wills were kindly provided via personal communication. "*This manuscript incorporates information from the Preliminary Statewide Site Condition Map of California (PSSCM), which is protected by the United States Copyright Law. The PSSCM can only be reproduced with the written consent of the State of California. For information contact the California Department of Conservation.* A careful review of the manuscript by J. Tinsley was helpful.

REFERENCES

Bardet, J. P. Nielsen, E. and Villacorta, R. 1998, ROSRINE Data Dissemination, http://geoinfo.usc.edu/rosrine/Publications/jpbardet/, 2/28/2002.

Borcherdt, R.D., 1992, Simplified site classes and empirical amplification factors for site-dependent code provisions, in, *Proceedings NCEER, SEAOC, BSSC workshop on site response during earthquakes and seismic code provisions*, G. Martin (editor), University of Southern California, Los Angeles, California, November 18 - 20, 1992.

Borcherdt, R.D. 1994. Estimates of site-dependent response spectra for design (Methodology and Justification), *Earthquake Spectra*, 10, p. 617-653.

Borcherdt, R.D., 1996, Preliminary amplification estimates inferred from strong ground-motion recordings of the Northridge earthquake of January 17, 1994, *International Workshop on Site Response Subjected to Strong Earthquake Motions, Procs.*, Port and Harbor Research Institute, January 16 - 17, 1996,Yokosuka, Japan, v I, p24-33 and v II, pp. 21-46.

Borcherdt, R. D., 2002, Empirical evidence for acceleration-dependent amplification factors, Bull. ***Seismol. Soc. Am***., accepted.

Borcherdt, R. D., 2002, Empirical evidence for site coefficients in building-code provisions, ***Earthquake Spectra***, accepted.

Fumal, T.E. 1978. Correlations between seismic wave velocities and physical properties of geologic materials in the San Francisco Bay region, California, *U.S. Geological Survey Open-File Report 78-1067*.

Fumal, T.E., Gibbs, J.F., and Roth, E.F., 1981, In-situ measurements of seismic velocity at 19 locations in the Los Angeles, California region: *U.S. Geological Survey Open-File Report 81-399*, p. 1-121.

Fumal, T.E., Gibbs, J.F., and Roth, E.F., 1982, In-situ measurements of seismic velocity at 10 strong motion accelerograph stations in central California: *U.S. Geological Survey Open-File Report 82-407*, p. 1-76.

Fumal, T.E., Gibbs, J.F., and Roth, E.F., 1982, In-situ measurements of seismic velocity at 22 locations in the Los Angeles, California region: *U.S. Geological Survey Open-File Report 82-833*, p. 1-138.

Fumal, T.E., Gibbs, J.F., and Roth, E.F., 1984, In-situ measurements of seismic velocity at 16 locations in the Los Angeles, California region: *U.S. Geological Survey Open-File Report 84-681*, p. 1-109.

Fumal, T.E. and Tinsley, J.C. 1985. Mapping Shear-wave velocities of near-surface geologic materials. *U.S. Geological Survey Professional Paper 1360*, p. 127-150.

Gibbs, J.F., Fumal, T.E., and Roth, E.F., 1980, In-situ measurements of seismic velocity at 27 locations in the Los Angeles, California region: *U.S. Geological Survey Open-File Report 80-378*, p. 1-167.

Gibbs, J. F., Tinsley, J. C., and Joyner, W. B., 1996, Seismic velocities and geological conditions at twelve sites subjected to strong ground motion in the 1994 Northridge California, earthquake: *U.S. Geological Survey Open-File Report 96-740*, 103 pp.

Gibbs, J. F., Tinsley, J. C., Boore, D. M., and Joyner, W. B., 1999, Borehole velocity measurements and geological conditions at thirteen sites in the Los Angeles, California region,: *U.S. Geological Survey Open-File Report 00-470*, 118 pp.

Gibbs, J. F., Tinsley, J. C., Boore, D. M., and Joyner, W. B., 2000, Seismic velocities and geological conditions at twelve sites subjected to strong ground motion in the 1994 Northridge California, earthquake: a revision of OFR 96-740: *U.S. Geological Survey Open-File Report 99-446*, 142 pp.

Jennings, C. W., Strand, R. G., and Rogers, T. H., 1977, Geologic map of California, California Division of Mines and Geology, Sacramento, CA.

Nigbor, R., 1998, ROSRINE Field Investigations, http://rccg03.usc.edu/rosrine/Publications/bnigbor/.

Porcella, R.L., Etheridge, E.C., Maley, R.P., and Acosta, A.V., 1994, Accelerograms recorded at USGS national strong-motion network stations during the Ms=6.6 Northridge, California earthquake of January 17, 1994, *U. S. Geological Survey Open-File Report 94-141*, 100 pp.

Shakal, A., Huang, M., Darragh, R., Cao, T., Sherburne, R., Malhotra, P., Cramer, C., Sydnor, R., Grazier, V., Maldonado, G., Petersen, C., and Wampole, J., 1994, CSMIP Strong-motion records from the Northridge, California earthquake of January 17, 1994, *California Strong-Motion Instrumentation Program Report Number OSMS 94-07*, 308 pp.

Tinsley, J.C. and Fumal, T.E., 1985, Mapping Quaternary sedimentary deposits for aerial variations in shaking response, in, Evaluating earthquake hazards in the Los Angeles region – an earth scienc3eperspoective; J. I. Ziony (editor), *U. S. Geological Survey Professional Paper 1360*, 101-126.

Trifunac, M.D., Todorovska, M.I., and Ivanovic`, S.S., 1994, A note on the distribution of uncorrected peak ground accelerations during the Northridge earthquake of 17 January 1994, University of Southern California.

Vucetic, M. and Doroudian, M., 1995, Task H-5: geotechnical site data base for southern California", *Final Task Report on* "The Characteristics of Earthquake Ground Motions for Seismic Design", Southern California Earthquake Center - SCEC, University of Southern California, **1**, **2**, and **3**, 1546 pp.

Wills, C.J., Petersen, M., Bryant, W. A., Reichle, M., Saucedo, G.J., Tan, S., Taylor, G. and Treiman J. (2001). A site conditions map for California based on geology and shear wave velocity, scale 1:250,000, California Division of Mines and Geology, Sacramento, CA.

Table 1. Identification, surface geology, and shear-wave velocity inferred from boreholes and surface-wave measurements for strong-motion stations that recorded the Northridge earthquake.

Station ID		Coordinates		Geology		*Shear-wave Velocity*				Site Code	
				Description	Symbol		$V_{s\,bh}$		$V_{s\,sw}$		
Name	code	Long.	Lat.			type*	m/s	SD $_{type4}$	m/s	Class	Notes
Sylmar Conv. Sta East	SCE	-118.481	34.312	Pleistocene alluv (Saugus)	Ts	1	366			C	
Jensen Plant, Admin.	JFP	-118.496	34.312	Fill/Hol medium alluvium	Qym	1	373			C	
Jensen Plant, Gener.	JFPG	-118.498	34.313	Pleistocene alluv (Saugus)	Ts	1	526			C	
Sylmar Converter Sta 7	SC7	-118.490	34.311	Holocene fine alluvium	Qyf	1	251			D	
Sylmar Prk Lot	SYL	-118.444	34.326	Holocene coarse alluvium	Qyc	1	441			C	
Rinaldi Recv Sta	RIN	-118.479	34.281	Holocene medium alluvium	Qym	1	333			D	
Newhall	NWH	-118.530	34.390	Alluvium	Qa	1	269			D	
Newhall Sun Oil-Potrero 1	NWS	-118.622	34.391	17.5m alluv/Pliocene siltstone	Qa/Tp	1	282			D	
Pacoima Dam	PCD	-118.396	34.334	Diorite gneiss	gn	3	880			B	Warm Springs site 75[7]
Pacoima Kagel	PKC	-118.375	34.296	Tertiary sandstone		1	509			C	
Sepulveda VA Hosp	VSP	-118.475	34.249	Pleistocene fine alluvium	Qof	1	365			C	
Arleta	ARL	-118.439	34.236	Holocene coarse alluvium	Qyc	1	302			D	
Sun Valley Ch	SVG	-118.422	34.221	Holocene medium alluvium	Qym	4	318	79	385	D	
Canyon Country	CCY	-118.426	34.419	Holocene medium alluvium	Qym	4	318	79		D	
Northridge -White Oak Ch	NRG	-118.517	34.209	Holocene medium alluvium	Qym	1	281		269	D	
North Hollywood C Sch	NHW	-118.412	34.194	Holocene coarse alluvium	Qyc	4	448	47	399	C	
Simi Valley- Knolls Elm Sch	SMI	-118.666	34.264	Holocene medium alluvium	Qym	1	561		308	C	
LA UCLA Gnds	UCG	-118.439	34.068	Pleistocene medium alluvium	Qom	1b	437			C	
Canoga Park-Epiphany Lut Ch	CPC	-118.606	34.212	Holocene medium alluvium	Qym	1	283		282	D	
Tarzana	TAR	-118.534	34.160	Mid-Late Miocene siltstone/shale	Tm	1	302			D	
Sunland Gleason Sch	SUN	-118.303	34.269	Holocene coarse alluvium	Qyc	4	448	47	361	C	
Santa Susana ETEC	SSA	-118.713	34.231	Cretaceous sandst(Chatsworth)	Kc	1	719			C	
LA F Sta 99	LF6	-118.440	34.132	M-Late Miocene sandst (Monterey)	Tmss	4	492	153	276	C	
Burbank C Rest	BCY	-118.302	34.204	Granitic rock	gr	4	828	115	874	B	

LA F Sta 108	LF5	-118.405	34.127	Mid-Miocene sandst(Mid-Topanga)	Tts	3	780		374	B	Devils Punchbowl[9]
La Crescenta	LCA	-118.254	34.238	Holocene v coarse alluvium	Qyvc	4	448	47	319	C	
Castaic Old Ridge Route	ORR	-118.642	34.564	Lt-Miocene mudst/sandst(Castaic)	Mc	2	451			C	
LA Wonderland Ave Elem Sch	LWE	-118.380	34.115	Granitic rocks	gr	1	1270		1235	B	
Lake Hughes Sta 12A	L12A	-118.560	34.571	Hol coarse al/Eocene sandst	Qyc/Esf	1	600			C	
Topanga F Sta	TOP	-118.599	34.084	Landsld/Low-Mio ss(Low-Topanga)	Ttlsc	3	780			B	Devils Punchbowl[9]
LA St Mary's Sch	MSM	-118.482	34.086	Santa Monica slate	sms	3	650		606	C	
LA Westlake Sch	LWS	-118.435	34.090	Pleistocene medium alluvium	Qom	4	414	85	368	C	
Big Tujunga Station	BTS	-118.225	34.286	Holocene very coarse alluvium	Qyvc	4	448	47	423	C	
Vasquez Rock Park	VRP	-118.327	34.492	3m Aluv/Olig.sandstone(Vasquez)	Tvss	3	780			B	Devils Punchbowl[9]
Glendale F Sch	GLF	-118.231	34.200	Holocene coarse alluvium	Qyc	4	448	47	239	C	
Hollywood Strg Lot FF	HSL	-118.339	34.090	Holocene fine alluvium	Qyf	2	318			D	
Century City North	CCN	-118.418	34.063	Pleistocene medium alluvium	Qom	1b	302			D	
Hollywood Child C	HLC	-118.365	34.088	Holocene fine alluvium	Qyf	4	240	56	360	D	
LA F Sta 23	LF3	-118.554	34.042	Holocene coarse alluvium	Qyc	4	448	47	348	C	
Lake Hughes Sta 9 Warm Sp	L09	-118.558	34.608	Sawtooth gneiss	sgn	1	882			B	
Santa Monica City Hall	SMC	-118.490	34.011	Pleistocene medium alluvium	Qom	2	426			C	Santa Monica site 52[6]
Moorpk. L. Hughes Arr	MPK	-118.881	34.288	Pleistocene medium alluvium	Qom	4	414	85		C	
Griffith Park Obs.	GPK	-118.299	34.118	Granodiorite	gr	1	980			B	
LA Dayton Hgts Sch	LDH	-118.298	34.082	Up-Miocene siltstone(Puente)	Tpsl	1	330		381	D	
LA F Sta 50	LF1	-118.244	34.115	Holocene coarse alluvium	Qyc	4	448	47	294	C	
LA Saturn St Sch	LSS	-118.355	34.047	Holocene fine alluvium	Qyf	1	296		264	D	
LA McBride Sch	MBS	-118.431	34.001	Holocene fine alluvium	Qyf	4	240	56	330	D	
Glendora Ch 120	GMC	-117.882	34.137	Holocene coarse alluvium	Qyc	4	448	47	348	C	
Baldwin Hills	BHL	-118.361	34.009	Shale, sandstone	Qom	1	293			D	
LA Temple and Hope	LAT	-118.246	34.059	Up-Miocene siltstone(Puente)	Tpsl	2	368			C	avg 3 sites (LC)
Lake Hughes Sta 4	L04	-118.478	34.650	Wthrd granite	gr	4	828	115		B	
Lake Hughes Sta 4B	L4B	-118.477	34.650	Hol med alluv/wthrd granite	Qym/gr	1	351			D	
LA St Thomas Sch	LST	-118.298	34.045	Pleistocene medium alluvium	Qom	4	414	85	244	C	
Pico & Sentous	PIC	-118.271	34.043	Holocene fine alluvium	Qyf	2	326			D	
LA Divine Saviour Sch	LDS	-118.222	34.088	Holocene coarse alluvium	Qyc	4	448	47	407	C	
LA F Sta 12	LF2	-118.189	34.113	Pleistocene medium alluvium	Qom	4	414	85	374	C	
Playa Del Rey	PDR	-118.432	33.960	Pleistocene medium alluvium	Qom	4	414	85	486	C	
Univ Hosp	UHS	-118.198	34.062	Up-Miocene siltstone(Puente)	Tpsl	1b	312			D	

unknown	UNK	-118.290	34.020	Holocene medium alluvium	Qym	4	318	79	305	D	
San Marino	SNM	-118.130	34.115	Pleistocene coarse alluvium	Qoc	3	650			C	Katella site 11[3]
Pt. Dume Sch Malibu	PDS	-118.800	34.013	M-Late Miocene shale(Monterey)	Tm	3	373			C	avg sites 39[4],40[4],45[4],TAR[10]
Alhambra	ALF	-118.150	34.070	Pleistocene medium alluvium	Qom	3	419		550	C	Alhambra site 47[6]
Mt Wilson	MTW	-118.057	34.224	Quartz diorite	qd	4	828	115		B	
Lake Hughes Sta 1	L01	-118.430	34.674	Hol med alluv/wthrd granite	Qym/gr	1	424			C	
Camarillo LH Array	CMO	-119.079	34.208	Holocene fine alluvium	Qyf	4	240	56		D	
Elizabeth Lake	ELK	-118.387	34.662	Holocene fine alluvium	Qyf	4	240	56		D	
Leona Valley Sta 2	LV2	-118.243	34.595	Pleistocene very coarse aluvium	Qovc	4	486	37		C	
Leona Valley 3	LV3	-118.243	34.596	Plio-Pleistocene v. coarse aluvium	QTcs	3	628			C	LA Dam[8]
Obregon Park	OBG	-118.178	34.037	Pleistocene medium alluvium	Qom	1	348			D	
Leona Valley Sta 4	LV4	-118.242	34.598	Pleistocene very coarse alluvium	Qovc	4	486	37		C	
Leona Valley Sta 5	LV5	-118.241	34.600	Holocene coarse alluvium	Qyc	4	448	47		C	
Anaverde Valley	AVY	-118.199	34.580	Holocene coarse alluvium	Qyc	4	448	47		C	
Leona Valley Sta 6	LV6	-118.244	34.604	Pleistocene coarse alluvium	Qoc	4	466	111		C	
Pasadena SMV Ave	SMV	-118.078	34.169	Holocene coarse alluvium	Qoc	4	466	111	291	C	
LA W V Sch	LVS	-118.279	34.005	Holocene medium alluvium	Qym	4	318	79	296	D	
Vernon City Sch	VCS	-118.230	34.004	Holocene medium alluvium	Qym	4	318	79	319	D	
Downey South Middle Sch	DWY	-118.137	33.920	Holocene medium alluvium	Qym	1	250		254	D	
San Gabriel Lin Sch	SGS	-118.093	34.092	Pleistocene medium alluvium	Qom	4	414	85	693	C	
LA 116th Str Sch	LAS	-118.260	33.929	Pleistocene medium alluvium	Qom	4	414	85		C	
Manhattan Bch. F Sta 2	MBF	-118.389	33.887	Pleistocene medium alluvium	Qom	4	414	85	308	C	
Lawndale LDS Church	LAW	-118.346	33.897	Pleistocene fine alluvium	Qof	4	364	46	265	C	
Arcadia	ARC	-118.059	34.127	Holocene medium alluvium	Qym	4	318	79	227	D	
Sandberg	SBM	-118.724	34.743	Granitic rock	gr	4	828	115		B	
Palm. Hwy 14 & P Blvd	P14	-118.135	34.581	Holocene coarse alluvium	Qyc	2	560		485	C	Palmdale HI site 67[6]
Arcadia Sch	ARS	-118.036	34.130	Holocene medium alluvium	Qym	4	318	79	362	D	
Inglewood Union OIl	IGU	-118.279	33.905	Pleistocene medium alluvium	Qom	4	414	85		C	
Bell Gardens Church	BGC	-118.158	33.965	Holocene medium alluvium	Qym	4	318	79	261	D	
Rolling Hills Estates	RHE	-118.356	33.787	M-Late Miocene shale(Monterey)	Tm	3	373			C	avg sites 39[4],40[4],45[4],TAR[10]
Littlerock B Canyon	LBC	-117.980	34.486	Wthrd granodiorite	gr	4	828	115		B	
Antelope Buttes	ANB	-118.361	34.758	Wthrd granodiorite	gr	4	828	115		B	
El Monte Ch 11338	EMC	-118.019	34.093	Holocene medium alluvium	Qym	4	318	79	289	D	
Downey Cnty Maint	DOW	-118.167	33.924	Holocene medium alluvium	Qym	2	250			D	
Laguna Peak	LPK	-119.065	34.109	Low-Miocene shale(Low-Topanga)	Ttlc	3	556			C	Morrison Cyn site 34[1]

Compton LDS Church	COM	-118.196	33.899	Holocene medium alluvium	Qym	4	318	79	185	D	
Baldwin Park Olive Sch	BPK	-117.974	34.100	Holocene medium alluvium	Qym	4	318	79	408	D	
Whittier	WHT	-118.029	34.015	Up-Miocene sed rock(Puente)	Tp	3	480			C	avg Kagel[10], Castaic[6]
Duarte Valley V Sch	DUA	-117.940	34.150	Holocene coarse alluvium	Qyc	4	448	47	485	C	
Carson Del Amo Dolphin Sch	CDA	-118.240	33.836	Holocene medium alluvium	Qym	1	190		262	D	
Santa Fe Springs	SFS	-118.087	33.944	Holocene medium alluvium	Qym	4	318	79	350	D	
Carson C Ave Sch	CAS	-118.270	33.812	Pleistocene fine alluvium	Qof	4	364	46	198	C	
Neenach	NEE	-118.536	34.848	Holocene medium alluvium	Qym	4	318	79		D	
West Covina	WCV	-117.952	34.064	Holocene medium alluvium	Qym	4	318	79	354	D	
Long Beach LC Libr	LBL	-118.194	33.840	Pleistocene medium alluvium	Qom	4	414	85		C	
Port Hueneme N Lab	PHN	-119.206	34.145	Holocene medium alluvium	Qyf	2	326			D	
Rancho Palos Verdes	PVC	-118.396	33.746	M-Late Miocene shale(Monterey)	Tm	3	373			C	avg sites 39[4],40[4],45[4],TAR[10]
Ventura Holiday Inn	VHI	-119.293	34.276	Holocene medium alluvium	Qym	3	248			D	Ventura Cty Gen site 26[3]
Baldwin Pk LDS Chu	CBP	-117.915	34.087	Holocene medium alluvium	Qym	4	318	79	347	D	
Rancho P V Mira Catalina Sch	RPV	-118.334	33.740	M-Miocene sandst/siltst(Monterey)	Tm	1	1038		328	B	
Huntington Beach	HBS	-118.044	33.727	Holocene fine alluvium	Qyf	4	240	56	203	D	
Long Beach City Hall	LBCH	-118.196	33.768	Pleistocene medium alluvium	Qom	1	372			C	Magnolia site 1[3]
La Puente	LAP	-117.918	34.026	Holocene medium alluvium	Qym	4	318	79	285	D	
Hacienda Heights	HHT	-117.943	33.990	Holocene medium alluvium	Qym	4	318	79	278	D	
Lakewood	LWD	-118.099	33.846	Holocene fine alluvium	Qyf	4	240	56	230	D	
P. V. 1414 W 25th	SPP	-118.309	33.722	M-Late Miocene shale(Monterey)	Tm	3	373			C	avg sites 39[4],40[4],45[4],TAR[10]
Terminal I F Sta 112	TMI	-118.269	33.736	Holocene medium alluvium	Qym	3	219		260	D	Terminal Is site 3[3]
Covina LDS Church	CCS	-117.871	34.078	Holocene medium alluvium	Qom	4	414	85	333	C	
La Habra	HBA	-117.973	33.921	Pleistocene fine alluvium	Qof	4	364	46	306	C	
Buena Park	BAP	-118.018	33.847	Holocene medium alluvium	Qym	4	318	79	220	D	
Seal Beach	SBO	-118.084	33.757	Holocene fine alluvium	Qyf	2	278			D	
Lancaster Airport	LNA	-118.214	34.739	Pleistocene lacustrine	Qpl	3	278			D	Rosamond site 60[6]
Rosamond Airport	ROS	-118.206	34.870	Pleistocene lacustrine	Qpl	3	278			D	Rosamond site 60[6]
Brea	BRA	-117.896	33.916	Holocene medium alluvium	Qym	4	318	79	289	D	
Wrightwood J Flat	WJF	-117.737	34.381	Pelona Schist	ps	4	828	115		B	
Garden Grove	GGS	-118.012	33.790	Holocene fine alluvium	Qyf	4	240	56	248	D	
Anaheim FSK Sch	AHM	-117.951	33.817	Holocene fine alluvium	Qyf	4	240	56	269	D	
Mt. Baldy Sch	MBS	-117.661	34.233	Thin Hol alluvium/granite	Qyc-vc/gr	3	800			B	Allen Ranch site 77[7]
Wrightwood S Valley	WSV	-117.658	34.369	Holocene coarse alluvium	Qyc	3	482			C	Wrightwood site 76[7]

Villa Park CV Sch	VPS	-117.818	33.821	Holocene medium alluvium	Qym	4	318	79	614	D	
Huntington B LS F Sta	HBF	-117.997	33.662	Pleistocene fine alluvium	Qof	3	248			D	avg 4 sites (LC)
Rancho C Deer Cyn.	RCM	-117.579	34.169	Granitic rock	gr	4	828	115		B	
Rancho C Law Cntr	RNC	-117.574	34.104	Holocene medium alluvium	Qym	4	318	79		D	
Featherly Park	FYP	-117.709	33.869	Holocene medium alluvium	Qym	4	318	79		D	
Newport Beach C Hwy	NBI	-117.902	33.634	Pleistocene medium alluvium	Qom	4	414	79		C	
Wrightwood Nielson R	WNR	-117.545	34.314	Holocene coarse alluvium	Qyc	3	482			C	Wrightwood site 76[7]
Mojave Hwys 14 & 58	M58	-118.175	35.070	Holocene medium alluvium	Qym	4	318	79		D	
Tustin SC Sch	TUS	-117.824	33.728	Holocene fine alluvium	Qyf	4	240	56	242	D	
Phelan	PWR	-117.520	34.467	Holocene medium alluvium	Qym	4	318	79		D	
Newport Beach	NNB	-117.931	33.623	Pleistocene fine alluvium	Qof	3	248			D	avg 4 sites (LC)
Receiving Sta	RST	-118.360	34.176	Holocene coarse alluvium	Qyc	1	332			D	
Brentwood VA Hosp.	BVA	-118.463	34.063	Pleistocene medium alluvium	Qom	1	421			C	
Wadsw. VA Hosp N	WVAN	-118.453	34.054	Pleistocene medium alluvium	Qom	1	389			C	
Wadsw. VA Hosp S	WVAS	-118.448	34.050	Holocene medium alluvium	Qym	1	410			C	
Monte Nido F Sta	MND	-118.693	34.078	Miocene basaltic breccia	Tcvbp	3	594			C	avg sites 23[1],28[1],40[2],57[2]
Malibu Epis Ch	MEC	-118.787	34.024	Pleist terrace deps/Miocene shale	Qom/Tm	3	373		368	C	avg sites 39[4],40[4],45[4],TAR[10]
Hawthorne	HAW	-118.377	33.896	Pleistocene medium alluvium	Qom	2	326			D	
Pasadena Wilson Ave.	PSW	-118.127	34.136	Pleistocene medium alluvium	Qom	2	416			C	CIT Athenaeum site 80[7]
Montebello SV Sch	MTL	-118.114	33.990	Pleistocene medium alluvium	Qom	4	414	85		C	
Point Mugu NAS	PMG	-119.119	34.113	Holocene fine alluvium	Qyf	1	217			D	
Norwalk North 2	NWN	-118.067	33.917	Holocene medium alluvium	Qym	4	318	79		D	
Norwalk North 3	NWN	-118.065	33.917	Holocene medium alluvium	Qym	4	318	79		D	
Norwalk South	NWS	-118.067	33.915	Holocene medium alluvium	Qym	4	318	79		D	
Littlerock Post Office	LRP	-117.991	34.522	Holocene medium alluvium	Qym	1	455			C	
Long Beach VA Hosp	VLB	-118.115	33.777	Pleistocene medium alluvium	Qom	1	364			C	
Brea Dam	BAD	-117.926	33.889	Holocene medium alluvium	Qym	2	350			D	
Diemer Filter Plant	DFL	-117.819	33.913	Up-Miocene Puente fm	Tpsc	3	480			C	avg Kagel[10], Castaic[6]
Huntington B Spd	HBS	-118.023	33.697	Holocene fine alluvium	Qyf	4	240	56	203	D	
Prado Dam	PRD	-117.640	33.888	Holocene medium alluvium	Qym	4	318	79		D	
Santa Felicia Dam	SFD	-118.753	34.460	M-Late Miocene shale(Monterey)	Tm	3	397			C	avg sites 39[4],40[4],45[4],TAR[10]
Arcadia Forest Station	CF1	-118.021	34.196	Hol coarse alluv/ granite	Qyc/gr	4	828	115		B	
Whittier Narrows	WND	-118.054	34.031	Holocene medium alluvium	Qym	4	318	79		D	
Leona Valley FS	LVF	-118.290	34.620	Holocene medium alluvium	Qym	1	323			D	
Long Beach Harbor	LBH	-118.200	33.754	Holocene medium alluvium	Qym	2	182			D	

Lancaster	LAN	-118.156	34.688	Pleistocene lacustrine	Qpl	3	278		D	Rosamond site 60[6]
Valyermo Forest Sta	VYO	-117.851	34.444	Holocene medium alluvium	Qym	4	318	79	D	
Paradise Springs	PSC	-117.805	34.397	<3m Hol coarse alluv/schist	sch	4	828	115	B	
Rosamond G Ranch	RGR	-118.265	34.827	Pleistocene lacustrine	Qpl	3	278		D	Rosamond site 60[6]
Wheeler Gorge	WG G	-119.273	34.511	<5m Hol crs al/ hard Eocene shale	Tcwsh	3	600		C	Canada Rd[5]
Anacapa Island	ANI	-119.362	34.016	Thin Hol alluv/granite	gr	4	828	115	B	
San Antonio Dam	SOD	-117.675	34.156	Holocene coarse alluvium	Qyc	4	448	47	C	
Lockwood Valley	LWV	-119.131	34.749	Holocene medium alluvium	Qym	4	318	79	D	
Costa Mesa FS	CM4	-117.931	33.658	Pleistocene fine alluvium	Qof	3	248		D	avg 4 sites (LC)
Cuddy Valley	CDY	-119.066	34.840	Holocene medium alluvium	Qym	4	318	79	D	
Wrightwood PO	WTW	-117.629	34.360	Holocene coarse alluvium	Qyc	1	482		C	Wrightwood site 76[7]
Palmdale Black Butte	PBB	-117.728	34.586	Quartz monzonite	qm	4	828	115	B	
Costa Mesa JW	JWA	-117.869	33.677	Pleistocene fine alluvium	Qof	2	248		D	avg 4 sites (LC)
Newport Beach	NNB	-117.931	33.623	Pleistocene medium alluvium	Qom	4	414	85	C	
Long Beach Recreation	LBR	-118.133	33.778	Pleistocene medium alluvium	Qom	2	364		C	Long Beach VA site 9[3]

* type 1 = borehole measurement (USGS/Agbabian) within 300 m of site (note: at some of these sites velocities were measured by both USGS and Agbabian. For these sites the USGS value is shown in the first column, Agbabian in the second.

type 1b = borehole measurement (CDMG/NUREG/Crandall) within 300 m of site

type 2 = borehole measurement (USGS/Agbabian/CDMG/NUREG/Crandall) within 1500 m of site

type 3 = inferred from average of borehole measurements in similar materials

type 4 = average velocity for geologic map unit

type 5 = surface-wave measurement

[1]USGS OFR 76-731
[2]USGS OFR 77-850
[3]USGS OFR 80-378
[4]USGS OFR 81-399
[5]USGS OFR 82-407
[6]USGS OFR 82-833
[7]USGS OFR 84-681
[8]USGS OFR 99-446
[9]USGS unpublished data
[10] Agbabian

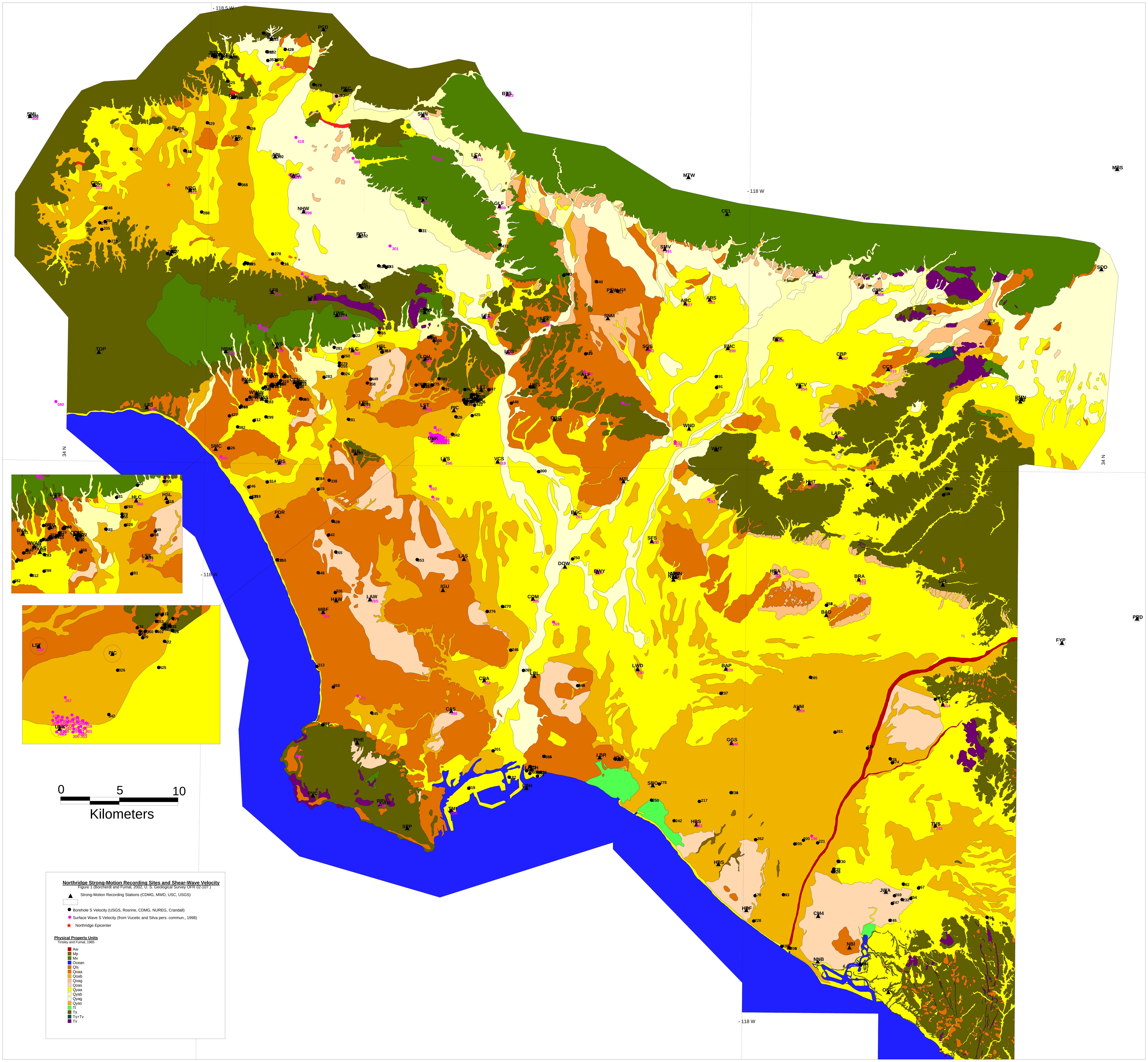


Figure 1. GIS map showing strong-motion recording sites and inferred shear velocity superimposed on base geologic map of Tinsley and Fumal (1985).

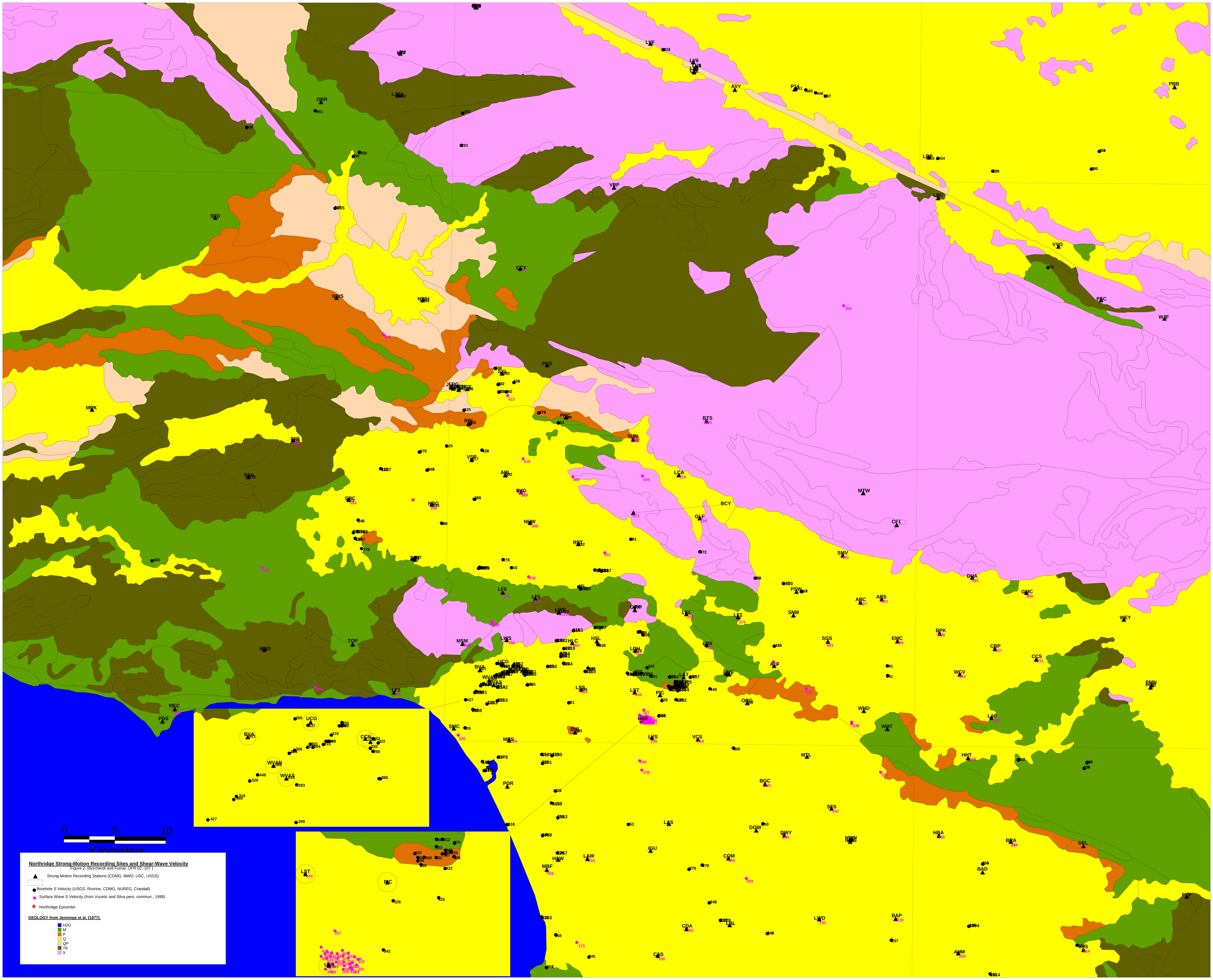


Figure 2. GIS map showing strong-motion recording sites and inferred shear velocity superimposed on base geologic map of Jennings et al. (1977).

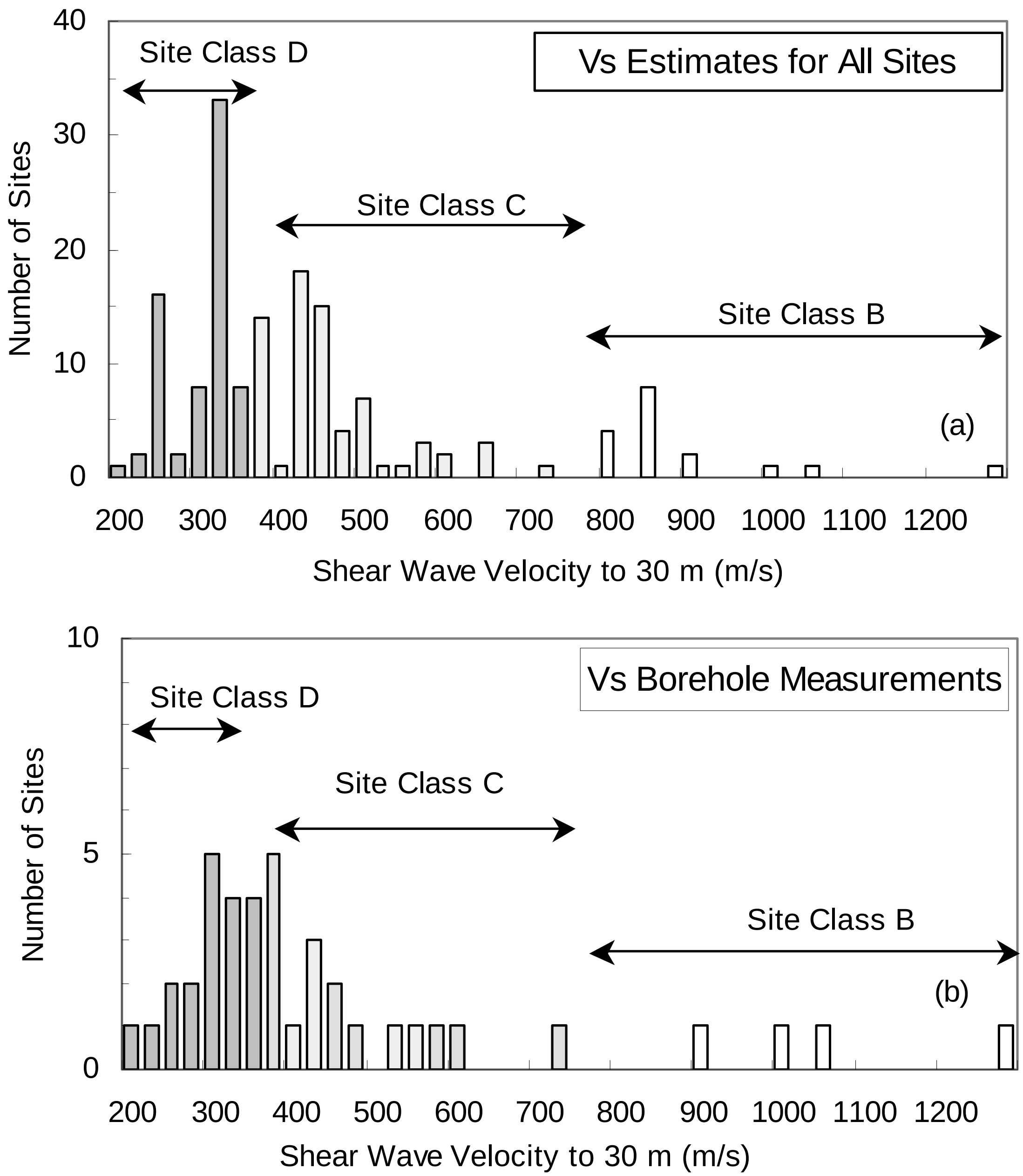
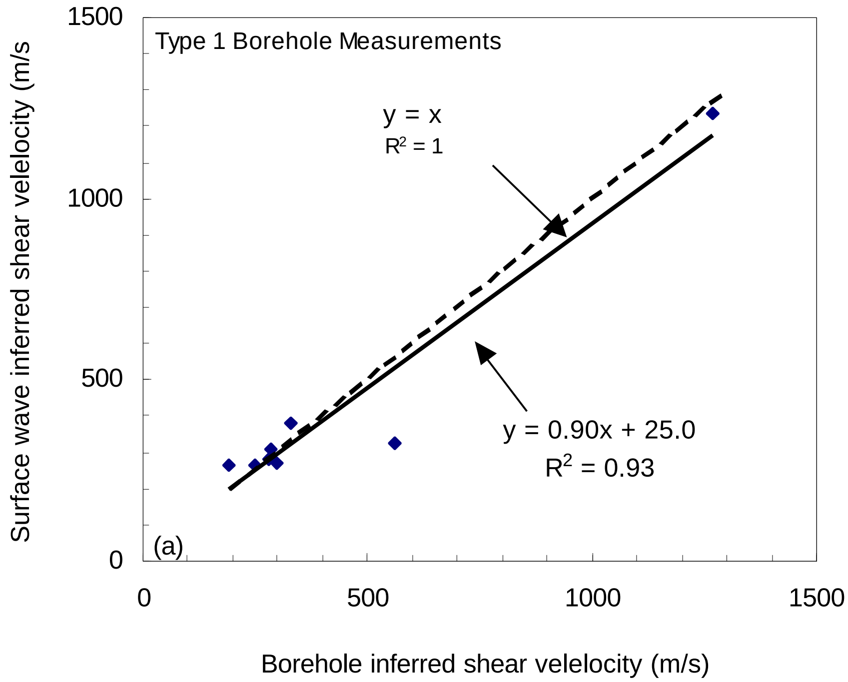


Figure 3. Histograms showing empirical distribution of shear-wave velocity estimates as inferred for each of the strong-motion recording sites (a) and for sites with borehole measurements (type 1 and 1b) as tabulated in Table 1. The distribution for all sites (a) suggests a tri-modal distribution centered at 337, 437, and 862 m/s. It shows that materials in site classes D, C, and B with shear velocities ranging between 200 and 1300 m/s underlie the strong-motion recording sites in southern California.



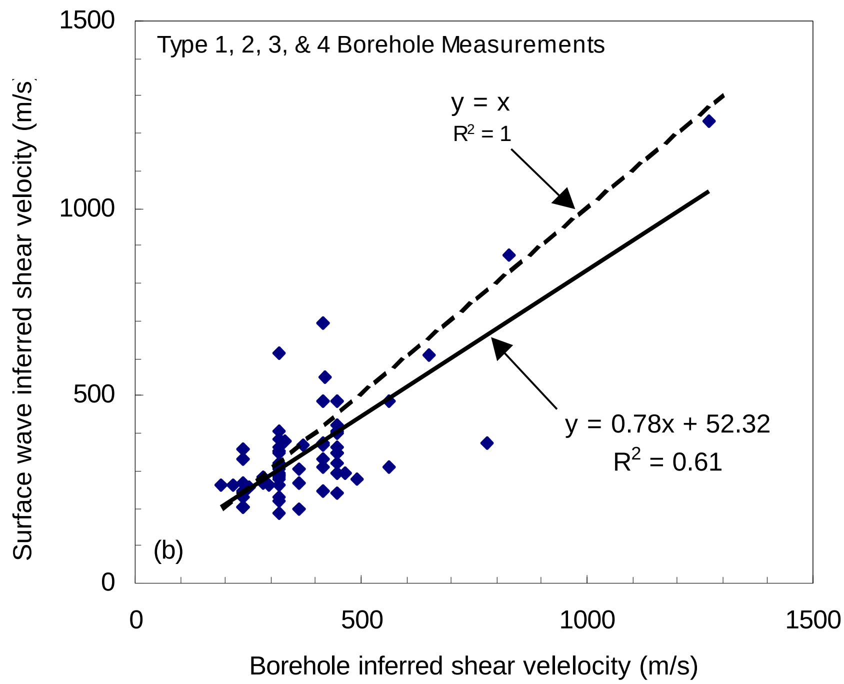


Figure 4. Estimates of shear-wave velocity inferred from surface-wave, shear-wave velocity measurements compared to those inferred from type-1 borehole measurements (a) and those inferred from type- 1, 2, 3, and 4 borehole information (b).