High-Resolution Surface-Seismic Imaging Techniques for NEHRP Soil Profile Classifications and Earthquake Hazard Assessments in Urban Areas

by
Robert A. Williams, William J. Stephenson, Jack K. Odum,
and **David M. Worley**

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ABSTRACT

The 17 January 1994 magnitude 6.7 Northridge earthquake caused widespread damage throughout the San Fernando Valley. There were also well-defined zones of significantly higher levels of building damage in the valley, such as in Sherman Oaks and in the vicinity of the California State Northridge campus. Previous aftershock site-response studies indicate that areas with extensive building damage are associated with high levels of ground motion amplification. We acquired high-resolution seismic-refraction data on the ground surface in some of these areas to help explain the earthquake damage patterns and the variation in ground motion. We used these data to determine the compressional- and shear-wave velocities (V_p and V_s) at 20 aftershock recording sites to 30-m depth. Two other sites are located in Sherman Oaks next to 90-m deep USGS boreholes with downhole V_p and V_s data and show that we imaged very similar seismic-velocity structures in the upper 40 m. We acquired two additional profiles in North Hollywood, an area lacking site response data but containing anomalous damage patterns.

In Sherman Oaks, we correlate the areas of high building damage and ground motion south of the Los Angeles River with a thick sequence of low V_s (~ 10 m thick at <185 m/s) and a 10-m deep water table. These deposits are distinct both in seismic velocity and grain size from the deposits located north of the Los Angeles River in Sherman Oaks.

Overall, high site response appears to be associated with low V_s in the near surface. Eleven sites can be classified as soil profile type D using the 1994 NEHRP guidelines (average V_s ($\overline{V}_{s30}$) of 180 to 360 m/s in the upper 30 m). Nine of the sites in this soil type had aftershock site amplification at least a factor of 3 higher than a reference site located on rock (Hartzell and others, 1996); the remaining 2 sites in this group had ground motions amplified by a factor of 2.3 and 2.8. We classified seven sites as NEHRP soil type C ($\overline{V}_{s30}$: 360 to 760 m/s), and five of these sites had site amplification factors above 2.0. One of the type C sites was considered to be a rock site during the aftershock site response study. Two rock sites were classified as soil type B ($\overline{V}_{s30}$: 760 to 1500 m/s), and their site amplification factors were 0.7 and 1.5.

INTRODUCTION

The 17 January 1994 magnitude 6.7 Northridge earthquake (Hauksson and others, 1994) ranks as one of the most damaging in history with total economic losses near 20 billion dollars (U.S. Geol. Survey and Southern California Earthquake Center, 1994). The earthquake caused widespread damage throughout the San Fernando Valley (SFV), but there were also well-defined zones of significantly higher levels of building damage in the valley. Heavily damaged areas included Sherman Oaks and several buildings on the California State Northridge campus. Previous studies show that decreasing mean shear-wave velocity in the near surface generally correlates with an increase in the average amplification of earthquake ground motion (Borcherdt, 1970; Borcherdt and Gibbs, 1976; Fumal, 1978). These earlier studies used downhole techniques to determine *P*- and *S*-wave seismic-velocity profiles in the upper 30 m of the ground surface. Following the guidelines of earlier studies, but changing the approach slightly, we used seismic-refraction methods on the ground surface to determine the near-surface compressional- and shear-wave velocities. In this study, we (1) report on the V_p and V_s determined for each site, (2) compare our results from two sites with nearby borehole data, (3) describe the correlation of near-surface geology with Vp and V_s, and (4) assess the correlation of site response from Hartzell and others (1996) with our assignment of a 1994 National Earthquake Hazard Reduction Program (NEHRP) (Building Seismic Safety Council, 1994) V_s soil profile type to 20 sites (table 1).

Table 1. NE*HRP Soil Profile Type Classifications*

Soil Profile Type	Average Shear-Wave Velocity to 30-m depth ($\overline{V}_{s30}$)
A	$\overline{V}_{s30} > 1500$ m/s, hard rock
B	760 m/s < $\overline{V}_{s30} \leq 1500$ m/s, rock
C	360 m/s < $\overline{V}_{s30} \leq 760$ m/s, very dense soil and soft rock
D	180 m/s < $\overline{V}_{s30} \leq 360$ m/s, stiff soil
E	$\overline{V}_{s30} < 180$ m/s

Nine high-resolution *P*- and *S*-wave refraction profiles were acquired at or near the portable seismograph stations established for the U.S.G.S.-Golden Northridge aftershock study (fig. 1; table 2). These sites are in addition to the eleven sites described in Williams and others, (1996) which are also shown in Figure 1. A generalized surficial geology map from Tinsley and Fumal (1985) is also shown in figure 1. In addition, we determined V_p and V_s at four other sites in the SFV: two sites (SOW and SOP) were selected adjacent to recently-drilled holes in Sherman Oaks to compare our results with V_p and V_s data derived from the boreholes (Gibbs and others, 1996). Additionally, two sites (NOHO and BAK) were located in North Hollywood, an area lacking aftershock site response data, to compare an area containing heavier building damage against an area of lighter damage 1.5 km away.

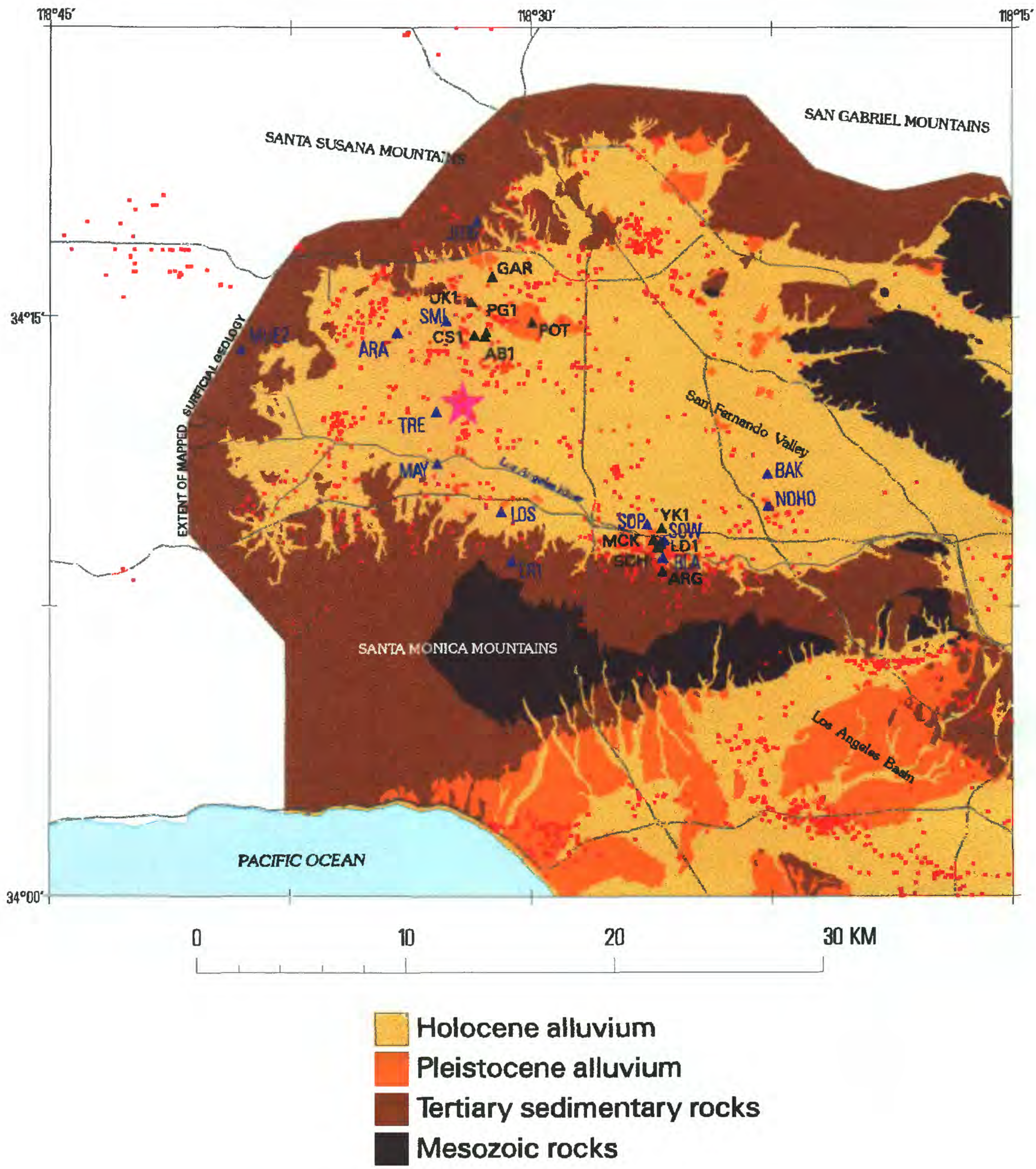

Figure 1. Generalized geologic map (Tinsley and Fumal, 1985) of the San Fernando Valley with station locations and site names where P- and S-wave seismic-refraction profiles were acquired (triangles). Sites in blue contain new data and are emphasized in this report. Sites in black were discussed in Williams and others (1996). Sites are roughly co-located with the aftershock recording stations. Red squares mark the locations of red-tagged buildings (uninhabitable) following the Northridge main shock. A star marks the Northridge main shock location. Light grey lines are the major freeways in the region.

Table 2- *Site locations, V_p and V_s, amplification factor, surficial geology, and NEHRP soil type.*

Site Name	Latitude (°N)	Longitude (°W)	Address	Average V_p upper 30 m (m/s)	Average V_s upper 30 m (m/s)	V_p/V_s	amplification factor*	Surficial Geologic Map Unit	NEHRP V_s Soil Profile Type
AB1	34.2419	118.5244	On sidewalk, 50 m west of collapsed parking garage, Cal State Northridge	390	293	1.3	3.1	Qyf	D
ARA	34.2437	118.5701	On paved street, Quakertown Ave, Northridge	660	320	2.1	2.3	Qyf	D
ARG	34.1405	118.4318	On soil, near 3826 Benedict Canyon drive, Sherman Oaks	1060	627	1.7	3.1	Ts	C
BAK	34.1830	118.3770	On paved street, Bakman Ave, North Hollywood	770	415	1.9	no data	Qyc	C
BLA	34.1469	118.4317	On paved street, Mammoth Ave, Sherman Oaks	1500	435	3.4	4.8	Qyf	C
CS1	34.2422	118.5293	On grass, east side of business admin. Building, Cal State Northridge	386	258	1.5	3.1	Qym	D
ER1	34.1450	118.5100	On soil, 1 km from aftershock recording site, Encino Reservoir	1600	970	1.6	0.7	Ts rock site	B
GAR	34.2677	118.5202	On paved street, 17745 Tribune, Granada Hills	650	413	1.6	4.4	Qym	C
JQ1	34.2920	118.5280	On paved street, Zelzah Ave, Porter Ranch	940	530	1.8	2.8	Ts rock site	C
LD1	34.1527	118.4328	On paved street, 4490 Matilija Ave, Sherman Oaks	1324	197	6.7	3.7	Qyf	D
LOS	34.1664	118.5160	On paved street, Weddington St., Encino	1305	500	2.6	1.4	Qom	C
MAY	34.1871	118.5486	On soil, along L.A. river near VanAlden Ave, Reseda	1355	255	5.3	3.3	Qyf	D
MCK	34.1545	118.4364	On paved street, 14000 Valleyheart, Sherman Oaks	poor data	277		7.3	Qyf	D
MUE	34.2364	118.6508	On paved street, Woolsey Canyon Dr., Chatsworth	1760	830	2.1	1.5	Ts rock site	B
NOHO	34.1690	118.3770	On soil, along S.P. railway at Lankershim Blvd, North Hollywood	590	255	2.3	no data	Qyc	D
PG1	34.2438	118.5231	On grass, 100 m north of collapsed parking garage, Cal State Northridge	378	264	1.4	4.1	Qyf	D
POT	34.2481	118.4999	On paved street, 16914 Kinzie St., Northridge	550	408	1.3	2.9	Qom	C
SCH	34.1508	118.4343	On paved street, 4410 Stern Ave, Sherman Oaks	1412	259	5.5	7.6	Qyf	D
SMI	34.2487	118.5444	On paved street, Labrador St., Northridge	515	322	1.6	4.9	Qyf	D
SOP	34.1610	118.4400	On grass, Sherman Oaks Park, Sherman Oaks	885	345	2.6	no data	Qym	D
SOW	34.1540	118.4310	On paved street, Valleyheart Dr, Sherman Oaks	1425	240	5.9	no data	Qyf	D
TRE	34.2095	118.5494	On paved street, Lull St., Reseda	1570	260	6.0	2.8	Qyf	D
UK1	34.2567	118.5312	On grass, near 10216 Rathburn Ave., Northridge	903	418	2.2	1.5	Ts	C
YK1	34.1594	118.4322	On paved street, 4858 Matilija Ave, Sherman Oaks	1228	290	4.2	1.8	Qym	D

*amplification factors are from Hartzell and others (1996); Qyf - Holocene fine-grained sediment (silt and clay), Qym - Holocene medium-grained sediment (sand), Qyc - Holocene coarse-grained sediment (gravel), Qom - Pleistocene medium-grained sediment (sand), Ts - Tertiary sedimentary rocks (Tinsley and Fumal, 1985).

The new Sherman Oaks profiles described below were located in the vicinity of the heavily damaged area and extend the comparison (begun in Williams and others, 1996) of the shallow *S*-

wave velocities at sites of higher amounts of building damage (sites BLA, SOW) south of the Los Angeles River, to one site (SOP) in an area of less damage north of the river. To check seismic velocities of the soils near the Los Angeles River outside of Sherman Oaks, we acquired one profile (MAY) at the site of a spectacular apartment collapse on the south edge of the Los Angeles River near the town of Reseda. We also tested site MAY because it is in an area of generally lower damage (the apartment collapse was a relatively anomalous occurrence in the area) as compared to Sherman Oaks. The position of site LOS, located south of the L.A. River in Encino, is similar to that of the Sherman Oaks sites relative to the northern edge of the Santa Monica Mountains and the river. Three 'rock' sites ER1, JQ1, and MUE were also tested, but due to space limitations at the aftershock recording stations, the seismic refraction profiles had to be located 1 to 2 km away from them, but still on or within about a meter above of the same mapped geological formation. Three other sites ARA, SMI, and TRE are located on Quaternary alluvium in Northridge and Reseda.

METHOD

With the exception of the rock profiles, the borehole sites, and the North Hollywood sites, these profiles were acquired within about 50 m of the aftershock recording site. Generally, the aftershock stations were located in the backyard of a private home while the seismic profiles were located on the paved street in front of the residence. We interpreted the data using the slope-intercept method of analysis (Mooney, 1984). A hypothetical dipping two-layer case and the formulas used to calculate the velocity structure by the slope-intercept method are shown in the Appendix. Recording parameters for the data acquired in 1996 are listed in table 3.

Table 3. - *Seismic data recording parameters*

Recording system: Geometrics StrataView (30 channels)
Sampling interval: 0.001 seconds
Record length: 1 second
Recording format: SEG-2
Geophones: 30 4.5-Hz horizontal, and 30 14-Hz vertical - single component
Geophone array: linear with single phones at 3-m intervals; vertical and shear phones planted within 0.3 m of each other
Source: 4.0 kg sledgehammer on metal plate or 100-kg vacuum-assisted weight drop (*P*-wave); 4.0-kg sledgehammer on weighted wood timber (*S*-wave)
Source array: Reversed spreads, multiple off-end shots

Reversed seismic *S*-wave profiles ranged in length from 87 to 132 m. These *S*-wave profile lengths resulted in a maximum survey depth range of about 30 m. In some cases no additional layers were detected below about 15 to 20 m. To estimate a maximum imaged depth in these cases, the maximum depth was approximated by assuming that a higher-velocity layer would have been detected on the next geophone beyond the end of the profile (Mooney, 1984). *P*-wave source energy was stronger for far-offset shots than the S-wave signal because we used a 100 kg vertical weight drop source; consequently, maximum depth ranges were greater and reached about 40 m in some cases.

The shear-wave seismic source consisted of a 4-kg sledgehammer manually impacted on a wooden timber placed on the pavement, weighted down by a vehicle, at right angles to the direction of the profile. As in the previous study, multiple impacts (usually 2 to 8) were summed to increase signal. The data were digitally recorded at 30 positions on the ground by 4.5-Hz horizontal geophones that were spaced at 3-m intervals and oriented transverse to the profile. Reversed polarity seismic energy was produced by striking opposite ends of the timber. The onset of the *S*-wave energy was usually clearly identified by over plotting normal and reversed polarity records and observing the first high-amplitude phase (fig. 2). Occasionally, there was interference from *P*- and

S-wave phases propagating through the pavement, but these phases attenuated strongly after traveling laterally about 10 m. We picked first-arrival phases assumed to be refracted from the same interface at all recording sites, calculated the velocity from the slope of the line connecting these phases, and then extended the line connecting these phases back to the zero offset point (fig. 2). The interpreted slopes (velocities), intercept times, calculated depths, seismic data, and individual site locations are shown for each site in the Appendix. Generally, alternative interpretations of the slopes of the lines connecting similar arrivals were within about 5 to 10 percent of each other, thus the calculated layer thicknesses determined in this study could vary by 5 to 10 percent. Noisier sites tend to have less certainty in their interpretation because phase arrival times can be obscured or emergent. There are two other limitations underlying this technique: (1) an assumption that layer velocity is constant across the length of the profile, and (2) low-velocity layers underlying a high-velocity layer (velocity inversions) cannot be detected. Given the length of the seismic profiles used in this study, the velocity we calculate for each layer is really an average over the length of the profile, and considering that the level of accuracy needed to get an average V_p and V_s over a 30 m depth interval, assumption (1) is probably not going to significantly affect the result. We also found that at most sites the individual layer velocities of the reversed shots were quite similar, suggesting continuity of layer velocity across the profiles. For assumption (2), we found velocity inversions appear to be a rare occurrence in the San Fernando Valley after examining previously published downhole data from 25 other sites. Significant velocity inversions (>10% change in velocity) were noted for V_p and V_s at only 4 and 2 sites, respectively, among the 25 sites examined. If undetected low velocity layers exist at the sites we studied, the calculated depths of layers below the low-velocity layer will always be greater than the true depths (Mooney, 1984).

Downhole - Surface Refraction Results Comparison

In spite of these assumptions and level of accuracy, the surface-refraction methods we employed in this study appear to generate accurate representations of near-surface V_p and V_s data based on comparison with two seismic velocity downhole profiles determined from co-located shallow boreholes in Sherman Oaks (Gibbs and others, 1996). Incidentally, no velocity inversions were found in the data for these boreholes. For V_p at site SOW our initial interpretation defined 2 layers: an 8-m thick surface layer with Vp of 300 m/s underlain by at least 32 m of deposits with Vp of 1900 m/s. Given the 2.5-m difference in elevation between the borehole and the seismic profile, this initial model agreed or closely agreed with the downhole data in: (1) number of seismically distinct layers, (2) thickness of the surficial layer to within 8%, (3) velocity of surficial layer to within 22%, and, (4) velocity of the second layer to within 8%. After referring to the Vp downhole data, we re-interpretated the refraction data and produced a refined model that decreased the difference in velocities of the surficial layer and second layer from 8% to 6% and from 8% to 7%, respectively (fig. 3). The new Vp depth model increased the thickness of the surficial layer to 9 m, which is still within 8% of the downhole data (fig. 3A).

We followed the same procedure for interpreting V_s data at this site as described for V_p above. In our preliminary V_s model, we interpreted 3 layers (with prospects for a 4^{th} layer) in the upper 50+ m, which compared to 4 layers interpreted in the downhole data. The velocities for the top two layers agreed to within less than 6%, and the thickness of the surficial layer agreed to within 4%. After referring to the downhole data, we had more confidence in including the 4^{th} layer, and the re-interpreted V_s model agreed with the downhole data to within 14% in layer depths and velocities in the upper 50+ m (fig. 3A).

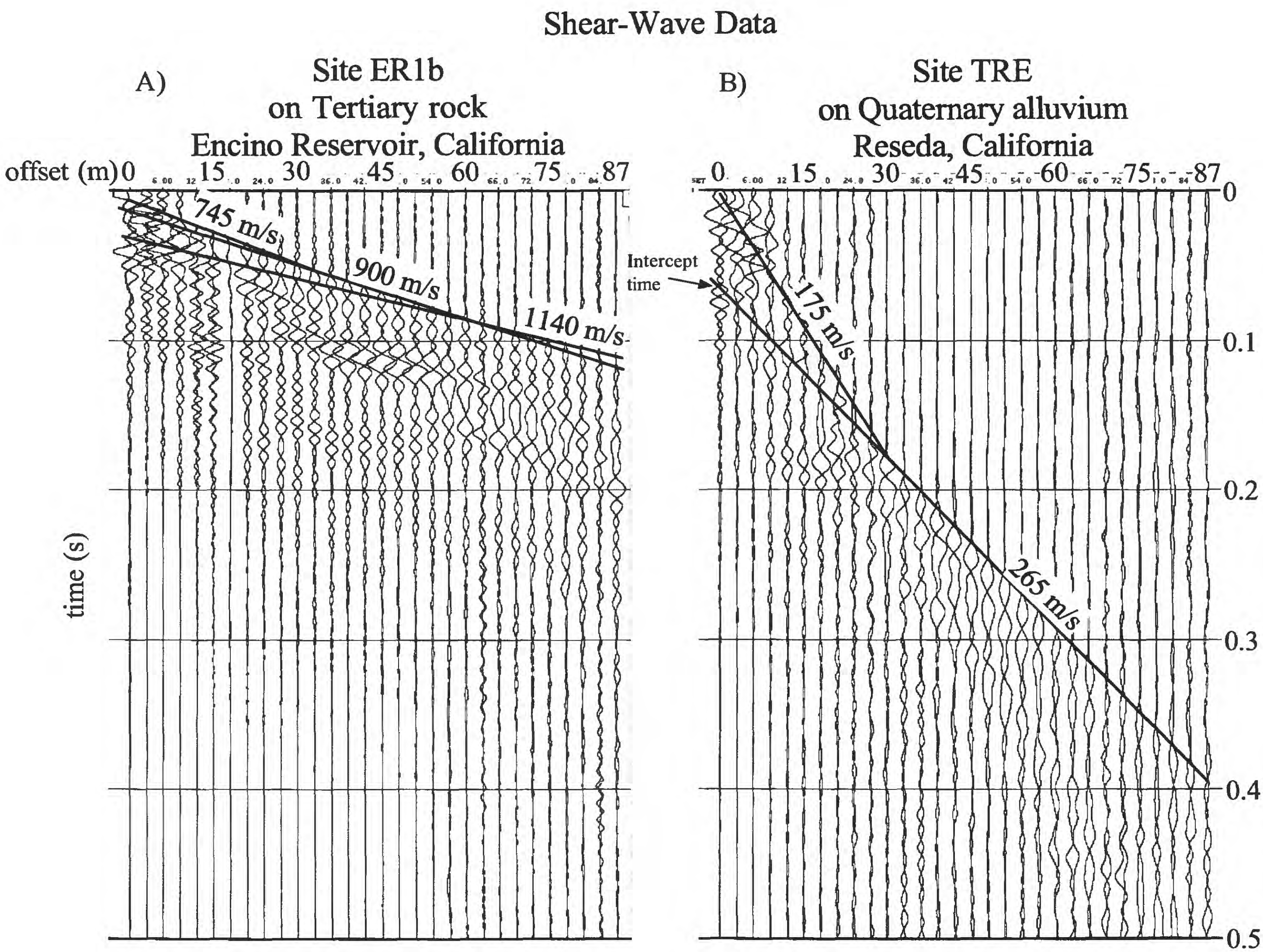

Figure 2. A) Shear-wave profile recorded at site ER1b, a rock site with the lowest site amplification measured by Hartzell and others (1996). B) Shear-wave profile recorded at site TRE on Quaternary alluvium in Reseda, California. Shear-wave source is at the zero-offset position in both profiles. Reverse polarity traces were generated by striking opposite ends of the source. Heavy lines on the data mark the distinct onset of S-wave arrivals emanating from a subsurface layer with common seismic velocity (annotated above the line).

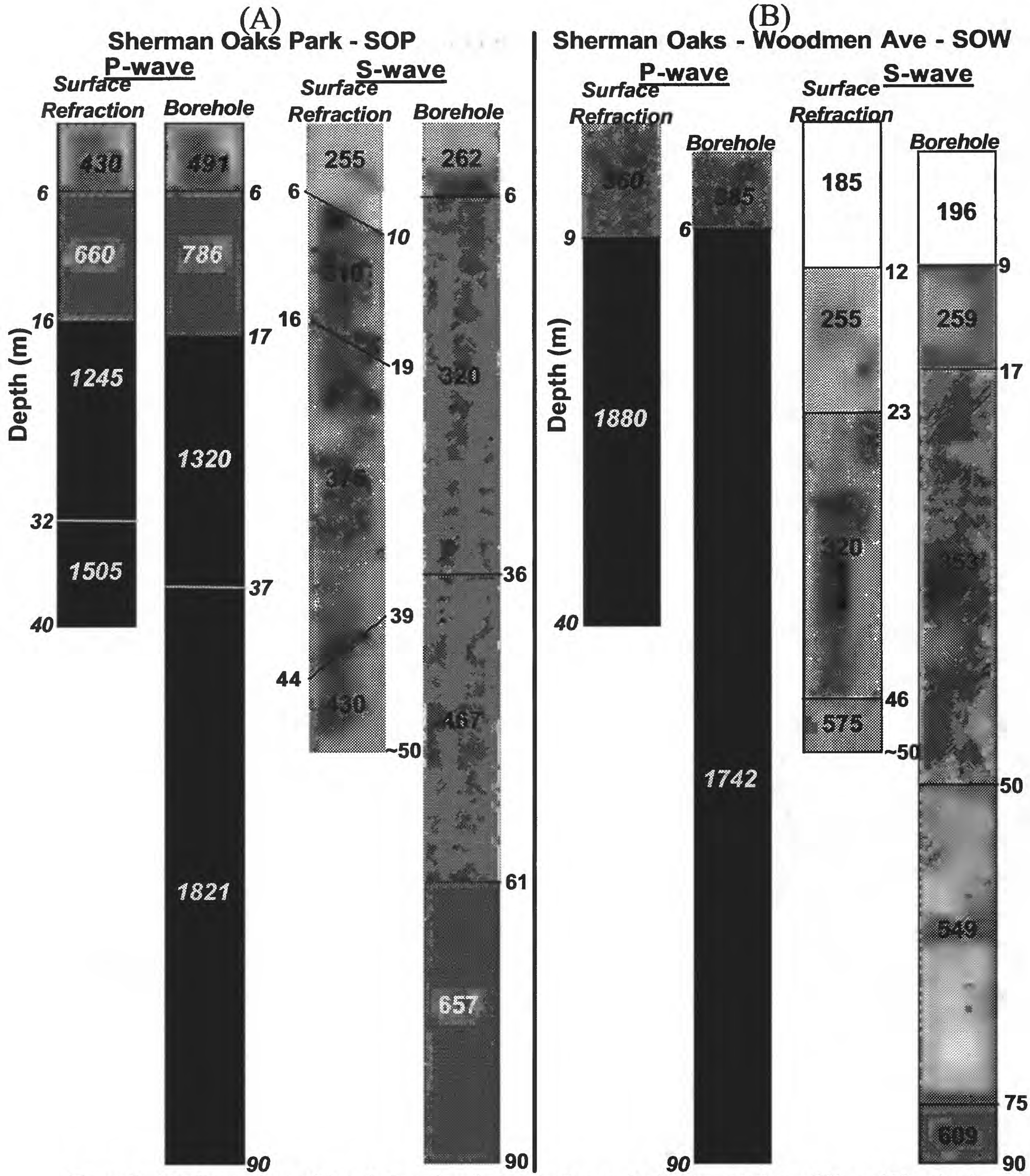

Figure 3. (A) Comparison of downhole and surface-refraction methods interpretations of Vp and Vs seismic velocity structures at site SOP. Annotated seismic velocities are in meters/second. (B) Comparison of downhole and surface-refraction methods interpretations of Vp and Vs seismic velocity structures at site SOW. Offset of refraction and borehole results shows 2.5 elevation difference between the two locations. Ninety-meter depth positions are not to scale.

At site SOP we generated a final interpretation of the refraction data without knowledge of the downhole data. The two data sets show similar numbers of layers in the upper 40 m, very similar velocities (average difference of 13% for V_p and 7% for V_s), and comparable layer thicknesses averaging 7% difference for V_p and 8% for V_s, assuming the two intermediate layers in the shear-wave refraction data are equivalent to the single layer interpreted in the downhole data over the same general interval (fig. 3B). These comparisons and the ones described in Williams and others (1996), gives us confidence that this time-tested method is a valid technique for determining near-surface seismic P and S velocities.

V_P AND V_S, NEHRP SITE CLASSIFICATIONS, AND SITE RESPONSE

Sherman Oaks

A previous study of aftershocks by Hartzell and others (1996) showed that the Sherman Oaks area south of the Los Angeles (L.A.) River produced some of the largest site amplification factors in the San Fernando Valley. This area also contains a characteristic sequence of surficial deposits with low V_s that correlates with the high site response and greater amounts of building damage (Williams and others, 1996). We acquired three new sites in the Sherman Oaks area BLA, SOW, and SOP, two of them south of the L.A. River (fig. 1), that have similar velocity structures to the 5 Sherman Oak profiles shown in Williams and others (1996). Because the previous results are discussed frequently in this report they are included in this report as Figure 4. The two new sites south of the L.A. River have the characteristic 10- to 12-m thick deposit at the surface with V_s below 200 m/s and the relatively high water table indicated by a Vp of about 1500 m/s at 6 to 9 m depth (fig. 5). Site SOP is located about 550 m north of the River and, like the one other Sherman Oaks site (YK1) surveyed north of the river (Williams and others, 1996), is characterized by a slightly higher V_s at the surface (255 m/s). The water table depth at site SOP is uncertainly determined to be between 16 and 32 m depth. This lack of certainty is created by the presence of a layer with a seismic velocity of 1245 m/s at 16 m depth that is probably partially saturated. Usually, a water-saturated unconsolidated deposit has a seismic velocity of about 1500 to 1600 m/s. This compares to about 12 m depth for site YK1, though this difference could be partially the result of a one year time difference between measurements. These sites in the Sherman Oaks area clarify the difference in V_p and V_s structure between the north and south sides of the river. This difference in seismic velocity structure may be related to a clear difference in grain size of mapped Holocene alluvial deposits (Tinsley and Fumal, 1985). Generally, north of the L.A. River in Sherman Oaks the deposits are mapped as medium-grained Holocene deposits, while south of the river they are mapped as fine-grained Holocene deposits.

Encino-Tarzana-Reseda

To compare seismic velocities from Sherman Oaks to other sites near the Los Angeles River we acquired: 1) profile LOS 2 km south of the river in Encino, Calif.; 2) profile MAY 30 m south of the channelized L.A. River; and 3) profile TRE 2 km north of the river in Reseda (fig. 1). All sites are located on Quaternary alluvium, but LOS is located on Pleistocene deposits while MAY and TRE are located on Holocene deposits (Tinsley and Fumal, 1985). Site MAY was acquired on the ground surface where a series of collapsed 2-story apartment buildings within a single complex were built over ground-level open carports (see title page photograph). The apartments were red-tagged and demolished after the earthquake and we were able to acquire the seismic profile on the soil where the old carports were located and the new apartments were being constructed. The V_p and V_s structure at MAY and TRE closely resemble the velocities observed south of the L.A. River in

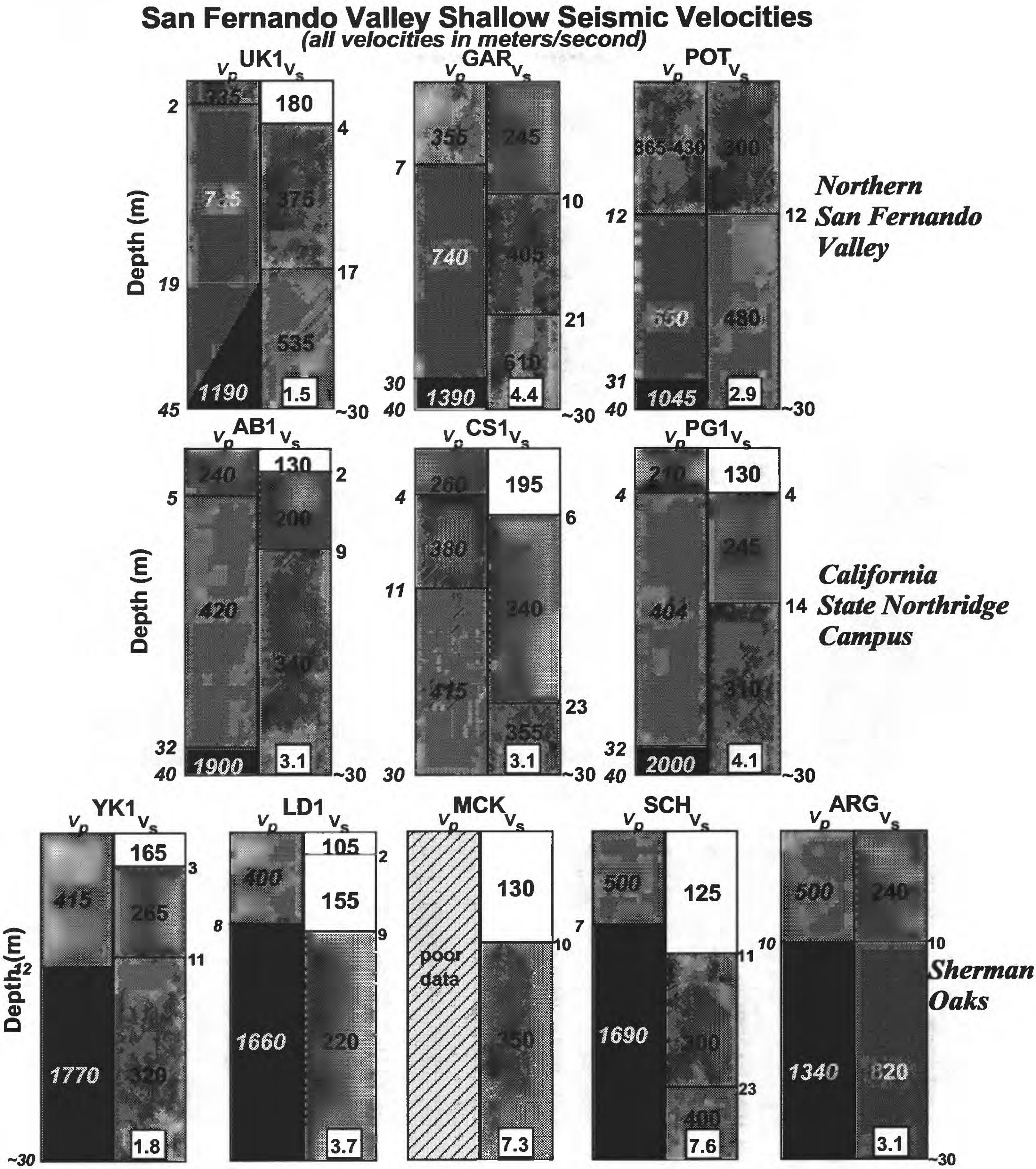

Figure 4. P- and S-wave velocity interpretations to about 30-m depth for the 11 refraction profiles described in Williams and others (1996). Site names annotated at the top of each rectangle. Seismic velocities are annotated in the shaded boxes. Boxes are shaded according to velocity value; the lower the velocity the lighter the shading. The small box inset at the bottom of the S-wave velocity column gives the mean shear wave site response amplification factor between 2 and 6 Hz (Hartzell and others, 1996) that is discussed in the text.

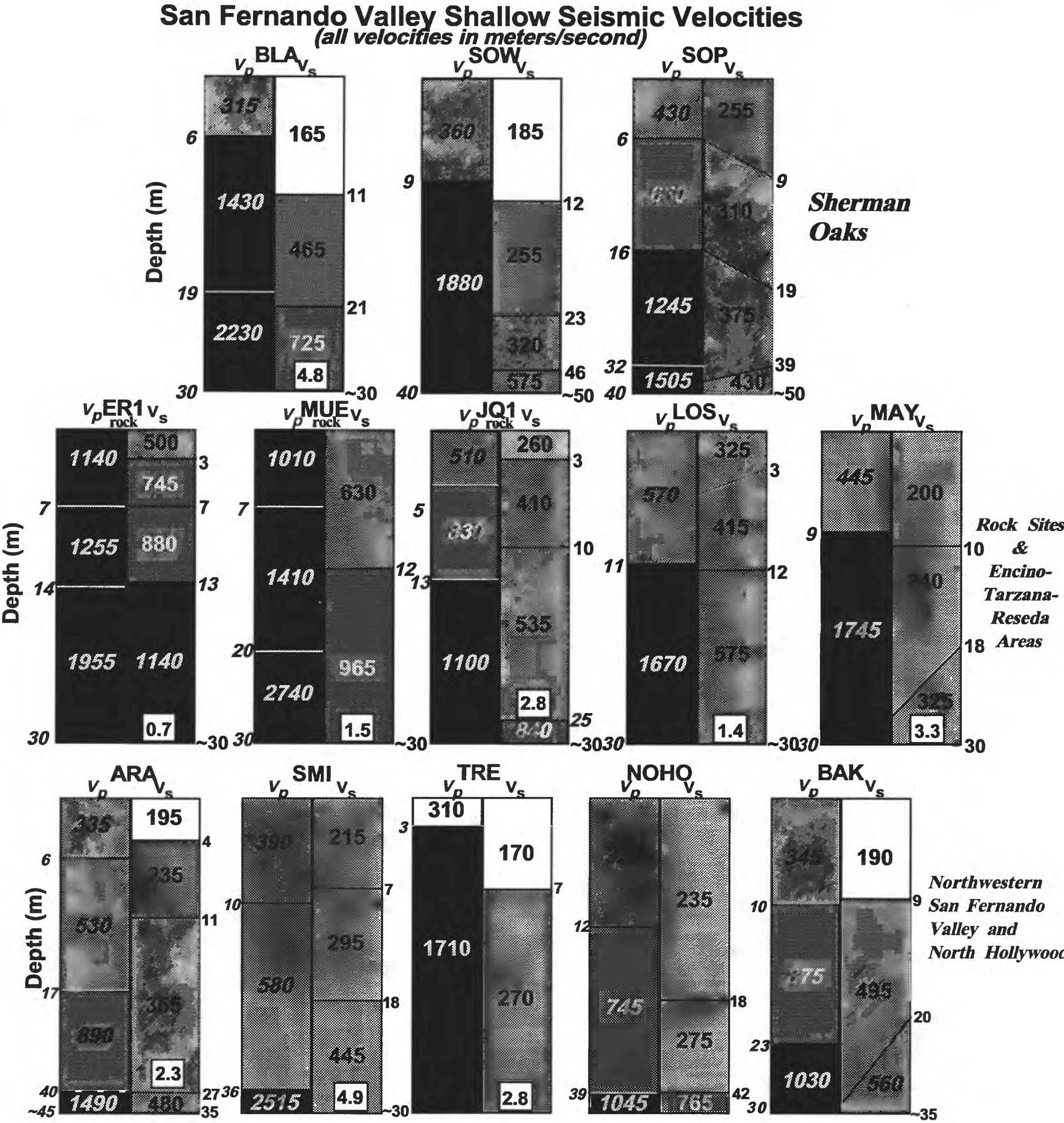

Figure 5. P- and S-wave velocity interpretations to about 30-m depth for the 13 refraction profiles with site names annotated at the top of each rectangle. Seismic velocities are annotated in the shaded boxes. Boxes are shaded according to velocity value; the lower the velocity the lighter the shading. The small box inset at the bottom of the S-wave velocity column gives the mean shear wave site response amplification factor between 2 and 6 Hz (Hartzell and others, 1996) that is discussed in the text.

Sherman Oaks (fig. 5), although some of the Sherman Oaks sites are about 20 to 30% slower in V_s in the upper 10 m. Each of these sites has at least 25 m of deposits with a V_s from 170 to 270 m/s and a water table at less than 10 m depth, thus both sites are classified as soil profile type D. Site TRE is about 500 m west of the Aliso Canyon Wash which could produce a high water table and thus a velocity structure more similar to a site near the L.A. River. The site amplification factors for sites MAY and TRE, however, are in the moderate range at 3.3 and 2.8, respectively (Hartzell and others, 1996). In contrast, possibly because site LOS is located on older, more compacted alluvium, the average V_{s30} data from this site classify it as soil type C. There is a layer with a 415 m/s velocity (soil profile type C) within 3 to 5 m of the surface (fig. 5), a much different structure than the Sherman Oaks sites and a correspondingly lower site amplification factor of 1.4. The water table depth at 11 m for site LOS, however, is quite similar to sites in Sherman Oaks. The results from site MAY and TRE indicate that the average seismic velocity structures in the upper 30 m of the Sherman Oaks sites south of the river are not unique, but the Sherman Oaks sites have the slowest V_s profiles in the upper 10 m of those investigated in the San Fernando Valley.

Northwestern San Fernando Valley

We profiled sites ARA and SMI in the northwestern part of the San Fernando Valley. Both have the same mapped surficial geology, similar near-surface seismic velocities, but differ by a factor of two in site amplification (table 2). Both sites are also located on fine-grained Holocene alluvium and are located within 100 m of fluvial washes. We found that these sites have a 1% difference in average V_s in the upper 30 m (320 m/s vs. 322 m/s) and are thus both classed as soil type D. The difference in average Vp is 22% (660 m/s vs. 515 m/s) (table 2). From these similar velocity profiles, the difference in site amplification at site SMI of 4.9 versus 2.3 at site ARA (Hartzell and others, 1996) is not explainable. Among other possible reasons the focusing effects of deeper structures may be responsible for the difference.

North Hollywood - Southeastern San Fernando Valley

Measured by the number and density of red-tagged buildings, the commercial-industrial area along Lankershim Blvd in North Hollywood sustained an anomalously high amount of building damage as compared to the surrounding parts of the community (fig. 1). Although no aftershock site amplification values are available for this area, we decided to compare the difference in near-surface seismic velocities between site NOHO in a heavily damage zone to site BAK outside this zone (fig 1). We found that the average V_s in the upper 30 m at site NOHO at 255 m/s (class D) is significantly slower than the 415 m/s (class C) average at site BAK (table 2). Though both sites are located on the same mapped unit, Holocene coarse-grained alluvium (Tinsley and Fumal, 1985), the central branch of the Tujunga Wash, 500 m from site NOHO and 1.8 km from BAK, probably more frequently supplied loosely consolidated deposits to site NOHO and lesser amounts to site BAK. This may help explain the difference in near-surface seismic velocities. Although there is a difference in building type between these two locations, it appears that low V_s in the near-surface of North Hollywood probably increased the site response and contributed to the higher levels of building damage along Lankershim Blvd.

Rock Sites

Three rock sites were profiled in this study and significant differences were found in near-surface velocity that appear to explain part of the measured differences in site amplification. The rock sites are located in the Santa Monica Mountains (ER1b), Simi Hills west of the SFV (MUE2), and the Santa Susana Mountains (JQ1b) north of the SFV (fig. 1). These sites are located on three different mapped geologic rock types. Site ER1b is located on the Topanga Formation, which consists of a conglomerate with an average V_s and V_p of 970 m/s and 1600 m/s, respectively (table 2 and fig. 5) at the profile location. This average V_s classifies site ER1b as soil profile type B. This is the highest average $\overline{V}_{s30}$ found among the 24 sites studied, it is also the site with the lowest site amplification factor in the SFV (Hartzell and others, 1996). Site MUE2 had the second lowest site amplification factor at 1.5 (Hartzell and others, 1996) and is located on the Chico Formation (sometimes called the Chatsworth Formation in this area), a massive brown sandstone at the profile location and at the aftershock station. The 830 m/s $\overline{V}_{s30}$ at this site is about 14% slower than at site ER1b and also classifies site MUE2 as a soil profile type B. The 1760 m/s $\overline{V}_{p30}$ at MUE2 is about 8% faster than at site ER1b. Although there is a correlation between lower V_s and higher site amplification at MUE2 than at ER1b, the velocity difference appears to be too small to explain the factor of 2 difference in site amplification. The third 'rock' site, JQ1b, is located on the lower member of the Saugus Formation and had an average site amplification factor of 2.5 (Hartzell and others, 1996; table 2). This level of site response is more like that of an unconsolidated alluvial site. The higher site amplification here may be partially explained by the relatively low $\overline{V}_{s30}$ of 530 m/s (table 2 and fig. 5). This V_s places JQ1b in soil profile type C, a different classification than the other two rock sites described above. The 940 m/s $\overline{V}_{p30}$ at JQ1b is also slower than the other two rock sites and suggests that the near-surface deposits at this site are much more loosely consolidated. This inference is supported by observing that consolidated rock is exposed in outcrops at the other two rock sites, while a roadcut, adjacent to the seismic profile at JQ1b, exposed outcrops of friable sandstone of the Saugus Formation. The variety of site amplifications and near-surface seismic-velocity profiles at these 'rock' sites emphasizes that not all rock sites will have the same seismic response, as noted by Boore and Joyner (1997), or fit the same NEHRP site classification.

CONCLUSIONS

Using seismic-refraction methods on the ground surface we have interpreted the seismic velocity structure in the upper 30 m at 13 sites to complement 11 others previously acquired by Williams and others (1996). Twenty of these sites were previously used as aftershock recording stations for a site response study of the Northridge earthquake. The technique is non-invasive, relatively fast (the data from 2 to 3 sites can be acquired in one day), and can be used on the city streets of populated areas at the site of interest in most cases. To check the accuracy of these methods, we co-located two profiles at two different boreholes with known V_p and V_s velocity structures. We found that without knowledge of the borehole data, we can produce a velocity structure by our methods that is within about 5 to 15 percent different than the borehole data in the upper 40 to 50 m in terms of seismic velocities and layer thicknesses. Thus the seismic refraction method appears to be a valid substitute for downhole surveys if only seismic velocity information in the upper 30 to 40 m is needed.

Using the seismic refraction data we also categorized the sites, including those described in Williams and others (1996), according to the soil and rock classification scheme defined by the NEHRP. We found that of the 20 sites studied that also have site response data, eleven of the sites can be classified as soil profile type D, seven sites as type C, and two sites as type B. These site classifications appear to be valid predictors of increased earthquake ground shaking as 91% of the sites in class D had site amplification factors above a factor of 2 and two of these sites had amplification factors above 7.0, which were the highest measured by Hartzell and others (1996); 71% of the sites in class C had ground motions that were amplified above a factor of 2, and none of the class B sites were amplified above a factor of 1.5. The weakness in these soil-type classifications and in attempts to correlate site response with V_s, is that there can be a wide range of site amplifications for a given soil type or V_s. This suggests that other factors, such as deep structures, that could tend to amplify or de-amplify seismic waves, can strongly influence earthquake ground motion at the surface. Thus, at this point, knowing a sites average V_s to 30-m depth will not permit precise prediction of the level of shaking, but it does appear to allow predictions that ground shaking will be amplified above a factor of 2 for moderate-sized earthquakes.

Only a few of the differences in NEHRP site types can be explained by looking at geologic rock type, age, or grain size of the alluvial deposits. For example, of the ten sites we studied which are located on what is mapped as recent (Quaternary) alluvium (Tinsley and Fumal, 1985), we placed three in soil type C and seven in soil type D. Only one of the type C sites stands out because it is located on Pleistocene deposits, while all of the other sites are located on Holocene deposits that span a range of grain sizes from coarse to fine (Tinsley and Fumal, 1985). We also studied two sites in North Hollywood that lacked site response data, but were quite different in terms of the amount of building damage. With our data, we classified the site with higher amounts of red-tagged building damage surrounding it as NEHRP soil type D and the site with lesser amounts of building damage as a type C. These two sites are both located on mapped coarse-grained Holocene alluvium, yet based on their $\overline{V}_{s30}$ we place them in different site classes.

Compared to the sites on alluvium, the differences in site type among the three rock sites can be easily seen in the differences in mapped rock type, measured V_s, and nearby outcrop. The three 'rock' sites were found to fall into site classes B and C with the class C 'rock' site having a factor of about 2 to 3 greater average site amplification than the two rock sites in class B. With a $\overline{V}_{s30}$ under 1000 m/s, all three 'rock' sites described in this study appear to fit into Boore and Joyner's (1997) 'tectonically active region rock site' class versus the 'very hard rock site' class with average Vs in excess of 2 km/s.

Three sites in the Sherman Oaks area confirmed the difference in near-surface seismic velocity structure north and south of the Los Angeles River that was interpreted by Williams and others (1996). These two regions are also clearly differentiated in their physical properties by grain size (Tinsley and Fumal, 1985). Both regions are mapped as Holocene alluvium with medium-sized grains generally north of the river and predominantly fine grained south of the river. But two profiles outside the Sherman Oaks area and in the vicinity of the Los Angeles River demonstrate that the low $\overline{V}_{s30}$ and high water table found in Sherman Oaks south of the Los Angeles River are not entirely unique.

ACKNOWLEDGMENTS

We thank John Michael of the U.S. Geological Survey for digitally drafting figure 1. We are grateful to Dr. Mary Templeton (Calif. State Univ. Fullerton) for providing a weight-drop seismic source used in this study. The manuscript was improved by a review from Edward Cranswick. This study was supported by NEHRP funding.

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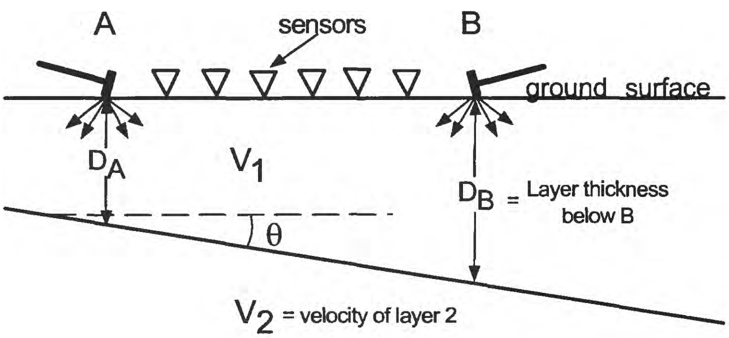
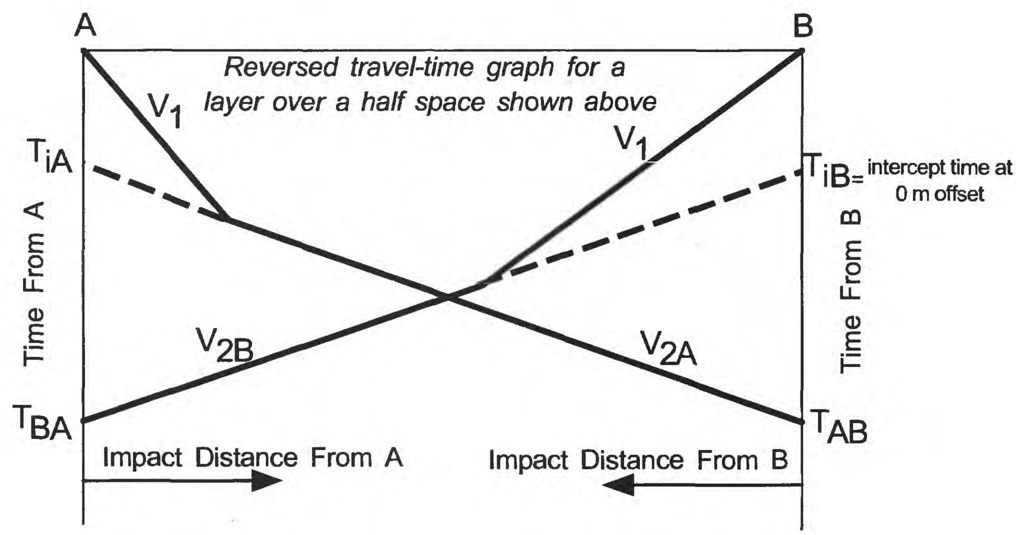
Appendix A

Example calculation and use of formulas in the slope-intercept method for a hypothetical dipping layer over a half space

(figures and formulas below excerpted from Mooney (1984))





Formulas for calculation of dip angle, true velocity of layer 2, and depth below source impact positions A and B

dip angle $\theta = [\,\sin^{-1}(V_1/V_{2B}) - \sin^{-1}(V_1/V_{2A})\,]$

true velocity $V_2 = 2\cos\theta \dfrac{V_{2A}V_{2B}}{V_{2A}+V_{2B}}$

Layer thickness below A $D_A = \dfrac{V_2 T_{iA}}{2\cos\theta}\,\dfrac{1}{[(V_2/V_1)^2 - 1]^{1/2}}$

Layer thickness below B $D_B = \dfrac{V_2 T_{iB}}{2\cos\theta}\,\dfrac{1}{[(V_2/V_1)^2 - 1]^{1/2}}$

Appendix B

P-Wave Results : Site ARA - NW Northridge, California

Data acquired August 1996; Interpretation 2/97

Layer 2 was not observed from the south and was assumed to be continuous across the profile in the calculations below.

Layer 4 was not observed in the data and is a guess at the next possible layer that would have been detected one station beyond the farthest offset trace recorded.

Data quality is slightly below average

Velocities in meters per second, time in seconds

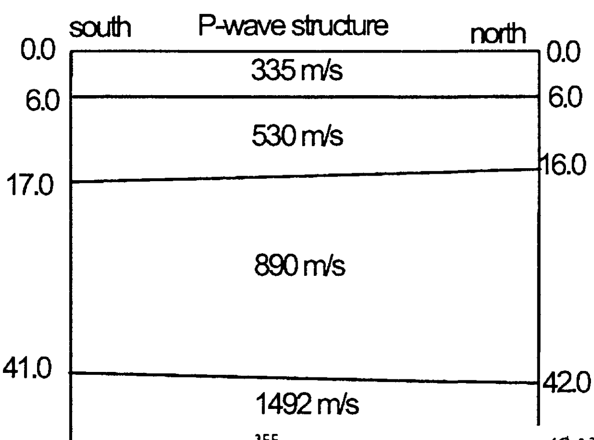
SPREAD LENGTH = 87.0 m

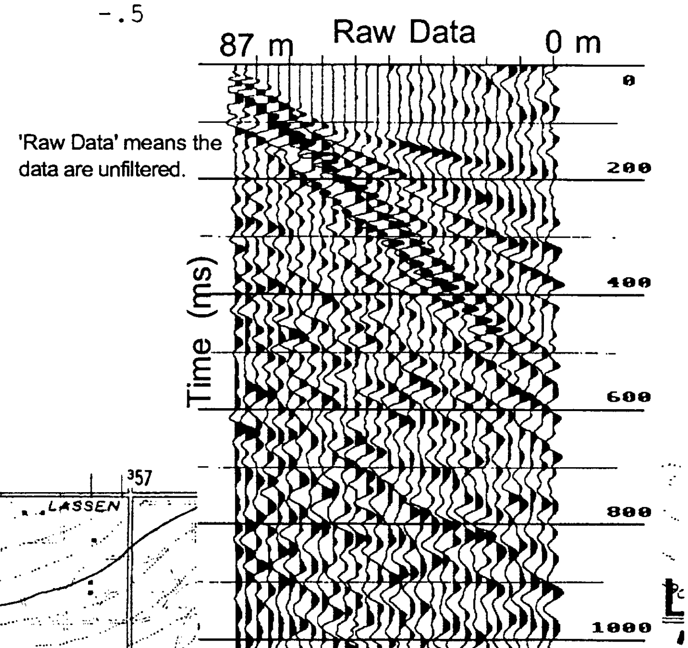
INPUT DATA

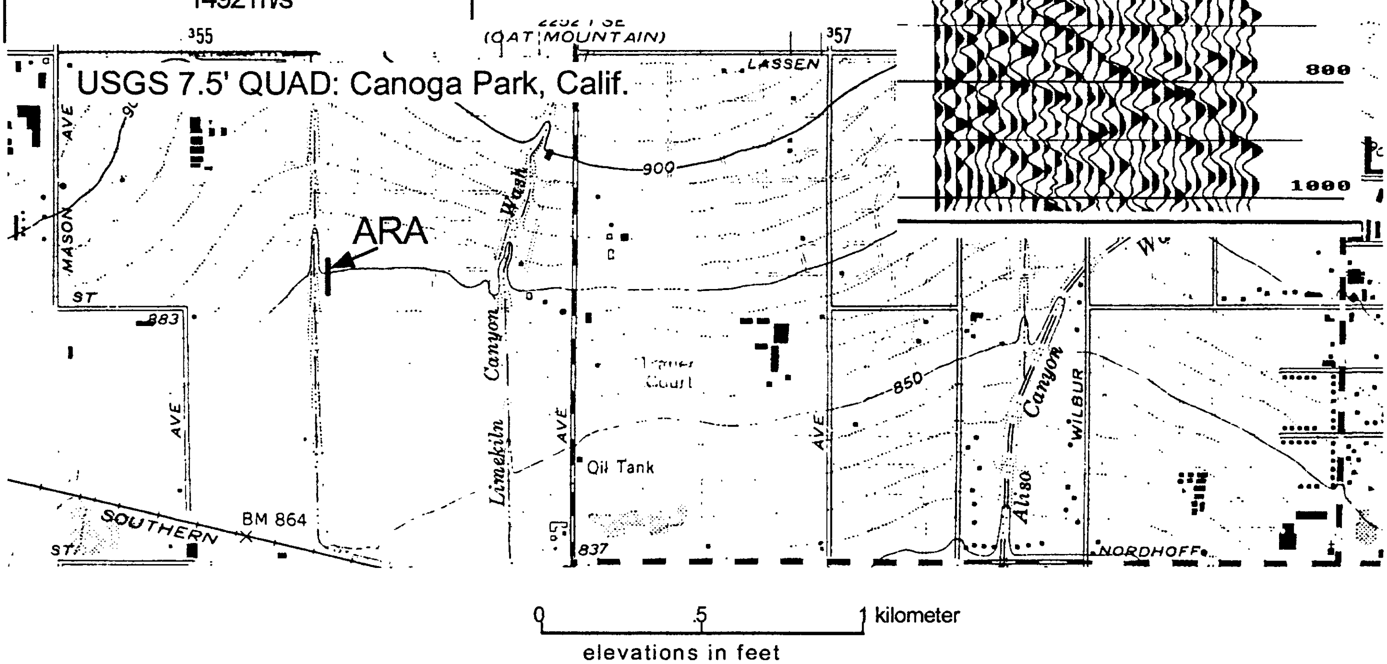
LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	333.0	333.0	.000	.000
2	531.0	531.0	.029	.029
3	900.0	879.0	.067	.063
4	1492.0	1492.0	.117	.117

COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	333.0	6.2	6.2		6.2	6.2
2	531.0	10.7	9.4	.0	16.9	15.6
3	889.3	23.7	26.3	.5	40.7	42.0
4	1491.8			-.5		







S-Wave Results
Site ARA - NW Northridge, California

Data acquired August 1996; Interpretation 2/97

Data quality is slightly below average

Velocities in meters per second, time in seconds

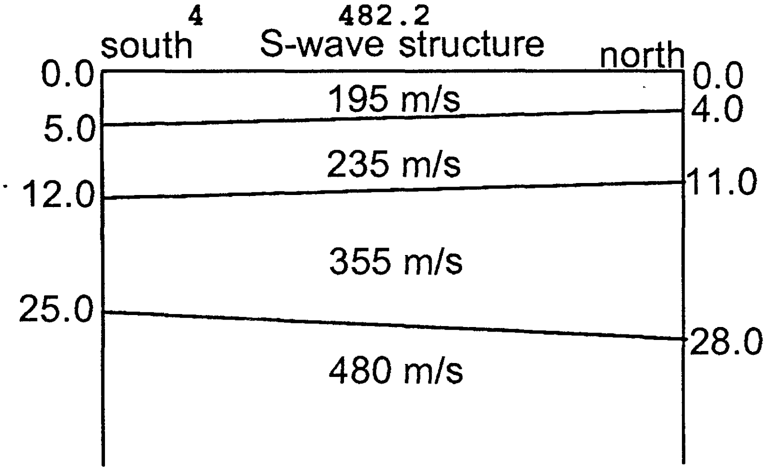
SPREAD LENGTH = 87.0 m

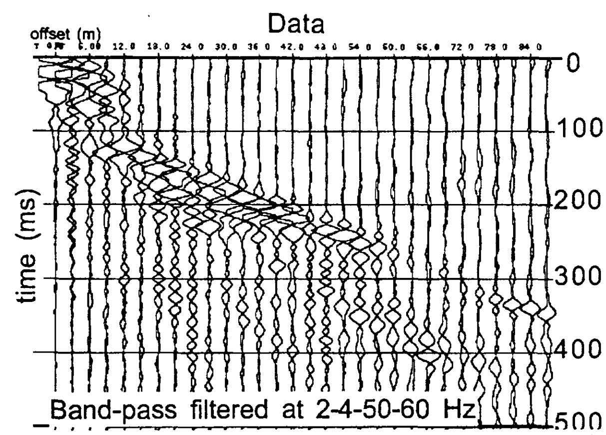
INPUT DATA

LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	195.0	195.0	.000	.000
2	238.0	230.0	.027	.021
3	352.0	358.0	.084	.077
4	489.0	476.0	.147	.153

COMPUTED STRUCTURE

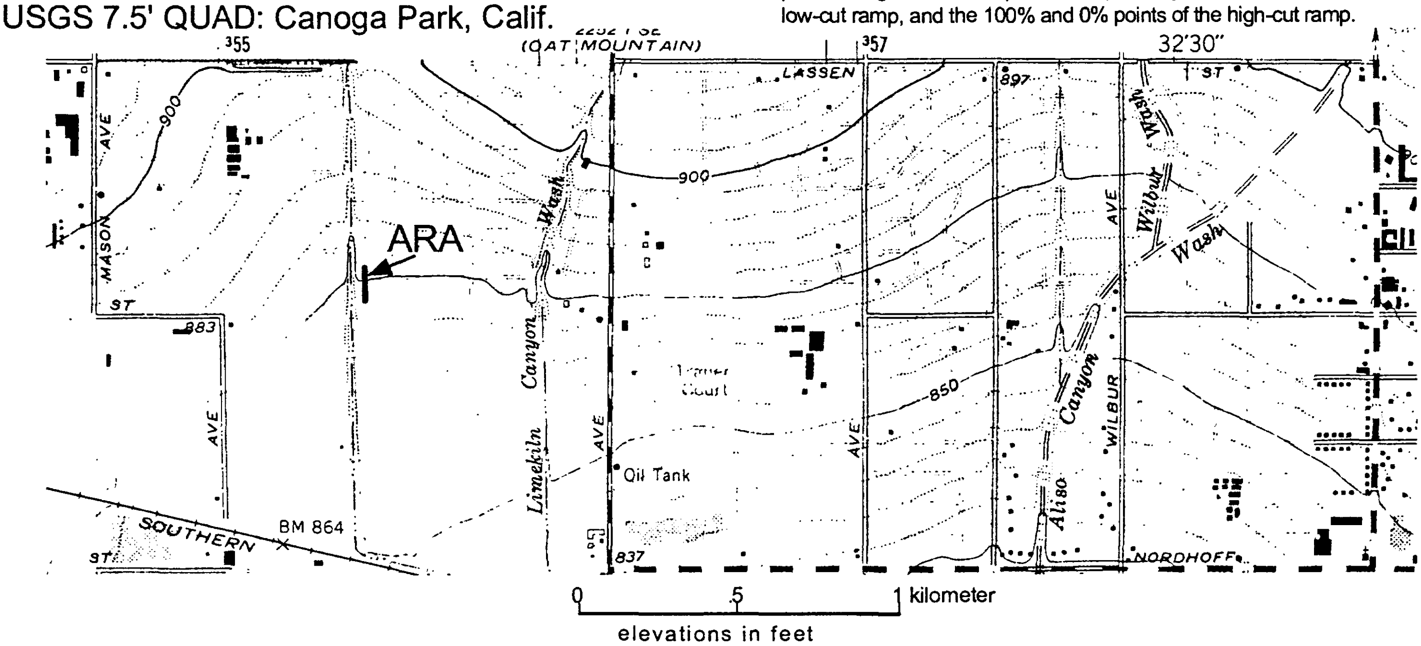
LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	195.0	4.8	3.7		4.8	3.7
2	233.9	6.7	7.0	1.5	11.5	10.7
3	354.8	13.7	17.2	-.9	25.1	27.9
4	482.2			1.0		





For all following displays in Appendix A where the data are filtered, 4 filter points are given which represent sequentially the 0% and 100% points of the low-cut ramp, and the 100% and 0% points of the high-cut ramp.

USGS 7.5' QUAD: Canoga Park, Calif.



P-Wave Results
Site BAK - North Hollywood, California

Data acquired August 1996; Interpretation 2/97

Seismic sources were on asphalt. Geophones were primarily planted in grass.

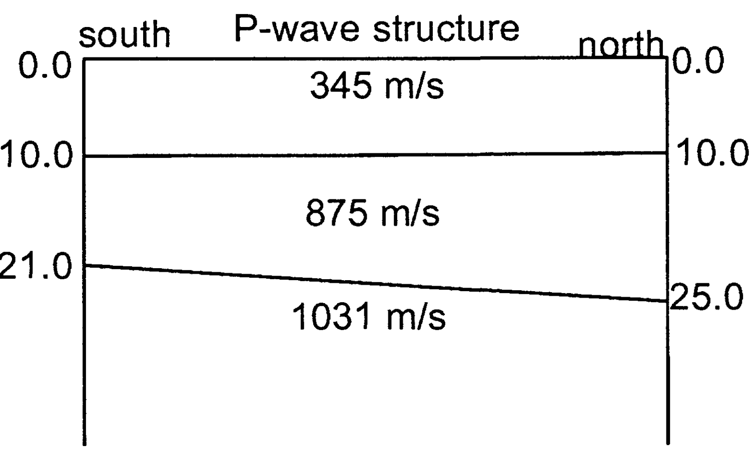
SPREAD LENGTH = 87.0 m

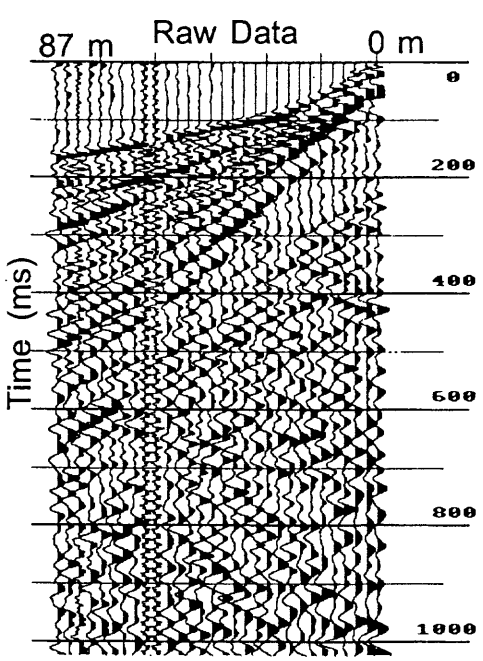
INPUT DATA

LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	345.0	345.0	.000	.000
2	878.0	872.0	.052	.053
3	1031.0	1031.0	.067	.072

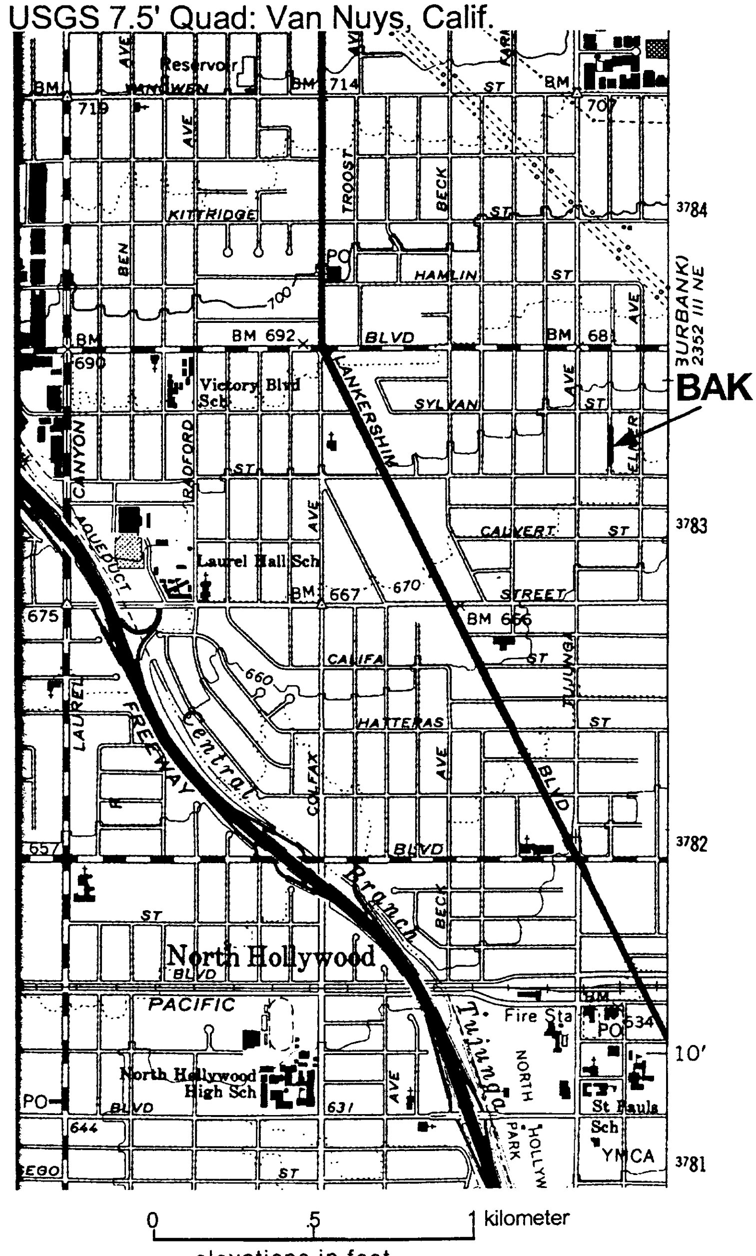
COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	345.0	9.8	9.9		9.8	9.9
2	875.0	11.3	14.6	.1	21.1	24.6
3	1031.0			-.3		





USGS 7.5' Quad: Van Nuys, Calif.



S-Wave Results
Site BAK - North Hollywood, California

Data acquired August 1996; Interpretation 2/97

Seismic sources were on asphalt. Geophones were primarily planted in grass.

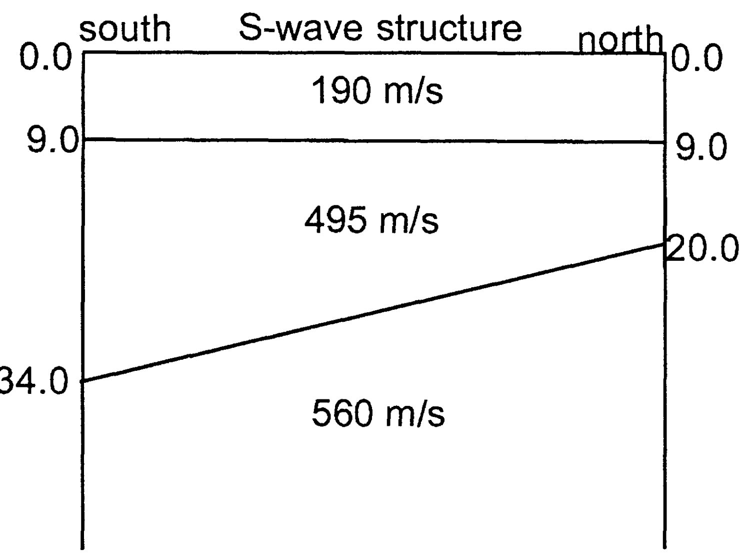
SPREAD LENGTH = 87.0 m

INPUT DATA

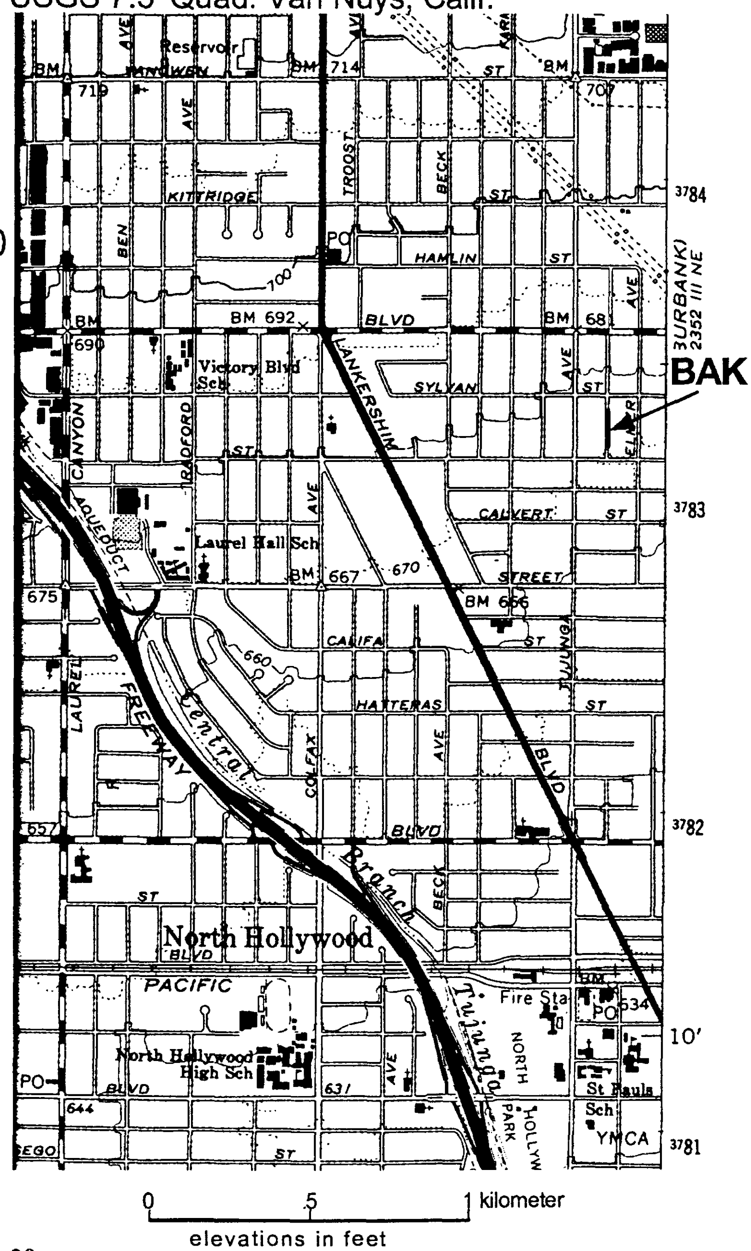
LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	190.0	190.0	.000	.000
2	497.0	488.0	.087	.090
3	581.0	540.0	.136	.113

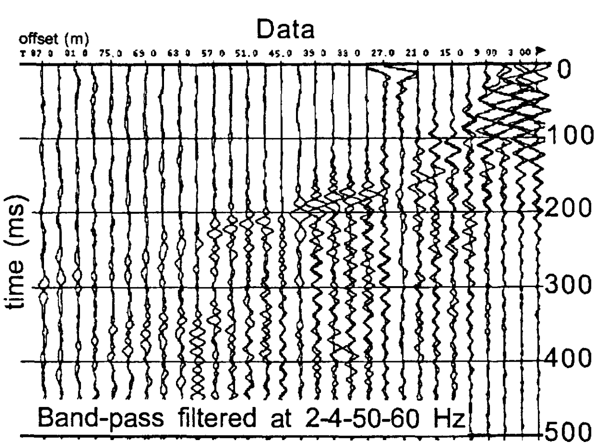
COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	190.0	9.0	9.3		9.0	9.3
2	492.5	24.6	11.1	.2	33.6	20.3
3	559.1			3.0		



USGS 7.5' Quad: Van Nuys, Calif.





P-Wave Results
Site BLA - Sherman Oaks, California

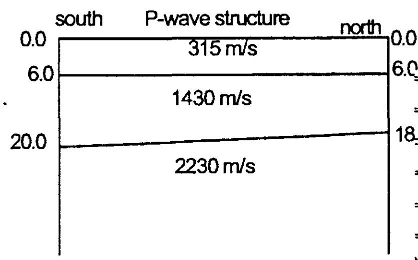
Data acquired August 1996; Interpretation 2/97
Seismic sources were on asphalt. Geophones were primarily planted in grass.
V2 was not observed from shots to the south and was inferred to be continuous across the profile.

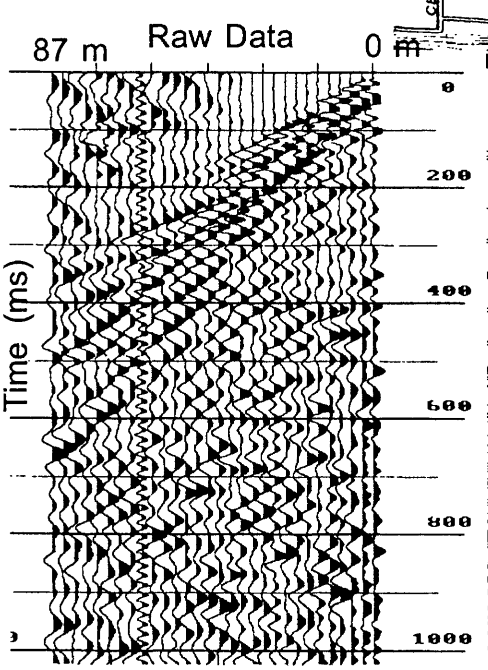
INPUT DATA

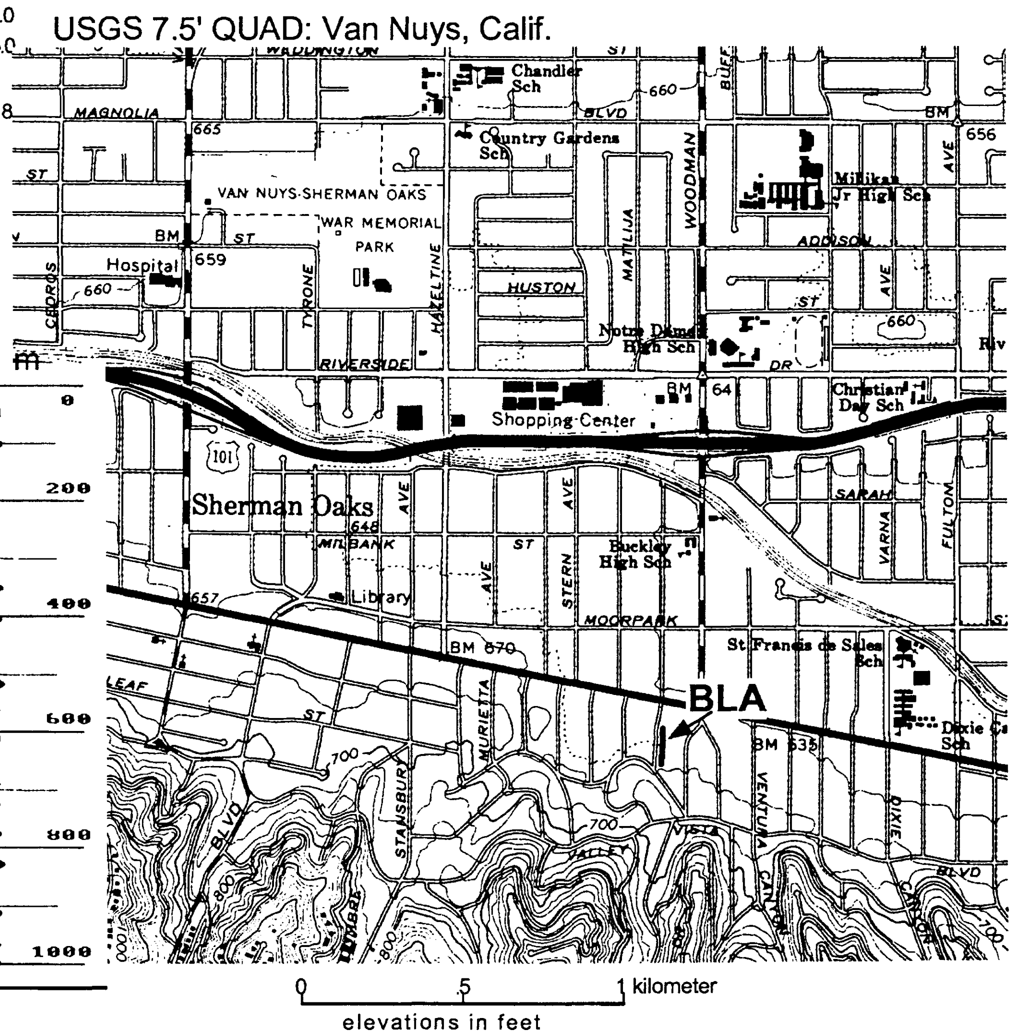
LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	317.0	317.0	.000	.000
2	1432.0	1432.0	.034	.034
3	2227.0	2231.0	.050	.048

COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	317	5.5	5.5	.0	5.5	5.5
2	1432.0	14.5	12.6	.0	20.0	18.1
3	2229.0			.0		







S-Wave Results
Site BLA - Sherman Oaks, California

Data acquired August 1996; Interpretation 2/97

Seismic sources were on asphalt. Geophones were primarily planted in grass.

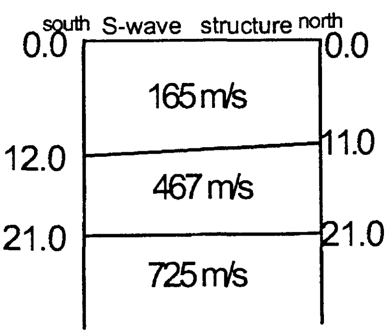
SPREAD LENGTH = 87.0 m

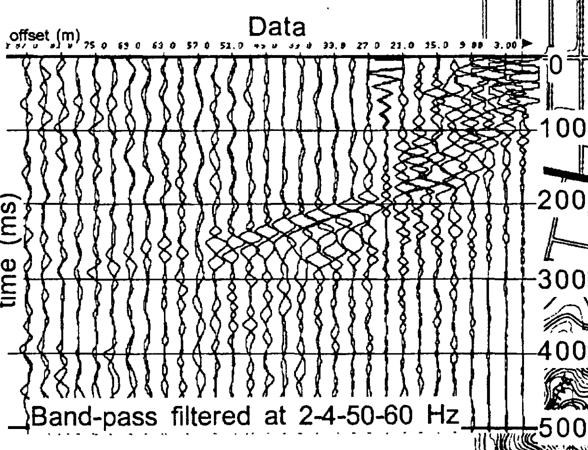
INPUT DATA

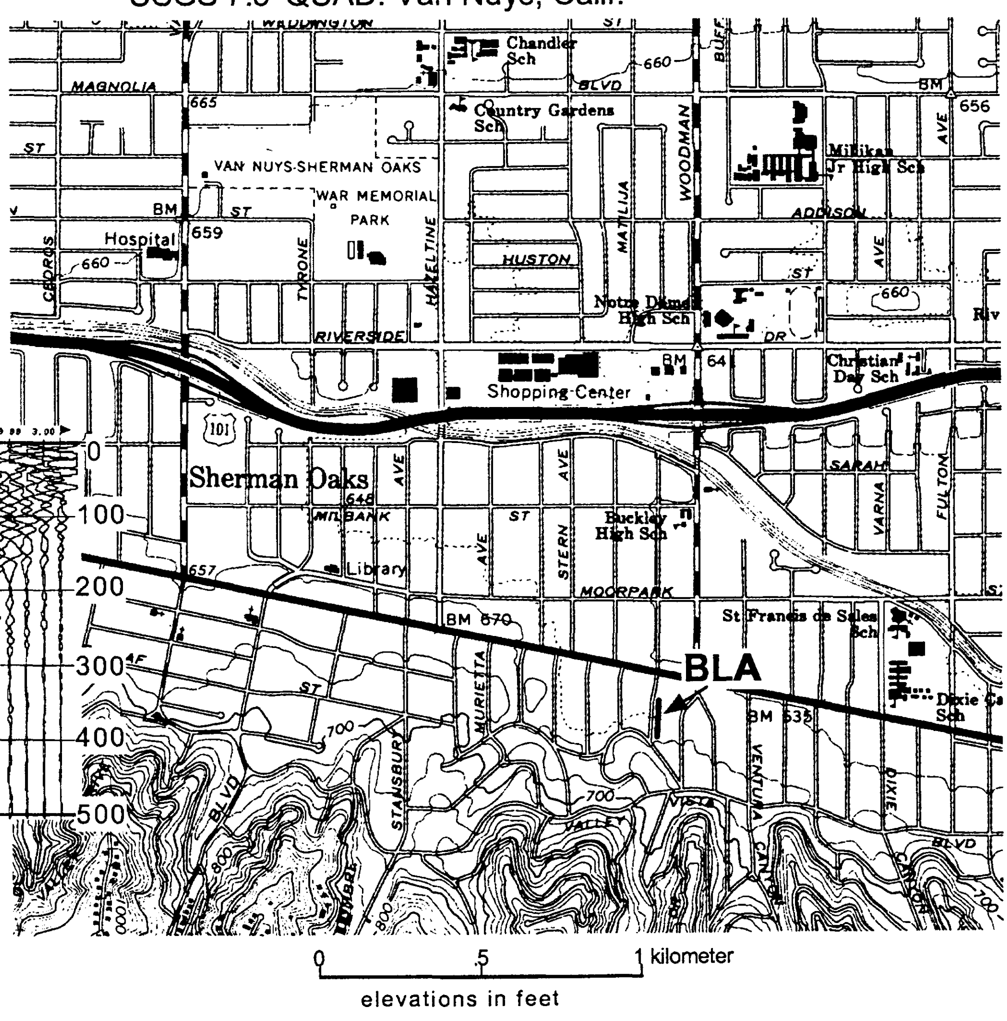
LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	167.0	167.0	.000	.000
2	541.0	412.0	.137	.118
3	724.0	756.0	.171	.157

COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	167.0	12.3	10.6		12.3	10.6
2	467.1	8.6	10.4	3.0	20.9	21.0
3	725.6			-8.7		







P-Wave Results
Site ER1 - Encino Reservoir, California

Data acquired August 1996; Interpretation 1/97
Seismic profile is about 0.8 km from aftershock recording station
V1 is an average of the 0 m offset reversed profiles
Velocities in meters/second and times in seconds
SPREAD LENGTH = 87.0 m

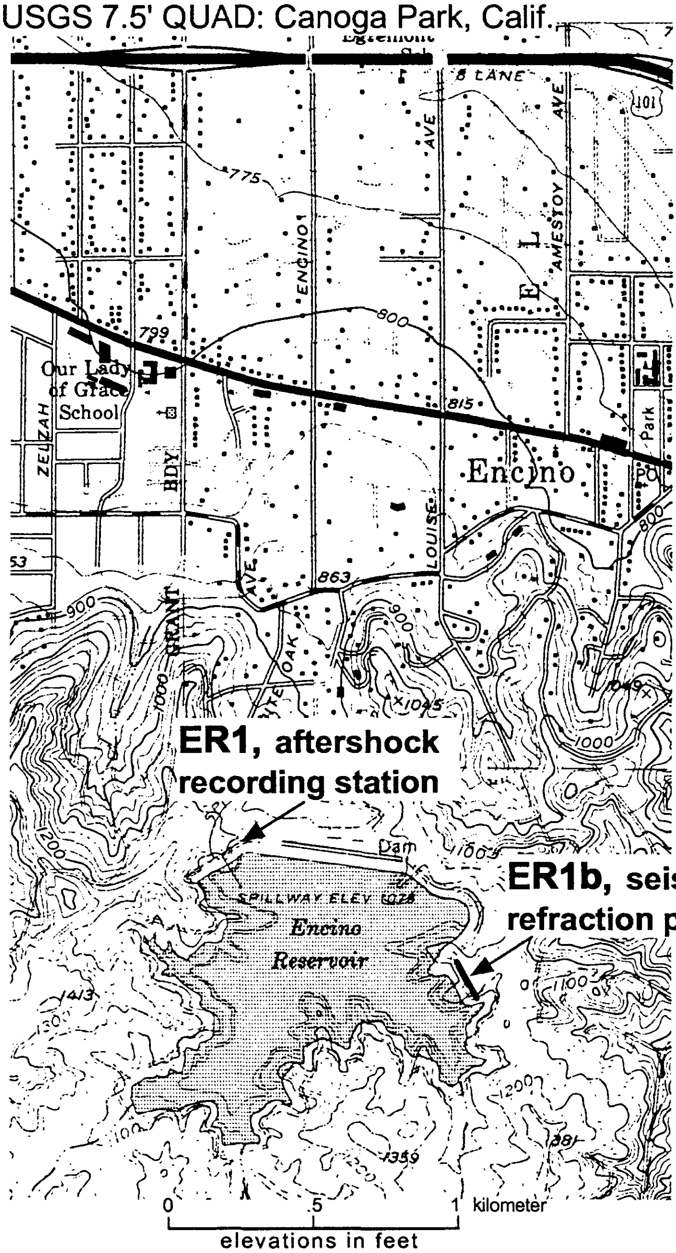
INPUT DATA

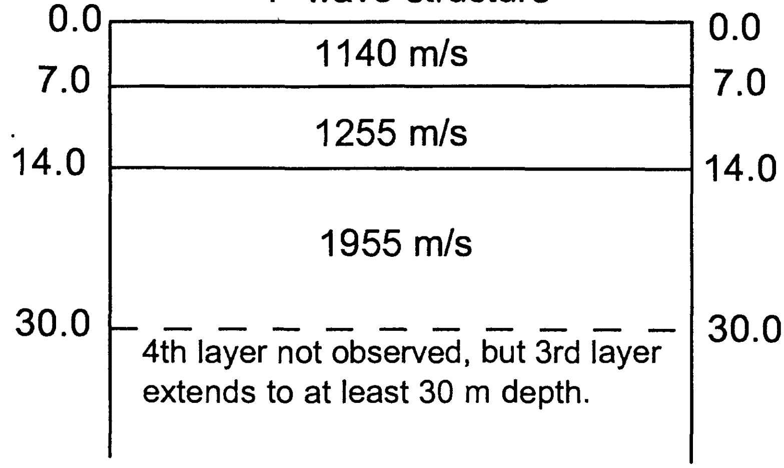
LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	1140.0	1140.0	.000	.000
2	1255.0	1255.0	.005	.005
3	1955.0	1955.0	.019	.019

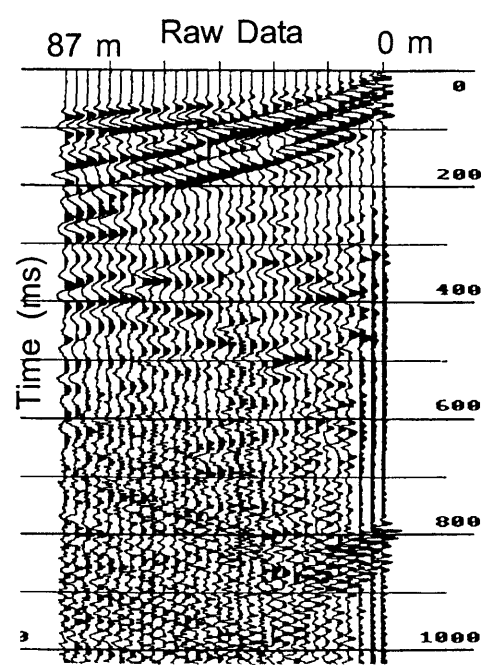
COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	1140.0	6.8	6.8		6.8	6.8
2	1255.0	7.6	7.6	.0	14.4	14.4
3	1955.0			.0		

USGS 7.5' QUAD: Canoga Park, Calif.







S-Wave Results
Site ER1 - Encino Reservoir, California

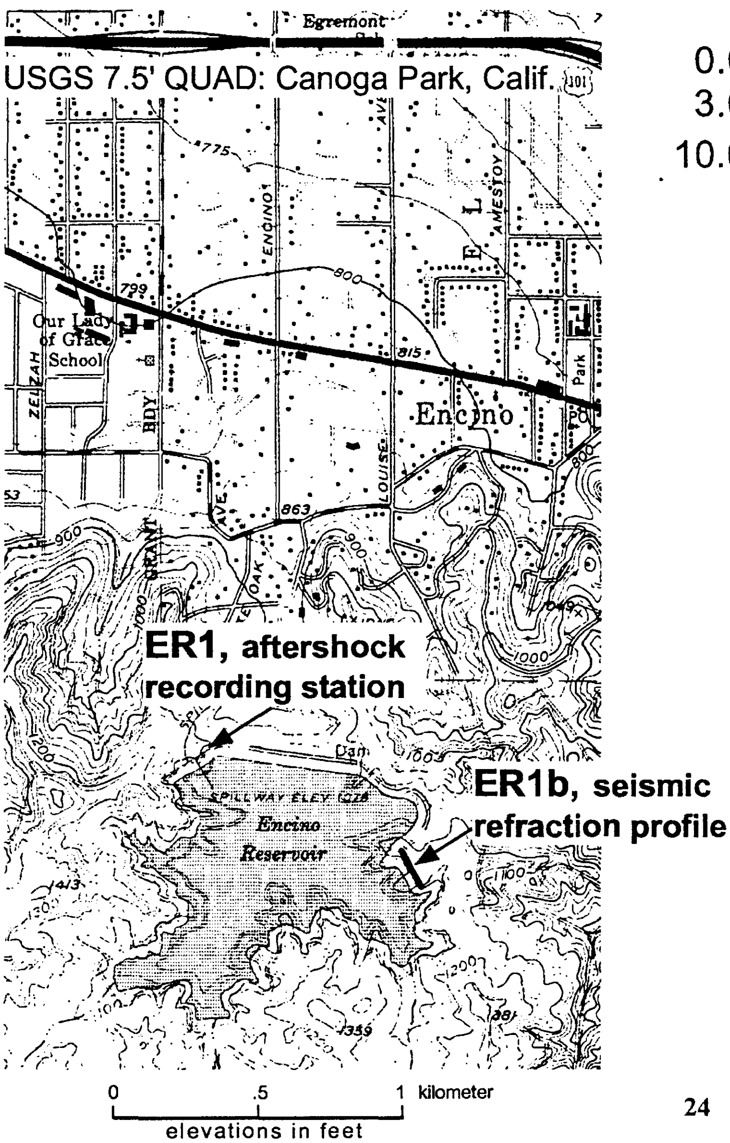
Data acquired August 1996; Interpretation 1/97
Seismic profile is about 0.8 km from aftershock recording station
V1 is an estimate. It was not clearly observed on both profiles.
V2 was not observed on profile B; it was assumed to be there.
V4 is an estimate; it was not observed. It is about .57 the speed of V3 on the P-wave data and is assumed to be the next deeper layer that would be observed. It is needed in order to get an estimate of the thickness of V3.
Velocities in meters/second and times in seconds
SPREAD LENGTH = 87.0 m

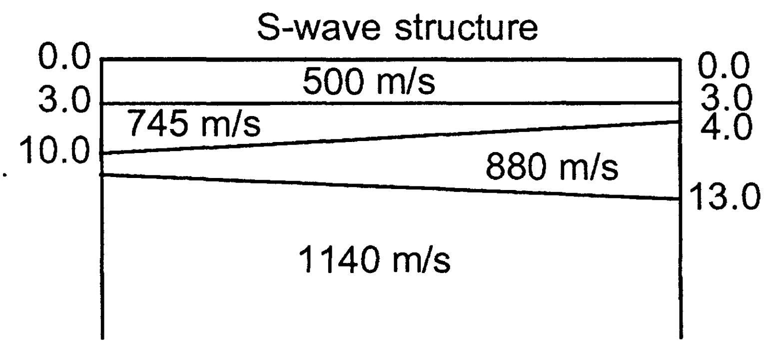
INPUT DATA

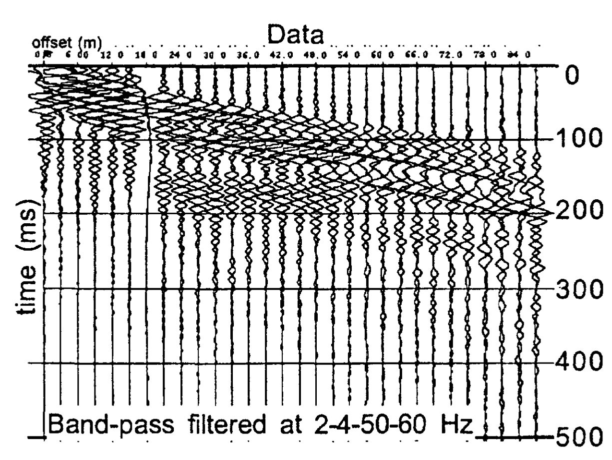
LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	500.0	500.0	.000	.000
2	745.0	745.0	.008	.008
3	901.0	862.0	.019	.010
4	1140.0	1140.0	.025	.025

COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	500.0	2.7	2.7		2.7	2.7
2	745.0	7.1	.8	.0	9.8	3.5
3	880.5	.6	9.5	2.0	10.4	13.0
4	1139.3			-.8		







P-Wave Results
Site JQ1 - Granada Hills, California

Data acquired August 1996; Interpretation 2/97

This site is about 1 km from JQ1 on the same rock type. Could not locate at JQ1: limited space.

These data were acquired on asphalt which directly overlies the sandstone.

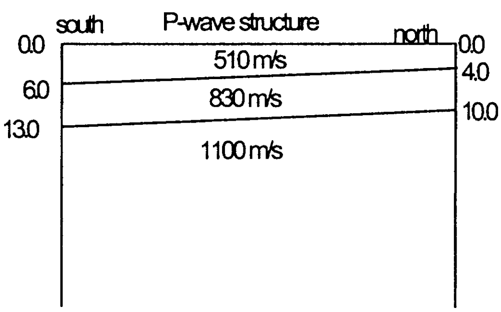
SPREAD LENGTH = 87.0 m

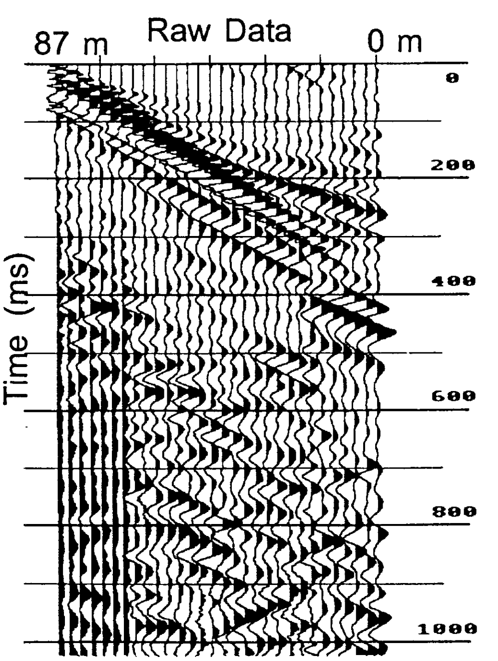
INPUT DATA

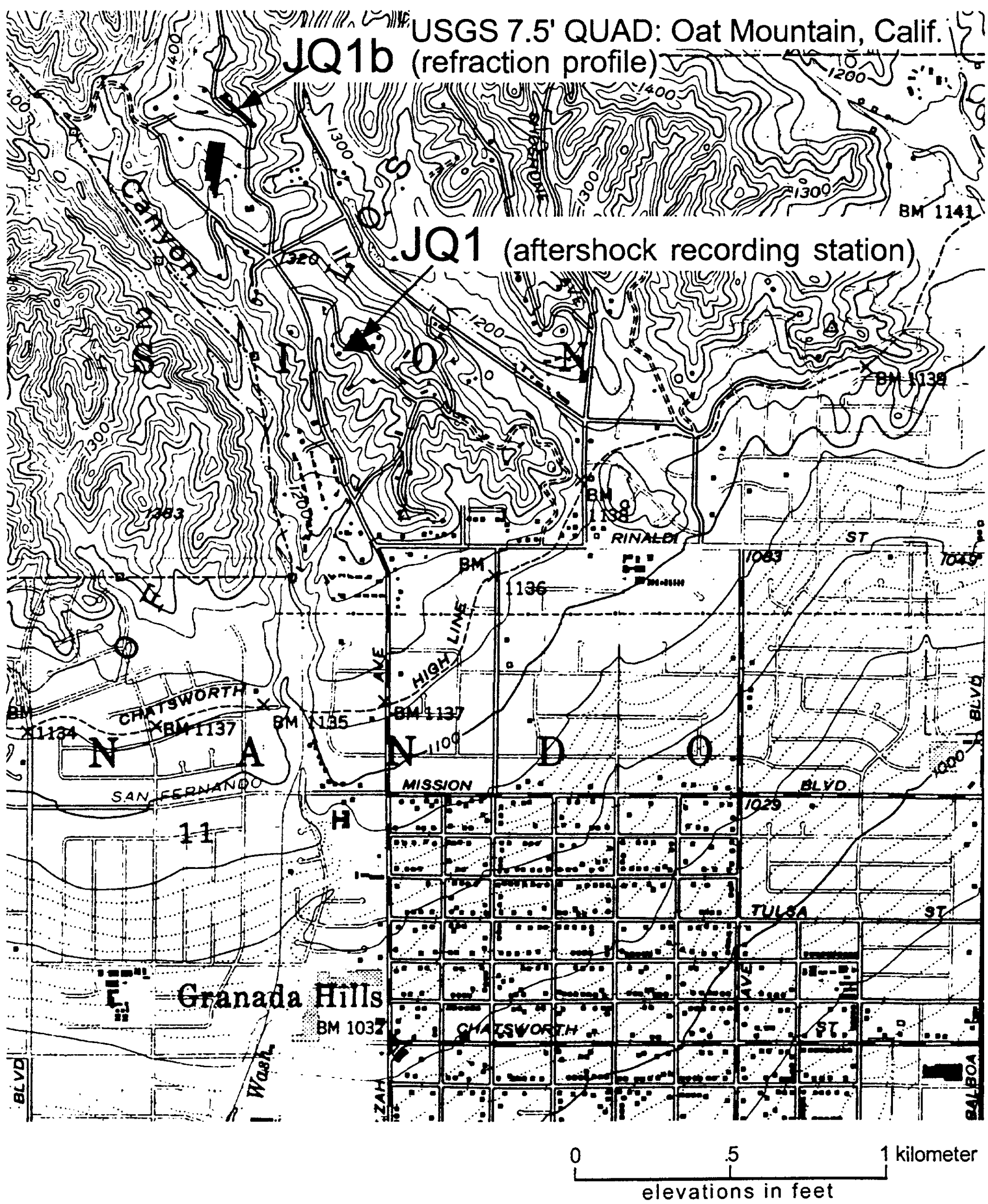
LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	511.0	511.0	.000	.000
2	828.0	828.0	.012	.018
3	1106.0	1097.0	.023	.032

COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	511.0	3.9	5.8		3.9	5.8
2	828.0	6.0	7.4	.0	9.9	13.2
3	1101.5			.3		







S-Wave Results
Site JQ1 - Granada Hills, California

Data acquired August 1996; Interpretation 2/97

Site is about 1 km from JQ1 on the same rock type. Space limitations did not permit locating at JQ1.

These data were acquired on asphalt which directly overlies the sandstone.

Layer with 408 m/s velocity was not observed in the data from south-end shots

Layer with 962 m/s velocity was not observed as a first break: 0-m offset time for this layer is suspect.

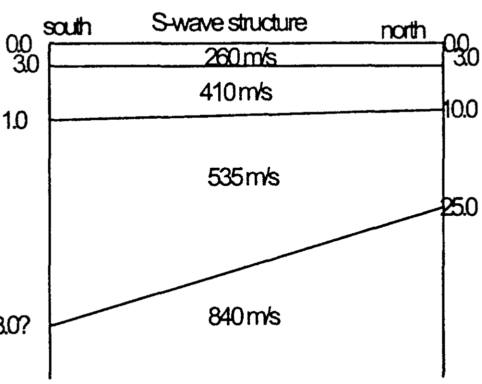
SPREAD LENGTH = 87.0 m

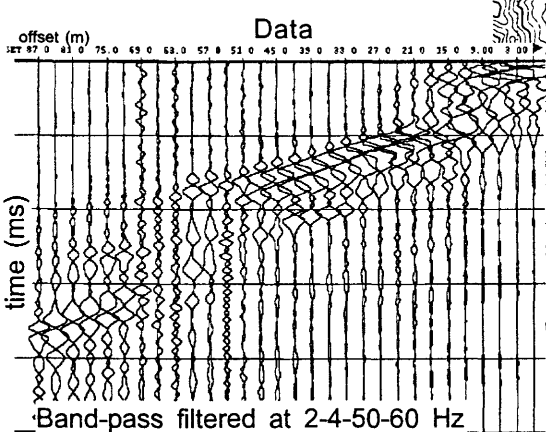
INPUT DATA

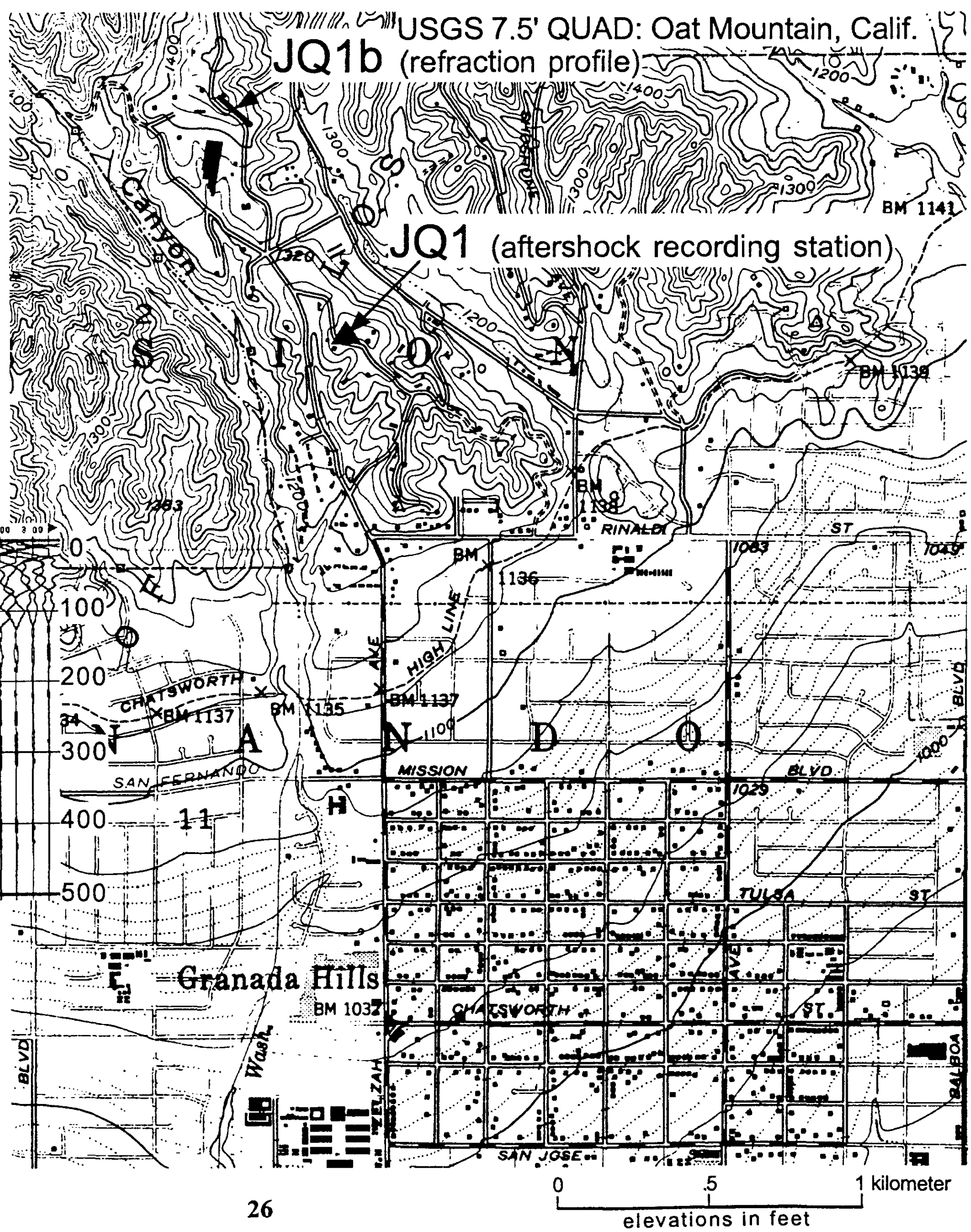
LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	262.0	262.0	.000	.000
2	408.0	408.0	.017	.017
3	530.0	542.0	.042	.045
4	752.0	962.0	.095	.147

COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	262.0	2.9	2.9		2.9	2.9
2	408.0	7.1	8.1	.0	10.0	11.0
3	535.9	15.2	31.9	-.8	25.2	42.9
4	840.7			-5.4		







P-Wave Results
Site LOS - Encino, California

Data acquired August 1996; Interpretation 2/97
Center of seismic profile on Weddington St is about 30 m from the aftershock recording station
Data quality are not as good as most sites, lots of ambient traffic? noise.

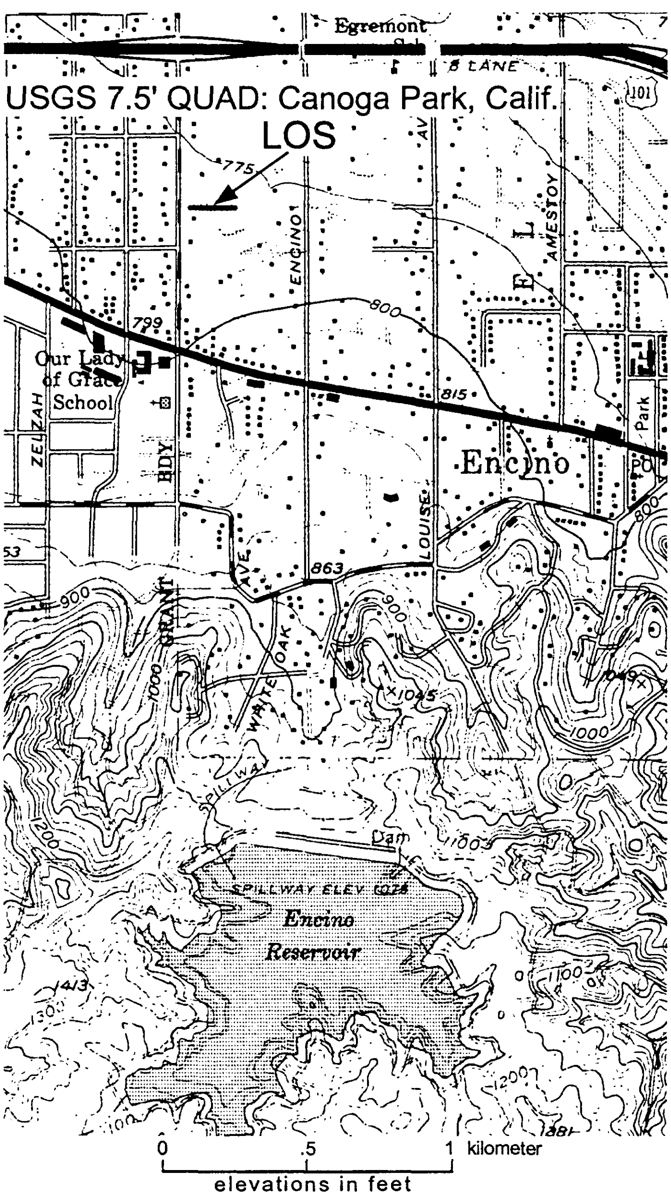
SPREAD LENGTH = 87.0 m

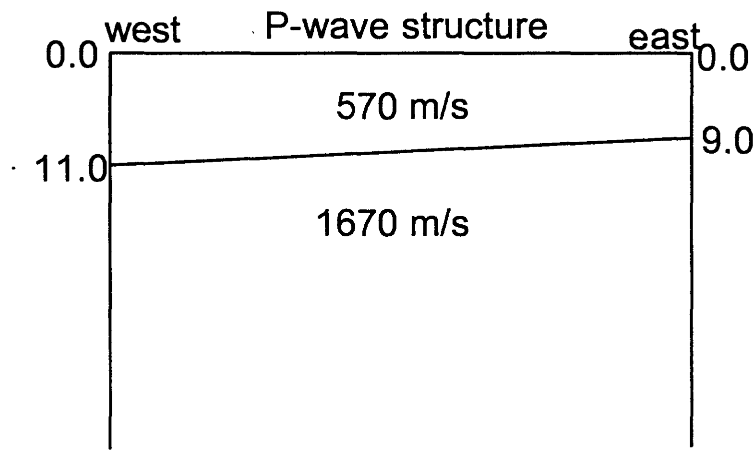
INPUT DATA

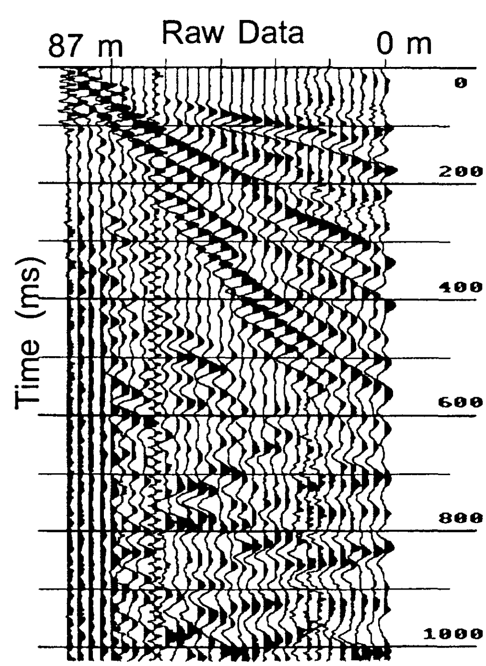
LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	572.0	572.0	.000	.000
2	1659.0	1680.0	.036	.029

COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	572.0	11.0	8.8		11.0	8.8
2	1669.4			-.1		







S-Wave Results
Site LOS - Encino, California

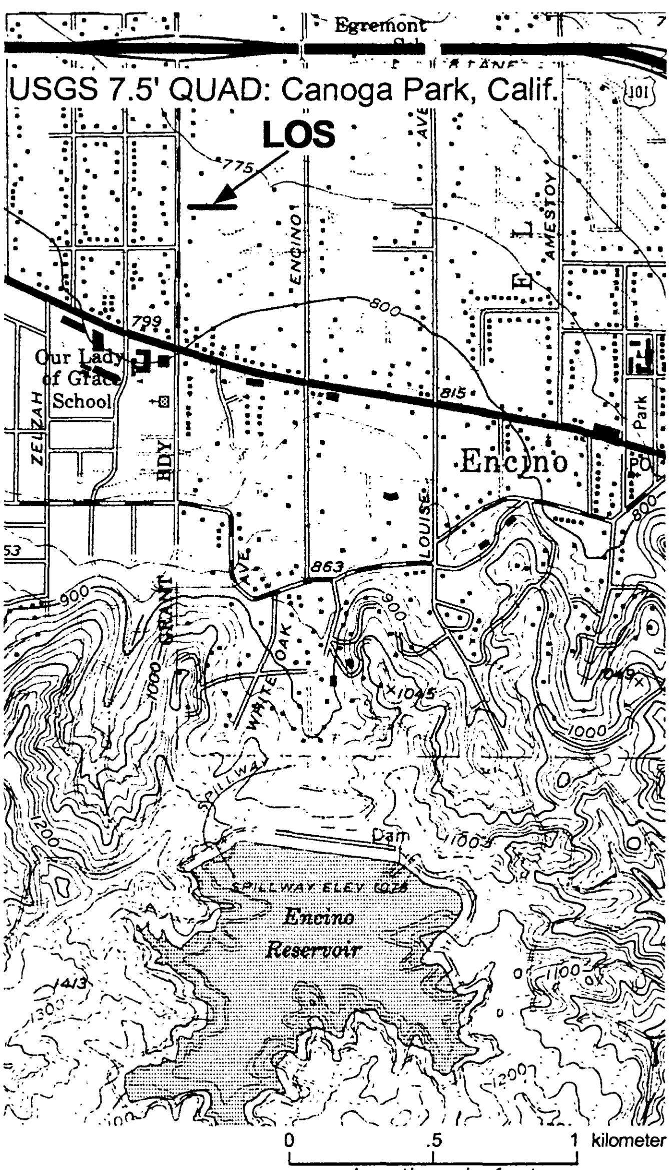
Data acquired August 1996; Interpretation 2/97
Center of seismic profile on Weddington St is about 30 m from the aftershock recording station
Data quality are not as good as most sites, lots of ambient traffic? noise.
SPREAD LENGTH = 87.

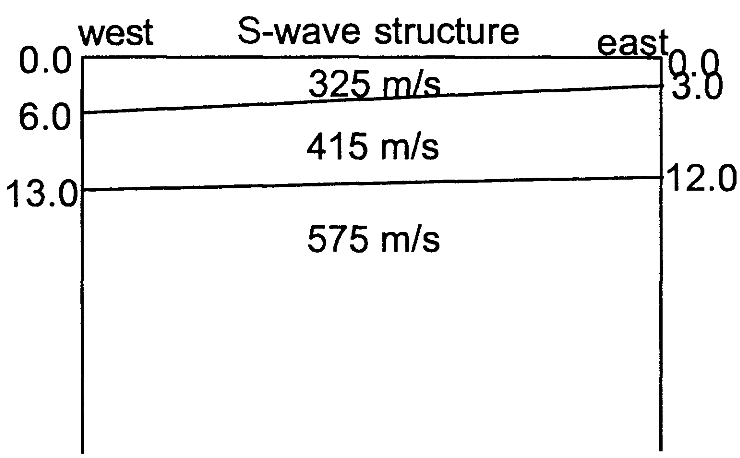
INPUT DATA

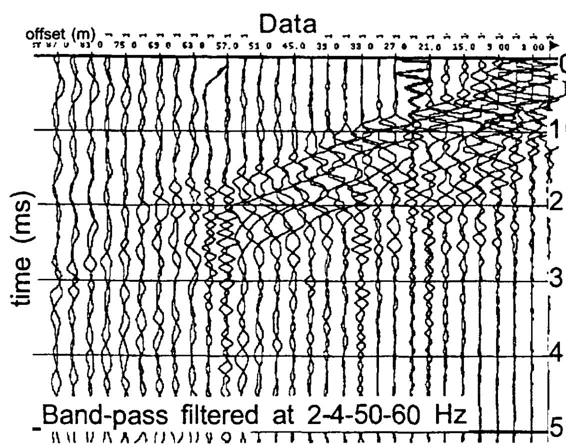
LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	325.0	325.0	.000	.000
2	428.0	403.0	.023	.010
3	605.0	549.0	.055	.045

COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	325.0	6.0	2.6		6.0	2.6
2	414.8	7.3	9.5	2.2	13.3	12.1
3	575.3			1.8		







P-wave Results
Site MAY - Next to Los Angeles River, Tarzana, California

Data Acquired August 1996, Interpretation 1/97

East end of Seismic profile is about 10 m west of the aftershock recording station.

V_1 is an average of both reversed shots. Data quality is relatively poor for V_1

SPREAD LENGTH = 87.0 m

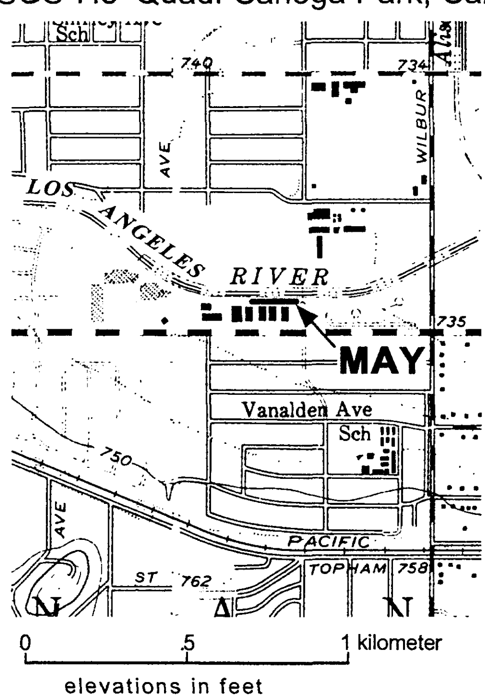
INPUT DATA

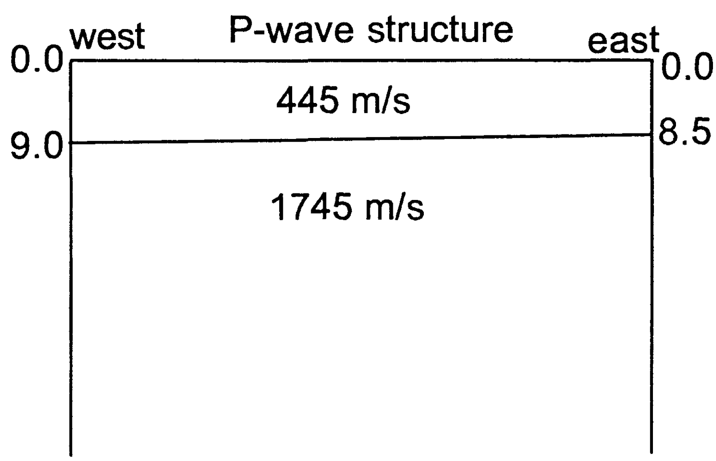
LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	445.0	445.0	.000	.000
2	1835.0	1662.0	.040	.037

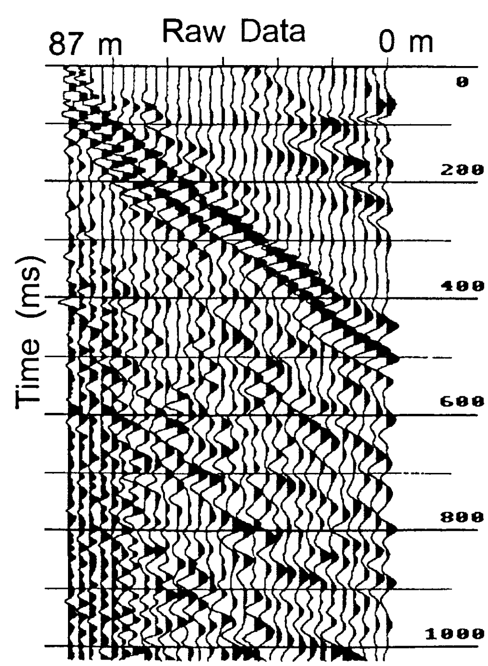
COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	445.0	9.2	8.5		9.2	8.5
2	1744.1			.7		

USGS 7.5' Quad: Canoga Park, Calif.







S-wave Results
Site MAY - Next to Los Angeles River, Tarzana, California

Data Acquired August 1996, Interpretation 1/97
East end of Seismic profile is about 10 m west of the aftershock recording station.

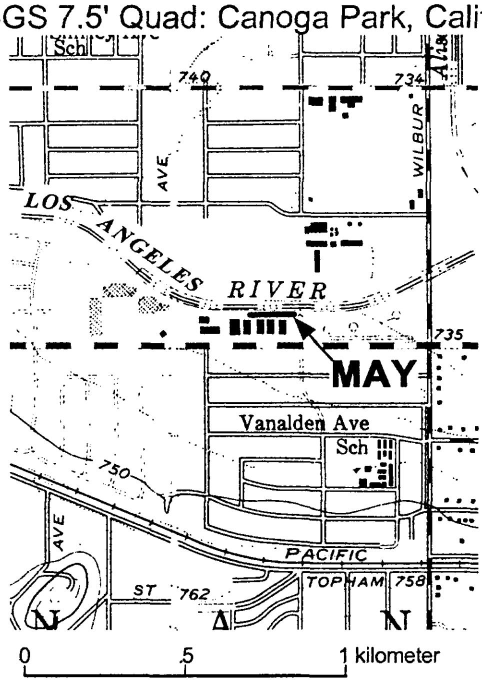
INPUT DATA

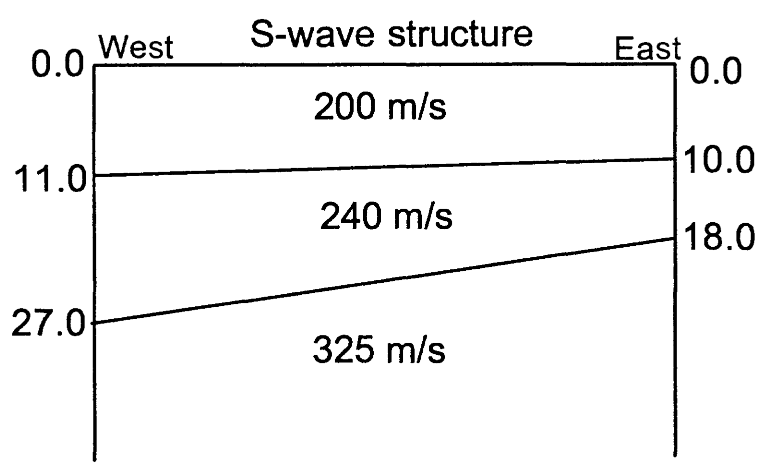
LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	200.0	200.0	.000	.000
2	240.0	240.0	.061	.055
3	360.0	297.0	.175	.122

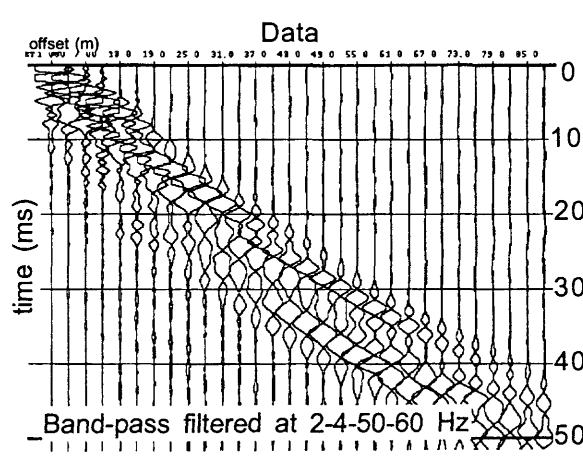
COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	200.0	11.0	9.9		11.0	9.9
2	240.0	15.9	7.9	.0	26.9	17.8
3	323.7			6.0		

USGS 7.5' Quad: Canoga Park, Calif.







P-Wave Results
Site MUE - West of Chatsworth, California

Data acquired August 1996; Interpretation 2/97
Site is on the same rock type about 2 km from the aftershock recording station MUE. Space limitations did not permit locating at MUE. Seismic sources were on asphalt which directly overlies the sandstone. Geophones were in soil.

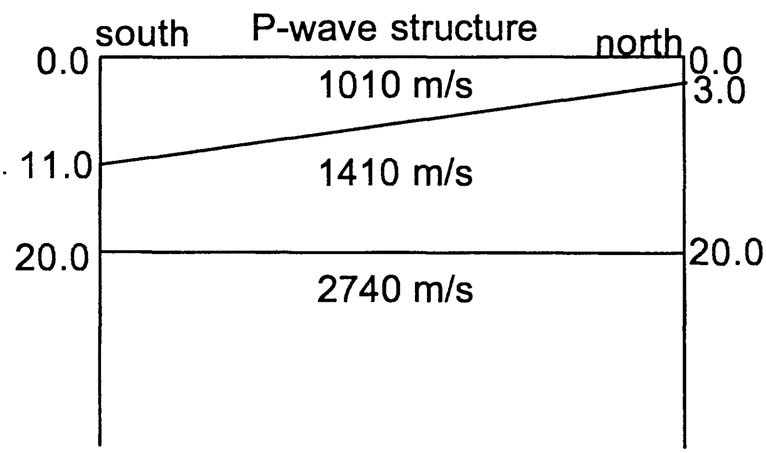
SPREAD LENGTH = 87.0 m

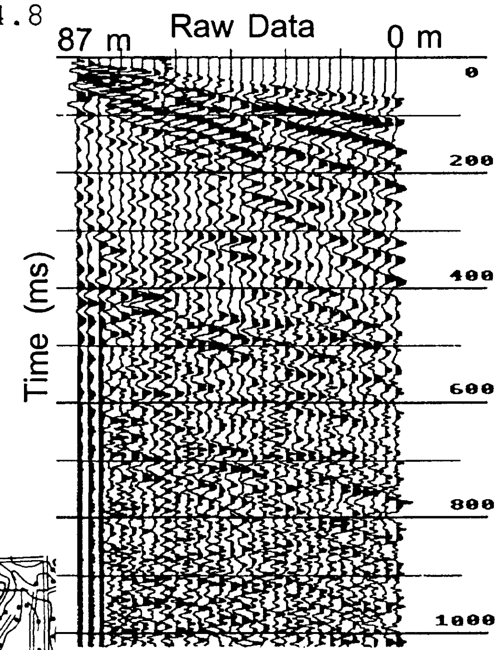
INPUT DATA

LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	1010.0	1010.0	.000	.000
2	1413.0	1410.0	.015	.004
3	3194.0	2413.0	.031	.026

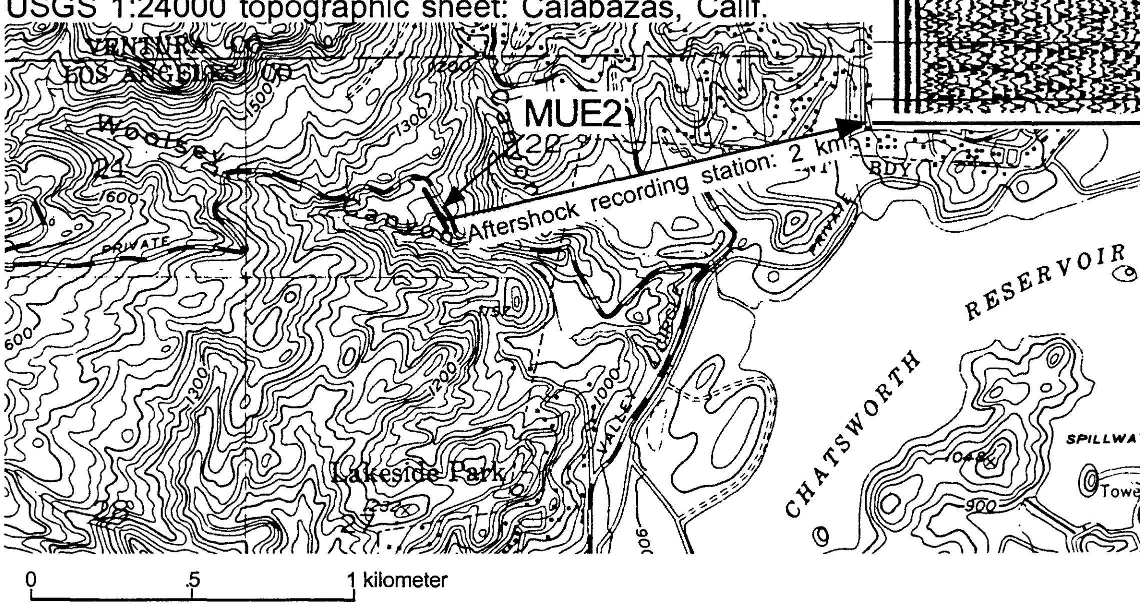
COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	1010.0	10.8	2.9		10.8	2.9
2	1411.5	9.1	17.1	.1	20.0	20.0
3	2739.7			4.8		





USGS 1:24000 topographic sheet: Calabazas, Calif.



elevations in feet

S-Wave Results
Site MUE - West of Chatsworth, California

Data acquired August 1996; Interpretation 2/97
Site is about 2 km from MUE on the same rock type. Space limitations did not permit locating at mue.
Seismic sources were on asphalt which directly overlies the sandstone. Geophones were in soil.

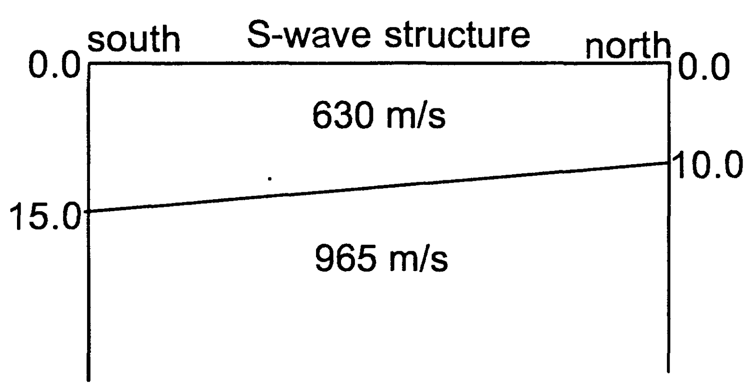
SPREAD LENGTH = 87.0 m

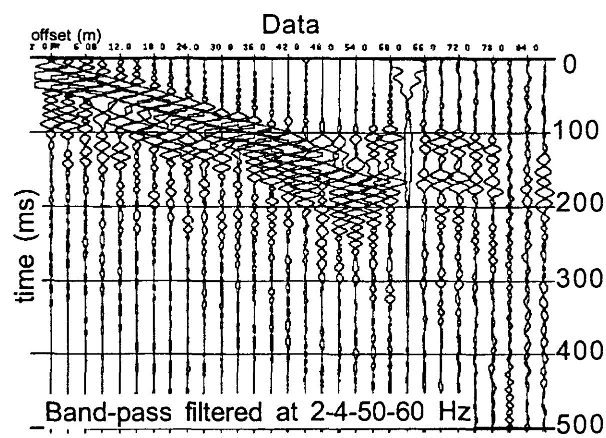
INPUT DATA

LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	632.0	632.0	.000	.000
2	963.0	969.0	.036	.023

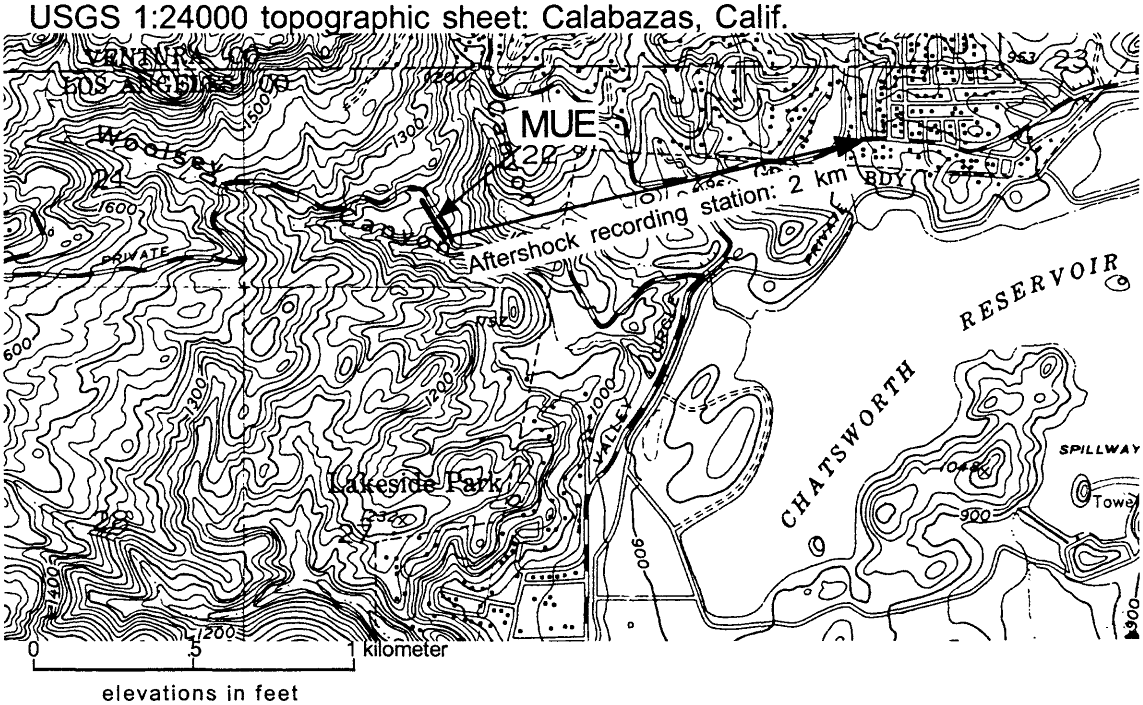
COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	632.0	15.0	9.6		15.0	9.6
2	966.0			-.2		





USGS 1:24000 topographic sheet: Calabazas, Calif.



P-Wave Results
Site NOHO - North Hollywood, California
Railroad site

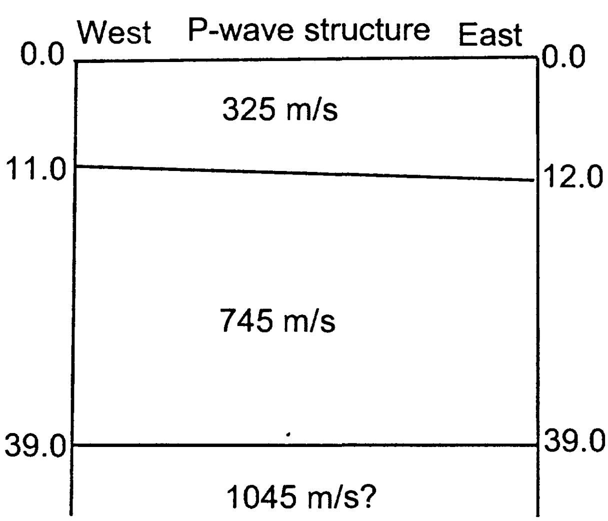
Data acquired August 1996; Interpretation 1/97
Seismic profile is along railroad right-of-way close to Lankershim Blvd in North Hollywood
V1 is an average of the two 0 m offset reversed profiles.
Velocities in meters/second and times in seconds
SPREAD LENGTH = 87.0 m

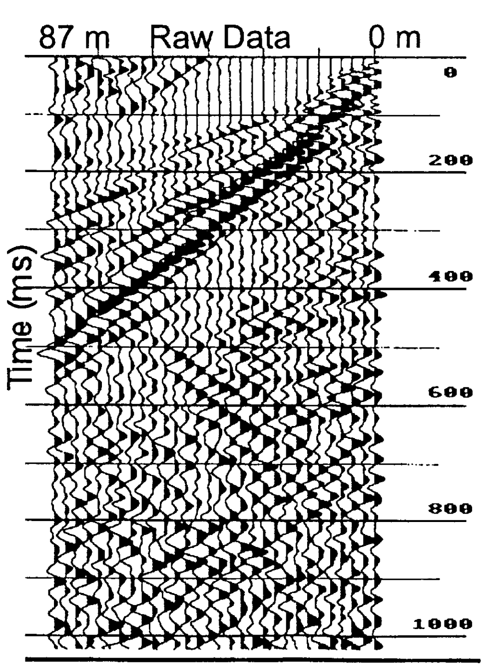
INPUT DATA

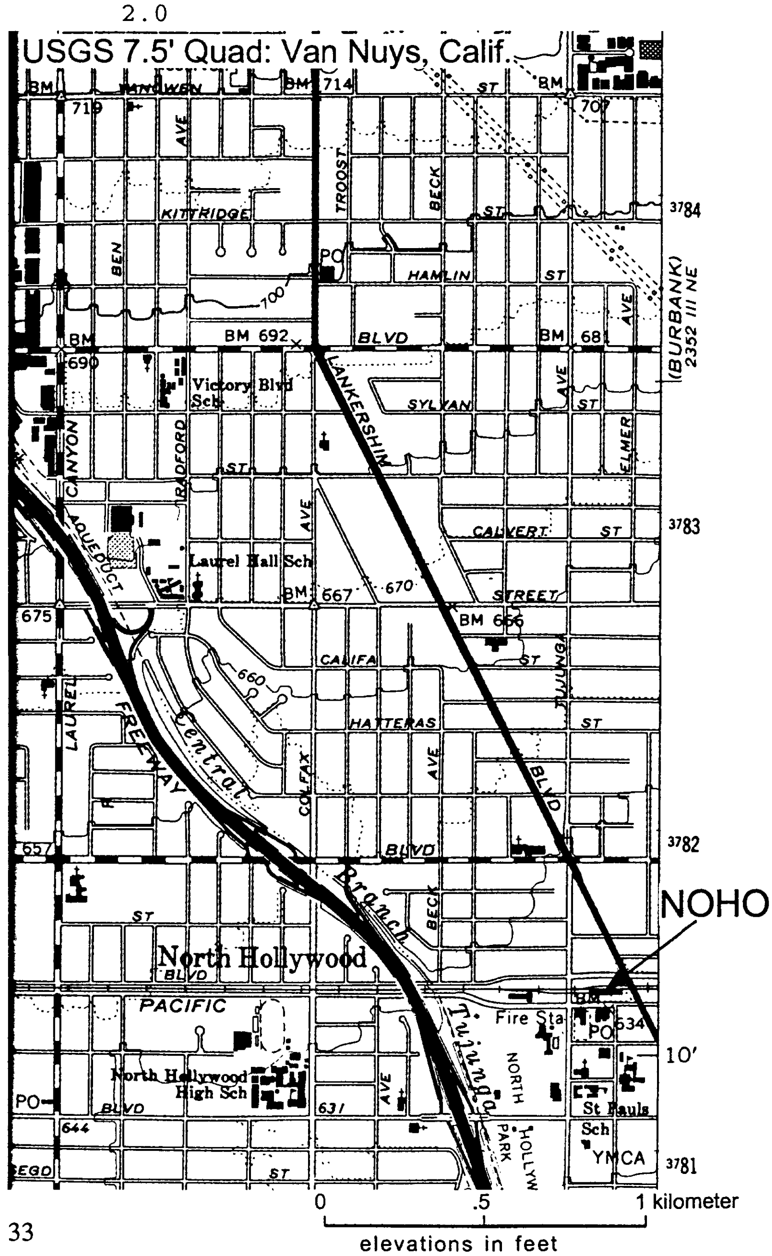
LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	325.0	325.0	.000	.000
2	740.0	745.0	.062	.065
3	1080.0	1015.0	.119	.120

COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	325.0	11.2	11.7		11.2	11.7
2	742.5	28.2	27.1	-.1	39.4	38.8
3	1045.8			2.0		







S-Wave Results
Site NOHO - North Hollywood, California
Railroad site

Data acquired August 1996; Interpretation 1/97
Seismic profile is along railroad right-of-way close to Lankershim Blvd in North Hollywood
V1 is an average of the two 0 m offset reversed profiles.
Velocities in meters/second and times in seconds

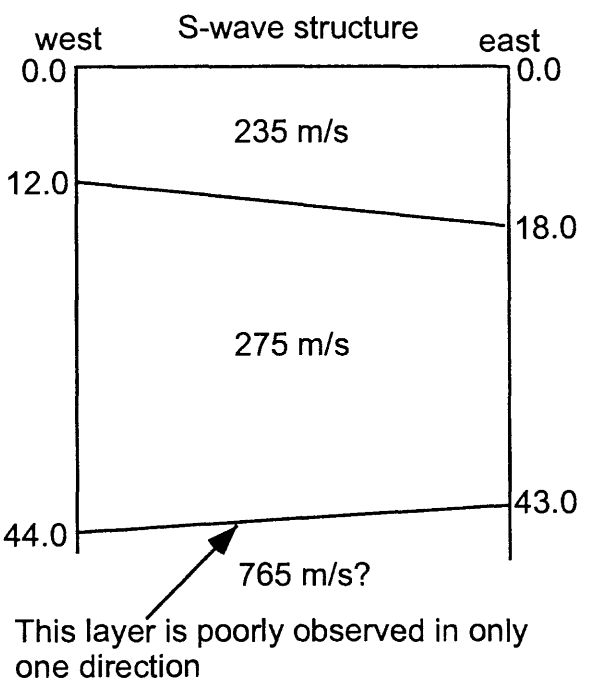
SPREAD LENGTH = 87.

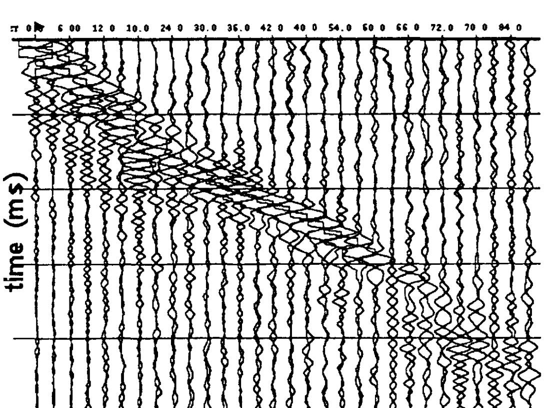
INPUT DATA

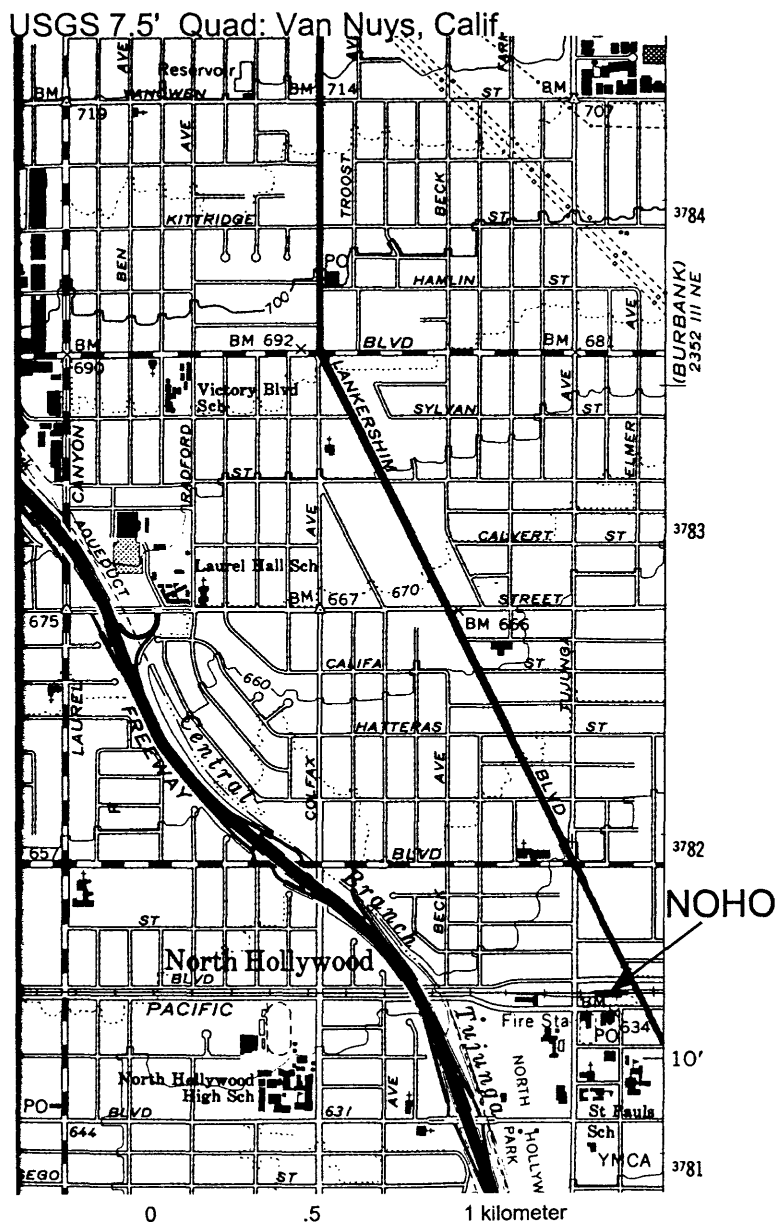
LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	235.0	235.0	.000	.000
2	288.0	262.0	.051	.082
3	764.0	764.0	.312	.312

COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	235.0	11.7	18.9		11.7	18.9
2	273.5	31.8	23.3	4.5	43.5	42.2
3	763.0			-.8		







P-wave Results
Site SMI - Northridge, California

Data acquired August 1996
Seismic sources were on asphalt. Geophones were primarily planted in grass.

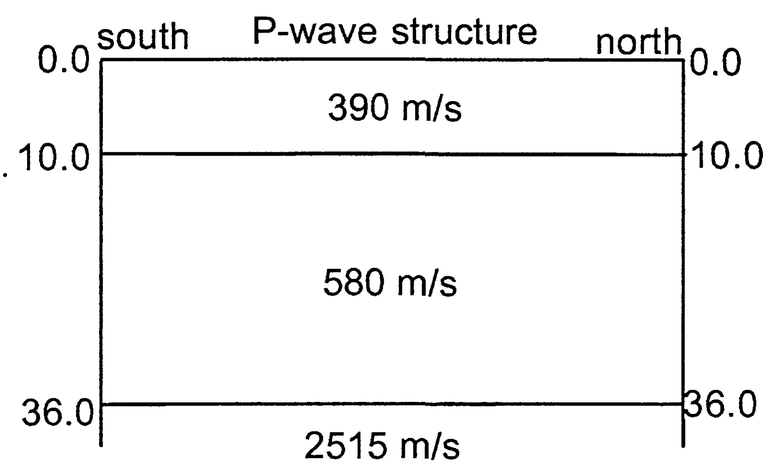
SPREAD LENGTH = 87.0 m

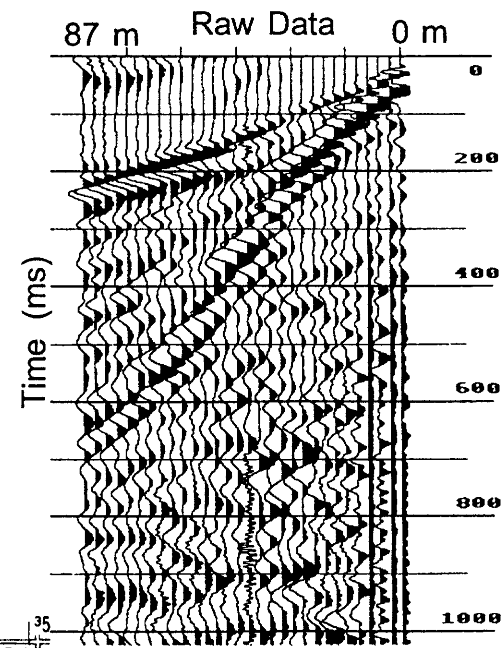
INPUT DATA

LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	390.0	390.0	.000	.000
2	557.0	606.0	.040	.039
3	2617.0	2430.0	.137	.138

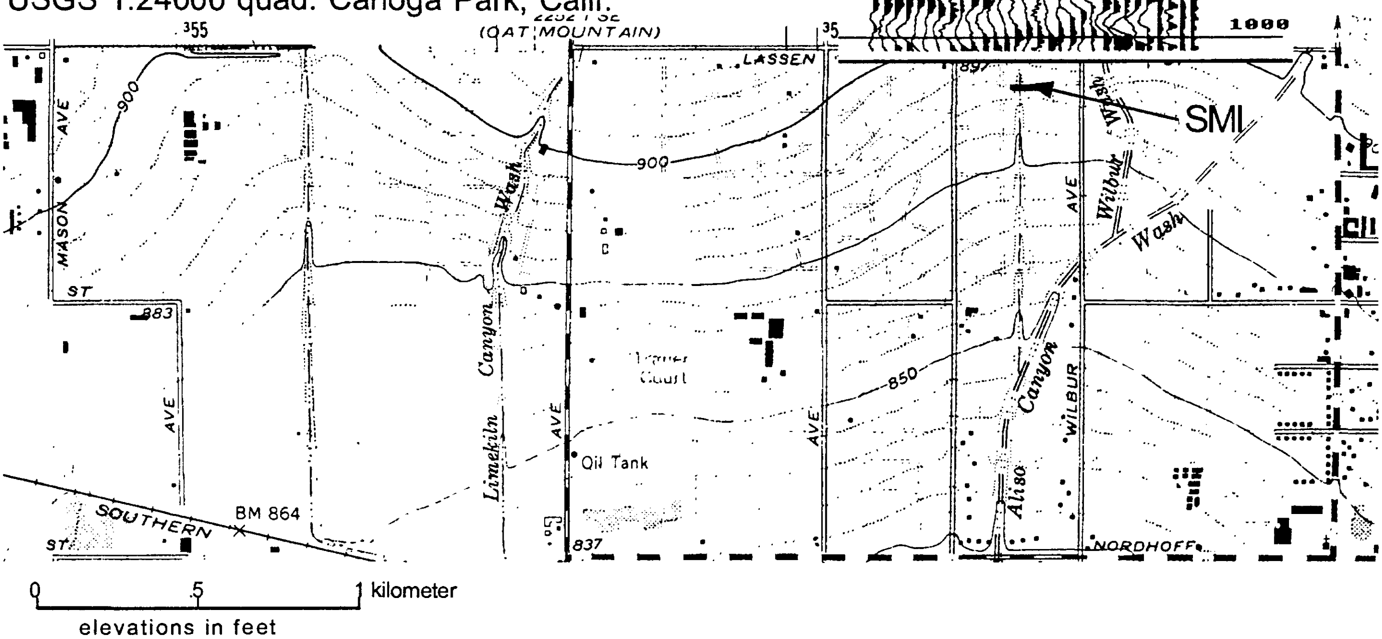
COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	390.0	10.5	10.3		10.5	10.3
2	580.0	24.9	25.6	-2.2	35.5	35.9
3	2516.9			1.6		





USGS 1:24000 quad: Canoga Park, Calif.



S-Wave Results
Site SMI - Northridge, California

Data acquired August 1996; Interpretation 2/97

Seismic sources were on asphalt. Geophones were primarily planted in grass.

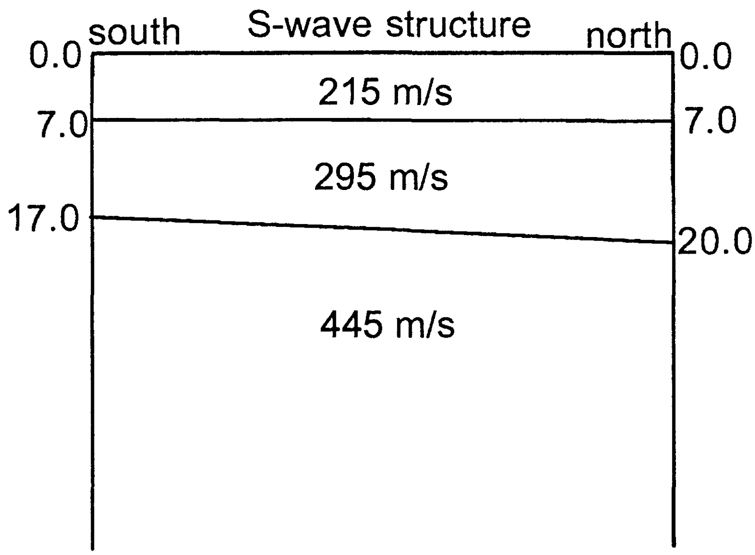
SPREAD LENGTH = 87.0 m

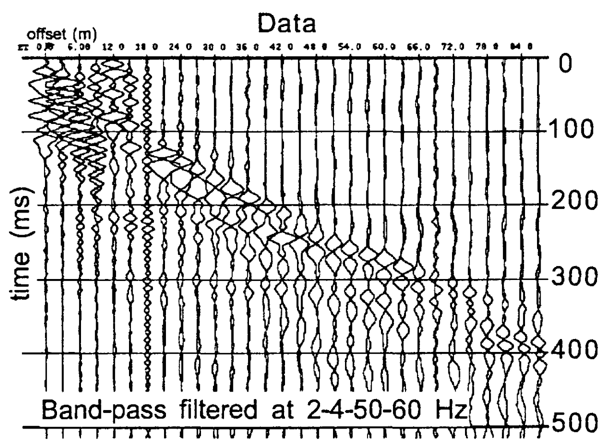
INPUT DATA

LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	216.0	216.0	.000	.000
2	269.0	325.0	.044	.043
3	381.0	543.0	.107	.122

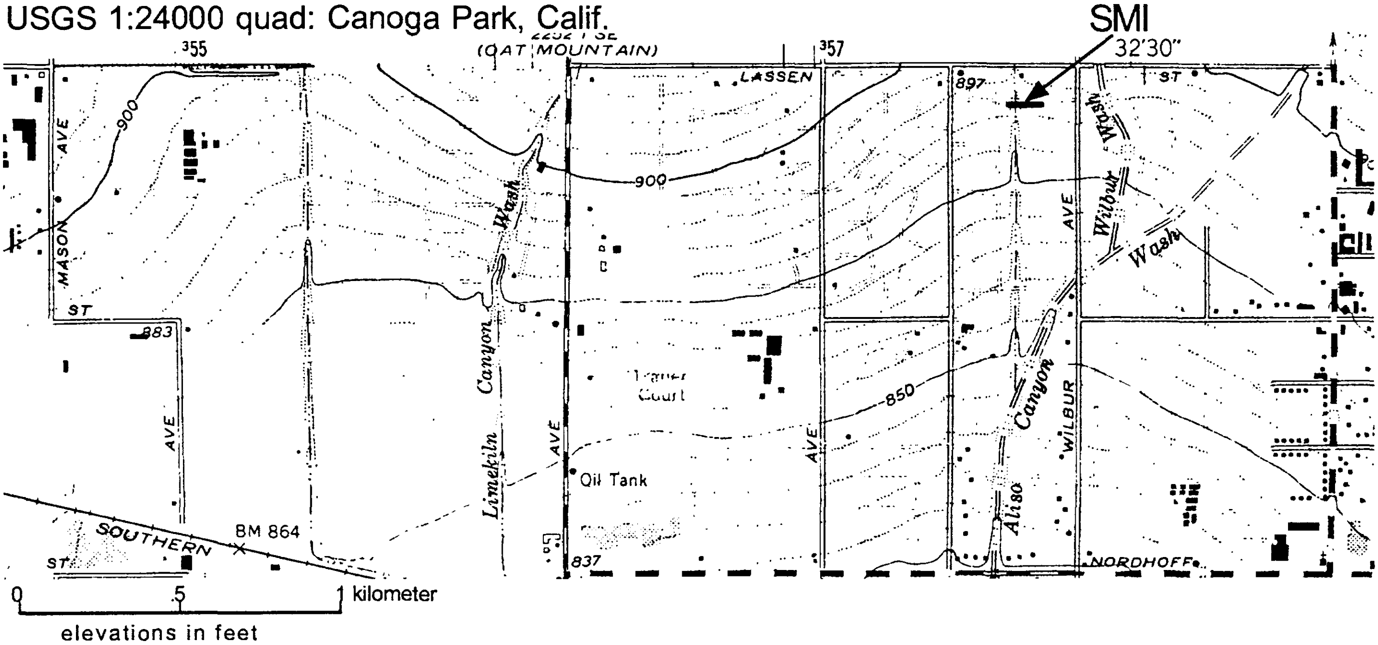
COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	216.0	7.1	6.9		7.1	6.9
2	292.8	9.7	12.9	-5.9	16.8	19.8
3	445.7			-5.4		





USGS 1:24000 quad: Canoga Park, Calif.



P-Wave Results
Site SOP - Sherman Oaks, California
Sherman Oaks Park

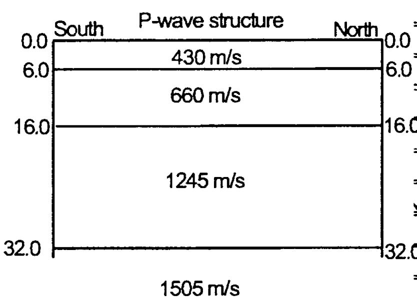
Data acquired August 1996; Interpretation 12/96
Seismic profile is 5 m south of USGS borehole SOP off of Hazeltine Ave. Geophones on grass.
V1 is an average of the two 0 m offset reversed profiles.
SPREAD LENGTH = 87.

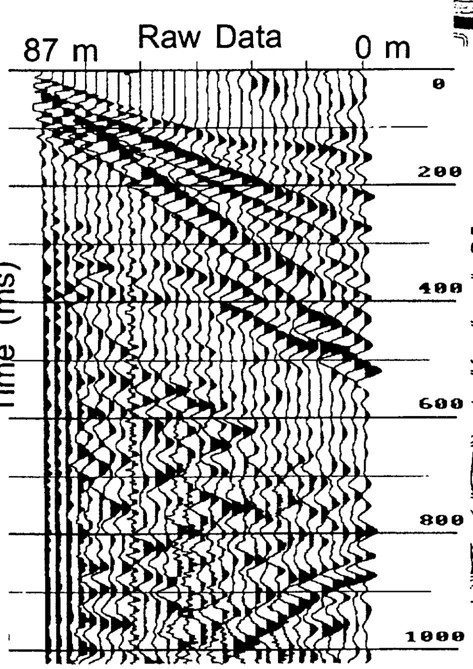
INPUT DATA

LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	430.0	430.0	.000	.000
2	645.0	676.0	.020	.020
3	1130.0	1388.0	.050	.050
4	1546.0	1523.0	.067	.067

COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	430.0	5.7	5.7		5.7	5.7
2	660.0	9.8	9.8	-1.2	15.5	15.5
3	1244.5	16.5	16.5	-2.9	32.0	32.0
4	1506.0			8.7		





USGS 7.5' Quad: Van Nuys, Calif.

S-Wave Results
Site SOP - Sherman Oaks, California
Sherman Oaks Park

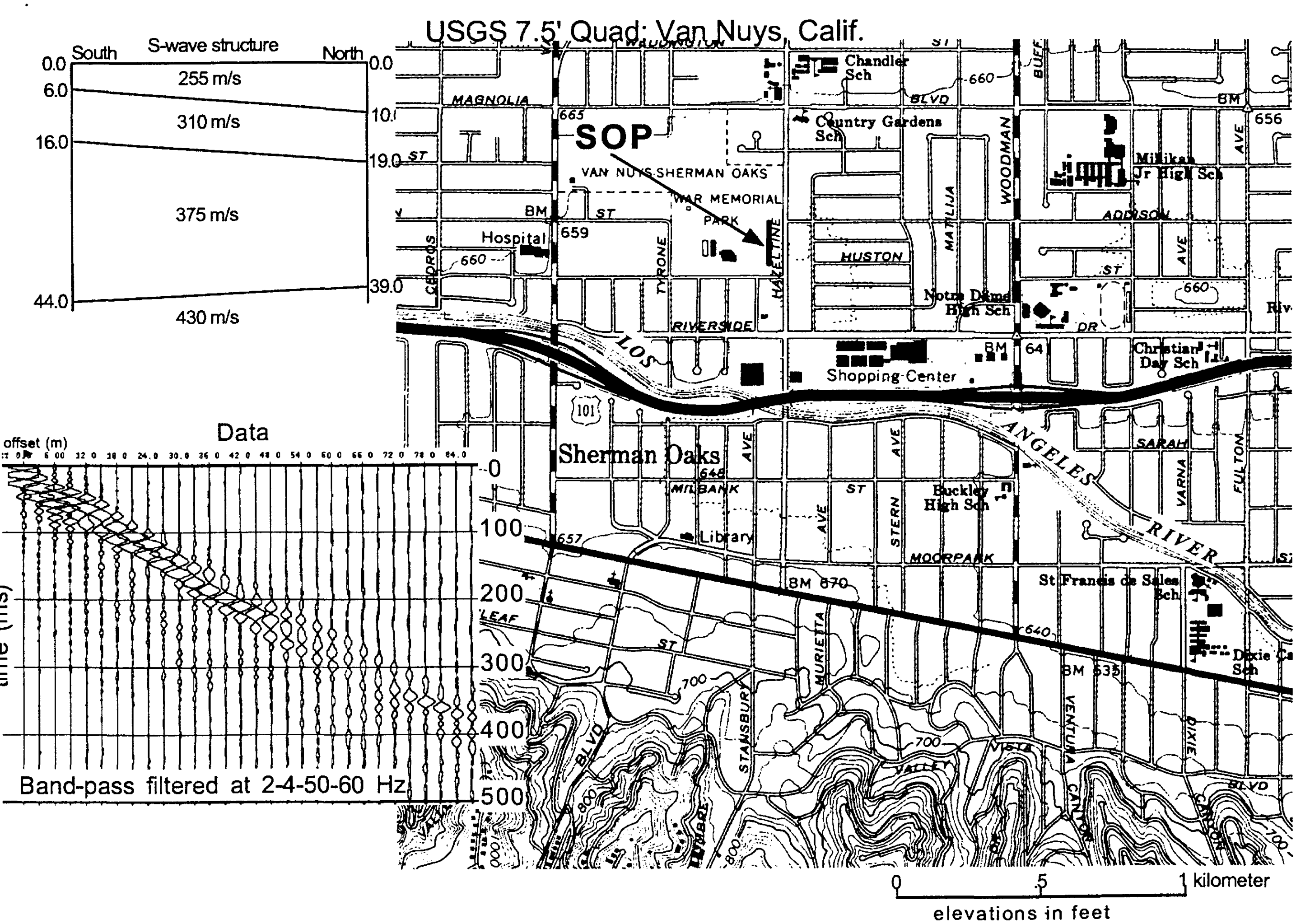
Data acquired August 1996; Interpretation 12/96
Seismic profile is 5 m south of USGS borehole SOP off of Hazeltine Ave
V1 is an average of the two 0 m offset reversed profiles.

INPUT DATA

LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	*257.0*	*257.0*	*.000*	*.000*
2	*320.0*	*300.0*	*.025*	*.045*
3	*370.0*	*380.0*	*.070*	*.091*
4	*415.0*	*455.0*	*.157*	*.157*

COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	*257.0*	*5.8*	*10.4*		*5.8*	*10.4*
2	*309.3*	*10.3*	*8.8*	*2.8*	*16.0*	*19.2*
3	*373.9*	*27.8*	*19.4*	*-2.7*	*43.9*	*38.7*
4	*432.3*			*-4.5*		



P-Wave Results
Site SOW - Sherman Oaks, California

Data acquired August 1996; Interpretation 12/96

Seismic profile is about 10 m south of USGS borehole SOW off of Woodman Ave, next to the L.A. River

V1 is an average of the two 0 m offset reversed profiles.

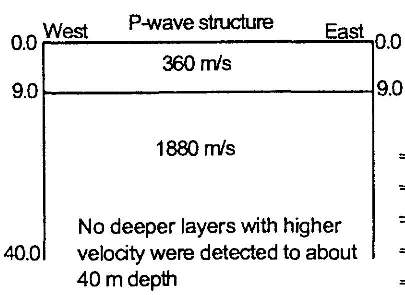
V2 is an average of 5 different shots.

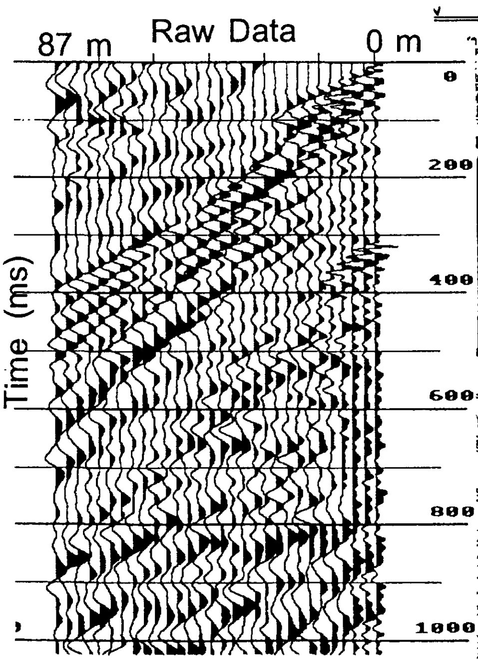
INPUT DATA

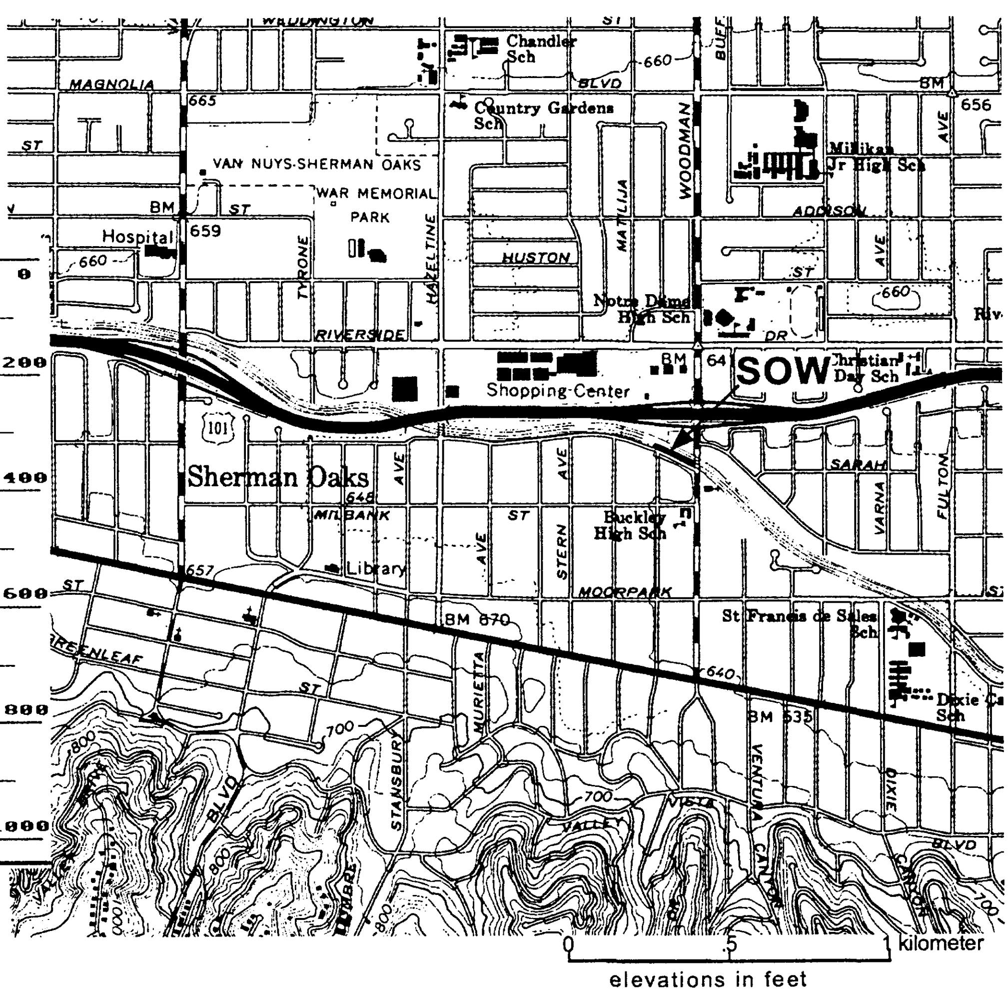
LAYER	APPARENT VEL., A m/s	APPARENT VEL., B m/s	INTERCEPT TIMES, A s	INTERCEPT TIMES, B s
1	361.0	361.0	.000	.000
2	1881.0	1881.0	.050	.050

COMPUTED STRUCTURE

LAYER	VELOCITY m/s	THICKNESS A m	THICKNESS B m	DIP	DEPTH A m	DEPTH B m
1	361.0	9.2	9.2		9.2	9.2
2	1881.0			.0		







S-Wave Results
Site SOW - Sherman Oaks, California

Data acquired August 1996; Interpretation 12/96
Seismic profile is about 10 m south of USGS borehole SOW off of Woodman Ave, next to the L.A. River
V1 is an average of the two 0 m offset reversed profiles.

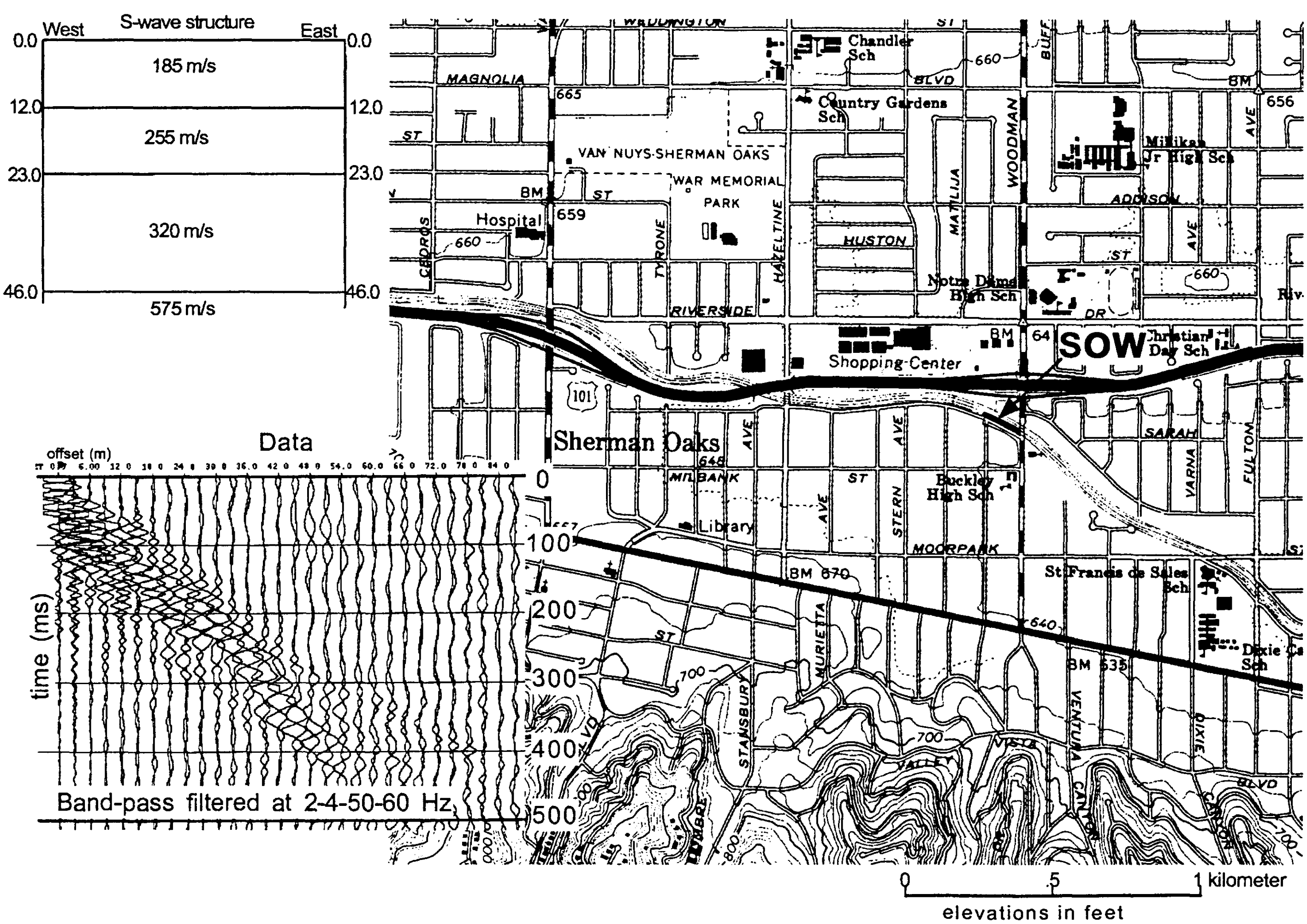
SPREAD LENGTH = 87.0 m

INPUT DATA

LAYER	APPARENT VEL., A m/s	APPARENT VEL., B m/s	INTERCEPT TIMES, A s	INTERCEPT TIMES, B s
1	185.0	185.0	.000	.000
2	255.0	255.0	.090	.090
3	320.0	320.0	.157	.157
4	575.0	575.0	.317	.317

COMPUTED STRUCTURE

LAYER	VELOCITY m/s	THICKNESS A m	THICKNESS B m	DIP	DEPTH A m	DEPTH B m
1	185.0	12.1	12.1		12.1	12.1
2	255.0	10.6	10.6	.0	22.7	22.7
3	320.0	22.8	22.8	.0	45.5	45.5
4	575.0			.0		



P-Wave Results
Site TRE - Reseda, California

Data acquired August 1996; Interpretation 2/97
Seismic sources were on asphalt. Geophones were primarily planted in grass.
V1 is not clearly determined because of seismic source noise and seismic waves in the pavement.
V3 is a guess of the next layer that would be observed with one more geophone offset. This was done to get an idea of the thickness of V2.

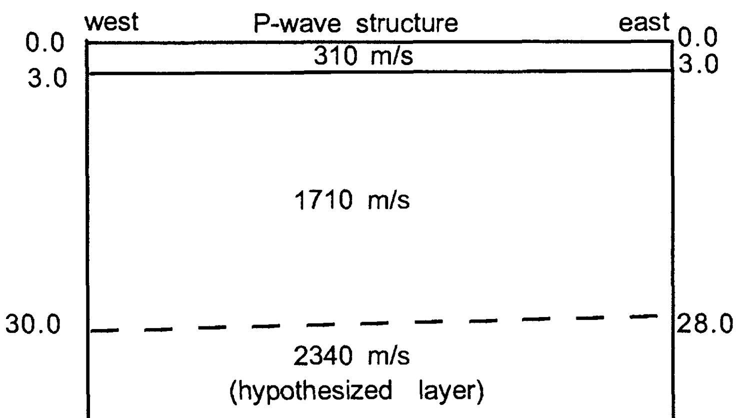
SPREAD LENGTH = 87.0 m

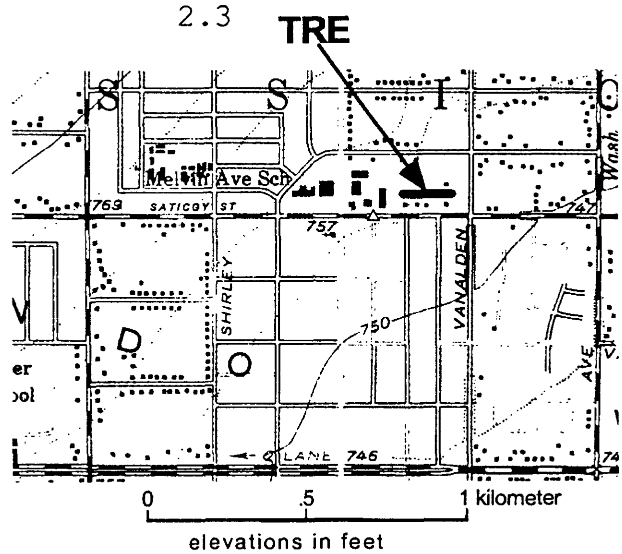
INPUT DATA

	LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
	1	310.0	310.0	.000	.000
	2	1659.0	1765.0	.017	.019
GUESS	3	2345.0	2345.0	.039	.039

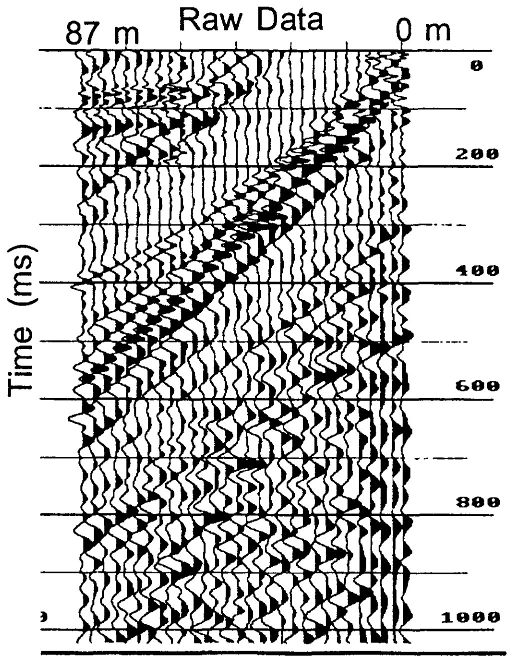
COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	310.0	2.7	3.0		2.7	3.0
2	1710.3	27.4	24.9	-.3	30.1	27.9
3	2342.6			2.3		





USGS 1:24000 quad: Canoga Park, Calif.



S-Wave Results
Site TRE - Reseda, California

Data acquired August 1996; Interpretation 2/97
Seismic sources were on asphalt. Geophones were primarily planted in grass.
V3 is a guess of the next layer that would be observed with one more geophone offset. This was done to get an idea of the thickness of V2.

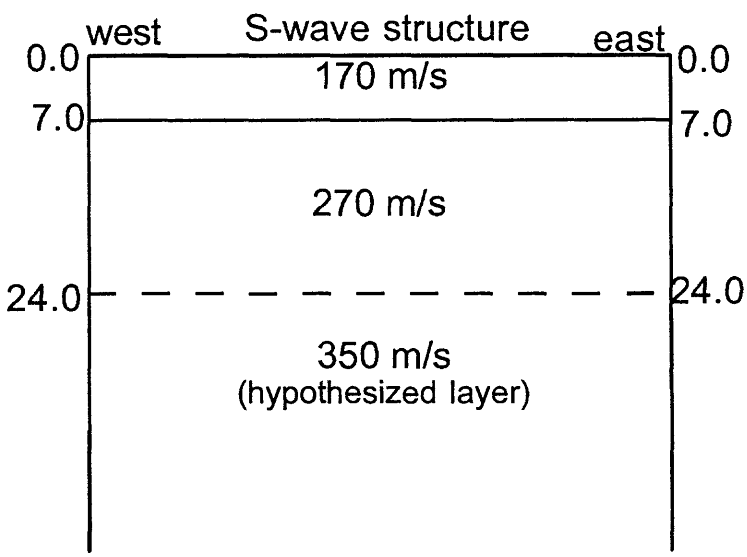
SPREAD LENGTH = 87.0 m

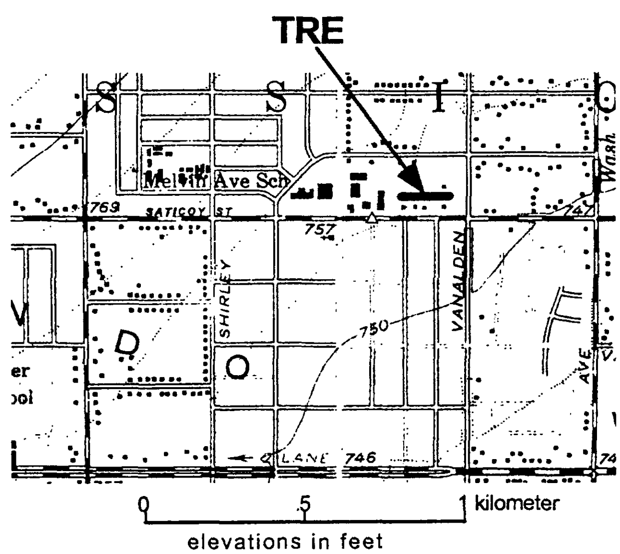
INPUT DATA

LAYER	APPARENT VEL., A	APPARENT VEL., B	INTERCEPT TIMES, A	INTERCEPT TIMES, B
1	170.0	170.0	.000	.000
2	278.0	265.0	.064	.063
3	350.0	350.0	.148	.148

COMPUTED STRUCTURE

LAYER	VELOCITY	THICKNESS A	THICKNESS B	DIP	DEPTH A	DEPTH B
1	170.0	7.0	6.9		7.0	6.9
2	271.3	16.4	16.6	1.1	23.4	23.5
3	349.7			-1.3		





USGS 1:24000 quad: Canoga Park, Calif.