Shallow Shear Velocity and Seismic Microzonation of the Urban Las Vegas, Nevada Basin

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Abstract

Las Vegas Valley has a rapidly growing population exceeding 1.5 million, subject to significant seismic risk. Surveys of shallow shear velocity performed in the Las Vegas urban area included a 13 km-long transect parallel to Las Vegas Boulevard ("The Strip"), and borehole and surface-wave measurements of 30 additional sites. The transect was completed quickly and economically using the refraction microtremor method, providing shear velocity versus depth profiles at 49 locations. The lowest velocities in the transect, NEHRP D class, are near intra-basin faults found near I-15 and Lake Mead Boulevard. Calcite cementation of alluvium (a.k.a. caliche) along the Las Vegas Strip elevates Vs30 values to 500-600 m/s, NEHRP C class. Our transect measurements correlate poorly against geologic map units, which do not predict the conditions of any individual site with accuracy sufficient for engineering application. Some USDA soil map units do correlate, and Vs30 predictions based on measurements of soil units match transect measurements in the transect area. Extending soil-map predictions away from the area of dense measurement coverage generally failed to predict new measurements. Further, for several test sites the predictions were not conservative, in that the soil model predicted higher Vs30 than was later measured (predicting lesser potential ground motion). Subsurface information is needed to build a Vs30 model extending predictions throughout Las Vegas Valley. A detailed stratigraphic model built by correlating >1100 deep well logs in Las Vegas predicts Vs30 better than surface maps, but again only in parts of the Valley well-measured for velocity. The stratigraphic model yields good predictions of our transect Vs30 measurements. It is less accurate, although at least conservative, when extended to sites away from the transect.

Introduction

Las Vegas, Nevada is a rapidly growing population center that occupies a basin with known Quaternary-age faults. In addition, recent seismicity has been recorded in the broader region. Therefore, an up-to-date assessment of the potential seismic hazard is needed. Vs30 is one predictor of earthquake ground motion amplification and potential hazard in similar alluvium-filled basins in California (Field et al., 2000). Under NEHRP-UBC provisions (BSSC, 2000) sites are categorized for shaking hazard using Vs30. Due to the costs of borehole and penetrometer measurement methods (e.g., ASTM standards D4428 and D5778), site classification in the Las Vegas area was previously based largely on geological maps with sparse downhole measurement support.

Wills et al. (2000) prepared a site-conditions map for nearby areas of California on such a basis. Extending their classification from the California border into Las Vegas Valley, the Holocene alluvium covering the fans and valley floor would result in a predicted NEHRP class of D (Vs30 = 180-360m/s) for the entire Valley. Such extrapolation is unwarranted, given the remoteness of the borehole measurements used by Wills et al. (2000). A shallow shear-velocity measurement campaign in Las Vegas Valley is needed to provide accurate microzonation mapping.

The purpose of this study was to determine the NEHRP site hazard classifications along the transect by providing a large number of measurements (49) of shear-wave velocity averaged to 30 m depth (Vs30). For two days in July of 2003, we conducted a refraction microtremor experiment across 13 km of the Las Vegas, Nevada basin (fig. 1). The transect follows the I-15 freeway south from Cheyenne Blvd. and parallels "The Strip" to Tropicana Blvd.

We attempted to extend the area of applicability of our refraction microtremor results with a basin depth model (Langenheim, et al., 2001), valley-wide stratigraphy data derived from >1100 deep well logs, thirty additional shallow shear-wave velocity measurements using crosshole, refraction microtremor, and SASW methods (often comparing multiple techniques at the same site), and geologic and soil map-based surficial data. This information was combined to produce trial valley-wide Vs30 models.

Refraction Microtremor Method

Most of our shear-wave velocity measurements of the Las Vegas basin were based on the refraction microtremor technique (Louie, 2001). This method uses ambient seismic noise (vehicle traffic, etc.) as a source producing Rayleigh waves in urban alluvium, obviating the need for an explosive or hammer source. The noisy urban environment was thus advantageous to this method. We recorded the Rayleigh waves with vertical geophones connected to seismograph arrays. Our array records were transformed into slowness-frequency space; dispersion was picked and then forward-modeled to produce a velocity-depth profile. Vs30 values were summarized from the profiles by slowness averaging.

For our array recording we used equipment and procedures very similar to those of Scott et al. (2004). We followed a 13 km-long transect beginning at Cheyenne Ave. on the north and ending at Tropicana Blvd. on the south (fig. 1). Three teams each placed 40 seismographs spaced at 20-m intervals along 800-m segments of our 13-km-long profile.

The array data were processed according to Louie's (2001) refraction microtremor analysis to produce a shear-velocity-versus-depth profile for each 13- or 14-instrument, 270-m segment. We picked fundamental-mode Rayleigh-wave dispersion points along a minimum-velocity envelope of the energy, following the procedures in Louie (2001). Typical Rayleigh dispersion runs from small slowness values at low frequencies, toward larger slowness values at higher frequencies. We interactively forward modeled the fundamental-mode Rayleigh dispersion curve for each 270-m segment along the transect to obtain a shear-velocity versus depth relationship. We computed Vs30 by arithmetically averaging slownesses to 30 m depth (averaging by slowness in order to preserve bulk travel time).

Refraction Microtremor Results

The modeled shear-wave velocity profiles obtained from the 49 microtremor array segments deployed along our transect are shown in the cross section fig. 2. The depth-averaged values of Vs30 we obtained are plotted in fig. 3. Large variations in Vs30 were observed due to variable occurrence of soil or groundwater carbonate (a.k.a. caliche) (Liu et al., 2005). The lowest shear wave velocities that were found on our transect occurred near the intersection of Interstate 15 and Lake Mead Boulevard (fig. 1). The lowest Vs30 value was 231 m/s, which is NEHRP D hazard class (Vs30 = 180-360m/s). A geologic map (Matti et al., 1987) of this part of the Valley shows a small area of faults crossing our transect. This fault zone may account for the lower velocities. The highest velocities measured along our transect were on its southern half, with Vs30 values between 500 and 650 m/s. These higher velocities are within the NEHRP C range (Vs30 = 360-760m/s) and are located near Sahara Boulevard. Calcite cementation of alluvium (a.k.a. caliche) along this portion of the Las Vegas Strip probably accounts for the increased velocities.

To assess the relationship between our measured values of Vs30, and mapped geologic formation or soil type, we consulted geologic maps (Matti and Bachhuber, 1985; and Matti et al., 1987) and soil maps (USDA-SCS, 1978) along the transect. A geologic unit and a soil type were assigned to each transect segment. The measured values of Vs30 from each segment are plotted for each geologic formation in fig. 4, and Table 1 describes the formations. The measured values of Vs30 for each soil type at each segment are plotted in fig. 5, and Table 2 describes the soil types.

Model Development

Drawing on data from several sources, we developed two trial Vs30 models for Las Vegas in an attempt to extrapolate transect measurements throughout the Valley. These efforts were made in an evaluation of what methods would be needed to develop a microzonation map for the entire urban area. Some of the soil units sampled by the transect appear in fig. 5 to have velocity ranges separable from other units. Using four soil-map quadrangles from USDA-SCS (1978) centered on the transect we assigned each soil unit its average Vs30 value as found on fig. 5. One additional soil unit was assigned a Vs30 value based on initial refraction microtremor measurements at the strong-motion rock site SGS at the foot of Frenchman Mountain (fig. 1). Units not sampled were assigned velocities from nearby units having similar soil descriptions (e.g., Table 2). Figure 6, on the left side, shows a map of the resulting Vs30 model.

For a model based on subsurface data, we compiled stratigraphic data from over 1100 well logs (the locations are shown as blue dots in fig. 1) and determined bedrock units from geologic maps (Matti and Bachhuber, 1985; Matti et al., 1999; Bingler, 1977; and Matti et al., 1987). Langenheim et al. (2001) produced a 3-D depth map of the Las Vegas basin based on gravity modeling supported by sparse borehole and refraction data. Their model depths are shown as depth contours in fig. 1, and put constraints on the shallow stratigraphic model. The SASW technique (Stokoe et al., 1994) was used to obtain Vs data from twelve sites. Velocity data from our refraction microtremor transect were then combined with data from SASW, and additional borehole Vs measurements to yield velocity-depth profiles at a total of 79 locations (shown as yellow dots in fig. 1). Extapolated stratigraphic-unit to velocity correlations were then derived for these locations.

Using the correlations, we developed a shallow shear-wave velocity model for the Valley based on six summary geologic units: pre-Tertiary, Tertiary, carbonate, gravel, sand and clay. The Vs measurements and corresponding stratigraphic units extrapolated from the well logs to the 79 measured velocity profiles were recorded at one-meter intervals (giving a total of 15,600 “counts”) to develop the histograms of fig. 7. There were no Vs measurements of the sand summary unit. In compiling the histograms, no depth-Vs dependencies were assumed, given the preliminary nature of the stratigraphic model; the x-axis bin sizes were arbitrarily chosen to yield a first approximation to a summary Vs value. Units in the stratigraphic model were assigned the shear velocity at their mode of occurrence. Depth-averaged velocities were computed from the stratigraphic model for a grid spanning most of Las Vegas Valley. The Vs30 model we developed is shown as a map on the right side of fig. 6. The stratigraphic model can produce a velocity map for any depth of averaging from 5 m to 200 m. Average velocity of the 100-m upper zone (Vs100) at each point is a basis for the finite-difference seismogram modeling we are currently performing for the Valley.

Discussion

Louie (2001) reports ±20% Vs30 accuracy for the refraction microtremor method. Stephenson et al. (2005) compared ReMi results to four borehole suspension logs in Santa Clara Valley, California. When comparing the Vs30 values, the ReMi results were within 15% of the suspension-logger values. The calculated Vs50 and Vs100 values (averages to 50 and 100 m depths, respectively) were all within 27% of the borehole values; most were within 15%. To assess the standard deviation due to noise source and dispersion-picking differences for the individual Vs30 values, eighteen of the transect locations were independently processed and modeled by different analysts. We concluded that the variability in the recorded sources of microtremor noise, and in the picking and modeling process could be expected to contribute perhaps less than ±10% error in Vs30.

We could find some predictive correlation between soil units and our Vs30 measurements, as seen in fig. 5. When we tested the soil unit correlations with the F statistic, we found only two soil types (390 and 302) with a statistically significant ($p = 0.99$) departure from the null hypothesis (standard deviation for the transect equal to the standard deviation for the soil type). We discounted the apparent correlation of soil type 615 because it represents urban land having significant alteration and geologic variability. In fig. 4, we can identify that the variance in Vs30 within each of the several geologic units along the transect is generally greater than the differences in the average Vs30 between geologic units. Tests with the F statistic confirmed the lack of correlation (only Qai showed a correlation at $p = 0.95$).

Our transect and models are a first step toward the preparation of a map showing NEHRP classifications for the Las Vegas basin based on local site-condition measurements. We performed initial tests of our Vs30 models by plotting the Vs30 measurements from our transect against the predicted values from the models. The results, given in fig. 8, show reasonably good correlation for both the soil-map and stratigraphic models, given all the simplifying assumptions used. The low predicted values of the stratigraphic model at transect distances of 5-7 km are probably due to low values of Vs30 for the corresponding stratigraphic units derived from nearby measured Vs profiles (dashed circles in fig. 6).

Although we could create models that made acceptable predictions of Vs30 in the area of our transect, where measurements are dense, we had only partial success creating models extrapolating Vs30 into the rest of Las Vegas Valley, where measurements are more sparse (fig. 1). Figure 9 plots predicted versus measured Vs30 for eight sites off the transect, using both the soil-map and stratigraphic models. Few of the predictions were accurate to within ±20%. Further, predictions from the soil-map correlations were not conservative, yielding velocities significantly larger than the later measurements. If used in public policy for building-code code compliance or zoning, non-conservative predictions could lead to an assumption of lesser ground-shaking hazard, and under-designed construction (BSSC, 2000). The predictions from the stratigraphic model were, at least, conservative, yielding velocities lower than the measured values. Such conservative predictions could lead to stronger but more expensive construction.

Thus, we cannot accurately extrapolate Vs30 across Las Vegas Valley based on geologic or soil maps, or even on a very detailed stratigraphic model. Our stratigraphic model, based on >1100 well logs more than 60 m deep, does a more conservative job predicting Vs30 than the surface maps. We will employ geographic partitioning techniques in the future to attempt to improve the accuracy of predictions from the stratigraphic model.

Conclusions

The plot in fig. 3 shows measured Vs30 values above 360 m/s for 80% of the transect, i.e., thirty-nine of forty-nine 270-m transect segments. A default classification of most of the Las Vegas basin as NEHRP D, based on the presence of young alluvium at the surface, is not warranted. Some USDA soil map units correlate with Vs30 measurements, and Vs30 predictions from soil mapping match transect measurements in the transect area. Extending soil-map predictions away from the area of dense measurement coverage failed to predict new measurements.

Subsurface information is helpful in building a Vs30 model extending predictions throughout Las Vegas Valley. The Vs30 model also gives reasonably good predictions in areas where there are many velocity measurements. Both models fail to predict velocities within ±20% when extrapolated to areas of sparse velocity measurements. The stratigraphic model may be preferred over the soil-map model because its predictions are conservative.

Acknowledgments

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More information on urban shear-wave velocity transects can be found at www.seismo.unr.edu/hazsurv .

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Geological Units Symbol	Excerpted Description
Qa	**Alluvium:** Thin alluvial deposits of uncemented and unweathered cobble to small pebble gravel, gravelly sand, sand, and silt. Locally cemented in modern washes by calcite cement.
Qai	**Intermittently active alluvium:** Pink to pale-brown sand and cobble to cobble gravel occurring mainly on between-channel alluvial flats and less commonly in incised washes; slightly to moderately consolidated.
Qoa	**Older alluvium of Red Rock fan:** Pink to brown pebble to small cobble gravel with subordinate pebble-bearing sand; moderately to well consolidated to locally cemented; may locally contain a petrocalcic carbonate horizon (calcrete) 1-1/2 to 2 m thick at or near surface.
Qs	**Sheetwash alluvium:** Pink to brown sand, pebble to cobble gravel, and petrocalcic fragments occurring as thin veneers downslope from fault scarps; unconsolidated to slightly consolidated.
QTs	**Consolidated sediments:** White and light-gray to light- and pale-red fine sand interstratified with silt, pebbly sand, pebble to small cobble gravel, and clay; moderately to well consolidated to strongly cemented layers of petrocalcic carbonate are common and have variable textures and fabrics; surface exposures are locally capped by a resistant petrocalcic crust.

Table 1: Las Vegas transect geological map classifications from Matti and Bachhuber (1985) and Matti et al. (1987).

Symbol	Excerpted Description
200	**Glencarb silt loam.** Very deep, well drained soil on recent alluvial flats. 0 to 2 percent slopes.
236	**Glendale very fine sandy loam, saline.** Very deep, well drained soil on recent alluvial flats. 0 to 2 percent slopes.
300	**Las Vegas gravelly fine sandy loam, 0 to 2 percent slopes.** Shallow, well drained soil on basin floor remnants. Formed in alluvium derived dominantly from limestone and dolomite.
302	**Las Vegas-McCarran-Grapevine complex, 0 to 4 percent slopes.** Unit on basin floor remnants; 40 percent Las Vegas, 25 percent McCarran, 20 percent Grapevine very fine sandy loam.
325	**McCarran fine sandy loam.** Very deep, well drained soil on relict alluvial flats. Formed in gypsiferous lacustrine sediment. 0 to 4 percent slopes.
341	**Paradise silt loam.** Very deep, poorly drained soil on recent alluvial flats. Drainage altered through pumping. Formed in alluvium with a high content of lime. 0 to 2 percent slopes.
380	**Skyhaven very fine sandy loam, 0 to 4 percent slopes.** Very deep, moderately well drained soil on relict alluvial flats. Formed in alluvium with a high content of lime.
390	**Spring clay loam.** Very deep , moderately well drained soil on alluvial flats. Formed in gypsiferous lacustrine sediment. 0 to 2 percent slopes.
615	**Urban land.**

Table 2: Las Vegas transect soil map classifications from USDA-SCS (1985).

Figures

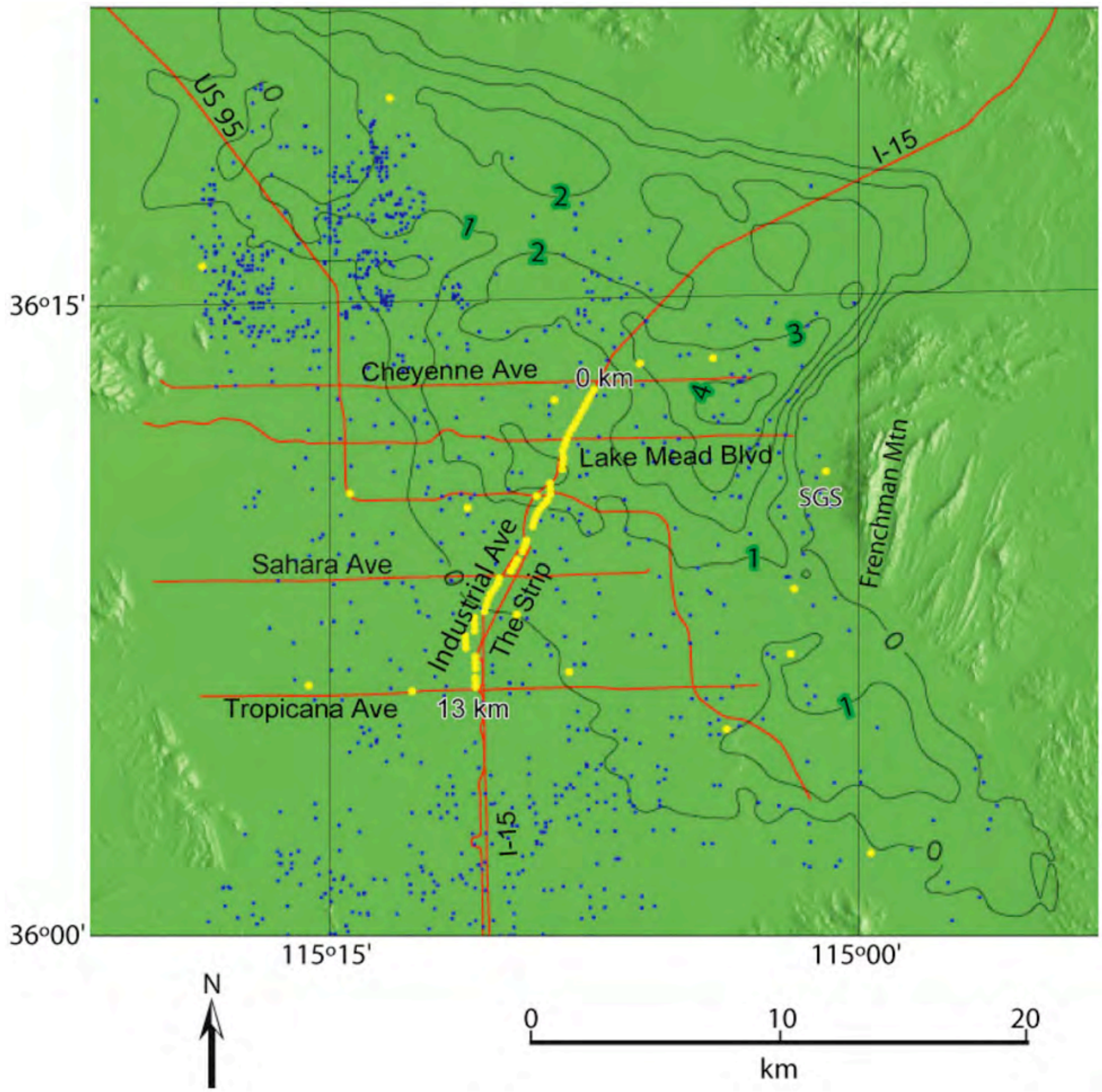

Fig. 1: Map showing the location of our transect across the Las Vegas, Nevada urban basin. Yellow dots mark the locations of Vs measurements and blue dots mark the locations of the wells used to provide stratigraphic data. Basin depths (one km contours) are from Langenheim et al. (2001). Transect distances at ends are indicated.

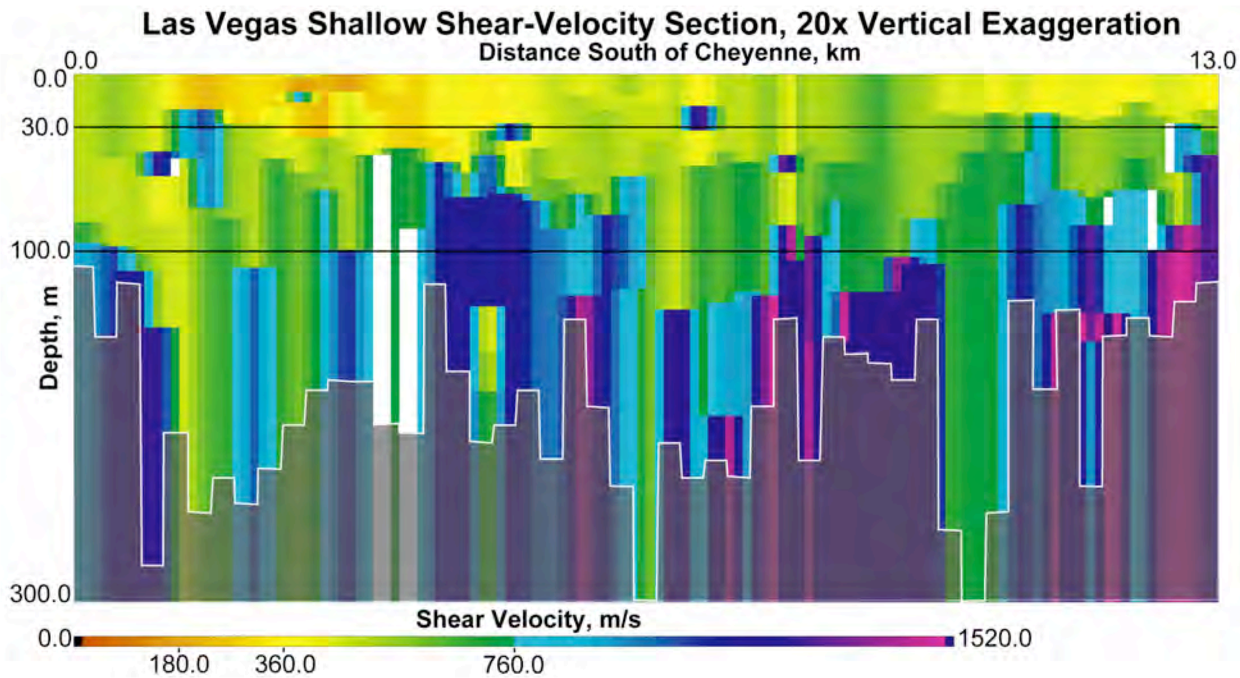

Fig. 2: Shear-wave-velocity section assembled from 49 velocity-depth profiles that model the dispersion curves derived from all forty-nine, 270-m-long microtremor array segments. Velocities deeper than 200 m are least constrained by the dispersion data, and thus vary widely among the segments. The white-line graph plots our best estimate of the maximum depth to which Vs is valid; thus the area below the white line is grayed out. This section has 20 times vertical exaggeration. Values contoured in color are in m/s. Only velocities above the line at 30 m depth are included in the depth-averaged Vs30 values in Fig. 3. The white velocity color represents velocities on the NEHRP B/C boundary (760 m/s). Refer to fig. 1 for geographical reference for transect distances.

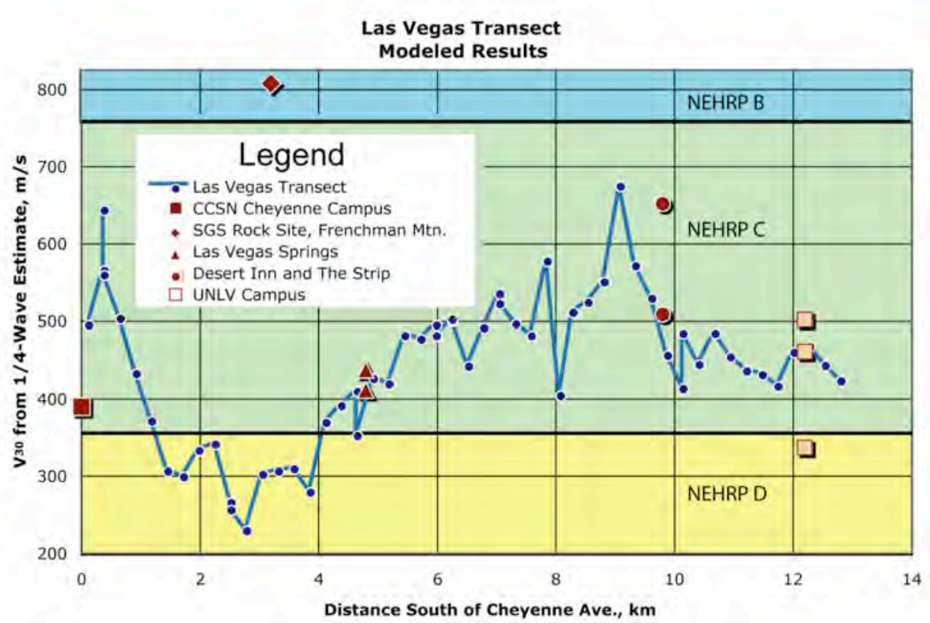

Fig. 3: Depth-averaged values of Vs30 for 49 points along the Las Vegas transect. Vs30 values are slowness-averaged from 49 modeled velocity-depth profiles. Eighteen of the transect locations were independently modeled by different analysts; all of the values they obtained are plotted. Refer to fig. 1 for geographical reference for transect distances. Vs30 values obtained by various techniques at sites off the transect are also plotted after projection onto the transect.

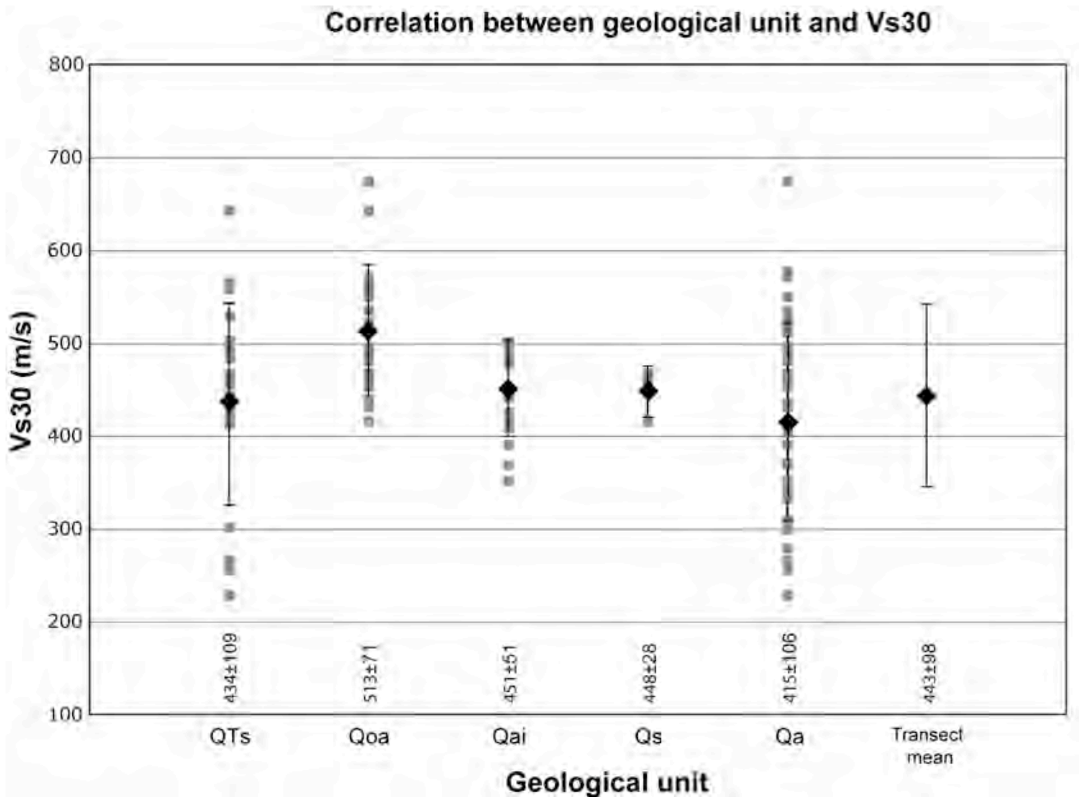

Fig. 4: Measured values of Vs30 for each geologic unit sampled by our transect (Table 1). Geology was drawn from the specific local classifications of Matti and Bachhuber (1985) and Matti et al., (1987). The velocity average and standard deviation for each unit and for the entire transect are indicated, in m/s.

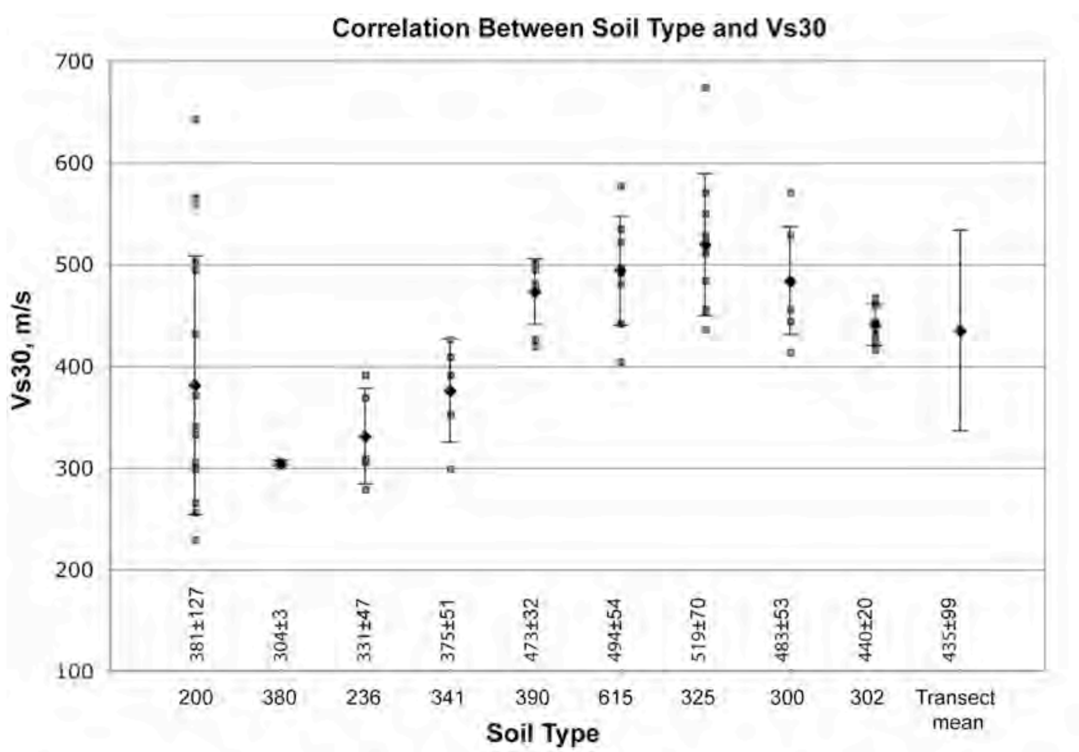

Fig. 5: Measured values of Vs30 vs. soil-type designations (Table 2). The mean velocity and standard deviation for each unit and for the entire transect are indicated, in m/s.

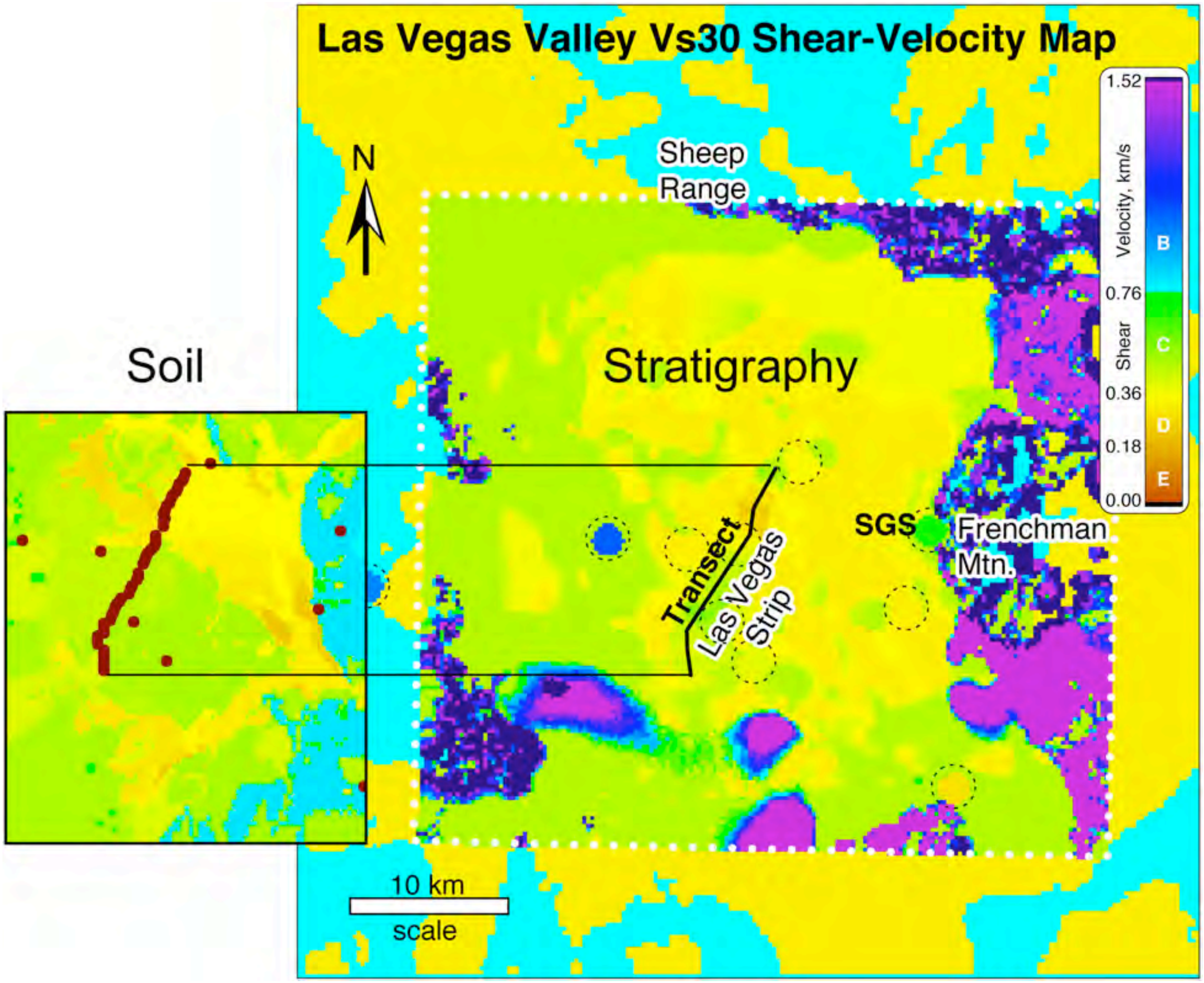

Fig. 6: Maps of Vs30 based on models derived from soil maps and from well-log stratigraphy. The Vs30 values represented by colors are derived for the soil-map model (on the left) from soil-unit correlations with transect measurements (fig. 6), and for the stratigraphic model (on the right) from stacks of the six stratigraphic units that are assigned valley-wide shear-velocity values. On the soil-model map (left) the red dots show Vs30 measurement locations. Only the transect and SGS measurements were used in developing the soil model. On the stratigraphic-model map (right) some measured Vs30 values are overlain on the model predictions within 1 km of the site (dashed circles). All 79 measurements were used in developing the stratigraphic model.

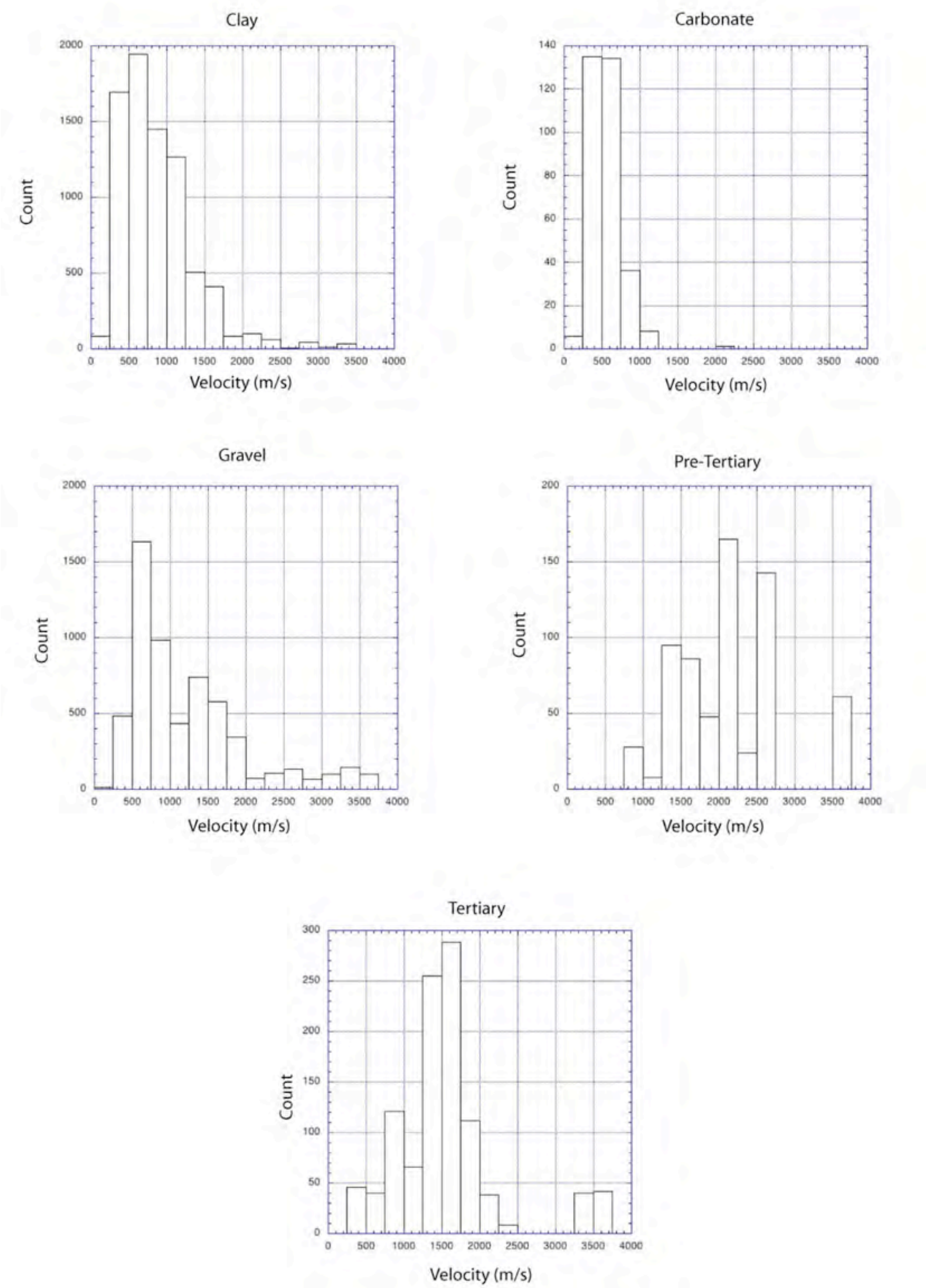

Fig. 7: Occurrences of velocities (from Vs versus depth profiles) for five of the six summary stratigraphic units, where they are coincident with the 79 Vs30 measurements in the transect and around the Valley. The Vs measurements and corresponding stratigraphic units of the well logs for the 79 boreholes were recorded at one-meter intervals (giving a total of 15,600 "counts") to develop the histograms. The units in the stratigraphic model were assigned the shear velocity at their mode of occurrence Valley-wide. There was no data for the sand unit.

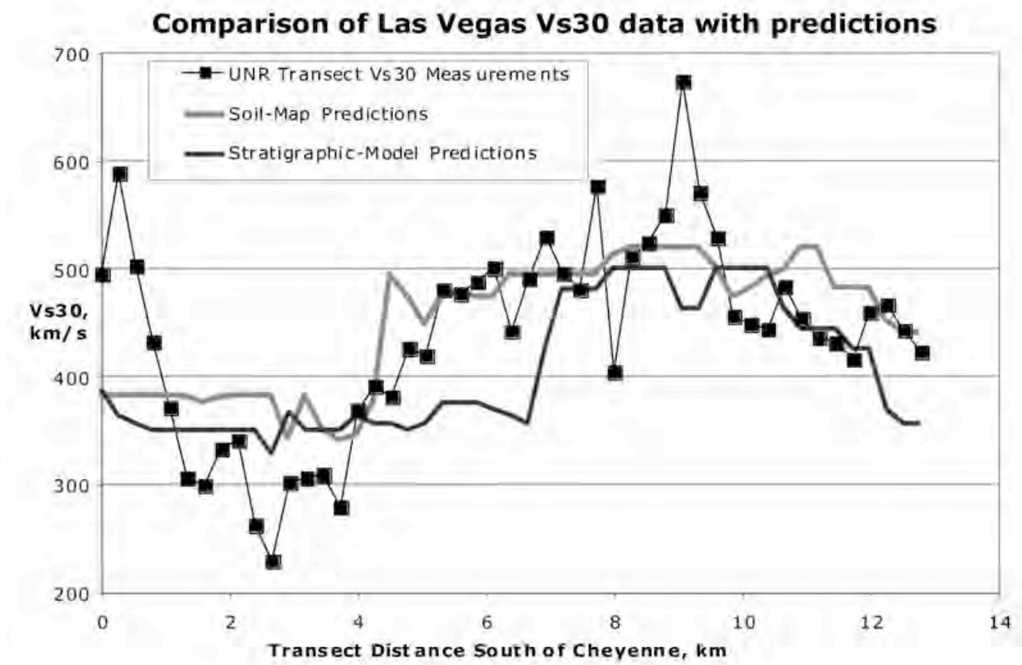

Fig. 8: Predictions of Vs30 compared to measured values along our transect, from both the soil-map and stratigraphic models. Refer to fig. 1 for geographical references for transect distances.

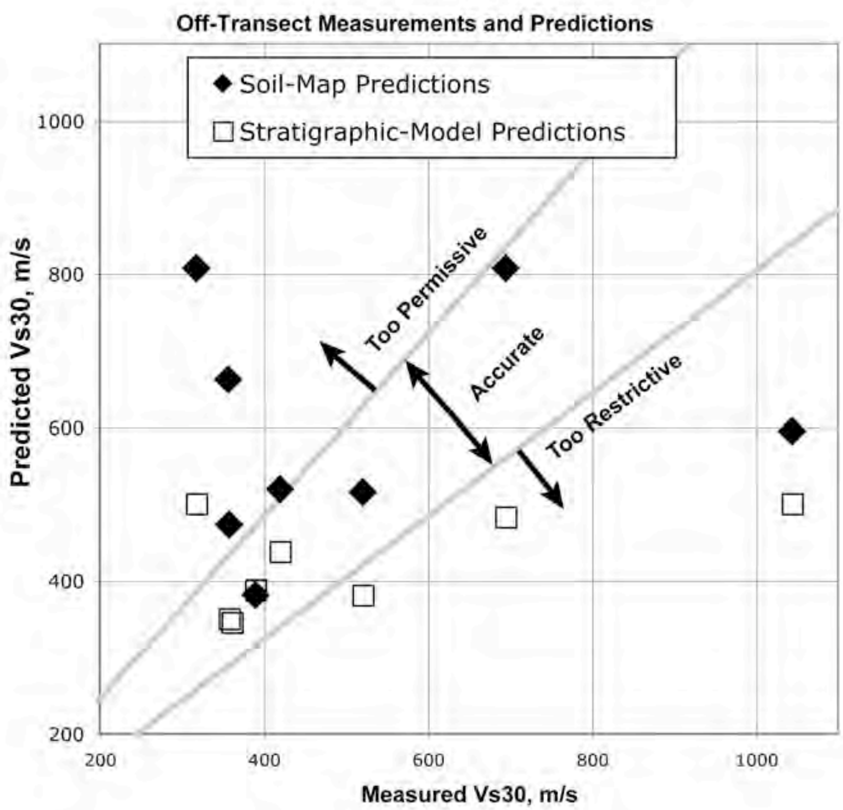

Fig. 9: Predicted vs. measured Vs30 based on soil-map and stratigraphic models for eight sites located off-transect. The two gray lines enclose the area where the predicted Vs30 would be accurate within ±20% of the measured Vs30.