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Shallow *P*- and *S*-Wave Velocities at Eleven Aftershock Recording Stations of the Northridge Earthquake, San Fernando Valley, California

by

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CONTENTS

Page

ILLUSTRATIONS

TABLES

Shallow *P*- and *S*-Wave Velocities at Eleven Aftershock Recording Stations of the Northridge Earthquake, San Fernando Valley, California

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 Calif. Earthquake Center, 1994). The earthquake caused widespread damage throughout the San Fernando Valley, 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 principles 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 these areas of higher damage to compare them with areas that were less damaged or had lower earthquake site response.

Eleven 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 1). A generalized surficial geology map from Tinsley and Fumal (1985) is also shown in figure 1.

Table 1- *Site locations*

Site No.	Site	Latitude (°N)	Longitude (°W)	Address
1	AB1	34.2419	118.5244	On sidewalk, 50 m west of collapsed parking garage, Cal State Northridge
2	ARG	34.1405	118.4318	On soil, near 3826 Benedict Canyon drive, Sherman Oaks
3	CS1	34.2422	118.5293	On grass, east side of business admin. building, Cal State Northridge
4	GAR	34.2677	118.5202	On paved street, 17745 Tribune, Granada Hills
5	LD1	34.1527	118.4328	On paved street, 4490 Matilija Ave, Sherman Oaks
6	MCK	34.1545	118.4364	On paved street, 14000 Valleyheart, Sherman Oaks
7	PG1	34.2438	118.5231	On grass, 100 m north of collapsed parking garage, Cal State Northridge
8	POT	34.2481	118.4999	On paved street, 16914 Kinzie St., Northridge
9	SCH	34.1508	118.4343	On paved street, 4410 Stern Ave, Sherman Oaks
10	UK1	34.2567	118.5312	On grass, near 10216 Rathburn Ave., Northridge
11	YK1	34.1594	118.4322	On paved street, 4858 Matilija Ave, Sherman Oaks

Four profiles were located in the vicinity of the heavily damaged Sherman Oaks area, to compare the shallow *S*-wave velocities at sites of higher amounts of building damage (sites MCK, SCH, and LD1) south of the Los Angeles River, to one site (YK1) outside of the high-damage area north of the river. One profile (ARG) was acquired in a lower damage zone located about 1 km south of the high damage area in Sherman Oaks. Three profiles were on the Northridge campus (AB1, CS1, PG1). Sites AB1 and PG1 were near the severely damaged parking structure where rapid changes in site response over short spatial distances were observed. Site CS1 was located adjacent to the business building. Finally, three profiles were acquired in the northern San Fernando Valley to examine the difference in *S*-wave velocity between areas where Tertiary (UK1), Pleistocene (POT), and Holocene (GAR) deposits are geologically mapped on the ground surface.

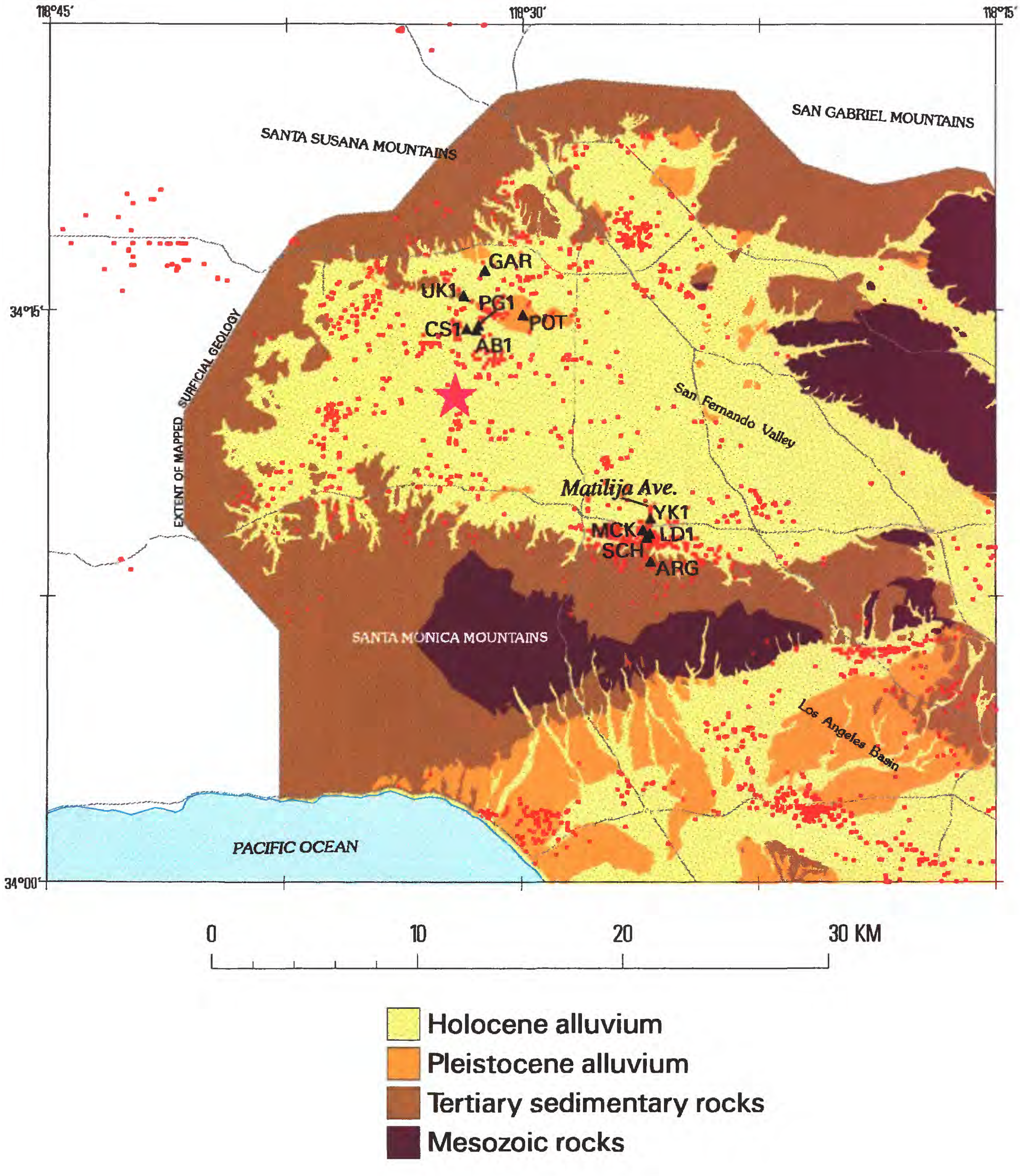

Figure 1. Generalized geologic map of the San Fernando Valley with station locations and site names where P–and S-wave seismic-refraction profiles were acquired (triangles). Sites are roughly co-located with the aftershock recording stations. Red circles mark the locations of red-tagged buildings (uninhabitable) following the Northridge main shock. A purple star marks the main shock location.

Method

These profiles were acquired within about 50 m of the aftershock recording site. In most cases, the aftershock stations were located in the backyard of a private home and 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). Recording parameters are listed in table 2.

Table 2. - *Seismic data recording parameters*

Recording system: OYO DAS-1 (96 channels) or Geometrics StrataView (48 channels)
Sampling interval: 0.001 seconds
Record length: 1 second
Recording format: SEG-2
Geophones: Twenty-four 3-component 10 Hz (OYO); 24 vertical, 40 Hz, & 24 horizontal, 14 Hz (Geometrics)
Geophone array: linear with single phones at 3-m intervals
Source: 4.0 kg sledgehammer on metal plate, or 100-kg vacuum-assisted weight drop (*P*-wave); 4.0-kg sledgehammer on wood timber (*S*-wave)
Source array: Reversed spreads, multiple off-end shots, plus a midspread shot

Reversed seismic *S*-wave profiles ranged in length from 70 to 100 m. These *S*-wave profile lengths resulted in a maximum survey depth range of about 30 m. Because no additional *S*-wave layers were detected below about 15 m on most profiles, 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 limitations were less restrictive; consequently, maximum depth ranges increased to about 40 m in some cases.

The shear-wave seismic source consisted of a wooden timber placed on the pavement beneath the wheels of the vehicle at right angles to the direction of the profile. Reversed polarity seismic energy was produced by striking opposite ends of the timber with a 4-kg sledgehammer. The data were digitally recorded at 24 positions on the ground by either 10-Hz or 14-Hz horizontal geophones that were spaced at 3-m intervals and oriented transverse to the profile. The onset of the *S*-wave energy was usually clearly identified by the high-amplitude reversed polarity signal (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, 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). We determined that the slopes were accurate to within about 10 percent, thus the calculated layer thicknesses had roughly the same accuracy. There are two 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 cannot be detected. In spite of these assumptions and level of accuracy, these data generally agree with two seismic velocity downhole profiles determined from shallow boreholes (Fumal and others, 1981; Fumal and others, 1982). In one of these boreholes, located about 400 m south of site PG1, the seismic velocities were within 10 or 20 percent of the velocities determined in this study, although the defined number of layers in the borehole were fewer and the depths were significantly different (fig. 3*A*). The second borehole, located within about 200 m of site UK1, agrees within 10 percent for *S*-wave velocity and layer depth, while the *P*-wave velocities agreed to within about 20 percent but differed significantly in layer depths (fig. 3*B*).

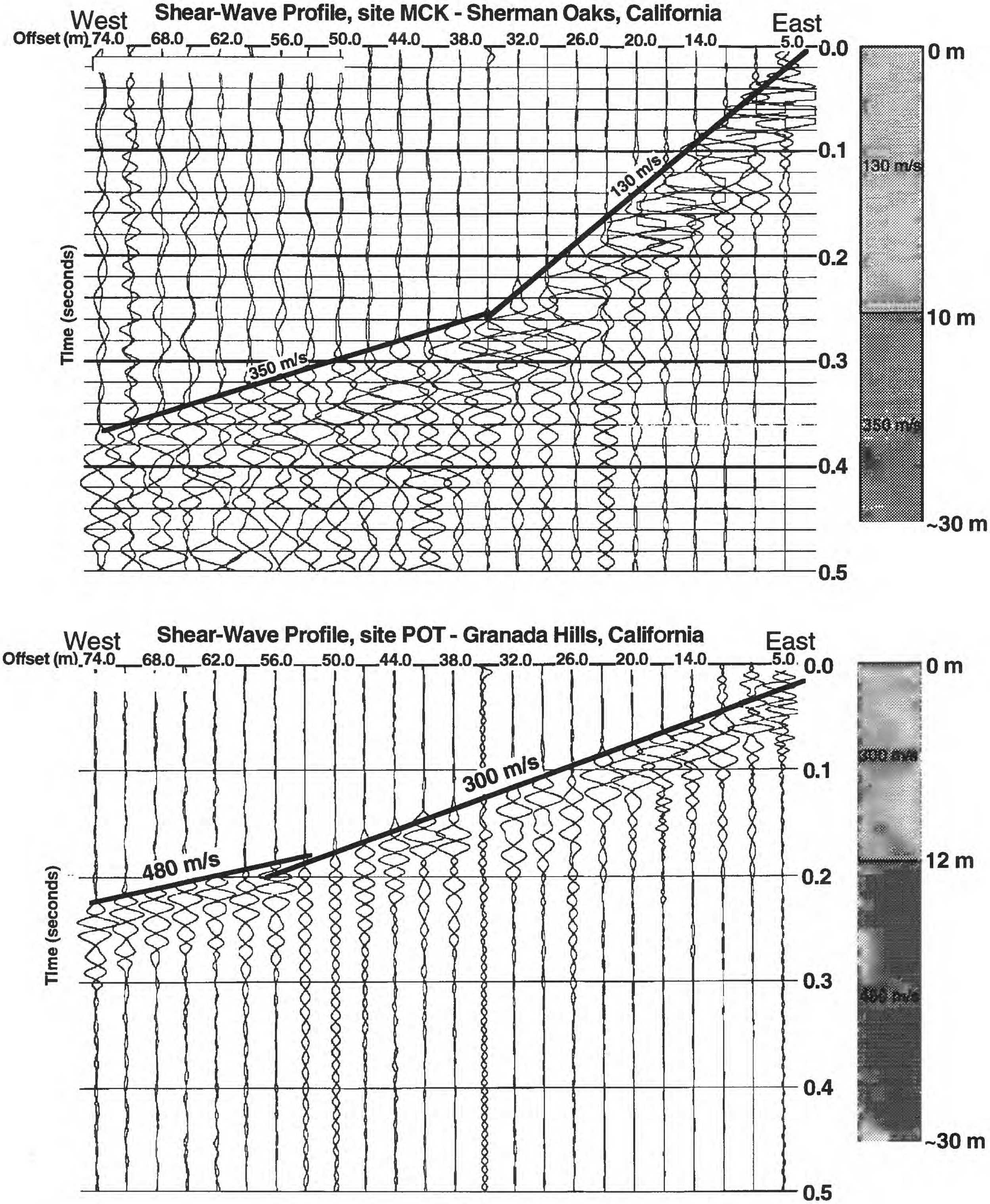

Figure 2. (Top) Shear-wave profile recorded at site MCK in the high damage zone of Sherman Oaks, and (bottom) site POT which is located in an area that experienced less damage. Source at same offset from near trace. Reversed polarity traces were generated by striking opposite ends of the source. Heavy 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). Depth interpretation is shown on the right.

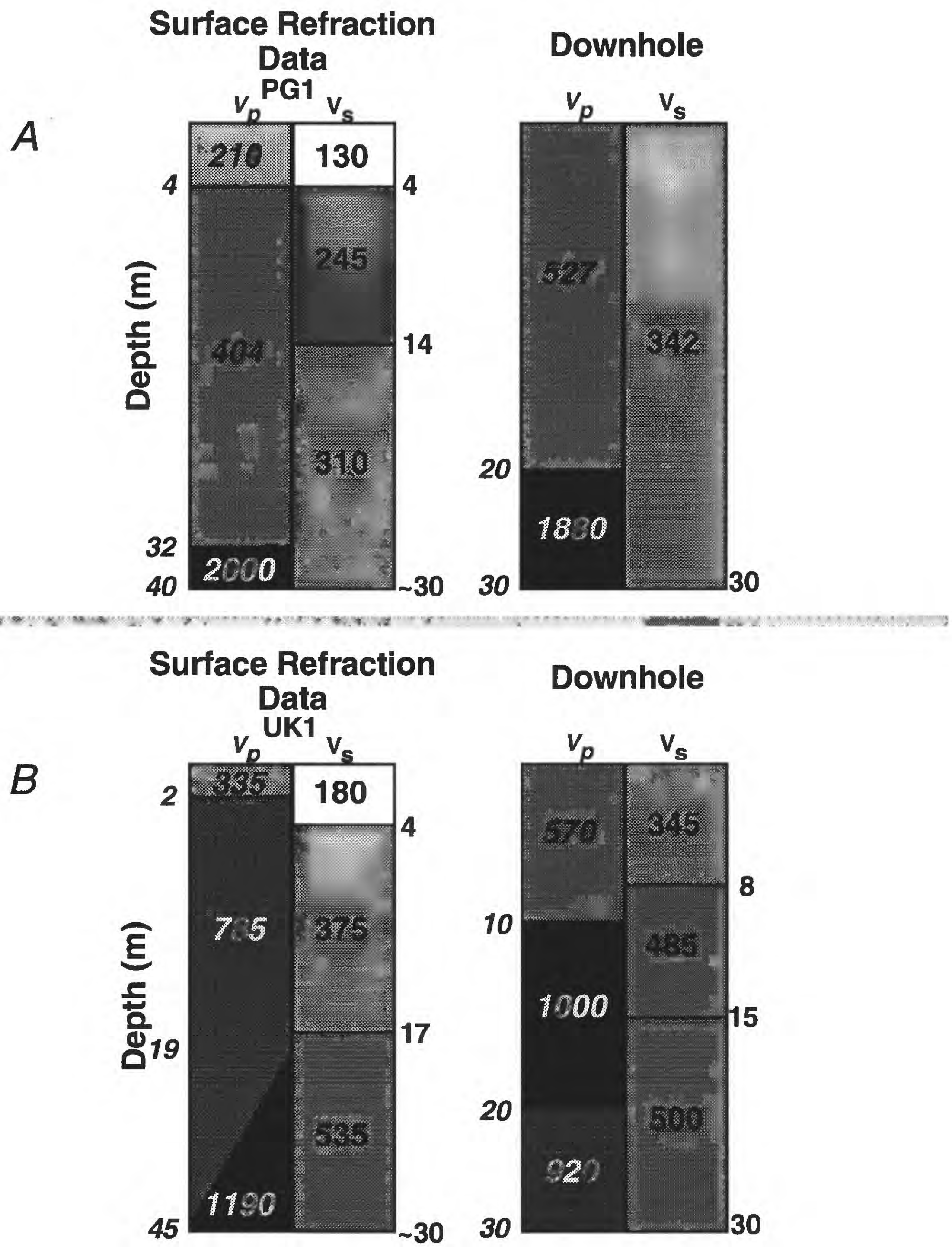

Figure 3. A) Comparison of velocity profiles derived from surface sseismic-refraction methods at site PG1 (left), and nearby downhole-derived data (right) after Fumal, and others (1981). The borehole was located about 500 m south of the seismic profile. B) Comparison of velocity profiles derived from surface seismic-refraction methods at site UK1 (left), and downhole-derived data (right) after Fumal, and others (1982). The borehole was located about 200 m east of the seismic profile.

RESULTS

Sherman Oaks

In a site response study that used Northridge aftershocks (Hartzell and others, 1996), some of the largest site amplification factors in the San Fernando Valley were found at sites MCK and SCH in Sherman Oaks, while site YK1, located about 1 km north, had a much lower site response factor. We interpret the *S*-wave velocity structures in the upper 30 m at sites MCK, SCH, and LD1 in Sherman Oaks to be similar (fig. 4). These sites also have the thickest sequence of low *S*-wave velocity deposits found in this study and differ significantly from site YK1. The sites south of the Los Angeles River and north of Ventura Blvd. in the Sherman Oaks area, are characterized by about 10 m of unconsolidated surficial deposits with *S*-wave velocity of about 105 - 155 m/s (fig. 2 and 3). These velocities are comparable to the low *S*-wave velocities found at 10 - 20 m depth in muds surrounding the San Francisco Bay (Fumal, 1978). Borehole drilling-rate data, acquired about 200 m west and east of site MCK during construction of the Ventura Freeway (Los Angeles City Bridge Department, written commun., 1995), support a thickness of about 12 - 14 m for the low velocity layer. At sites LD1 and SCH, an increase in *P*-wave velocity from about 450 m/s to over 1600 m/s at 7 - 8 m depth is interpreted to represent the position of the water table within the zone of severe damage. *P*-wave data from site MCK were of too poor quality to interpret. *P*-wave data from site YK1 suggest the water table is slightly deeper at 12 m. The inferred water table depths in the Sherman Oaks area are the shallowest detected in this study.

Underlying this low-velocity layer at sites MCK, SCH, and LD1 is a sequence of deposits at least 20-m thick with 220 m/s to 400 m/s *S*-wave velocities. Site YK1 north of the river, on the other hand, has only a 3-m thick layer of deposits with *S*-wave velocity of 165 m/s, yet it is also underlain by at least 27 m of deposits with *S*-wave velocities of 265 m/s to 320 m/s.

About 1 km south of Ventura Blvd., a profile was acquired at site ARG in a lower damage zone on deposits mapped as Tertiary sedimentary rock (Tinsley and Fumal, 1985) at the foot of the Santa Monica Mountains. This site, located about 50 m from one of the 'rock' sites of Hartzell and others' (1996) site response study, was the only rock site profiled in this study. It has at least 20 m of 820 m/s *S*-wave velocity deposits in the upper 30 m - the fastest *S*-wave velocity found in this study at these depths (fig. 4). Based on an exposure in a nearby roadcut, the upper 10 m of this site is highly fractured and weathered diatomaceous shale and has an *S*-wave velocity of 240 m/s. The *P*-wave velocities of 500 - 1340 m/s in the upper 30 m seem relatively low for a 'rock' site. These low velocities may partially explain why this location had the highest site response among the 'rock' sites studied by Hartzell and others (1996).

Though it appears the zone of increased damage in Sherman Oaks can be correlated with both a prominent layer of low *S*-wave velocity and a higher water table, the presence of the low-velocity deposits does not by itself explain the higher damage and stronger ground shaking. The influence of a high water table on ground shaking is not well known other than being a factor in an increased potential for liquefaction, but no liquefaction effects were observed or reported in Sherman Oaks. The effects of low *S*-wave velocities in the near surface are better understood. For example, a simple quarter-wavelength resonance calculation for the 10-m thick low-velocity layer at site MCK suggests an *S*-wave resonance at about 3.25 Hz. However, the site response results of Hartzell and others (1996) indicate strong *S*-wave resonances at 2, 4, and 8 Hz. Also, given the similar near-surface velocity profiles at the Sherman Oaks sites, we would be inclined to predict that their average response would be the same, but the average site response at SCH and MCK is a factor of 2 greater than LD1. Thus, at this point of the study, we do not know how the low *S*-wave velocity

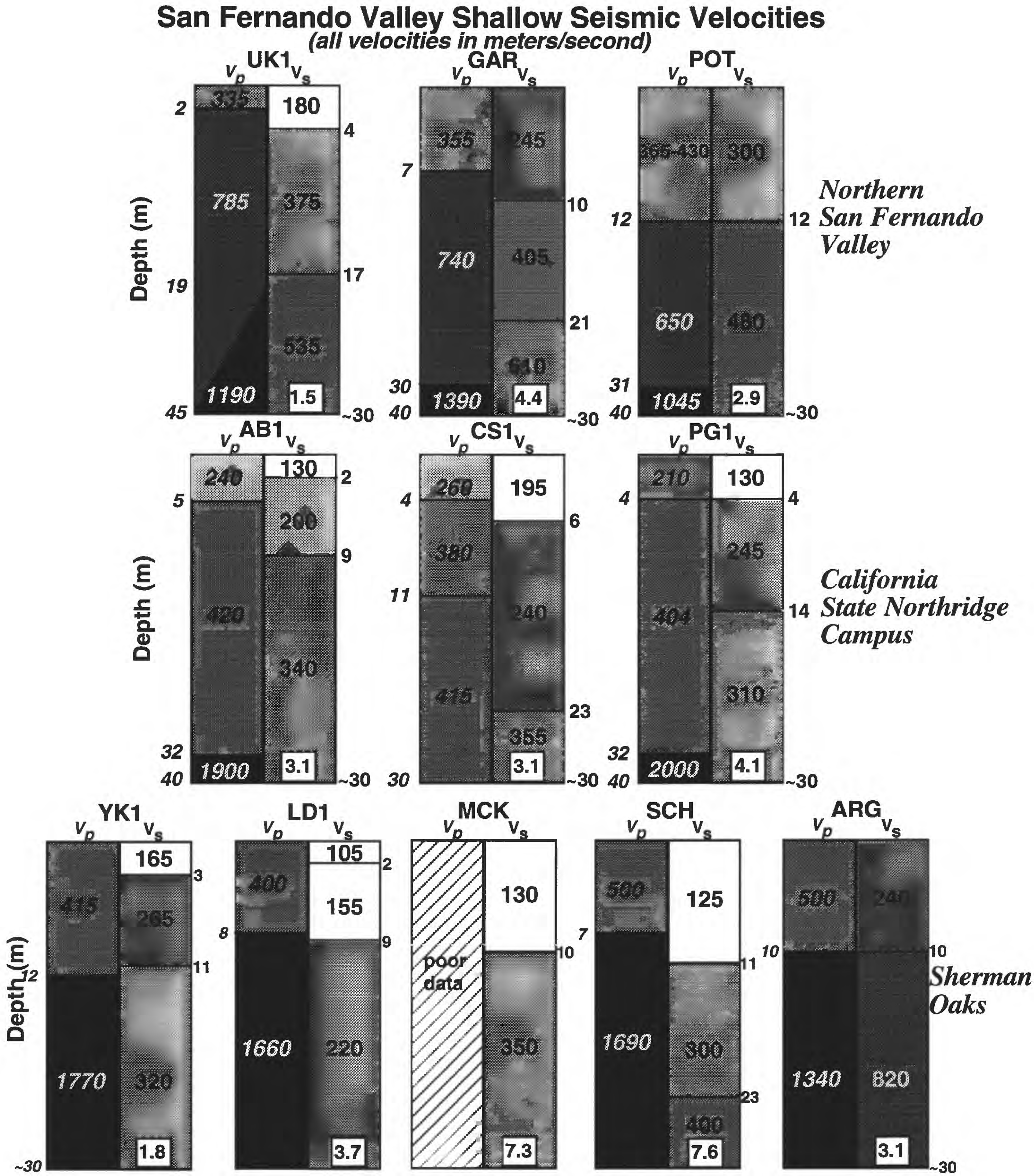

Figure 4. P- and S-wave velocity interpretations to about 30-m depth for the 11 refraction profiles with site names annotated at the top of each rectangle. Seismic velocities are annotated in the shaded boxes. Boxes are shaded according to velocity value; the lower the velocity the lighter the shading. 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.

layers and the higher water table in Sherman Oaks area contributed to the anomalously high damage or ground shaking.

Northridge Campus

Aftershock recording stations PG1 and AB1 were located about 200 m apart on the northern and western sides of the collapsed campus parking garage, respectively. The mapped surficial geology of both sites is the same (Tinsley and Fumal, 1985), but site PG1 had almost a factor of 2 larger mean site response (Hartzell and others, 1996). However, the *S*-wave velocity profiles in the upper 30 m at these sites were not sufficiently different to account for the difference in site response (fig. 4). One apparently minor difference is that although both sites have a 130 m/s layer at the surface, at site PG1 this layer is twice the thickness (4 m versus 2 m) it is at AB1 (fig. 4). Coincidentally, this 4-m-thick layer at site PG1 could potentially induce an *S*-wave resonance of about 8 Hz, which happens to be the most prominent spectral peak observed in the spectral ratio data for site PG1 (Hartzell and others, 1996). However, the impedance contrast at 4 m depth at site PG1 (fig. 4), could theoretically induce only a factor of 2 amplification, not the factor of 6 amplification observed at this 8 Hz peak in the site response data (Hartzell and others, 1996). *P*-wave velocities from these sites in the upper 30 m are low, about 405 m/s to 420 m/s, and suggest soft, dry soils (fig. 4). The highest *P*-wave velocity layer detected in this study, 1900 m/s to 2000 m/s, was found at about 32 m depth at these sites. This *P*-wave velocity is indicative of firm, possibly saturated rock.

The third site at the Northridge campus, CS1, was located adjacent to a newly constructed 4-story campus building that sustained substantial damage. We interpreted the *S*-wave velocity structure here to have a thicker sequence of <250 m/s deposits than at PG1 or AB1 (fig. 4). This implies that we might expect increased amplification of ground motion relative to PG1 and AB1. But the site response data show that the average site amplification is lower than PG1 and slightly higher than AB1. The *P*-wave velocity structure at CS1 is similar to AB1 and PG1 except that a high velocity layer was not detected at CS1 in the upper 40 m (fig. 4). The lowest *P*-wave velocities found in this study were detected in the upper 5 m of each of these three sites. The low velocities, ranging from 210 to 260 m/s, are all below the speed of sound in air, suggesting a dry, aerated soil.

Northwestern San Fernando Valley

Three profiles from this area were selected to study the difference between sites mapped as Tertiary sedimentary rock (site UK1), Pleistocene alluvium (site POT), and Holocene alluvium (site GAR). Excluding site ARG, which was located on mapped Tertiary rock, these three sites have the highest average *S*-wave velocities in this study with velocities reaching 500 to 600 m/s in the upper 30 m (fig. 4). Although site UK1 is mapped as Tertiary sedimentary rock, the data suggest that a thin layer of unconsolidated material, perhaps weathered bedrock, is at the surface (fig. 4). Site GAR has the lowest mean *S*-wave velocity of these sites down to about 10 m, but it is only about 20 percent slower than either sites UK1 or POT. Thus, without knowing a priori the mapped surficial geology and the homogeneity of the deposits, it would be difficult to assign the *S*-wave velocity structures from these sites to distinct surficial geologic units. In terms of mean site response, Hartzell and others (1996) found site GAR with the highest, followed by site POT and then site UK1. At this stage of interpretation for these three sites, a correlation between site response and *S*-wave velocity in the upper 30 m is not clear. *P*-wave velocities at these three sites in the upper 30 m are generally higher overall than at the Northridge campus sites, but a high-velocity layer or water table was not detected in the upper 40 m. The velocity structures indicate that dry, unconsolidated deposits underlie these sites in the upper 40 m. Because the *P*-wave velocity structures are also similar, discriminating between Tertiary, Pleistocene, and Holocene deposits at these sites based on seismic velocity is not possible.

CONCLUSIONS

In Sherman Oaks, high site response from aftershock recordings and anomalously high level of damage from the Northridge earthquake can be correlated to the thickest sequence of low *S*-wave velocities and the highest water table found in this study. At Cal State Northridge, the causes of the high site response at site PG1 relative to AB1 are not apparent from their similar *P*- and *S*-wave velocity structures in the upper 30 m. In the northern San Fernando Valley, slight differences in seismic velocity structure between deposits mapped on the surface as Tertiary, Pleistocene, and Holocene do not appear to be significant enough to influence site response. The results from Cal State Northridge and the northern San Fernando Valley suggest that other factors, such as deeper geologic features, below the near-surface deposits examined in this study, may make a significant contribution to the cumulative site response observed at the surface. But, based on local *P*- and *S*-wave velocity structural similarities in the upper 30 m, we can preliminarily group these 11 sites into 4 categories: (1) The high-damage and high ground response sites of Sherman Oaks (sites MCK, LD1, and SCH) with *S*-wave velocities below 150 m/s in the upper 10 m and a high water table, (2) "mid-valley" sites (YK1, AB1, CS1, and PG1) with *S*-wave velocities above 200 m/s in the upper 10 m and a mixture of moderate to low site response, (3) "northern-valley" sites (UK1, GAR, and POT) with *S*-wave velocities above 400 m/s in the upper 20 m, slightly elevated *P*-wave velocities relative to the mid-valley sites, and moderate to low site response, and (4) 'rock' sites (site ARG) with *S*-wave velocity above 800 m/s in the upper 15 m and with moderate site response.

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